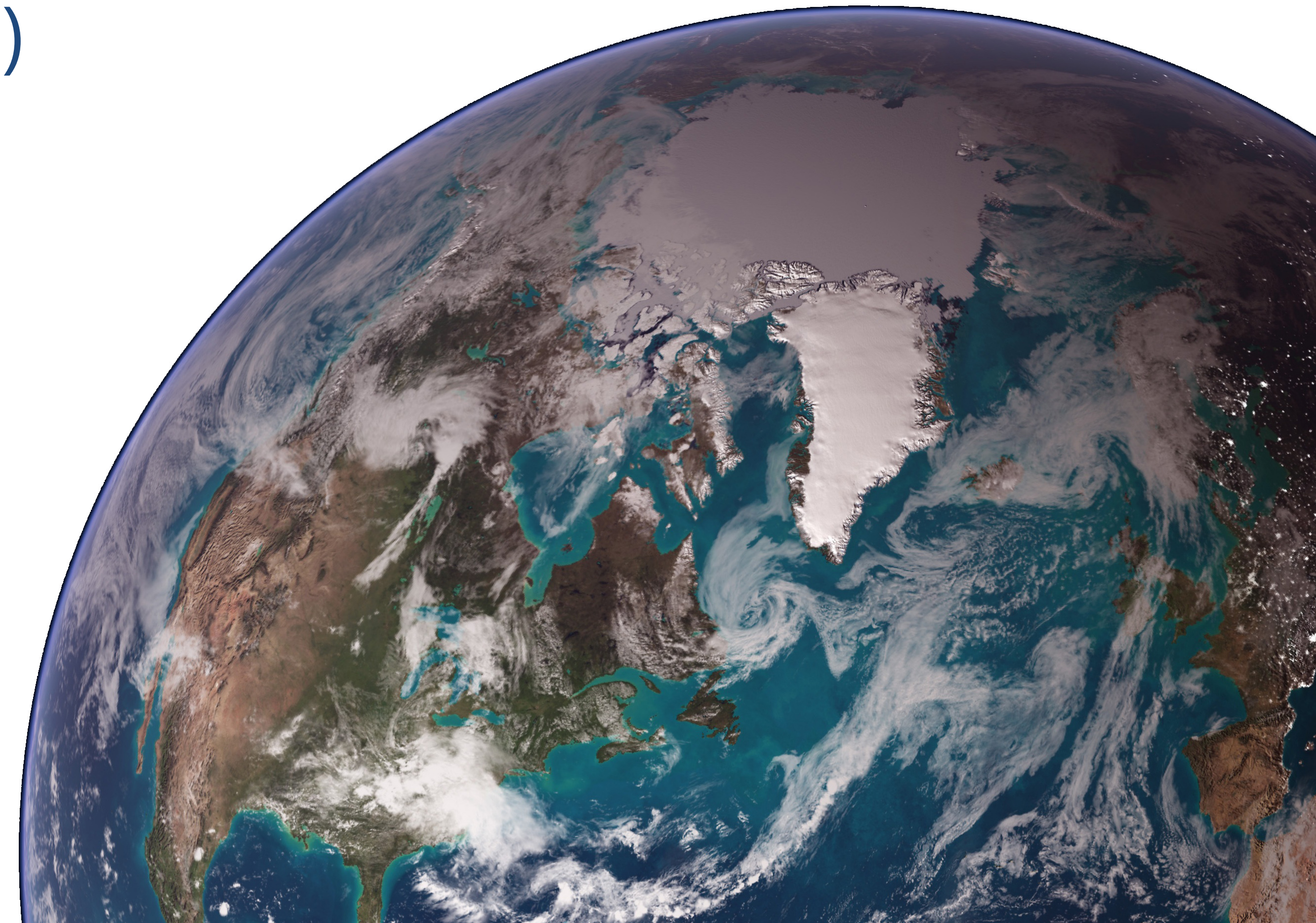
NOAA RESEARCH • ESRL • PHYSICAL SCIENCES DIVISION

Measurements of Soil Moisture and Ocean Wind Using Reflected Global Navigation Satellite System (GNSS) Signals

