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STRATUS: SaTellite RAdar sounder for earTh sUb-surface Sensing

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STRATUS Team

Science Team	
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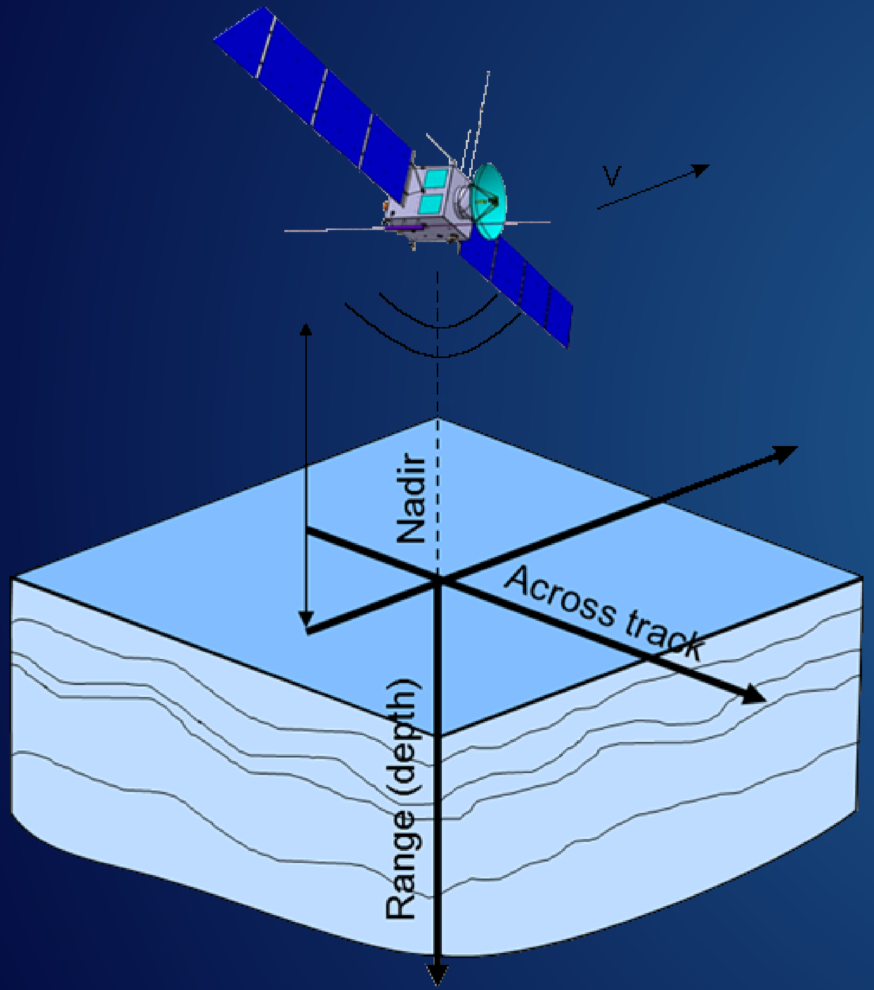
Massimo Frezzotti	Università degli Studi "Roma Tre", Italy
Essam Heggy	Univ. of Southern California (USC)
Ala Khazendar	Jet Propulsion Laboratory
Wlodek Kofman	Centre National de la Recherche Scientifique (CNRS/UJF)
Joaquin Munoz-Cobo Belart	National Land Survey of Iceland and University of Iceland
Gian Gabriele Ori	International Research School of Planetary Sciences
Andrew Shepherd	University of Leeds
Frank Wilhelms	Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung

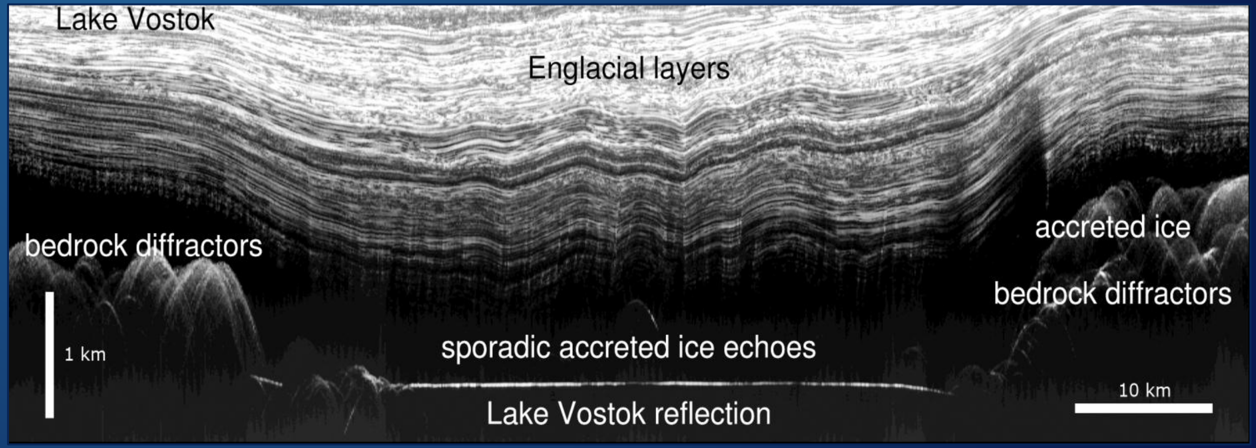
Industrial Partner: Thales Alenia Space Italy (TAS-I)	
Marco Iorio (System Architecture)	TAS-I, Italy
Andrea Olanda (System Engineering Management)	TAS-I, Italy
Gianni Alberti (Payload Sys. Eng.)	Consorzio di Ricerca su Sistemi di Telesensori Avanzati (CORISTA), Italy

