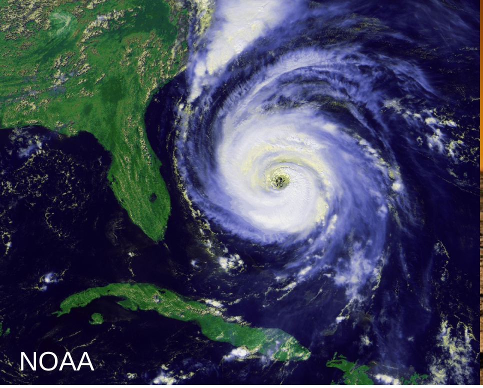
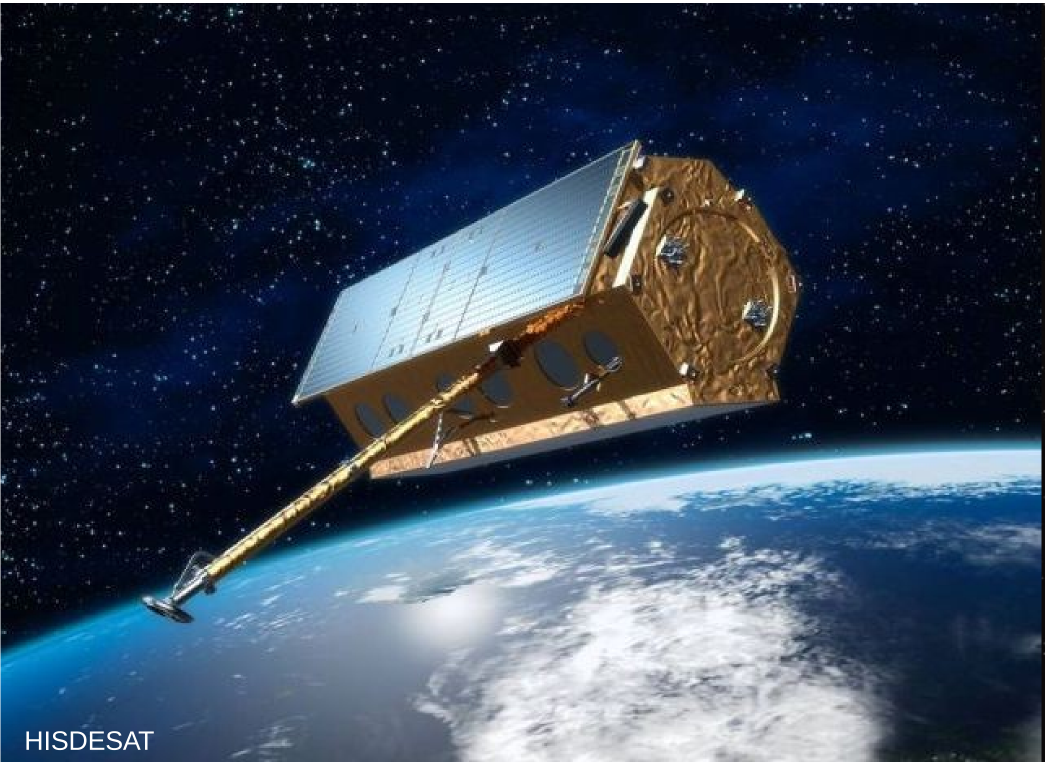
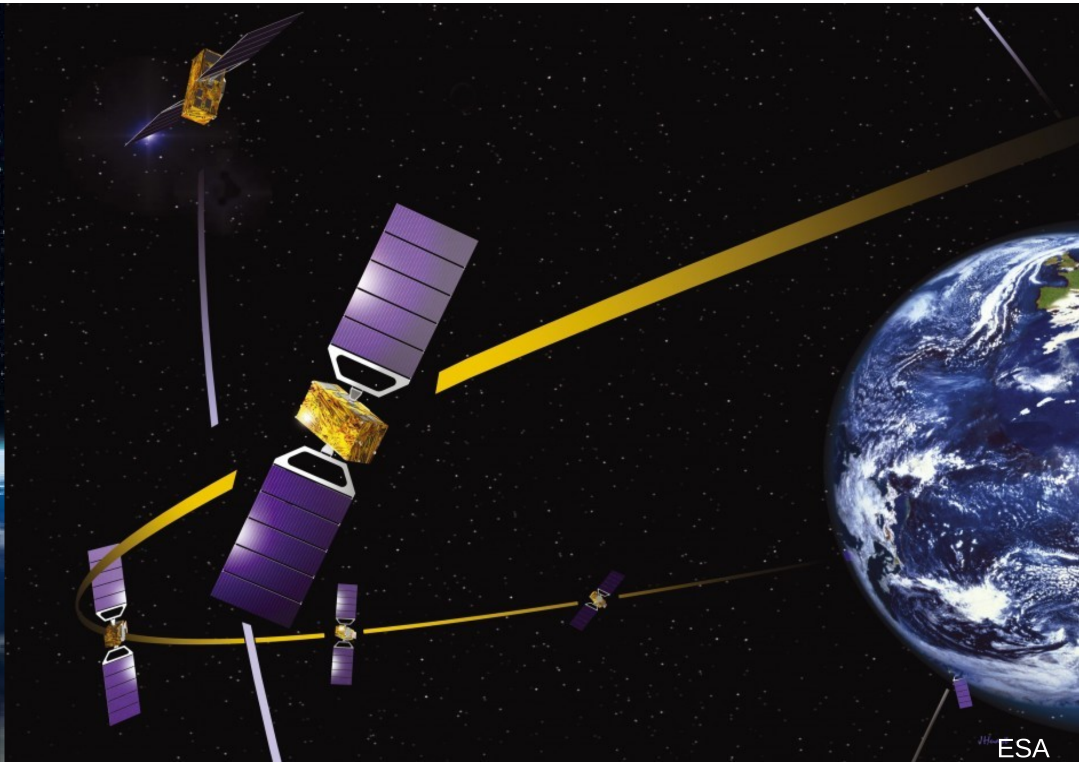


Review of GNSS as sources of opportunity for Earth Observation

Dr. Estel Cardellach (ICE-CSIC/IEEC, Spain)





Overview

- **Motivation:** contribution to a sustained and efficient Earth observation system
- **GNSS contribution to the observing system**
- **GNSS Reflectometry**
- **GNSS Radio-Occultations**

Motivation

Understanding, forecasting, adapting, mitigating and reacting to natural and anthropogenic Earth-system phenomena requires a challenging **Earth observation** approach. It should

- run continuously and in the long term,
- cover the whole Globe,
- with fine spatial resolution,
- sufficient temporal resolution,
- and providing good quality data (precision, accuracy, repeatability.

