FOURTH SWARM SCIENCE MEETING
AND GEODETIC MISSIONS WORKSHOP

ESA's magnetic field and geospace explorer
constellation mission widening the context

ABSTRACT BOOK

20–24 March 2017 | Banff, Alberta, Canada
Fourth Swarm Science Meeting
&
Geodetic Missions Workshop

20 - 24 March 2017
Banff, Alberta, Canada

Last update: 13 March 2017
# Table of Contents

## 1PM1: Mission status and overview ........................................................................................................................................

1. The Status of Swarm: from Core to Magnetosphere Three and a Half Years after Launch .................................
2. Geomagnetic Field Modeling Efforts with Swarm – What is Possible with the Present Data and What are Future Opportunities? ..........................................................................................................................................
3. Swarm Instruments Status and Data Quality after Three Years in Operations ....................................................
4. Swarm Flight Dynamics Operations Experiences and Mission Analysis ...............................................................
5. New Synergistic Opportunities for Magnetosphere-Ionosphere-Thermosphere Coupling Investigations Using Swarm and CASSIOPE e-POP .................................................................................................................................

## 1PM2: Deep Earth I ...................................................................................................................................................

1. Keynote: Geomagnetic Data Assimilation And Modeling Of Core Field Changes ..............................................
2. An Accelerating High-latitude Jet in Earth's Core .................................................................................................
3. Modelling of Geomagnetic Secular Variation with Swarm: Past, Present and Future .........................................
4. Ultra Low Viscosity Geodynamo Models With Scale Separation ..........................................................................
5. Application of Swarm Measurements to Data Assimilation Studies of Core Dynamics ...............................
6. On Zonal Flows and Axial Dipole Field Changes ...................................................................................................  

## 2AM1: Aurora ...........................................................................................................................................................

1. Alfvénic Dynamics and Structuring of Discrete Auroral Arcs: Swarm and e-POP Observations ..........................
2. Optical Signatures of Field Line Resonances: Comprehensive Survey and Precipitation Mechanisms ...........
3. Swarm Observation of Field-Aligned Currents In Multiple Arc System .................................................................
4. Ionospheric Electron Heating Associated With Pulsating Auroras --- Swarm Survey and Model Simulation ..... 
5. Aurorasaurs Citizen Science Observations of Aurora During the Solar Maximum ...........................................

## 2AM2: Deep Earth II..............................................................................................................................................

1. Temporal Variability In Core Surface Flows Inferred From Satellite ‘Virtual Observatory’ Secular Variation ....
2. Keynote: Earth Dynamics: The big picture ...........................................................................................................
3. Simultaneous Inversion of Magnetospheric and Tidal Satellite Signals Constrain Electrical Conductivity from Crust to Mid-Mantle ..............................................................
4. Global Shallow-Earth Structure Models Hand in Hand with Satellite Gravimetry ...........................................
2PM1: Novel analysis methods for geophysics and geospace research .................................................................19

Examining the Current and Magnetic Perturbations at LEO Altitude Due to Plasma Pressure Gradient and Gravity Forces ..............................................................................................................................................19

Separating Earth’s Internal and External Field in SWARM Observations with the Help of Global Magnetosphere - Ionosphere - Thermosphere Simulations ........................................................................................................19

An Analysis of Ionospheric Versus Oceanic Tidal Magnetic Signals .........................................................................20

The lithospheric Magnetic Field Measured by the Swarm Satellite Constellation ..........................................................20

Hemispherical Differences in the Ionospheric Current System as Seen by Swarm and CHAMP ..............................21

Identifying Intervals of Spatio-Temporally Invariant Field-Aligned Currents from Swarm: Assessing the Validity of Single Spacecraft Methods ..............................................................................................................21

2PM2: Ionosphere ..........................................................................................................................................................21

Keynote: GNSS-Based Studies of the Ionosphere and the Role of Swarm and Complementary Missions ...........21

The Canadian Ionosphere and Atmosphere Model and Its Application in Support of Satellite Missions ..........22

Atmospheric Signatures in the EEJ During Stratospheric Warming Events and Comparison Between Ground and Space Based Magnetic Observations .........................................................................................22

Observation and Modeling of Ionospheric Equinoctial Asymmetry ........................................................................22


3AM1: Remote sensing of earthquakes, lightning and radiation belts ........................................................................23

Swarm Satellite Data Analysis For Earthquake Preparatory Phase Studies ....................................................................23

The Search of the Cross Correlation Between the Ground Based and Swarm Registration of the Thunderstorms and TLE’s Effects ...............................................................................................................................24

Lightning-Generated Whistlers Observed during ASM Burst Mode Sessions ...................................................................24

The Contribution of CSES Mission to Study Lithosphere-Atmosphere-Ionosphere Coupling Phenomena Through the Analysis of Combined Missions Data and Ground Measurements ..............................................................24

How Swarm Can Help Solve the Mystery of Extremely Fast Ultra-Relativistic Electron Loss in the Outer Van Allen Radiation Belt ........................................................................................................25

10-year Time Series of GNSS Daily Solutions, Geomagnetic Storms and Biggest Earthquakes ....................................26

3AM2: Equatorial ionosphere .........................................................................................................................................26

Evolution of Swarm-derived Equatorial Electrojet Signatures Using Vector Magnetic Measurements .....................26

Constellation Strategies for Observing Plasma Bubbles in the Terrestrial Ionosphere ........................................................26

Relation Between Diamagnetic Effects and Formation of the Nighttime Ionospheric Plasma Density Enhancements ........................................................................................................................................27

Electromagnetic Features of Equatorial Field Aligned Plasma Irregularities as Observed by the Swarm Mission ..............................................................................................................................................27

3PM1a: Satellite geodesy missions today I ......................................................................................................................27

Keynote: Geodetic Space Sensors for Height System Unification and Absolute Sea Level Determination ............27
Keynote: GNSS-Augmented Radar Transponders for InSAR Datum Connection

Potential of Global SAR Positioning for Geodetic Applications – Lessons Learned from TerraSAR-X and Sentinel-1

European Gravity Service For Improved Emergency Management

Near Realtime Mass Transport Products for Monitoring of Hydrological Extreme Events

3PM1b: Quasi-static coupling of the magnetosphere-ionosphere-thermosphere system

Keynote: A Swarm Perspective on M-I-T Coupling

Longitudinal Gradients in Ionospheric Currents as Deduced with the Method of Spherical Elementary Current Systems

Evidence That Field-Aligned Currents Do Not Saturate

Unified Global and Local Perspectives on High-latitude Ionospheric Electrodynamics

Poynting Flux Estimation from Electric and Magnetic Field Data of the Swarm Constellation

Birkeland Current Boundary Flows

3PM2a: Future of geodesy from space

Keynote: New Missions for Improving the Terrestrial Reference Frame: Means and Impacts

Current Status of the GRACE Follow-On Mission


Towards a Sustained Observing System for Mass Transport to Understand Global Change and to Benefit Society

Impact of Orbit Design Choices on the Gravity Field Retrieval of Next Generation Gravity Missions - Insights on the ESA-ADDCON Project

GOCE and Beyond: Status and Activities

3PM2b: Magnetosphere-ionosphere-thermosphere coupling: turbulence and waves

Keynote: Magnetic Field Turbulence and Scaling Features in the Polar Ionosphere: Results from Swarm Mission

Diagnosing the Electrodynamics of Magnetosphere-Ionosphere Coupling Using the Swarm Satellite Constellation: The Role of Alfven Waves?

Ion Energization Processes Observed by ePOP, DMSP, and SWARM

Statistical Analysis of the Field-Aligned Currents in the Cusp with Swarm

FLR Event Studies With SWARM-SuperDARN Conjunctions

Coordinated Swarm In Situ and THEMIS All Sky Imager (ASI) Observations of the Motion of Patchy Pulsating Aurora

4AM1: Cryosphere & geodesy

Large Precipitation Event Influences Sub-Glacier Hydrology and Ice Flow of Recovery Ice Stream, East Antarctica

Estimate of Regional Glacial Isostatic Adjustment in Antarctica Considering a Lateral Varying Earth Structure (ESA-STSE Project REGINA)

Arctic Gravity Field from Cryosat-2
High-Resolution Mass Changes of the Greenland and Antarctica Ice Sheets from Combined CryoSat and GRACE Inversion .................................................................36
High Mountain Asia Glacier Mass Balance Estimates Using Satellite Geodetic Observations .........................37
4PM1: Upper mantle and lithosphere ..................................................................................................................37
Keynote: With GOCE and Swarm Towards the 3D Lithosphere ........................................................................37
Large-Scale Constraints on Tectonics and Macroscopic Magnetic Properties of the Earth's Lithosphere from the Swarm Constellation and CHAMP .................................................................37
A New Lithospheric Field Model based on CHAMP and Swarm Magnetic Satellite Data ...............................38
An Updated Global lithospheric Model by Implementing 3D Joint Inversion of Gravity, Geoid, Topography and the Gravity gradients in Spherical Coordinates .........................................................38
Imaging Small-scale Seafloor and Sub-seafloor Tectonic Fabric Using Satellite Altimetry ...............................39
4PM2: Satellite geodesy missions today II ...........................................................................................................39
Towards the best GOCE Gravity Gradients ...........................................................................................................39
GOCE Southern Polar Gap now Closed – Results of the ESA Antarctica PolarGap Project ............................39
The Status and Current Contributions of the GRACE Mission ........................................................................40
GRACE High-Frequency Temporal Gravity Solution on Hydrology Applications .............................................40
Swarm as an Observing Platform for Large Surface Mass Transport Processes ...............................................41
HISST And SLR - Bridging the Gap Between GRACE and GRACE-Follow On ................................................41
5AM1: Thermosphere ........................................................................................................................................41
Keynote: Thermosphere-Ionosphere-Magnetosphere Modeling and Validation Efforts Using SWARM, CHAMP, and GOCE Measurements .................................................................41
Models and GOCE Measurements of Thermosphere Density and Wind Below 250 km ...............................42
Spatio-temporal Variability of Thermospheric Density using ESA (Swarm mission) Data .................................43
Swarm Mass Density and Plasma Observations During the St. Patrick's Day Storm Event 2015 and its Global Numerical Modelling Challenges ..................................................................................43
Detection of Thermospheric Density Variations via Spacecraft Accelerations Observed Using the CASSIOPE GAP Instrument .................................................................43
5AM2: The future: extended mission, future missions ........................................................................................44
Investigation of a Future Constellation Geometry and Orbit Evolution of the Swarm Mission ..........................44
Nanosatellite Space Physics: Multispacecraft Missions Inspired by Swarm ....................................................44
Aiming at Enhancing the Science Return of the Swarm Mission: the Swarm Delta NanoMagSat Project ........44
Poster Session ..................................................................................................................................................47
Three Times Three: Three Years of Swarm Routine Operations and Beyond ..................................................47
CASSIOPE e-POP Mission Development and Operation ..................................................................................47
Options for the Swarm Orbit and Constellation Evolution ...............................................................................47
SWARM Instruments Performance Issues since Commissioning: Identification and Mitigation ..................48
Swarm Payload Data Ground Segment: Status and Future Outlook .............................................................48
"VirES for Swarm" - Evolution of the Swarm Data Visualisation Tool .............................................................48
Swarm Data Exploitation and Valorisation at CDPP .................................................................................................................. 49
Swarm Magnetic Data Quality Overview .................................................................................................................. 49
Statistical Analysis of Geomagnetic Field Intensity Differences between ASM and VFM Instruments Onboard Swarm Constellation ............................................................................................................................................. 49
Recent Results from Analysis of the Sun Induced Magnetic Disturbance .......................................................................................................................... 51
Searching for the Cause of Small, but Systematic, Magnetic Field Anomalies Observed on Board the Swarm Satellites when Flying in non-Nominal Attitudes .......................................................................................................................... 51
A Comparison of Three Years of Swarm experimental ASM-V and Nominal VFM Data Using a Global Geomagnetic Field Modeling Approach ............................................................................................................................................. 51
An Overview of Results from the Flux-gate Magnetometer on the C/NOFS Satellite ............................................................................................................................................. 51
Particle-in-cell Modeling of Interaction Between Nanosatellite And Ionosphere ............................................................................................................................................. 52
The Swarm Langmuir Probes: Status and Ongoing Activities ............................................................................................................................................. 52
Swarm Thermal Ion Imager Instruments: Overview and Operational Status ............................................................................................................................................. 53
CSES Electric Field Detector Calibration Tools Based on IRI, IGRF, and SWARM Data ............................................................................................................................................. 53
Overview of Swarm Accelerometer Data Quality ............................................................................................................................................. 53
Improvements of the Swarm Accelerometer Data Processing ............................................................................................................................................. 54
Swarm DISC: New Swarm Products and Services ............................................................................................................................................. 54
Swarm SCARF Comprehensive Inversion, 2017 Production ............................................................................................................................................. 54
Swarm Level-2: Dedicated Core Field Model (DCO) ............................................................................................................................................. 54
Recent BGS Activities for the Swarm Data Innovation and Science Cluster ............................................................................................................................................. 55
The Canadian Cordillera Array (CCArray): Taking Earth-Based Observations to the Next Level ............................................................................................................................................. 55
Review of Data Recorded by the e-POP Radio Receiver Instrument (RRI) ............................................................................................................................................. 55
Statistical Characterisation of Penetrating Radiation Fluxes near 500 km Altitude Based on Swarm EFI Thermal Ion Imager CCD Artefacts ............................................................................................................................................. 56
Signature of the Inner Core in Surface Core Flow Variations ............................................................................................................................................. 56
A Quasi-Geostrophic Magnetoconvection Model of the Decadal Zonal Flow Dynamics in Earth’s Core ............................................................................................................................................. 56
Gravity Signal of the Crust-Mantle Boundary and Density Structures in this Region ............................................................................................................................................. 57
Swarm-Aurora: Identifying Auroral Conjunctions Using an Online and Offline Cross-Platform Set of Tools ............................................................................................................................................. 57
New Insight into Auroral Arc Microphysics from e-POP ............................................................................................................................................. 57
Inferring Ionospheric Convection from Sequences of Auroral Images: A Complement to Swarm EFI ............................................................................................................................................. 58
The Isinglass Auroral Sounding Rocket Campaign ............................................................................................................................................. 58
A Localized Lithospheric Magnetic Model of Australia Incorporating Spectrally Diverse Aeromagnetic and Satellite Observations ............................................................................................................................................. 58
Localized Crustal Magnetic Vector and Gradient Anomaly Components of the Antarctic from a Global Spherical Harmonic Model of the Swarm Observations ............................................................................................................................................. 59
A Regional Geomagnetic Secular Variation Model of East Asia Using Spherical Slepian Functions ............................................................................................................................................. 59
Distribution of the Magnetic Anomaly for the Swarm Satellite in China and Adjacent Area ............................................................................................................................................. 59
Balloon Gradient Magnetic Research at Altitudes of 20-40 Km in Addition to the Project "Swarm" ............................................................................................................................................. 60
Using Variable Quad Geometry to Better Characterize the Field-Aligned Currents with Swarm

A New Approach for Retrieving Time Series of External and Internal Spherical Harmonic Coefficients Describing Signals of Magnetospheric Origin

On the Role of Fine-Scale Non-Stationary Magnetic Field Perturbations in FAC Systems: Swarm Satellite Observations

The Revised Time-Frequency Analysis (R-TFA) Tool of the Swarm Mission

In Situ Measurements in Perturbed Plasma

Magnetic Remote Sensing of Ocean Heat Content

Observations of the Drift of Plasma Depletions Using SWARM Constellation and LISN TEC Measurements

Characteristics Of Polar Cap Patches Observed By Multi-Instruments

American Polar Cap Patches are Denser and more Structured than European Ones

Analysis of Ionospheric Patches Based on Swarm Langmuir Probe and TEC Data

Characteristics of Electron Density Variations at Equator Crossings

Comparison between IRI and Electron Density Swarm Measurements during the St. Patrick Storm Period

NeSTAD: A Tool to Tag Electron Density Anomalies with Swarm Data

Relationship between Plasma Density Gradients and Swarm GPS Data

Ground Based Kinematic GNSS Contribution Dealing with Space Weather Observations

Swarm for Space Weather monitoring

Determination of CASSIOPE Topside Ionospheric Total Electron Content Using GPS Precise Point Positioning Techniques

Modeling the Sq and Equatorial Electrojet Magnetic Fields from 3 years of Swarm Data

Exploring the Development of GICs Related to Large dB/dt Variations in Space

Swarm Observations of ULF Pulsation Activity and the August 2016 Central Italy Earthquake

Ionosphere Precursors before Large Earthquakes

Quasi Simultaneous Tropical Cyclone And Earthquake Action On The Ionosphere

Analysis of Local Anomalous Characteristics of Lithospheric Magnetic Field before Pishan M6. 5 Earthquake in Xinjiang in 2015

Detecting Seismic Anomalies from Satellite and Ground Based Electromagnetic Data Using Big Data Analytics Approaches

Statistical Analysis of Magnetic Field Disturbances Before Major Earthquakes Based on the DEMETER Magnetic Waveform Data

Occurrence Of Schumann Resonances In Swarm ASM Burst Mode Data

Using Swarm For Gravity Field Determination – An Overview After 3+ Years In Orbit

Estimation of Mass Variations in Greenland Using Leakage-Reduced GRACE Data

Geoid Requirements for Height Systems and their Unification

Low-Degree Temporal Gravity Field Solution from SWARM Constellation of Satellites Using the Energy Balance Approach

Time Variable Gravity Field and Ocean Mass Change From SWARM Data
Continental Grids of Disturbing Gravity Tensor Components over North America ............................................. 71
Impact Of Wiese-Approach In The Mitigation Of Ocean-Tide Aliasing Errors In Monthly GRACE Gravity Field Solutions ...................................................................................................................................................... 71
Combined Swarm/Sentinel Gravity Fields ............................................................................................................ 71
ESA's Studies of Next Generation Gravity Mission Concepts .................................................................................. 71
Cold Atom Interferometers Used in Space (CAIUS) for Measuring the Earth’s Gravity Field .............................. 72
GNSS-SLR Co-Location On-Board GNSS Satellites: Possible Contribution to the Realization of Terrestrial Reference Frames ............................................................................................................................... 72
Effect of Swarm A/C Orbital Configuration and Magnetic Field Inclination on the Spherical Elementary Current Systems (SECS) Analysis Method .......................................................................................................................... 72
A Tentative Procedure to Assess / Optimize the Swarm Electric Field Data and Derive the Ionospheric Conductance in the Auroral Region ................................................................................................................. 73
Field-Aligned Current Response to Increasing Solar Indices .................................................................................. 73
Analysis of Thick, Finite, and Non-Planar Field-Aligned Currents in the Polar Regions with Swarm Magnetic Field Measurements ............................................................................................................................................. 73
Multi-point Analysis of Current Structures in the Inner Magnetosphere ................................................................. 73
Energy Input to the Ionosphere-Thermosphere Due to Inductive Coupling with the Magnetosphere ........... 74
Dynamics of CME and HSS Storms Revealed from Auroral Imaging and Field aligned Currents .................. 74
Magnetopause Erosion During the March 17, 2015, Magnetic Storm: Combined Field-Aligned Currents, Auroral Oval, and Magnetopause Observations .................................................................................................................. 75
Electromagnetic ULF Wave Energy Leakage through the Ionosphere as Observed by Low-Orbiting Satellites SWARM and Ground AMBER Array ........................................................................................................................................................................ 75
Strong Ambipolar-driven Ion Upflow Within the Cleft Ion Fountain During Low Geomagnetic Activity ......... 75
Diagnosing the Topside Ionosphere Using Synchronous E- and B-field Measurements from the Swarm Satellite Constellation ......................................................................................................................................................... 76
Interpretation of the Impedence Spectrum in the Ionospheric Alfvén Resonator .............................................. 76
Validation of a Comprehensive Numerical Model of Ionosphere by Comparison with EISCAT Observations..... 76
Pc1 Wave Observations in the Topside Ionosphere with Swarm Satellites ............................................................... 77
Modelling Anisotropic Temperature Ratios in the Weakly Collisional Altitude Region Observed by Swarm ..... 77
Satellite Gradients for Lithospheric Modelling – Sensitivity Tests Over the Northern Segment of the Trans-European Suture Zone ...................................................................................................................................................... 77
Constraining Lateral Variations of Upper-Mantle Electrical Conductivity Using Satellite-Detected Tidal Magnetic Signals ..................................................................................................................................................... 78
Linking GIA and Lithospheric Structure of Antarctica with Satellite Gravity Gradients .................................. 78
Processing and Analysis of Satellite Gravity and Magnetic Data for Modelling the Lithosphere in Framework of 3D Earth ........................................................................................................................................................................ 78
Impact of Heat Flow and Laterally Varying Susceptibility on the Crustal Field .................................................... 78
Global Thermochemical Imaging of the Lithosphere Using Satellite and Terrestrial Observations ................. 79
Analysis of Lithospheric Stresses Using Satellite Gravimetry: Hypotheses and Applications to North Atlantic .80
2 Committees

ORGANISING COMMITTEE

• Rune Floberghagen
• Roger Haagmans
• David Knudsen
• Michael Sideris
• Pierre Langlois
• John Manuel
• Giuseppe Ottavianelli
• Mike Rast
• Diego Fernandez Prieto
• Tommaso Parrinello
• Simonetta Cheli
• Anne-Lisa Pichler
• Jerome Benveniste

SCIENTIFIC COMMITTEE

• Patrick Alken
• George Balasis
• Aleš Bězdek
• Stephan Buchert
• Johnathan Burchill
• Jörg Ebbing
• Gauthier Hulot
• Andrew Jackson
• Adrian Jäggl
• Kirstie Kauristie
• Mioara Mandea
• Octav Marghitu
• Stefan Maus
• Nils Olsen
• Terence Sabaka
• Claudia Stolle
• Alan Thomson
• Pieter Visser
• Kathy Whaler
• Andrew Yau
Abstracts

The Status of Swarm: from Core to Magnetosphere Three and a Half Years after Launch
Floberghagen R., Haagmans R., Swarm Team
European Space Agency

The ESA Earth Observation Swarm satellite mission, a constellation of three satellites to measure the Earth’s magnetic and electric fields as well as the neutral environment, was launched on November 22, 2013. The mission delivers observations that provide new insight into the Earth system by improving our understanding of the Earth’s interior as well as the near Earth electro-magnetic environment. The unprecedented high-accuracy and high spatial resolution measurements of the strength, direction and time variations of the magnetic field, complemented by precise navigation, accelerometer and electric field measurements, provide the required observations to model the various sources of the geomagnetic field.

Swarm is ESA’s fourth Earth Explorer mission This innovative mission is dedicated to identifying and measuring, very precisely, the different magnetic signals that stem from Earth’s core, mantle, crust, oceans, ionosphere and magnetosphere – which together form the magnetic field around Earth. Analysing how it changes over time, provides new insights into our planet’s interior and near-Earth environment. This presentation will include the mission status a three and a half years after launch and focus also on the mission objectives, products studies and result. Evidently, the magnetic field behaviour at present indicates that it is as one of the fastest changing variables related to global change. Meanwhile, it is clear that new science beyond the original objectives of Swarm has already emerged. The presentation will report on these aspects and what can be expected in the near future.

Geomagnetic Field Modeling Efforts with Swarm – What is Possible with the Present Data and What are Future Opportunities?
Olsen N., Tøffner-Clausen L., Finlay C.C.
Technical University of Denmark, Denmark

We discuss field modeling efforts based on more than 3 years of Swarm satellite data, with focus on the additional information that is provided by the East-West gradients (approximated by the difference between Swarm Alpha and Charlie) and the North-South gradient (approximated by the along-track first differences of each satellite). We also present results of experiments concerning the future development of the Swarm constellation mission over the next decade.

Swarm Flight Dynamics Operations Experiences and Mission Analysis
Sieg D.1, Petrucciani F.2, Ziegler G.3
1ESA/ESOC, Germany; 2CS GmbH at ESA/ESOC, Germany; 3SCISYS Deutschland GmbH at ESA/ESOC, Germany

The three satellites of ESA’s magnetic field mission Swarm were launched into a common low Earth circular orbit in November 2013. Since completion of the orbit acquisition phase in April 2014 one satellite (B) is flying in a higher orbit with an inclination of 87.8 deg and an altitude decaying from 520 km. The other two satellites (A/C) form the lower pair with an initial altitude of 473 km, an inclination of 87.4 deg and an ascending node difference of 1.4 deg.

The paper gives an overview about the observed orbit evolution, the fuel consumption and the constellation maintenance operations which have been performed by the Flight Dynamics Division at ESA/ESOC. Latest simulation results about the future orbit evolution and
as an added component to the Swarm satellite. Unique measurement capabilities of CASSIOPE e-POP, particularly altitude and local time, coverage and advantage of the complementary nature of the orbital thermosphere (MIT) coupling investigations, by taking

We present a recent study to identify new synergistic Geosciences, Germany

Canada; 8GFZ German Research Centre for Physics. GDC will characterize and understand the global dynamics and momentum exchange between ionized/neutral gases at all latitudes including their coupling and feedback to the magnetosphere and their response to forcing from below. A comprehensive mission is envisioned in which measurements are continuously gathered of state parameters and their drivers on multiple, identical satellites with near-polar, circular orbits evenly spaced in local time. (Notionally, we consider 6 satellites providing measurements of 12 local times every 90 min.) Furthermore, GDC will carry out these measurements at low altitudes (i.e., 300-400 km) where the neutral and plasma gases are strongly coupled through dynamical and chemical processes.

GDC will reveal the global dynamics of the gas populations and how they influence their number density and composition. It will carry out this in-depth investigation during both quiet and disturbed conditions, promising to reveal, in particular, how the ionosphere/upper atmosphere responds at all latitudes during storms. It will provide the global patterns and interplay of mid- and low-latitude plasma drifts and winds as a function of magnetic activity and IMF, both above and below the F-peak. Continuous sampling at high rates addresses shorter scale, highly dynamic phenomena.

New Synergistic Opportunities for Magnetosphere-Ionosphere-Thermosphere Coupling Investigations Using Swarm and CASSIOPE e-POP


University of Calgary, Canada; ESRIN, Italy; Delft University of Technology, Netherlands; Institute de Physique du Globe de Paris, France; University of New Brunswick, Canada; University of Alberta, Canada; Technical University of Denmark, Denmark; GFZ German Research Centre for Geosciences, Germany

We present a recent study to identify new synergistic opportunities for magnetosphere-ionosphere-thermosphere (MIT) coupling investigations, by taking advantage of the complementary nature of the orbital (particularly altitude and local time) coverage and unique measurement capabilities of CASSIOPE e-POP, as an added component to the Swarm satellite constellation under European Space Agency’s Third Party Mission programme.

The coordinated operation of the e-POP payload with Swarm, in particular the Magnetic Field (MGF), GPS-receiver-based Attitude, Positioning and Profiling (GAP) and Fast Aurora Imager (FAI) instruments, will enable or enhance a host of new investigations on the Earth’s magnetic field and related current systems, upper atmospheric dynamics, auroral dynamics, and related MIT coupling. These include (a) magnetic field perturbations at high latitudes, specifically their small scale structures, altitude distribution and longitudinal extent; (b) thermospheric density variations, plasma density irregularities, and density forecasts for orbit prediction; and (c) electrodynamics of the auroral arcs and magnetosphere-ionosphere coupling.

These investigations are expected to contribute significantly to two of Swarm’s four primary research objectives, and to advance our fundamental knowledge on MIT coupling and the effects of associated space weather processes on the Earth’s magnetic field and its ionosphere and thermosphere.

Keynote: An Overview of the Scientific and Space Weather Motivation for the “Notional” Geospace Dynamics Constellation Mission

Pfaff R., Rowland D.

NASA/GSFC, United States of America

The Geospace Dynamics Constellation (GDC) is a strategic mission recommended as NASA’s next major Living With a Star (LWS) initiative by the NAS/NRC Committee on a Decadal Strategy for Solar and Space Physics. GDC will characterize and understand the global dynamics and momentum exchange between ionized/neutral gases at all latitudes including their coupling and feedback to the magnetosphere and their response to forcing from below. A comprehensive mission is envisioned in which measurements are continuously gathered of state parameters and their drivers on multiple, identical satellites with near-polar, circular orbits evenly spaced in local time. (Notionally, we consider 6 satellites providing measurements of 12 local times every 90 min.) Furthermore, GDC will carry out these measurements at low altitudes (i.e., 300-400 km) where the neutral and plasma gases are strongly coupled through dynamical and chemical processes.

GDC will reveal the global dynamics of the gas populations and how they influence their number density and composition. It will carry out this in-depth investigation during both quiet and disturbed conditions, promising to reveal, in particular, how the ionosphere/upper atmosphere responds at all latitudes during storms. It will provide the global patterns and interplay of mid- and low-latitude plasma drifts and winds as a function of magnetic activity and IMF, both above and below the F-peak. Continuous sampling at high rates addresses shorter scale, highly dynamic phenomena.
An overview of the notional GDC mission is presented, including remarks on the number of satellites and time constants needed to capture key global processes. Notional instruments include in situ probes to measure neutral and ion gas properties, fields, and energetic particles. Sounders, Fabry-Perot interferometers and other instruments are candidates as well. Key mission elements include a strong ground-based component, as well as a strong theory and modeling component, important for mission definition and data analysis.

With these comprehensive, simultaneous measurements at all local times, GDC will generate unprecedented knowledge for data-starved models and space weather applications, while providing breakthroughs in our understanding of how the ionosphere-thermosphere behaves as a system.

************************

Keynote: Geomagnetic Data Assimilation And Modeling Of Core Field Changes

Gillet N.
ISTerre, France

The past decade has seen the advent of geomagnetic data assimilation techniques. These aim at considering together information from both magnetic records (historical, ground-based, satellite...) and from a dynamical model advecting the state of the Earth’s outer core. I will review the several avenues considered by our community. Important advances have been recently performed concerning the forward integration of three-dimensional geodynamo simulations, that time-step primitive equations (induction, momentum, heat). Run at today’s extreme parameters they show Earth-like features (e.g. non-axisymmetric equatorial westward drift, torsional waves), but nevertheless struggle to produce a magnetic energy as important as it is the case in the core, enhancing dissipation and thus filtering MHD waves possibly important for the interpretation of magnetic observations. Alternative strategies have thus been followed, with promising (although not yet operational) reduced models involving e.g. the quasi-geostrophic assumption or large-eddy simulations. I will also show that whatever the employed model, it is mandatory to consider the unmodelled physics (through e.g. stochastic representation of the unresolved quantities) in order to obtain an unbiased estimate of the core dynamics.

************************

An Accelerating High-latitude Jet in Earth’s Core
Livermore P., Finlay C., Hollerbach R.

1School of Earth and Environment, University of Leeds, United Kingdom; 2DTU Space, Technical University of Denmark, 2800 Kgs. Lyngby, Copenhagen, Denmark; 3School of Mathematics, University of Leeds, United Kingdom

Observations of the change in Earth’s magnetic field, the secular variation, provide information on the motion of liquid metal within the core that is responsible for its generation.

The very latest high-resolution observations from ESA’s Swarm satellite mission show intense field change at high-latitude localised in a distinctive circular daisy-chain configuration centred on the north geographic pole.

Here we explain this feature with a localised, non-axisymmetric, westwards jet of 420 km width on the tangent cylinder, the cylinder of fluid within the core that is aligned with the rotation axis and tangent to the solid inner core. We find that the jet has increased in magnitude by a factor of three over the period 2000-2016 to about 40 km/yr, and is now much stronger than typical large-scale flows inferred for the core.

The current accelerating phase may be a part of a longer term fluctuation of the jet causing both eastwards and westwards movement of magnetic features over historical periods, and may contribute to recent changes in torsional wave activity and the rotation direction of the inner core.

************************

Modelling of Geomagnetic Secular Variation with Swarm: Past, Present and Future
Brown W.
British Geological Survey, United Kingdom

The magnetic field generated by the motion in Earth’s fluid outer core is by far the largest contribution to the geomagnetic field. The shape and intensity of this field changes through time (known as secular variation), occasionally in unpredictable ways. We observe this field evolution with missions such as the Swarm constellation. From such measurements, models of the geomagnetic field can be built to study the temporal and spatial variations, from the core’s surface to satellite altitudes.

We present results derived from the latest iteration of the BGS Model of the Earth’s Magnetic Environment (MEME), updated with the latest Swarm and ground observatory data from 2017 as well as data from previous satellite missions CHAMP and Ørsted. Given that recent secular variation has been significant in some regions, with rapid variations known as geomagnetic jerks observed in 2014 and 2015, we assess how well these changes are captured by this model, particularly when in close proximity to the end of the data span. We also look ahead to the state of the geomagnetic field in the near future as predicted by
extrapolation of MEME and provide an outlook with respect to the possible future orbit evolutions of the Swarm satellites.

******************************

**Ultra Low Viscosity Geodynamo Models With Scale Separation**
Jackson A.1, Sheyko A.1, Finlay C.2
1ETH Zurich, Switzerland; 2Danish Technical University, Denmark

The mechanism by which the Earth’s magnetic field is generated is thought to be thermal convection in the metallic liquid iron core. Energy is converted into magnetic fields by motional induction, which creates electric currents from the convection and thus creates magnetic fields. Computational considerations previously restricted most numerical simulations to a regime where the diffusivities of momentum and electric current are roughly equal, leading to similar spectra for both velocities and magnetic fields. Here we present results of spherical shell computations where, in some cases, there is a twenty-fold difference in the aforementioned diffusivities, leading to significant scale separation between magnetic and velocity fields, the latter being dominated by small scales. When the magnetic diffusivity is larger than the momentum diffusivity by a large factor (a regime rarely simulated in a spherical dynamo), this leads to a likelihood that self-exciting dynamos will die; such dynamos are, however, possible when the Ekman number is similarly reduced to values lower than previously used, of $O(10^{-7})$. Our dynamos dissipate energy primarily through Ohmic dissipation and we show how this scales with magnetic energy. This permits a new estimate of the Ohmic dissipation in the core of 2-STW.

******************************

**Application of Swarm Measurements to Data Assimilation Studies of Core Dynamics**
Finlay C.1, Barrois O.2, Hammer M.1, Gillet N.2
1DTU Space, Denmark; 2ISTERRE, Université Grenoble 1, CNRS 1381, France

Time variations of the core-generated magnetic field can be monitored, on timescales of months and longer, using robust mean estimates of the vector magnetic field on a global grid of reference locations. Here, we present results from this approach, known in the literature as "Virtual Observatories" (VO) (Mandea and Olsen, 2006; Olsen and Mandea, 2007), as applied to data from Swarm and CHAMP, and taking advantage of along-track and across-track field differences. Comparisons with ground observatories and the CHAOS-6 field model will be used to illustrate the quality of the secular variation point estimates.

The next generation of models of core dynamics will be based on data assimilation techniques, that is the combination of magnetic observations with physics-based models of core MHD. A serious obstacle to this goal is presently the lack of suitable observation-based data covariance information - this is essential in order to optimally adjust the model to fit the observations. Preliminary attempts at data assimilation have been based primarily on spherical-harmonic field models but these typically have no (or very limited) covariance information due to the difficulty of estimating covariance properties for the very large number of instantaneous satellite data. Point estimates of secular variation from Swarm data provide a way round this problem: deriving observation-based covariances for a global grid of say 250 locations, and considering mean values over a month or longer rather instantaneous measurements, is feasible. As an example, we shall briefly discuss our efforts to assimilate Swarm data into a model of core dynamics based on geodynamo simulation statistics.

******************************

**On Zonal Flows and Axial Dipole Field Changes**
Dumberry M.1, Schaeffer N.2
1University of Alberta, Canada; 2ISTERRE, Université Grenoble Alpes, France

First noted a few decades ago, there is a good temporal correlation between the changes of the axial dipole magnetic field and changes in the length of day (LOD) over the past 100 years. LOD changes are carried by zonal (axially symmetric) azimuthal flows which, by themselves, should not produce changes in the axially symmetric part of the magnetic field, including the axial dipole part. As shown by core flow models, changes in the axial dipole can be accounted for by the globally integrated effect of the non-linear interactions between local flow eddies and magnetic field. The correlated changes in LOD and dipole field may then simply reflect that they are both the product of a common underlying dynamical system. An alternative view is that there is a more direct connection between the zonal flows and the dipole. Such a view has been suggested recently, in which zonal flows are a manifestation of MAC waves in a stratified layer at the top of the core and are connected to a north-south axially symmetric flow. The latter is then responsible for the observed dipole field changes. In this scenario, the zonal flows deduced from the secular variation only reflect those at the top of the core. Yet the good fit between observed and predicted LOD changes is based on rigid flows, extending deep inside the core and having little variations in the direction of rotation. Here, we explore the possibility that rigid zonal flows -- generated by the convective dynamics -- can generate a similar north-south flow at the top of the core through a boundary layer effect.
Alfvénic Dynamics and Structuring of Discrete Auroral Arcs: Swarm and e-POP Observations

Miles D.¹, Mann I.¹, Pakhotin I.¹, Knudsen D.², Burchill J.², Howarth A.², Wallis D.²

¹University of Alberta, Canada; ²University of Calgary, Canada

Dynamic dual discrete arc aurora with anti-parallel flow along the arcs was observed nearly simultaneously on March 11, 2016 by the enhanced Polar Outflow Probe (e-POP) and the adjacent Swarm A and C spacecraft. Auroral imaging from e-POP reveal 1-10 km structuring of the arcs which move and evolve on second timescales and confound the traditional field-aligned current algorithms. High-cadence magnetic data from e-POP shows 1-10 Hz, presumed Alfvénic, perturbations co-incident with, and at the same scale size as, the observed dynamic auroral structures. Analysis of high-cadence E- and B-field data from the adjacent Swarm A spacecraft reveals non-stationary electrodynamics involving reflected and interfering Alfvén waves and signatures of modulation consistent with trapping in the Ionospheric Alfvén Resonator (IAR). Taken together, these observations suggest a causative role for Alfvén waves, perhaps also the IAR, in discrete arc dynamics on 0.2-10s timescales and ~1-10 km spatial scales.

Optical Signatures of Field Line Resonances: Comprehensive Survey and Precipitation Mechanisms

Gillies D. M., Donovan E., Knudsen D., Spanswick E., Fenrich F.

University of Calgary, Canada

Auroral arcs are perhaps the best known example of a cosmic plasma process, and have been the focus of scientific interest for well over a century. Advances in optical instrumentation have enabled the identification of over 300 auroral arcs with an infrequently observed auroral morphology. We observe this morphology with the 6300 Å auroral emission wavelength and have connected it to global magnetospheric wave modes known as field line resonances (FLRs). Here we present FLR observations from the redline geospace observatory (REGO) and the recently launched European Space Agency Swarm mission. We will demonstrate that this particular class of auroral arc is associated with FLRs.

Ionospheric Electron Heating Associated With Pulsating Auroras --- Swarm Survey and Model Simulation

Liang J., Yang B., Donovan E., Burchill J., Knudsen D.

University of Calgary, Canada

In this study, we report a survey on the ionospheric plasma signatures (electron temperature, plasma density and field-aligned current etc.) of pulsating auroras using Swarm satellite data. Via the survey of 37 patch crossing events, we repeatedly identify a strong electron temperature enhancement associated with the pulsating aurora. On average, the electron temperature at Swarm satellite altitude (~460 km) increases from ~2100 K at sub-auroral altitudes to a peak of ~3000 K upon entering the pulsating aurora patch. This indicates that the pulsating auroras act as an important heating source of the nightside ionosphere/thermosphere. On the other hand, no well-defined trend of plasma density variation associated with pulsating auroras is identified in the survey. The field-aligned currents within the pulsating aurora patch are mostly upward, with mean magnitude on order of ~1 uA/m². We then perform a numerical simulation to explore the potential mechanisms that may account for
the strong electron heating associated with the pulsating aurora. Via the simulation we find that, to account for the realistic electron temperature observation, the pulsating auroras would likely be associated with a substantial magnetospheric heat flux on order of $\sim 10^{10}$ eV/cm$^2$/s. We propose that such a magnetospheric heat flux may be pertinent to one long-hypothesized nature of pulsating auroras, namely the coexistence of a magnetospheric cold-plasma population in addition to energetic electrons constituting the pulsating auroral precipitation.