Mission Concept



Heritage

- ✓ Airborne Radar sounder used in polar areas (e.g., HiCARS, MCoRDS)
- ✓ MARSIS (ESA MARS express - MEX)
- ✓ SHARAD (NASA Mars Reconnaissance Orbiter - MRO)
- ✓ RIME (ESA JUpiter ICy moon Explorer - JUICE)



HiCARS radargram (central frequency 60 MHz) of Lake Vostok, Antarctica (courtesy University of Texas)

Motivations

- ✓ STRATUS provides new data enabling fundamental science returns on cryosphere, climate change and arid areas.
- ✓ This type of data has not been acquired by any other past or present satellite mission and is not foreseen in any future approved mission.
- ✓ Available airborne radar sounder data are heterogeneous, irregular and sparse in space and time.
- ✓ STRATUS is based on a satellite VHR radar sounder that has the capability to obtain sub-surface measurements:
  - with regular revisit in time and space;
  - at a large spatial scale;
  - with homogeneous coverage and quality in space and time.

Primary Objectives: Cryosphere

I1. Mapping the basal interface topography and ice-sheet thickness.

I2. Investigating the near-surface reflectivity and dielectric properties of ice sheets.

I3. Mapping the structure of internal layers.

I4. Determining basal boundary conditions and processes.

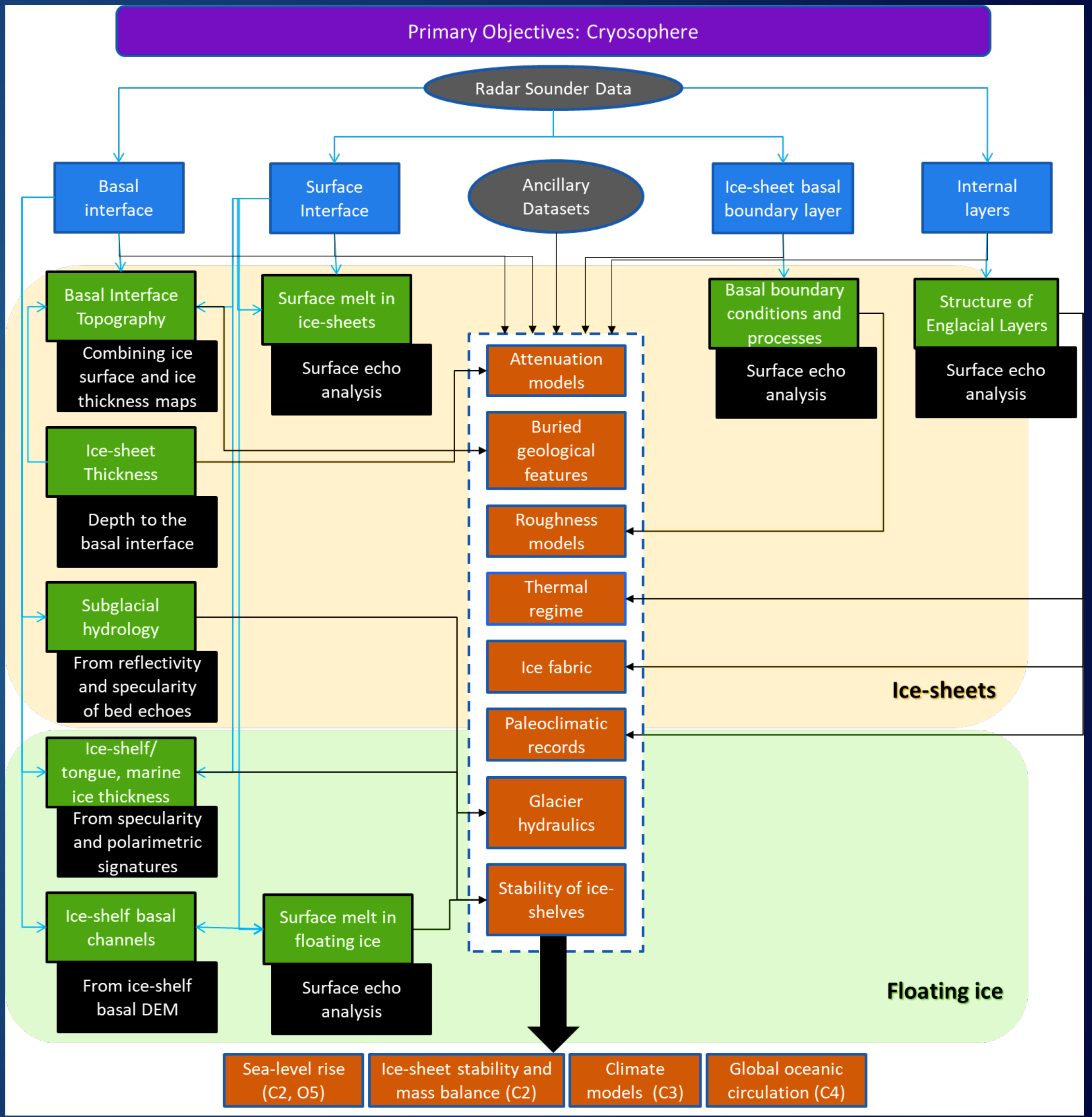
I5. Estimating the ice-sheet thermal regime.