Valery Zavorotny



Science Review
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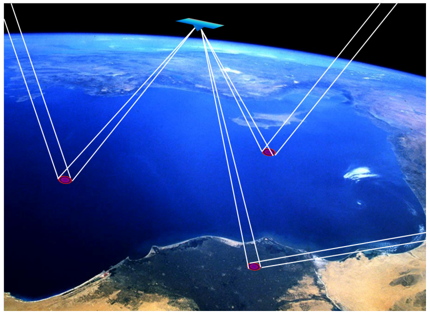
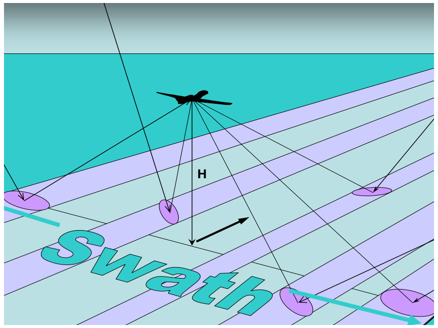
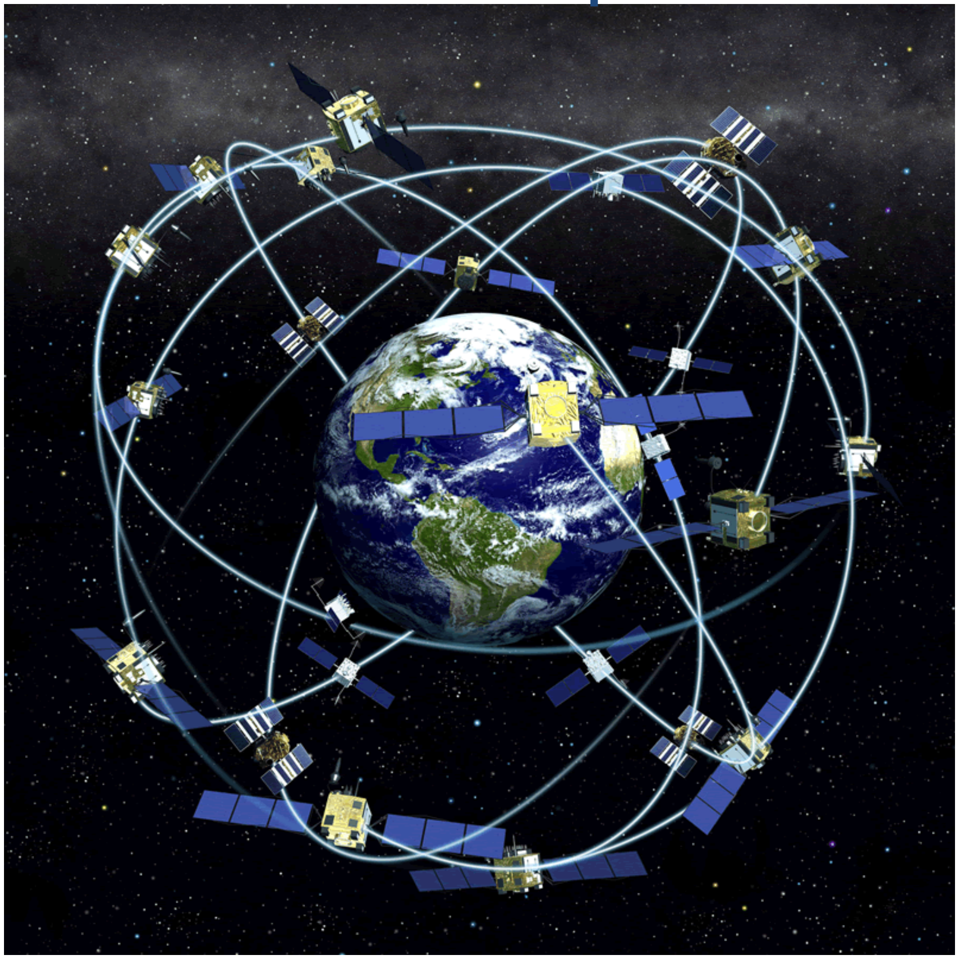
Filling the Gaps in Soil Moisture, Snow and Ocean Winds Measurements Using a New GNSS Technology

