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TAKING THE PULSE
OF OUR PLANET FROM SPACE

The HydroGNSS Scout science goals

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and the HydroGNSS Science Team

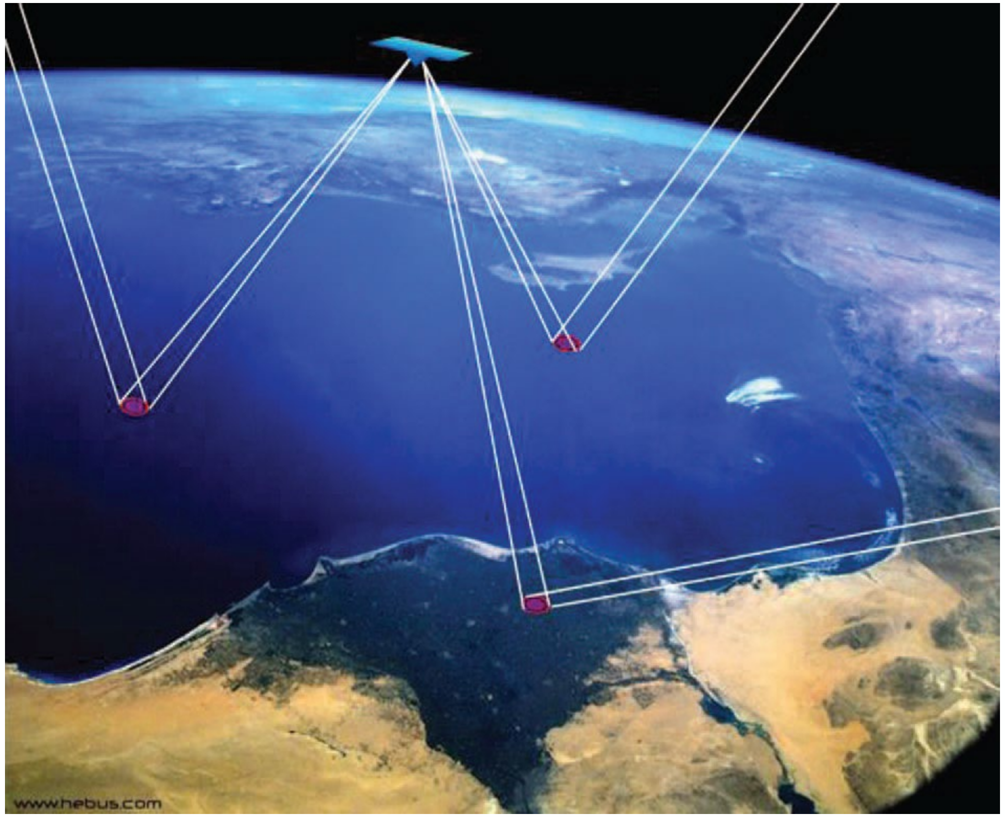
25 May 2022

Content

- GNSS-R concept
- HydroGNSS scientific team
- HydroGNSS objectives
- The HydroGNSS End To end Simulator
- Scientific Readness Level assessment

GNSS Reflectometry Concept

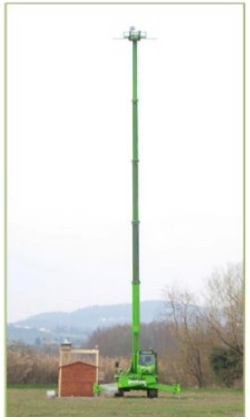
Surface reflections of Global Navigation Satellite Systems signals, including GPS and Galileo, are collected from low Earth orbit



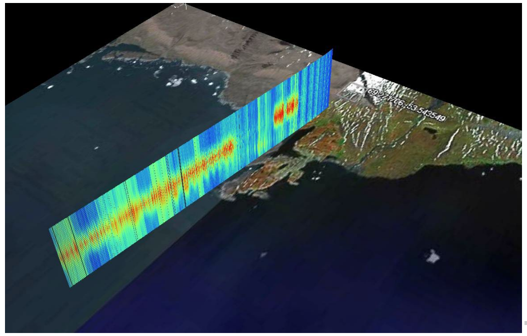
- >100 sources of L-Band signals in orbit
- Forward specular reflection i.e. bistatic radar
- European-developed technology:
  - UK DMC (2004)
  - UK TechDemoSAT-1 (TDS-1) (2014)
  - NASA 8-sat CYGNSS constellation (2017)
- GNSS-R ocean wind and wave applications established
- Cryosphere applications shown with TDS-1
- Ocean altimetry promising (interferometric, grazing obs)

20 Years of Land Sensing with GNSS-R

- GNSS-R for land applications work dates back to 2000
- Ground based receivers used to retrieve soil moisture and snow depth
- 2008+ Experiments demonstrated the sensitivity to moisture, vegetation & ice
- 2014+ TDS-1 and CYGNSS stimulated land applications from space
- Sensitivity shown to permittivity (water content) and attenuation (biomass)



LEiMON: Land Monitoring with Navigation Signals (Starlab et al.)

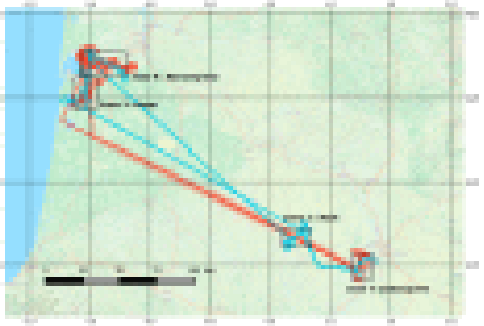


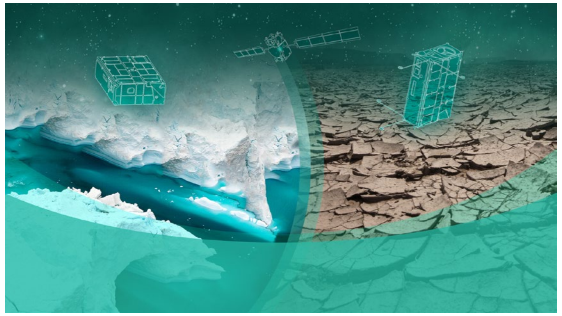
GOLD_RTR MINING (IEEC)

GRASS: GNSS Reflectometry Analysis for biomaSS monitoring (IFAc et al.)