I6. Mapping the subglacial hydrologic systems: subglacial lakes and channels.

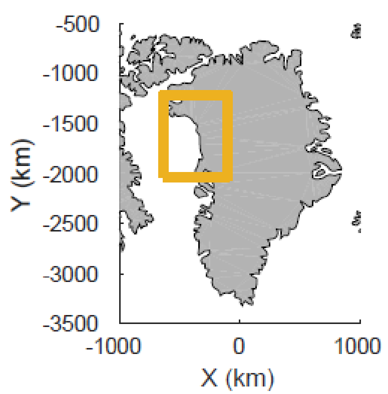
I7. Estimating the thickness of floating ice, and marine and meteoric ice, and detecting the grounding zone.

I8. Mapping the channels at the base of ice-shelves.

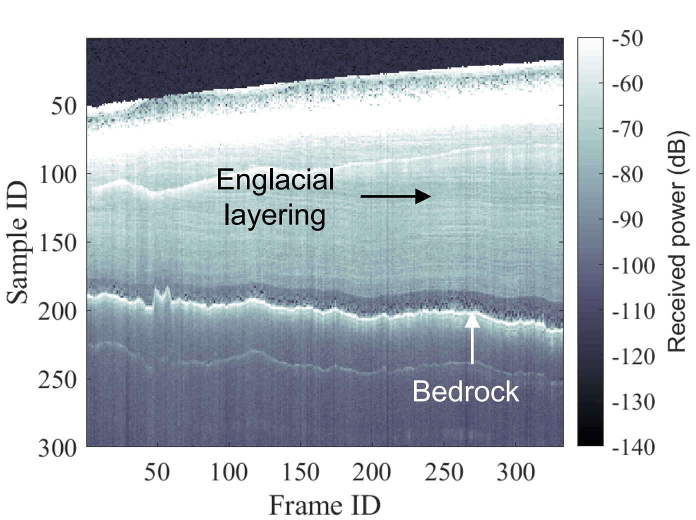
I9. Investigating the near-surface reflectivity and dielectric properties of floating ice.