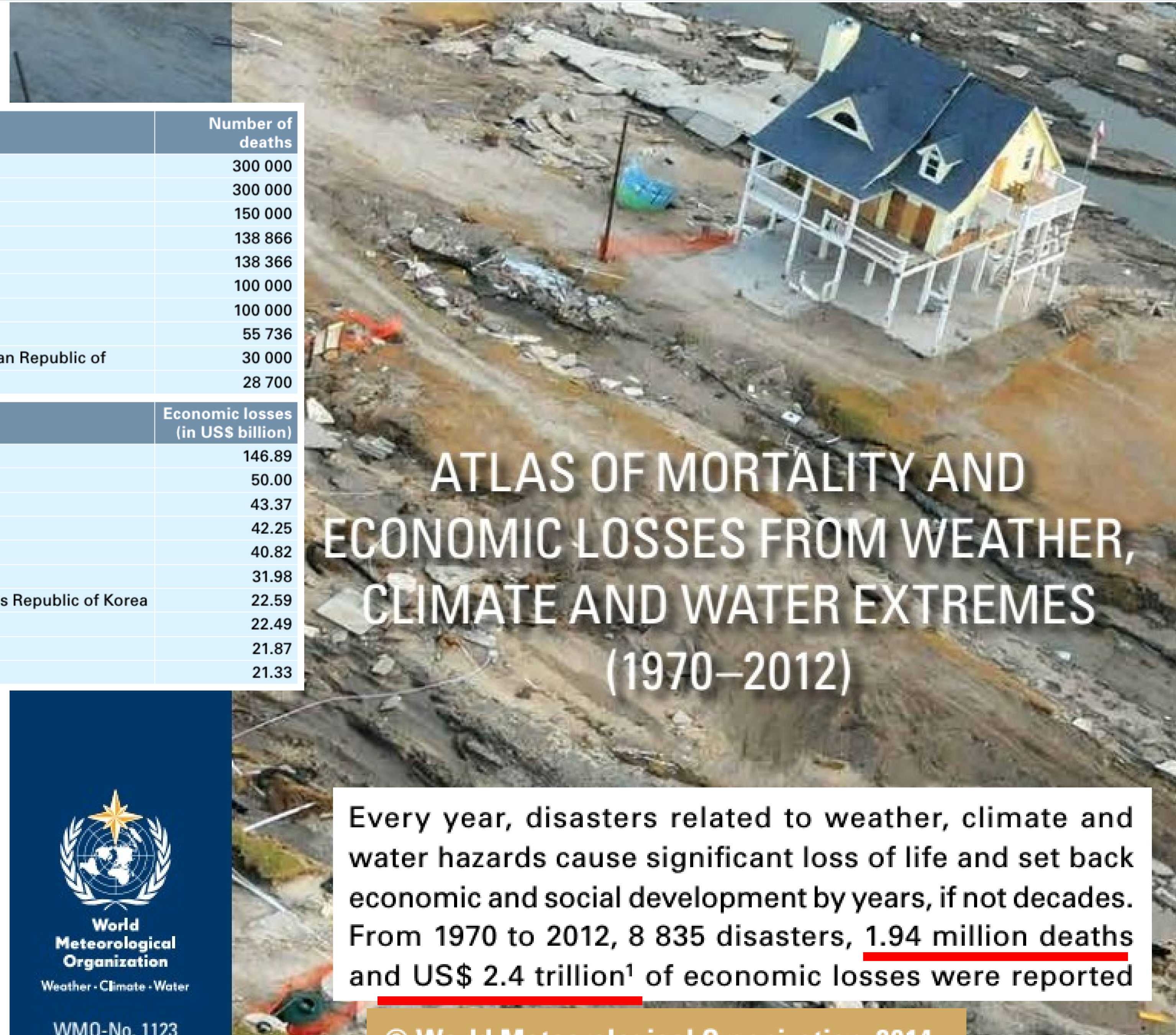
Moreover, it should be **sustainable** and run at **reasonable cost**

Motivation

Example

(a)	Disaster type	Year	Country	Number of deaths
1	Drought	1983	Ethiopia	300 000
2	Storm (TC[a])	1970	Bangladesh	300 000
3	Drought	1984	Sudan	150 000
4	Storm (TC[b])	1991	Bangladesh	138 866
5	Storm (*Nargis*)	2008	Myanmar	138 366
6	Drought	1975	Ethiopia	100 000
7	Drought	1983	Mozambique	100 000
8	Extreme temperature	2010	Russian Federation	55 736
9	Flood	1999	Venezuela, Bolivarian Republic of	30 000
10	Flood	1974	Bangladesh	28 700

(b)	Disaster type	Year	Country	Economic losses (in US$ billion)
1	Storm (*Katrina*)	2005	United States	146.89
2	Storm (*Sandy*)	2012	United States	50.00
3	Storm (*Andrew*)	1992	United States	43.37
4	Flood	1998	China	42.25
5	Flood	2011	Thailand	40.82
6	Storm (*Ike*)	2008	United States	31.98
7	Flood	1995	Democratic People's Republic of Korea	22.59
8	Extreme temperature	2008	China	22.49
9	Storm (*Ivan*)	2004	United States	21.87
10	Drought	1994	China	21.33



Every year, disasters related to weather, climate and water hazards cause significant loss of life and set back economic and social development by years, if not decades. From 1970 to 2012, 8 835 disasters, 1.94 million deaths and US$ 2.4 trillion[1] of economic losses were reported

Motivation

Moreover, scientific challenges:

Some of these phenomena are not fully understood/modeled. A few examples:

- **Extreme precipitación** → difficult to study, to model and to forecast, in the long term climate models diverge.
- **Hurricanes and typhoons** → difficult to study (partly because of the cloudy/rainy walls), no improvement in the accuracy of intensity forecasts in the last 25 years.
- **Atmosphere-Ocean interface** being revised → **sub-mesoscale phenomena**, of relatively small amplitude, size and short in time might have larger role in energy interchange and distribution.
- **Wetlands** play a hydrological function as Climate controlers, and they are under threat.

In these scientific challenges, a key aspect is the lack of appropriate observational data

HOW GNSS CAN CONTRIBUTE TO THE OBSERVATION SYSTEM?

GNSS are signals of opportunity “quasi-permanent” (long-term programmes).

→ A GNSS-based sensor does not need to transmit signal, “passive”, smaller, cheaper

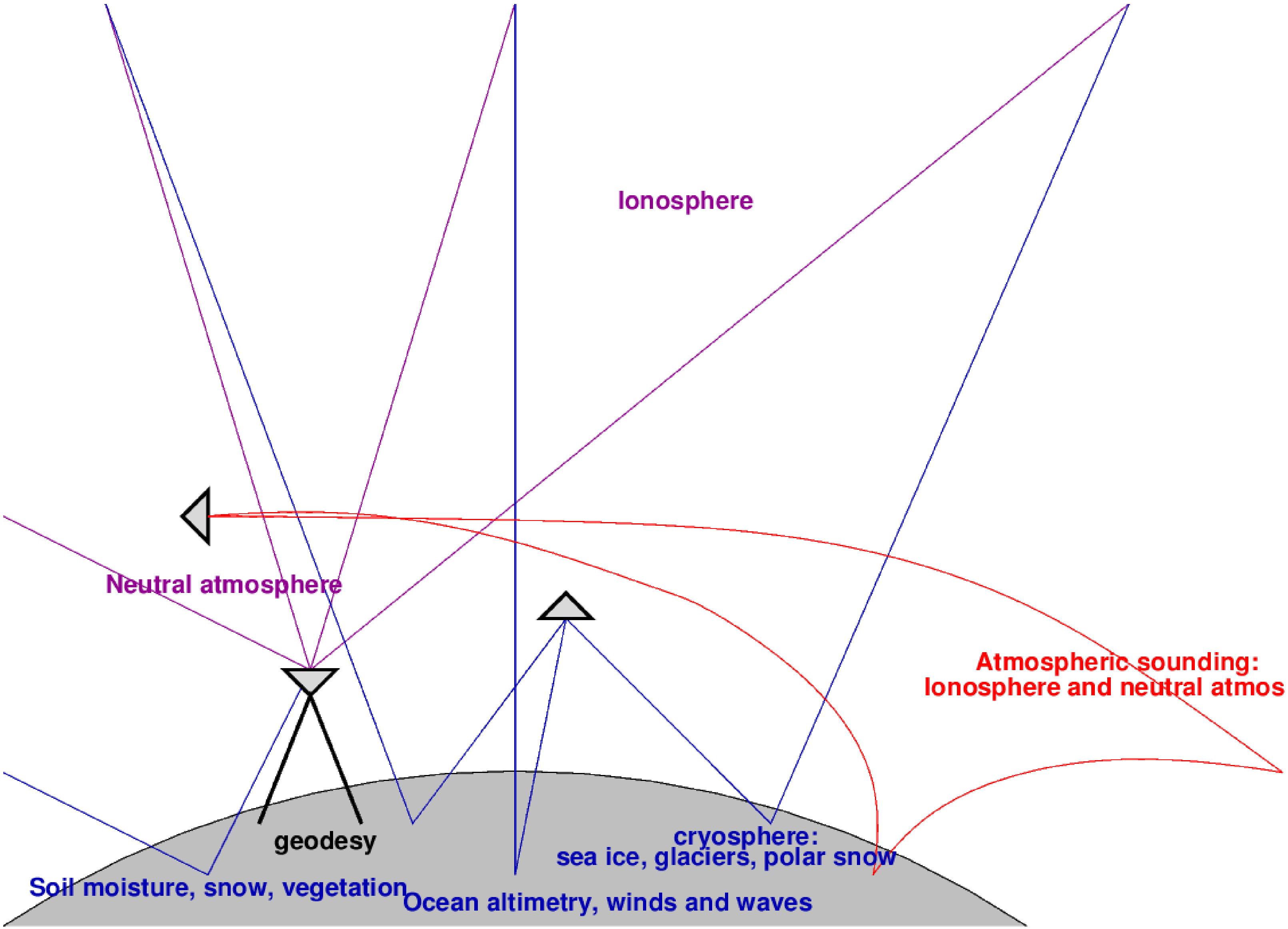
→ this enables small platforms, constellations