Aurorasaurus Citizen Science Observations of Aurora During the Solar Maximum
MacDonald E.A.
NASA Goddard Space Flight Center, United States of America

The Aurorasaurus citizen science project has been collaborating with a global network of amateur observers for four years resulting in a validated new database for auroral studies. These studies have shown the scientific value of crowd-sourced observations for ground-truthing of coarse, statistical auroral models as well as disruptive, discovery based science. We will discuss the background and operations of the Aurorasaurus platform with public participation in research. One unexpected result is that significant numbers of people are able to see aurora during storms further south than the leading model would predict. A second unexpected result is the discovery of the STEVE phenomena by citizen scientists. We will highlight new results showing the improvements possible to aurora modeling and knowledge by combining non-traditional soft sensor techniques with traditional ground-based imaging and satellite conjunctions, such as SWARM and the University of Calgary all-sky camera arrays.

Mesoscale Magnetosphere-Ionosphere Coupling Along Open Magnetic Field Lines Associated with Airglow Patches: Field-Aligned Currents and Precipitation
Zou Y.1, Nishimura Y.1,2, Lyons L.1, Shiokawa K.3, Burchill J.K.4, Knudsen D.K.4, Buchert S.5, Chen S.6, Nicolls M.J.6, Ruohoniemi J.M.7, McWilliams K.A.8, Nishitani N.9
1Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, USA; 2Department of Electrical and Computer Engineering and Center for Space Physics, Boston University, Boston, Massachusetts USA; 3Center for International Collaborative Research, Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan; 4Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada; 5Swedish Institute of Space Physics, Uppsala, Sweden; 6SRI International, Menlo Park, California, USA; 7The Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, Virginia, USA; 8Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, Canada; 9Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan

Although airglow patches are traditionally regarded as high-density plasma unrelated to local field-aligned currents (FACs) and precipitation, past observations were limited to storm-time conditions. Recent non-storm time observations show patches to be associated with azimuthally narrow ionospheric fast flow channels that substantially contribute to plasma transportation across the polar cap and connect dayside and nightside explosive disturbances. We examine whether non-storm time patches are related also to localized polar cap FACs and precipitation using Swarm- and FAST-imager-radar conjunctions. In Swarm data, we commonly (66%) identify substantial magnetic perturbations indicating FAC enhancements around patches. These FACs have substantial densities (0.1-0.2 $\mu$A/m$^2$) and can be approximated as infinite current sheets (typically 75 km wide) oriented roughly parallel to patches. They usually exhibit a Region-1 sense, i.e. a downward FAC lying eastward of an upward FAC, and can close through Pedersen currents in the ionosphere, implying that the locally enhanced dawn-dusk electric field across the patch is imposed by processes in the magnetosphere. In FAST data, we identify localized precipitation that is enhanced within patches in comparison to weak polar rain outside patches. The precipitation consists of structured or diffuse soft electron fluxes. While the latter resembles polar rain only with higher fluxes, the former consists of discrete fluxes enhanced by 1-2 orders of magnitude from several to several hundred eV. Although the precipitation is not a major contributor to patch ionization, it implies newly reconnected flux tube that retain electrons of magnetosheath origin can rapidly traverse the polar cap from the dayside. Therefore non-storm time patches should be regarded as part of a localized magnetosphere-ionosphere coupling system along open magnetic field lines, and their transpolar evolution as a reflection of reconnected flux tubes traveling from the dayside to nightside magnetosphere.
Temporal Variability In Core Surface Flows Inferred From Satellite ‘Virtual Observatory’ Secular Variation

Whaler K.1, Hammer M.2, Finlay C.2, Olsen N.2

1University of Edinburgh, United Kingdom; 2DTU Space, Denmark

We derive the temporal variability of the flow at the core surface explaining the geomagnetic secular variation (SV) over the period of the CHAMP and Swarm missions using satellite-derived ‘virtual observatory’ (VO) data. Time series of monthly values of the vector field components, with their uncertainties, have been derived from data from sectors of satellite paths crossing regularly arranged volumes. The data are reduced to a single point value at the centre of the volume using a local harmonic expansion of the magnetic scalar potential. First differences of field values provide SV estimates. We invert the data assuming the main field is known, specified by the CHAOS model. We allow the maximum amount of temporal variability by solving for a series of flows steady over 3 months, and also with the minimum amount of variability by restricting variability from epoch to epoch. Flows are regularised spatially. We compare the flows with those inferred from observatory data, and examine them for features associated with geomagnetic jerks. Future plans include deriving and taking account of a more sophisticated data covariance matrix, and using spherical Slepian functions to localise the flow e.g. into regions inside and outside the tangent cylinder, and outside the ambiguous area for tangentially geostrophic flows.

Keynote: Earth Dynamics: The big picture

Torsvik T.H.
University of Oslo, Norway

The Earth is a stable degree-2 planet dominated by two antipodal large low shear-wave velocity provinces in the lower mantle beneath Africa (TUZO) and the Pacific (JASON). TUZO and JASON are probably both denser and hotter in the lowermost parts and the Earth’s residual geoid is largely a result of buoyant upwellings above them. Subduction zones show a predominantly large-scale pattern, especially the “ring of fire” circling the entire Pacific and thus slabs sinking all the way to the lowermost mantle also relate to long-wavelength lower mantle structure dominated by degree-2.

Conceptually, the link between plate tectonics and the deep Earth’s mantle can be viewed as a simple mass-balance: subducted lithosphere slabs restore mass to the mantle and trigger the return flow toward the surface – including mantle plumes – rising from the margins of TUZO and JASON. The surface manifestations of plumes are hotspot lavas, kimberlites and large igneous provinces (LIPs), which punctuate plate tectonics by creating new plate boundaries as well as driving rapid climate changes. This realistic model of surface-mantle interaction has emerged after the recognition of a remarkable correlation between reconstructed LIPs and the position of deep mantle structures, showing that TUZO and JASON have been stable for at least 300 Myrs, and probably much longer.

True Polar Wander (TPW) is a process whereby the entire solid Earth (mantle and lithosphere) rotates with respect to the spin-axis in response to changes of the planetary moment of inertia arising from redistribution of density heterogeneities within the mantle. The pattern of TPW can be interpreted as slow oscillatory swings around an axis close to the centres of TUZO and JASON, and adding dense subducted material to the upper mantle at intermediate to high latitudes is a primary cause for TPW. Whilst TUZO and JASON stabilize the moment of inertia through time, their presence may lead to significant non-dipole field contributions. Many hotspots (e.g. Hawaii and Reunion) are rooted in the margin of TUZO and JASON and imaged from the core-mantle boundary to the surface; surface volcanics are associated with pronounced inclination (latitude) anomalies attributed to strong lateral variations in core–mantle boundary heat-flow.
Global Shallow-Earth Structure Models Hand in Hand with Satellite Gravimetry

Sebera J.1, Hoagmans R.2, Floberghagen R.2, Fernández Prieto D.3, Ebbing J.1
1ESA, ESRIN, Italy; 2ESA, ESTEC, The Netherlands; 3Christian-Albrechts-Universität zu Kiel, Germany

Apart from the non-trivial conversion of seismic velocities to the volumetric mass density, the global Earth's density distribution from seismic tomography is still being improved in the accuracy, lateral as well as the vertical resolution. In our contribution, we look at the gravitational signal generated by the model Litho1.0 and the signal obtained from the satellite gravimetry. Litho1.0 provides about 10% of the total Earth's gravitational acceleration and sheds light on the spectral properties between the main “players” – the crust, the lithosphere and the remaining upper mantle. It will be shown that GOCE gravitational gradients can provide a strong feedback to density distribution models. The gradients better localize a possible problem in the density than the gravity vector and are less sensitive to distant sources in the mantle. Thus, the next logic step is to use these gravimetric constraints in the seismic inversion or in density structure modelling. Essentially the same thinking applies to the magnetic susceptibility distribution in the magnetic lithosphere and the satellite magnetometry represented now by the ESA’s mission Swarm.

************************

2PM1: Novel analysis methods for geophysics and geospace research

Examining the Current and Magnetic Perturbations at LEO Altitude Due to Plasma Pressure Gradient and Gravity Forces

Maute A., Richmond A.
National Center for Atmospheric Research, United States of America

In the last several decades Low Earth Orbit (LEO) satellites have provided extensive magnetic measurements to advance our understanding of the complex ionospheric current system. Interpreting the measured magnetic field and its associated current is still challenging since the measured magnetic field reflects the influence of various current sources. At high latitude ionospheric currents are mainly driven by the magnetosphere-ionosphere coupling through ion convection and field-aligned current. At mid- and low latitude the collisional interaction between thermospheric winds and ions is important and sets up electric fields and currents. Smaller low latitude current is produced by gravity and plasma pressure gradient forces. Although the latter currents are weak they can produce persistent 5-7 nT perturbations at LEO altitudes in regions of enhanced plasma as in the equatorial anomaly region, and its effect can last into the evening. The effect of the plasma pressure gradient force on the magnetic perturbations can be estimated with the diamagnetic approximation but the gravity force contribution is difficult to estimate. Knowledge about the characteristics of these currents and their associated magnetic perturbation is important for studies analyzing day and evening low latitude LEO magnetic perturbations.

In this presentation we will introduce a numerical model capable of calculating the 3D ionospheric current system and its associated magnetic perturbation at LEO altitude. We apply this model to examine the current system and the magnetic perturbations associated with gravity and plasma pressure gradient forces with respect to local time, season and solar cycle. We will evaluate the diamagnetic approximation by comparing with the magnetic perturbation derived from considering the simulated 3D current system. We will discuss the value of the simulation results with respect to studies based on LEO magnetic field measurements.

************************

Separating Earth's Internal and External Field in SWARM Observations with the Help of Global Magnetosphere - Ionosphere - Thermosphere Simulations

Raeder J., Cramer W.D., Jensen J.
University of New Hampshire, United States of America

We use Open Geospace General Circulation Model (OpenGGCM) simulations to predict magnetic field perturbations at Low Earth Orbiting (LEO) satellites such as SWARM, at high latitudes. The simulations allow us to separate three different major contributions to the observed perturbations, i.e., the perturbations caused by currents in the outer magnetosphere, field-aligned currents (FACs), and the currents flowing in the ionosphere. We find that at an altitude of 500 km the strongest contribution comes from FACs, followed by the perturbations caused by the ionospheric currents, while the magnetospheric currents make only a minor contribution. The high latitude perturbations do not average out over extended quiet time periods. There are significant variations in the patterns; however, on a large scale, the basic shape of the pattern remains stable. Thus, without explicitly removing the perturbations from the data, any spherical harmonics fit is expected to incur a bias. Although the predicted OpenGGCM perturbations do not compare particularly well with SWARM data, the simulations reproduce the overall pattern. However, they may still be useful to reduce the bias of...
the ensemble and produce better global spherical harmonic fits, by producing an ensemble whose external field contributions average out. Since this paper only scratches the surface of the role that models of the external field can play in producing unbiased internal field models, much progress is still possible, for example by improving the external model, investigating larger ensembles, and by considering data from geomagnetically disturbed times.

An Analysis of Ionospheric Versus Oceanic Tidal Magnetic Signals

Regmi Schnepf N.1, Nair M.1, Maute A.2, Pedatella N.2, Kuvshinov A.2, Richmond A.2

1CIRES/University of Colorado Boulder, United States of America; 2High Altitude Observatory, National Center for Atmospheric Research, United States of America; 3Institute of Geophysics, ETH Zürich, Switzerland

Motional induction in the ocean by lunar tides has long been observed by both land and satellite measurements of magnetic fields. Recent progress has been made using satellite-detected oceanic tidal magnetic signals to perform inversions for lithospheric and upper mantle conductivity (Grayver et al., 2016; Schnepf et al., 2015). The main benefits of using tidal signals for electromagnetic (EM) sensing are 1) that the source galvanically interacts with the underlying lithosphere and mantle (opposed to being inductively coupled, as is the case in traditional magnetotelluric studies), and 2) because the global tidal signal is a grid of sources, a small number of frequency components are needed for probing conductivity. In fact, using only one tidal mode (i.e. one frequency) can still provide a good picture of oceanic lithospheric and upper mantle conductivity.

The use of M2 magnetic signals for regional 3-D inversions of conductivity calls for a more accurate separation of ocean and ionospheric signals for two reasons. First, the persistence of weak ionospheric M2 signals in the nighttime magnetic data is measurable. Second, limiting the analysis to nighttime data when jointly inverting with submarine cable voltage data cannot separate the ionospheric and ocean signals. To better constrain this error, we have conducted a global analysis of the tidal signals at geomagnetic observatories and compared the observations with predictions by physics-based models of the ionospheric and oceanic M2 signals. Our study focuses on the recent deep solar minimum (May 28-August 28, 2009), when the magnetic disturbance was minimum.

Our global analysis used hourly data from 63 non-polar geomagnetic observatories. We directly fit for the M2 amplitudes using the robust least-squares method of Schnepf et al. (2014) for the northward (X), eastward (Y), downward (Z) and total field (F) components.

Studies that have used tidal EM signals for EM sensing relied on the downward component (eg., Grayver et al., 2016) and our results suggest that the ionospheric M2 component is weakest for this component—in fact, across ocean regions this predicted signal is generally under 0.1 nT. However, the horizontal signal is much larger. The northward component of the signal approaches 2 nT near the equatorial electrojet and polar electrojet, whereas the eastward component is broadly strong in the summer hemisphere with its largest amplitudes near the northern geomagnetic pole.

The results of our 1x1 degree forward modeling agree well with the observed estimated signals. Using data from 64 stations, we determined the chi-squared value for 63 degrees of freedom and found that for the total scalar field it is 37, whereas for the downward component it is 39, for the northward component it is 17, and for the eastward component it is 9. The agreement between the physics-based model predictions and the observations is very encouraging for EM sensing applications as we will be able to separate ionospheric and oceanic lunar magnetic signals.

The Lithospheric Magnetic Field Measured by the Swarm Satellite Constellation

Thébault E.1, Vigneron P.2, Hulot G.2

1Laboratoire de Planétologie et de Géodynamique de Nantes, France; 2Institut de Physique du Globe de Paris, France

The Swarm constellation of satellites was launched in November 2013 and has since then delivered high quality scalar and vector magnetic field measurements. A consortium of several research institutions was selected by the European Space Agency (ESA) to provide a number of scientific products which are made available to the scientific community. Models describing the lithospheric magnetic field are now produced on a yearly basis thanks to a continuous effort in improving the software design and taking explicit advantage of the Swarm satellite orbits and configuration.

In this presentation, we will report on the activities carried out to analyze and process the magnetic field measurements and to assess the third update of the lithospheric magnetic field model. Current limitations and difficulties with respect to source field separation and signal to noise ratio will be discussed particularly in view of the possible evolutions of the Swarm constellation geometry and orbit in the forthcoming years.
Hemispherical Differences in the Ionospheric Current System as Seen by Swarm and CHAMP
Laundal K.M.¹, Finlay C.C.², Olsen N.², Reistad J.¹, Tenfjord P.²
¹University in Bergen, Birkeland Centre for Space Science, Norway; ²DTU Space, Technical University of Denmark, Kongens Lyngby, Denmark

We present an empirical model of the global ionospheric current system, with emphasis on the polar regions. The model is based on magnetic field measurements from the Swarm and CHAMP spacecraft, after removal of a model main magnetic field. The magnetic field measurements are used to fit spherical harmonic potentials associated with Birkeland currents and horizontal equivalent ionospheric currents. The combination of these potentials can be used to calculate the true horizontal current, without any assumption about ionospheric conductivity. We parametrize the spherical harmonic coefficients in terms of sunlight conditions, solar wind speed, the F10.7 index, and the interplanetary magnetic field. Global spherical harmonics are used, so that the currents in both hemispheres are modeled simultaneously. The differences in main magnetic field between hemispheres are taken into account by use of magnetic apex coordinates. Comparisons between hemispheres can thus be made approximately independent of hemispheric, longitudinal, and temporal variations in the Earth’s main magnetic field. We use the model to challenge previous observations that more currents flow through the Northern hemisphere.

Identifying Intervals of Spatio-Temporally Invariant Field-Aligned Currents from Swarm: Assessing the Validity of Single Spacecraft Methods
Forsyth C.¹, Rae I.J.¹, Mann I.R.², Pakhotin I.P.²
¹UCL Mullard Space Science Laboratory, United Kingdom; ²University of Alberta, Canada

Field-aligned currents (FACs) are a fundamental component of coupled solar-wind-magnetosphere-ionosphere systems. By assuming that FACs can be approximated by spatially and temporally invariant infinite current sheets, single-spacecraft magnetic field measurements can be used to estimate the currents flowing in space. By combining data from multiple spacecraft on similar orbits, these stationarity assumptions can be tested. In this Technical Report, we present a new technique that combines cross-correlation and linear fitting of multiple spacecraft measurements to determine the reliability of the FAC estimates. We show that this technique can identify those intervals in which the currents estimated from single spacecraft techniques are both well-correlated and have similar amplitudes, thus meeting the spatial and temporal stationarity requirements. Using data from ESA’s Swarm mission from 2014 and 2015, we show that larger scale currents (>450 km) are well correlated and have a one-to-one fit up to 50% of the time, whereas small scale (<50 km) currents show similar amplitudes only ~1% of the time despite there being a good correlation 18% of the time. It is thus imperative to examine both the correlation and amplitude of the calculated FACs in order to assess both the validity of the underlying assumptions and hence ultimately the reliability of such single spacecraft FAC estimates.

Keynote: GNSS-Based Studies of the Ionosphere and the Role of Swarm and Complementary Missions
Skone S.
University of Calgary, Canada

Global Navigation Satellite System (GNSS) technologies are rapidly developing with new constellations emerging from Europe, Russia and China in addition to the original U.S. GPS. By the end of this decade there will be more than 150 navigation satellites transmitting more than 400 multi-frequency signals. Positioning accuracies are approaching the threshold of sub-centimetre globally with a multitude of new services supporting everything from precision timing to autonomous platforms and drones. GNSS signals experience propagation delays and attenuation in the Earth’s ionosphere and these effects must be quantified with high levels of accuracy and mitigated for precise positioning.

GNSS signals also provide opportunity for ionospheric remote sensing. The ubiquity of GNSS observations available from ground-based and space-borne receivers allows direct calibration of ionospheric parameters, modeling of signal propagation errors, and monitoring of regional and global space weather events. Phenomena of interest include storm-enhanced density, polar patches and aurora. Observations from Swarm instruments and those from complementary missions allow resolution of such events for GNSS integrity studies and GNSS-based models of ionospheric electron density. This presentation describes opportunities for exploiting new capabilities in the context of current GNSS-based initiatives and needs for future GNSS services.
The Canadian Ionosphere and Atmosphere Model and Its Application in Support of Satellite Missions

Chen Y.1, Martynenko O.1, Fomichev V.1, Shepherd G.1, Shepherd M.1, Ward W.1, Knudsen D.2, McWilliams K.4, Yau A.1, Tang G.5, Ince S.6
1York University, Canada; 2University of Calgary, Canada; 4University of New Brunswick, Canada; 5University of Saskatchewan, Canada; 6Beijing Aerospace Control Center, China; 6GFZ German Research Centre for Geosciences, Germany

The C-IAM is a first principles global three-dimensional model extending from the Earth’s surface to the inner magnetosphere, which incorporates all known major physical and chemical processes of importance within its domain. The model is able to calculate in a self-consistent manner the atmospheric composition (including neutral species, ions and electrons), temperature (neutral, ion, electron), motion (wind and electromagnetic drift of charged components) and the electric field of both magnetospheric and dynamo origin. A two-way coupling between the ionosphere and neutral atmosphere is implemented that allows for the reproduction of both the impact of the lower atmosphere on the ionospheric plasma and the impact of the ionosphere on the neutral atmosphere (including the impact of geomagnetic storms on the thermosphere). The presentation will describe the model and obtained results including first comparisons of the modeling results with direct in situ satellite observations.

Observation and Modeling of Ionospheric Equinoctial Asymmetry

Lomidze L., Knudsen D.
University of Calgary, Calgary, Alberta, Canada

Ionospheric Equinoctial Asymmetry (IEA) is a phenomenon that reveals itself by significantly larger F region ionospheric electron densities during the March equinox than during the September equinox irrespective of similar levels of solar energy input into the Earth’s upper atmosphere. The causes of the asymmetry are not fully understood and its modeling remains a challenge. In this work we investigate the IEA globally in the topside ionosphere by analyzing different ionospheric plasma parameters, such as electron and ions densities and temperatures, from various satellite missions ( Swarm, CHAMP, COSMIC, ROCSAT). Our analysis reveals that plasma densities are considerably larger (often exceeding 100 %) around March than around September globally. The electron and ion temperatures show reversed asymmetry indicating hotter electron and ion gases during September. This difference is more pronounced for the electron temperatures at low and middle latitudes where it exceeds several hundreds of Kelvins. In order to understand possible causes of the observed equinoctial asymmetry, we employ physics-based ionospheric and coupled ionosphere-thermosphere models to simulate the observations. The model calculations are performed with default and modified ionospheric drivers. Specifically, we investigate the role of neutral composition, temperature, thermospheric winds and E×B drifts, and quantify their relative contribution to the asymmetry. We show observation and modeling results and also discuss limitations of ionosphere/thermosphere models used in this study.

We also show a direct comparison between space observations of the EEJ from the Swarm satellites with ground magnetometer data from equatorial stations at Huancayo (-75.3° ion), Tatuoca (-48.5° ion), and Tirunelveli (77.8° ion).

************************

Atmospheric Signatures in the EEJ During Stratospheric Warming Events and Comparison Between Ground and Space Based Magnetic Observations

Stolle C.1, Siddiqui T.A.1, Matzka J.1, Alken P.2
2GFZ Potsdam, Germany; 3NOAA/NGDC, Boulder, USA

Vertical coupling between atmospheric layers is detectable in modulations of ionospheric currents. Due to its high conductivity, the equatorial E region is especially sensitive. Based on suitable ground magnetic observations, we investigate modulations of the Equatorial Electrojet (EEJ) that show enhanced wave activity in lunital periods during northern winter months, e.g. during those with weakening of the stratospheric polar vortex (Stratospheric Warming) events. Timing and amplitude of EEJ modulations correlates significantly with respective stratospheric observations. From observatories at different longitude sectors, it was found that the effect in the ionosphere/lower thermosphere is longitudinal dependent. The longitudinal variation is confirmed by EEJ observations from LEO satellites like CHAMP, when separated into longitudinal sectors. This is new since previous studies only considered global averages of satellite data.

We show a direct comparison between ground and space based magnetic observations of the EEJ from the Swarm satellites with ROCSAT. Our analysis reveals that plasma densities are considerably larger (often exceeding 100 %) around March than around September globally. The electron and ion temperatures show reversed asymmetry indicating hotter electron and ion gases during September. This difference is more pronounced for the electron temperatures at low and middle latitudes where it exceeds several hundreds of Kelvins. In order to understand possible causes of the observed equinoctial asymmetry, we employ physics-based ionospheric and coupled ionosphere-thermosphere models to simulate the observations. The model calculations are performed with default and modified ionospheric drivers. Specifically, we investigate the role of neutral composition, temperature, thermospheric winds and E×B drifts, and quantify their relative contribution to the asymmetry. We show observation and modeling results and also discuss limitations of ionosphere/thermosphere models used in this study.


McGranaghan R.M.1,2,3, Mannucci A.2, Verkhoglyadova O.2, Malik N.1
1Dartmouth College, Hanover, NH 03757, USA; 2University Center for Atmospheric Research (UCAR), Boulder, CO 80301, USA; 3Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

System science has emerged as a promising approach to understanding, and ultimately predicting, the
complex, coupled magnetosphere-ionosphere-thermosphere (MIT) environment. Fundamental to the success of system science in the MIT system is the ability to describe coupling phenomena, especially in the polar regions where the effects are most direct. This coupling is controlled by the system of field-aligned currents (FACs) that flow between the magnetosphere and ionosphere. FACs at high-latitudes are ubiquitous across the high-latitude regime and have unique characteristics depending on the magnetospheric or solar wind source mechanism, and, therefore, mapping location in the ionosphere (i.e. auroral zone, polar cap, cusp). Further complicating the picture, FACs also exhibit a large range of spatial and temporal scales. In order to create new understanding of FAC spatial and temporal scales, their cross-scale effects, and the impact on the polar region new data analysis approaches are required.

In this work we apply network analysis [Newman, 2003] to investigate relationships between Swarm FAC data and polar features. We develop our approach to answer the question of whether characteristic ionospheric scales of FACs drive observable signatures in ionospheric total electron content (TEC) from Global Navigation Satellite System (GNSS) signals. Swarm data are used to specify periods during which specific FAC characteristics exist, in terms of geomagnetic location and scale, and TEC data are analyzed for observable signatures and spatio-temporal relationships. Given the dense, global coverage of polar features provided by GNSS signals and that these data are critical for the future of space weather and geospace system science research, exploring Swarm-TEC synergies extends the future utilization of Swarm data.

We find significant new relationships between FACs and polar ionospheric TEC features, which can be exploited for future modeling and prediction of the geospace system.

Reference:

Zhang S.
MIT Haystack Observatory, United States of America

Using multiple incoherent scatter radar observations spanning from a few solar cycles up to 50+ years at middle (Millstone Hill), auroral (Poker Flat/Chatanika) and higher (Sondrestrom) latitudes, we estimate ionospheric climate (long-term) changes over the broad E and F region altitude range. Significant ionospheric cooling in ion temperature (Ti) is found which generally increase in height from the F2 peak region into the topside. The lower altitude Ti trend is an indicator of the neutral atmospheric long-term change which has been known from satellite drag measurements over multiple decades, however, the topside Ti trend involves additional forcing and possibly magnetosphere-ionosphere-thermosphere processes. Nevertheless, the topside ionosphere is expected to experience appreciable long-term decrease in electron density and should be detectable with the topside in situ measurements.

***************

Swarm Satellite Data Analysis For Earthquake Preparatory Phase Studies
De Santis A.1, De Franceschi G.2, Di Giovambattista R.2, Perrone L.2, Alfonsi L.2, Cianchini G.1, Pavón-Carrasco F.J.1,2, Cesaroni C.1, Spogli L.1, Malagnini A.1, Piscini A.1, Marchetti D.1, De Santis A.1, Abbattista C.1, Amoruso L.2, Santoro F.3
1Istituto Nazionale di Geofisica e Vulcanologia, Italy; 2Universidad Complutense de Madrid, Spain; 3Planetek Italia spa

The primary goal of the Swarm three-satellite mission is to measure the magnetic signals from the Earth, in order to better monitor and study with greatest detail its planetary magnetic field. One of the STSE Swarm + Innovation ESA funded project, SAFE (Swarm for Earthquake study), aims at applying the new approach of geosystemics to the analysis of Swarm magnetic and electron density data for investigating the preparatory phase of earthquakes as seen from space, with integration of ground based (ionosonde and GPS/GNSS) data. The main objective is to explore the possible link between magnetic/ionospheric anomalies and large earthquakes. This contribution shows the importance of this novel approach for several earthquake case studies. Finally, in the framework of the SAFE project, a web exploitation platform has also been developed, in order to show, demonstrate and help scientific stakeholders in understanding and analyzing the possible relations between Swarm, in situ and ancillary data and possible earthquake precursors

***************
The Search of the Cross Correlation Between the Ground Based and Swarm Registration of the Thunderstorms and TLE’s Effects

Blecki J.S., Slomińska E., Mlynarczyk J., Slomiński J., Kulak A., Wronowski R., Haagmans R.

1Space Research Centre PAS, Warsaw, Poland; 2OBSEE, Warsaw, Poland; 3AGH University of Science and Technology, Cracow, Poland; 4ESTEC, Noordwijk, Netherland.

The main goal of this presentation is discussion of the cross correlation between the ground based and Swarm registration of the effects related to the thunderstorm and TLE’s. The brief review of the expected effects is given as an introduction. The simple model of the connection between ground effects and satellite registration is given in next part. Further the main results are presented. Ground-based observations of atmospheric discharges in the ELF range are carried out using broadband low noise magnetometers currently operated in three ELF stations. The Hylaty ELF station is located in Poland, near the Bieszczadz National Park, Hugo station, installed in May 2015, is located in Colorado, USA and the Patagonia station, installed in March 2016, is located in southern Patagonia, Argentina. The three stations form the WERA system (World ELF Radiolocation Array) that enable us to observe very strong atmospheric discharges occurring anywhere on Earth. 430 lightning discharges with charge moment 1000 [Ckm] has been identified as potential candidates for the cross-analysis with the Swarm measurements. Spatial distribution of these events is presented. The Swarm data are variations of the magnetic field with sampling frequency 50Hz and electron density from Langmuir probe with sampling 1Hz. Steps distinguished in the magnetic data processing chain are as follows: δBi residuals retrieval from the measured signal for three B components, FFT transformation applied to the δBi residuals, generation of time-frequency spectrograms for δBi along the orbit in the frequency range up to 25Hz, integration of lightning’s database with derived Swarm δBi spectra. Identification of signals generated by strong electric discharges is based on the analysis of time-frequency spectrograms for the wave data. The response of Swarm to sequence of sprites documented with ground based optical sensor is presented. The event registered on August 17, 2016 at 21:40:57.8 took place in Croatia eastwards from Novigrad 45.35 N 13.75E.

********************

Lightning-Generated Whistlers Observed during ASM Burst Mode Sessions

Coïsson P., Deram P., Hulot G., Beggan C., Léger JM.

1Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, F-75005 Paris, France; 2British Geological Survey, Murchison House, West Mains Road, EH9 3LA, Edinburgh, UK; 3CEA, LETI, MINATEC Campus, F-38054 Grenoble, France.

Lighting-released energy covers a wide band of the electromagnetic spectrum. The propagation of the corresponding electromagnetic signal is not limited to the neutral atmosphere, and specific whistler-modes of propagation can enter the ionosphere, thus allowing their detection by LEO satellites. Though most of the whistler energy is released between 1 and 10 kHz, part of it appears to be also released in the frequency band 10-125 Hz detectable by the Swarm Absolute Scalar Magnetometers (ASM) operated in burst mode (250 Hz).

Several hundreds of whistler events were indeed recorded in this way when a few burst-mode sessions were operated during the commissioning phase of the Swarm mission, at the beginning of 2014. These events have been unambiguously correlated with strong lightning strikes detected and located on ground by the World Wide Lightning Location Network (WWLLN). We developed a simple ray-tracing software to understand the propagation properties of these low-frequency whistlers. It uses the Appleton refraction index through the ionosphere plasma in the Earth magnetic field and solves the Haselgrove equations of propagation. We have thus been able to recover satisfyingly the propagation time and dispersion relation observed in the Swarm data.

********************

The Contribution of CSES Mission to Study Lithosphere-Atmosphere-Ionosphere Coupling Phenomena Through the Analysis of Combined Missions Data and Ground Measurements


1Agenzia Spaziale Italiana, Italy; 2INFN - Sezione Roma 2, Rome, Italy; 3INFN - TIFPA, Trento, Italy; 4INFN - Sezione di Bologna, Bologna, Italy; 5INFN - LNF, Frascati, Italy; 6INFN - Sezione di Napoli, Napoli, Italy; 7INFN - Sezione di Perugia, Perugia, Italy; 8University of Bologna, Bologna, Italy; 9University of Perugia, Perugia, Italy; 10University of Tor Vergata, Roma, Italy; 11University of Trento, Trento, Italy; 12Uninettuno University, Rome, Italy; 13INAF-IAPS, Rome, Italy; 14INGV, Rome, Italy; 15Fondazione Bruno Kessler, Trento, Italy; 16CEA, Beijing, China; 17National Research Nuclear University MEPhI, Moscow, Russia.
We present the CSES (China Seismo-Electromagnetic Satellite) mission that aims at investigating electromagnetic field, plasma and particles in the near-Earth environment in order to study: seismic precursors, particles fluxes (from Van Allen belts, cosmic rays, solar wind, etc.), anthropogenic electromagnetic emissions and more in general the atmosphere-ionosphere-magnetosphere coupling mechanisms that can also affect the climate changes. CSES – the first of two twin missions developed by the CNSA (China National Space Agency) together with the ASI (Italian Space Agency) – will be launched by the summer of 2017 on a polar orbit, at about 500 km, for a lifespan greater than 5 years. Several studies (such as the DEMETER analyses, the SAFE (SwArm For Earthquake study) project funded by the ESA, etc.) have shown that LEO satellite observations of electromagnetic fields, plasma parameters and particle fluxes can be able to investigate electromagnetic emissions possibly associated to earthquakes of medium and high magnitude. Although the earthquakes forecasting is not possible today, it is certainly a major challenge for science in the near future. The claims that the reported anomalies are seismic precursors are still intensely debated and analyses for confirming correlations are still lacking. In fact, in order to identify seismo-associated perturbations, it is needed to reject the “normal” background effects of the e.m. emissions due to: geomagnetic storms, tropospheric phenomena, and artificial sources (such as power lines, VLF transmitters, HF stations, etc.). Currently, the largest available database for studies of seismo-associated phenomena is that collected by the DEMETER satellite and by observations executed by some other space missions, non-dedicated to this purpose. The CSES satellite aims at continuing the exploration started by DEMETER with advanced multi-parametric measurements. In order to execute observations of energetic particle fluxes, ionospheric plasma parameters and electromagnetic fields - in a wide range of energy and frequencies – CSES is equipped with several instruments: HEPD (High Energy Particle Detector); HEPP (Low Energy Particle Detector); LP (Langmuir Probes); IDM (Ion Drift Meter); ICM (Ion Capture Meter); RPA (Retarding Potential Analyzer); EFD (Electric Field Detectors) with 4 probes installed on 4 deployable booms; HPM (High Precision Magnetometer); and SCM (Search-Coil Magnetometer). The SWARM satellites and CSES will be flying in the same time, at a similar altitude/inclination, by executing measurements of several similar parameters. The observations executed by CSES (and by its twin CSES-2) can complement those performed by SWARM increasing the monitoring capability and the range of observations. On the other side, the CSES multi-instruments payload includes two particles detectors and an electric-field detector (not installed on SWARM satellites) that can improve the capability to study the top side ionosphere giving an important contribution in monitoring the solar-terrestrial interactions. Finally, CSES will be the only satellite, with these characteristics, flying in the near future simultaneously with the SWARM mission. In this framework, we will discuss the CSES mission, its complementarity and differences with SWARM, as well as the possible overlap between the scientific investigations performed by the two missions.


Ozeke L.1, Mann I.2, Pakhotin I.1, Murphy K.2
1University of Alberta, Canada; 2NASA Goddard Space Flight Centre, Greenbelt, Maryland, USA

Understanding the dynamics of the relativistic electrons in the Earth’s Van Allen radiation belts remains one of the most important and fundamental challenges in space physics. One of the major challenges is the fact that the dynamics of the outer radiation belt are controlled by a delicate balance between electron acceleration and loss processes. Enhancements in the outer radiation belt flux can be caused by multiple different processes which may occur at the same time during magnetic storms, such as local acceleration of the electrons by chorus waves and inward ULF wave radial diffusion. Geomagnetic storms are also times of electron loss from the potential action of multiple possible processes. For example, enhanced outward radial diffusion and magnetopause shadowing can cause the loss of electrons through the magnetopause, whilst pitch-angle scattering of the electrons into the loss cone can cause electron loss to the atmosphere by wave-particle interactions with waves such as chorus, hiss and EMIC waves. Several observations of rapid decreases in the flux of ultra-relativistic electrons in the outer radiation belt measured with the Van Allen probes during geomagnetic storms will be presented. Simulations of the electron flux dynamics during these geomagnetic storms will also be presented obtained using our radiation belt model. These simulation results illustrate that an additional loss process is required in our radiation belt model to reproduce the observed rapid electron flux decrease. Using Swarm measurements we show that EMIC waves were present during the rapid decreases in the flux of ultra-relativistic electrons, and show that once the effects of EMIC wave scattering of electrons into the atmosphere are included in our model, then the electron flux dynamics observed by the Van Allen probes during these geomagnetic storms can be accurately reproduced by our model. The results highlight the importance of the Swarm probes for detecting short duration (<2 hour) EMIC waves and for determining the range of L-shells where these waves are occurring.
10-year Time Series of GNSS Daily Solutions, Geomagnetic Storms and Biggest Earthquakes
Balodis J.1, Janpaule I., Normand M.1,2, Jumare I.1, Silabriedis G.1
1University of Latvia, Latvia; 2Riga Technical university
10-year GNSS daily solutions performed at the University of Latvia by using Bernese software, EUREF recommended methodology and IGS/EPN reference network. The daily solutions were performed for continuously operating GNSS RTK reference network stations in Latvia. The graphs are designed for 10-year time series where the information of both each year 50 strongest geomagnetic storms and earthquakes in the world of magnitude 6.0 and stronger, correspondingly. The effect of small earthquakes in surrounding counties is analysed. Some statistics has been summarized on the relation of computed daily coordinates and both space weather and earthquakes in the world.

Evolution of Swarm-derived Equatorial Electrojet Signatures Using Vector Magnetic Measurements
Alken P.1, Maute A.2, Richmond A.2, Egbert G.3, Vanhamäki H.4, Chulliat A.1, Hulot G.5
1University of Colorado at Boulder, United States of America; 2High Altitude Observatory, Boulder, CO, USA; 3Oregon State University, USA; 4University of Oulu, Finland; 5Institut de Physique du Globe de Paris, Paris, France
The Swarm Level-2 equatorial electric field (EEF) and equatorial electrojet (EEJ) product is based on a single satellite approach and uses only scalar field data. While this product currently produces good estimates of the eastward EEJ current strength at the magnetic equator, it may be possible to derive estimates of the other components of the current by using the full vector measurements along with the Swarm constellation configuration. In particular we are interested in the possibility of recovering estimates of the EEJ vertical and meridional current system. In this study we investigate two possible approaches toward this goal. The first is based on fitting Spherical Elementary Current Systems (SECS) to the low and mid latitude magnetic data. This approach is used routinely to investigate high-latitude ionospheric current systems but has not been used frequently at low and mid latitudes. The second approach is to use the TIEGCM physics-based ionosphere model to derive empirical orthogonal functions (EOFs) which contain statistically significant information about the spatial geometries of the various ionospheric current systems. These EOFs are then fit to the Swarm constellation data and the resulting currents are compared with the SECS method.