Potential of Spaceborne GNSS-R for Land Applications (Sapienza et al.)

GLORI campaigns (Cesbio)

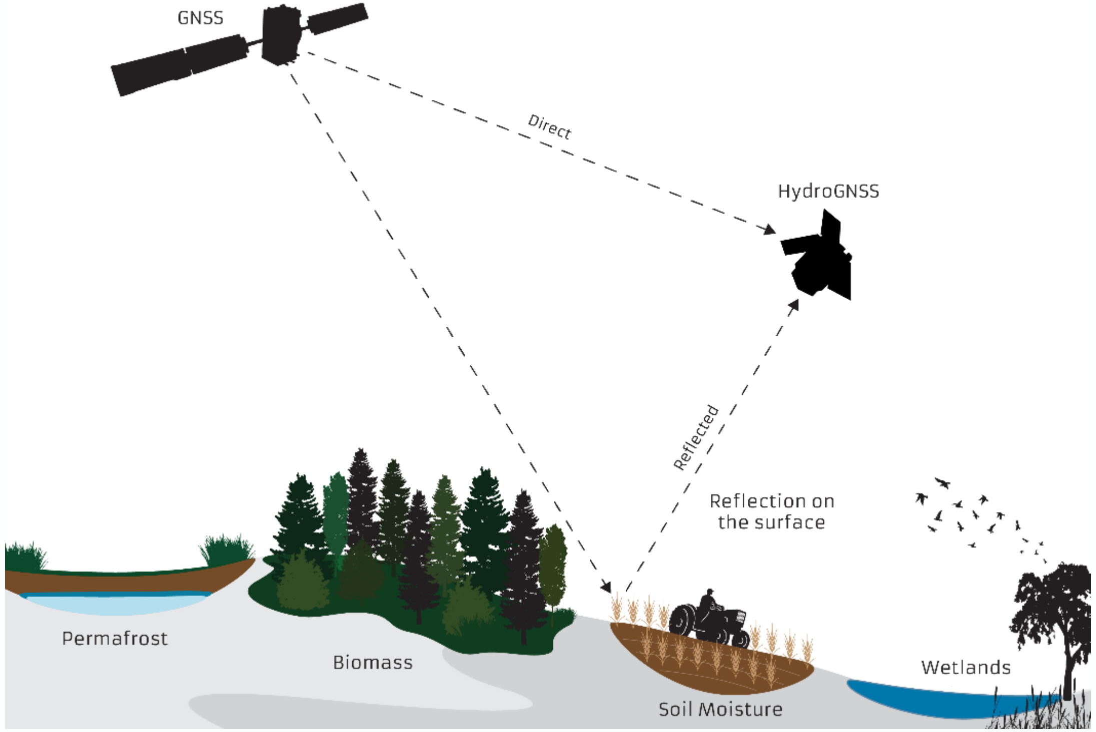




FSSCat CubeSats Copernicus Master Competition (ESA / UPC)

HydroGNSS Objectives

- **4 ECV related parameters -** HydroGNSS delivers products related to hydrological Essential Climate Variables, covering all land every 30 days (with one satellite):
  - **Soil Moisture**
  - **Inundation / Wetlands**
  - **Freeze / Thaw State**
  - **Forest biomass**
- **GNSS-Reflectometry** - exploits **L-band** navigation satellite signals as forward scattering radar sources
  - Proven good resolution, vegetation penetration, targeting permafrost, wetlands and biomass with new methodology
  - **Gap continuity** between SMOS & SMAP missions and Copernicus CIMR and ROSE-L, complements Biomass mission



Science Team

Name	Organisation	Country	Role
Nazzareno Pierdicca	Sapienza	IT	SAG Chair, soil moisture and E2E simulator L1
Estel Cardellach	IEEC	ES	SAG Deputy Chair, wetland/inundation and raw data processing
Martin Unwin	SSTL	UK	Executive Officer, mission PI
Kimmo Rautiainen	FMI	FI	Freeze / Thaw
Giuseppe Foti	NOC	UK	Calibration, ocean products
Leila Guerriero	Tor Vergata	IT	E2E simulator L2
Emanuele Santi	CNR-IFAc	IT	Biomass
Paul Blunt	**NGI**	IT	GNSS technology