→ which increase spatio-temporal sampling at reasonable cost

→ L-band penetrates 'all weather', it might penetrate some vegetation canopies over wetlands

→ low SNR, but for many applications the observable is the precise measurement of time, self-calibrated system.

HOW GNSS CAN CONTRIBUTE TO THE OBSERVATION SYSTEM?



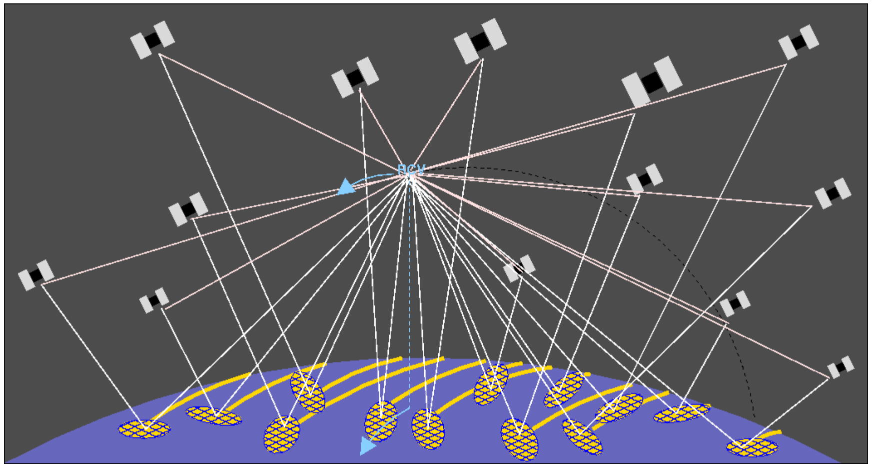
GNSS contribution

Geometries

GNSS-R: Reflectometry

- Signals received after they have bounced off the Earth surface

- Bi-static radar → information about the reflecting surface

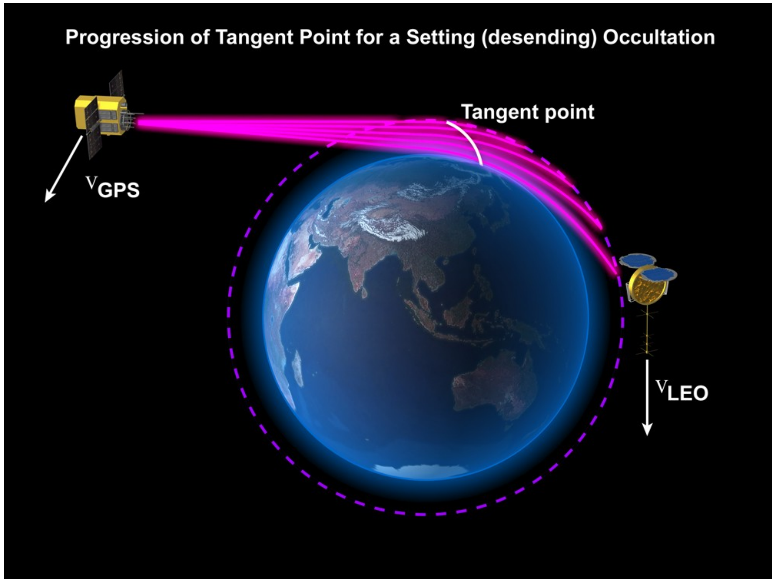


[Shuanggen, Cardellach, Xie, Springer 2014]

GNSS-RO: Radio-Occultation

- Signals received when the source sets below the horizon, behind the Earth

- Refractive effects due to atmospheric gradients → atmospheric sounding



www.cosmic.ucar.edu

GNSS contribution

Geometries

GNSS-R: Reflectometry

- Relatively novel, **not fully mature**

- Before 2014 (UK-TDS1 launch), only a few spaceborne opportunistic data samples were available

- Planned missions:

  + **CYGNSS constellation**/NASA (2016)

  + **3Cat-2**/UPC, Spain (2016)

  + **GEROS-ISS/ESA** (under feasibility studies)

GNSS-RO: Radio-Occultation

- **Mature technique**, heritage from Planetary RO sounding

- 95 GPS/MET, demonstration LEO

- Several other spaceborne missions followed, including **constellations (COSMIC)**

- **Operational RO** aboard EUMETSAT polar satellites

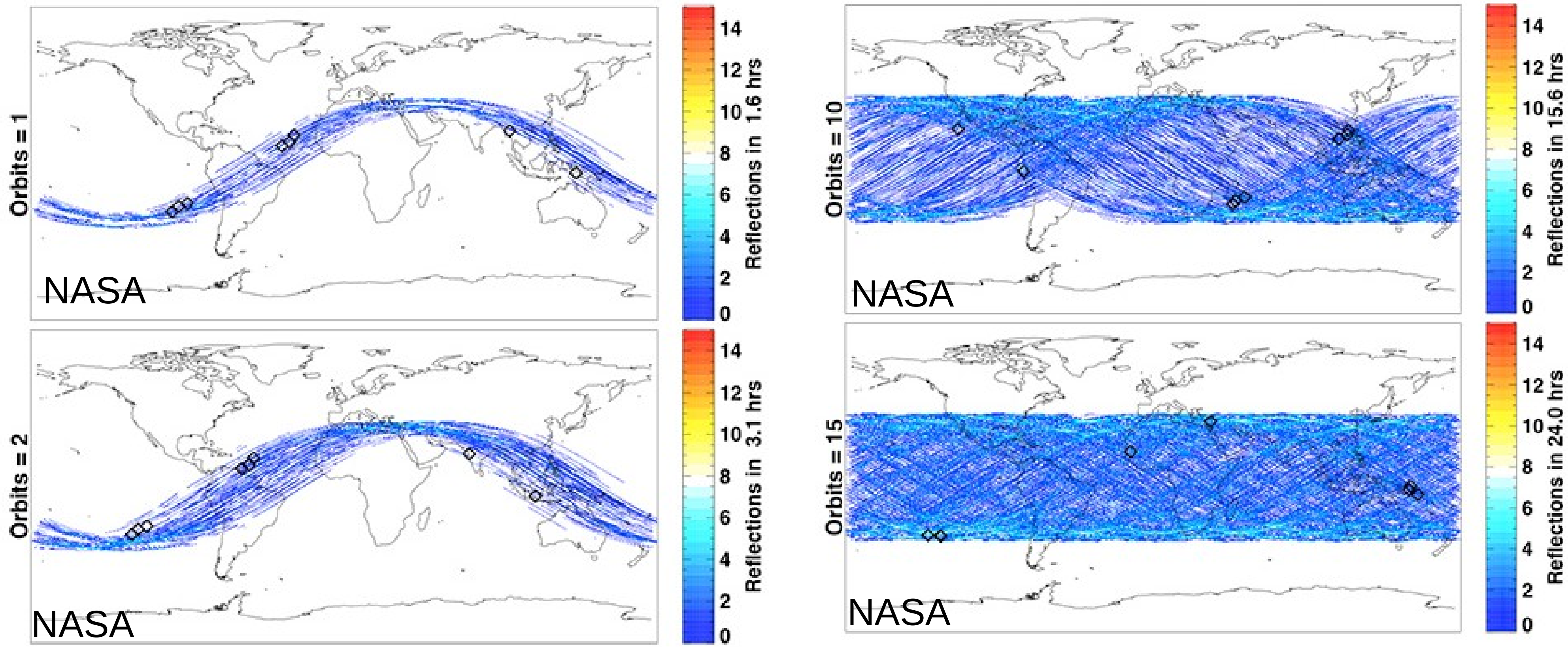
- **COSMIC-2** constellation approved

- New **polarimetric concept** suggested, to be tested aboard PAZ LEO (launch Q1 2016)