Constellation Strategies for Observing Plasma Bubbles in the Terrestrial Ionosphere
Klenzing J.1, Huba J.2, Pfaff R.1, Stoneback R.3
1NASA / GSFC, United States of America; 2Naval Research Laboratory, United States of America; 3The University of Texas at Dallas, United States of America
The low-latitude ionosphere is home to many plasma irregularities such as plasma bubbles that wreak havoc on critical radio waves, including GPS, radar, and communication signals. Observations of plasma bubbles were first reported nearly eighty years ago, but day-to-day variability of bubble formation remains a significant question in ionospheric physics. While satellite observations provide important information about longitudinal variability, the chosen satellite orbit strongly affects the observations of the density depletions and hence may influence their interpretation. For example, the C/NOFS satellite had an elliptical orbit with a 65-day precession period of perigee through all local times, limiting the potential observation of low-altitude bubbles in the post-sunset sector. Using the SAMI3 model and comparisons to the C/NOFS database, we will discuss the effect of different orbital parameters (e.g., altitude, inclination, circular vs elliptical) on optimizing the detection of plasma bubbles by in situ satellite instrumentation, as well as improvements offered by using multiple spacecraft. Applications to DMSP, Swarm, and GDC will be discussed.
Relation Between Diamagnetic Effects and Formation of the Nighttime Ionospheric Plasma Density Enhancements
Slominska E.1, Blecki J.2, Haagmans R.3, Slominski J.2
1OBSEE, Poland; 2CBK PAN, Poland; 3European Space Agency

The interest of this study is focused on the mechanism governing the phenomenon of the nighttime electron density enhancements observed in the upper layer of the ionosphere. This type of ionospheric behavior is particularly interesting when phenomena such as the Weddell Sea Anomaly (WSA) or the mid-latitude nighttime summer anomaly (MSNA) are considered. Numerous studies make an attempt to provide concise explanation of mechanism responsible for the observed anomalies, focusing mainly on the interaction between ionosphere and thermosphere, with thermospheric winds considered as major drivers of phenomena. But it is still unclear why mentioned anomalies are confined only to certain regions.

Approach presented in this study concentrates on the role of diamagnetic currents, which so far has not been considered in the context of the WSA or MSNA. Spatial variations of ionospheric plasma density are often accompanied by signatures in the magnetic field strength because of the diamagnetic effect. Diamagnetic currents can be expressed as the effect of forces on a plasma due to gradients in the plasma pressure, resulting from variations in electron density. Such signatures have been observed in the equatorial and low-latitude ionosphere. This study expands discussion to mid-latitude regions, concentrating on spatial and temporal trends of magnetic field fluctuations.

Joint analysis utilizes Swarm MAG_HR and LP electron density data. Initial analysis of residuals derived from the scalar magnetic field exhibits pronounced structures of intensified emissions spatially corresponding to regions where density anomalies are detected.

-------------------------------

Electromagnetic Features of Equatorial Field Aligned Plasma Irregularities as Observed by the Swarm Mission
Rodríguez-Zuluaga J.1,2, Stolle C.1,2
1GFZ German Research Centre for Geosciences, Germany; 2Faculty of Science, University of Potsdam, Germany

The electromagnetic properties of F-region field-aligned irregularities (FAIs) are key parameters in the understanding of their spatial and temporal distribution. So far, electric and magnetic fields associated with FAIs have been studied mostly by simulations and theoretical models, and in a minor fraction by observations. In this work, some static and dynamic electromagnetic characteristics of equatorial FAIs are investigated using observations from the Swarm constellation. First, the spatial and temporal distribution of irregularities are presented based on their magnetic response of their related field-aligned and pressure-gradient-driven currents. Second, the direction of their associated electromagnetic energy flow deduced from the Poynting theorem is shown for some selected events. The results are discussed in the light of numerical simulations and theoretical models.

-------------------------------

3PM1a: Satellite geodesy missions today I

Keynote: Geodetic Space Sensors for Height System Unification and Absolute Sea Level Determination
Gruber T.
Technical University of Munich, Germany

Sea level research nowadays is based on a number of geodetic space sensors, which all have their own characteristics and deliver different type of observations. Over the oceans, satellite altimetry is the main information source providing the absolute sea level at a specific location and at a specific time with respect to a geometric reference frame. By analysis of these measurements in the space and time domain one can derive mean sea surfaces over specific areas and periods and/or its change in time. At the coasts, sea level is usually observed with tide gauges delivering instantaneous sea surface heights relative to a zero marker of the tide gauge station. In order to get absolute sea level heights at tide gauges two additional quantities are required. These are observation of the relative motion of the zero marker with respect to a global geometric reference frame delivering instantaneous geometric heights and the gravimetric equipotential surface going through the tide gauge zero marker and its difference to an equipotential surface defining a global height reference system. By scaling the potential difference with gravity accelerations one can obtain physical heights of the tide gauge zero marker. Subtracting these physical heights from the geometric sea surface height one can finally get absolute sea level heights at tide gauge stations in case consistent geometrical and physical reference frames are applied.

Height system unification and absolute sea level determination therefore requires observations from a number of different geodetic space sensors delivering geometric and physical quantities in consistent
reference frames. Geometric heights are delivered from satellite altimeters, GNSS stations and synthetic aperture radars (SAR), while physical heights need knowledge about the Earth gravity field as it is delivered from GOCE, GRACE and GRACE-FO, complemented by surface and airborne observations. As of today the observing systems exhibit several weaknesses, which are crucial to height system unification and absolute sea level determination. For example, only a few tide gauge stations are equipped with permanent GNSS receivers. Therefore, new approaches for the geometric station monitoring need to be implemented, which for example can be based on SAR absolute and relative positioning techniques. Further-on, a high resolution geoid at the tide gauge station is needed in order determine physical heights with the required accuracy. Finally, in all processing steps involved, it has to be ensured that the geometric and physical reference systems are compatible and that all sensors deliver consistent information.

The paper introduces the problem of height system unification and absolute sea level determination, investigates potential problems in the joint use of geodetic sensor data for this purpose and identifies possible research topics to be addressed by future studies. Special emphasis will be given to absolute point positioning with SAR techniques and its possible benefit for this application. It concludes with some ideas on how to set up a global height system/sea level observing system.

************************

**Keynote: GNSS-Augmented Radar Transponders for InSAR Datum Connection**

Ramon Hanssen, Hans van der Marel, Freek van Leijen and Karsh Patel.

Geodetic Missions Workshop

20-24 March 2017

Banff, Alberta, Canada

InSAR deformation estimates form a ‘free network’ referred to an arbitrary datum, e.g. by assuming a reference point in the image to be stable. Consequently, the estimates of any measurement point in the image are dependent of these postulations on reference point stability, and the estimates cannot be compared with datasets of other types of measurement (e.g. historical levelling data or sea-level changes). Yet, some applications require ‘absolute’ InSAR estimates, i.e. expressed in a well-defined terrestrial reference frame (TRF). We achieve this using collocated InSAR and GNSS measurements, achieved by rigidly attaching phase-stable millimetre-precision compact active transponders to permanent GNSS antennas. The InSAR deformation estimates at these transponders are then estimated in a TRF using the GNSS measurements. Consequently, deformation estimates at all other scatterers are now also defined in the same TRF.

Here we report on latest experiments with a new type of low-cost radar transponders.

************************

**Potential of Global SAR Positioning for Geodetic Applications – Lessons Learned from TerraSAR-X and Sentinel-1**

Gisinger C.1, Willberg M.1, Balss U.2, Hackel S.3, Eineder M.4, Gruber T.1

1 Chair of Astronomical and Physical Geodesy, TUM, Germany; 2 Remote Sensing Technology Institute, DLR, Germany; 3 German Space Operations Center, DLR, Germany

With our implementation of geodetic techniques for data processing and data correction, spaceborne Synthetic Aperture Radar (SAR) has attained the possibility of fixing global positions of dedicated radar points at the low centimeter accuracy level. Such points can be created by passive radar corner reflectors, and the positioning method relies on the inherent ranging capabilities of SAR sensors. Thus, we may refer to the method as SAR imaging geodesy or geodetic SAR.

Determining accurate long-term global positions of objects on the Earth’s surface is typically associated with Global Navigation Satellite Systems (GNSS) and one of the core elements of modern space geodesy. In order to do so, high-grade geodetic equipment with constant power supply, as well as the possibility for data transfer are required, limiting dense application on a large scale and poses difficulties for very remote areas with little or no infrastructure. Whereas certain regions like Japan or the San Andreas Fault are densely covered by GNSS such coverage may not be achievable everywhere on the globe.

To improve the situation, we present a concept of jointly using SAR and GNSS for expanding geodetic positioning to applications requiring long-term coordinate monitoring. In future, the use of cost-effective passive reflectors in X-band SAR or low-cost battery-powered active transponders, which are currently in development for C-band SAR, could provide global coordinates anywhere where SAR imagery is acquired under multiple incidence angles. The main requirements are precise orbit determination, processing of the SAR imagery omitting geometric approximations, as well as the rigorous correction of perturbations caused by atmospheric path delay and signals of the dynamic Earth. If a reflector or transponder already has known reference coordinates, e.g. from co-location with GNSS, the perturbing signals can be mitigated for surrounding radar points by applying differential SAR positioning techniques similar to differential GNSS, provided that all the points are included in the same radar image. In this contribution we discuss these geodetic SAR methods with respect to our experiences gained from the TerraSAR-X mission.
and present first results of experiments carried out with Sentinel-1 data.

************************

European Gravity Service For Improved Emergency Management

Jäggi A.1, Weigelt M.2, Flechtner F.3, Güntner A.3, Mayer-Gürr T.4, Martinis S.5, Bruinsma S.6, Flury J.7, Bourgogne S.8, & EGSIEM team1

1University of Bern, Switzerland; 2University of Luxembourg, Luxembourg, now University of Hannover, Germany; 3German Research Centre for Geosciences, Germany; 4Technical University of Graz, Austria; 5Deutsches Zentrum für Luft - und Raumfahrt, Germany; 6Centre National D’Etudes Spatiales, France; 7University of Hannover, Germany; 8Géode & Cie, Toulouse, France

The European Gravity Service for Improved Emergency Management (EGSIEM) is a project of the Horizon 2020 Framework Programme for Research and Innovation of the European Commission. It shall demonstrate that observations of the redistribution of water and ice mass derived from the current GRACE mission, the future GRACE-FO mission, and additional data provide critical and complementary information to more traditional Earth Observation products and shall open the door for innovative approaches to flood and drought monitoring and forecasting. We give an overview of the current status of the project and present the latest results from the three key objectives that EGSIEM shall address: 1) to establish a scientific combination service to deliver the best gravity products for applications in Earth and environmental science research based on the unified knowledge of the European GRACE community, 2) to establish a near real-time and regional service to reduce the latency and increase the temporal resolution of the mass redistribution products, and 3) to establish a hydrological and early warning service to develop gravity-based indicators for extreme hydrological events and to demonstrate their value for flood and drought forecasting and monitoring services.

************************

Near Realtime Mass Transport Products for Monitoring of Hydrological Extreme Events

Flechtner F.1, Gruber C.1, Kvas A.1, Mayer-Gürr T.2, Güntner A.1, Gouweleeuw B.2, Chen Q.3, van Dam T.3

1GFZ Potsdam, Germany; 2TU Graz, Austria; 3University Luxembourg, Luxembourg

The nominal time delay of the GRACE Level-1 instrument data (11 days) and of the derived monthly global Level-2 gravity field products (60 days) makes the application of GRACE for monitoring of e.g. hydrological extremes difficult. Flood forecast models need, e.g. near-real time (NRT) information to estimate the probable development of the event in terms of flood stage or river discharge with typical lead times of a few days for larger river basins.

To enable the application of GRACE (and later GRACE-FO) mass redistribution data for rapid monitoring of hydrological extreme events, the EU funded project EGSIEM (European Gravity Service for Improved Emergency Management) has established a NRT and Regional Service, that aims to reduce the time delay of mass transport products to less than 5 days, to increase the time resolution from one month to one day, and to improve the quality by providing regional solutions based on alternative representations of the gravity field, e.g. space-localizing radial basis functions. The quality of the NRT mass transport products will be tested using GNSS loading and ocean bottom pressure data as well as hydrological flood events. Assuming that GRACE Quick-Look data (provided by JPL) will still be available in April 2017 an operational test run of the NRT Service is planned for about 6 months. Here the NRT products will be provided on a daily basis to the EGSIEM Hydrological Service which derives NRT flood indicators to be used within DLR’s Center for Satellite-based Crisis Information. The presentation will focus on the current status of the project in view of the upcoming milestone “Operational Service Readiness”.

************************

3PM1b: Quasi-static coupling of the magnetosphere-ionosphere-thermosphere system

Keynote: A Swarm Perspective on M-I-T Coupling

Marghitu O.

Institute for Space Sciences, Bucharest, Romania

With its multi-point observations of the magnetic field, electric field, and neutral atmosphere, Swarm provides an unprecedented platform to investigate the ionosphere (I) and thermosphere (T), their mutual interaction, as well as their further coupling to the magnetosphere (M). This talk will provide a concise overview of M-I-T investigations relevant to Swarm, will present a selection of Swarm results, and will address further Swarm prospects to contribute to the field. The talk will emphasize specific assets of the mission, like the coordination with ground stations, conjugate observations with other space-based platforms (e.g. Cluster, e-POP, DMSP), or the possibility to explore systematically the longitudinal dimension of M-I-T coupling and its potential impact on auroral research. Last but not least, the talk will touch also the upcoming
Evidence That Field-Aligned Currents Do Not Saturate

**Weimer D.R.**, **Edwards T.R.**, **Luhr H.**

*Virginia Tech, United States of America; GFZ German Research Centre for Geosciences, Potsdam, Germany*

For well over a decade there have been several studies that have shown evidence that the ionospheric, polar cap electric potentials exhibit a "saturation" behavior in response to the levels of the driving by the interplanetary magnetic field (IMF) and electric field (IEF) in the solar wind. This saturation behavior is manifested in the potential versus driving function as a nearly linear response at low driving levels, followed with a roll-over and leveling off as the strength of the driving increases. Several different theoretical explanations have been presented for this behavior, yet so far no direct observational evidence has existed to confirm one mechanism over another. In most saturation theories the interaction of the field-aligned currents (FAC) with the coupled, solar wind/magnetosphere/ionosphere system has a role in this potential saturation; even so, the behavior of the FAC in response to the driving of the IEF has not been investigated as thoroughly as the electric potentials.

In order to resolve the question of whether or not the FAC also exhibit saturation, we have processed the magnetic field measurements from the Oersted, CHAMP, and Swarm missions, spanning more than a decade, in order to determine how the total FAC responds to the solar wind. We will present evidence showing that the field-aligned currents have a response to the IEF that remains highly linear well beyond the level at which the electric potentials begin to roll over. It appears that the currents do not saturate. On the other hand, at very extreme levels of driving, as seen with IMF magnitudes over 25 nT, the number of such events are so sparse that it is difficult to provide an unequivocal determination that the total current does level off at some upper level.

**Longitudinal Gradients in Ionospheric Currents as Deduced with the Method of Spherical Elementary Current Systems**


1Finnish Meteorological Institute, Finland; 2University of Oulu, Finland

We study how the method of Spherical Elementary Current Systems (SECS) can be applied to Swarm magnetic data in order to create new data products estimating electric currents in the auroral ionosphere. Our aim is to release a validated set of these data products for open test use during the year 2017. Exact content of this data set and the methodology used to create it will be described in the presentation. We show some results from comparisons of our products with ground-based ionospheric observations by the MIRACLE network and with the already existing Swarm L2 current products. Pros and cons of the Swarm-SECS approach in statistical studies will be discussed with the focus in the optimal spatial resolutions that the method can provide for different current components. As an example of harvesting the new data set we demonstrate how the pair of Swarm A and C satellites can be used to study longitudinal gradients in horizontal currents and their connection with the intensity of field-aligned currents in different magnetic local time sectors.

**Unified Global and Local Perspectives on High-latitude Ionospheric Electrody namics**

**Matsuo T.**, **Stolle C.**

1University of Colorado Boulder, United States of America; 2GFZ Potsdam, Germany

By combining Swarm data with other global geospace observations (e.g., Iridium/AMPERE, SuperMag, and SuperDARN) with the help of a comprehensive data assimilation and inverse procedure (namely the Assimilative Mapping Ionospheric Electrodynamics (AMIE) [Richmond and Kamide, 1988]) and the latest development under AMIE Nextgen [e.g., Matsuo et al., 2015, Cousins et al., 2015]), we can unravel how fine-scale transient features of high-latitude ionospheric electrodynamic features are embedded in large-scale structures. Such an approach provides unified global and local perspectives that facilitate interpretation of localized phenomena, such as cusp neutral mass density enhancements in response to localized heating, in the global context of magnetosphere-ionosphere-thermosphere coupling, and extends the utility of Swarm data for space science research.


************************

**Evidence That Field-Aligned Currents Do Not Saturate**

**Richmond A.**

1Virginia Tech, United States of America; 2GFZ German Research Centre for Geosciences, Potsdam, Germany

For well over a decade there have been several studies that have shown evidence that the ionospheric, polar cap electric potentials exhibit a "saturation" behavior in response to the levels of the driving by the interplanetary magnetic field (IMF) and electric field (IEF) in the solar wind. This saturation behavior is manifested in the potential versus driving function as a nearly linear response at low driving levels, followed with a roll-over and leveling off as the strength of the driving increases. Several different theoretical explanations have been presented for this behavior, yet so far no direct observational evidence has existed to confirm one mechanism over another. In most saturation theories the interaction of the field-aligned currents (FAC) with the coupled, solar wind/magnetosphere/ionosphere system has a role in this potential saturation; even so, the behavior of the FAC in response to the driving of the IEF has not been investigated as thoroughly as the electric potentials.
In space science Poynting flux represents the direction and magnitude of electromagnetic energy flow, which is an important clue to reveal the energy source of many geophysical phenomena. In spite of the long history of electric and magnetic field measurements on Low-Earth-Orbit (LEO) satellites, however, only a few studies could estimate Poynting flux at those altitudes, mainly because of difficulties in simultaneous and precise observations of electric and magnetic fields. In this presentation we investigate Poynting flux deduced from Swarm observations at mid- and high-latitude regions near 500 km altitudes. First, the statistical distribution of Poynting flux at nighttime mid-latitude regions is presented and discussed in the context of medium-scale traveling ionospheric disturbances (MSTIDs). Second, statistical distribution of high-latitude Poynting flux is investigated, and the results are compared with previous satellite observations conducted at much higher magnetospheric altitudes. Finally, ionospheric reflection coefficients are estimated from the Poynting flux and Alfvén velocity data obtained by the Swarm constellation.

Birkeland Current Boundary Flows
Archer W.1, Knudsen D.1, Burchill J.2, Jackel B.1, Donovan E.1, Connors M.2, Juusola L.3
1University of Calgary, Canada; 2Athabasca University, Canada; 3Finnish Meteorological Institute

Intense ion velocity spikes in the northern night-side auroral zone are measured during quiet geomagnetic conditions by the Swarm satellites around 500 km altitude. These velocity spikes, exceeding 1 km/s in over 50% of orbits measured, range from 20-100 km in latitudinal thickness and reach a maximum at the boundary between upward and downward field-aligned current. On average they represent a potential difference of approximately 3 kV between the R1/R2 currents. This boundary also separates different regions of electron temperature and meridional flow, and is associated with ion upflows and anisotropic heating. Both downward and upward velocity field spikes are observed, including some oppositely-directed pairs bounding regions of upward field-aligned current. Coincident ground-based observations place ion velocity spikes adjacent to auroral arcs, embedded in the auroral electrojets. Previous literature has focused on fast flows occurring in regions of relative low conductivity surrounding auroral arcs, typically during geomagnetically active conditions, and does not address the occurrence frequency of these events. We show ion velocity spikes to be a persistent and ubiquitous property of the electrodynamics of quiet time R1/R2 current closure near midnight.

3PM2a: Future of geodesy from space

Keynote: New Missions for Improving the Terrestrial Reference Frame: Means and Impacts
Biancale R.
CNES, France

The Terrestrial Reference Frame (TRF) is defined by positions and velocities of geodetic sites all around the Earth. DORIS, GNSS, SLR and VLBI techniques are used purposely to realize the TRF whose quality depends on system characteristics and processing pertinence. Mostly the TRF determination suffers from two fundamental problems: yet unrevealed systematic effects in the observations of individual space geodetic techniques and difficulties to accurately measure local ties between the system reference points. Unfortunately these imperfections reflect on many applications, for instance any bias or drift in the TRF components propagates into the geophysical interpretations that depend on the reference frame, e.g. GIA and mean sea level variability in space and time. The global sea level rise of about 3.3 mm/yr is numerically small, but is well within the range of observational ability. Hence one way to compensate the current TRF weaknesses is to implement all the space geodetic techniques on a same satellite platform with a very accurate determination of the radio phase centers or laser reflection point against the satellite center of mass. An on-board time unity will reduce as well some technique systematisms. That is why different GRASP-like satellite missions have been proposed to space agencies with the aim of improving the TRF at the GGOS recommended level: accurate and stable at 1 mm and 0.1 mm/yr respectively. The presentation aims at discussing the quality level of current TRF, at outlining the error propagation into
some geophysical interpretations, at presenting the impact of GRASP-like proposed missions...

************************

Current Status of the GRACE Follow-On Mission

Flechtner F.1, Webb F.2, Watkins M.2, Landerer F.2, Dahle C.1, Bettadpur S.2
1GFZ Potsdam, Germany; 2NASA Jet Propulsion Laboratory, Pasadena, CA, United States; 3Center for Space Research, University of Texas, Austin, TX, United States

As of the time of this abstract submission, the GRACE Follow-On satellites have been constructed and transferred to Ottobrunn near Munich for several months of operational testing in the IABG test centre. The Russian/Ukrain Dnepr launcher had to be exchanged and a corresponding new contract has been signed by GFZ and Iridium Satellite LLC. This includes a “Rideshare” between GRACE-FO and 5 Iridium-Next satellites on a Space-X Falcon-9 from Vandenberg Air Force Base in California within the launch period December 2017 till February 2018.

The project team is conducting tests of satellite and instrument operation and performance and putting together updated simulations of expected performance on-orbit, including intersatellite ranging (both microwave and laser), accelerometer, thermal variability and deformation, and other errors. In addition, all required ground analysis software of the Science Data System is in development and testing at JPL, UTCSR, and GFZ, in preparation for fully integrated end-to-end (international) testing from Level-1 through Level-3 data within 2017. In this presentation, we will provide the detailed status of project integration and test, the latest simulations of science performance, and schedule for remaining project milestones.

************************


Pail R.
TU Munich, Germany

In an internationally coordinated initiative among the main user communities of gravity field products under the umbrella of IUGG (International Union of Geodesy and Geophysics) the science and user needs for a future gravity field mission constellation (beyond GRACE Follow-On) have been reviewed and defined. Consensus among the user communities of hydrology, ocean, cryosphere, solid Earth, and atmosphere on consolidated science requirements could be achieved. In the frame of this activity, the achievements of the first generation of dedicated gravity missions (CHAMP, GRACE, GOCE) have been discussed, and also the current limitations of these missions have been identified.

The consolidation of the user requirements became necessary, because several future gravity field studies have resulted in quite different performance numbers as a target for a future gravity mission (2025+). Based on limited number of mission scenarios, which took also technical feasibility into account, a consolidated view on the science requirements among the international user communities was derived, distinguishing between a threshold scenario and a more ambitious target scenario. Research fields that could not be tackled by current gravity missions have been identified, and the added value (qualitatively and quantitatively) of these scenarios with respect to science return has been evaluated. Beyond scientific objectives, also the societal benefit of sustained observation of the Earth’s gravity field and its temporal variation, such as operational and service applications, have been identified.

Beyond the resulting documentation, which shall form the basis for further programmatic and technological developments, this international initiative also triggered the IUGG Resolution No. 2 adopted by the IUGG Council (Prague 2015), underlining the importance of “Future Satellite Gravity and Magnetic Mission Constellations”.

In this contribution, the main results of this initiative will be presented. An overview of the specific requirements of the individual user groups, the consensus on consolidated science and user needs for observing global mass transport to understand global change and to benefit society, as well as the new research fields that have been identified during this process will be outlined and discussed. Additionally, the feasibility of the proposed mission scenarios will be analysed, focussing on the design of and double pair missions based on inter-satellite tracking, and innovative processing and gravity modelling approaches for this type of missions will be presented and discussed.

************************

Towards a Sustained Observing System for Mass Transport to Understand Global Change and to Benefit Society

Visser P.N.1, Bettadpur S.2, Chambers D.3, Diament M.4, Gruber T.5, Hanna E.6, Rodel1M.7, Wiese D.8
1Delft University of Technology, Netherlands, The; 2University of Texas at Austin, USA; 3University of South Florida, USA; 4Institut de Physique du Globe de Paris, France; 5Technische Universität München, Germany; 6University of Sheffield, United Kingdom; 7NASA Goddard Space Flight Center, USA; 8Jet Propulsion Laboratory, California, USA

The NASA and ESA space agencies established the Interagency Gravity Science Working Group (IGSWG) in 2013 to advise on future gravity mission concepts. Both NASA and ESA acknowledge the need for continued global observation of mass transport. Observing mass transport with the highest possible accuracy and spatial resolution and with temporal resolutions from daily to...
monthly is crucial for understanding the functioning and evolution of the Earth system (climate, geo-hazards, water cycle). Improved observation of global mass transport in terms of temporal and spatial resolution would benefit a diversity of Earth science domains (e.g. hydrology, oceanography, cryospheric sciences, solid Earth sciences, atmospheric sciences) for both scientific and application focused users, and are necessary to fully characterize diverse global change processes.

The working group finalized its activities in 2016 by delivering a report with the title "Towards a sustained observing system for mass transport to understand global change and to benefit society”. This report addresses the compatibility between user requirements, constellation concepts, and expected performance. In addition, a roadmap for implementation in the post-2020 time frame is included. This roadmap defines the path towards sustained observation of mass transport with the required accuracy and spatio-temporal resolution, while addressing the need for cooperation between different space agencies and/or providers, and assessing required activities such as studies and technological developments for both the near and longer terms.

**Coordinators ESA and NASA**

John Labreque, Thomas Johnson, Ben Phillips (NASA)
Roger Haagmans, Luca Massotti, Christian Siemes (ESA)

**Impact of Orbit Design Choices on the Gravity Field Retrieval of Next Generation Gravity Missions - Insights on the ESA-ADDCON Project**

Daras I.\(^1\), Visser P.\(^2\), Sneeuw N.\(^3\), van Dam T.\(^3\), Pail R.\(^1\), Gruber T.\(^1\), Tabibi S.\(^1\), Chen Q.\(^1\), Liu W.\(^4\), Tourian M.\(^4\), Engels J.\(^4\), Saemian P.\(^4\), Siemes C.\(^5\), Haagmans R.\(^5\)

\(^1\)Technical University of Munich, Germany; \(^2\)Delft University of Technology, Netherlands; \(^3\)University of Luxembourg, Luxembourg; \(^4\)University of Stuttgart, Germany; \(^5\)European Space Agency

Next Generation Gravity Missions (NGGMs) expected to be launched in the mid-term future have set high anticipations for an enhanced monitoring of mass transport in the Earth system, establishing their products applicable to new scientific fields and serving societal needs. The European Space Agency (ESA) has issued several studies on concepts of NGGMs. Following this tradition, the project “Additional Constellations & Scientific Analysis Studies of the Next Generation Gravity Mission” picks up where the previous study ESA-SC4MGV left off.

One of the ESA-ADDCON project objectives is to investigate the impact of different orbit configurations and parameters on the gravity field retrieval. Given a two-pair Bender-type constellation, consisting of a polar and an inclined pair, choices for orbit design such as the altitude profile during mission lifetime, the length of retrieval period, the value of sub-cycles and the choice of a prograde over a retrograde orbit are investigated. Moreover, the problem of aliasing due to ocean tide model inaccuracies, as well as methods for mitigating their effect on gravity field solutions are investigated in the context of NGGMs.

The performed simulations make use of the gravity field processing approach where low-resolution gravity field solutions are co-parameterized in short-term periods (e.g. daily) together with the long-term solutions (e.g. 11-day solution). This method proved to be beneficial for NGGMs (ESA-SC4MGV project) since the enhanced spatio-temporal sampling enables a self-de-aliasing of high-frequency atmospheric and oceanic signals, which may now be a part of the retrieved signal. The potential added value of having such signals for the first time in near real-time is assessed within the project.

This paper demonstrates the preliminary results of the ESA-ADDCON project focusing on aspects of orbit design choices for NGGMs.

-----------------------------------

**GOCE and Beyond: Status and Activities**

Floberghagen R., Haagmans R.
European Space Agency

This presentation provides an overview of the current status of activities in ESA related to the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission which was ESA’s first Earth Explorer in orbit between 17 March 2009 and 11 November 2013. GOCE determined geoid heights with centimetre-level accuracy and spatial variations in the static gravity field to one part per million (ppm), in both cases with a (half-wavelength) spatial resolution of 100 km on Earth’s surface. The geoid, gravity and gravity gradients of GOCE have been used for many scientific and practical applications. These related to for example to oceanography, solid Earth geophysics, aeronomy, height unification and GNSS levelling. Also more recently studies on time variations of gravity signals and ice mass balance were performed and global modelling efforts like 3D Earth were initiated. Recently, the latest, most up to date GOCE processing that led to the release 5 models has been critically reviewed and ideas for the future activities emerged. These will also be presented.

-----------------------------------
3PM2b: Magnetosphere-ionosphere-thermosphere coupling: turbulence and waves

Keynote: Magnetic Field Turbulence and Scaling Features in the Polar Ionosphere: Results from Swarm Mission
Consolini G.¹, De Michelis P.², Tozzi R.², Marcucci M.F.¹
¹INAF-Istituto di Astrofisica e Planetologia Spaziali, Italy; ²Istituto Nazionale di Geofisica e Vulcanologia, Italy

The characterization of ionospheric turbulence plays an important role for all those communication systems affected by the ionospheric medium, such as, for instance, the Global Navigation Satellite Systems (GNSS). Swarm measurements of the Earth's magnetic field allow a precise characterization of ionospheric turbulence and scaling features through magnetic field fluctuations, using a set of scaling indices derived from structure function analysis. This work focuses on some recent results dealing with the analysis of the scaling properties of magnetic field increments/fluctuations as measured by Swarm in the polar regions of the Northern Hemisphere. We discuss the obtained results in the framework of magnetic field turbulence, investigating also the variability of the observed turbulence features in relation to different IMF conditions and ionospheric polar convection patterns.

****************************

Diagnosing the Electrodynamics of Magnetosphere-Ionosphere Coupling Using the Swarm Satellite Constellation: The Role of Alfvén Waves?
Mann I.R.¹, Pakhotin I. P.¹, Forsyth C.², Rae I.J.³, Knudsen D.J.³, Burchill J.³, Özeker I.J.¹, Murphy K.R.⁴, Gjerloev J.W.⁵, Balasis G.⁶, Daglis I.A.⁷
¹University of Alberta, Edmonton, Alberta, Canada; ²Mullard Space Science Laboratory, University College London, London, UK; ³University of Calgary, Alberta, Canada; ⁴NASA Goddard Space Flight Center, Greenbelt, MD, USA; ⁵John Hopkins University Applied Physics Laboratory, Laurel, MD, USA; ⁶National Observatory of Athens, Athens, Greece; ⁷National and Kapodistrian University of Athens, Athens, Greece

We use data from the Swarm satellite constellation to examine the role of Alfvén waves in magnetosphere-ionosphere coupling (MIC), including the potential impact of the ionospheric Alfvén resonator (IAR). Exploiting the unique capabilities of the SWARM constellation, including multi-point measurements and the combination of high cadence and high resolution electric and magnetic field data, we investigate the impacts of the incidence, reflection and interference of Alfvén waves on magnetosphere-ionosphere coupling. The multi-point Swarm magnetic field data reveals a remarkable non-stationarity on ~10 second timescales, with contemporaneous E- and B-field measurements from single satellites additionally indicating the characterization of such disturbances as Alfvén waves. Moreover, statistical analysis of the magnetic fluctuations and the related single spacecraft field-aligned current (FAC) data product reveal that the stationarity assumption implicit in deriving such FAC estimates is frequently not valid. Whilst the large scale FAC profiles at spatial scales larger than ~150km are typically characteristic of the standard ljjima and Potemra region 1 and region 2 current systems, smaller scale presumably Alfvénic structures appear to behave differently and to have energetically significant consequences for MIC. We use the Swarm dataset to investigate the consequences of these Alfvén waves for potentially changing the standard paradigms for magnetosphere-ionosphere energy transport.

****************************

Ion Energization Processes Observed by ePOP, DMSP, and SWARM
Peterson W.K.¹, Redmon R.J.¹, Burchill J.³, Howarth J. ³, Knudsen D.³, Yau A.W.³
¹University of Colorado, United States of America; ²NOAA, Boulder Colorado, USA; ³University of Calgary, Alberta, CA

One of the outstanding problems in magnetosphere / ionosphere coupling is a detailed understanding of the processes energizing oxygen and other heavy ions to escape velocity in the top-side ionosphere. We present magnetic conjunction data from ePOP, DMSP, and SWARM taken at different altitudes that can begin to put constraints on the temporal and spatial extent of these processes.

****************************

Statistical Analysis of the Field-Aligned Currents in the Cusp with Swarm
Bai X.¹, Pitout F.¹, Lühr H.², Bogdanova Y.V.³, Buchert S.C.⁴
¹Institut de Recherche en Astrophysique et Planétologie (IRAP), France; ²Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences; ³RAL Space, Rutherford Appleton Laboratory, STFC, Oxfordshire, UK; ⁴Swedish Institute of Space Physics, Uppsala, Sweden

The cusp connects the dayside magnetosphere and the polar ionosphere region through the open field lines. Particles from the solar wind directly precipitate into the ionosphere and may form various field-aligned current structures. Our goal is to study the distribution and variation of the field-aligned currents in the cusp, driven by the solar wind-magnetosphere-ionosphere interactions. In this work, we have analyzed Swarm
data in the early phase of the mission, when the three satellites were still on the same orbit (as a string of pearl) and overflying Earth’s polar regions a couple of minutes apart. We have identified all cusp crossings according geometric considerations (magnetic latitude and MLT sector) and plasma signatures. We have statistically studied the characteristics of the currents and searched for possible correlations with solar wind/IMF parameters.

FLR Event Studies With SWARM-SuperDARN Conjunctions

Fenrich F., Knudsen D., Donovan E., Megan Gillies D.
University of Calgary, Canada

Field line resonances (FLRs) are standing shear Alfven waves along Earth’s magnetic field lines. They play an important role in solar wind-magnetosphere-ionosphere coupling and are known to be associated with discrete auroral arcs, substorm onset, and radiation belt dynamics. The large spatial coverage of SuperDARN and the orbital tracks of the SWARM spacecraft provide a great opportunity for conjunction event studies of FLRs. Intervals of conjunction between SuperDARN and SWARM during FLR wave activity will be identified and analyzed. SuperDARN backscattered velocities will be used to calculate the FLR wave plasma flows and electric fields which will then be used to estimate field aligned currents associated with the FLR. These wave parameters will be compared to simultaneous SWARM measurements of electric fields, plasma flows and field aligned currents as SWARM passes through the region of the FLR. The aim is to find numerous event conjunctions which will allow comparison of FLR wave parameters for a variety of wave frequencies and wavelengths. These comparisons will lead to new knowledge of FLRs and may provide new insight into the role that FLRs play in auroral arc generation.

Coordinated Swarm In Situ and THEMIS All Sky Imager (ASI) Observations of the Motion of Patchy Pulsating Aurora

Yang B., Donovan E., Liang J., Burchill J., Spanswick E., Knudsen D.
University of Calgary, Canada

Patchy pulsating aurora (PPA) is a common ionospheric phenomenon and as such offers a unique opportunity to study the inner magnetosphere. Patchy Pulsating Aurora (PPA) patches typically preserve the shape over several minutes. Although it has yet to be proven, structures of PPA patches are believed to move with ionospheric convection. In this presentation, we show observations of auroral structures from THEMIS All Sky Imagers during two PPA events and simultaneous Swarm EFI observations of convection in the topside ionosphere over those structures. We demonstrate that the latitudinal variation of velocity from Swarm EFI is consistent with the motion of the PPA structures from the auroral images. Given that the processes that define the shape of PPA patches occur near the magnetospheric equator, our results indicate that cold magnetospheric plasma plays a key role in determining patch shape and evolution.

Large Precipitation Event Influences Sub-Glacier Hydrology and Ice Flow of Recovery Ice Stream, East Antarctica

Das I.1, Schlegel N.2, Scambos T.3, Csatho B.4, Babonis G.4
1Columbia University, United States of America; 2Jet Propulsion Laboratory, NASA, California, USA; 3University of Colorado in Boulder, Boulder, USA; 4University at Buffalo, Buffalo, New York, USA

We observe a period of anomalous net positive accumulation of several gigatons over Recovery Ice Stream in 2006 using both GRACE and climate model data. The accumulation anomaly, manifest by higher-than-average precipitation, reversed the sign of Recovery Ice Stream mass balance over a period of a few months as observed by GRACE within the course of a year. ICESat and IceBridge laser altimetry data confirmed a thickening signal corresponding to the precipitation event. The timing of the precipitation event was correlated with movement of water in subglacial lakes over the Recovery Ice Stream. We propose that the large precipitation event caused a significant change in the ice overburden pressure at the base of the ice sheet, prompting subglacial water movement. This anomalous precipitation event may not be an isolated incident; climate models and reanalysis data suggest events of similar magnitude may occur a few times in a decade. We will present preliminary results using satellite and airborne laser altimetry and modeling.
Estimate of Regional Glacial Isostatic Adjustment in Antarctica Considering a Lateral Varying Earth Structure (ESA-STSE Project REGINA)

Sasgen I.1, Martin-Español A.2, Horvath A.3, Klemann V.4, Petrie E.J.5, Wouters B.5, Horwath M.5, Pail R.5, Bamber J.L.6, Clarke P.J.6, Konrad H.6, Drinkwater M. R.10

1Alfred Wegener Institute, Germany; 2School of Geographical Sciences, University of Bristol, University Road, Clifton, Bristol BS8 1SS, United Kingdom; 3Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstraße 21, 80333 München, Germany; 4Department of Geodesy, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany; 5School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, United Kingdom; 6Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC, Utrecht, The Netherlands; 7Institut für Planetare Geodäsie, Technische Universität Dresden, Helmholtzstr. 10, 01069 Dresden, Germany; 8School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, United Kingdom; 9School of Earth and Environment, University of Leeds, LS2 9JT, United Kingdom; 10Mission Science Division, European Space Agency, European Space Research and Technology Centre, Keplerlaan 1, Noordwijk 2201 AZ, The Netherlands.

The mass balance of the Antarctic ice sheet from satellite gravimetry, and to a lesser extent altimetry, observations remains uncertain due to the poorly known correction for the glacial isostatic adjustment of the solid Earth (GIA). Although much progress has been made in consistently modelling ice-sheet evolution, related bedrock deformation and sea-level change, predictions of GIA remain ambiguous due to the lack of observational constraints in Antarctica. Here, we present an improved GIA estimate based on the joint inversion of GRACE, Envisat/ICESat and GPS measurements, making use of the different sensitivities of the satellite observations to surface-mass and solid Earth processes. We base our joint inversion on viscoelastic response functions to a disc load forcing, allowing us to account for lateral variations in the lithosphere thickness and mantle viscosity in Antarctica. Our estimate is able to reproduce extreme GPS-measured uplift rates (up to 3 cm yr-1) in the Amundsen Sea Embayment, indicating that large parts of the uplift are caused by GIA induced by recent load changes in the presence of a low-viscosity upper mantle. We compare our GIA inversion estimate with the prediction obtained with a coupled model of the ice sheet and solid Earth, as well as with published estimates. We evaluate its impact on the determination of ice-mass balance in Antarctica from gravimetry and altimetry. The results presented here are the final results of the Support To Science Element Project REGINA and its Supplementary Study of the European Space Agency, www.regina-science.eu.

Arctic Gravity Field from Cryosat-2

Andersen O.B., Knudsen P., Abulaitijiang A., Holmes S. DTU Space, Denmark

Cryosat-2 data offers a unique possibility to derive the Arctic gravity field due to its near geodetic orbit of 369 days repeat. Its the only satellite besides the old ERS-1 flown 20 years ago which provide satellit altimetry of geodetic quality in the Arctic Ocean.

We will present and evaluate our new DTU15 global marine gravity field as well as our pre-releasable DTU17 arctic gravity field in the Arctic Ocean.