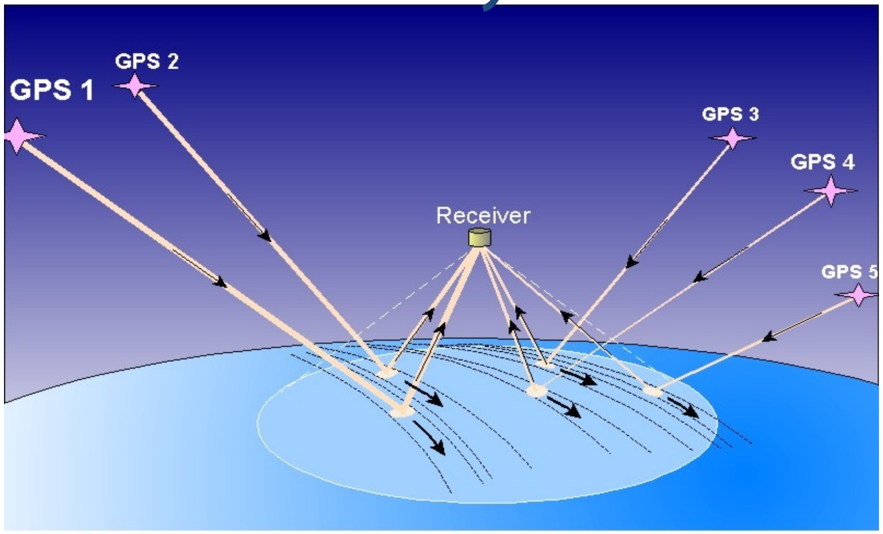
- Observe, understand, and predict the water cycle across the various time and space scales is a formidable task.
- Two biggest gaps in hydrological observations are gaps in data on soil moisture an snow water equivalent/cover area. It is desirable to fill those gaps using additional techniques.
- Current techniques to measure soil moisture or a snow pack use instrumentation that measures either at point scale or at very large (satellite pixel) scale.
- Dedicated remote sensing satellites are very expensive.
- Multiple-day revisit times obtained with current space borne sensors do not resolve short time-scale processes in tropical cyclones. Their signals cannot penetrate through the precipitation encountered in the TC core.
- Cost-effective techniques based on reflected GNSS signals combined with other techniques used at NOAA should fill the current gap in prediction of the water cycle budget.