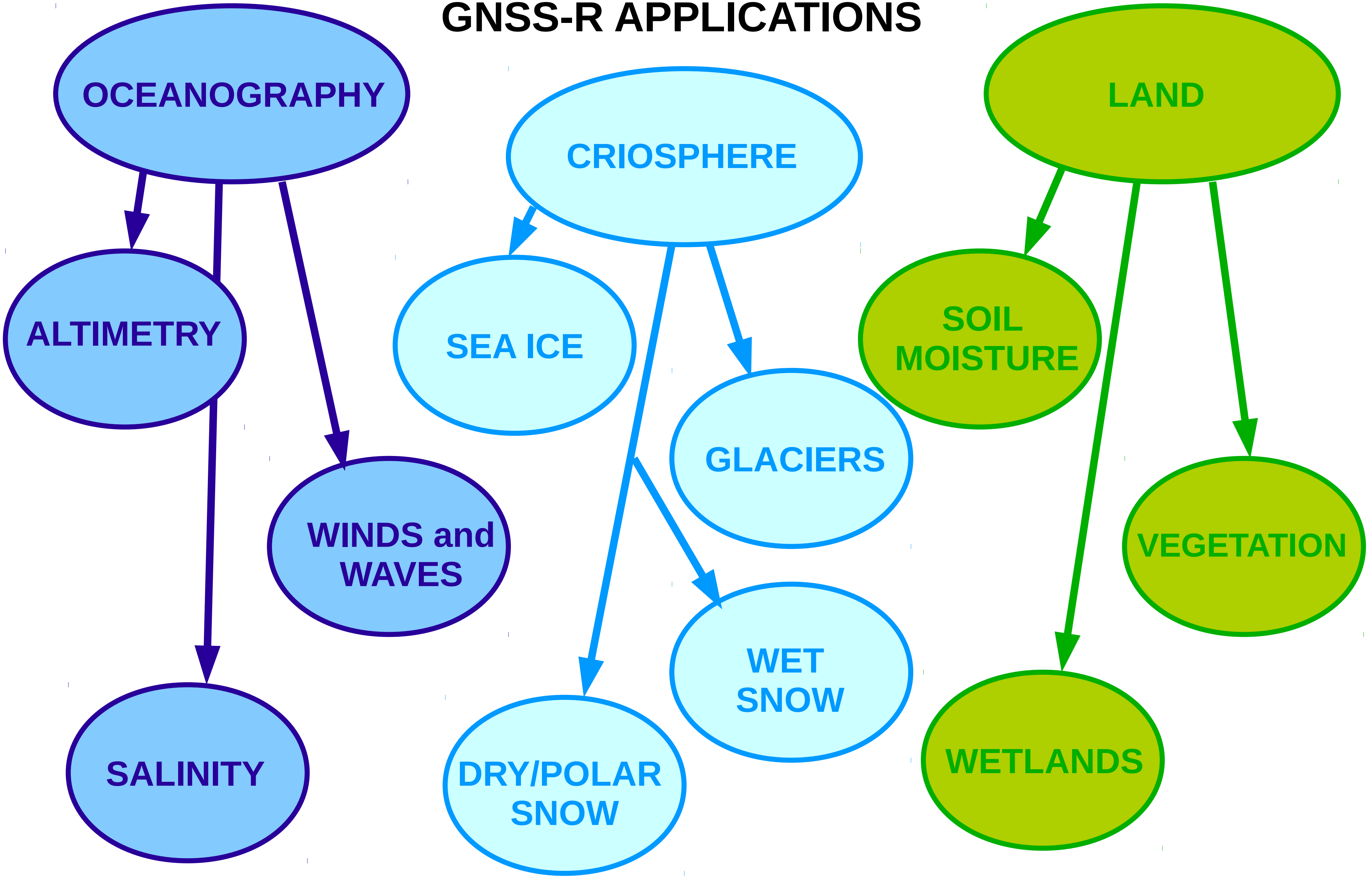
GNSS contribution

Example of sampling

CYGNSS, NASA Venture mission, constellation of 8 GNSS-R microsatellites (launch October 2016)



GNSS-R APPLICATIONS



Altimetry

- Is one of the most challenging GNSS-R applications: **demanding user requirements**.

- Measurement principle: precise delay of the reflected signal.

- Ocean scattering diffuses signal, becomes weak and incoherent, phase cannot be locked. **Group-delay measurement**.

- Wide bandwidth public codes and/or new acquisition techniques required, e.g. iGNSS-R (*interferometric GNSS-R*).