Both are based on retracked altimetry from Cryosat-2 and ERS-1 in the Arctic Ocean. In the Arctic Ocean we are testing an new combined empirical/physical retracking system that uses physical retracking of the LRM data using a reduced parameter system in combination with empirical retracking of the SAR and SAR-In data in particularly high latitude regions.

An advantage of the Cryosat-2 is its ability of provide new accurate sea surface height information for gravity field determination in the northernmost part of the Arctic Ocean upto 88N where no altimeters have measured before.

Also the first evaluation of the use of Cryosat-2 SAR data in a few relative narrow fjords of Greenland will be presented.

**********************************

High-Resolution Mass Changes of the Greenland and Antarctica Ice Sheets from Combined CryoSat and GRACE Inversion

Forsberg R., Simonsen S. DTU Space, Denmark

The combination of space-based remote sensing data, especially gravity field changes from GRACE and elevation changes from CryoSat, may yield time series of Greenland and Antarctica mass balance with both high temporal and spatial resolution, highlighting the varying individual mass loss behaviour of major glaciers systems, while still keeping a “correct” overall ice sheet wide mass loss, within the uncertainty of the glacial-isostatic effects. Although the GIA-related errors continue to be large in Antarctica, the temporal changes in mass balance are well determined, and show significant acceleration both over the Antarctic Peninsula and the Pine Island/Thwaites glacier systems. For Greenland the large yearly melt event of 2012 followed by extraordinary cool summers have meant that the Greenland ice sheet mass loss have been slightly decreasing during the CryoSat period 2010-16, with large variations between individual glaciers and ice streams.

In the presentation we outline change results from CryoSat and GRACE 2010-2016, for both Greenland and Antarctica, and outline the basis of a high resolution point mass estimation method, and the associated use firn compaction and density models. We also include estimates of the northern Canadian ice cap changes to reduce GRACE leakage errors for Greenland. We
estimate an overall mass balance of Greenland around -265 GT/yr and for Antarctica -145 GT/yr, representing nearly a doubling of Antarctica mass loss since 2002, while Greenland show only relatively small overall accelerations, with large regional melt region variations, clearly pointed out by CryoSat.

High Mountain Asia Glacier Mass Balance Estimates Using Satellite Geodetic Observations
Sun J.
Ohio State University, United States of America
The 2013 Intergovernmental Panel for Climate Assessment (IPCC) Fifth Assessment Report (AR5) concluded that the observed and explained geophysical causes of global geocentric sea-level rise, 1993–2010, is much closer towards closure. However, the discrepancy reveals that up to approximately 30% of the observed sea-level rise remains unexplained, despite contemporary reports on reconciled mass balance estimates of ice-sheet and mountain glaciers during the early 21st century. This discrepancy is primarily attributable to the wide range of estimates of respective contributions of Greenland and Antarctic ice-sheets and mountain glaciers to sea-level rise. In particular, the High Mountain Asian glacier systems remains a focus of public and scientific debate, as the uncertainty of its mass balance estimates and its future projection have a significant implication of water resource problems affecting 1.5 billion people in the region. It is also not clear, in the case of the High Mountain Asia glacier system that glacier ablation would instantaneously contribute to sea-level rise, as melt water is largely dammed up resulting from anthropogenic activities in the region. The use of satellite altimetry for glacier elevation change has been problematic primarily because of steep terrains causing grossly inaccurate gradient corrections hindering the ability to generate ice elevation time series. Here we use available DEMs developed using the Indian Cartosat-1 (2.5 m resolution) and the KH-9 Hexagon, and ALOS PALSAR and Envisat ASAR InSAR measurements over glaciers, such as the Siachen Glacier system in the East Karakoram for gradient corrections to generate altimetry-based glacier elevation time series. In particular, we use ICESat and multi-mission radar altimeter data including TOPEX, ERS-1/-2, Envisat, SARAL/Altika, CryoSat-2, as well as GRACE gravimetry data, and improved mountain glacier masks developed using optical/IR and SAR data, to provide an update of the glacier mass balance estimate in the High Mountain Asia region.

Keynote: With GOCE and Swarm Towards the 3D Lithosphere
Ebbing J.
Kiel University, Germany
Satellite measurements of the Earth gravity and magnetic field as from the GOCE and Swarm satellite missions have an increasing resolution. Their global coverage and specific characteristics (e.g. gradient measurements for GOCE) make them an ideal data sets for studying the lithosphere in combination with seismological models. Such a combined lithosphere is one of the goals of the ESA STSE “3D Earth”.

The prime objective of our project is to integrate seismological models and satellite observation towards a consistent image of the crust and upper mantle in 3D. Satellite gravity and (electro-) magnetic data help to transfer velocity images towards composition and temperature that reflect the tectonic state and evolution of the Earth and offer a novel understanding of the processes that shape our planet.

We will analyse the limitations and sensitivities of the different geophysical methods in the context of their imaging capability and in combination for forward and inverse modelling of the Earth’s internal structure. Such analysis will for example help to assess the role of isostatic (lithospheric) and dynamic (deep Earth) effects in shaping the surface of the Earth.

Large-Scale Constraints on Tectonics and Macroscopic Magnetic Properties of the Earth’s Lithosphere from the Swarm Constellation and CHAMP
Purucker M.E.1, McEnroe S.2
1NASA, Goddard Space Flight Center; 2Norwegian University of Science and Technology
We constrain large-scale macroscopic magnetic properties (susceptibility, remanence and their geometry) of the earth’s lithosphere in three regimes (continent, ocean, and subducted slab) using the latest high degree CHAOS and CM models, and compare those constraints to measured compilations of magnetic properties. At the highest degrees, these models still reflect a significant contribution from CHAMP, but the difference with the latest Swarm models is narrowing. In the oceanic realm, the magnetic symmetry across spreading centers, and presence of transform faults, are clearly evident only in
the fastest spreading ridges (e.g. East Pacific Rise). Both the CHAOS and CM models can now extract along-track features in the lithosphere. We discuss the implications for large-scale oceanic and continental tectonics in these latest models, and anticipate some of the results when the Swarm satellites are at lower altitudes.

************************

A New Lithospheric Field Model based on CHAMP and Swarm Magnetic Satellite Data

Olsen N.¹, Ravat D.², Finlay C.C.¹
¹Technical University of Denmark, Denmark; ²University of Kentucky

We used magnetic field observations from the last two years of the CHAMP satellite mission (at altitudes between 280 and 350 km), augmented with Swarm satellite gradient data, to determine a model of the lithospheric field. We first subtracted predictions of the core and large-scale magnetospheric field as given by the CHAOS-6 model from the observations. No further data treatment was applied (e.g., no orbit-by-orbit filtering or “line leveling” of the individual satellite tracks was done). The lithospheric field is described by 35,000 point sources at 100 km depth below Earth’s surface. We estimate the amplitudes of these point sources from the observations using an Iteratively Reweighted Least Squares approach with robust weighting, to account for non-Gaussian data errors. The model is regularized by minimization of the L1 norm of the vertical magnetic field at the surface (WGS84 ellipsoid). In a final step we expand our point-source model in series of spherical harmonics up to degree and order \( N = 185 \), accounting for \( \nabla \times \mathbf{B} = 0 \).

We will present our modeling approach and discuss the obtained lithospheric model, in particular how it compares with other lithospheric field models and with independent data sets.

************************

An Updated Global Lithospheric Model by Implementing 3D Joint Inversion of Gravity, Geoid, Topography and the Gravity Gradients in Spherical Coordinates

Salajegheh F., Afonso J.C.
CCFS, Department of Earth and Planetary Sciences, Macquarie University, Sydney, New South Wales, Australia

The ever-increasing interest in the generation of high-resolution models of the whole of the lithosphere by industry and academia has stimulated the development of probabilistic inversions of multiple geophysical datasets. These types of inversions are computationally expensive and rely on efficient algorithms to solve the forward problems. Potential field data (e.g. gravity, geoid and GOCE gravity gradients) is of particular interest given their complementary sensitivities to both crustal and deep lithospheric structure, particularly when jointly inverted with seismic data. When the inversion is performed in 3D Cartesian geometry, very efficient solvers exist, and this why current implementations of multi-observable probabilistic inversions rely on such geometry. This, however, precludes the application of the inversion method to large-scale domains (e.g. continental or global studies).

For the forward calculation, we have implemented the prism approximation for calculating the tesseral’s gravity effects. Thus, the lack of modelling singularities at the prism’s surface allows us to compute the gravity effects on the surface. If a prism instead of a tesseral is used in the spherical system, the effect of the potential or its first and second derivatives is obtained in the local edge system of the prism. Therefore, these effects have to be transformed to the local reference frame of the observation point.

We have applied a smoothness-constrained least-squares algorithm based on the joint interpretation of free-air gravity, geoid, topography and gravity gradients data. The used inversion method is a linearized iterative inversion procedure in order to obtain variations in MOHO depth, average crustal density, average asthenosphere density and LAB depth. This method is able to provide in relatively efficient time a simplified global lithospheric model, which may utilize as the lateral extension of the model for the large scale study in a more complicated modelling using probabilistic inversion algorithm (e.g. LitMod3D_inv) to directly image the thermal and compositional structure of the lithosphere and sub-lithospheric upper mantle in the spherical coordinates. The prior information for this study has been extracted from the LITHO1.0 model.

In the meantime, the ScalAPCK package has been used for parallelizing the inversion calculations. ScalAPACK is a collection of routines written in Fortran77 for solving dense and banded linear systems, least squares problems, eigenvalue problems, and singular value problems in the distributed memory concurrent supercomputers.

************************
Towards the best GOCE Gravity Gradients

Siemes C.1, Haagmans R.2
1RHEA for ESA - European Space Agency, The Netherlands; 2ESA - European Space Agency, The Netherlands

The GOCE gravity gradients show perturbations that correlate with the geomagnetic field. In particular the cross-track gravity gradient is significantly perturbed in the regions around the geomagnetic poles. Recently, it was found that the perturbing effect is due to an unmodelled quadratic factor that occurs in the conversion from the electrode control voltages to accelerations, which caused the highly dynamic acceleration signal from cross-track drag to map onto the cross-track gravity gradient. Fortunately, it is possible to model and completely remove the perturbing effect, arriving at a more accurate, “clean” cross-track gravity gradient, which is demonstrated in this presentation.

Also the other gravity gradients show perturbations that correlate with the magnetic field. Those perturbations are much smaller than the perturbation of the cross-track gravity gradient, but appear systematic and are therefore important to remove as well. We will show in this presentation to which extent these perturbation can be removed from the gravity gradients by re-calibrating the accelerometer data and assess the impact on the gravity field retrieval from GOCE data.

GOCE Southern Polar Gap Now Closed – Results of the ESA Antarctica PolarGap Project

Forsberg R.1, Olesen A.1, Jordan T.1, Ferraccioli F.2, Matsuoka K.3
1DTU Space, Denmark; 2British Antarctic Survey; 3Norwegian Polar Institute

The GOCE gravity field mission 2009-13 left polar gaps beyond latitudes of 83.6 degrees due to the orbit inclination. The Antarctic polar gap, essentially void of terrestrial gravity field data, was covered with airborne gravity data in the 2015/16 ESA “Polar Gap” project. With the Arctic gap covered by several airborne gravity campaigns in the last decade, the complete global mapping of the earth’s gravity field at GOCE resolution (~80 km) has thus now been achieved, a “holy grail” for geodesy for more than a century.

The Polar Gap project used a Twin-Otter aircraft, operating from remote field camps and the Amundsen-Scott South Pole station. The aircraft was equipped with a Lacoste and Romberg gravimeter supplemented with a high-grade iMAR IMU unit, providing reliable airborne gravity measurements at 2 mGal accuracy in spite of the rough conditions. The survey was tied to absolute gravity coastal sites at sub-mGal accuracy to secure bias-free airborne gravity data. The PolarGap data has been augmented with other data, especially sparse NASA IceBridge gravity tracks and AGAP IPY data, for computation of gravity gradients at GOCE altitudes as well. Comparisons of all data confirms the high quality of the new gravity data, to be eventually included in future global gravity field models.

In addition to the gravity sensors, magnetometers, ice penetrating radar, scanning lidar and the ESA 13 GHz ASIRAS radar was also flown, providing supplementary data for both SWARM and CryoSat in the polar gap, as well as general geophysical data for understanding subglacial topography and geology. Major new features detected from the geophysical data includes a deep subglacial valley system between the Pole and the Filchner-Ronne ice shelf region, as well as extended mountain systems under the ice, consistent with observed ice flow patterns from spaceborne radar velocity measurements.

************************

Imaging Small-scale Seafloor and Sub-seafloor Tectonic Fabric Using Satellite Altimetry

Sandwell D.T.1, Müller R.D.2, Matthews K.J.3
1UCSD, United States of America; 2Univ. of Sydney, Australia; 3Univ. of Oxford, United Kingdom

Marine gravity anomalies derived from satellite radar altimetry now provide an unprecedented resolution for mapping small-scale seafloor and sub-seafloor tectonic fabric. Most of the new information comes from the CryoSat-2 satellite, which has routinely collected altimetry data over ice, land, and ocean since July 2010. The satellite has a long 369-day repeat cycle resulting in an average ground track spacing of 3.5 km at the equator. To date it has completed more than 6 geodetic mappings of the ocean surface. These data are augmented by a complete 14-month geodetic mapping of the ocean surface by Jason-1 from its lower inclination orbit of 66° that compliments the higher inclination orbit CryoSat-2 (88°). The most recent global marine gravity anomaly map based on all of these geodetic mission data with 2-pass retracking for optimal range precision has an accuracy that is 2 times better than the maps derived from Geosat and ERS-1. The new data reveal the detailed fabric of fracture zones, previously unmapped, now extinct oceanic microplates in the central Pacific, and fault networks buried beneath thick sediments along continental margins. By combining satellite altimetry with marine magnetic anomalies and seafloor age dates from rock samples we are able to pinpoint the geometry and age of major plate reorganisations, particularly the enigmatic 100 Ma event, which occurred during the Cretaceous Magnetic Superchron.

4PM2: Satellite geodesy missions today II

Towards the best GOCE Gravity Gradients

Siemes C.1, Haagmans R.2
1RHEA for ESA - European Space Agency, The Netherlands; 2ESA - European Space Agency, The Netherlands

The GOCE gravity gradients show perturbations that correlate with the geomagnetic field. In particular the cross-track gravity gradient is significantly perturbed in the regions around the geomagnetic poles. Recently, it was found that the perturbing effect is due to an unmodelled quadratic factor that occurs in the conversion from the electrode control voltages to accelerations, which caused the highly dynamic acceleration signal from cross-track drag to map onto the cross-track gravity gradient. Fortunately, it is
The Status and Current Contributions of the GRACE Mission
Tapley B.D. 1, Flechtner F. 2, Watkins M. 3, Bettadpur S. 1
1University of Texas at Austin, United States of America; 2GFZ German Research Centre for Geosciences, Germany; 3NASA Jet Propulsion Laboratories, United States of America

The twin satellites of the Gravity Recovery and Climate Experiment (GRACE) were launched on March 17, 2002 and have operated for nearly 15 years. The mission objectives are to sense the spatial and temporal variations of the Earth’s mass through its effects on the gravity field at the GRACE satellite altitude. The major cause of the time varying mass is water motion and the GRACE mission has provided a continuous decade long measurement sequences which characterizes the seasonal cycle of mass transport between the oceans, land, cryosphere and atmosphere; its inter-annual variability; and the climate driven secular, or long period, mass transport signals. In 2012, a complete reanalysis of the mission data, referred to as the RL05 data release, was initiated. The monthly solutions from this effort were released in mid-2013 with the mean fields following in subsequent years. The mission is entering the final phases of operations with mission end expected to occur before July 1, 2017. The current mission operations strategy emphasizes extending the mission lifetime to minimize the break measurements before the GRACE Follow-On Mission is launched. This presentation will review the mission status and the projections for mission lifetime, describe the issues that influence the operations philosophy, discuss the approaches to bridge the gap between GRACE and GRACE FO and discuss the content of science data products during this transition period.

GRACE High-Frequency Temporal Gravity Solution on Hydrology Applications
Shum C.K. 1,2, Shang K. 1, Guo J. 1, Zhang Y. 1, Forootan E. 3, Akyilmaz O. 4, Dai C. 1, Kuo C. 5, Kusche J. 6, Liu G. 7, Liu R. 8, Merca H. 1, Schwartz F. 1, Schmidt M. 9, Zhong M. 2, Zotov L. 9
1The Ohio State University, United States of America; 2Institute of Geodesy & Geophysics, Chinese Academy of Sciences, Wuhan, China; 3School of Earth & Ocean Science, Cardiff Univ., Cardiff, UK; 4Institute of Geodesy, Istanbul Technical University, Turkey; 5Dept. of Geomatics, National Cheng Kung Univ., Taiwan; 6University of Bonn, Institute of Geodesy and Geoinformation, Bonn, Germany; 7Institute of Applied Mathematics, AMSS, CAS, China; 9Technische Universität München, Deutsches Geodätisches Forschungsinstitut, Germany; 9Sternberg Astronomical Institute, MSU, Russia; 10Bowling Green State University

It is estimated that by 2025 five billion people worldwide will live in water-stressed countries. Moreover, problems of water balance and availability will likely be aggravated by anthropogenic climate change, population shifts, and land-use changes. Extreme hydrology and weather hazards also significantly affect social well-being and economics. In this study, we will use the improved formulation for the energy balance approach (EBA) to estimate the high-frequency temporal gravity field using data from the GRACE twin satellites, which will be applied to surface and ground water storage estimation over several aquifers and river basins. Specifically, we will: (1) apply the GRACE high-frequency temporal gravity field on groundwater estimation; (2) evaluate the impact of different hydrology models on separating groundwater signal; (3) identify and quantify extreme hydrology and weather hazards using high-frequency GRACE solutions; (4) evaluate different input atmosphere models on the output high-frequency gravity inversion and the impact on the extreme hydrology and weather hazards analysis.

************************
Swarm as an Observing Platform for Large Surface Mass Transport Processes

Teixeira da Encarnacao J.1,2, Arnold D.3, Bezdék A.2,3, Dahle C.4,2, Doornbos E.5, van den Ijssel J.6, Jäggi A.2, Mayer-Gürr T.7, Sebera J.1, Visser P.9, Zehentner N.5

1Center for Space Research, University of Texas at Austin; 2Astronomical Institute, University of Bern; 3Astronomical Institute, Czech Academy of Sciences; 4GFZ German Research Centre for Geosciences; 5Delft University of Technology; 6Institute of Geodesy, Graz University of Technology; 7ESRIN, ESA

The Swarm satellite mission provides important information regarding the temporal changes of Earth’s gravity field. Several European institutes routinely process Swarm GPS data to produce kinematic orbits, which forms the basis for the estimation of monthly gravity fields. Each institute follows a different gravity field estimation approach and all together they provide complementary advantages. As a result, the combined gravity field model is superior to any individual contribution, improving the accuracy of the measurement of mass transport processes. These models are an integral part of the European Gravity Service for Improved Emergency Management project (http://egsiem.eu), thus providing independent input, in additional to dedicated geodetic data.

We illustrate the agreement of the Swarm models with the much more accurate GRACE solutions, at 1666km wavelength and over most of the Swarm mission lifetime. We additionally highlight large surface mass transport processes represented by the Swarm GPS data.

HISST And SLR - Bridging the Gap Between GRACE and GRACE-Follow On

Weigelt M.1, Jäggi A.2, Meyer U.2, Arnold D.3, Maier A.7, Sosnica K.3, Dahle C.4, Flechtner F.4

1Leibniz University Hanover, Germany; 2Astronomical Institute, University Bern, Switzerland; 3Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Poland; 4GeoForschungsZentrum Potsdam, Germany

GRACE is undoubtedly one of the most important sources to observe mass transport on global scales. Numerous applications have shown the validity and impact of using its data. Within the EGSIEM project GRACE gravity field solutions from various processing centers are processed and combined to further increase the spatial and temporal resolution. However, it is expected that GRACE will not continue to observe mass variations from space till is successor GRACE-Follow On will be operational. Thus there is a need for an intermediate technique that will bridge the gap between the two missions and will allow 1) for a continued and uninterrupted time series of mass observations and 2) to compare, crossvalidate and link the two time series. Here we will focus on the combination of high-low satellite-to-satellite tracking (hISST) of low-Earth orbiting satellites by GNSS in combination with SLR. SLR is known to provide highest quality time-variable gravity for the very low degrees (2-5). HISSST provides a higher spatial resolution but at a lower precision in the very low degrees. Thus it seems natural to combine these two techniques and their benefit has already been demonstrated in the past. Here we make use of the lessons learned within the EGSIEM project and focus on various aspects of combination such as the optimal strategy and relative weighting schemes. We discuss also the achievable spatial and temporal resolutions of different satellite scenarios, such e.g. using Swarm satellites in combination with Sentinel and/or single GRACE satellites.

Keynote: Thermosphere-Ionosphere-Magnetosphere Modeling and Validation Efforts Using SWARM, CHAMP, and GOCE Measurements

Ridley A.1, Doornbos E.2, Cnossen I.3, Wang H.4

1University of Michigan, Ann Arbor, MI, United States of America; 2Technical University Delft, Delft, The Netherlands; 3British Antarctic Survey, Cambridge, United Kingdom; 4Wuhan University, Wuhan, China

Space Weather is a term that is used to describe the time-varying conditions in the near-Earth space environment. Some of these conditions can be detrimental to technologies that are either on the surface or in space. For example, when large auroral events occur, significant amounts of energy are added to our upper atmosphere, causing it to heat and expand. This expansion can cause the density at low-Earth orbiting satellite altitudes to sometimes increase by an order of magnitude. These increases are not well modeled and therefore, the resulting changes in satellite trajectories are not well predicted.

As another example, strong currents and electric fields in the upper atmosphere, driven by processes in the magnetosphere, and often associated with the aurora once again, can drive currents in power lines that can overwhelm power transformers. These events have the potential to cause massive power outages in high-latitude countries.

Because of the complexity of the thermosphere-ionosphere-magnetosphere system, it is impossible to predict these types of events without the use of models. Global models of the magnetosphere and ionosphere-thermosphere system are used to predict satellite drag, geomagnetically induced currents, the
radiation environment, communication losses, and other space weather driven effects.

While the act of modeling the space environment is an important first step, it is crucial that the models be validated against measurements of the near-Earth space environment. The SWARM mission, as well as many other European led missions that have come before it, have played vital roles in improving our ability to model space weather and its effects.

In this talk, we will discuss some of the models that are being used to simulate the near-Earth space environment and the validation efforts that have been conducted using some of the data provided by missions such as SWARM, CHAMP, and GOCE. Particularly, we will discuss long-term validation efforts between the Global Ionosphere Thermosphere Model (GITM), the Thermosphere Ionosphere Electrodynamic General Circulation Model (TIEGCM) and GOCE inferred mass densities and winds in the thermosphere as well as global MHD simulations of the Earth’s magnetosphere and efforts to validate the field-aligned currents produced by the models using CHAMP and SWARM data.

Models and GOCE Measurements of Thermosphere Density and Wind Below 250 km

Doornbos E.1, Visser P.1, Cnossen I.2, Förster M.3, Prokhorov B.3, Ridley A.4
1Delft University of Technology, The Netherlands; 2British Antarctic Survey, UK; 3Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany; 4University of Michigan, USA

The last year of the science mission and the deorbit phase of GOCE offer a unique opportunity to assess the results of models of the density and wind in the middle and lower thermosphere. After depletion of GOCE’s xenon fuel on the morning of October 21, 2013, when the satellite’s mean geodetic altitude was 239 km, it took 3 weeks before the satellite disintegrated during re-entry, shortly after UTC midnight on November 11. A continuous record of instrument and housekeeping data was received until about 7 hours before re-entry, at which point the satellite’s minimum geodetic altitude was just 138 km. Although the along-track axes of the accelerometers on GOCE were saturated two days before the re-entry, accurate acceleration data could still be derived from the continuous GPS tracking up to the final day. The result is that a unique set of partially redundant, but largely complementary data on the aerodynamic interaction of the atmosphere with the spacecraft is available for this sparsely sampled altitude range. Density and wind data derived for the GOCE deorbit phase, as well as the science data from the period of October 2012 to October 2013, have been compared with both empirical models (NRLMSISE-00, JB-2008, DTM-2013, HASDM, HWM07, HWM14) and general circulation models (WACCM-X, TIE-GCM, GITM, UAM-P), exposing the relative strengths and weaknesses of these models.
Spatio-temporal Variability of Thermospheric Density using ESA (Swarm mission) Data
Yeasmin A. 1,2, Norman R. 1,2, Zhang K. 2
1SERC Limited; 2SPACE Research Centre, RMIT University, Melbourne, Victoria, Australia
Monitoring and understanding the variability and driving mechanisms of atmospheric density in the thermosphere can lead to improved atmospheric density models. Thermospheric dynamics are predominantly driven by temporal variations and spatial distributions of solar irradiance, geomagnetic forcing, redistributed composition and energy within the thermosphere. Variations in the external forcing, internal dynamics of the system, and coupling between the thermosphere and ionosphere, can drive complicated neutral temperature and composition variations, which vary neutral density scale heights and causes complicated density variations. Temporal variations include abrupt changes with a time scale of minutes to hours, diurnal variation, multi-day variation, solar- rotational variation, annual/semi-annual variation, solar-cycle variation, and long-term trends with a time scale of decades and spatial variations include latitudinal and longitudinal variations, as well as variation with altitude. In this study, we discuss and summarize these density variations from atmospheric density data, measured by accelerometers on-board the Swarm satellite. This research has the potential to improve atmospheric density modeling using Swarm accelerometer level2 data.

Swarm Mass Density and Plasma Observations During the St. Patrick’s Day Storm Event 2015 and its Global Numerical Modelling Challenges
Foerster M. 1, Prokhorov B. 1, Doornbos E. 2, Astafyeva E. 3, Zakharenkova I. 3
1GFZ German Research Centre for Geosciences, Germany; 2Delft University of Technology, Faculty of Aerospace Engineering, The Netherland; 3Institut de Physique du Globe de Paris, France
The most severe geomagnetic storm in solar cycle 24 started with a sudden storm commencement (SSC) at 04:45 UT on St. Patrick’s day March 17, 2015. It occurred without any significant precursor X- or M-type solar flares and appeared as a two-stage geomagnetic storm with a minimum SYM-H value of -233 nT. In the response to the storm commencement in the first activation, a short-term positive effect in the ionospheric vertical electron content (VTEC) occurred at low-and mid-latitudes on the dayside. The second phase commencing around 12:30 UT lasted longer and caused significant and complex storm-time changes around the globe with hemispherical different ionospheric storm reactions in different longitudinal ranges. Swarm-C observations of the neutral mass density variation along the orbital path as well as Langmuir probe plasma measurements of all three Swarm satellites and global TEC records during the storm interval are used for physical interpretations and modelling of the positive/negative storm scenario. At mid-latitudes, positive storm signatures were observed in the Northern Hemisphere (NH) of the European sector, whereas a large positive storm occurred in the Southern Hemisphere (SH) of the American sector. The negative storm phase was found to be strongest in the Asian sector, in particular in the NH, but developed globally on March 18 at the beginning of the recovery phase. These observations pose a challenge for the global numerical modelling of thermosphere-ionosphere storm processes as the storm, which occurred around spring equinox, obviously signify the existence of other impact factors than seasonal dependence for hemispheric asymmetries to occur. First numerical simulation trials using the Potsdam version of the Upper Atmosphere Model (UAM-P) are presented to explain these peculiar ionospheric storm processes.

Detection of Thermospheric Density Variations via Spacecraft Accelerations Observed Using the CASSIOPE GAP Instrument
White R., Langley R.
University of New Brunswick Geodesy and Geomatics Engineering
As one of eight instruments of the Enhanced Polar Outflow Probe (e-POP) payload on the Canadian CAScade, Smallsat and IOnospheric Polar Explorer (CASSIOPE) small satellite, the GPS Attitude, Positioning, and Profiling experiment (GAP) can employ one or more of the four GAP-A dual-frequency GPS receivers and associated zenith-facing antennas to provide high-resolution spatial positioning information, flight path velocity determination, and real-time, high-stability timing. Preliminary processing of raw GPS data acquired from one of the GAP-A GPS receivers using the University of New Brunswick’s GAPS Analysis and Positioning Software (GAPS) precise point positioning (PPP) utility has produced sub-decimetre root-mean-square positions and correspondingly accurate velocities for the CASSIOPE spacecraft. Spacecraft acceleration can also be determined by subsequent processing of the velocity estimates. To further enhance the precision and accuracy of CASSIOPE position, velocity, and acceleration estimates, the creation of a specialized low-Earth-orbit PPP processing engine is currently under development. This improved processing engine will be used to produce high-accuracy time series of CASSIOPE’s orbit, thus allowing for analysis of the spacecraft’s long-term orbital evolution as it approaches atmospheric re-entry. The proposed software will also allow for precise determination of short timescale accelerations of the spacecraft through the differencing of sequential high-rate velocity estimates using an appropriate filter. These precise acceleration determinations can subsequently be used to infer density variations in the thermosphere via algorithms previously developed within the SWARM science data system.
Investigation of a Future Constellation Geometry and Orbit Evolution of the Swarm Mission
Kotsiaros S.1,2, Sabaka T.J.1, Alken P.3
1NASA Goddard Space Flight Center, United States of America; 2Universities Space Research Association, Greenbelt, MD, USA; 3University of Colorado at Boulder, Boulder, CO, USA

The Swarm satellite trio is currently very healthy with sufficient fuel remains for several series of orbit maneuvers. This provides an excellent opportunity to prolong the mission significantly and therefore extend the mission objectives. We propose a future orbit evolution scenario for Swarm Alpha and Charlie and present a sensitivity analysis investigating the added scientific benefit of this proposal. The scenario can be broken down into four main scenes. Scene one: gradually reduce the longitudinal separation of Alpha and Charlie. This is expected to further exploit the cross-track gradient information and increase the sensitivity to the small-scale features of the lithospheric field, which are not captured so far by Swarm. In addition, a smaller separation is expected to suppress variable external field signals with short spatial distributions and might improve the sensitivity to the oceanic signals. Scene two: minimize the longitudinal separation and enter a tandem (string-of-pearls) configuration. This will enable the estimation of instantaneous along-track gradients and is expected to assist in decoupling the temporal and spatial correlations of the external fields along the orbit tracks. Scene three: increase the longitudinal separation of Alpha and Charlie beyond the initial separation of 1.4°. Larger separations are expected to benefit the investigation of high-latitude external field structures such as the auroral electrojets. Scene four: lift Alpha and Charlie to higher altitude and let them descend until the next solar minimum in 2030. This extends the mission duration which is important for core and external field studies as well as improving the internal field sensitivity with low altitude data at the end of the mission.

Aiming at Enhancing the Science Return of the Swarm Mission: the Swarm Delta NanoMagSat Project
Hulot G.1, Léger J-M.2, Vigneron P.1, Jager T.2, Bertrand F.2, Coïsson P.1, Astafyeva E.1, Tomasin L.3
1Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, F-75005 Paris, France; 2CEA, LETI, MINATEC Campus, F-38054 Grenoble, France; 3Centre National d’Etudes Spatiales, Toulouse, France

ESA’s Swarm mission aims at studying all sources of Earth’s magnetic field. It consists of two satellites (Alpha and Charlie), which fly side-by-side on near polar orbits at an altitude of slightly less than 500 km, and of a third satellite (Bravo) on a similar but slightly more polar and higher orbit, which progressively drifts with respect to that of Alpha and Charlie. This orbital configuration has proven extremely valuable, as evidenced by the many results obtained from the first three years of the mission. These results, however, also reveal that geomagnetic field modeling and investigation efforts are now hampered by the still limited local time coverage provided by this constellation. This affects our ability to accurately characterize time changes in the ionospheric and magnetospheric field contributions, and to model the electrical conductivity of the Earth’s mantle. It also indirectly limits our ability to model the core and lithospheric field. More generally, many of the “residual signals” detected in the very accurate magnetic data of the Swarm mission can still not fully be exploited. Further increasing the scientific return of the Swarm mission by squeezing more out of these data, however, would be possible if a fourth “Delta” satellite were to be launched soon enough to join the constellation at a similar altitude but much lower inclination orbit (such as 60°). Such a satellite would provide less geographical coverage but a much faster mapping of all local times over these latitudes. Its inclined orbit would also provide very useful “tie points” (with crossings at 60°) that would be very beneficial for lithospheric field investigations. In this

Nanosatellite Space Physics: Multispacecraft Missions Inspired by Swarm
Burchill J.K
University of Calgary, Canada

Advances in miniaturization have led to the potential for precision attitude determination and control, orbit control and formation flying, boom deployment, and large telemetry bandwidth on platforms ~10 kg or less and ~10 cm on a side. The low-cost-to-orbit nanosatellite technology affords means we can dream of new kinds of massively parallel missions. In this talk I argue the scientific merits of a space physics ‘Miniaturized Multispacecraft Mission’ for basic research into ionosphere-thermosphere-magnetosphere, training, and operational near-real-time space weather.

5AM2: The future: extended mission, future missions
presentation, we will report on an on-going CNES Phase 0+ aiming at designing a free-orbiting gradient stabilized 12U nanosatellite, “NanoMagSat”, that could be launched on such an orbit before the end of the Swarm mission (currently expected well beyond 2022) and act as the Swarm Delta satellite at a much reduced cost. We will report on progress in the satellite design, instrument miniaturization and performance, as well as on mission simulation activities.

************************
Three Times Three: Three Years of Swarm Routine Operations and Beyond

Clerigo I., Maestroni E., Diekmann FJ.
ESA, European Space Operations Centre (ESOC), Germany

Swarm is the magnetic field mission of the ESA Earth Observation program composed by three satellites flying in a semi-controlled constellation. Its history in-orbit began in the afternoon of the 22nd November 2013, when the three identical spacecraft separated perfectly from the upper stage of the Rockot launcher at an altitude of about 499 km. Control of the trio was immediately taken over by the ESA’s Space Operations Centre (ESOC) in Darmstadt, Germany. Following the successful completion of the Launch and Early Orbit Phase and platform check-out, during the commissioning phase operations focused on two main activities: the first in-flight calibration and characterization of the four instruments and the acquisition of the initial nominal orbit constellation for science exploitation.

The payload commissioning was concluded in spring 2014 and precious scientific data has been provided almost without interruption since then. Several contingencies and the need for improving science data quality have translated into a number of activities not foreseen before launch and which have kept the operations team very active during the first three years of routine operations. The main focus of this paper is to provide a summary of the most significant activities performed by the Flight Control Team to support payload investigations to improve science quality: the progressive tests and continuous parameter update for the Electrical Field Instrument (EFI); the slew manoeuvres performed to support the investigation of the scalar measurements residual between the Absolute Scalar Magnetometer (ASM) and the Vector Field Magnetometer (VFM); the thermal and dynamic tests performed for the characterisation of the Accelerometers (ACC) signals and the increase of the GPS field-of-view and the fine-tune of its loop bandwidths to improve its performance.

Furthermore this paper provides an overview of the Swarm operational concept with a special emphasis of the multi-spacecraft aspect of the mission and its impact in the ground segment design and the day-to-day management by the Flight Control Team (FCT). The Swarm constellation is described and some details on the routine manoeuvres are provided together with the impact of contingency collision avoidance manoeuvres. Finally, the paper concludes with some considerations of the operational impact of extending the mission beyond the nominal phase and the challenges the Flight Control Team will face to keep the Swarm satellites safely flying and providing many more years of fruitful science data.

CASSIOPE e-POP Mission Development and Operation

Enno G.A.\(^1\), Entus B.\(^2\), Hemingway J.\(^2\), Howarth A.\(^2\), Kachor T.\(^1\), Roberts J.\(^1\), Senez M.\(^2\), White A.\(^1\), Yau A.W.\(^1\)
\(^1\)University of Calgary, Canada; \(^2\)MDA Systems Ltd.

The CASCADE Smallsat and Ionospheric Polar Explorer (CASSIOPE) mission was successfully launched on September 29, 2013, and is currently in its fourth year of continuous operation. CASSIOPE uses the Canadian small satellite bus to carry the Enhanced Polar Outflow Probe (e-POP) scientific (space weather research) payload and the CASCADE communications technology demonstration payload into an elliptic polar orbit of 325 × 1500 km at an 80.9º inclination. This orbit makes possible the sampling of data over the full altitude range and at latitudes and local times of interest over the course of each year during the mission. The e-POP payload is comprised of a suite of eight high-resolution plasma, magnetic field, radio, and optical instruments designed for in-situ observations in the topside polar ionosphere at the highest-possible resolution. The payload utilizes the advanced data storage and telemetry downlink capability of CASCADE to meet its large data downlink bandwidth requirements while demonstrating the capabilities of CASCADE in the process. We give a brief description of the mission design, and operational experience to date in the context of opportunities for coordinated observations with other low-altitude polar-orbiting satellites such as the Swarm constellation.

Options for the Swarm Orbit and Constellation Evolution

Sieg D.\(^1\), Petrucciani F.\(^2\), Ziegler G.\(^3\)
\(^1\)ESA/ESOC, Germany; \(^2\)CS GmbH at ESA/ESOC, Germany, Germany; \(^3\)SCISYS Deutschland GmbH at ESA/ESOC

ESA’s Swarm magnetic field mission consists in three satellites flying in different circular Low Earth Orbits to form a constellation. Since completion of the orbit acquisition phase in April 2014 one satellite (B) is flying in a higher orbit while the other two satellites (A/C) form the lower pair with an ascending node difference of 1.4 deg. Along-track separation between A and C is maintained between 4 and 10 seconds. No altitude maintenance is performed.
Orbital planes are currently drifting: separation in LTAN between the lower pair and the highest one is increasing at a rate of 1.5 h per year, mainly due to inclination difference between the orbits (0.4 deg).

In the next future the constellation evolution will experience new phases: indeed, the decay rate of the satellites is strongly dependent on solar activity, which is foreseen to reach its minimum at the end of 2019, with a new maximum in 2024. Basing on currently available predictions of solar activity, different options can be chosen in order to maximise the scientific return of the mission. The poster focuses on these options.

A major constrain is the availability of fuel. During the initial orbit acquisition phase 40% of the fuel was consumed. Since then the yearly consumption has been less than 1% of the initial fuel and is mainly spent by the on-board attitude control. Taking into account future attitude control and orbit maintenance manoeuvres, still some fuel is remaining to reach various constellation configuration.

A list of options and their feasibility from the flight dynamics point of view is presented. Simulation results are shown for:
- control of LTAN difference between B and A/C to stay around 6 h (90 deg) for an extended time period.
- keep the LTAN difference increasing to reach counter-rotating orbits (delta LTAN = 12h around 2021).
- special formations of the lower pair satellites, i.e. reducing as possible their separation or let them follow the same ground track.
- increase mission lifetime beyond 2024 solar maximum to reach the following solar minimum in 2030. Possibilities are different for B only and for A/C.
- collect high accuracy measurement with A/C during the 2019 solar minimum at low altitude. A trade-off between amount of orbit lowering and length of subsequent altitude maintenance until fuel depletion is needed.

Finally some considerations are given on how the various options can be combined.

*************

**SWARM Instruments Performance Issues since Commissioning: Identification and Mitigation**

Vogel P.1, Ottavianelli G.2, Qamili E.2, Coco I.2, Siemes C.1, Mecozzi R.1, Floberghagen R.2, Kornberg M.1, Hoyos B.1

1ESA/ESTEC, Netherlands, The; 2ESA/ESRIN, Italy

Each SWARM satellite embarks a complex Payload. Several issues have affected the performance of the three Payloads since Commissioning. The purpose of this paper is to indicate how each issue has been addressed by the Phase E2 teams, providing first a short description of each issue, then informing on the progress in its characterisation or identification. The aim is to provide any SWARM interested reader with an overview of the problems encountered, of their current status, and - where relevant - with a plan of additional efforts to complete mitigation.