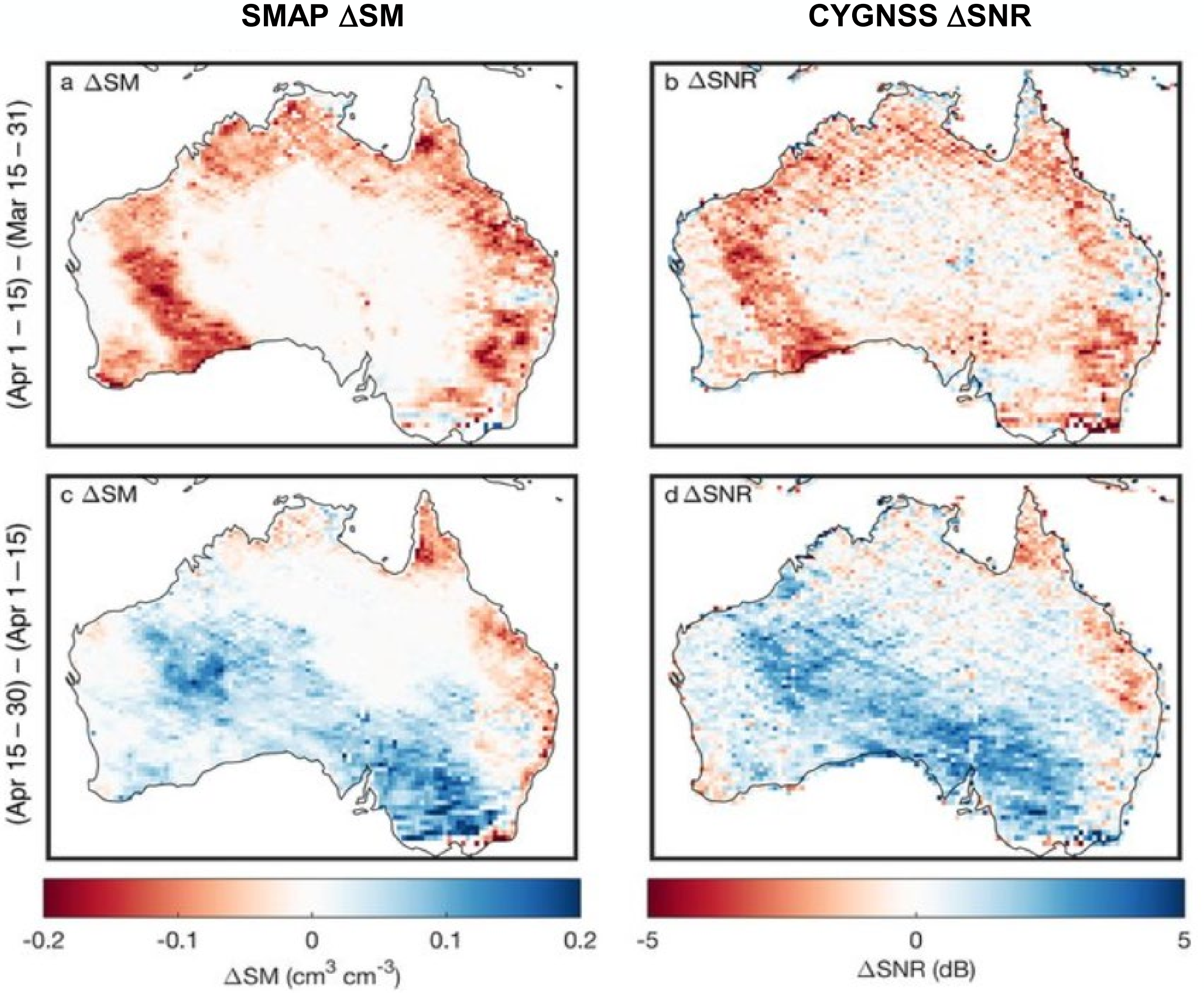
Composition of the Scientific Advisory Group (SAG)

Name	Organisation	Country	Role
Nazzareno Pierdicca	Sapienza	IT	Chair
Estel Cardellach	IEEC	ES	Deputy Chair
Martin Unwin	SSTL	UK	Executive Officer
Maria Paola Clarizia	ESA	Europe (NL)	ESA nominee
Kimmo Rautiainen	FMI	FI	Freeze / Thaw
Wolfgang Wagner	Tech Un. Wien	AT	Soil Moisture
Mehrez Zribi	CESBIO/CNRS	FR	Soil Moisture / Vegetation
Joaquin Munos Sabater	C3S / ECMWF	Europe (UK)	Application for Climate Service
Cinzia Zuffada	NASA JPL	USA	Wetlands

GNSS-R Evidence – Soil Moisture

- Sensitivity to soil permittivity comparable to monostatic radar
  - ~**1.5 dB** for 10% soil moisture
- Confounidn effects from roughness and vegetation attenuation
- Potential resolution of **2-7 km**18]
  - When signal becomes coherent
  - Otherwise ~ 25 km
- GNSS-R soil moisture product at low latitudes developed from CyGNSS
  - Now need higher latitude coverage
- Dual polarisation will help detangle moisture and roughness effects

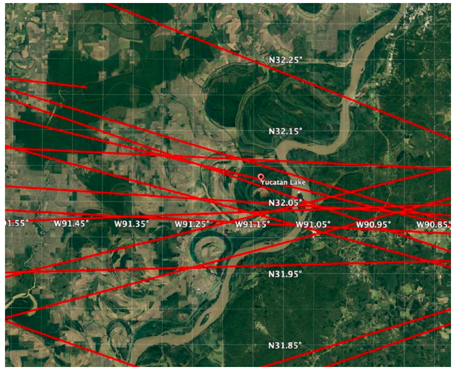
GNSS-R SNR vs SMAP soil moisture changes [Ref C. Chew]



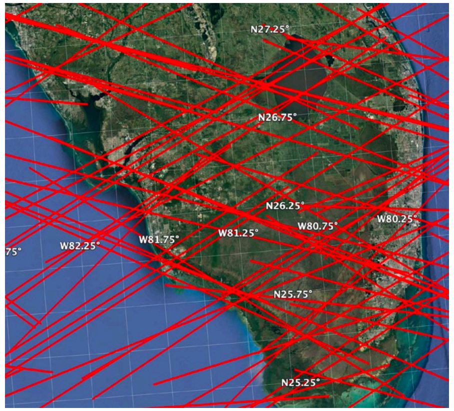
GNSS-R Evidence – Inundation / Wetlands

- GNSS-R bistatic forward scattering stronger over flat, high reflectivity wetlands
- GNSS (L-band) signals can penetrate thick vegetation
  - Uniquely senses water underneath jungle canopies
- Proven concept from spaceborne GNSS-R data (TDS-1, CYGNSS)
- With proposed coherent channel, increased resolution and may allow:
  - Water detection with weaker signals
  - River width and lake altimetry measurements