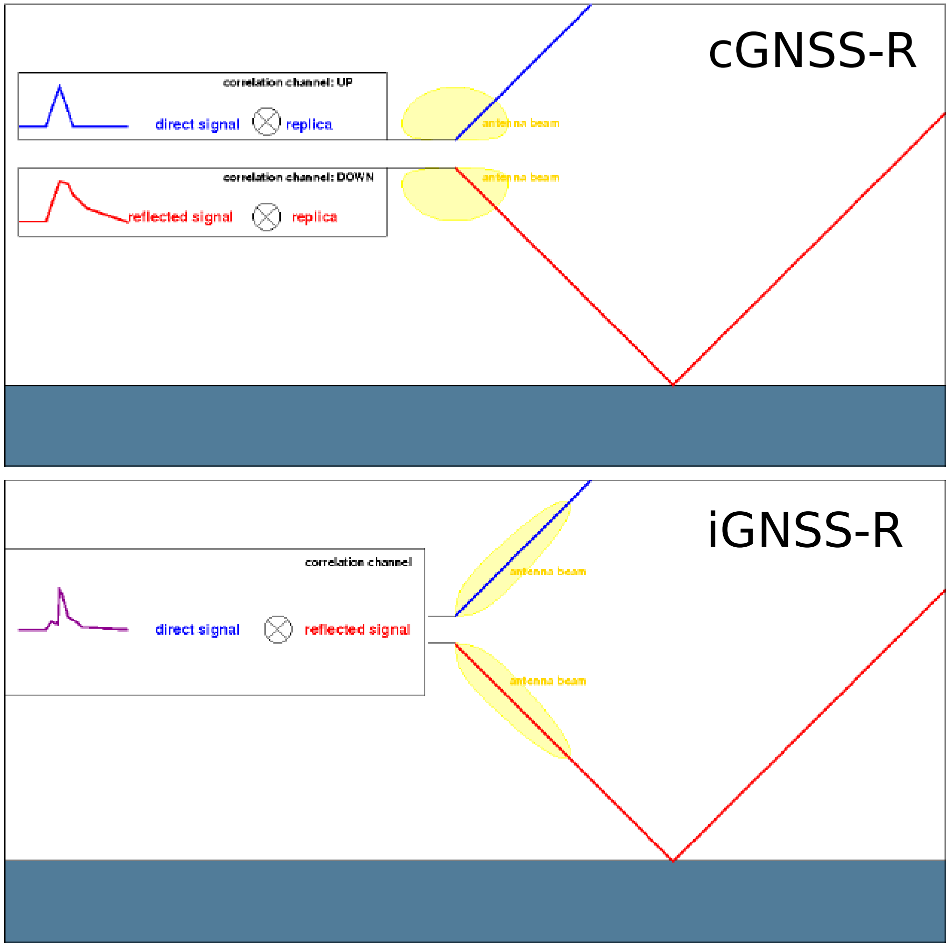
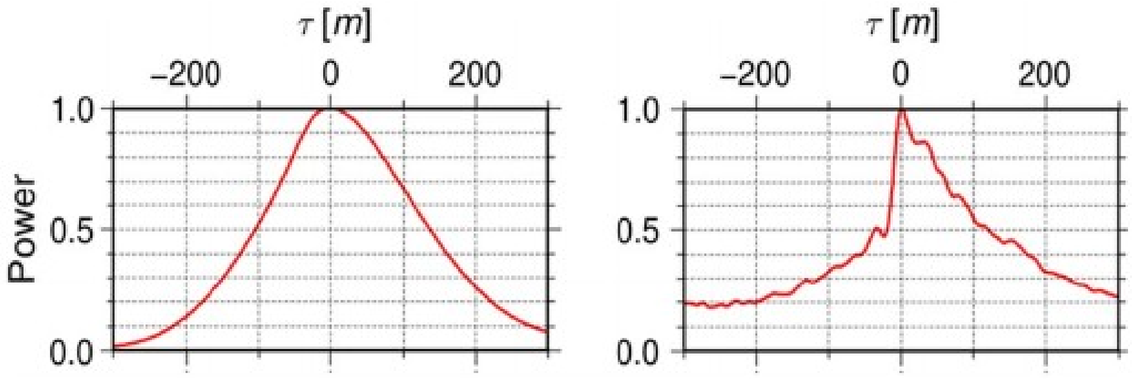
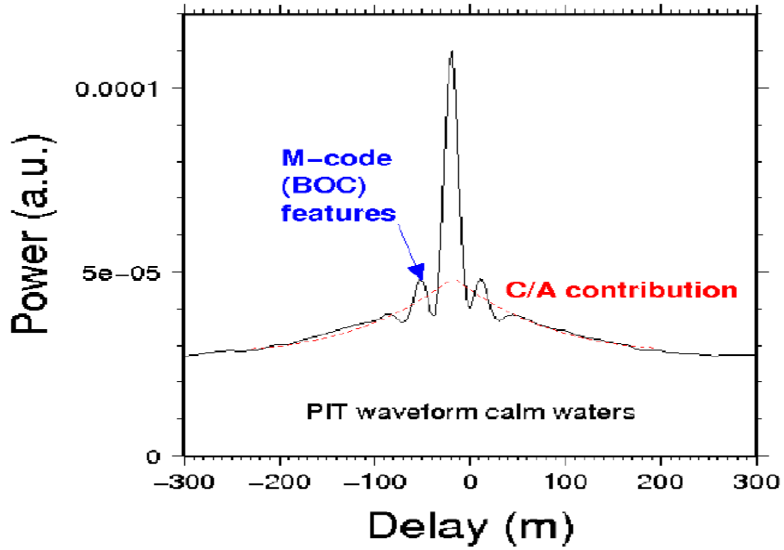


Illustration of conventional clean-replica GNSS-R (top) and interferometric GNSS-R, suggested in [Martin-Neira et al., 2011] (bottom). Figure from [Jin, Cardellach, Xie, 2014]

Altimetry airborne iGNSS-R:

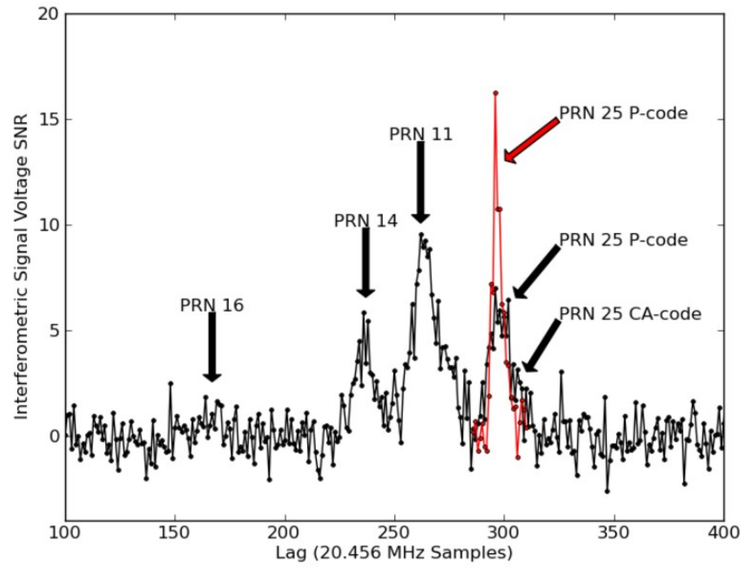


[Cardellach et al., 2013] Waveforms of open waters reflected signals (airborne, 3000 m. altitude), and the altimetric GNSS-R solution. SSH gradients of 2cm/km have been measured.



[Rius et al., 2013] Actual GNSS-R airborne data, 200 m. altitude over calm waters. IGNSS-R acquisition technique.

Hybrid, or reconstructed airborne rGNSS-R:

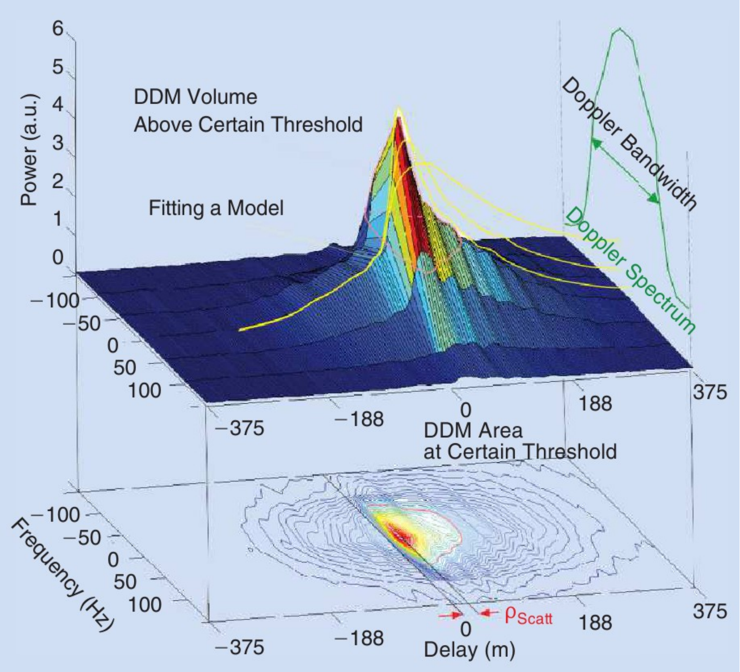


[Lowe et al., 2014] Actual airborne iGNSS-R (black) and rGNSS-R (red). From raw data obtained in 2002 flight over Pacific Ocean.