Thus the paper will elaborate on the following topics: perturbations on the Vector Magnetic Field measurements in sunlight, Absolute Scalar Magnetometer measurements deviation with changing satellite orientation, Star Tracker Boresight Alignment variation and correction, Electric Field Instrument image blurring, optimisation of Global Positioning System Receiver settings, Langmuir Probes measurements issues, Accelerometer measurements pollution, other anomalies.

*************

**Swarm Payload Data Ground Segment: Status and Future Outlook**

de la Fuente A., Ottavianelli G., Lopes C., Maltese A., Mariani L., D'Alba L., Floberghagen R.

ESA, Italy

The Swarm Payload Data Ground Segment (PDGS) is in charge of the Swarm data processing, archiving, products quality control; calibration and performance monitoring, and products’ dissemination.

This poster provides an overview of the current status of the Swarm PDGS and future outlook, highlighting the aspects more relevant to the end-users as the Level-1 and Level-2 Cat-2 processors’ status, reprocessing plans, new products’ integration, user’s registration, and data access.

*************

**“VirES for Swarm” - Evolution of the Swarm Data Visualisation Tool**

Santillan Pedrosa D., Toresen M.

EOX IT Services Gmbh, Austria

The virtual research service “VirES for Swarm” (http://vires.services) adds discovery and visual analytics capabilities to the European Space Agency’s online data access services established for the Swarm geomagnetic satellite mission constellation. VirES provides a highly interactive data manipulation and retrieval web interface for the official Swarm product archive and for a number of ancillary data sets. It includes multi-dimensional geographical visualization, interactive plotting and on-demand processing tools for studying Earth magnetic models and their time variations for comparing them to the Swarm satellite measurements at given global context of space weather. Subsets of Swarm data selected by versatile filtering methods can be downloaded in different encoding formats. The data downloaded can be combined to fit various use cases. VirES is also an environment for preparation of publication-ready graphics and charts through an intuitive and powerful yet customizable interface. An embedded online tutorial introduces the features of the VirES service to first-coming users. The VirES service is actively and continuously being
developed by ESA in close collaboration with leading experts of geomagnetism to ensure the best possible user experience and scientific validation of the presented information. At the 4th Swarm Science meeting the authors present the latest status of the VirES service to further stimulate wide usage of this tool and to collect valuable feedback from users for future evolutions.

********************

Swarm Data Exploitation and Valorisation at CDPP
Pitout F.1, Génot V.1, Budnik E.1,2, Marchaudon A.1, Bai X.1, Floberghagen R.2
1IRAP (CNRS/UT3), Toulouse, France; 2Noveltis, Labège, France; 
CDPP (http://cdpp.eu), the French database for space plasma physics, offers a set of services for, among other things, data exploitation and orbit visualisation. For data exploitation, the Automated Multi Dataset Analysis (AMDA, http://amda.cdpp.eu) is a web-based interface that offers plotting facilities, data mining and cross-database access via web services. AMDA archives and makes available data from most of the magnetospheric and planetary missions, and is now being extended to low-Earth orbit satellites such as Swarm. Besides, a 3D orbit visualisation tool (3DView, http://3dview.cdpp.eu) allows the user, on top of all traditional orbit visualisation capabilities, to plot data along the orbit of a spacecraft. We shall show through examples how Swarm data can advantageously be exploited and their use boosted with the tools offered by CDPP. We shall also introduce on-going developments of complementary tools.

********************

Swarm Magnetic Data Quality Overview
Qamili E.1, Ottavianelli G.1, Tøffner-Clausen L.2, Igual Bets C.3, Mecozzi R.4, Miedzik J.3, Vogel P.4, Coco I.1, Floberghagen R.1
1European Space Agency – Esrin, Italy; 2DTU Space, Technical University of Denmark; 3GMV, Poland; 4European Space Agency – Estec, The Netherlands

The ESA Swarm satellites, launched in November 2013, carry on-board instruments devoted to measure extremely accurate data necessary to improve our understanding of Earth’s magnetic field. Each spacecraft carry on-board an Absolute Scalar Magnetometer (ASM) for measuring the Earth’s magnetic field intensity and a Vector Field Magnetometer (VFM) measuring the Earth fixed coordinate frame is obtained by a three-head Star Tracker (STR) mounted close to the VFM instrument. In these three years of operations, the Swarm Magnetic instruments have provided high precision and high resolution data, allowing a better mapping of the Earth’s magnetic field.

This poster aimed at providing an extensive overview of the Swarm magnetic instrument status, magnetic data availability and quality.

********************

Statistical Analysis of Geomagnetic Field Intensity Differences between ASM and VFM Instruments Onboard Swarm Constellation
Tozzi R.1, De Michielis P.1, Consolini G.2
1Istituto Nazionale di Geofisica e Vulcanologia, Italy; 2INAF-Istituto di Astrofisica e Planetologia Spaziali

From the very first measurements made by the magnetometers onboard Swarm satellites launched by European Space Agency (ESA) in late 2013 it emerged a discrepancy between scalar and vector measurements. An accurate analysis of this phenomenon brought to build an empirical model of the disturbance, highly correlated with the Sun incidence angle, and to correct vector data accordingly. The empirical model adopted by ESA results in a significant decrease of the amplitude of the disturbance affecting VFM measurements so greatly improving the vector magnetic data quality. This study is focused on the characterization of the difference between magnetic field intensity measured by the absolute scalar magnetometer (ASM) and that reconstructed using the vector field magnetometer (VFM) installed on Swarm constellation. Applying empirical mode decomposition (EMD) method we find the intrinsic mode functions (IMFs) associated with ASM-VFM total intensity differences obtained with data both uncorrected and corrected for the disturbance correlated with the Sun incidence angle. Surprisingly, no differences are found in the nature of the IMFs embedded in the analyzed signals, being these IMFs characterized by the same dominant periodicities before and after correction. The effect of correction manifests in the decrease of the energy associated with some IMFs contributing to corrected data. Some IMFs identified by analyzing the ASM-VFM intensity discrepancy are characterized by the same dominant periodicities of those obtained by analyzing the temperature fluctuations of the VFM electronic unit. Thus the disturbance correlated with the Sun incidence angle could be still present in the corrected magnetic data. Furthermore, the ASM-VFM total intensity difference and the VFM electronic unit temperature display a maximal shared information with a time delay that depends on local time. Taken together, these findings may help to relate the features of the observed VFM-ASM total intensity difference to the physical characteristics of the real disturbance thus contributing to improve the empirical model proposed for the correction of data.

********************
Recent Results from Analysis of the Sun Induced Magnetic Disturbance

Tøffner-Clausen L.
DTU Space, Denmark

The efforts to investigate and characterise the Sun driven disturbances of the magnetic field measurements are continuing. This presentation shows the recent results from the co-estimation of the empirical model of the Sun driven magnetic disturbance and the characterisation of the magnetometer measurements on-board the Swarm satellites. With more than three years of data the estimation of the model characterisation parameters seem to converge towards stable solutions. The recent models employ a homogenous, exponentially decaying sensitivity consistent with the expected behaviour of the vector magnetometer instruments.

************************

Searching for the Cause of Small, but Systematic, Magnetic Field Anomalies Observed on Board the Swarm Satellites when Flying in non-Nominal Attitudes

Hulot G., Vigneron P.
Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, F-75005 Paris, France

On several occasions since the launch of the mission in November 2013, Swarm satellites went through a number of attitude manoeuvres. During these approximately one-day sessions, non-nominal attitudes (sideway, backward, or else) were successively maintained for each satellite over at least half a dozen orbits, allowing inter-satellite comparisons of magnetic field readings (on both the absolute scalar (ASM) and vector (VFM) magnetometers). This revealed small (at the nT level), but systematic, anomalies affecting the two instruments in a qualitatively similar way when a satellite is in non-nominal attitude, the VFM appearing to be slightly more affected. In this presentation, we will report on our systematic investigation of this intriguing effect, which is different from the Sun-driven effect already known to affect the readings of the VFM instrument in nominal attitude, and which does not appear to be due to trivial induced or remanent magnetization effects on board the satellites.

************************

A Comparison of Three Years of Swarm experimental ASM-V and Nominal VFM Data Using a Global Geomagnetic Field Modeling Approach

Vigneron P.¹,², Hulot G.¹, Deram P.², Olsen N.², Léger JM.³, Jager T.³

¹Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, F-75005 Paris, France; ²DTU Space, National Space Institute, Technical University of Denmark, Kongens Lyngby, Denmark; ³CEA, LETI, MINATEC Campus, F-38054 Grenoble, France.

Each of the three Alpha, Bravo and Charlie satellites of the ESA Swarm mission carries an Absolute Scalar Magnetometer (CNES customer furnished ASM instrument designed by CEA-Léti) that provides the nominal 1 Hz scalar data of the mission, but also delivers 1 Hz experimental vector data. Geomagnetic field models have already been published, using one year of such ASM-only data (without resorting to any of the nominal vector field magnetometer (VFM) data of the mission). These models demonstrated the good reliability of the ASM as a standalone instrument and the strong rigidity of the boom mechanically linking the ASM to the star imager (STR). They nevertheless also revealed small (at a few nT level) but systematic disagreements when compared to analogous models built using the nominal VFM data. In this presentation, we will report on our efforts to build a new extended model, now relying on three years of ASM-only data, which we will again compare to an analogous model built in the same way from nominal VFM data. Differences between these models will be discussed. It is hoped that such new comparisons will bring additional insight into the best way to further improve the nominal Swarm data.

************************

An Overview of Results from the Flux-gate Magnetometer on the C/NOFS Satellite

Pfaff R.F., Freudenreich H., Le G.
NASA/GSFC, United States of America

The instrument suite that comprises the Vector Electric Field Investigation (VEFI) onboard the C/NOFS spacecraft includes a sensitive fluxgate magnetometer to measure DC and ULF magnetic fields in the low latitude ionosphere. The instrument includes a DC vector measurement at 1 sample/sec with a range of ± 45,000 nT whose primary objective is to enable accurate measurements of both $V \times B$ fields and $E \times B$ drifts. The magnetic field data also address a variety of important scientific research topics involving ionospheric and magnetospheric current systems. For example, at low latitudes, magnetic field residuals allow studies of the temporal evolution and local-time asymmetry of the storm-time ring current, typically studied as Dst signatures, which provide continuous local time information every 97 minutes, given C/NOFS’s low inclination orbit of 13 degrees. The C/NOFS magnetometer data also provide information concerning low latitude ionospheric currents, such as the equatorial electrojet and F-region dynamo, as well as other distinct variations with local time and geographic location not readily associated with these currents. The VEFI magnetometer also includes an AC-coupled vector measurement in the 0.05 – 8 Hz frequency range sampled at 16 samples/sec with an output range of ± 900 nT in order to measure small-scale filamentary currents, diamagnetic currents, and
Alfvén waves associated with low latitude plasma depletions, enhancements, and structures. When analyzed in conjunction with the electric field data, the combined magnetic and electric field signatures show Poynting Flux measurements directed poleward, along the magnetic field direction, associated with depleted magnetic flux-tubes. These data are used to help advance our understanding of the electrodynamics of low latitude plasma instabilities and large scale plasma structures. This talk presents an overview of a number of scientific results gathered with the flux-gate magnetometer on the C/NOFS satellite.

***********************

Particle-in-cell Modeling of Interaction Between Nanosatellite And Ionosphere

Imtiaz N. 1, Marchand R. 2
1 PINSTECH, Pakistan; 2 Dept. Physics, University of Alberta, Canada

We numerically investigate interaction between the nanosatellite, CubeSat and surrounding plasma. The Dynamic Ionosphere CubeSat Experiment (DICE) is a Low Earth Orbit mission which is launched on October 28, 2011 with objectives to understand the near Earth space environment and its impacts on the Earth. The DICE mission consists of the two identical 1.5 U CubeSats. Each CubeSat’s payload carry two spherical Langmuir probes mounted on the booms extending out about 8cm from the payload in the opposite direction along the spin axis. The CubeSat payload is spin stabilized with a frequency of 0.2 Hz which gives an apparent rotation to the plasma flow in the frame of reference of the satellite. The payload spin axis tends to align itself with the Geodetic axis such that as the CubeSat moves toward the Northern latitude then the North pointing probe is in the ram and South-pointing probe is in the wake of the spacecraft. However the situation is opposite when the spacecraft moves toward the Southern latitudes. As a result spinning of the CubeSat payload with Langmuir probes deployed on it provides spin-modulated in-situ measurements of plasma parameters in the F2 region of the ionosphere.

This study will be helpful to understand the detailed interaction between the nanosatellites and the mesothermal plasma environment.

********************

The Swarm Langmuir Probes: Status and Ongoing Activities

Coco I. 1,2, D’Amicis R. 1,3, Buchert S. 4, Nilsson T. 4, Stolle C. 5, Foerster M. 5, Albini G. 6, Patterson D. 7, Burchill J. 7, Ottavianelli G. 5
1ESA, Esrin, Italy; 2Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; 3Istituto Nazionale di Astrofisica, Rome, Italy; 4IRF – Swedish Institute of Space Physics – Uppsala, Sweden; 5GFZ – German Research Center for Geosciences – Potsdam, DE; 6ESA, Esoc, Germany; 7University of Calgary, Canada

The Swarm Langmuir Probes (LP) are one of the two instruments which compose the Electric Field Instrument (EFI) on board Swarm spacecraft. They are devoted to the measurement of the electron density and temperature in the ionosphere and the measurement of the spacecraft potential which is auxiliary to the data processing of the other EFI instrument, the Thermal Ion Imager.

After three years in operations, the Swarm LPs equipment provides high quality observations especially for electron density, which turns to be the most reliable and stable Swarm plasma parameter product. Swarm electron density data have been used successfully in many scientific studies from polar to equatorial regions.

The operations team support even further improvements of Langmuir Probe operations, in particular: 1) the correct interpretation of the electron temperature measurements, still showing unexplained spikes widely observed throughout the whole dataset; 2) the calibration and validation of LP data by comparisons with models and independent datasets (e.g. Incoherent Scatter Radars, plasma parameters inferred from the measurement of the spacecraft’s faceplate currents).

This work will give an overview of the LP data validation activities and results during the first three years of mission operations, and suggests future validation/calibration plans.

********************
Swarm Thermal Ion Imager Instruments: Overview and Operational Status

Coco I.1,2, D’Amicis R.1,2, Kornberg M.3, Knudsen D.5, Burchill J.1, Floberghagen R.1, Albini G.3, Patterson D.6, Vogel P.4, Ottavianelli G.1

1ESA, Esrín, Italy; 2Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; 3Istituto Nazionale di Astrofisica, Rome, Italy; 4ESA, Estec, Netherlands; 5University of Calgary, Canada; 6ESA, Esoc, Germany

The Thermal Ion Imager (TII) is one of the two instruments which compose the Electric Field Instrument on-board each of the three Swarm spacecrafts. The TII instruments are devoted to measure the velocity and temperature of the bulk O+ distribution in the ionosphere, and to infer the ionospheric Electric field.

Despite the overall good health of the instruments and their associated equipment, in-orbit operations showed an unforeseen behaviour in the three TII. This is related to a non-permanent degradation of raw images that take place on continuous operations. After careful analysis of the data and several in-orbit tests, it was concluded that the observed image degradation is most likely due to water contamination in the sensor head. Several tests have been run in-orbit and a summary will be presented in the poster.

In order to tackle the unforeseen in-orbit behaviour, and for maximizing the quality of scientific data, an operational scenario was implemented where the instrument is switch-on for a few orbits per day. Discussions took place inside the science community, in order to achieve a sustainable operation plan for the TII, taking into account the most interesting configurations for science (e.g. particular latitude and local times, operations in conjunction with other spacecraft or ground based facilities). In this poster we will also show the new operational concept that ESA and the science experts developed in order to maximize the amount of good measurements with respect to the prevailing science needs.

CSES Electric Field Detector Calibration Tools Based on IRI, IGRF, and SWARM Data

Diego P.1, Bertello I.1, Candidi M.1, Coco I.2, Mura A.1, Ubertini P.1

1INAF, Italy; 2INGV, Italy

CSES (China Seismo-Electromagnetic Satellite) is a scientific mission mainly dedicated to the simultaneous and continuous monitoring of perturbations in the atmosphere, ionosphere, and magnetosphere, and to study their correlations with seismic events. Furthermore, CSES mission will allow to study the physical characteristics of the ionospheric plasma at the satellite altitude, to characterize the ionosphere in quiet and disturbed conditions. The satellite, 3-axis attitude stabilized, will be placed at a 98° Sun-synchronous circular orbit at an altitude of 500 km. The launch is scheduled in the first half of 2017 and the expected lifetime is 5 years.

The Electric Field Detectors (EFD) will measure electric fields in the range DC – 3.5 MHz with a precision ≤ 1 µV/m.

Such kind of measure is strongly affected by instrumental features and environmental parameters. These effects can reach several mV/m, therefore, are orders of magnitude higher than the signal we want to detect. Moreover, these factors show a large variability along the satellite orbit since they also depend on the plasma parameters and the geomagnetic field.

In order to evaluate the data correction factors we analysed data from IRI and IGRF models, and SWARM measurements.

Comparison between CSES simulations and SWARM data will help us to perform calibration tools to be used during their simultaneous flights at longitude close to each other. In particular, the SWARM EFI data will be used to evaluate the ion drift that allow to correct the EFD geometrical factor.

************************

Overview of Swarm Accelerometer Data Quality


1RHEA for ESA - European Space Agency, The Netherlands; 2Leibniz Universität Hannover, Germany; 3Delft University of Technology, The Netherlands; 4GFZ German Research Centre for Geosciences, Germany; 5Technical University of Denmark, Denmark; 6Serenum, a.s., Czech Republic

The Swarm satellites carry accelerometers as part of their scientific payload. These instruments measure the non-gravitational acceleration due to forces like drag or radiation pressure acting on the spacecraft, from which thermospheric neutral densities and potentially winds can be derived.

Unfortunately, the acceleration measurements suffer from a variety of perturbations, the most prominent being slow temperature-induced bias variations and sudden bias changes. Other less prominent perturbation includes spikes and artificial periodic signals. Though all perturbation are visible in the measurements of all Swarm accelerometers, their severity is much different for the three Swarm satellites. In this presentation, we illustrate all known disturbances and assess their severity for scientific exploitation of the accelerometer data separately for each Swarm satellite.

************************

***************
Swarm DISC: New Swarm Products and Services

Jensen J.K. 1, Knudsen D.J. 2, Olsen N. 1

1Technical University of Denmark, Denmark; 2University of Calgary

One task of Swarm DISC (Data, Innovation, and Science Cluster) is the identification, development and production of new products and services to enhance the scientific return of the Swarm mission.

Four new products have been selected during a first “call for ideas” in autumn 2016 and are presently being implemented. A second “call” is planned for early summer 2017.

We will present Swarm DISC, the approach to identify new products, and the status of the new initiatives that were selected in 2016.

**************************************************************

Swarm SCARF Comprehensive Inversion, 2017 Production

Tøffner-Clausen L. 1, Sabaka T.J. 2, Olsen N. 1, Finlay C. 1

1DTU Space Denmark; 2NASA / Goddard Space Flight Center USA

The Swarm SCARF (Satellite Constellation Application and Research Facility), a consortium of several research institutions, has been established with the goal of deriving Level-2 products by combination of data from the three satellites, and of the various instruments. Here we present the results of the Swarm SCARF team at DTU Space and NASA Goddard who conducts the Comprehensive Inversion (CI) magnetic field model processing chain; we present the results from using three years of Swarm data. The CI chain takes full advantage of the Swarm constellation by doing a comprehensive co-estimation of the magnetic fields from Earth’s core, lithosphere, ionosphere, and magnetosphere together with induced fields from Earth’s mantle and oceans using single and dual satellite gradient information. Level-2 products containing the corresponding model parameter estimations will be generated regularly throughout the Swarm mission and distributed via ESA.

**************************************************************

Swarm Level-2: Dedicated Core Field Model (DCO)

Rother M.

GFZ German Research Centre for Geosciences, Germany

The DCO (Dedicated Core) geomagnetic model submission for Swarm's third-year Level-2 product generation using Swarm-only data will be presented, as well as comparisons between the submitted version with its variants through adding observatory data or, taken advantage of the Swarm constellation, using data differences only (along-track and/or cross-track satellite data). Results in searching for Ocean Tide signals in the DCO model residuals will be discussed as a benchmark for the achieved quality of the presented models.

**************************************************************

Improvements of the Swarm Accelerometer Data Processing

Svítílova S. 1, Siemies C. 2, Doornbos E. 1, Encarnacao J. 1, Kraus J. 1, Peresty R. 1, Grunwaldt L. 1, van den IJssel J. 1, Flury J. 1, Rotter D. 1, Apelbaum G. 3, Holmåhl Olsen P.E. 4

1TU Delft, The Netherlands; 2RHEA for ESA, The Netherlands; 3GFZ German Research Centre for Geosciences; 4VZLÚ Aeronautical Research and Test Institute; 5Leibniz Universität Hannover, Hanover, Germany; 6Technical University of Denmark

The Swarm satellites carry accelerometers and GPS receivers as part of their scientific payload. The GPS receivers are not only used for locating the position and time of the magnetic measurements, but also for determining non-gravitational forces like drag and radiation pressure acting on the spacecraft. The accelerometers measure these forces directly, at much finer resolution than the GPS receivers, from which thermospheric neutral densities and potentially winds can be derived. Unfortunately, the acceleration measurements suffer from a variety of disturbances, the most prominent being slow temperature-induced bias variations and sudden bias changes. These disturbances required significant changes to the processing algorithms, which as a side effect caused a significant delay of the accelerometer data release.

In this presentation, we describe the new processing that is required for transforming the disturbed acceleration measurements into scientifically valuable thermospheric neutral densities. In the first stage, the sudden bias changes in the accelerometer measurements are removed using a dedicated software tools. We present a new option of automated step detection and correction, which should speed up the accelerometer data release. The second stage is the calibration of the accelerometer measurements against the non-gravitational accelerations derived from the GPS receiver, which includes the correction for the slow temperature-induced bias variations. The identification of validity periods for calibration and correction parameters is part of the second stage. In the third stage, the calibrated and corrected accelerations are merged with the non-gravitational accelerations derived from the GPS receiver by a weighted average in the spectral domain, where the weights depend on the frequency. The fourth stage consists of transforming the corrected and calibrated accelerations into thermospheric neutral densities. We describe the methods used in each stage, highlight the difficulties encountered, and comment on the quality of the thermospheric neutral density data set.

**************************************************************

Swarm SCARF Comprehensive Inversion, 2017 Production

Tøffner-Clausen L. 1, Sabaka T.J. 2, Olsen N. 1, Finlay C. 1

1DTU Space Denmark; 2NASA / Goddard Space Flight Center USA

The Swarm SCARF (Satellite Constellation Application and Research Facility), a consortium of several research institutions, has been established with the goal of deriving Level-2 products by combination of data from the three satellites, and of the various instruments. Here we present the results of the Swarm SCARF team at DTU Space and NASA Goddard who conducts the Comprehensive Inversion (CI) magnetic field model processing chain; we present the results from using three years of Swarm data. The CI chain takes full advantage of the Swarm constellation by doing a comprehensive co-estimation of the magnetic fields from Earth’s core, lithosphere, ionosphere, and magnetosphere together with induced fields from Earth’s mantle and oceans using single and dual satellite gradient information. Level-2 products containing the corresponding model parameter estimations will be generated regularly throughout the Swarm mission and distributed via ESA.

**************************************************************

Swarm Level-2: Dedicated Core Field Model (DCO)

Rother M.

GFZ German Research Centre for Geosciences, Germany

The DCO (Dedicated Core) geomagnetic model submission for Swarm's third-year Level-2 product generation using Swarm-only data will be presented, as well as comparisons between the submitted version with its variants through adding observatory data or, taken advantage of the Swarm constellation, using data differences only (along-track and/or cross-track satellite data). Results in searching for Ocean Tide signals in the DCO model residuals will be discussed as a benchmark for the achieved quality of the presented models.

**************************************************************
Recent BGS Activities for the Swarm Data Innovation and Science Cluster

Brown W., Hamilton B., Macmillan S., Beggan C., Thomson A.

British Geological Survey, Edinburgh, United Kingdom

The British Geological Survey is responsible for the fast-track magnetospheric field model product (MMA_SHA_2F), geomagnetic observatory data (AUX_OBS*2_) products and Level 2 CAT-1 product validation, as part of the consortium of institutes making up the Swarm Expert Support Laboratory. We summarise these activities and provide updates since the Living Planet Symposium in June 2016.

The fast-track magnetospheric field model product is generated automatically and disseminated on a daily basis after receipt of the Swarm L1b files. With more than three years of accumulated models, we comment on the longer-term behaviour of the magnetospheric field.

The observatory hourly-mean (AUX_OBS_2_) data product is updated every 3 months using a selection of definitive and quasi-definitive data from observatories around the world. Since Swarm was launched, good quality data from about 120 observatories are available.

BGS started issuing new observatory data products in October 2016 with a 4-day lag. Regular updates are made if new data are found. These products consist of 1-second observatory (AUX_OBSS2_) and 1-minute (AUX_OBSM2_) quasi-definitive data from the start of the Swarm mission, and are made available on the BGS anonymous FTP server at ftp://ftp.nerc-murchison.ac.uk/geomag/Swarm/AUX_OBS/.

A summary of temporal and spatial coverage of all observatory data products is provided.

Validation of the Level 2 CAT-1 products comprises comparisons of the Swarm-based models to independent models and data where possible, and inter-comparisons of models from the dedicated and comprehensive processing chains. A selection of plots from recent validation reports is given.

The Canadian Cordillera Array (CCArray): Taking Earth-Based Observations to the Next Level

Boggs K.¹, Eaton D.², Donovan E.², Sideris M.²

¹Mount Royal University, Canada; ²University of Calgary, Canada

CCArray is a bold initiative to deploy a network of telemetered solar-powered remote observatories, instrumented with riometers, weather stations, GNSS, permafrost monitors, atmospheric gas sensors and broadband seismometers, with the goal of characterizing Earth systems from the core to the magnetosphere. The proposed observation network will span the Canadian Cordillera (all of the mountainous regions of western Canada) from the Beaufort Sea to the US Pacific northwest with a spatial resolution of up to 1 degree.

A recent workshop at Fall AGU explored the potential for monitoring the formation of auroras in the magnetosphere, imaging subducted slabs in the mantle, improving our understanding of earthquake dynamics and tsunami hazards, extending critical zone (region from tree canopy through the soil into bedrock – the portion of Earth critical for life) monitoring stations into regions of permafrost, and improving modeling of atmospheric gravity waves (important for enhancement of numerical weather modeling). Here we will present a summary of some of the potential applications of such a network, expanding on integrated research results that have emerged out of the US Earthscope program together with outcomes from a series of workshops and planning meetings held across Canada and the US over the past year.

CCArray is envisioned as the initial component of a broader research collaboration that will extend within a rolling array across Canada from west to east. While many of the stations will be in place for up to three years, the intention is to leave some stations permanently fixed to enable long-term monitoring of Earth systems across Canada.

While the SWARM satellite program examines magnetic components of our planet from the magnetosphere down to Earth’s core, CCArray represents a complementary initiative with imaging capability that extends upwards to the magnetosphere from the Earth’s surface and downwards from the surface deep into the mantle.

Review of Data Recorded by the e-POP Radio Receiver Instrument (RRI)

James H.G.¹, Perry G.W.², Yau A.W.²

¹Retired, Canada; ²University of Calgary

The SWARM-ePOP collaborative opportunity comes as the CASSIOPE/e-POP scientific mission enters the second half of its estimated orbital life. ePOP scientists are contemplating how the resources of the remainder of the mission should be allocated. The e-POP Radio Receiver Instrument (RRI) has a 31-kHz bandwidth, and uses four 3-m distributed monopoles to detect spontaneous or artificial electromagnetic waves between 10 Hz and 18 MHz. In all data recordings made so far, the monopoles have been connected to the RRI high-impedance front end as orthogonal 6-m dipoles. In-phase and quadrature voltage signals are sampled on both dipoles at 62500 s⁻¹. CASSIOPE-ephemeris, RRI-Quick-Look, RRI-summary and RRI-detailed-Lv1 data are all available to the public at epop-data.phys.ucalgary.ca. Recently, the ePOP Science Operations Centre also released a free computer application called eDEx for metadata searches of data from all e-POP instruments.
To anticipate RRI experiments of possible interest to the Swarm community, we review principal findings from RRI recorded on about 900 CASSIOPE passes, most of which are 2-3 min long. These include about 350 Very-Low-Frequency (VLF) passes band-centred at 15.6 kHz, largely at high latitude. Signals from powerful VLF communications systems are received near apogee at locations far distant from their transmitters. In the High-Frequency domain, fruitful coordinations with ionospheric heaters and with coherent backscatter radars signals have been planned and carried out on well over 100 passes. These are being analyzed for the purpose of understanding the importance of propagation effects in the interpretation of ionospheric modification and scatter, respectively. We ePOP/RRI scientists wish to exploit productive coordinated experiments, both with other e-POP instruments and with external facilities throughout the world. We remain open to proposals for collaboration for the rest of the mission.

************************

Statistical Characterisation of Penetrating Radiation Fluxes near 500 km Altitude Based on Swarm EFI Thermal Ion Imager CCD Artefacts

Kouznetsov A., Burchill J., Knudsen D.
University of Calgary, Canada

The three Swarm satellites have been flying in polar circular low-Earth orbits since November 2013. Each satellite carries one electric field instrument (EFI) having two CCD67 charge-coupled devices from e2v for imaging ion energy distributions. A previous study (Knudsen and Man, 2007) estimated the effects of CCD radiation exposure on EFI measurements based on modelled incoming proton fluxes and radiation transport calculations. That study found that radiation-induced dark current was expected to be negligible at the end of the nominal 4-year Swarm mission, and furthermore provided a global statistical model of radiation fluxes at Swarm altitudes (~500 km). We revisit that study using (brief explanation of new methodology). In particular, we examine TII full images (sampled at a rate of ~1 / minute per sensor) for signatures of penetrating radiation and produce a geographical distribution of affected images. We compare that distribution with a distribution of south-atlantic anomaly (SAA) trapped proton and galactic cosmic ray (GCR) events calculated by ESA.

************************

Signature of the Inner Core in Surface Core Flow Variations

Gillet N.1, Finlay C.2
1ISTerre, Grenoble, France; 2DTU space, Copenhagen, Denmark

Satellite missions Oersted, CHAMP and Swarm now offer almost two decades of continuous monitoring of the geomagnetic field from space. This enables us to investigate interannual variations of core motions with an unprecedented accuracy. For this purpose, we rely on magnetic field models constructed using prior information compatible with the occurrence of geomagnetic jerks, which allows us to benefit from estimates of field changes uncertainties. These are required to reduce as much as possible biases in the core flow inverse problem. We focus on the analysis of time-dependent flow at the top of the core between 1998 and 2017. We find a minimum (resp. maximum) of the radial (resp. azimuthal) flow on interannual timescales at the location of the tangent cylinder (the virtual cylinder aligned with the rotation axis that contains the inner core). This observation is consistent with the quasi-geostrophic assumption, which assumes that the Coriolis acceleration dominates the force balance. It suggests that interannual core motions are only weakly sensitive to a proposed stratified layer at the top of the core inferred from seismology. We discuss implications concerning the density structure and mixing below the core surface.

************************

A Quasi-Geostrophic Magnetocoonvection Model of the Decadal Zonal Flow Dynamics in Earth’s Core

More C., Dumberry M.
University of Alberta, Canada

Geomagnetic data allows the reconstruction of fluid flow in Earth’s outer core. These reconstructions predict mean zonal accelerations on several timescales. The coupling of angular momentum between the core and mantle confirms the presence of such accelerations through the strong agreement between predicted and observed length-of-day changes. Scaling arguments for Earth suggest that mean zonal accelerations on both interannual and decadal timescales should be forced by magnetic, rather than inertial, forces. However, numerical models of the geodynamo have not been able to enter the parameter regime necessary to test this theory.

We have constructed a quasi-geostrophic model of magnetocoonvection, with thermally-driven flows perturbing a steady, imposed background magnetic field. The Taylor-Proudman theorem is used to justify this two-dimensional approach, in which velocities vary little parallel to the rotation axis. The reduction in dimensionality allows access to different areas of parameter space compared to three-dimensional models.
At Alfvén numbers similar those in Earth’s core, an analysis of the force balance responsible for mean zonal accelerations shows that magnetic forces dominate. We reproduce in our model both the free Alfvén waves and forced accelerations, the latter occurring at a larger timescale. Our model shows that decadal zonal accelerations can be produced by the underlying convective dynamics in Earth’s core.

************************

Gravity Signal of the Crust-Mantle Boundary and Density Structures in this Region

Root B., van der Wal W., Ebbing J.

1TU Delft, Netherlands, The; 2University of Kiel, Germany

The mass sources that are responsible for the long-wavelength gravity field of the Earth are not yet fully understood. The biggest candidate to describe these anomalies is mantle convection, yet models that can explain the mantle convection and the gravity field are not available. Another candidate is the core-mantle boundary with a density contrast of 4500 kg/m³ between the ferrous core and the silicate mantle. Due to the high density contrast variations in the core-mantle boundary can have a great impact on the gravity field. Also, density anomalies above the core-mantle boundary are large enough to be seen in the gravity field. The geometry of these anomalies amount to hundreds of km’s with density contrast up to 100 kg/m³.

Sensitivity tests using similar dimensions and density contrasts show that gravity anomalies of 10-100 mGal can be computed, which is in the same as the long-wavelength part of the gravity field. We argue that the gravity signal from structures at the deepest part of the lower mantle should be part of any global analysis. During the 3D Earth project, we will use seismic models of the core-mantle region to simulate more realistic geometries and density anomalies to study their effect on the global gravity field.

This presentation is part of the ESA Support To Science Element - 3D Earth – which is presented by Jörg Ebbing

************************

Swarm-Aurora: Identifying Auroral Conjunctions Using an Online and Offline Cross-Platform Set of Tools

Chaddock D., Donovan E., Spanswick E., Knudsen D., Frey H., Kauristie K., Partamies N., Jackel B., Gillies M., Holmdahl Olsen P.

1University of Calgary, Canada; 2University of Alberta, Canada

New Insight into Auroral Arc Microphysics from e-POP

Perry G., Shen Y., James G., Howarth A., Cogger L., Knudsen D., Miles D., Yau A.

1University of Calgary, Canada; 2University of Alberta, Canada

Using a full complement of instruments onboard the Enhanced Polar Outflow Probe (e-POP) on the CAScade, Smallsat and IOnospheric Polar Explorer (CASSIOPE) spacecraft, we investigate the plasma and auroral dynamics of an active auroral arc identified using e-POP’s Fast Auroral Imager (FAI). As CASSIOPE approached, crossed, and retreated from the arc, its International Geomagnetic Reference Field (IGRF) footprint remained within the FAI’s field-of-view. Because of this, we are able to study the
interconnection of the optical, plasma, and electromagnetic properties of the arc.

At the time of closest approach to the arc CASSIOPE was located at 457 km altitude. The e-POP Magnetic Field instrument (MfI) observed magnetic field perturbations indicative of structures of field-aligned currents coincident with the arc. Data from e-POP’s Imaging and Rapid-Scanning Mass Spectrometer (IRM) show a highly structured, O⁺ dominated plasma in the vicinity of the arc, with a strong asymmetry in vertical plasma flows on either side of the arc. Additionally, measurements from e-POP’s Radio Receiver Instrument (RRI) show intensified auroral hiss signatures at the location of the arc, and a region of strong sub-kHz radio wave activity poleward of the arc. Meanwhile, data from e-POP’s Suprathermal Electron Imager (SEI), which was operating in ion-mode, displays ion heating signatures near the poleward edge of the arc, indicative of the possibility of significant ion heating at the location of the arc. We assimilate e-POP’s highly-resolved contemporaneous dataset in order to provide new and compelling insight into the microphysics of dynamic magnetosphere-ionosphere coupling processes.

*Inferring Ionospheric Convection from Sequences of Auroral Images: A Complement to Swarm EFI*

Grono E.M.¹, Donovan E.¹, Murphy K.R.², Yang B.¹, Spanswick E.¹, Knudsen D.¹
¹University of Calgary, Canada; ²NASA Goddard Space Flight Center, Greenbelt, MD, United States

Patchy pulsating aurora (PPA) is frequently observed in the evening and morning sector auroral oval. While the precipitating electrons span a wide range of energies, there is increasing evidence that the shape of the PPA patches is controlled by structures in the near-equatorial cold plasma; structures in PPA are thought to move with ionospheric convection, for example. If this is true, then Swarm EFI observations of ionospheric convection will be significantly augmented by velocity maps inferred from auroral image sequences (e.g., from THEMIS ASI).

While developing a system of automatically processing the immense and rapidly growing amount auroral image data to extract convection, it became clear that the aurora referred to as PPA is at least two separate phenomena. One of these types of aurora is comprised of patches that move with convection, while the other exhibits profoundly different spatio-temporal behaviour and must arise from a fundamentally different electromagnetic/Alfvénic process.

In this talk, we will demonstrate the technique used to separate the two types of PPA, and an initial analysis of the differences between the phenomena. A key result is that the two types of PPA have different MLT distributions which may provide a clue as to their nature. The results of pattern recognition and image classification studies that identify aurora and PPA automatically will be presented, and we will demonstrate how to infer velocities of these structures that can augment convection measurements obtained via Swarm EFI observations.

*The Isinglass Auroral Sounding Rocket Campaign*

Lynch K.A.
Dartmouth College, United States of America

The NASA auroral sounding rocket mission Isinglass will be launched from Poker Flat Alaska in February of 2017. This mission consists of two separate 6-payload sounding rockets, over an array of ground-based observations. The science goal is to collect two case studies, in two different auroral events, of the gradient scale sizes of auroral disturbances in the ionosphere. Data from the 6 payloads and the ground-based observations will be assimilated into an ionospheric model, and the results will be studied to learn about the scale sizes of ionospheric structures which have significance for magnetosphere-ionosphere auroral coupling.

The in situ instrumentation includes thermal ion sensors (at 5 points), thermal electron sensors (at 2 points), DC magnetic fields (2 point), DC electric fields (one point, plus the 4 thermal ion RPA observations of drift), and an auroral precipitation sensor (one point). The ground-based array includes filtered auroral imagers, the PFISR and SuperDarn radars, a coherent scatter radar, and a Fabry-Perot interferometer array. The ionospheric model to be used is a 3D electrostatic model including the effects of ionospheric chemistry.

*A Localized Lithospheric Magnetic Model of Australia Incorporating Spectrally Diverse Aeromagnetic and Satellite Observations*

Kim H.R.¹, von Frese R.²³
¹Kongju National University, Korea, Republic of (South Korea); ²The Ohio State University, Columbus, Ohio, USA

A localized lithospheric magnetic anomaly model of Australia was developed from aeromagnetic total intensity data and CHAMP satellite vector observations. This joint inversion model was based on spherical Slepian functions that maximize power over a 20°-radius spherical cap centered on Australia. The spherical Slepian model to degree 360 was used to represent anomaly features of 1° (~111 km) and longer. Relative to global spherical harmonic modeling, localized Slepian modeling requires significantly fewer harmonic coefficients to represent the anomaly features. For the Australian study area, some 6,104 Slepian coefficients were used to model the near-surface and satellite altitude magnetic anomaly vectors and gradients to all orders within the working precision of the observations. This study also considers the use of spherical Slepian functions for combining spectrally diverse compilations of near-surface and satellite observations.
magnetic observations over spatially restricted spherical patches of the Earth. This approach is being developed for the next Antarctic Digital Magnetic Anomaly Project phase (ADMAP-2) that is compiling near-surface and satellite magnetic data for the Antarctic region south of 60°S. In this application, the gradient-like observations from the Swarm mission’s satellite constellation are being investigated to augment regional gaps in the aeromagnetic data coverage.