Yucatan Lake



Everglades

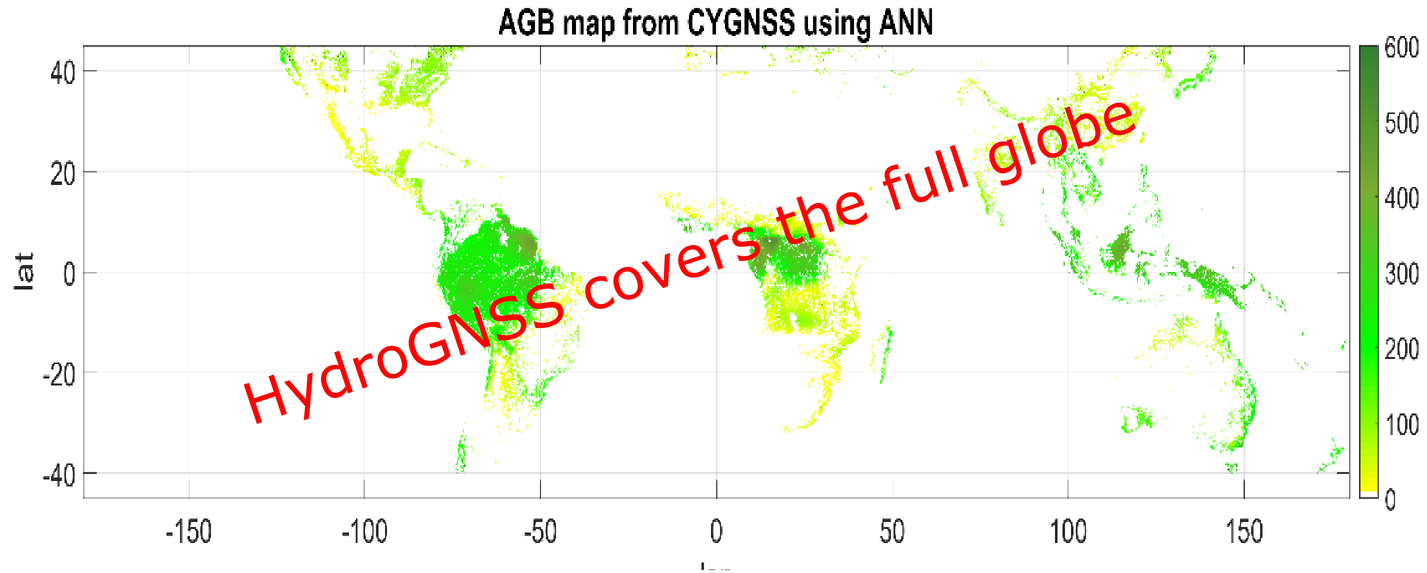


Amazon

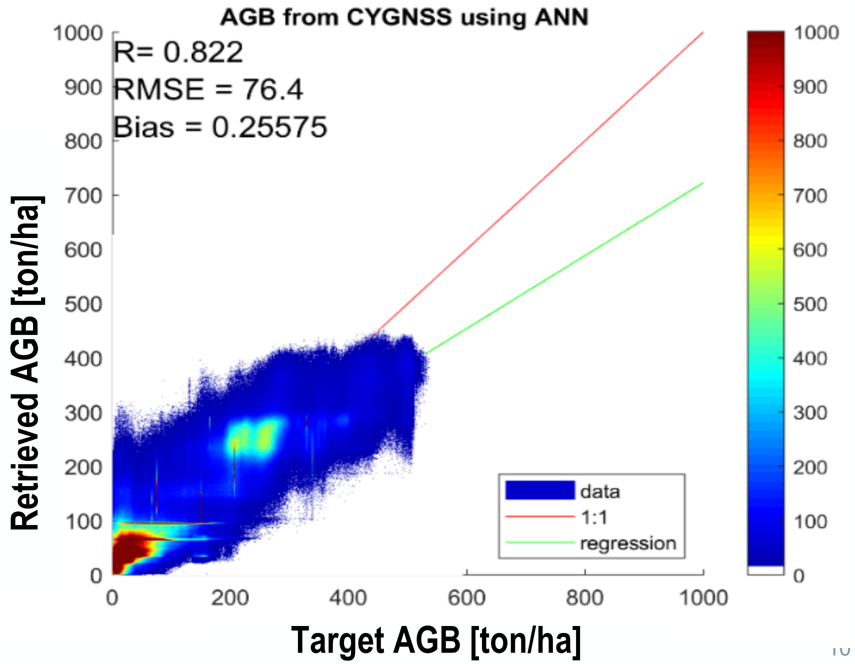
CyGNSS tracks over candidate HydrpGNSS validation sites (Ref. IEEC)

GNSS-R Evidence – Forest Biomass

- Vegetation attenuates soil specular reflection due to absorption and scattering [17]
  - Sensitivity of signal wrt biomass (AGB) does not saturate as for L-band backscatter
- Long coherent integration highlights that dependence as it reduce diffuse scattering [29]
- Dual polarisation will help discimination of coherent term