GNSS-R

Sea surface roughness

[Zavorotny et al., 2014]

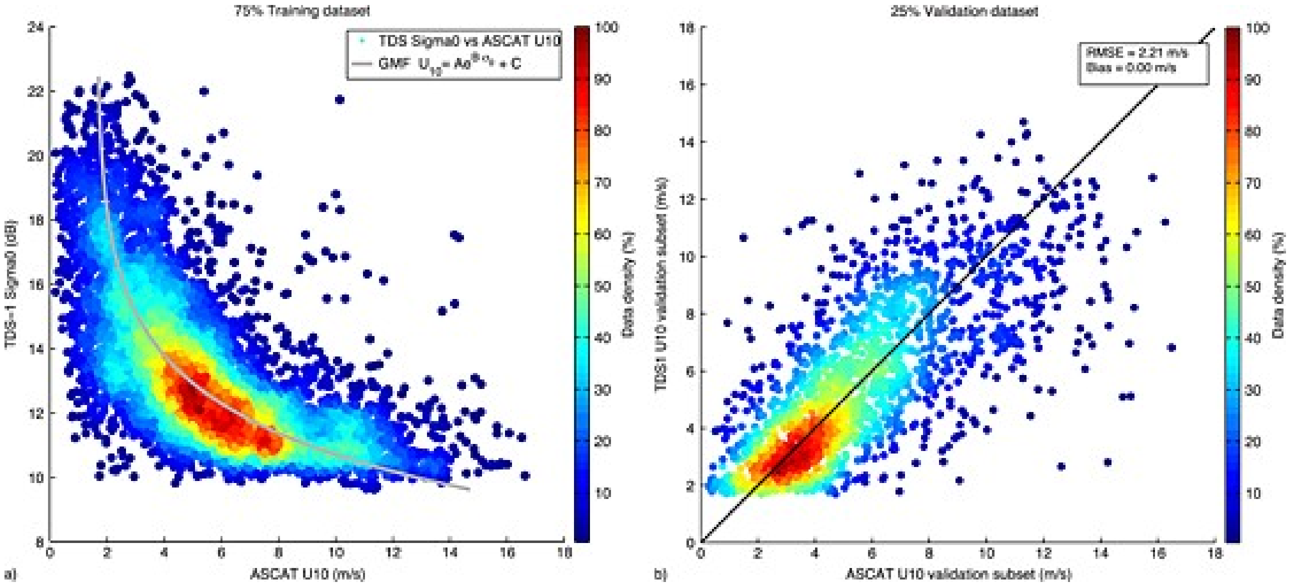


- Simpler application, enables relatively **simple receivers**.

- Measurement principle based on the received **power** and the **deformation** of the waveform.

- The geophysical parameters relate with **wind** and **waves**.

- It works even under thick clouds and heavy rain → suitable for Tropical Cyclons



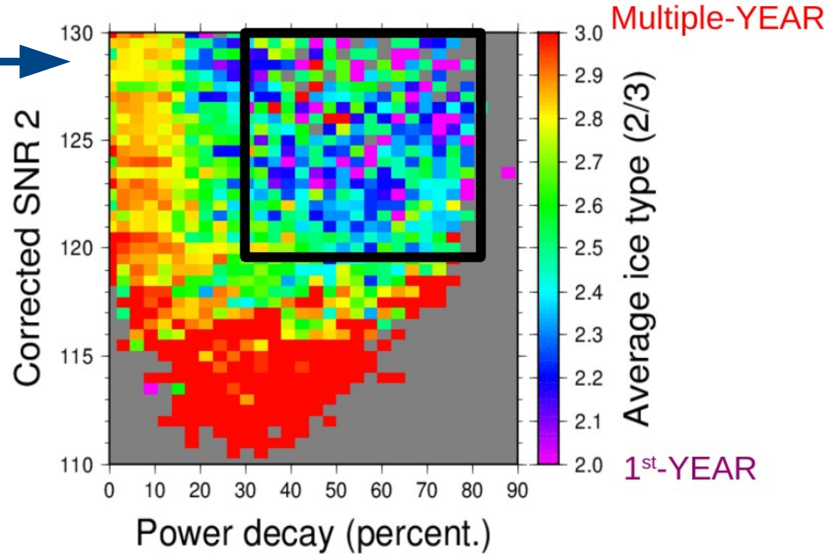
[Foti et al., 2015]

GNSS-R

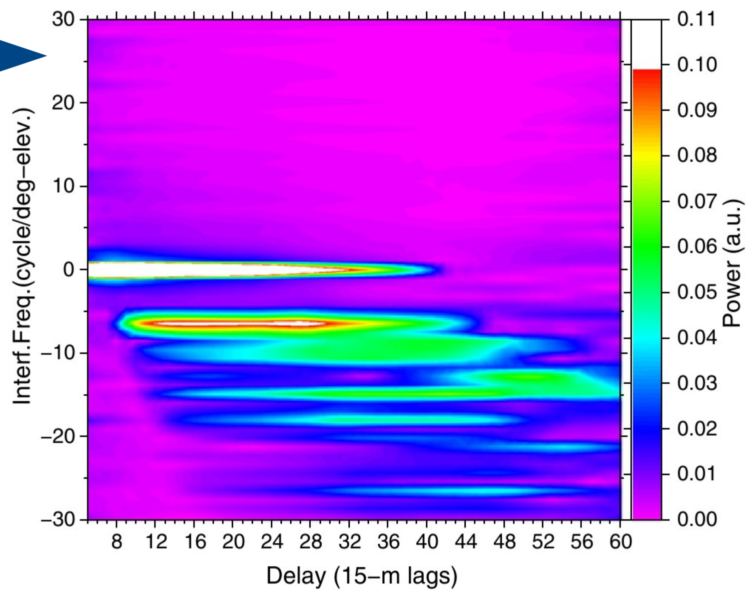
Sea ice and Polar snow

- The UK-TDS1 polar orbiter has captured **hundreds of GNSS-R tracks over the Poles**. Preliminary studies indicate that **sea ice type** from the Arctic can be characterized.

[Cardellach et al., IGARSS 2015]



- Antarctic continental snow is very dry and light, rather **transparent** to L-band. It penetrates a few hundreds of meters. Interferences produced by multiple reflection off internal snow layers can be analyzed to infer **internal structure of the snow**, down to 300 meter depth.



[Cardellach et al., 2012]

GNSS-R

Land applications

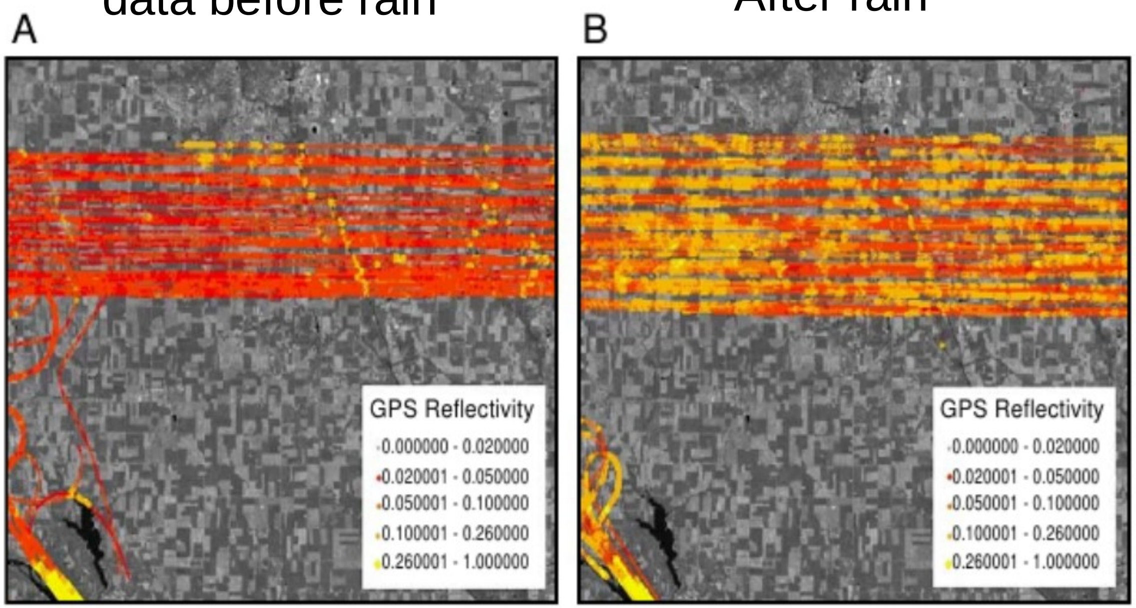
- L-band signals are sensitive to soil moisture (1-2 cm depth), which changes permittivity of the surface.