************************

Localized Crustal Magnetic Vector and Gradient Anomaly Components of the Antarctic from a Global Spherical Harmonic Model of the Swarm Observations

Kim H.R.1, Hong JK.2, von Frese R.3, Taylor P.4, Kim J.W.5
1Kongju National University, Korea, Republic of (South Korea); 2Korea Polar Research Institute, Songdo, Incheon, Korea, Republic of (South Korea); 3The Ohio State University, Columbus, Ohio, USA; 4Goddard Space and Flight Center, NASA, Greenbelt, Maryland, USA; 5Geomatics Engineering, Univ. of Calgary, Alberta, Canada

Crustal magnetic vector and gradient components are modeled by spherical Slepian functions over the 20°-radius spherical cap centered on the South Pole. The orbital configuration of the three Swarm satellites provides additional constraints for modeling the crustal magnetic gradient components by spherical Slepian functions for regional studies of the Antarctic crust south of 70°S. The advantages in localized Slepian versus spherical harmonic modeling include avoiding the need for a global distribution of data, far fewer numbers of spherical harmonic coefficients are required, and significantly more efficient computation of the higher degree components. In addition, spherical Slepian basis functions are orthogonal, and thus can be transformed into global spherical harmonic coefficients. In this study, localized spherical Slepian functions are developed to represent the three vector and six gradient magnetic anomaly components over the Antarctic from a global spherical harmonic model of the crustal magnetic anomalies of Swarm measurements. The role of Slepian functions for joint modeling of the Antarctic’s near-surface terrestrial, marine, and airborne magnetic data with satellite altitude magnetic observations is also considered.

************************

A Regional Geomagnetic Secular Variation Model of East Asia Using Spherical Slepian Functions

Kim H.R.1, von Frese R.2, Taylor P.3
1Kongju National University, Korea, Republic of (South Korea); 2The Ohio State University, Columbus, Ohio, USA; 3Goddard Space and Flight Center, NASA, Greenbelt, Maryland, USA

A regional secular variation model of the geomagnetic field for East Asia was made by fitting geomagnetic observatory data with spherical Slepian functions. This method is widely used in modeling the spherical coordinate attributes of spatially limited distributions or patches of geopotential field anomalies. The localized Slepian method is particularly efficient for updating the conventional global spherical harmonic secular model with new data. The annual means of vector components observed from 1997 to 2011 by four East Asia INTRAMAGNET observatories (i.e., Kakioka, Kanoya, Memambetsu, and Beijing) were modeled and compared with the global CHAOS-4 model. Cubic splines were adapted to produce secular coefficients at half-year intervals to maximum degree 8. Statistical and graphical comparisons with the global CHAOS-4 model illustrate the effectiveness of localized spherical Slepian functions for geomagnetic secular field modeling.

************************

Distribution of the Magnetic Anomaly for the Swarm Satellite in China and Adjacent Area

Wang C.1, Ding X.2, Chen B.3
1IGP Institute of Geophysics, China Earthquake Administration, Beijing, China; 2China Earthquake Administration of Xinjiang

The three-satellite constellation mission Swarm was launched by the European Space Agency (ESA) on 22 November 2013. The mission provided reliable measurements from which the global lithospheric magnetic field. Based on 3 years (2004~2006) of Swarm satellite magnetic field data, we derive the magnetic anomaly in China and adjacent area.

At satellite altitude the amplitude of the lithospheric field is very small, in particular that of the small-scale features. To isolate this signature, the first step is therefore to select the least-disturbed data. High and low latitudes exhibit very different properties in terms of ionospheric current intensities, we only selected and processed the middle-latitude data as ranging from 55° to 55° magnetic latitude. We are interested in night side effects, we have limited our study to the hours 22 to 03 local time (LT), during which the influence of F region currents can be neglected. Furthermore, we took only data from periods of low geomagnetic activity(Kp ≤2+ and DST ≤|30| ). Contaminated tracks were identified here by an automatic detection process and have been discarded. Then the main magnetic field, magnetospheric field, ionospheric field and induction fields were removed from the scalar data by subtracting the field model CHAOS, and finally some unrealistic observed data were deleted.

The Swarm magnetic anomalies show that satellite magnetic anomalies we obtained correspond quite well to characteristics of the large scale structure in China and adjacent area. Four magnetic anomaly areas formed by all the positive and negative anomalies, they are Songliao magnetic anomaly, Sichuan magnetic
anomaly, Tarim magnetic anomaly, and Tibet magnetic anomaly, each of them have one or more magnetic anomaly centers.

Balloon Gradient Magnetic Research at Altitudes of 20-40 Km in Addition to the Project "Swarm"

BrekhoV O.1, Tsvetkov Y.2, Filippov S.2

1Moscow Aviation Institute (National Research University), Russian Federation; 2Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of Russian Academy of Sciences (IZMIRAN), Russian Federation

The stratospheric balloon magnetic gradiometer at the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of Russian Academy of Sciences (IZMIRAN) and the Moscow Aviation Institute (MAI) is developed. It has two-stage measuring base of 6 km general length, oriented along the vertical line by means of the gravity. Balloon gradient magnetic research expands design possibilities "Swarm" for the geomagnetic field (GMF). The problem dealing with an investigation of the interior structure of the Earth crust by means of remote sensing methods is under consideration. This problem can be reliably solved on the base of the Earth magnetic field (EMF) data obtained at two space altitudes (30 and 500 km). The validation of the main global analytical models of the main EMF is examined by means of the gradient magnetic surveys executed on the stratospheric balloon flights at altitude of 30 km. The opportunity to use these models for the magnetic anomaly detection from the balloon surveys data derived at the altitude of 30 km is investigated. The stratospheric balloon gradient geomagnetic data of IZMIRAN-2010 experiment are used. Normal (main) and regional (crust) geomagnetic fields are separately considered. Daily mean spherical harmonious model (DMSHAM) derived from CHAMP data is used for study of the normal EMF. In this case the secular variations of EMF can be considered with accuracy up to 0.1 nT. Regional EMF is investigated by means of comparison of the experimental data with ground base data and EMM2010 model data derived from satellite and ground base data. It is shown that the EMM2010 model limited of 13 spherical harmonics have mistakes up to 15 nT. The balloon data show that EMM/720 model unsatisfactorily displays the EMF at 30 km altitudes. Regional EMF (anomaly geomagnetic field) derived from EMM2010 model differs (70%) from the measured one on the balloon. Improved model of the EMF derived from the satellite and balloon magnetic survey data could show the reliable information about the regional crust magnetic field and could give the way to see deep magnetic structure of the Earth's crust. The qualitative model of the main geomagnetic field cannot be constructed by means of satellite and ground base data only. It is shown, that an adequate global model of magnetic anomalies must be constructed only in accordance with the data obtained at satellite and stratospheric altitudes.

Using Variable Quad Geometry to Better Characterize the Field-Aligned Currents with Swarm

Blagau A.1,2, Vogt J.2, Marghitu O.1

1Institute for Space Sciences, Romania; 2Jacobs University Bremen, Germany

The algorithm used to generate the L2 dual-sat Field-Aligned Current (FAC) product is based on data provided by the lower satellite pair, i.e. SwA and SwC and relies on a rigid geometry of the four-point quad configuration (regular trapezoid, with fixed, i.e. 5s, along track separation). Depending on the FAC geographic location and inclination, other configurations are expected to provide a more accurate current density estimation. During the cal/val activities a dual-sat least squares (LS) method [Vogt et al. 2013] developed for a Swarm-like mission was shown to offer some advantages by allowing a more flexible geometry and by providing a framework for error assessment. The results supported the idea of using variable parameters for the quad configuration along the orbit, e.g. a smaller along track separation in the regions close to the geographic poles and a larger separation at lower latitudes, in order to increase the accuracy of FAC density estimation, as specified by the level of errors dependent on the geometry. In addition, since at least at the beginning of the mission, the orbital plane of SwB was close enough to the lower satellites' orbital planes, the LS dual-sat method can be successfully applied also to the combination SwB-SwA or SwB-SwC. In such events, the standard SwA-SwC FAC density estimate can be complemented with one (or sometimes two) additional estimate(s). The present contribution reports on the progress made by the ESA project SIFACIT, towards using the full capability of Swarm to better characterize the FAC system. Dual-sat FAC density estimations that rely on flexible SwA-SwC quad configuration, tailored to the FAC location, are presented and compared with the official dual-sat L2 product. At the same time, examples are shown when the use of SwB-SwA or SwB-SwC configuration provides valuable and complementary results, like in the region near the geographic poles or when the difference in orbital phase between SwB and SwA or SwC is smaller than between SwA and SwC.
A New Approach for Retrieving Time Series of External and Internal Spherical Harmonic Coefficients Describing Signals of Magnetospheric Origin

Kuvshinov A.1, Grayver A.2, Sabal T.3, Olsen N.3
1ETH Zurich, Switzerland; 2NASA Goddard Space Flight Center, Greenbelt, MD, USA; 3National Space Institute, Technical University of Denmark, Lyngby, Denmark

3-D electrical conductivity distribution at mid mantle depths (400-1500 km) was envisaged to be one of the Swarm Cat-1 L2 products. In order to detect 3-D variations of conductivity it was planned to exploit Swarm and observatory magnetic field signals of magnetospheric origin and to invert the so-called matrix Q-responses. These responses relate spherical harmonic (SH) coefficients of internal (induced) and external (inducing) parts of the magnetic potential. Time series of these coefficients are estimated within Comprehensive Inversion framework using potential method. Interpretation of Q-responses estimated from more than 3 years of Swarm and observatory data did not reveal, however, any meaningful 3-D variations of mid mantle conductivity, most probably due to a poor recovery of the induced coefficients responsible for 3-D effects.

We propose an alternative approach for retrieving time series of induced (and inducing) coefficients. It is based, in particular, on the fact that the horizontal magnetic field components are much less influenced by effects from 3-D inhomogeneities of the Earth compared to the vertical component. This suggests a two-step procedure for retrieving time series of the inducing and induced coefficients: First, by analysing horizontal component and assuming that the Earth’s background conductivity is known, one determines time series of inducing coefficients. Second, with the retrieved time series of inducing coefficients one determines induced coefficients by analysing vertical component only. This study discusses challenges and numerical details of the proposed approach.

************************

On the Role of Fine-Scale Non-Stationary Magnetic Field Perturbations in FAC Systems: Swarm Satellite Observations

Pakhotin I.P.1, Mann I.R.1, Knudsen D.J.K.2, Burchill J.K.2, Ozeke L.1, Gjerloev J.W.1, Roe J.J.4, Forsyth C.4, Murphy K.5, Balasis G.6, Daglis I.A.7
1University of Alberta, Edmonton, Alberta, Canada; 2University of Calgary, Calgary, Alberta, Canada; 3John Hopkins University Applied Physics Laboratory, Laurel, MD, USA; 4Mullard Space Science Laboratory, University College London, London, UK; 5NASA Goddard Space Flight Center, Greenbelt, MD, USA; 6National Observatory of Athens, Athens, Greece; 7National and Kapodistrian University of Athens, Athens, Greece

The orbital configuration of the Swarm satellites, with along-track and cross-track separations on the scales of tens of kilometers, allows for the estimation of field-aligned current (FAC) density during traversals of the auroral zones. However, such FAC estimates rely on the assumption that the magnetic field perturbations are quasi-stationary on the temporal scales of the crossings. Past work has focused on elucidating large-scale current features employing techniques such as low-pass filtering to remove any large-amplitude Alfven waves and/ or azimuthally localised current filaments which might invalidate these assumptions. In the new work presented here, we present evidence that in a significant proportion of auroral zone crossings the quasi-stationarity assumption may be violated and that the scales at which it is violated are energetically significant and cannot be easily discounted as small scale filamentations. Large-amplitude non-stationarities appear to be ubiquitous in the FAC associated with the coupled magnetosphere-ionosphere system and may have the potential to account for a significant part of the total energy budget. The non-stationarities are analysed statistically with relation to season, meridian and IMF Bz to further elucidate the nature of these dynamics and the potential extend of their energetic significance.

************************

The Revised Time-Frequency Analysis (R-TFA) Tool of the Swarm Mission

Balasis G.1, Papadimitriou C.1, Daglis I.A.1, Giannakis O.1, Vasalos G.1, Daglis I.A.2
1National Observatory of Athens, Greece; 2University of Athens, Greece

The IAASARS/NOA team has developed versatile signal processing tools suitable for the verification and validation of Swarm Level 1b products of the magnetic field [vector fluxgate magnetometer (VFM) and absolute scalar magnetometer (ASM) measurements] as well as of the electric field and electron density [Electric Field Instrument (EFI) measurements]. These tools can be used for the study of magnetospheric Ultra Low Frequency (ULF) waves and ionospheric Equatorial Spread-F (ESF) events, which are phenomena of space weather with effects on technology infrastructure. They are also useful for deriving sets of data suitable for lithospheric and main magnetic field modelling. These tools can help to extract information needed to detect space weather events as well as to complement other validation tools used on Swarm mission. Developed to derive the characteristics of ULF waves, the Time-Frequency Analysis (TFA) methodology, based on wavelet transforms, has proven to be effective when applied to the Swarm data to retrieve, on an operational basis, new information about the near-Earth electromagnetic environment. Processing Swarm measurements with the TFA tools helps elucidate the physical processes influencing the generation and propagation of ULF waves, which in
Magnetic Remote Sensing of Ocean Heat Content

Tyler R.H., Sabaka T.J.
NASA GSFC, United States of America

Understanding and predicting climate and sea level change requires monitoring the amount of heat stored in the ocean. A primary concern is that the extent of global warming may currently be masked by unaccounted heat increases in the ocean. Despite the recognized importance, adequate monitoring of ocean heat content has remained elusive using established in situ observational methods.

Here we demonstrate that monitoring of ocean heat content may be performed by satellite magnetometers by exploiting a phenomenon whereby ocean flow generates weak magnetic-field fluctuations that reach far outside of the ocean, even passing through sea ice. These magnetic fluctuations are modulated by the ocean’s electrical conductance (i.e. depth-integrated electrical conductivity) which we show to be linearly related to depth-integrated ocean temperature and thereby depth-integrated heat content. Inversion of magnetic data using the electromagnetic induction equation and appropriate methodology might then provide a means of remotely monitoring ocean heat content. Demonstration of this opportunity is made timely by the global magnetic survey underway by the recently launched ESA Swarm constellation of satellites that provides for the first time two-component gradiometric remote measurements of the magnetic field. Although we discuss here an example using just one ocean tidal constituent (the semi-diurnal M2), the larger opportunity allows joint inversions of a variety of induced and motionally induced ocean magnetic signals.

Our research actively underway so far specifically shows (a) a strong linear relationship between conductance and heat content; (b) a proof in concept that a highly accurate description of conductance can be recovered from synthetic (i.e. numerically modeled) ocean tidal (M2) magnetic data as would be observable remotely; (c) an M2 tidal magnetic field extracted from observations that agrees well with the synthetic prediction; and (d) that despite this agreement conductance obtained by inverting the observed M2 magnetic data can show disproportionate differences that are sensitive to the inversion method currently used (a factor of the well-known ill-posedness in inverse problems) such that observational noise and/or modeling errors presently limit the practical reliability of results. Addressing this challenge are the improved observational data being collected by Swarm, and continuing efforts at NASA GSFC to extract further oceanic signals to be used jointly in the inversions while also improving the data processing, modeling, and inversion methodologies.

************************

In Situ Measurements in Perturbed Plasma

Resendiz Lira P.A.
University of Alberta, Canada

Humanity relies more on space technology now than it ever did. The optimal use of space technology must be based on a good understanding of the interaction between hardware and space environment. Previous work has suggested that this interaction may cause aberration for in situ measurements. Since the presence of instruments perturbs the space plasma, measurement devices collect information of a modified state of the environment. The preliminary purpose of this work is to study the role of the earth magnetic field on in situ measurements obtained with a Langmuir probe. A 3D-particle-in-cell, fully electrostatic code is used to simulate the interaction between the Langmuir Probe and the space environment. The code provides detailed diagnostics, such as the particle flux and current for both species, electric field and potential, and velocity distributions. These parameters are used to construct the current-voltage characteristic of the Langmuir probe. From this electrostatic relation, the temperature and density of the plasma are calculated. Preliminary results show that the orientation of the magnetic field yields to a discrepancy in the measured temperature that is in agreement with reported data. The preliminary simulations suggest that the earth magnetic field connects the Langmuir probe with other parts of the spacecraft by driving currents that modify the particle flux collected by the probe. Since the space plasma temperature is strongly related to the collection of particles, the electron temperature inferred from probe characteristics is directly affected by the earth magnetic field’s orientation. Further research needs to be done in order to have a better understanding of all the physical processes involved.

************************

Magnetic Remote Sensing of Ocean Heat Content

Tyler R.H., Sabaka T.J.
NASA GSFC, United States of America

Understanding and predicting climate and sea level change requires monitoring the amount of heat stored in the ocean. A primary concern is that the extent of global warming may currently be masked by unaccounted heat increases in the ocean. Despite the recognized importance, adequate monitoring of ocean heat content has remained elusive using established in situ observational methods.

Here we demonstrate that monitoring of ocean heat content may be performed by satellite magnetometers by exploiting a phenomenon whereby ocean flow generates weak magnetic-field fluctuations that reach far outside of the ocean, even passing through sea ice. These magnetic fluctuations are modulated by the ocean’s electrical conductance (i.e. depth-integrated electrical conductivity) which we show to be linearly related to depth-integrated ocean temperature and thereby depth-integrated heat content. Inversion of magnetic data using the electromagnetic induction equation and appropriate methodology might then provide a means of remotely monitoring ocean heat content. Demonstration of this opportunity is made timely by the global magnetic survey underway by the recently launched ESA Swarm constellation of satellites that provides for the first time two-component gradiometric remote measurements of the magnetic field. Although we discuss here an example using just one ocean tidal constituent (the semi-diurnal M2), the larger opportunity allows joint inversions of a variety of induced and motionally induced ocean magnetic signals.

Our research actively underway so far specifically shows (a) a strong linear relationship between conductance and heat content; (b) a proof in concept that a highly accurate description of conductance can be recovered from synthetic (i.e. numerically modeled) ocean tidal (M2) magnetic data as would be observable remotely; (c) an M2 tidal magnetic field extracted from observations that agrees well with the synthetic prediction; and (d) that despite this agreement conductance obtained by inverting the observed M2 magnetic data can show disproportionate differences that are sensitive to the inversion method currently used (a factor of the well-known ill-posedness in inverse problems) such that observational noise and/or modeling errors presently limit the practical reliability of results. Addressing this challenge are the improved observational data being collected by Swarm, and continuing efforts at NASA GSFC to extract further oceanic signals to be used jointly in the inversions while also improving the data processing, modeling, and inversion methodologies.

************************
Observations of the Drift of Plasma Depletions Using SWARM Constellation and LISN TEC Measurements

Valladares C.E.1, Coisson P.2, Khadka S.3, Buchert S.4
1The University of Texas at Dallas, United States of America; 2Institut de Physique du Globe de Paris, France; 3Boston College, United States of America; 4Uppsala University, Sweden

During the early commissioning phase of the SWARM mission, the distance between the trajectories of all three satellites of the constellation was tens of km and the temporal separation was only a few minutes. This unique geometry allows us to conduct multiple and almost simultaneous in-situ measurements through the same low-latitude plasma depletion to investigate their spatial coherence and the motion of structures embedded within the equatorial plasma bubbles. We have used number density measured with the Langmuir Probe (LP) on board each of the three satellites of the SWARM constellation during December 2013 and concurrent TEC values obtained by ground-based GPS receivers to fully diagnose the bubble characteristics at multiple scale sizes. TEC values measured on the ground indicated that the plasma depletions moved with a velocity near 50 m/s and had a westward tilt of order 10\degree. Density depletions observed with SWARM indicated that the bubble velocities were also ~50 m/s. We have also found the velocity of density structures within the bubbles with scale sizes less than 100 km. This presentation will show results for several specific days of SWARM observations during passes throughout the South American continent.

------------------------

Characteristics Of Polar Cap Patches Observed By Multi-Instruments

Zou S.1, Ren J.1, Gillies R.2, Donovan E.2
1University of Michigan, United States of America; 2University of Calgary, Canada

Polar cap patches refer to the islands of high F-region plasma density within the polar cap. Their formation on the dayside and deformation on the nightside are not well understood. The F-layer ionosphere density is strongly influenced by electric field, thermospheric wind as well as soft particle precipitation. This study combines observations from multiple instruments, including Resolute Bay incoherent scatter radar, GPS TEC and LEO satellites, to investigate the effects of highly structured electric fields and winds on the modulation of polar cap patches. We will also discuss variations of the auroral emissions associated with the patch evolution.

------------------------

American Polar Cap Patches are Denser and more Structured than European Ones

University of Oslo, Norway

The Swarm satellites offer an unprecedented tool to survey polar cap patches, which are the main space weather issue in the polar caps. Using a new algorithm that automatically identifies polar cap patches in the plasma density data measured by Swarm, we computed the seasonal distributions of the patches detected between December 2013 and July 2016. We observe clear seasonal variations of the patch occurrence rate in both hemispheres. In the Northern hemisphere (NH), polar cap patches are mainly winter phenomena, with an occurrence rate enhanced during local winter and minimal during local summer. In the Southern hemisphere, the patch occurrence rate is also higher during local winter than during local, but the seasonal difference is not as marked as in the NH.

Additionally, we show that in the NH, patches that have been created above the American sectors exhibit larger densities and stronger fluctuations than the ones created over European sectors, and that this trend is reversed in the SH. As the electron density gradients and irregularities associated with patches can degrade HF radio and Global Navigation Satellite Systems (GNSS) signals, this study may have important implications for space weather forecasts.

------------------------

Analysis of Ionospheric Patches Based on Swarm Langmuir Probe and TEC Data

Chartier A.T.1, Mitchell C.N.2
1Johns Hopkins University Applied Physics Laboratory, United States of America; 2University of Bath, Claverton, Bath, BA2 7AY, United Kingdom

Dense, fast-moving regions of ionization called patches are known to occur in the high-latitude ionosphere. This investigation uses Swarm Langmuir probe and upward-looking GPS data to detect patches in both hemispheres. Statistical occurrence rates are produced from analysis of all the data from 2016. Patch formation theories characterize the phenomenon as occurring during winter or equinox, with plasma from the sunlit ionosphere drawn across a dark polar cap by magnetospheric convection. However, a recent statistical study by Noja et al. [2013] using CHAMP upward-looking GPS data indicates that this is not the case in the southern hemisphere, with detections peaking in summer in the southern hemisphere. This investigation applies the same patch filter methodology to Swarm’s upward-looking GPS data in order to validate the CHAMP findings, and addresses potential limitations of that dataset using in situ Langmuir probe electron density measurements. Results are validated using independent, ground-based GPS tomographic images of the ionosphere from the MIDAS algorithm.
Characteristics of Electron Density Variations at Equator Crossings

Buchert S. 1, Nilsson T. 1, Aol S. 2, Polin A. 1
1Swedish Institute of Space Physics, Sweden; 2Mbarara University of Science and Technology, Uganda

We present characteristics of electron density variations and irregularities at kilometer scales observed with the Swarm satellites at equator crossings.

Comparison between IRI and Electron Density Swarm Measurements during the St. Patrick Storm Period

Pignalberi A. 2, Pezzopane M. 1, Tozzi R. 1, De Michelis P. 1, Coco I. 1,3
1Istituto Nazionale di Geofisica e Vulcanologia, Italy; 2Dipartimento di Fisica e Astronomia, Università di Bologna, Italy; 3Serco Italia S.P.A, Italy

Preliminary Swarm Langmuir probe measurements recorded during March 2015, a period of time including the St. Patrick storm, are considered. Swarm electron density values are compared with the corresponding output given by the International Reference Ionosphere (IRI) model, according to its three different options for modelling the topside ionosphere. The similarity of trends embedded in the Swarm and IRI time series is investigated in terms of Pearson correlation coefficient. The analysis shows that the electron density representations made by Swarm and IRI are different for both quiet and disturbed periods, independently of the chosen topside model option. Main differences between trends modelled by IRI and those observed by Swarm emerge, especially at equatorial latitudes, and at northern high latitudes, during the main and recovery phases of the storm.

Moreover, very low values of electron density, even lower than $2 \times 10^4 \text{ cm}^{-3}$, were simultaneously recorded in the evening sector by Swarm satellites at equatorial latitudes during quiet periods, and at magnetic latitudes of about ±60° during disturbed periods. The obtained results are an example of the capability of Swarm data to generate an additional valuable dataset to properly model the topside ionosphere.

NeSTAD: A Tool to Tag Electron Density Anomalies with Swarm Data

Spogli L. 1,2, Cesaroni C. 1
1Istituto Nazionale di Geofisica e Vulcanologia, Italy; 2SpacEarth Technology, Italy

The identification and characterization of the ionospheric irregularities is of paramount importance to study how the forcing from outer space and lower atmosphere determines the ionospheric variability. The NeSTAD (Ne Single Track Anomaly Detection) algorithm is a recently developed tool able to support an ad hoc tagging of electron density (Ne) anomalies evaluated on Swarm Langmuir Probe electron density data. Directly interfacing with the Swarm data repository, NeSTAD is able to ingest Langmuir Probe (EFIx_PL and Plasma Preliminary) and Ionospheric Bubble Index (IBI/TMS) data, together with Dst index (derived from NASA-omniweb portal to providing the geomagnetic characterization). NeSTAD is able to assign to the measurements acquired along each track, i.e. a portion of Swarm data covering a region of interest in a given time interval, some “anomaly parameters”, that identifies anomalous behaviour of the electron density. The anomaly parameters, introduced in detail in the paper, are obtained from the derivative of the relative variation of the electron density along each satellite. Starting from such quantity, evaluated track by track for each of the three Swarm satellites, outlier analyses are performed to identify the anomaly parameters. Such track anomaly parameters can then be used to define “tagging criteria” to tag anomalies of interest for different applications, such as ionospheric irregularities formation studies, lithosphere-atmosphere-ionosphere coupling studies, etc. The NeSTAD has been developed in the frame of the SAFE (SwArm for Earthquake Study, http://safe-swarm.ingv.it) project, funded by ESA in the frame of STSE Swarm+Innovation. NeSTAD is written in MATLAB and implemented to work on both Linux and Windows operative systems. In the present contribution, the main characteristics of the algorithm and examples of application in the above mentioned field of research are presented.

Relationship between Plasma Density Gradients and Swarm GPS Data

Faehn Folkestad A. 1, Clausen L.B.N. 1, Miloch W.J. 1, van den Ijssel J. 2
1University of Oslo, Norway; 2Delft University of Technology, Delft, The Netherlands

GPS signals are subject to disturbances in the polar regions, caused in part by clouds of high density plasma (polar cap patches). For the Swarm satellites, this noise results in positioning errors in the order of centimeters. In this study, we use data from the GPS receiver and compare it to in situ density gradient data from the Langmuir probes.
We find that when GPS satellites are in front (azimuth φ=0±20°) of the Swarm, there is a direct proportionality between the density gradient dn/ds and the GPS observable dL4/dt. The same is true for when GPS satellites are positioned behind the Swarm satellite (azimuth φ=180±20°). Our results suggest that dL4/dt measurements from any satellite can be used to extrapolate the distribution of the plasma density gradient in the surrounding volume of the satellite, so that plasma density gradients can be detected from GPS receiver data alone.

************************

Ground Based Kinematic GNSS Contribution Dealing with Space Weather Observations

Balodis J., Haritonova D., Normand M., Silabriedis G.
University of Latvia, Latvia

The five-minute resolution GNSS observation results are computed in kinematic mode by scientific post-processing software for the 30 continuously operating GNSS reference stations covering territory of Latvia. The cases of disturbed coordinates are searched among computed results in four selected periods: the week of St. Patrick’s Day storm in March 2015, June and September 2015, and January 2016. The events of computed coordinate disturbances are found. They are noticed as features of the ionospheric scintillation, which causes the failed coordinate appearance. The statistics of the disturbance occurrences is analyzed in comparison with a geomagnetic storms registered by international services. Events of both disturbances and domes of affected GNSS reference stations are listed and the comparison with a list of geomagnetic storms is performed. Graphs of occurrences of coordinate disturbances at the GNSS continuously operating reference stations are designed. The subset of most affected GNSS reference stations is discovered.

Conclusion is carried out that the five-minute resolution GNSS observations results computed in kinematic mode for the GNSS ground based continuously operating reference stations are representing a reasonable contribution for recognition of space weather anomalies.

************************

Swarm for Space Weather monitoring

Stolle C.1, Olsen N.2, Gullikstad Johnsen M.3, Kervalishvili G.1, Rauberg J.1, Berdermann J.4, Doornbos E.5, Dunlop M.6, Heilig B.7, Langhans M.1, Marghitu O.8, Thomson A.W.P.9
1GFZ Potsdam, Germany; 2DTU Space, Denmark; 3TGO, Tromsø University, Norway; 4DLR Neustrelitz, Germany; 5TUD, The Netherlands; 6STFC RAL, UK; 7MFGI, Hungary; 8ISS, Romania; 9BGS NERC, UK

ESA’s Swarm LEO satellite constellation mission provides high precision measurements of magnetic field, plasma and neutral densities, and electric field. On board GPS observables are used for sounding ionospheric and plasmaspheric total electron content. Continuous data sets from LEO satellites, including Swarm have been used for developing empirical models of the temporal occurrence and local distribution of typical structures in near-Earth space, like the expansion of the auroral oval, the location of the plasmapause, or plasma structures in the F region ionosphere. Among others, these phenomena can harm, for example, continuous radio navigation and communication (e.g., Galileo, GPS) through the development of severe ionospheric plasma gradients, and the intensity and location of auroral currents indicates the probability of geomagnetically-induced currents, e.g., during geomagnetic storms.

ESA’s Space Situational Awareness/Space Weather segment (SSA SWE) runs the “Swarm Utilization Analyses” (SUA) study for integration of Swarm products into ESA’s SSA SWE webportal, where day-by-day Swarm observations, combined with information from empirical models, are used to provide nowcast of such events. This paper will therefore report on recent results from the SUA study, including implementations and other potential space weather products.

This paper will also report on developments of the existing Field-Aligned Current, the Total Electron Content, and Ionospheric Bubble Index products, currently provided as continuous Swarm Level-2 Category-2 products.

************************

Determination of CASSIOPE Topside Ionospheric Total Electron Content Using GPS Precise Point Positioning Techniques

Nicholson H.N., Langley R.B.
University of New Brunswick, Canada

Since the advent of satellite technology, there has been an increased need for accurate information on plasma density variation within the ionosphere. Such information can subsequently be used to improve the modeling and forecasting of ionospheric conditions under varying states of plasma activity. As part of the Enhanced Polar Outflow Probe (e-POP) payload on the Canadian CAScade, Smallsat and Ionospheric Polar Explorer (CASSIOPE) small satellite, the GPS Attitude, Positioning, and Profiling (GAP) experiment’s dual-frequency GPS receivers and associated zenith-facing antennas (GAP-A) can be utilized to derive plasma density variation estimates above the satellite. To provide these estimates, a specialized precise point positioning (PPP) software package is under development that will be used to post-process the raw carrier-phase and pseudorange observables obtained from up to three of the four GAP-A GPS receivers. This new software package will make use of both the standard PPP and array-aided PPP (A-PPP) techniques. As the A-PPP total electron content (TEC) estimation technique requires data from multiple, collocated receivers with fixed baseline offsets, the GAP-A
in terrestrial electrical power grids as a result of the geomagnetically induced currents (GICs) can be driven through densification of existing datasets used to generate various ionospheric models. The determination of TEC is essential to the continued understanding of the solar-terrestrial impact of the ionosphere on navigation systems with polar regions being of ever-increasing importance.

***************

**Modeling the Sq and Equatorial Electrojet Magnetic Fields from 3 years of Swarm Data**

Chulliat A.1,2, Vigneron P.3, Hulot G.3
1University of Colorado Boulder, United States of America; 2NOAA National Centers for Environmental Information (NCEI), United States of America; 3Institut de Physique du Globe de Paris, France

The Dedicated Ionospheric Field Inversion (DIFI) is a Swarm level-2 processing chain calculating spherical harmonic models of the ionospheric magnetic field at mid- to low-latitudes. DIFI includes descriptions of the seasonal and solar cycle variations and provides both the primary and secondary (induced) magnetic fields at ground and satellite altitudes. The DIFI-2 model, released in May 2016, was based on more than two years of Swarm data and data from 79 ground observatories. It revealed some new features of the Sq current system, including a peculiar seasonal variability and a wave-4 longitudinal variability in the Southern hemisphere. Here we present a new model, DIFI-3, based on three years of Swarm data. The larger time interval provides a better local time coverage due to the slow increase of the local time difference between the lower pair of satellites and the upper satellite. We exploit this better coverage to investigate the robustness of the Sq features found in DIFI-2 by calculating models from subsampled datasets.

***************

**Exploring the Development of GICs Related to Large dB/dt Variations in Space**

Dimitrakoudis S.1, Mann I.R.1, Murphy K.R.2, Rae I.J.1, Denton M.3, Milling D.K.1
1University of Alberta, Canada; 2NASA Goddard Space Flight Center, Greenbelt, Maryland, USA; 3Mullard Space Science Laboratory, University College London, Dorking, UK

Geomagnetically induced currents (GICs) can be driven in terrestrial electrical power grids as a result of the induced electric fields arising from magnetic field changes driven in the coupled magnetosphere-ionosphere-ground system. Substorms are often hypothesised to be associated with the largest GIC effects on the ground, especially at higher latitudes. However, recent studies have suggested that other dayside phenomena such as sudden impulses and even ULF wave trains might also drive significant GICs. To investigate the evolution of magnetospheric disturbances, ionospheric currents, and their associated GICs, we have searched for conjugate magnetometer measurements from the GOES East and West, Swarm, and e-POP satellites, and the CARISMA ground array. We have focused on large dB/dt events, since ground dB/dt can be used as a GIC proxy. Several such events in space have been found with dB/dt of the order of hundreds of nT in the span of a only a few seconds. These are observed in both the nightside and dayside, and, as such, we seek to establish connections to drivers affecting both sides of the terminator; tail activations and substorms on the nightside, large amplitude ULF waves, solar wind sudden impulses, and rapid changes in MIC current systems on the dayside. The short duration of these events, coupled with the use of conjugate satellite measurements and ground magnetometer arrays when possible, allows us to investigate their localization and the latitudinal extent of their effects. Overall we further examine the potential role of non-substorm phenomena in generating the GICs which may have adverse impacts on electrical power grids.

***************

**Swarm Observations of ULF Pulsation Activity and the August 2016 Central Italy Earthquake**

Balasis G.1, Papadimitriou C.1, De Santis A.2, Cianchini G.2, Mandea M.3, Giannakis O.1
1National Observatory of Athens, Greece; 2Istituto Nazionale di Geofisica e Vulcanologia, Italy; 3Centre national d’études spatiales, France

There have been several studies suggesting that ultra low frequency (ULF) pulsations may be associated with earthquakes. The majority of these studies refers to the detection of these signals in ground-based magnetometer measurements. On the other hand, there is only a handful of studies that have been attempted to correlate ULF pulsations with seismic activity from space-borne magnetometer measurements using low Earth orbit (LEO) satellites (e.g. CHAMP, DEMETER). A 6.2 magnitude near-surface earthquake hit Central Italy on 24 August 2016 at 01:36 UT causing the death of almost 300 people. The Swarm satellites were flying above the epicenter area only a few hours before the occurrence of the earthquake. Satellite passes above the epicenter areas close to the time of occurrence of big earthquakes are rather rare. Herein, we study the ULF pulsation activity observed by Swarm mission a few days before and after the Central Italy earthquake and compare to ground-based magnetometer recordings.
Ionosphere Precursors before Large Earthquakes

Yang Y., Shen X., Huang J.
The Institute of Crustal Dynamics, China Earthquake Administration, China

From single satellite observations (e.g., DEMETER satellite), various previous works have proved that ionosphere behaves abnormal before large earthquakes. However, there are also some unsolved problems from single spacecraft observations. For example, it is impossible to describe ionosphere abnormal differences for different altitude around the epicenter area. Fortunately, ESA’s SWARM mission, which includes three satellites A, B and C, will provide a unique chance to solve some of these problems. In this work, ionospheric precursors before several large earthquakes will be introduced, and their phenomena in different altitude will be discussed.

Quasi Simultaneous Tropical Cyclone And Earthquake Action On The Ionosphere

Vanina-Dart L.1,2
1The “Seeinggear”eLibrary, Battle, United Kingdom; 2Space Research Institute, Moscow, Russian Federation

Rune Floberghagen, ESA's Swarm mission manager, said, “We have very few ways of probing deep into the structure of our planet, but Swarm is making extremely valuable contributions to understanding Earth’s interior, which then adds to our knowledge of how Earth works as a whole system.”

The evidence that our planet works as a whole system could be better demonstrated in extreme situations - global cataclysms or hazards. We use different major characteristics to separate these disasters. But often we have situation when disasters are close to each to others. It’s no secret that tropical cyclone often accompanies earthquake during tropical season.

Tropical cyclone (TC) is only one of several major natural disasters. There are also earthquakes, floods, fires, volcanic eruptions and many more. It is desirable, where possible, to give advance warning of an impending disaster so that people can take evasive action. An earthquake strikes suddenly and often without specific warning and a lot of scientific research has been devoted to attempting to predict earthquakes. In one sense a TC strikes suddenly; it comes in from the ocean and its damage is (mostly) done where and when it reaches the land. But before it makes landfall it has been tracked for quite a while and it has built up as it has travelled across the ocean, gathering strength as it goes. The problem is on following the TC over a matter of a few days before it makes landfall and predicting exactly where and when it will strike the land.

We do not know the real reason for TC's birth. We cannot predict the life length of a tropical cyclone. We know how to classify TC. We can observe its birth, progress and death. We know the area where hurricanes can appear. For example, it is common for TC's to appear in areas where earthquakes are active. But we don't know why. Do we know all about TC's? Answer is “Of course, not”.

What is a possible mechanism for the interaction of different layers like lithosphere, atmosphere and ionosphere during hurricane action? It has been proved that processes in the lithosphere have an electrodynamic influence on the ionosphere. Two of the possible “Earthquakes – Ionosphere” and “TC-Ionosphere” interaction mechanisms are the Gravity Waves and the electric. The ionosphere is important element in the “Earthquakes - TCs” interaction. It is extremely difficult to establish the precisely effect that the presiding earthquake has had on the TC by measuring ionospheric parameters.

With new opened SWARM data the author has possibilities to discuss a possible electrodynamic influence on the ionosphere during TC action. In this presentation the author analyzes the dynamic ocean parameters, earthquake and ionospheric parameters, received in the process of satellite remote sensing above TC (above Australia) in the last years in the south-eastern area of the East hemisphere. The aim of this topic to assess the contribution of both possible “Earthquakes – Ionosphere” and “TC-Ionosphere” mechanisms during quasi simultaneous TC and earthquake action on the ionosphere.