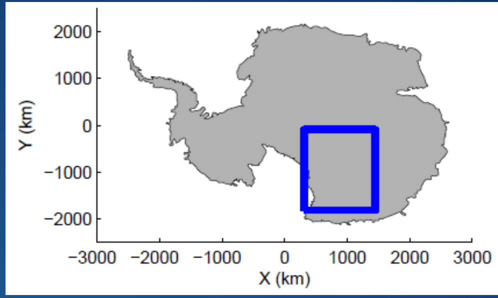


Cryosphere: Simulated STRATUS Radargrams

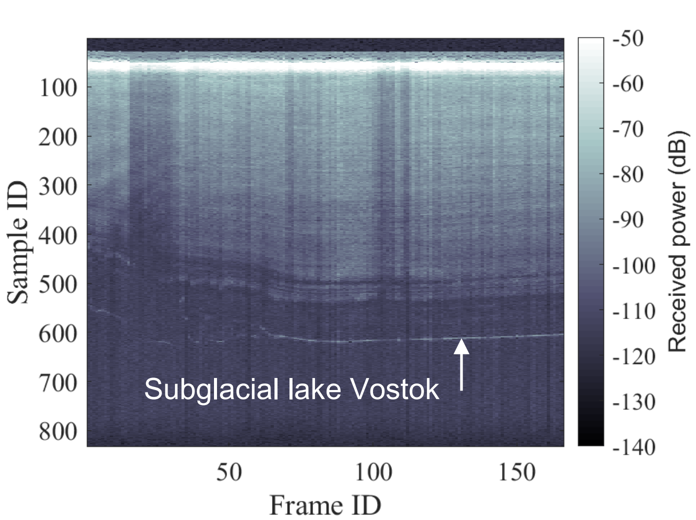


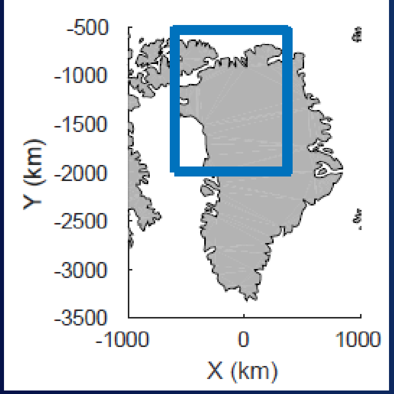
Northwest Coastal C
Greenland ice-sheet



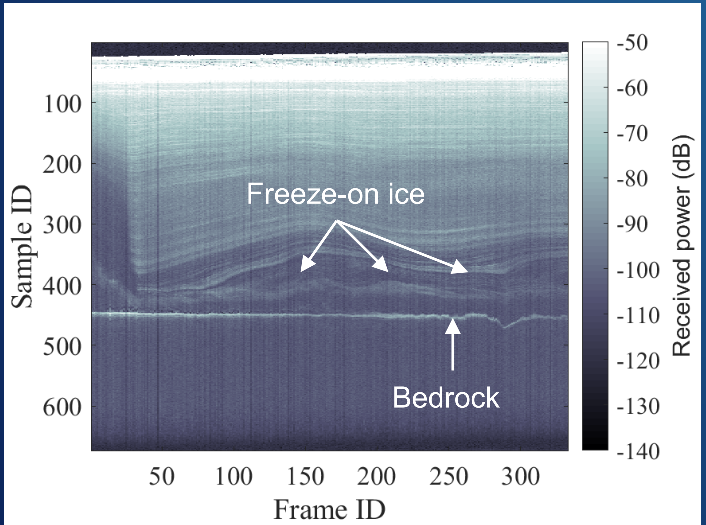


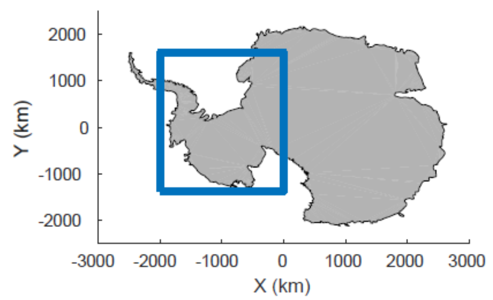
East Antarctica
Dome C



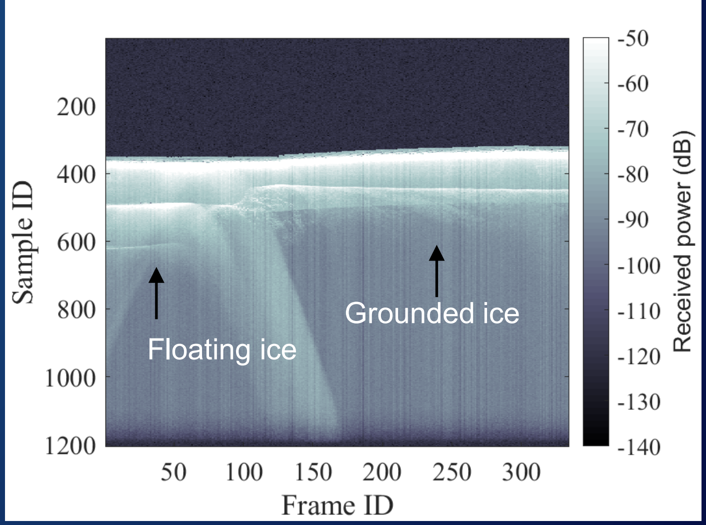


North glaciers
Greenland ice-sheet





Ronne Filchner Ice shelf
Antarctica