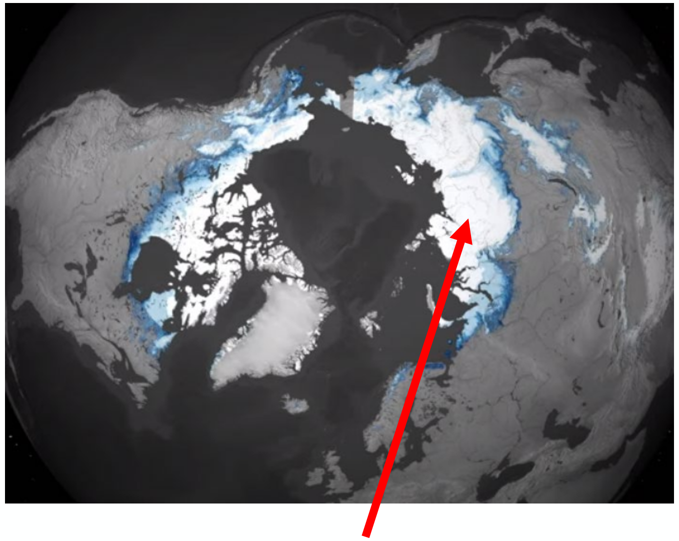
HydroGNSS covers the full globe



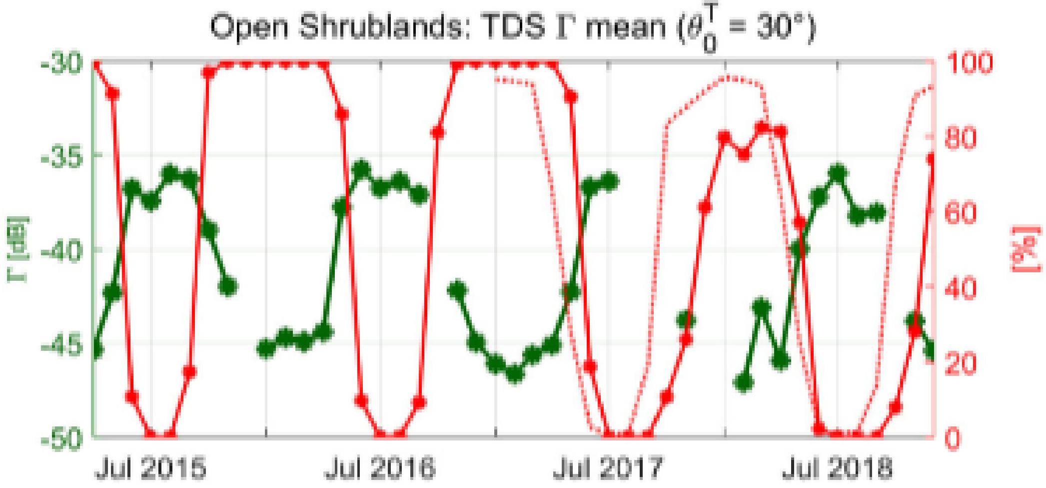
CYGNSS GNSS-R ANN derived Above Ground Biomass (AGB) compared to pan-tropical map from Avitabile

GNSS-R Evidence – Soil Freeze/Thaw

- Recently demonstrated GNSS-R reflection diminishes in frozen conditions
  - Frozen soil has lower permittivity than thawed soil
  - Unrelated to temperature, c.f. radiometry
- Observed change in reflectivity with F/T matches models
- High similarity between SMAP F/T products, in situ temperatures and GNSS-R (TDS-1) monthly means



[11]



Plot: TDS-1 seasonal reflectivity (green) compared to SMAP F/T product (red) over Siberian permafrost shrublands

Level 2 Requirements

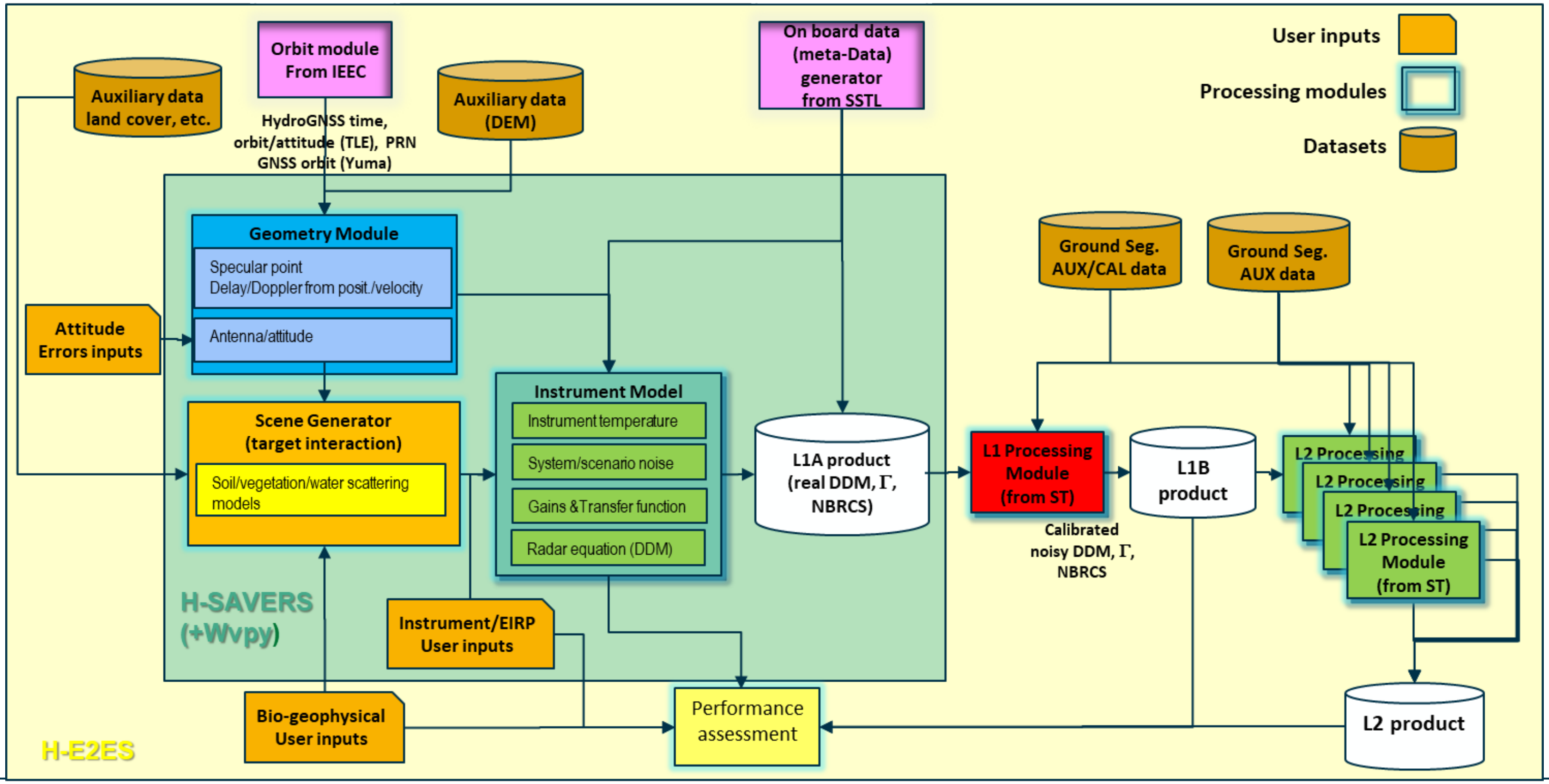
Products	Units	Horizontal resolution target	Uncertainty target	Dependencies
Surface Soil Moisture	m^3/m^3	25 km Requirement 1 km Goal	0.08 m^3/m^3 requirement, 0.04 m^3/m^3 goal	Reflectivity
Surface Inundation	Flag	25 km Requirement 1 km Goal	90% classification accuracy	Reflectivity, Coherence
Freeze/Thaw	Flag	25 km Requirement 1 km Goal	90% classification accuracy	Reflectivity
Above Ground Biomass	t/ha	25 km Requirement 1 km Goal	30% requirement 20% goal or 10 t/ha for <=50 t/ha	Reflectivity
Ocean Wind Speed	m/s	25 km	2 m/s (up to 20 m/s)	NBRCS
Ice Extent	Flag	25 km	90% classification accuracy	NBRCS