Analysis of Local Anomalous Characteristics of Lithospheric Magnetic Field before Pishan M6.5 Earthquake in Xinjiang in 2015

Ding X.
China Earthquake Administration of Xinjiang, China, People’s Republic of

Mobile vector geomagnetic survey is a kind of method to obtain seismic precursor, experimentaion and survey proved, the value of geomagnetic anomalies is small which caused by earthquake preparation, so we should as far as possible to elimination errors of data processing. By using the stable performance and high accuracy instruments, we obtained the accurate and reliable three-phases mobile geomagnetic vector observation data in the north and south Tianshan Mountain area during 2013 and 2014. We eliminate the effects of the diurnal variation and the secular variation of the geomagnetic field through correction, calculate each terms surface spline model of the interior geomagnetic field, separate the distribution of the geomagnetic anomalous field, and get the differences between two successive terms of the geomagnetic anomalous field and acquire the variation of the geomagnetic anomalous field. Then we analyzed the dynamic variation characteristics of the lithosphere local magnetic field before Pishan M6.5 on Jul. 3, 2015 in Xinjiang to research its relationship with the earthquake. The analysis result showed that there is a
another better schedule. The DEMETER (Detection of
processing technical details can be determined by
payloads is on the last test phase. However, many
2017. The scientific data processing system of 8
Satellite Mission (CSES) will be launched in August
Earthquake Dynamics of China, Institute of Geology,
Zhao G.²
²Ulster University, United Kingdom; ²Key Laboratory of
Earthquake Regions) mission, especially its data
applications, give us a clear guide to process the CSES
test data.
Publications based on DEMETER science data, including
the spectrum and waveform of electromagnetic (EM)
data and plasma data, suggested that the DEMETER
scientific data are reliable. However, the studies based
on the waveform data of Instrument Magnétomètre
Search-Coil (IMSC) are rare. Many information related
to earthquakes embedded in these waveform data is
cannot be provided by the spectrum. This studies aim
at (1) obtaining science data processing experiences
and (2) mining deep information of EM anomalies may
related to earthquakes.
Processing on the waveform data of magnetic field
obtained by DEMETER micro-satellite was conducted.
Statistical characteristics of the disturbances before
major earthquakes (larger than M7.0) during 2005-
2010 were extracted. First, the preprocessing, including
removing linear drifts of the instrument and the
interferences from the satellite platform, was
conducted. Second, the background of the waveform
field was constructed, using three months’ data before
major earthquakes in the 6 years’ revisiting data.
Meanwhile, an index demonstrating the complexity of
the magnetic waveform data was defined to identify
anomalies. Further, the statistical studies on the
differences between the magnetic field during major
earthquakes and the background were conducted
based on this complexity index.

***********************

Detecting Seismic Anomalies from Satellite and
Ground Based Electromagnetic Data Using Big Data
Analytics Approaches
Bi Y., Christodoulou V.¹, Wilkie G.¹, Kong X.¹, Glass D.¹,
Zhao G.²
¹Ulster University, United Kingdom; ²Key Laboratory of
Earthquake Dynamics of China, Institute of Geology,
China Earthquake
This work will report the comparative studies undertaken in the project supported by the Dragon 3
programme – the largest cooperation between European Space Agency and Ministry of Science and
Technology of China – which is aimed to developing viable methods and techniques for detecting anomalies
from space and terrestrial electromagnetic data that are observed by the SWARM satellite and the network of the Control Source Extremely Low Frequency (CSELF) in China and investigating the correlation between anomalies and earthquakes. We have developed a number of algorithms for detecting anomalies from time series data and evaluated them over benchmark datasets, as well as preliminarily on Outgoing Longwave Radiation observed by the NOAA satellites and electromagnetic data observed by the Swarm satellites and the network of the Control Source Extremely Low Frequency (CSELF). We first will presents the development of anomaly detection algorithms, including Geometric Moving Average Martingale (GMAM) method, Weighted Local Outlier Factor LOF method and Hot SAX methods, the Cumulative Sum (CUSUM) and the Exponentially Weighted Moving Average (EWMA), and two variants of a combined Cusum-EWMA. Secondly we will describe various comparative analysis methodology. Finally by incorporate the Wenchuan, Lushan, Puer, Haiti earthquakes, we present the various comparative case study analysis results over the Swarm and CSELF data sets.

********************

Statistical Analysis of Magnetic Field Disturbances
Before Major Earthquakes Based on the DEMETER
Magnetic Waveform Data
Wang Q., Huang J., Shen X.
Institute of Crustal Dynamics, China Earthquake
Administration, China, People’s Republic of
The first satellite of the China Seismo-electromagnetic
Satellite Mission (CSES) will be launched in August
2017. The scientific data processing system of 8
payloads is on the last test phase. However, many
processing technical details can be determined by
another better schedule. The DEMETER (Detection of

***********************

Occurrence Of Schumann Resonances In Swarm ASM
Burst Mode Data
Beggan C.¹, Brown W.¹, Hulot G.², Deram P.², Coïsson
P.²
¹British Geological Survey, United Kingdom; ²Institute
de Physique du Globe de Paris, France
The Schumann Resonances (SR) consist of a series of
peaks in spectral power in the magnetic and electric
field at frequencies of around 8, 14, 22 and 27 Hz. They
arise from the continuous occurrence of equatorial
lightning strikes which are on average contained within
a single source region at any one time during the day,
following the sub-solar point. The broadband
electromagnetic emission from each lightning strike is
contained within a waveguide, bounded by the Earth’s
surface and the ionosphere at around 110 km in
altitude. Thus particular EM wavelengths can resonate
effectively for a few cycles before dissipating. The strike
rate is around 100/second which leads to the formation
of a steady background signal. The SR are detectable on
the ground using sensitive search-coil magnetometers
and have peak power of around 5 pT/V(Hz) in the first
resonance, diminishing with increased frequency in the
magnetic components. They have a large Q-factor (i.e.
broad peaks) and an obvious diurnal and seasonal
variation due to the location of the continents.
Although, the electric field from SR have been detected in space using the C/N0FS satellite in 2010/11 at altitudes of 600 km, there have been no confirmed measurements using magnetic field instruments. There are theoretical arguments that the ionosphere acts to fully shield the magnetic signal from penetrating out of the atmosphere to Swarm altitudes, though other models suggest some secondary signals may be excited by the SR. We examine the Swarm ASM Burst Mode data (250 Hz) collected on the 19-Jan-2014 during the commissioning phase of the mission to look for signals which could be attributable to the SR.

************************

Using Swarm For Gravity Field Determination – An Overview After 3+ Years In Orbit

Dahle C.1,2, Arnold D.2, Jäggi A.2, Meyer U.2, König R.1, Michalak G.1, Neumayer Kh.1

1GFZ German Research Centre for Geosciences, Germany; 2Astronomical Institute, University of Bern, Switzerland

Besides its primary objective, observing the Earth’s magnetic field and the ionosphere, the Swarm Mission can also be regarded as a gravity field mission. Its payload, in particular GPS receivers and star trackers, allows to estimate the long-wavelength part of the Earth’s gravity field and its variations in time by means of high-low satellite-to-satellite tracking (hl-SST). This capability has gained even more relevance since the dedicated gravity field mission GRACE will soon reach the end of its nominal mission and the successor GRACE-FO will not be launched before December 2017. Thinking of ways to bridge the gap between GRACE and GRACE-FO in a best possible manner, the Swarm satellites will likely play an essential role.

At the Astronomical Institute of the University of Bern (AIUB), kinematic Swarm orbits are routinely processed and gravity field solutions are derived thereof. Their quality has significantly improved since the first results have been presented. Most prominently, first Swarm gravity fields were degraded by systematic errors along the Earth’s geomagnetic equator caused by ionospheric disturbances which affect the GPS observations. Initially, this degradation has been minimized by a crude GPS data screening procedure. However, recent investigations have shown that updated tracking loop settings of the GPS receivers onboard Swarm are also very beneficial for gravity field recovery allowing for a less aggressive GPS data screening or even making it obsolete. In this presentation, we give an overview of Swarm gravity field processing at AIUB and present the latest results of the (currently more than 3 years long) AIUB Swarm gravity field time-series. Special focus is set on the influence of the various tracking loop updates as well as on the GPS data screening. Concerning the latter, an optimal screening threshold depending on factors like ionospheric activity and GPS receiver settings is investigated.

Fully independent of AIUB, Swarm Level-1b GPS observations are directly used in a dynamic orbit and gravity field determination approach at the German Research Centre for Geosciences (GFZ). The sensitivity of the resulting gravity field solutions to the ionospheric disturbances as mentioned before is investigated and the GFZ solutions are compared to the ones from AIUB.

************************

Estimation of Mass Variations in Greenland Using Leakage-Reduced GRACE Data

Piretzidis D., Sideris MG.
University of Calgary, Canada

In this study, the CSR Release 05 GRACE monthly models are used to estimate and monitor mass variations over Greenland. The data span the period from January 2003 to December 2014. The methodology for estimating mass variations focuses on the correction of leakage effects due to the implementation of smoothing filters in GRACE monthly solutions. The error due to leakage effects is reduced by taking into account the contribution of leaked masses in the extended area of Greenland. Using forward modeling techniques with tesseroid mass elements, the potential of the leakage-reduced masses is calculated.

After correcting the leakage effect, two approaches are used to derive mass variations over Greenland. For the first approach, global spherical harmonic analysis is implemented to derive the Stokes coefficients of the leakage-reduced potential, which are later converted into equivalent water height using Love numbers. The second approach uses inverse modeling and Tikhonov regularization of the leakage-reduced potential to directly derive surface density information over Greenland and convert it into equivalent water height. The second approach corresponds to a flat tesseroid mascon solution.

Two data sets of mass variations over Greenland are produced for the 11-year period of GRACE data. The first data set is in the form of Stokes coefficients, while the second data set is in the form of a spatial grid. Results indicate that the first method tends to overestimate the mass variations, providing amplified equivalent water height with 10% greater magnitude than the second method. The second method provides a smoother solution that agrees better with the results of the forward modeling and, therefore, is recommended.

************************
Geoid Requirements for Height Systems and their Unification

Willberg M., Gruber T., Pail R.
Technical University of Munich, Germany

Tide gauge stations define the origin of height systems around the world and therefore are key points for height system unification as well as sea level determination. Because tide gauges are only able to measure the relative motion of the sea to a zero marker one needs on-site connection to the global geometric reference frame (e.g. GNSS or SAR) for the actual sea change rate. To get the absolute sea level or compare station heights globally, the equipotential surface of the tide gauges zero marker needs to be known as well.

With the results of GOCE it becomes possible to define a globally consistent geoid with centimeter accuracy and a spatial resolution of 80-100 km, but this still differs from a true equipotential surface due to omission and commission errors. The fine structure of the Earth gravity field (omission error), which mainly depends on the topography, can be taken into account with local geoid modelling using terrestrial and/or airborne gravity data. After an optimal combination of these measurements with the available satellite data it is possible to determine physical heights and make them compatible in an absolute sense.

This paper introduces the importance of the geoid on the definition of height systems and their unification. For the combination of satellite and terrestrial data, the impacts of omission and commission error are examined and evaluated. Furthermore, we investigate the influence of data density, distribution and accuracy from which we can define requirements for the data basis that is necessary for height systems unification.

Low-Degree Temporal Gravity Field Solution from SWARM Constellation of Satellites Using the Energy Balance Approach

Shang K.1, Shum C.K.1,8, Bezdek A.2, Zhang Y.1, Akyilmaz O.3, Teixeira da Encarnação J.4,9, Dai C.1, Forootan E.5, Guo J.1, Klokočník J.7, Kuo C.6, Sebera J.7

1The Ohio State University, United States of America; 2Astronomical Institute, Czech Academy of Sciences, Czech Republic; 3Institute of Geodesy, Istanbul Technical University, Turkey; 4Delft Univ. of Technology, The Netherlands; 5School of Earth & Ocean Science, Cardiff Univ., Cardiff, UK; 6Dept. of Geomatics, National Cheng Kung Univ., Taiwan; 7European Space Agency, ESRIN, Italy; 8Institute of Geodesy & Geophysics, Chinese Academy of Sciences, Wuhan, China; 9Center for Space Research, Univ. of Texas at Austin, USA

ESA's SWARM constellation of three near-polar satellites was launched on 22 November 2013, with the primary scientific objective to map the Earth's magnetic field and its variations. Although not among its primary scientific objectives, the specific orbital formation geometry of the three identical SWARM accelerometer-equipped satellites allows recovery for more accurate low-degree temporal gravity field. Equipped with satellite laser ranging retro-reflectors, accelerometers and geodetic-quality GPS receivers, data from the SWARM satellites have been used to estimate low-degree temporal gravity field based on the acceleration, short-arc, and celestial mechanics approaches, with geopotential solutions complete to degree and order 15. Here we will use the improved formulation for the energy balance approach (EBA) to estimate the temporal gravity field using data from the SWARM satellites. The improved energy balance approach to generate in situ geopotential difference measurements using the GRACE KBR data has achieved the measurement accuracy by more than 3 orders of magnitude compared to previous studies. Specifically, we will: (1) assess the accuracy of SWARM temporal gravity field EBA solutions by comparing with solutions using other approaches and versus GRACE solutions using GPS and using KBR; (2) assess the impact on low-degree temporal gravity field EBA solutions using kinematic or dynamic SWARM GPS orbits; (3) evaluate low-degree temporal gravity solutions with or without accelerometer-corrections for data from individual SWARM satellite or from the combined constellation of SWARM satellites; (4) evaluate and confirm the maximum achievable degree and order of temporal gravity field model using data from the SWARM constellation of satellites, and (5) investigate the fidelity of the estimated SWARM second degree zonal geopotential coefficients and other approaches, as well as the solutions using other data, including SLR, other GPS, and GRACE KBR solutions.

Time Variable Gravity Field and Ocean Mass Change From SWARM Data

Lück C.1, Rietbroek R.1, Löcher A.1, Kusche J.1, Ren L.2, Schön S.5

1University of Bonn, Germany; 2University of Hanover, Germany

Variations of ocean mass and bottom pressure changes are still not sufficiently understood on long time scales. The observation of these signals at the global scale has only become possible since the advent of the GRACE mission. Within the project “Consistent Ocean Mass Time Series from LEO Potential Field Missions” (CONTIM), we investigate how time series of gravity changes and ocean mass variations can be extended beyond and before the GRACE mission lifespan, making use of geodetic measurements of Low Earth Orbiters (LEO), and how these may be used for gap-filling of the GRACE time series.

Here, we use different kinematic orbits from SWARM, including orbits computed in this project, to estimate gravity fields of low spherical harmonic degree and order. We show how these fields compare to the more accurate GRACE solutions, and how the choice of non-conservative force modelling, solution
aliasing errors, which we provide for the major diurnal allows us to specify upper bounds for the ocean-tide model are used monthly solutions by using simulated data. Only the ocean-tide aliasing errors affect the sub-monthly and (two-day) solutions often denoted as the Wiese approach. In this study, we specifically look at how the higher harmonic degrees and orders can be reduced via spherical harmonic coefficients, their impact on the monthly time-variable GRACE gravity field solutions is of special interest in the view of a potential gap between the dedicated gravity missions GRACE and GRACE-FO.

In this contribution we present gravity fields based on the hl-SST of the three Swarm, as well as the Sentinel-1A, -2A, and -3A satellites. Based on different combination schemes we show that the Sentinel satellites are well suited to contribute to the longest-wavelength part of the Earth gravity field. We show that, unlike Swarm prior to the GPS tracking loop updates of May and October 2015, the Sentinel GPS data is not affected by systematic degradations along the geomagnetic equator. The addition of Sentinel data for the gravity field recovery has, therefore, the potential to improve the low degrees of the Swarm gravity fields. This can especially be interesting for times during which the omission of corrupted GPS data is mandatory for the mitigation of the systematic spurious features in the recovered Swarm gravity fields along the geomagnetic equator.

Impact Of Wiese-Approach In The Mitigation Of Ocean-Tide Aliasing Errors In Monthly GRACE Gravity Field Solutions Devaraju B., Weigelt M., Mueller J. Leibniz University of Hannover, Germany

The aliasing of tidal and non-tidal geophysical signals with frequencies of less than one month into the monthly time-variable GRACE gravity field solutions is an often observed but only partially understood phenomenon. With the increasing sensor accuracy, the aliasing errors have been identified as the major stumbling blocks for the geophysical applications of satellite gravimetry data. While aliasing affects all the spherical harmonic coefficients, their impact on the higher harmonic degrees and orders can be reduced via parameter pre-elimination of low-degree sub-monthly (two-day) solutions often denoted as the Wiese approach. In this study, we specifically look at how the ocean-tide aliasing errors affect the sub-monthly and monthly solutions by using simulated data. Only the static gravity field and an ocean-tide model are used for simulating a GRACE-like mission scenario. This allows us to specify upper bounds for the ocean-tide aliasing errors, which we provide for the major diurnal and semi-diurnal ocean-tides. In addition to this, we investigate the possibility of the use of nuisance parameters to absorb the ocean-tide aliasing errors.

Combined Swarm/Sentinel Gravity Fields Arnold D.1, Meyer U.1, Dahle C.2, Jäggi A.2 1Astronomical Institute, University of Bern, Switzerland; 2GFZ German Research Centre for Geosciences, Potsdam, Germany

With their geodetic-grade on-board GPS receivers and star trackers the satellites of the Swarm mission can serve as probes for the long-wavelength part of the Earth gravity field by means of high-low satellite-to-satellite tracking (hl-SST). This is also true for the satellites of the ESA Sentinel mission, even if their slightly higher orbital altitude degrades their sensitivity to the high-frequency part of the gravity field. These gravity field solutions are of special interest in the view of the Earth's mass transport phenomena causing temporal variations in the gravity field, at different temporal and spatial scales, due to ice mass changes of ice sheets and glaciers, continental water cycles, ocean masses dynamics and solid-earth deformations.

The ESA initiatives started in 2003 with a study on observation techniques for solid Earth missions and continued through several studies focussing on the

Field Solutions

Continental Grids of Disturbing Gravity Tensor Components over North America Habel B., Janak J. Slovak University of Technology, Slovak Republic

The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission resulted in 20 measurement cycles which more-or-less completely, except of the polar gaps and some short periods of missing data, covered the Earth. Most of the cycles were performed at the mean altitude of 254.9 km and the orbital resonance 979:61 but the last 4 cycles were gradually lowered down to 223.9 km and the orbital resonance 2311:143. GOCE Consortium and also several other scientific teams compiled the global grids of particular components of disturbing gravity tensor and pointed out that they contain additional high-frequency signal comparing to GOCE global gravity field models based on spherical harmonics. This contribution presents the new methodology of preparation of tile-like continental grids based on 2 dimensional local empirical covariance functions. Our first practical experiences with this approach have been presented at Living Planet Symposium 2016 in Prague. Based on these experiences we produced the continental grid of disturbing gravity tensor components over the North-America at 2 different altitudes. The question of mutual connection and discrepancies between the sub-areas (tiles) and reliability of our results at different altitudes are discussed.

Impact Of Wiese-Approach In The Mitigation Of Ocean-Tide Aliasing Errors In Monthly GRACE Gravity Field Solutions

Devaraju B., Weigelt M., Mueller J.

Leibniz University of Hannover, Germany

The aliasing of tidal and non-tidal geophysical signals with frequencies of less than one month into the monthly time-variable GRACE gravity field solutions is an often observed but only partially understood phenomenon. With the increasing sensor accuracy, the aliasing errors have been identified as the major stumbling blocks for the geophysical applications of satellite gravimetry data. While aliasing affects all the spherical harmonic coefficients, their impact on the higher harmonic degrees and orders can be reduced via parameter pre-elimination of low-degree sub-monthly (two-day) solutions often denoted as the Wiese approach. In this study, we specifically look at how the ocean-tide aliasing errors affect the sub-monthly and monthly solutions by using simulated data. Only the static gravity field and an ocean-tide model are used for simulating a GRACE-like mission scenario. This allows us to specify upper bounds for the ocean-tide aliasing errors, which we provide for the major diurnal

Continental Grids of Disturbing Gravity Tensor Components over North America Habel B., Janak J. Slovak University of Technology, Slovak Republic

The GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission resulted in 20 measurement cycles which more-or-less completely, except of the polar gaps and some short periods of missing data, covered the Earth. Most of the cycles were performed at the mean altitude of 254.9 km and the orbital resonance 979:61 but the last 4 cycles were gradually lowered down to 223.9 km and the orbital resonance 2311:143. GOCE Consortium and also several other scientific teams compiled the global grids of particular components of disturbing gravity tensor and pointed out that they contain additional high-frequency signal comparing to GOCE global gravity field models based on spherical harmonics. This contribution presents the new methodology of preparation of tile-like continental grids based on 2 dimensional local empirical covariance functions. Our first practical experiences with this approach have been presented at Living Planet Symposium 2016 in Prague. Based on these experiences we produced the continental grid of disturbing gravity tensor components over the North-America at 2 different altitudes. The question of mutual connection and discrepancies between the sub-areas (tiles) and reliability of our results at different altitudes are discussed.

Impact Of Wiese-Approach In The Mitigation Of Ocean-Tide Aliasing Errors In Monthly GRACE Gravity Field Solutions

Devaraju B., Weigelt M., Mueller J.

Leibniz University of Hannover, Germany

The aliasing of tidal and non-tidal geophysical signals with frequencies of less than one month into the monthly time-variable GRACE gravity field solutions is an often observed but only partially understood phenomenon. With the increasing sensor accuracy, the aliasing errors have been identified as the major stumbling blocks for the geophysical applications of satellite gravimetry data. While aliasing affects all the spherical harmonic coefficients, their impact on the higher harmonic degrees and orders can be reduced via parameter pre-elimination of low-degree sub-monthly (two-day) solutions often denoted as the Wiese approach. In this study, we specifically look at how the ocean-tide aliasing errors affect the sub-monthly and monthly solutions by using simulated data. Only the static gravity field and an ocean-tide model are used for simulating a GRACE-like mission scenario. This allows us to specify upper bounds for the ocean-tide aliasing errors, which we provide for the major diurnal

Combined Swarm/Sentinel Gravity Fields

Arnold D.1, Meyer U.1, Dahle C.2, Jäggi A.2

1Astronomical Institute, University of Bern, Switzerland; 2GFZ German Research Centre for Geosciences, Potsdam, Germany

With their geodetic-grade on-board GPS receivers and star trackers the satellites of the Swarm mission can serve as probes for the long-wavelength part of the Earth gravity field by means of high-low satellite-to-satellite tracking (hl-SST). This is also true for the satellites of the ESA Sentinel mission, even if their slightly higher orbital altitude degrades their sensitivity to the high-frequency part of the gravity field. These gravity field solutions are of special interest in the view of a potential gap between the dedicated gravity missions GRACE and GRACE-FO.

In this contribution we present gravity fields based on the hl-SST of the three Swarm, as well as the Sentinel-1A, -2A, and -3A satellites. Based on different combination schemes we show that the Sentinel satellites are well suited to contribute to the longest-wavelength part of the Earth gravity field. We show that, unlike Swarm prior to the GPS tracking loop updates of May and October 2015, the Sentinel GPS data is not affected by systematic degradations along the geomagnetic equator. The addition of Sentinel data for the gravity field recovery has, therefore, the potential to improve the low degrees of the Swarm gravity fields. This can especially be interesting for times during which the omission of corrupted GPS data is mandatory for the mitigation of the systematic spurious features in the recovered Swarm gravity fields along the geomagnetic equator.

Combined Swarm/Sentinel Gravity Fields

Arnold D.1, Meyer U.1, Dahle C.2, Jäggi A.2

1Astronomical Institute, University of Bern, Switzerland; 2GFZ German Research Centre for Geosciences, Potsdam, Germany

With their geodetic-grade on-board GPS receivers and star trackers the satellites of the Swarm mission can serve as probes for the long-wavelength part of the Earth gravity field by means of high-low satellite-to-satellite tracking (hl-SST). This is also true for the satellites of the ESA Sentinel mission, even if their slightly higher orbital altitude degrades their sensitivity to the high-frequency part of the gravity field. These gravity field solutions are of special interest in the view of a potential gap between the dedicated gravity missions GRACE and GRACE-FO.

In this contribution we present gravity fields based on the hl-SST of the three Swarm, as well as the Sentinel-1A, -2A, and -3A satellites. Based on different combination schemes we show that the Sentinel satellites are well suited to contribute to the longest-wavelength part of the Earth gravity field. We show that, unlike Swarm prior to the GPS tracking loop updates of May and October 2015, the Sentinel GPS data is not affected by systematic degradations along the geomagnetic equator. The addition of Sentinel data for the gravity field recovery has, therefore, the potential to improve the low degrees of the Swarm gravity fields. This can especially be interesting for times during which the omission of corrupted GPS data is mandatory for the mitigation of the systematic spurious features in the recovered Swarm gravity fields along the geomagnetic equator.

Combined Swarm/Sentinel Gravity Fields

Arnold D.1, Meyer U.1, Dahle C.2, Jäggi A.2

1Astronomical Institute, University of Bern, Switzerland; 2GFZ German Research Centre for Geosciences, Potsdam, Germany

With their geodetic-grade on-board GPS receivers and star trackers the satellites of the Swarm mission can serve as probes for the long-wavelength part of the Earth gravity field by means of high-low satellite-to-satellite tracking (hl-SST). This is also true for the satellites of the ESA Sentinel mission, even if their slightly higher orbital altitude degrades their sensitivity to the high-frequency part of the gravity field. These gravity field solutions are of special interest in the view of a potential gap between the dedicated gravity missions GRACE and GRACE-FO.

In this contribution we present gravity fields based on the hl-SST of the three Swarm, as well as the Sentinel-1A, -2A, and -3A satellites. Based on different combination schemes we show that the Sentinel satellites are well suited to contribute to the longest-wavelength part of the Earth gravity field. We show that, unlike Swarm prior to the GPS tracking loop updates of May and October 2015, the Sentinel GPS data is not affected by systematic degradations along the geomagnetic equator. The addition of Sentinel data for the gravity field recovery has, therefore, the potential to improve the low degrees of the Swarm gravity fields. This can especially be interesting for times during which the omission of corrupted GPS data is mandatory for the mitigation of the systematic spurious features in the recovered Swarm gravity fields along the geomagnetic equator.
satellite system, technology development for propulsion and distance metrology, preferred mission concepts, the attitude and orbit control system, as well as the optimization of the satellite constellation. These activities received precious inputs from the in-flight lessons learnt from the GOCE and GRACE missions. More recently, several studies related to new sensor concepts based on cold atom interferometry were initiated, mainly focusing on technology development for different instrument configurations (GOCE-like and GRACE-like).

The latest results concerning the preferred satellite architectures and constellations, payload design and estimated science performance will be presented as well as remaining open issues for future concepts.

************************

Cold Atom Interferometers Used in Space (CAIUS) for Measuring the Earth’s Gravity Field

Carraz O.1, Massotti L.1, Siemes C.1, Haagmans R.2, Mondin L.2, Silvestrin P.2

1RHEA for ESA - European Space Agency, The Netherlands; 2ESA - European Space Agency, The Netherlands

In the past decades, it has been shown that atomic quantum sensors are a newly emerging technology that can be used for measuring the Earth’s gravity field. Whereas classical accelerometers typically suffer from high noise at low frequencies, Cold Atom Interferometers are highly accurate over the entire frequency range.

There are two ways of making use of that technology: one is a gravity gradiometer concept, which relies on a high common mode rejection that relaxes the drag free control compare to GOCE mission; and the other one is a gravity gradiometer concept, which relies on a low-low satellite-to-satellite ranging concept to correct the spectrally colored noise of the electrostatic accelerometers in the lower frequencies. We will present for both concepts the expected improvement in measurement accuracy and for the gravity gradiometer concept the expected improvement of Earth gravity field models, taking into account the different types of measurements (e.g. single vs. 3 axis, integration time, etc.) and different mission parameters such as attitude control, altitude of the satellite, time duration of the mission, etc.

************************

GNSS-SLR Co-Location On-Board GNSS Satellites: Possible Contribution to the Realization of Terrestrial Reference Frames

Bruni S.1, Zerbini S.1, Altamimi Z.2, Rebischung P.2, Errico M.1, Santi E.1

1DIFA Department of Physics and Astronomy, University of Bologna, Italy; 2IGN, LAREG, Univ Paris Diderot, Sorbonne Paris Cité, Paris, France

The International Terrestrial Reference Frame (ITRF) is computed on the basis of the data provided by four space geodetic techniques (GNSS, SLR, VLBI and DORIS). Their independent ground networks are currently connected by terrestrial ties measured at those ITRF sites where instruments of at least two different techniques are co-located. As a possible alternative or complementary approach, the geodetic community has been long discussing the possibility of exploiting the technique co-location in space, relying on spacecrafts equipped with positioning payloads of different techniques. In principle, space ties could overcome two major limitations of terrestrial ties, namely their poor spatial distribution and infrequent updates. On the other hand, the efficiency of their performance shall be carefully addressed under actual operative conditions. This study assesses the potential of the GNSS-SLR ties on-board GNSS satellites for the realization of homogeneous Terrestrial Reference Frames. For this purpose, the data collected by the whole SLR network and about 100 GNSS stations during the period 2011-2014 were analyzed and combined. Both long-term and quasi-instantaneous reference frames were computed, in order to verify whether the selected space ties could transfer the origin and scale information from the SLR to the GNSS network. The study was complemented by a series of simulations investigating the impact of possible future improvements in tracking performances. This analysis revealed that, at present, the GNSS-SLR co-location on-board GNSS satellites is not sufficient to realize a homogeneous technique combination. In addition, the achieved results highlighted that a deep understanding of the mechanisms driving the sensitivity of each geodetic technique to the reference frame parameters is fundamental in order to fully exploit the co-location in space.

************************

Effect of Swarm A/C Orbital Configuration and Magnetic Field Inclination on the Spherical Elementary Current Systems (SECS) Analysis Method

Vanhamäki H.1, Kauristie K.2, Aikio A.1, Workayehu A.1, Köki S.2, Juusola L.2

1Oulu university, Finland; 2Finnish Meteorological Institute, Helsinki, Finland

The method of Spherical Elementary Current Systems (SECS) was adapted for analyzing magnetic data from the Swarm mission by Amm et al. (2015). The method can be used to estimate not only the field-aligned current (FAC), but also the ionospheric sheet current in a narrow strip around the A and C satellites’ track. If the B satellite is close to the A/C pair, as happened frequently during the first mission year, it can also be included in the analysis.

The recent results by Juusola et al. (2016), who compared ground-based equivalent current estimates with the divergence-free part of the current as inferred from Swarm data, show that large-scale electrojet-type sheet current systems can be determined from the
satellite data with good accuracy. However, they concluded that the Swarm satellites' altitude and the longitudinal separation of the A/C pair severely limits our ability to resolve smaller scale structures in the horizontal sheet current. Using synthetic but realistic models of various ionospheric current systems, we will investigate how much the SECS results could be improved by tuning the orbital configuration of the A/C pair.

In the present form the SECS analysis method is limited to high magnetic latitudes, due to the simplifying assumption of radial FAC direction. We will describe some proposed efforts to include a more realistic description of the FAC geometry, so that the SECS-based Swarm analysis method could be extended to middle and low latitudes.

Amm et al. (2015): https://dx.doi.org/10.1002/2014JA020154

***************

A Tentative Procedure to Assess / Optimize the Swarm Electric Field Data and Derive the Ionospheric Conductance in the Auroral Region

Marghitu O.1, Vanhamaki H.2, Madalin I.1, Juusola L.1, Blagau A.1,4, Kauristie K.3,5
1Institute for Space Sciences, Bucharest, Romania; 2University of Oulu, Oulu, Finland; 3Finnish Meteorological Institute, Helsinki, Finland; 4Jacobs University Bremen, Bremen, Germany

Electric field is essential to understand the coupling processes in the magnetosphere-ionosphere-thermosphere (M-I-T) system and, as such, is one of the key quantities measured onboard Swarm. This paper introduces a procedure, illustrated with a couple of event studies, that may help the assessment and, when necessary, optimization of the electric field data, at the same time with providing estimates of the ionospheric conductance. The procedure applies primarily in the auroral region and relies, essentially, on the closure of the field-aligned current (FAC) by ionospheric current, on Ohm’s law that relates the ionospheric current, electric field, and conductance, as well as on a conductance proxy (Robinson et al., 1987), based on the energy flux and average energy of the precipitating electrons. The ionospheric current can be derived from Swarm magnetic field observations by the technique of Spherical Elementary Current Systems (SECS – introduced by Amm, 1997, and adapted for Swarm by Amm et al., 2015). Further on, by plugging the derived ionospheric current together with the observed electric field into the Ohm’s law, one can estimate the ionospheric Pedersen and Hall conductance (with a precision that depends on the quality of the electric field data) along the footprints of individual satellite tracks. At the same time, by following Robinson et al. (1987), the ratio of the Hall to Pedersen conductance can be used to infer the average electron energy (over upward current regions), the electron energy flux can be derived by multiplying the electron energy by the number flux inferred from the (upward) FAC density, and eventually one can derive an alternative estimate of the Pedersen conductance. Finally, by comparing the two estimates of the Pedersen conductance, one can assess the quality of the electric field data. Moreover, the minimization of the root mean square difference of the two conductance estimates provides a potentially powerful tool to optimize the electric field data in the auroral region and to derive reliable conductance information.

***************

Field-Aligned Current Response to Increasing Solar Indices

Edwards T.R., Weimer D.R.
Virginia Tech, United States of America

While many studies of field-aligned current (FAC) response to driving parameters have been done, few have focused on the impacts of changing solar radiative index. A new FAC model has been developed utilizing magnetometer measurements from the CHAMP, Orsted, and Swarm missions. Using this model, an analysis of changing solar radiative index has been done. What has been found is that there is a nonlinear behavior in response to increases in the F10.7, S10.7, and M10.7 indices, while the Y10.7 index remains very linear. This may suggest that the height integrated conductivity does not have a linear response with increasing F10.7, S10.7, and M10.7 indices. Surprisingly, the Y10.7 response is highly linear, which may be due to it’s relation to the D-region of the ionosphere, while most of the current closes in the E- and F- regions.

***************

Analysis of Thick, Finite, and Non-Planar Field-Aligned Currents in the Polar Regions with Swarm Magnetic Field Measurements

Bai X., Pitout F., Bliely PL., Marchaudon A.
Institut de Recherche en Astrophysique et Planétologie (IRAP), France

The calculation of field aligned currents and the study of their morphology has long been a crucial problem in space plasma physics. The most commonly used method is to use the magnetic field vector measurement of a single satellite, subtracting a proper background field, to approximately calculate the current density under the assumption of a planar and infinite current sheet. When multipoint measurements are available (Cluster, Swarm), one can calculate the curl of magnetic field and infer the field-aligned current density from the Ampere’s law (curlometer technique). In this work, we take advantage of the two Swarm satellites flying side by side (Swarm A and C) to establish a model of finite, thick, and non-planar current sheet. We shall present the underlying formalism of our model and its capabilities: not only does it derive the magnitude of the current, but also
the morphology parameters of the current sheet, including curvature, radius and spatial extent.

************************

Multi-point Analysis of Current Structures in the Inner Magnetosphere

Dunlop M.W. 1,2, Yang J.1, Yang Y.3

1BUAA, China, People’s Republic of; 2RAL_space, STFC, UK; 3China Earthquake Administration, Beijing 100085, China.

The RC and connecting R2 FACs influence the geomagnetic field at low Earth orbit (LEO) and are both sampled in situ by the four Cluster spacecraft, while FACs are sampled by Swarm. Here, the capability of Swarm-Cluster coordination for probing the behaviour of the field aligned currents (FAC) at medium and low orbits and signatures both adjacent to and within the ring current (RC) is explored. Joint signatures of R1 and R2 FACs can be confirmed and multi-spacecraft analysis can also access perpendicular currents associated with the FAC signatures at the Swarm locations. Using the Swarm configuration, statistical correlation analysis of the local time variation of R1/R2 FACs can also be shown and compared to standard MVA analysis. The sensitivity of the analysis to the data cadence, and hence the time dependencies of the signals, is also investigated. For context, we identify the associated auroral boundaries through application of a method to determine the FAC intensity gradients in order to interpret and resolve the R1 and R2 FACs. We also show preliminary results of an extended survey of the ring current crossings for different years, estimating the local current density, field curvature and total current and analysing the spatial extent of the ring current region.

************************

Energy Input to the Ionosphere-Thermosphere Due to Inductive Coupling with the Magnetosphere

Verkhoglyadova O. P.1, Mannucci A. J.1, Meng X.2, Hatch S.M.3

1Jet Propulsion Laboratory, California Institute of Technology, United States of America; 2Department of Physics and Astronomy, Dartmouth College, United States of America

Uncertainty in mechanisms and in the amount of energy being transferred from the solar environment to the Earth’s magnetosphere-ionosphere-thermosphere (M-I-T) constitutes one of the core space weather problems. A reliable estimate of the IT energy budget is an important condition for improving forecasting capabilities of the IT system. It is generally considered that the IT response to solar wind driving can be represented by an evolving set of quasi-steady-state electrostatic processes. This approach is applicable to describe physical processes with temporal scales larger than ~1000s (16 min) and spatial scales larger than ~1000 km (Richmond, 2010). These scales are too conservative for intense storms or strong substorms which feature high-latitude inductive ionospheric electric fields (reaching up to ~ 20% - 50% of a potential field) and inductive field-aligned currents (Vanhamäki, Amm and Viljanen, 2007).

We discuss theoretical foundations of inductive magnetosphere-ionosphere coupling due to ULF waves. Our focus will be on waves which provide the most efficient energy transport and M-I-T coupling. Based on inductive mechanisms we suggest modifications to IT energy budget estimates and definitions of Joule heating. We will also analyze the capabilities of satellite measurements of electric and magnetic wave fields to estimate energy transport and dissipation in the ionosphere.

References:


************************

Dynamics of CME and HSS Storms Revealed from Auroral Imaging and Field aligned Currents

Lyons L. R 1, Zou Y.1, Nishimura T.2, Donovan E.3, Angelopoulos V.1

1UCLA, United States of America; 2Boston University, United States of America; 3University of Calgary, Canada

Auroral imaging can reveal important spatial and temporal features of magnetic storms that are difficult to reveal otherwise. For CME storms, we find that shock impact with southward IMF quickly drives rapid auroral-oval poleward expansion (implying strong nightside reconnection), strong auroral activity, and rapid filling of newly closed field lines with new plasma. Another important CME storm feature is a strong dominance of auroral streamer activity relative to substorm activity during strongly southward IMF, suggesting that plasma sheet flow bursts are common but the plasma sheet is more stable to substorm onset than often expected for strong driving. Episodes of significant equatorward penetration of the auroral oval during CME storms appear to occur in association with auroral streamers, and thus with plasma sheet flow bursts. Evidence suggests that these flow bursts are accompanied by other major stormtime phenomena such as enhancement and equatorward motion of ionospheric and field-aligned currents, equatorward motion of the ionospheric trough, earthward injection of particles into the ring current, and transport of high TEC features into the auroral oval from the polar cap. Unlike CME storms, high-speed stream (HSS), with their fluctuating IMF, show many substorms as well as streamers. Also, major episodes of equatorward penetration of the auroral oval appear to occur in a steady, classical manner as well as via Streamers. The
structure of field aligned currents appears to be reflect this difference. Common to all storms, are frequent intense auroral omega bands on the morning side, though their cause and effects on storm dynamics remain unknown. Another common feature is very clear streamer triggering of substorms and of omega bands, the triggering streamers appearing to be associated with flow bursts bringing new plasma into the evening convection and morning convection cell, respectively.