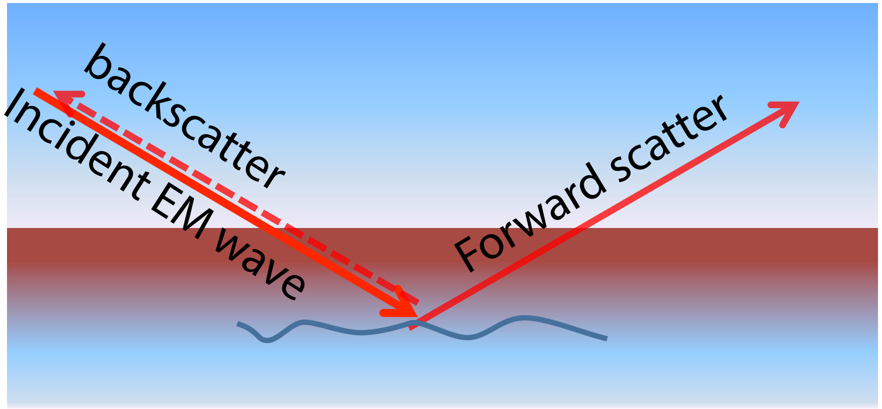




Concept of GNSS Reflectometry

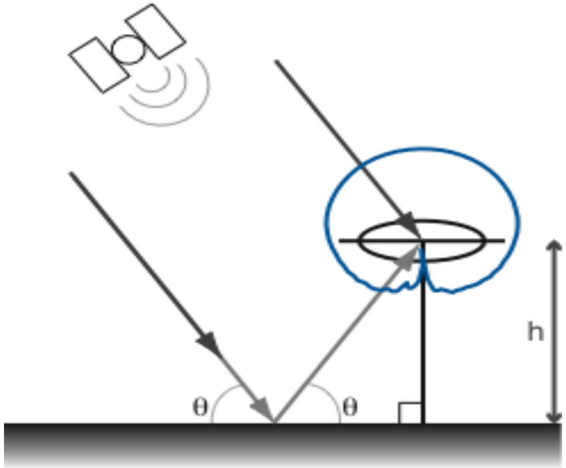


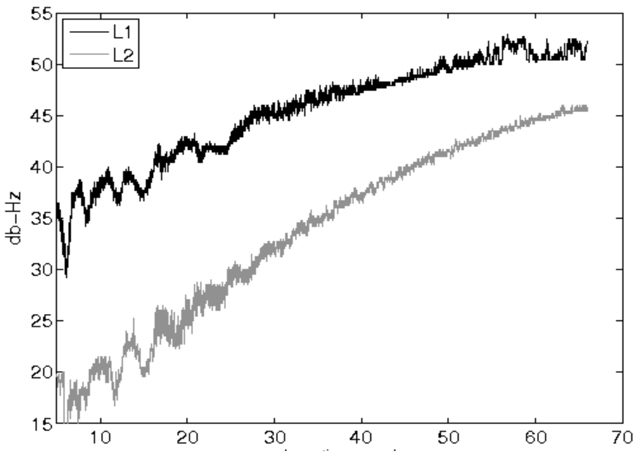




Benefits: (1) the transmitter is already out there, for free; (2) the receiver has a small form factor, a low power consumption; (3) forward scattering differs from backscattering and provides plenty of signal compared to monostatic radar; (4) less rain/snow attenuation compared to X and K-band.

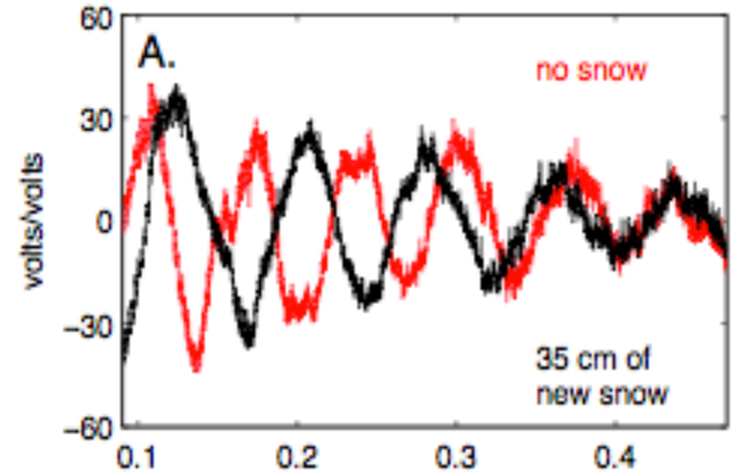
GNSS Multipath Interferometry with Geodetic Receivers





Elevation angle (deg)

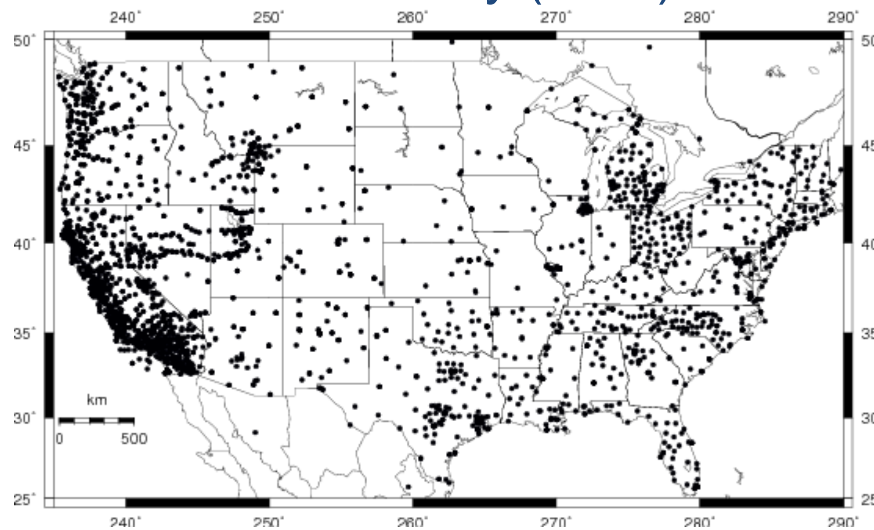
Examples of the observed SNR modulation patterns for:
bare soil (left) and snow (right) conditions.