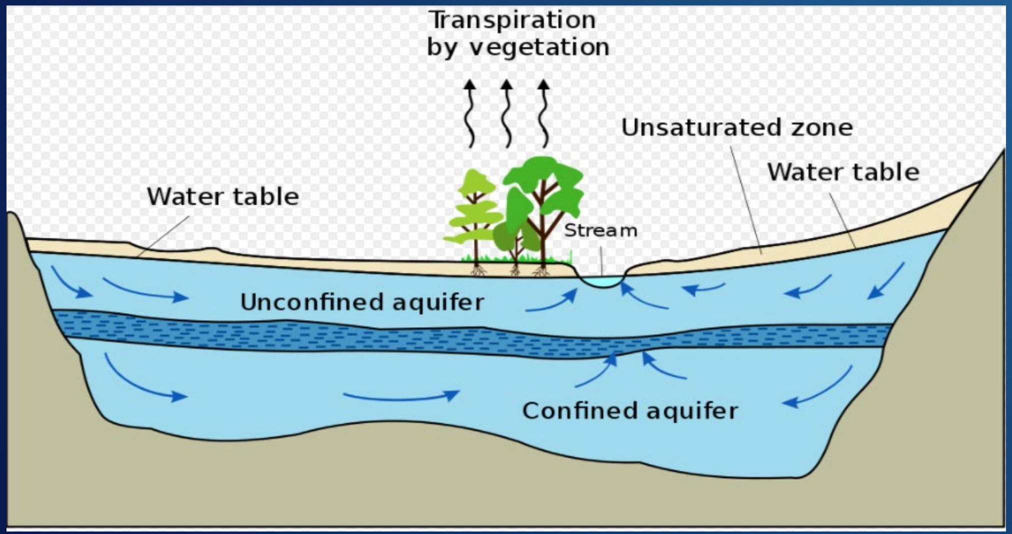


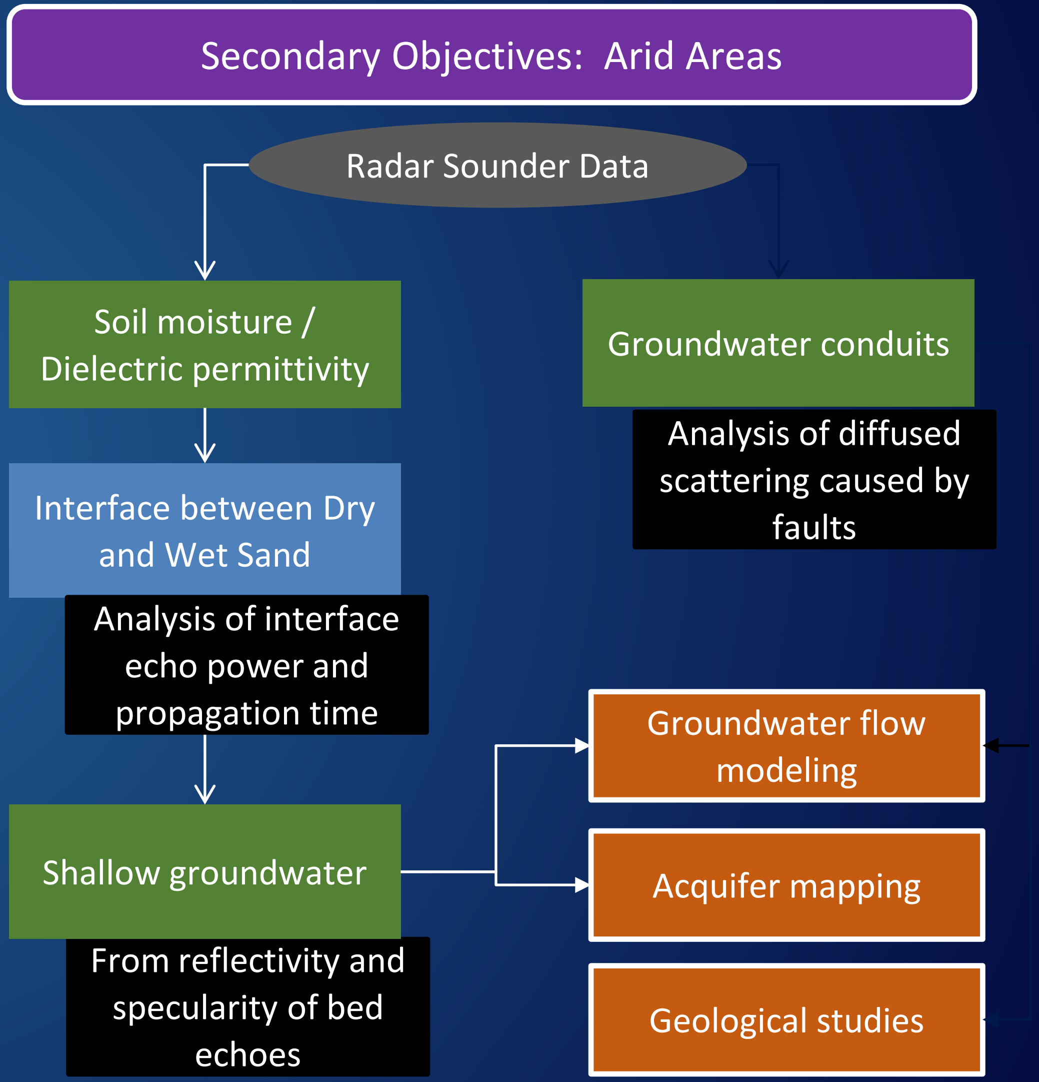
Thakur, S., Donini, E., Bovolo, F., & Bruzzone, L. (2021). An Approach to the Assessment of Detectability of Subsurface Targets in Polar Ice From Satellite Radar Sounders. IEEE Transactions on Geoscience and Remote Sensing.

Secondary Objectives: Arid Areas

II1. Probing the water table of shallow aquifers.

II2. Mapping groundwater conduits.