- This can be measured through received and calibrated power or its SNR.

- Initial results indicate that GNSS-R reflectivity off rice crops are mostly sensitive to the water underneath (wetland water monitoring).

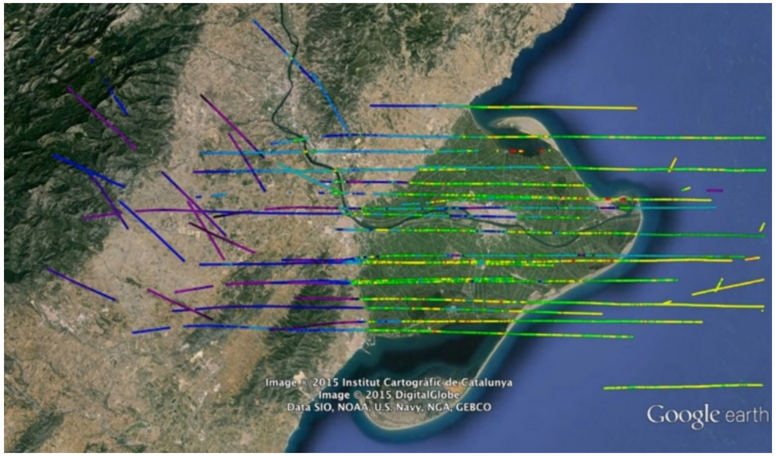
Airborne GNSS-R data before rain

After rain



[Katzberg et al., 2005]

GNSS-R SNR off Ebre Delta rice crops, July 2005.



GNSS-R

GNSS-R missions

- **2005:** UK-DMC (SSTL) switched on a GNSS-R payload. ~50 samples of data, of a few seconds each (Ocean, Land, Sea Ice)

- **2014:** UK-TSD1 (SSTL) launched July 14 in polar orbit. cGNSS-R receiver (C/A code), plenty of data! testbed for CYGNSS

- **10/2016:** planned launch for CYGNSS/NASA, **8 satellites** microsat constellation, low inclination orbit. cGNSS-R C/A code receiver. **FOCUS: Tropical Cyclones**

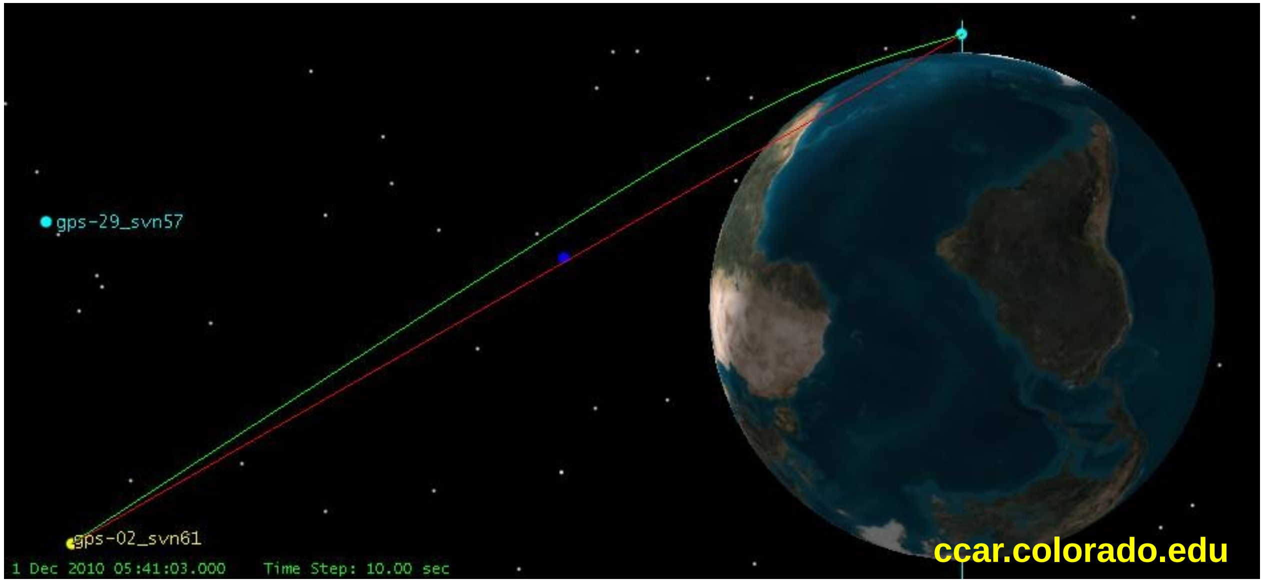
- **2016:** planned launch for ³Cat-2, 6U cubesat, cGNSS-R and rGNSS-R receiver, polar orbit, **2-polarizations**

- **2019:** planned GEROS-ISS/ESA, ISS platform, **iGNSS-R**, in feasibility studies, **FOCUS: Altimetry**

GNSS-RO

MAIN APPLICATION OF THE GNSS-RO

THERMODYNAMIC VERTICAL PROFILING OF THE NEUTRAL ATMOSPHERE



Time, positioning, and velocities of both receiver and transmitter

Measured Doppler effect

Estimated Doppler effect (straight line)

Bended propagation, bending angle α

Time sequence, which is also vertical sequence $\alpha(h)$

Abel transform:

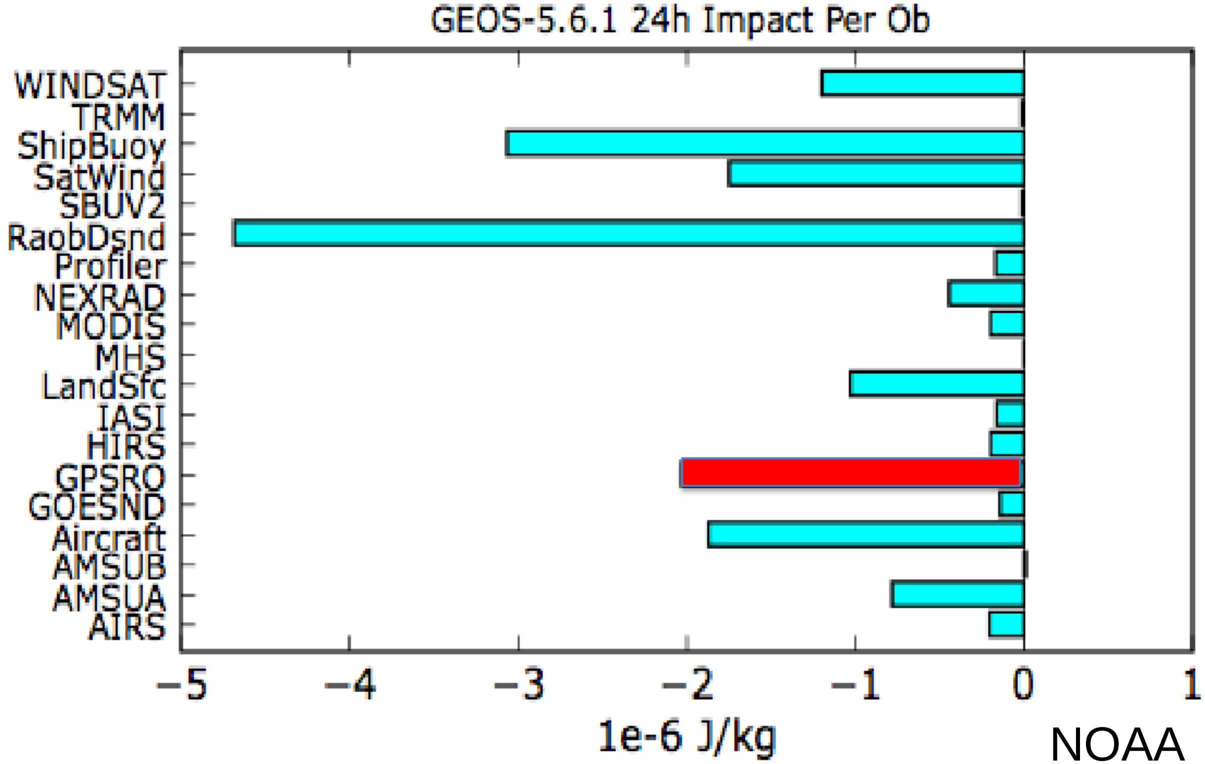
$$n(x) = \exp\left(\frac{1}{\pi}\int_x^{\infty} \frac{\alpha(a)}{(a^2 - x^2)^{1/2}} da\right)$$