Magnetopause Erosion During the March 17, 2015, Magnetic Storm: Combined Field-Aligned Currents, Auroral Oval, and Magnetopause Observations


1NASA Goddard Space Flight Center, Greenbelt, MD, USA, United States of America; 2GFZ German Research Centre for Geosciences, Potsdam, Germany; 3The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; 4University of California, Los Angeles, CA, USA; 5NOAA Space Weather Prediction Center, Boulder, CO, USA; 6University of Michigan, Ann Arbor, MI, USA; 7High Altitude Observatory, UCAR, Boulder, CO, USA; 8Space Research Institute, Austrian Academy of Sciences, Graz, Austria; 9Korea Astronomy and Space Science Institute, Daejeon, Korea; 10University of New Hampshire, Durham, NH, USA

We present multi-mission observations of field-aligned currents, auroral oval, and magnetopause crossings during the March 17, 2015 magnetic storm. Dayside reconnection is expected to transport magnetic flux, strengthen field-aligned currents, lead to polar cap expansion and magnetopause erosion. Our multi-mission observations assemble evidence for all these manifestations. After a prolonged period of strongly southward interplanetary magnetic field, Swarm and AMPERE observe significant intensification of field-aligned currents. The dayside auroral oval, as seen by DMSP, appears as a thin arc associated with ongoing dayside reconnection. Both the field-aligned currents and the auroral arc move equatorward reaching as low as ~60° MLat. Strong magnetopause erosion is evident in the in-situ measurements of the magnetopause crossings by GOES-13/15 and MMS. The coordinated Swarm, AMPERE, DMSP, MMS and GOES observations, with both global and in-situ coverage of the key regions, provide a clear demonstration of the effects of dayside reconnection on the entire magnetosphere.

Electromagnetic ULF Wave Energy Leakage through the Ionosphere as Observed by Low-Orbiting Satellites SWARM and Ground AMBER Array

Pilipenko V.1, Zelikson I.2

1Space Research Institute, Russian Federation; 2Institute of the Earth Physics, Russian Federation

We study the transmission of ULF waves in the band Pc2-3/Pi2 through the ionosphere to the ground. For that the synchronous data from the low-orbiting satellites SWARM and ground magnetometer AMBER array have been used. The analysis of combined satellite/ground observations gives a possibility to reveal a physical nature of Pc2-3 and Pi2 waves in the upper ionosphere.

Strong Ambipolar-driven Ion Upflow Within the Cleft Ion Fountain During Low Geomagnetic Activity

Shen Y.1, Knudsen D.2, Burchill J.1, Howarth A.1, Yau A.1, Redmon R.2, Miles D.2, Varney R.3, Nicolls M.4

1University of Calgary, Canada; 2National Centers for Environmental Information, USA; 3University of Alberta, Canada; 4SRI international, USA

We investigate low-energy (<10 eV) ion upflows (mainly O+) within the cleft ion fountain (CIF) using conjunctions of the Enhanced Polar Outflow Probe (e-POP) satellite, the DMSP F16 satellite, the SuperDARN radar, and the Resolute Bay Incoherent Scatter Radar North (RISR-N). The SEI instrument onboard e-POP enables us to derive ion upflow velocities from the 2-D images of ion distribution functions with a frame rate of 100 images per second, and with a velocity resolution of the order of 25 m/s. We identify three cleft ion fountain events with very intense (>1.6 km/s) ion upflow velocities near 1000 km altitude during quiet geomagnetic activity (Kp < 3). Such large ion upflow velocities have been reported previously at or below 1000 km, but only during active periods. Analysis of the core ion distribution images allows us to demonstrate that the ion temperature within the CIF does not rise by more than 0.3 eV relative to background values, which is consistent with RISR-N observations in the F region. The presence of soft electron precipitation seen by DMSP and lack of significant ion heating indicate that the ion upflows we observe near 1000 km altitude are primarily driven by ambipolar electric fields.
Diagnosing the Topside Ionosphere Using Synchronous E- and B-field Measurements from the Swarm Satellite Constellation

Pakhotin I.¹, Mann I.R.¹, Knudsen D.J.², Burchill J.K.², Ozeke L.¹, Gjerloev J.W.³, Rae J.I.⁴, Forsyth C.⁴, Murphy K.⁵, Balasis G.⁶, Daglis I.A.⁷

¹University of Alberta, Canada; ²University of Calgary, Calgary, Alberta, Canada; ³John Hopkins University Applied Physics Laboratory, Laurel, MD, USA; ⁴Mullard Space Science Laboratory, University College London, London, UK; ⁵NASA Goddard Space Flight Center, Greenbelt, MD, USA; ⁶National Observatory of Athens, Athens, Greece; ⁷National and Kapodistrian University of Athens, Athens, Greece

This study explores the potential for using the synchronous E-field and B-field measurements from the Swarm satellite constellation for diagnosing the topside ionosphere. Within the framework of reflected and interfering Alfvén waves interacting with a reflecting boundary, we examine the use of the spectral properties of these fields to infer key local ionospheric parameters such as Pedersen conductivity, Alfvén speed and distance from the reflective layer. These techniques have the potential to present more accurate estimates of the potential dynamical and spatial variation of these important quantities than relying on empirical or statistical models such as International Reference Ionosphere. A methodology to infer the Alfvén speed and density from multi-spacecraft Alfvén wave observations is also discussed, which could allow the validity of the Langmuir probe measurements to be tested.

***************

Interpretation of the Impedence Spectrum in the Ionospheric Alfvén Resonator

Bryant M.S., Knudsen D.J.
University of Calgary, Canada

It has been known since the very first space-based measurements that magnetic fields can be highly structured in both space (due to structured field-aligned currents) and time (e.g. the dayside cleft region [Boehm et al, 1990]). Separating spatial from temporal structures from a moving spacecraft is challenging but can be done by applying a physical model to the fluctuating electric and magnetic fields. Knudsen et al. [1990; 1992] showed that for Alfvén wave frequencies, temporal fluctuations can be identified by examining both the amplitude and phase of the complex impedance spectrum \( Z(f) = \mu_0 E(f)/B(f) \), where \( Z \), \( E \), and \( B \) are all complex. In the lower magnetosphere, impedance spectrum structure is determined by the reflection coefficient at the ionospheric reflecting boundary, the number and location of peaks being determined by the electrical distance to the observation point. It is important not to misinterpret impedance peaks as an indication of resonant behavior. We use a full-wave model of shear Alfvén waves to show how properties of the topside ionosphere relate to features of impedance spectra amplitude and phase.

***************

Validation of a Comprehensive Numerical Model of Ionosphere by Comparison with EISCAT Observations

Sydorenko D., Rankin R.
University of Alberta, Canada

The authors developed a numerical model of coupled ionosphere and magnetosphere. The model was applied to simulate ionospheric dynamics in the post-midnight pre-dawn sector observed by EISCAT radar in Tromso during periods of low magnetospheric activity. The model demonstrated good quantitative agreement with the observations of electron density and temperature and ion temperature for altitudes between 100 km and 450 km during a 2 hour time interval. This was achieved after adding the following physics: (i) Chemistry model distinguishes metastable oxygen ion states (4S, 2D, 2P). (ii) EUV flux changes according to the Earth rotation. (iii) Photoelectrons produce ionization and are a source of electron heating (a transport code for the photoelectrons was developed accounting for ionization by secondary electrons). (iv) Production of O+ by photoelectrons is split between the three metastable ion states. (v) High-altitude boundary condition for the electron and ion temperatures corresponds to a zero heat flux. (vi) The electric field has both meridional and azimuthal components producing both Pedersen and Hall currents. (vii) Azimuthal plasma density variation associated with the Earth rotation contributes to plasma density modification by the global convection (a method has been found to include this effect in a model which is essentially 1D). With the updated model, significant modification of the ion composition was found: densities of molecular ions N2+ and NO+ are a few times higher while the density of the dominant ion species O+ is a few times lower than values predicted by the model before the aforementioned changes. This study demonstrated that the model can be a valuable tool for analysis of ground based and spacecraft observations.

***************
**Pc1 Wave Observations in the Topside Ionosphere with Swarm Satellites**

Balasis G.1, Papadimitriou C.1, Mann I.R.2, Pakhotin I.2, Daglis I.A.2, Giannakis O.1, Haagmans R.4

1National Observatory of Athens, Greece; 2University of Alberta, Canada; 4ESTEC, Netherlands

The ongoing Swarm satellite mission provides an opportunity to a better knowledge of the near-Earth electromagnetic environment. Herein, we study the occurrence of ultra low frequency (ULF) wave events in the Pc1 frequency range (0.2-5 Hz) observed by the Swarm satellite mission for a period spanning two years after the constellation's final configuration. We present maps of the dependence of Pc1 wave power with magnetic latitude and magnetic local time as well as geographic latitude and longitude from the three satellites at their different locations in the topside ionosphere. The observed wave events are disturbances in the Pc1 band in the Swarm frame - which could be Pc1 proper at low L-shell value but likely are related to magnetosphere-ionosphere coupling at higher latitudes. Our initial results emphasize the fact that the Pc1 power distribution at low-Earth orbit as provided by the Swarm spacecraft is better organized in geographic than geomagnetic coordinates.

********************

**Modelling Anisotropic Temperature Ratios in the Weakly Collisional Altitude Region Observed by Swarm**

Goodwin L.V., St-Maurice JP.
University of Saskatchewan, Canada

Using the Swarm EFI detector, Archer et al. [Geophys. Res. Lett., 42, 981, 2015.] obtained large and unexpected ratios of the ion temperatures perpendicular to the magnetic field to the ion temperatures parallel to the magnetic field at 550 km. In these measurements, both the ion temperatures parallel and perpendicular to the magnetic field were large, the electric fields were strong and highly localized, and strong ion upflows were observed. These new findings have prompted further study into previous work on the effect frictional heating has on the ion velocity distribution. In a first set of studies, we have revisited previously proposed cross-sections for resonant charge exchange collisions between O+ and atomic oxygen. In a second set of studies, given the 550 km altitude of the Swarm observations, we have advanced the previous studies made by Loranc and St-Maurice [J. Geophys. Res., 99, 17429, 1994.], who studied the effect of the altitude transition from highly collisional regions below 400 km to weakly collisional regions higher up. In our study, the ions are taken to be collisionless above a given boundary altitude, and the velocity distribution evolves as a result of the vertical transport of newly heated ions, with the fastest ions being the first to reach a particular altitude above the prescribed boundary altitude. Below that boundary, frictional heating is occurring and producing velocity distributions of the kind found with the Monte Carlo analysis of Winkler et al. [J. Geophys. Res., 97, 8399, 1992]. In our upgraded model of the weakly collisional altitude region, we have studied the effects of changing velocity distributions at the collisional boundary. This model includes the effect of temporal electric field changes on a convecting magnetic field line, as well as the effect of changing densities at the boundary owing to chemistry that accompany the strong electric fields. In addition, the effect of the evolving densities on the polarization electric field above the collisional boundary has also been incorporated. From this analysis we have obtained anisotropic temperature ratios, plasma densities, ion heat flows, and ion upflows as a function of time and altitude for a variety of trigger conditions and a variety of possible ion-neutral cross-sections. The goal of this work is to match the conditions of the Swarm observations through modeling and compare our calculations to what is observed.

********************

**Satellite Gradients for Lithospheric Modelling – Sensitivity Tests Over the Northern Segment of the Trans-European Suture Zone**

Weise B.1, Ebbing J.1, Bouman J.2, Baykiev E.3, Bröchner M.4, Holzrichter N.1, Kotsiaros S.5, Pappa F.1, Szwillus W.1, Haagmans R.7

1Kiel University, Germany; 2Bundesamt für Kartographie und Geodäsie, Frankfurt, Germany; 3NTNU, Trondheim, Norway; 4Geological Survey of Norway, Trondheim, Norway; 5NASA Goddard Space Flight Center, Greenbelt, MD, USA; 6Universities Space Research Association, Greenbelt, MD, USA; 7ESA-ESTEC

In the framework of the ESA Support To Science Element ‘SLIM – Satellite Magnetic Gradients for Lithospheric Modelling’, we explore if gradients calculated from the Swarm satellite data can improve modelling of lithosphere structures. Our test area is the northern segment of the Trans-European Suture Zone (TESZ), which shows a distinct magnetic anomaly on aeromagnetic and satellite data. In addition, we exploit a pre-existing model of the lithosphere, which provides structural (Depth to the Top Basement and to the Moho) constraints and isotherms (e.g. the depth to the Curie isotherm). In our approach we first invert aeromagnetic data for the susceptibility distribution within different geometries, where the deepest magnetic sources are limited by (i) 15 km depth, (ii) the Moho) and (iii) the Curie isotherm. Forward modelling of data at satellite height of 400km shows that the three models are not very distinct in the calculated fields. The gradients are more sensitive to the differences, especially the invariants and the so-called curvature component Txy.

In the following, we discuss the gain by lowering the satellite height to distinguish the different lithospheric models. A lower calculation height of 200 or 300 km
increases the lithospheric signal significantly, and especially the gradients allow to differentiate the different models. Inverse modelling of the synthetic data allows to a certain degree to recover the effective induced magnetisation, when gradients are used, while the vector field is more sensitive to regional trends. However, Swarm is not measuring gradients directly, but these are calculated from the vector data. This means that only the gradients along and between the tracks are available. In our study area, already single-component inversion of the Txy component helps to establish a first-order model of the magnetisation within a pre-defined geometry. Such a model can be used as background or reference model for modelling of aeromagnetic data.

Constraining Lateral Variations of Upper-Mantle Electrical Conductivity Using Satellite-Detected Tidal Magnetic Signals
Grayver A., Kuvshinov A.
ETH Zurich, Institute of Geophysics, Switzerland

Data from CHAMP and Swarm satellites were shown to contain magnetic signals due to M2 tidal flow which were recently used to image the global electrical structure of the oceanic lithosphere and upper mantle down to a depth of about 250 km. This represents an important complement to the long-period magnetospheric responses, which lack resolution in the upper mantle. An open question is whether we can infer lateral variations in upper mantle conductivity from satellite-detected tidal magnetic signals and associate them with various tectonic processes? This study presents a comprehensive 3D feasibility study and 3D inversion results using real data.

Linking GIA and Lithospheric Structure of Antarctica with Satellite Gravity Gradients
Ebbing J.1, Pappa F.2, Barletta V.2, Blank B.3, Ferraccioli F.4, Forsberg R.5, v.d. Wal W.6, Kern M.7
1Kiel University, Germany; 2DTU Space, Copenhagen, Denmark; 3TU Delft, The Netherlands; 4British Antarctic Survey, Cambridge, UK; 5ESA-ESTEC

In the ESA Support to Science Element GOCE+Antarctica, we study the influence of the lithospheric structure on estimates of GIA. From recent geophysical, especially seismological, studies new insights on the deep structure of the Antarctic continents are available. However, the seismological models differ in resolution and do not provide a consistent image of the lithosphere. This is critical in analysing the feedback between the lithosphere and glacial loading or unloading.

To reduce such ambiguities, we combine the latest seismological models with gravity gradient data derived from the GOCE satellite mission. The gradients are in particular sensitive to the geometry and density variations of the main lithospheric layers, i.e. ice and sediment thickness, the Moho depth and the temperature and composition of the upper mantle. Initial results indicate that differences exist in the mode of compensation for West and East Antarctica related to different mantle properties.

The impact of an improved lithospheric model on GIA modelling is estimated by testing the sensitivity to the new temperature and density distribution and by comparing 1D and 3D viscosity models, especially in areas of low viscosity as in the Amundsen Sea sector.

Processing and Analysis of Satellite Gravity and Magnetic Data for Modelling the Lithosphere in Framework of 3D Earth
Holzrichter N.1, Ebbing J.1, Bouman J.2, Kotsiaros S.3
1CAU Kiel, Germany; 2Bundesamt für Kartographie und Geodäsie, Frankfurt, Germany; 3NASA Goddard Space Flight Center, Greenbelt, MD, USA

Shape index calculations and curvature analysis from GOCE gravity gradients are used successful for global tectonic and geological interpretations. The same techniques are applied to the Swarm magnetic data. Out test area is located over the northern part of the Trans-European Suture Zone (TESZ).

In a first step, the shape index is calculated from the spherical harmonic global model CHAOS 5 and 6. Low spherical harmonic degrees, related to the main field are suppressed, which results in ringing due the cut-off of the filter. Such data cannot be used for shape index calculation directly. We filter the data with different bandpass and cosine filters to remove those cut-off effects.

In a second step, we calculate magnetic gradients directly from track vector data for supposed magnetic quiet periods (Kp < 3). Still, some tracks compromise large outliers and a further quality analysis is performed to remove those outliers, e.g. lower noise level, only dark data, noise reduction by levelling. Next, a global reduction to pole techniques with varying inclination is applied to link the location of the magnetic anomalies to geological sources and to calculate meaningful gradient products.

This work has been performed in the framework of the ESA-STSE "SLIM - Swarm magnetic gradients for lithospheric modelling" and will be continued in the "3D Earth - a dynamic living planet".
Impact of Heat Flow and Laterally Varying Susceptibility on the Crustal Field

Szwillis W.¹, Baykiev E.², Ebbing J.¹²
¹Kiel University, Germany; ²Norwegian University of Science and Technology

The Curie isotherm should represent the lower limit of magnetization in the crust/lithosphere. This provides an opportunity to connect measurements of the magnetic field with thermal modelling. Using a simple thermal model, we infer the depth of the Curie isotherm from heat flow and LAB depth. In the modelling, we assume exponentially decaying heat production in the crust and a constant temperature of 1300 °C at the LAB. We calculate the magnetic crustal field caused by the estimated Curie isotherm assuming laterally constant susceptibilities for crust and mantle respectively.

The crustal/lithospheric field thus derived can explain some features of the magnetic field, namely those with a likely thermal origin. However, the overall fit is very poor.

For comparison we used a model of Vertically Integrated Susceptibility based on geological provinces to derive susceptibilities and ultimately the magnetic field. The model with laterally varying susceptibility has a better fit to the observed data.

We will discuss the uncertainties of the thermal modelling and their impact on the magnetic field.

Global Thermochemical Imaging of the Lithosphere Using Satellite and Terrestrial Observations

Fullea J., Lebedev S., Martinec Z.
Dublin Institute for Advanced Studies, Ireland

Conventional methods of seismic tomography, topography, gravity and electromagnetic data analysis and geodynamic modelling constrain distributions of seismic velocity, density, electrical conductivity, and viscosity at depth, all depending on temperature and composition of the rocks within the Earth. However, modelling and interpretation of multiple data sets provide a multifaceted image of the true thermochemical structure of the Earth that needs to be appropriately and consistently integrated. A simple combination of gravity, electromagnetic, geodynamics, petrological and seismic models alone is insufficient due to the non-uniqueness and different sensitivities of these models, and the internal consistency relationships that must connect all the intermediate parameters describing the Earth involved.

Thermodynamic and petrological links between seismic velocities, density, electrical conductivity, viscosity, melt, water, temperature, pressure and composition within the Earth can now be modelled accurately using new methods of computational petrology and data from laboratory experiments. The growth of very large terrestrial and satellite (e.g., Swarm and GOCE ESA missions) geophysical data sets over the last few years, together with the advancement of petrological and geophysical modelling techniques, now present an opportunity for global, thermochemical and deformation 3D imaging of the lithosphere and underlying upper mantle with unprecedented resolution.

This project combines state-of-the-art seismic waveform tomography (using both surface and body waves), newly available global gravity satellite data (geoid and gravity anomalies and new gradiometric measurements from ESA's GOCE mission) and surface heat flow and elevation within a self-consistent thermodynamic framework. The aim is to develop a method for detailed and robust global thermochemical image of the lithosphere and underlying upper mantle. In a preliminary study, we convert a state-of-the-art global waveform tomography velocity model into a mantle density model based on thermodynamic considerations and compute its 3D synthetic gravity response to compare with satellite data. As part of work in progress we present a lithospheric model based on integrated geochemical-petrological inversion of surface wave dispersion curves (Rayleigh and Love), topography, lithospheric geoid and surface heat flow. Broadband Rayleigh and Love fundamental mode phase velocity dispersion curves come from global phase velocity maps, computed in a broad period range using a large global dataset of phase velocity measurements, obtained using waveform inversion. The inversion is a non-linear gradient search combining steepest descent and local quadratic algorithms (Lavenberg-Marquardt) including dumping to a reference model and regularization for smoothness. The parameter space includes crustal structure (three layers with constant density, seismic velocities, heat production and thickness), mantle structure (Lithosphere-Asthenosphere boundary depth and temperature, composition and temperature distribution within the sublithosphere) and seismic radial anisotropy.
Analysis of Lithospheric Stresses Using Satellite Gravimetry: Hypotheses and Applications to North Atlantic
Minakov A., Medvedev S.
University of Oslo, Norway

Analysis of lithospheric stresses is necessary to gain understanding of the forces that drive plate tectonics and lithospheric deformation, the structure and strength of the lithosphere. The main source of lithospheric stresses is believed to be in variations of surface topography and lithospheric density. The traditional approach to stress estimation is based on direct calculations of the Gravitational Potential Energy (GPE), the depth integrated density moment of the lithosphere column. GPE is highly sensitive to density structure which, however, is often poorly constrained. Density structure of the lithosphere may be refined using methods of gravity modeling. However, the resulted density models suffer from non-uniqueness of the inverse problem. An alternative approach is to directly estimate lithospheric stresses (depth integrated) from satellite gravimetry data, skipping intermediate steps of density modeling.

Recent satellite geodetic and gravimetric measurements by the ESA GOCE mission combined with land and airborne gravity data ensures a wealth of data for mapping lithospheric stresses if strong link between data and stresses or GPE can be established theoretically.

Unfortunately, the non-uniqueness of interpretation of sources of the gravity signal corrupts solution in this case as well. Such as, a gravity signal from sources in the lower mantle, which affect lithospheric stresses insignificantly, can be interpreted in terms of a shallower lithospheric density structure, which controls the stress pattern. Therefore, the data analysis cannot apply blindly everywhere and needs testing on particular case study region with good constraints provided by other geophysical methods and published models. As a test study region we selected the North Atlantic where reliable additional constraints are supplied by both controlled-source and earthquake seismology.

The study involves comparison of three methods: (1) the traditional (Medvedev, 2016); (2) the filtered geoid (Coblentz et al., 2015); and (3) the direct utilization of the gravity gradient tensor (Camelbeeck et al., 2013) available from the GOCE mission. Whereas the first two approaches (1)-(2) calculate GPE and utilize a computationally expensive finite element mechanical modeling to calculate stresses, the approach (3) uses a much simpler numerical treatment but requires simplifying assumptions that yet to be tested. The modeled orientation of principal stresses and stress magnitudes by each of the three methods are compared with the World Stress Map. We discuss the discrepancies by different methods in terms of theoretical models behind including various treatments and definitions of ‘isostasy’.

References:


CHAMP, GRACE, GOCE and Swarm Thermosphere Density Data with Improved Aerodynamic and Geometry Modelling
March G., Doornbos E., Visser P.
TU Delft, Netherlands, The

Since 2000, accelerometers on board of the CHAMP, GRACE, GOCE and Swarm satellites have provided high-resolution thermosphere density data, improving knowledge on atmospheric dynamics and coupling processes in the thermosphere-ionosphere layer.

Most of the research has focused on relative changes in density. Scale differences between datasets and models have been largely neglected or removed using ad hoc scale factors. The origin of these variations arises from errors in the aerodynamic modelling, specifically in the modelling of the satellite outer surface geometry and of the gas-surface interactions. Therefore, in order to further improve density datasets and models that rely on these datasets, and in order to make them align with each other in terms of the absolute scale of the density, it is first required to enhance the geometry modelling. Once accurate geometric models of the satellites are available, it will be possible to enhance the characterization of the gas-surface interactions, and to enhance the satellite aerodynamic modelling.

This presentation offers an accurate approach for determining aerodynamic forces and torques and improved density data for CHAMP, GRACE, GOCE and Swarm. Through detailed high fidelity 3-D CAD models and Direct Simulation Monte Carlo computations, flow shadowing and complex concave geometries can be investigated. This was not possible with previous closed-form solutions, especially because of the low fidelity geometries and the incapability to introduce shadowing effects. This inaccurate geometry and aerodynamic modelling turned out to have relevant influence on derived densities, particularly for satellites with complex elongated shapes and protruding instruments, beams and antennae.

Once the geometry and aerodynamic modelling have been enhanced with the proposed approach, the accelerometer data can be reprocessed leading to
higher fidelity density estimates. An overview of achieved improvements and dataset comparisons will be provided together with an introduction to the next gas-surface interactions research phase.

GPS-derived Density Data for the Swarm Satellites During the Declining Phase of the Solar Cycle
Doornbos E., van den IJssel J.
Delft University of Technology, Netherlands, The

After the detection of many anomalies in the accelerometer data, the development and production of GPS-derived acceleration and thermosphere density products for the three Swarm satellites has been intensified. In order to convert the range and phase information in the Swarm GPS measurements into accelerations, a precise orbit determination approach needs to be used, in which gravitational accelerations are modelled with a very high fidelity, but in which the non-gravitational accelerations are part of the parameters to be estimated. After initial tests with both batch least-squares and Kalman filter orbit determination approaches, a Kalman filter approach was tuned and selected for computing the acceleration data. The resulting GPS-derived accelerations currently serve as a baseline for the correction of Swarm C along-track accelerometer data. In addition, the GPS-derived accelerations for all three Swarm satellites are converted directly to thermosphere neutral density data. This GPS-derived density data can serve as a replacement for the originally planned accelerometer thermosphere density products, albeit at a much lower temporal resolution than the accelerometers would have been able to deliver. The accuracy at which accelerations, and subsequently densities, can be derived from the GPS range and phase observations depends on the parameterisation in the orbit determination process. In principle, a higher accuracy can be traded off against a lower temporal resolution. An additional source of error is the modelling of radiation pressure accelerations, which need to be removed from the estimated signal to arrive at the aerodynamic accelerations, which are used as a source to determine density. We have assessed the impact of the declining solar activity level on the currently available acceleration and density data, as well as the impact of various scenarios for the future evolution of the Swarm orbits. Most of the currently available data contains a significant signal well above 2 cycles per orbit revolution at high solar activity. At low solar activity this maximum significant frequency is reduced. A complicating factor is that it would not be very useful for the interpretation of the data to estimate the accelerations and densities above 1 but below 2 cycles per revolution. Currently, the Swarm satellites are still in relatively high orbits, while solar activity is getting lower. Our conclusion is that with the current level of error sources, and keeping the orbits at the current altitude or higher, as proposed in some scenarios, will make it very difficult to resolve latitudinal density variability at solar minimum, using Swarm GPS data.

Horizontal and Vertical Wind Measurements from GOCE Angular Accelerations
Visser T., Doornbos E.N., de Visser C.C., N.A.M. Visser P.
Delft University of Technology, Netherlands, The

Because of the highly accurate accelerometers, the GOCE mission has proven to be a unique source of thermosphere neutral density and cross-wind data. In the current methods, in which only the horizontal linear accelerations are used, the vertical winds cannot be obtained. In the algorithm proposed in this paper, angular accelerations derived from the individual gradiometer accelerations are used to obtain the vertical wind speeds as well. To do so, the measured angular rate and acceleration are combined to find a measurement of the torque acting on the spacecraft. This measurement is then corrected for modeled control torque applied by the magnetic torquers, aerodynamic torque, gravity gradient torque, solar radiation pressure torque, the torque caused by the misalignment of the thrust with respect to the center of gravity, and magnetic torque caused by the operation of several different subsystems of the spacecraft bus. Since the proper documentation of the magnetic properties of the payload were not available, a least squares estimate is made of one hard- and one soft-magnetic dipole pertaining to the payload, on an aerodynamically quiet day. The model for aerodynamic torque uses moment coefficients from Monte-Carlo Test Particle software ANGARA. Finally the neutral density, horizontal cross-wind, and vertical wind are obtained from an iterative process, in which the residual forces and torques are minimized. It is found that, like horizontal wind, the vertical wind responds strongly to geomagnetic storms. This response is observed over the whole latitude range, and shows seasonal variations.
Long-term Variations of the Upper Atmosphere Parameters on Rome Ionosonde Observations and their Interpretation
Perrone L.¹, Mikhailov A.², Cesaroni C.¹, Alfonsi L.¹, De Santis A.², Pezzopane M.², Scotto C.¹
¹INGV, Italy; ²IZMIRAN, Russian Federation

A new self-consistent approach to the analysis of thermospheric and ionospheric long-term trends has been applied to Rome ionosonde summer noontime observations for the (1957-2015) period. This approach includes: i) a method to extract foF2, hmF2, foF1 long-term trends; ii) a method to retrieve thermospheric neutral composition (O, O2, and N2), exospheric temperature Tex, and the total solar EUV flux with λ<1050 Å from routine foF1 ionosonde data. The method was tested using CHAMP/STAR neutral gas density measurements.; iii) a combined analysis of the ionospheric and thermospheric parameter long-term variations using the theory of ionospheric F-layer formation.

In accordance with the geomagnetic control concept daytime 11-year smoothed (δfoF2)11y and (δfoF1)11y manifest mainly anti-phase with Ap11y variations. Periods of increasing geomagnetic activity correspond to negative trends in (δfoF2)11y and (δfoF1)11y and vice versa. On the contrary, (δhmF2)11y demonstrate in-phase with Ap 11y variations. The retrieved neutral gas density r, atomic oxygen [O], and exospheric temperature Tex, from monthly median foF1 noontime observations for the period of ~ 5 solar cycles (1957-2015), exhibit very small (< 1% per decade) and insignificant linear trends. This contradicts the results obtained on satellite drag measurements and those derived from ground-based incoherent scatter radars. The retrieved thermospheric parameter long-term variations were shown to be controlled only by solar and geomagnetic activity. Atomic oxygen, [O] and [O]/[N2] ratio control foF1 and foF2 while neutral temperature, Tex controls hmF2 long-term variations. Noontime foF2 and foF1 long-term variations demonstrate a negative trend over the (1962-2010) period which should be attributed to atomic oxygen decrease after ~1990.

The “Rocket Experiment for Neutral Upwelling 2 (RENU2)” Sounding Rocket
University of New Hampshire, United States of America

Thermospheric upwelling has been known to exist since the earliest days of the space program, when observers noted increased satellite drag associated with solar activity. Scientists quickly attributed the upwelling to Joule heating effects, explaining that increased solar activity results in increased Joule heating, which can couple energy to the ambient neutral gases to cause the upwelling. Observations by the CHAMP satellite, however, have shown that neutral upwelling often occurs on much smaller scales and is highly correlated with small-scale field-aligned currents in the vicinity of the cusp region. Several theories have since been put forward that seek to explain this phenomenon. Motivated by these competing theories and outfitted with a comprehensive suite of instruments, the RENU2 sounding rocket was launched into a Poleward Moving Auroral Form (PMAF) in the cusp region on December 13, 2015. In this highly successful mission, instruments on the payload did, in fact, record neutral atomic oxygen above the payload at 350 km as it passed through the PMAF. In addition, signatures of N2+ ions also appeared above the PMAF, evidence of so-called “sunlit aurora”. In this presentation, initial results will be presented from this mission and discussed in the context described above.
Impact of Swarm GPS Receiver Modifications on Baseline Determination

Mao X., Van den Ijssel J., Visser P.
Delft University of Technology, Netherlands, The

The European Space Agency (ESA) Swarm mission is a satellite constellation launched on 22 November 2013 aiming at observing the Earth geomagnetic field and its temporal variations. The constellation consists of two satellites flying in pendulum formation in low earth polar orbits and one satellite flying separately in a higher polar orbit. The three identical Swarm satellites are equipped with high-precision 8-channel dual-frequency Global Positioning System (GPS) receivers, which make the Swarm constellation a good test bed for baseline determination. High-precision baseline determination between low earth orbiting satellites is relevant for e.g. Interferometric Synthetic Aperture Radar (InSAR) research, proximity operations between spacecraft, and possibly gravity field determination.

For Swarm, special attention has to be paid to several aspects regarding the baseline determination. These aspects include the synchronization of the GPS observations collected by the GPS receivers on the different Swarm satellites, the determination of in-flight frequency-dependent Phase Center Variation (PCV) and Code Residual Variation (CRV) antenna patterns, and half-cycle carrier-phase ambiguity resolution. In addition, a number of GPS receiver modifications were made in the October 2014 to August 2016 time frame, such as changes in the Field-of-View (FoV), tracking loop bandwidth, and Receiver Independent Exchange Format (RINEX) converter updates. Moreover, the on-board GPS receiver performance is greatly influenced by the seasonal ionospheric scintillation, which is caused by irregular plasma bubbles that mostly occur at equatorial and polar areas.

The impact of the factors mentioned above is assessed for baseline determination of the pendulum formation flying Swarm-A and -C satellites. They fly at altitudes lower than Swarm-B and their baseline length varies between 30 and 180 km. The assessment is done for four different periods: August 2014, November 2014, August 2016 and November 2016 - are implemented, respectively. These four periods have been selected to especially study the impact of different levels of ionospheric scintillations (normally low in August and high in November) and GPS receiver modifications.

The assessment includes a consistency check between so-called kinematic and reduced-dynamic baseline solutions, a validation of the associated absolute orbit solutions by comparison with Satellite Laser Ranging (SLR) observations, overlap analyses between consecutive baseline solutions, success rate of ambiguity fixing, and analysis of observation residuals. First results indicate the usefulness and importance of the GPS receiver modifications and RINEX converter updates. It is found that the GPS receiver modifications significantly reduce the impact of ionospheric scintillations and improve the baseline determination. Especially, a larger carrier phase tracking loop bandwidth is found to be the most beneficial factor for baseline determination.

Impact of GPS Receiver Tracking Loop Modifications on Precise Swarm Orbits

van den Ijssel J.
Delft University of Technology, Netherlands, The

The European Space Agency (ESA) Swarm mission was launched on 22 November 2013 to study the dynamics of the Earth’s magnetic field and its interaction with the Earth system. The mission consists of three identical satellites flying in near polar orbits. Two satellites are flying almost side-by-side at an initial altitude of 480 km, while the third satellite was placed in a higher orbit at about 530 km altitude. The Swarm satellites are equipped with high-precision 8-channel, dual-frequency GPS receivers, which are used to compute Precise Science Orbits (PSOs). These PSOs nominally consist of a reduced-dynamic orbit for the geolocation of the onboard scientific instrument observations with highest accuracy, and a kinematic orbit for gravity field determination purposes. Independent Satellite Laser Ranging (SLR) validation shows that the reduced-dynamic Swarm PSOs have an accuracy of better than 2 cm, while the kinematic orbits have a slightly reduced accuracy of about 4–5 cm.

Despite this good performance, the Swarm GPS receivers are shown to be susceptible to ionospheric scintillation. Generally, ionospheric scintillation is most intense in the equatorial and polar regions. When flying over these areas, the Swarm GPS receivers show a slightly degraded performance, resulting in occasional tracking losses, larger GPS carrier phase residuals and a reduced consistency between the kinematic and reduced-dynamic PSOs. For gravity fields determined from Swarm GPS data this can lead to severe systematic errors along the geomagnetic equator. In order to try to make the Swarm GPS receivers more robust for ionospheric scintillation, the GPS tracking loops have meanwhile been adjusted several times. The bandwidth of the L1 carrier loop has been increased from 10 to 15 Hz, while the L2 carrier loop bandwidth was increased from its original value of 0.25 Hz, to, respectively, 0.5 Hz, 0.75 Hz and 1.0 Hz.

To assess which of these settings is optimal, an extensive analysis has been conducted. Because the different tracking loop modifications were first implemented on Swarm-C only, their impact can be assessed by a comparison with the close flying Swarm-A satellite. The assessment includes an analysis of the amount of collected GPS observations and their residual errors, the consistency between the kinematic and reduced-dynamic orbit solutions, as well as SLR validation. This analysis is performed using data collected during different seasons, to take differences in ionospheric scintillation conditions into account. Other low flying satellites with similar GPS receivers,
Like e.g. the Sentinels, might also benefit from this analysis.

-----------------------------

**GPS-based Kinematic Orbit Determination of Swarm Satellites**
Ren L.¹, Schönh C.², Lück C.², Rietbroek R.², Kusche J.²
¹Institut für Erdmessung (IfE), Leibniz Universität Hannover, Germany; ²Institut für Geodäsie und Geoinformation (IGG), Rheinische Friedrich-Wilhelms Universität Bonn, Germany

The Swarm mission launched on November 22, 2013 is ESA’s first constellation of satellites to study the dynamics of the Earth’s magnetic field and its interaction with the Earth system. This mission consists of three identical satellites in near-polar orbits, Swarm A and C flying almost side-by-side at an initial altitude of 460 km, Swarm B flying in a higher orbit of about 530 km. Each satellite is equipped with a high precision 8-channels dual-frequency GPS receiver from RUAG Space for precise orbit determination, which is essential in order to take full advantage of the data information provided by this constellation, e.g. for the recovery of gravity field from the kinematic orbits.

In this contribution, we will analyse first the performance of the Swarm on-board receivers, especially under the influence of ionospheric scintillation. After analysing and sophisticated preprocessing of the observations, kinematic orbits for Swarm satellites are generated with a MATLAB-based Precise Point Positioning software which is developed of IfE Hannover using the least-squares adjustment method. The generated kinematic orbits are compared with the reduced-dynamic orbits provided by ESA Swarm Level 2 Product. The root mean square (rms) of the position residuals for Swarm satellites in along, cross and radial track are around 1.5, 1.5 and 2 cm, respectively. Next the impact on gravity field solutions is investigated by IGG Bonn. Finally, we will show first results from the kinematic baselines between Swarm satellites and compare the baseline components with differences between their kinematic orbits, respectively.

-----------------------------

**Improvements in Crustal Field Modeling with Swarm at Lower Altitudes**
Alken P.¹, Chulliat A.¹, Kotsiaros S.²
¹University of Colorado at Boulder, Boulder, CO, USA; ²NASA Goddard Space Flight Center, Greenbelt, MD, USA

Lowering the Swarm pair A and C is assumed to be necessary for new advances in crustal field modeling. To our knowledge, no one has yet quantified how much improvement can be gained from lower altitudes. In this work, we will construct a realistic Swarm dataset at a lower altitude using several years of actual Swarm ephemeris, and reducing the altitudes by about 100km. The data will be corrected for main and ionospheric field effects at the lower altitude. MF7 will be subtracted from the nominal Swarm data, and a high-degree synthetic crustal field model will be added to the lower altitude data. The resulting dataset will contain a known synthetic high-degree crustal field, as well as realistic external fields. The lower altitude dataset will be inverted using east-west gradients between Swarm A and C to determine how much of the known crustal field can be recovered at the lower altitude.

-----------------------------

**Lowering SWARM’s AC Satellites and Implications for Studying Ocean Circulation**
Schnepp N.¹, Nair M.¹, Alken P.¹, Chulliat A.¹, Kuvshinov A.²
¹University of Colorado Boulder, United States of America; ²Institute of Geophysics, ETH Zürich, Switzerland

Decreasing the altitude of the Swarm pair A and C for the upcoming solar minimum may be very beneficial for magnetic detection of ocean circulation. Simulations of magnetic induction due to ocean circulation predict most oceanic areas would have an increase in signal strength of 10-20% should A and C lower to a 350 altitude orbit. Regions along the Antarctic Circumpolar Current, North Pacific Gyre and North Atlantic Gyre may see a 100+% improvement in signal strength should the satellites decrease to a 350 altitude orbit.

Besides discussing the predicted field strength at different orbital altitudes, we will attempt to determine the minimum threshold circulation signal strength needed for recovery from gradient data. We will process the current altitude SWARM data to concentrate on signals of ocean variability by applying the following corrections: 1) Subtracting a model of the Earth’s internal magnetic field and removing time-varying contributions from the core, as well as a significant portion of the static crustal field; 2) subtracting time-varying models of the ionospheric and magnetospheric contributions; 3) subtracting the oceanic tidal signal.

To this dataset, we will add the signal produced from the forward model to strengthen the circulation signal. Pairs of fully processed repeated tracks will then be subtracted from each other in order to remove any remaining static contributions. By altering the strength of the forward model results added to the data, we can evaluate the minimum threshold circulation signal strength needed for recovery from this gradient data and recommend the orbit altitude to achieve that.

-----------------------------