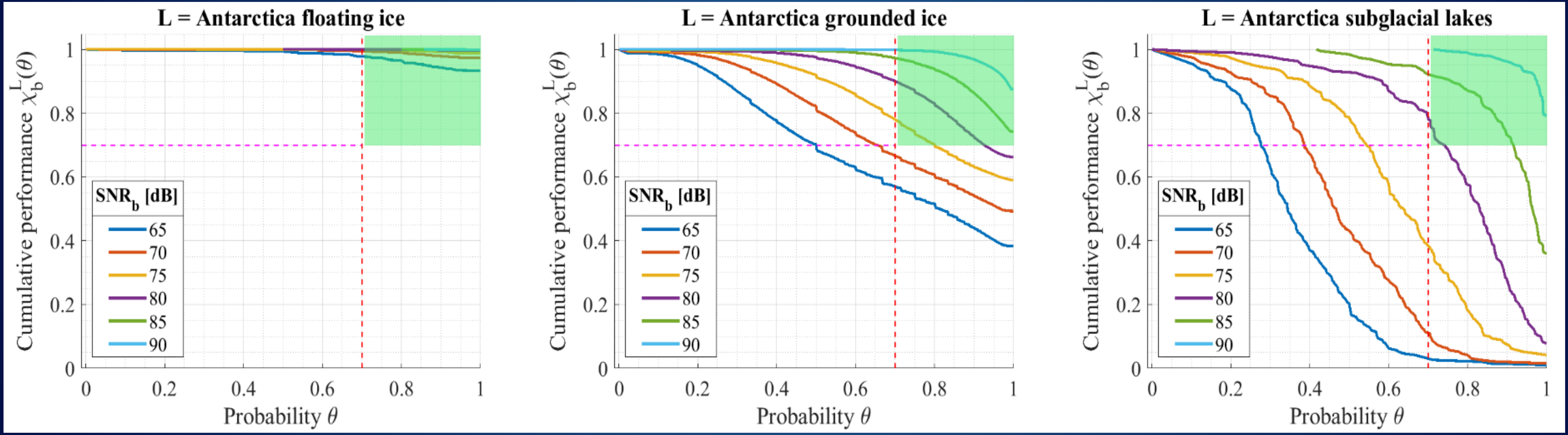


Science Objectives and Observation Requirements

Science Objective	Scale of Observation		Science Requirements		
	Spatial (track spacing)	Temporal (repeat interval)	Penetration Depth	Vertical resolution	Along-track resolution
I1. Mapping the basal interface topography and ice-sheet thickness.	3 – 10 km	-	2 – 4.5 km	≤20 m	1.5 – 5 km
I2. Investigating the near-surface reflectivity and dielectric properties.	3 – 10 km	seasonal	-	≤15 m	7 – 10 km
I3. Mapping the structure of internal layers.	3 – 10 km	-	2 – 4 km	≤15 m	1.5 – 5 km
I4. Determining basal boundary conditions and processes.	3 – 10 km	-	2 – 4.5 km	≤15m	1.5 – 5 km
I5. Estimating the ice-sheet thermal regime.	3 – 10 km	-	2 – 4 km	≤15 m	1.5 – 5 km
I6. Mapping the subglacial hydrologic systems: subglacial lakes and channels.	3 – 10 km	seasonal	2 – 4.5 km	≤20m	1.5 – 5km
I7. Estimating the thickness of floating ice, and marine and meteoric ice, and detecting the grounding zone.	3 – 10 km	seasonal	< 1km	≤15m	1.5 – 5km
I8. Mapping the channels at the base of ice-shelves.	3 – 10 km	seasonal	< 1km	≤20m	1.5 – 5km
I9. Investigating the near-surface reflectivity and dielectric properties of floating ice.	3 – 10 km	seasonal	--	≤15m	7 – 10km
II1. Probing the water table of shallow aquifers.	3 – 10 km	seasonal	< 100 m	≤15m	1.5 – 5km
II2. Mapping groundwater conduits.	3 – 10 km	-	< 100 m	≤15m	1.5 – 5km

Perfomance Analysis: Example

Diagrams show the fraction of layers in the along-track (vertical axis) and range (horizontal axis) detectable in simulated STRATUS radargrams at different surface SNR budget ($\mathrm{SNR_b}$) in different cryosphere regimes.



Thakur, S., Donini, E., Bovolo, F., & Bruzzone, L. (2021). An Approach to the Assessment of Detectability of Subsurface Targets in Polar Ice From Satellite Radar Sounders. *IEEE Transactions on Geoscience and Remote Sensing*.

STRATUS Characteristics

Parameter	Value
Instrument type	Distributed Radar Sounder
Maximum Peak Radiated Power	800 W
Frequency band	40-50 MHz (VHF)*
Maximum penetration depth	< 4.7 km in ice < 100 m in arid areas
Along track resolution	< 1.3 km
Across track resolution	< 7.5 km
Range resolution (vertical resolution)	< 15 m (in ice)
Surface SNR	92 dB
Orbit	Polar (90°) or SSO (~97°), Altitude 400-500 km

*STRATUS frequency Allocation will be discussed at WRC-23 – ITU. Activities are in progress within the ITU Working Groups for defining the allocation parameters. Currently, no showstoppers identified.

Carrer, L., Gerekos, C., Bovolo, F., & Bruzzone, L. (2019). Distributed Radar Sounder: A Novel Concept for Subsurface Investigations Using Sensors in Formation Flight. *IEEE Transactions on Geoscience and Remote Sensing*, *57*(12), 9791-9809.

Distributed Sounder Configurations

✓ The distributed radar sounder architecture can be implemented with different strategies:

Baseline

One mothership transmits and all the sensors are receiving. This configuration offers risk additional mitigation: in case of failure the mothership is fully functional as a single sounder.