n(h) → pressure, temperature, humidity

GNSS-RO

OPERATIONAL USE OF GNSS-RO IN WEATHER FORECAST

- N(h) or α(h) measured by COSMIC and METOP **ARE OPERATIONALLY ASSIMILATED** into numerical weather prediction models (NWPM).
- The impact in reducing the forecast errors has been proven to be very high, the 5th out of 24 (ECMWF), or the 3rd out of 19 when normalized by number of observations (NOAA).

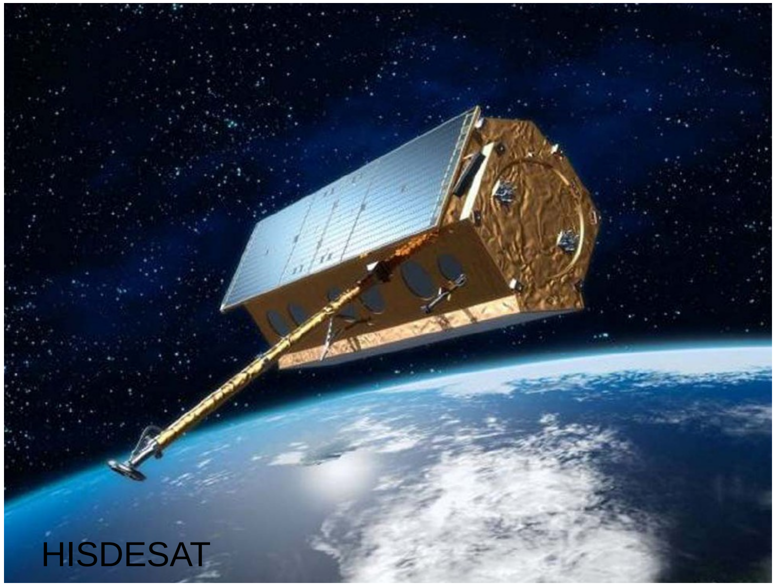


NOAA

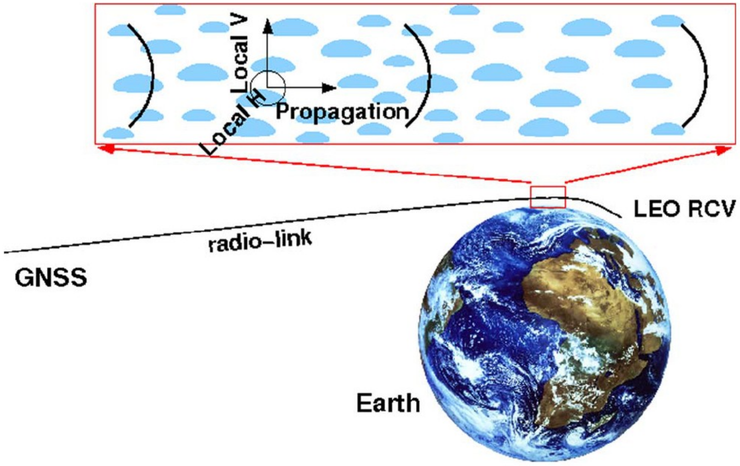
GNSS-RO

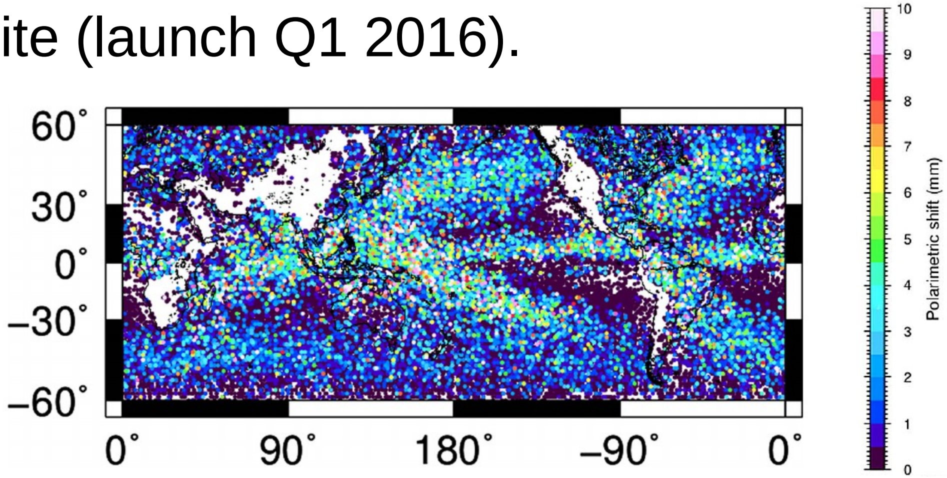
NEW MEASUREMENT CONCEPT:
POLARIMETRIC GNSS-RO:

- Upgrade the receiving system with 2-pol capabilities.
- To measure the phase-shift or delay between received H-pol and V-pol.
- Numerical models, simulation work and a ground-based experiment have shown that **heavy rain and other hydrometeors** induce polarimetric phase-shift of measurable magnitude
- **CONCEPT IMPLEMENTED aboard PAZ** satellite (launch Q1 2016).



[Cardellach et al., 2014]





GNSS signals

In general, GNSS remote sensing would benefit from:

- Higher transmitted power
- Wider bandwidth modulation codes of public access
- Adding a higher band carrier frequency
- Availability to good characterization of transmitters' antenna patterns, including phase and polarimetry

Conclusion

- There is a **need of Earth observation data** to help both understanding some phenomena and long-term monitoring essential variables in a sustained way.

- **GNSS signals can contribute**, enabling low cost, passive, and self-calibrated measurement systems, constellation-like approaches are feasible → increase coverage and time-scale resolution

- GNSS-Reflectometry and GNSS-Radio Occultations are two possible GNSS remote sensing techniques.

- **GNSS-R** offers ocean, cryosphere and land applications, being ocean altimetry a challenging one.

- To improve measurement precision, wider bandwidth codes or novel acquisition techniques (to use full band information) are required: e.g. iGNSS-R

- GNSS-R spaceborne missions recently launched or to be launched soon.

- GNSS-RO is a mature technique for atmospheric sounding, orbiting missions since 1995. New aspects being investigated in GNSS-RO include the interference with reflected signals and polarimetric receiving systems to extend RO applications.

Motivation

Some weaknesses of the current observational system:

- Lack of continuity of scientific spaceborne missions
- Instruments and missions not suited to monitor:
  - Opaque extreme weather phenomena, even at some microwave frequencies (e.g. heavy rain, hurricane inner walls).
  - Similarly, vegetation blocks the remote sensing of water in wetlands.
  - Weak, quick and synoptic signals generated by Tsunamis cannot be resolved (it hinders warning systems).
  - Sub-mesoscale sampling (both in space and time) is not sufficient to properly capture the full life of these events.

GNSS-RO

Novel techniques in GNSS-RO

→ potential use of reflected signals found in GNSS-R?

- ~70% of GNSS-RO over the Oceans present reflected signals
- These present seasonal behavior and respond to climate cycles (El Niño)