Sin of elev. angle

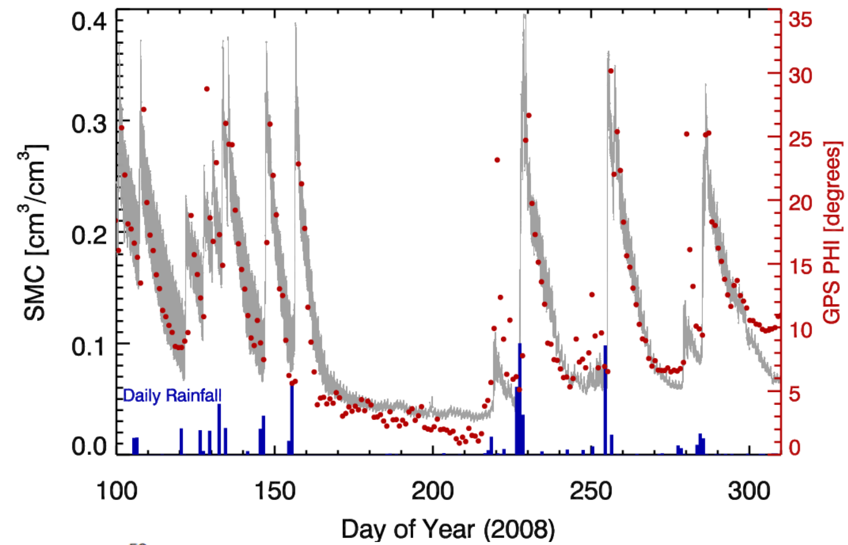
Soil Moisture Content and Snow Depth Obtained with the PBO H_2O Network

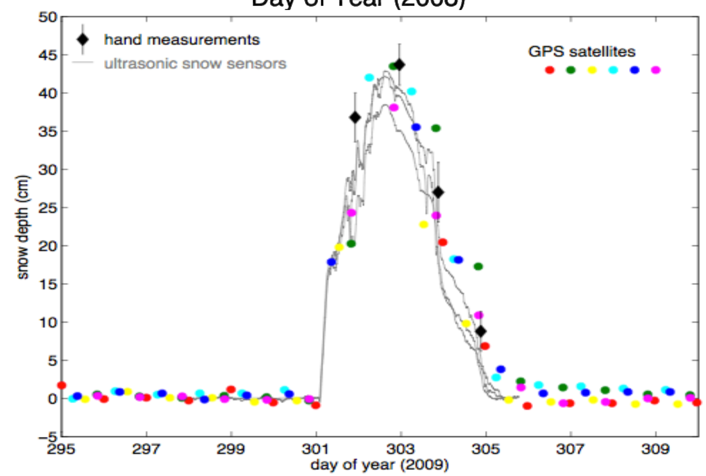
Earthscope Plate Boundary Observatory (PBO)



Locations of geodetic-quality continuously operating GPS sites with data that are free and publicly available. Most of the sites in the western US are associated with the Plate Boundary Observatory Sites in the east are coordinated by the NGS (http://www.ngs.noaa.gov/CORS).

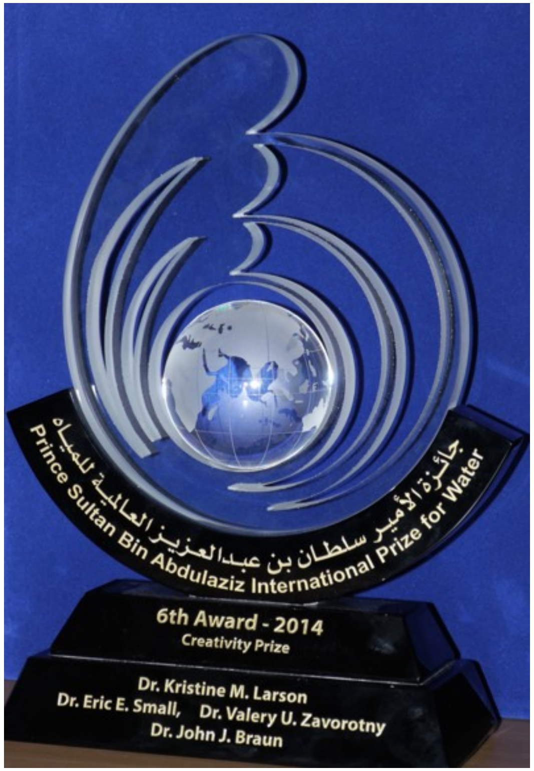
32 PBO GPS receivers in California with meteorological data packages are used by NOAA PSD. They allow measuring integrated water vapor, a key ingredient of Atmospheric Rivers and the fuel for generating precipitation.