- Goal resolution achievable when signal is purely coherent, otherwise <25 km
- Revisit time depends on number of satellites: 30 days with one satellite over a 25 km grid

HydroGNSS E2E Simulator

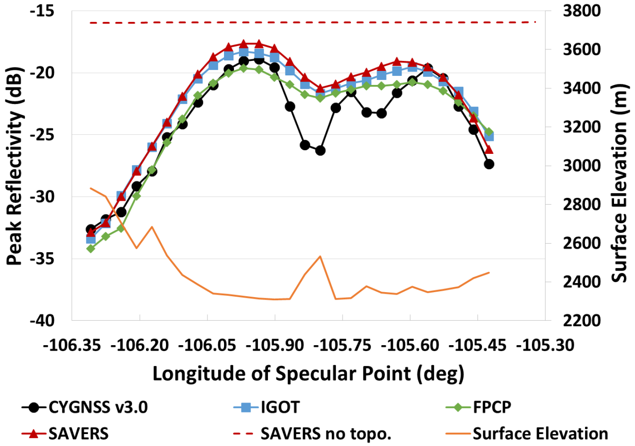
The HydroGNSS End-To-End Simulator (**H-E2ES**) simulates HydroGNSS products at all proc. levels. It integrates:

- SAVERS updated (**H-SAVERS**) to account for other targets and instrument effects (contribution from IEEC Wavpy)
- **L1A to L1B processor** L1PP (3 releases: placeholder at PDR, α- at CDR, β- at GSAR)
- **L1B to L2 processors** L2PP's (3 releases: placeholder at PDR, α- at CDR, β- at GSAR)
- **Input orbit and Metadata** from external modules

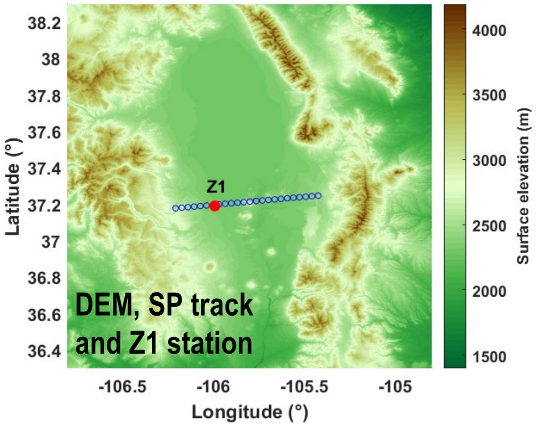


SAVERS validation example

- ✓ San Luis Valley, Colorado: simulations with spatially homogenous soil moisture 4% and soil roughness 1 cm (derived from in-situ data in the frame of CyGNSS modelling Science Team working group)
- ✓ SAVERS, Michigan Univ. and Univ. South California models compared to CyGNSS peak reflectivity track [*Ref. Camp*