Option

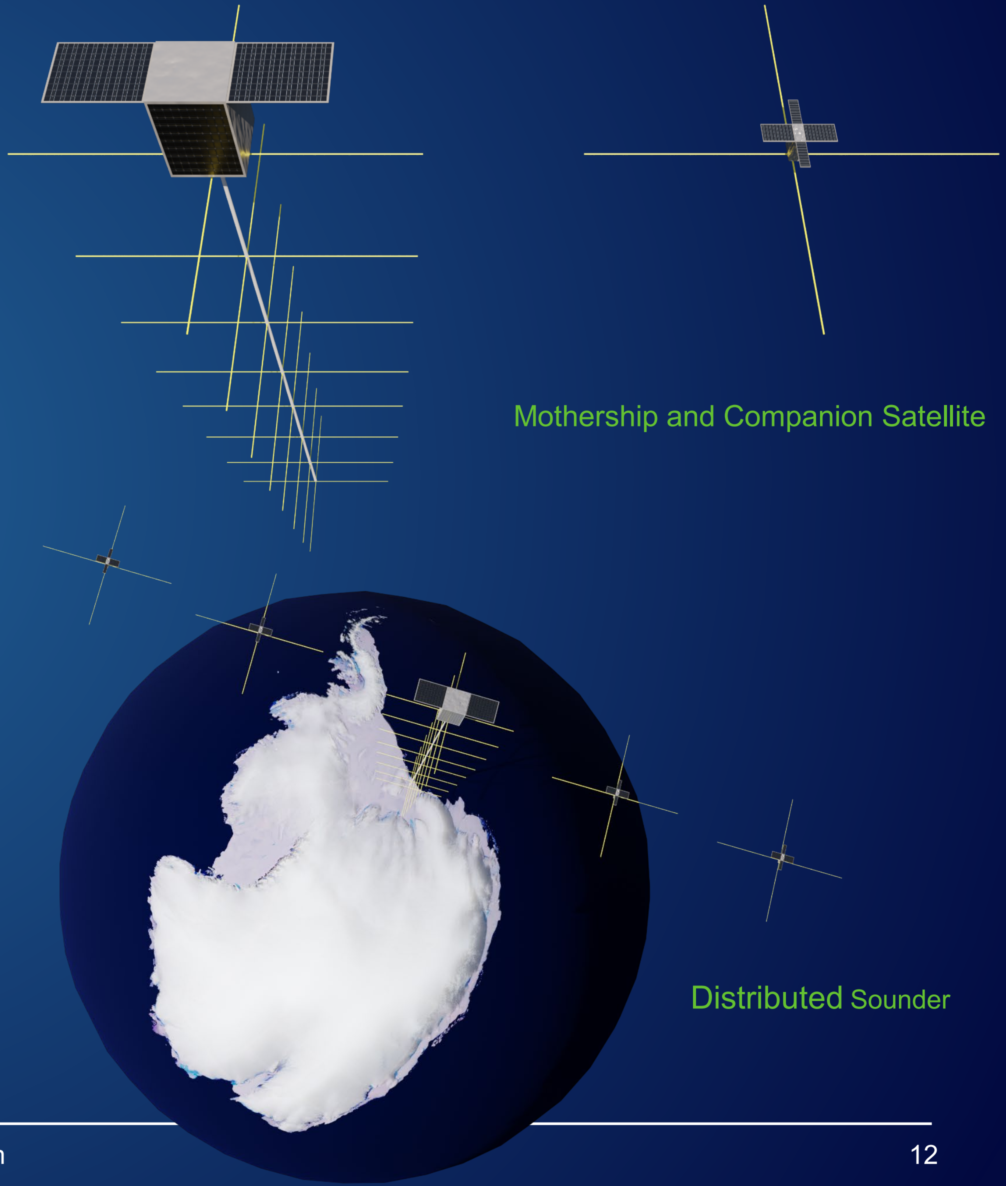
All the sensors are transmitting and receiving

✓ Both configurations provide significant benefits with respect to single sounding platform:

- Superior ambiguities suppression capability → better data interpretation by scientists;
- Improved penetration depth;
- Improved spatial resolution.

Mission Components

Architecture	• Multiple recurrent very small platforms and radar sensors in formation flying.
Antenna	• Crossed Dipole (e.g-, filar) or LPDA (mother ship).
Main Technical Complexities (No showstoppers identified)	• Inter-satellite Communication Link. • Accuracy of relative positioning of the sensors (~0.5 m) and synchronization. • Distance between sensors in the order of tens of meters.
Mission Duration and Orbit	• STRATUS baseline is a 3 years mission. • Seasonal full coverage of the icy regions (i.e., winter/summer). • Current baseline is a polar orbit. • Possibility of switching to a Sun Synchronous orbit for improving the coverage over coastal areas.
Launcher	• Launcher configurations are available for deploying STRATUS formation in a single launch.



Mothership and Companion Satellite

Distributed Sounder

Main Challenges

Challenge	Impact	Solution
Earth's Ionosphere	Radar Signal Distortion resulting in potential performance losses	✓ Adjust Acquisition Planning (e.g, season, time of the day). STRATUS is expected to operate at night-time when the Ionosphere is less charged. ✓ State of the Art Ionosphere Compensation Techniques [1]. ✓ Repeat Acquisitions by exploiting coverage margins. ✓ Ionosphere is expected to be less charged as a result of expected solar activity decrease in the fore coming solar cycles.
Collision Avoidance between Sensors	Performance Losses	✓ Suitable orbital configurations for collision avoidance: • Sail. • Helix.
Sensors Synchronization	Performance Losses	✓ There are several technologies for achieving the proper synchronization between sensors: • ISL (Inter-Satellite Link). • GNSS.