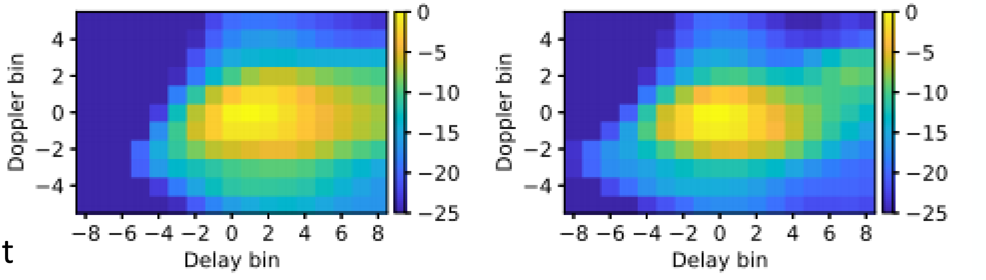


Trackwise simulations of peak (equivalent) reflectivity

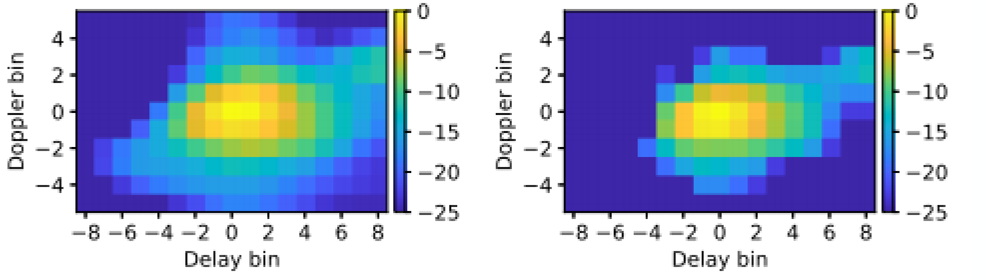


DEM, SP track and Z1 station

Single shot simulation of full DDM

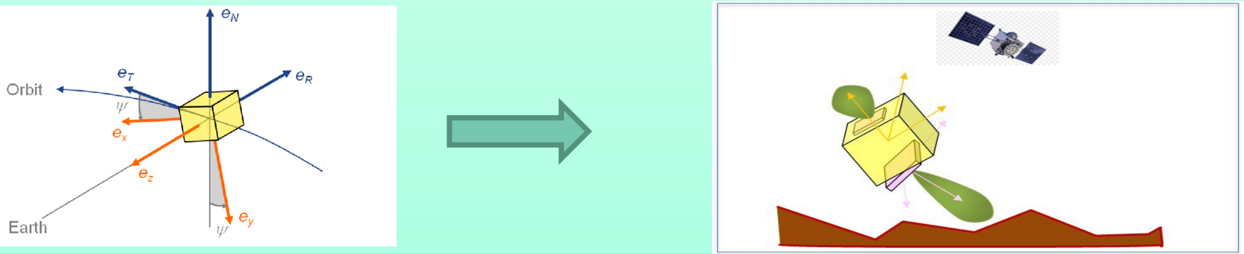


(a) FPCP (b) SAVERS



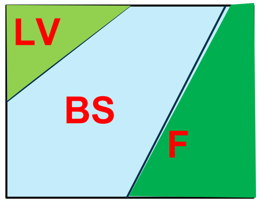
(c) IGOT (d) CYGNSS v3.0

First order system effects

Nadir and zenith Antenna Noise Temperature TA	$P_N^* = P_A + P_{REC} = G_D L_N G k\left[\eta_\ell T_A + (1-\eta_\ell) T_0 + (F-1) T_{RX}\right] B$
Receiver Noise	
Signal fluctuations	$P_r^{Tinc}(x) + N^{Tinc}(x) = P_r[1 + (1-\alpha) n_r^*(x)] + P_N[1 + n_t^*(x)]_{n^*(t) = N(x\,\|\,0,1/\sqrt{N_s}}$
Receiver uncertainties (Gain, Noise Figure, RX physical temperature)	$G'_{LNA} = G_{LNA} \pm \Delta \qquad F' = F \pm \Delta \qquad T'_{LNA} = T_{LNA} \pm \Delta$
Transmitter power and EIRP	*Power*: transmitter ID $\Rightarrow W_T \qquad W'_T = W_T \pm \Delta$; *Pattern*: $G'_T \Leftrightarrow G_T$
Transmit antenna polarisation mismatch	$\sigma_{RR} = 4\pi \left\langle \left\| \frac{1}{\sqrt{1+\cos^2\theta}} \begin{bmatrix} \cos\theta \\ -j \end{bmatrix} \cdot \underline{\underline{\mathbf{S}}} \frac{1}{\sqrt{1+\cos^2\theta}} \begin{bmatrix} \cos\theta \\ -j \end{bmatrix} \right\|^2 \right\rangle \qquad \sigma_{LR} = 4\pi \left\langle \left\| \frac{1}{\sqrt{1+\cos^2\theta}} \begin{bmatrix} \cos\theta \\ j \end{bmatrix} \cdot \underline{\underline{\mathbf{S}}} \frac{1}{\sqrt{1+\cos^2\theta}} \begin{bmatrix} \cos\theta \\ -j \end{bmatrix} \right\|^2 \right\rangle$
Receive antenna polarisation mismatch	
Platform attitude error (uncertainty on illumination and received power)	

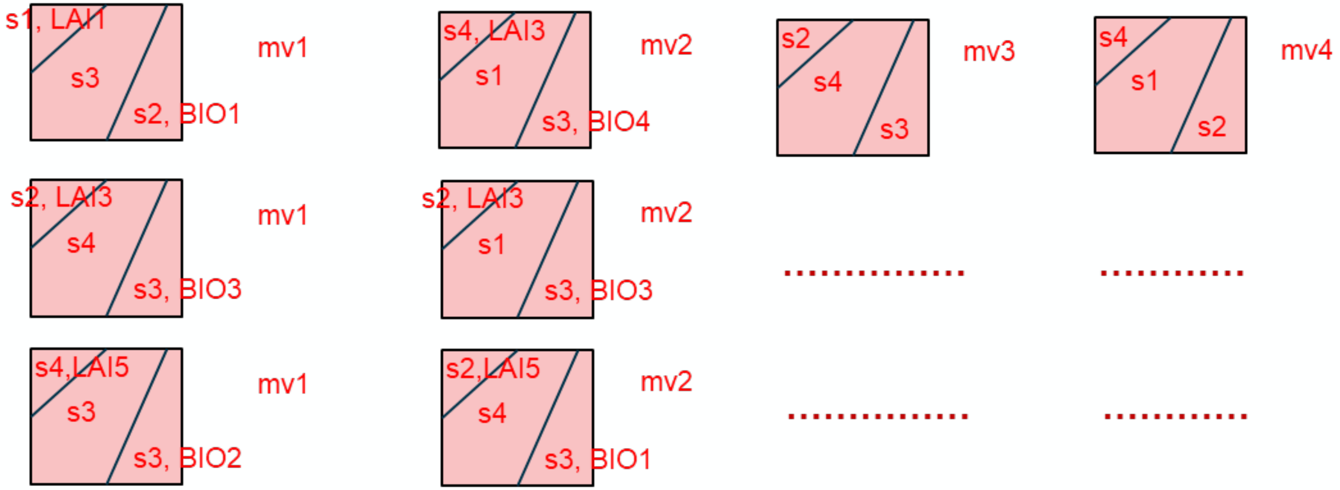
- Errors can be introduced as bias (asses sensitivity) or random (assess overall performances)

Monte Carlo approach of observed scenario



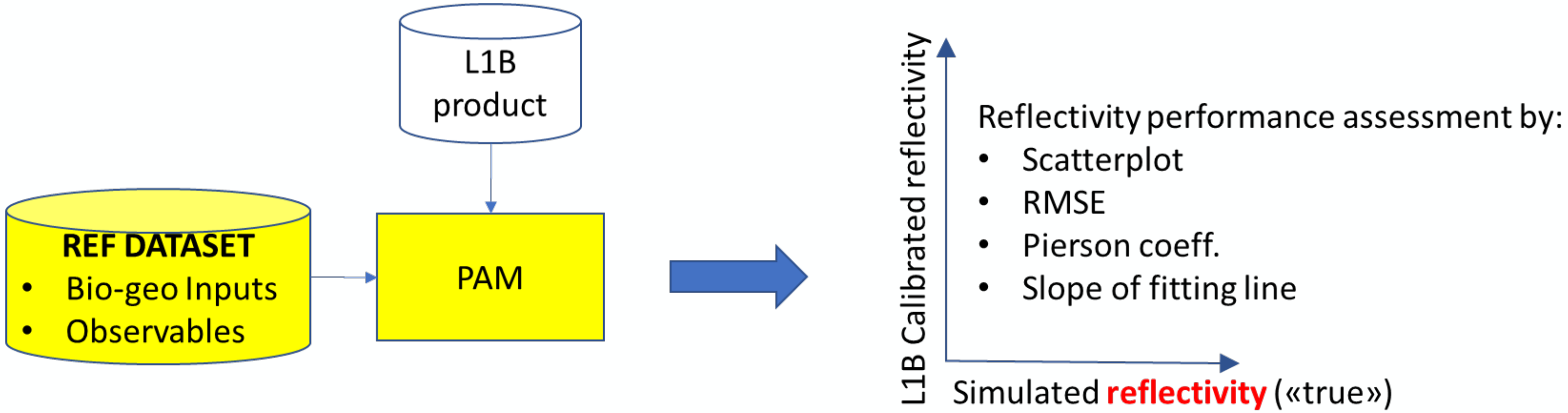
- Example: realistic site (cover, topography) with three classes, Forest (F), Bare Soil (BS), Low Vegetation (LV)
- Assessment of soil moisture performances

- Range of bio/geo values, i.e., moisture (mv), roughness (s), LAI, biomass (BIO) prescribed by the user as min and max.
- Target parameter, i.e. moisture, is incremented systematically within the site
- The other bio/geo parameters are set randomly (uniform distribution) for each land cover
- Example for soil moisture target parameter, 12 scenarios to be simulated



Performance Assessment output

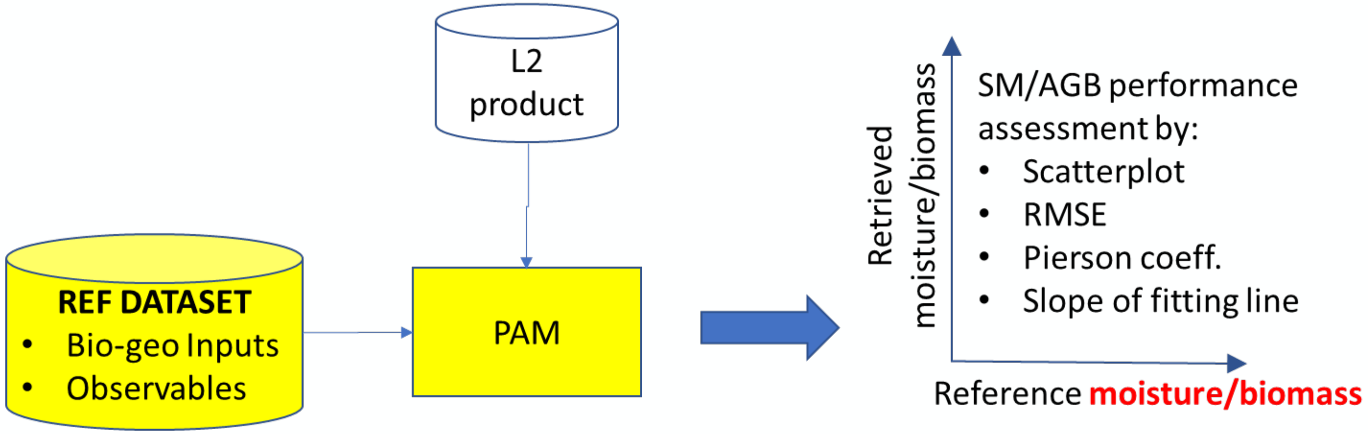
- **Level 1B assessment**



Reflectivity performance assessment by:

- Scatterplot
- RMSE
- Pierson coeff.
- Slope of fitting line

- **Level 2 assessment (moisture, biomass, F/T, inundation)**



SM/AGB performance assessment by:

- Scatterplot
- RMSE
- Pierson coeff.
- Slope of fitting line

	Frozen	Thawed
Frozen		
Thawed		

	Water	Dry
Water		
Dry		

Conclusions

- HydroGNSS targets bio-geophysical parameters related to ECV's pertaining to land (soil moisture, wetland/inundation, forest biomass, freeze/thaw state)
- It exploits GNSS Reflectometry technique measuring L-band reflections from GNSS signals of opportunities
- Evidences of GNSS-R potentiality and complementarity over land are consolidated
- An End To End Simulator is in place to demonstrate SRL 5 taking into account system errors and effects of confounding bio-geophysical parameters

Thank you for your attention