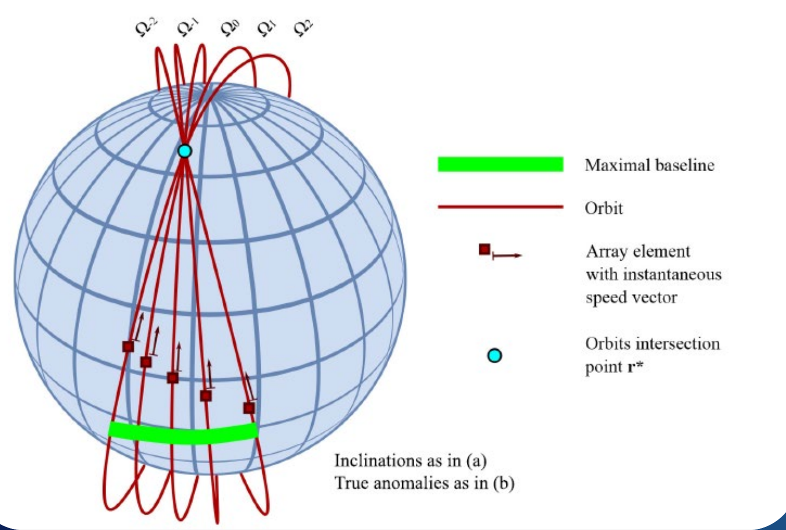
[1] Scuccato, T., Carrer, L., Bovolo, F., & Bruzzone, L. (2018). Compensating Earth Ionosphere Phase Distortion in Spaceborne VHF Radar Sounders for Subsurface Investigations. IEEE Geoscience and Remote Sensing Letters, 15(11), 1672-1676.

Conclusions

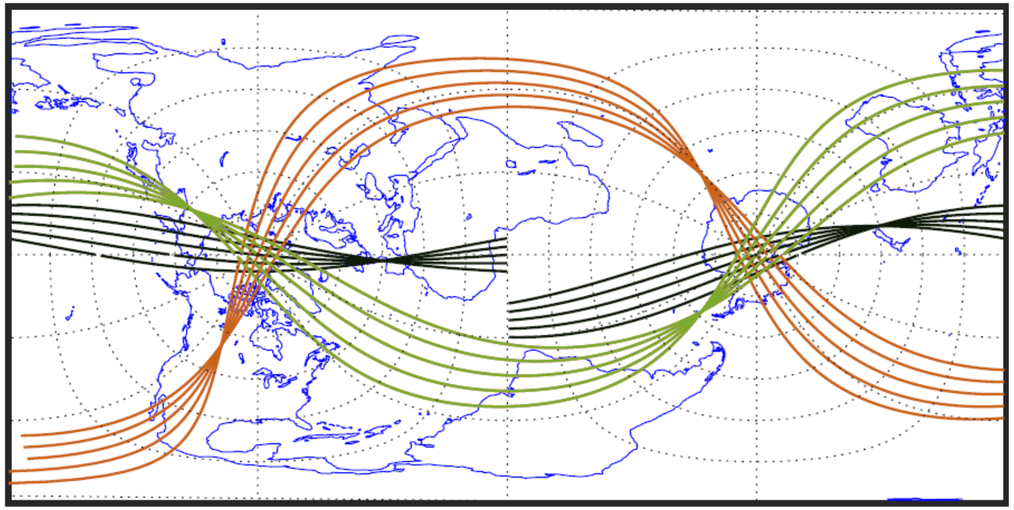
- ✓ STRATUS is a satellite mission for Earth Observation with an instrument on-board capable to directly measure the sub-surface of the Earth.
- ✓ STRATUS exploits a new concept of distributed radar sounder [1] that overcomes the limitations of using a single platform sounder.
- ✓ STRATUS has the unique capability to obtain sub-surface measurements:
  - in many unexplored icy areas (and few arid regions);
  - regularly in time;
  - at a large spatial scale;
  - with homogeneous coverage and quality.
- ✓ STRATUS exploits the huge heritage of both planetary radar sounders and airborne systems.

[1] Carrer, L., Gerekos, C., Bovolo, F., Bruzzone, L. (2019). Distributed Radar Sounder: A Novel Concept for Subsurface Investigations Using Sensors in Formation Flight. *IEEE Transactions on Geoscience and Remote Sensing*, *57*(12), 9791-9809.

STRATUS: Orbit Design



Schematic of the array configuration.
The sensors are in a pendulum configuration (i.e. sail) to avoid collision at the nodes.



Distributed radar sounder ground track for about one orbital period on the 1st orbit (black), the 50th orbit (red), and the 100th orbit (green).
For visualization purposes, actual distancing between sensors is greatly exaggerated.