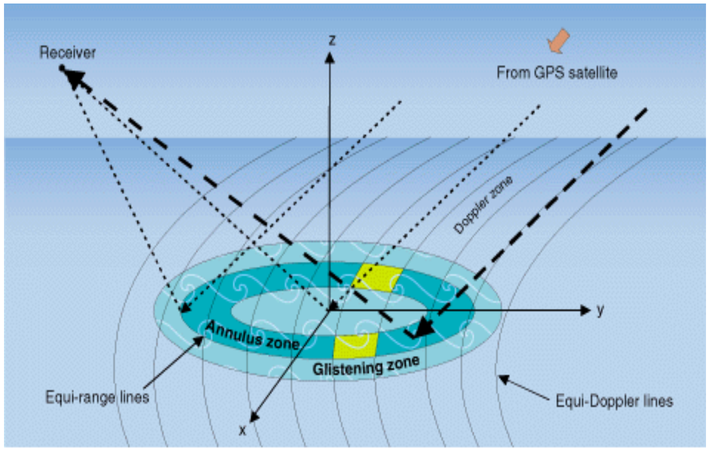
GNSS Multipath Interferometry Technique: a Successful Collaboration with the CU Group

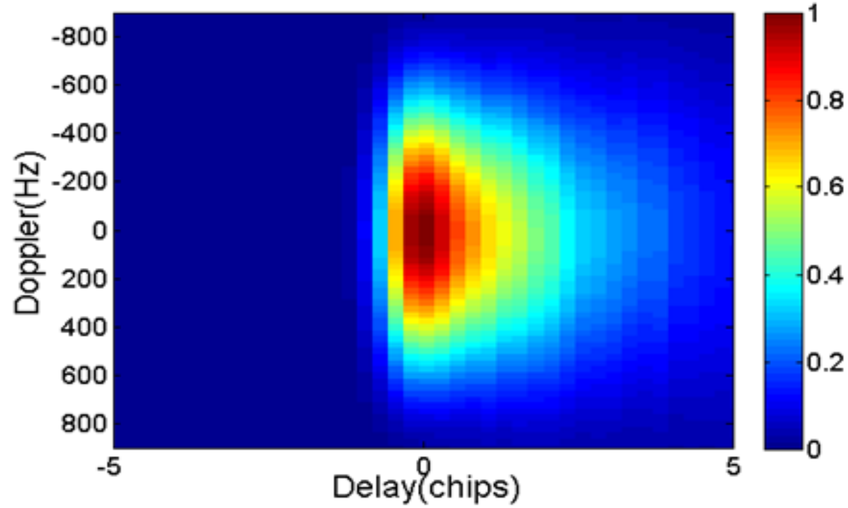
In October 2014 K. M. Larson, E. E. Small, J. J. Braun, and V. U. Zavorotny were awarded the Prince Sultan Bin Abdulaziz International Creativity Prize for Water "for development of a new, unexpected, and cost-effective technique, GPS Interferometric Reflectometry (GPS-IR), to measure soil moisture, snow depth, and vegetation water content."



1. K. M. Larson, E.E. Small, E. D. Gutmann, A. D. Bilich, J. J. Braun, and V. U. Zavorotny, "Use of GPS receivers as a soil moisture network for water cycle studies," *Geosci. Res. Lett.*, 2008.
2. K.M. Larson, E.D. Gutmann, V.U. Zavorotny, J.J. Braun, M.W. Williams, and F. G. Nievinski, "Can we measure snow depth with GPS receivers?" *Geosci. Res. Lett.*, 2009.
3. V. Zavorotny, K. M. Larson, J. J. Braun, E. E. Small, E. Gutmann, and A. Bilich, "A physical model for GPS multipath caused by ground reflections: Toward bare soil moisture retrievals," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, 2010.
4. K. Larson, J. Braun, E. Small, V. Zavorotny, E. Gutmann, and A. Bilich, "GPS multipath and its relation to near-surface soil moisture content," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, 2010.
5. E. D. Gutmann, K. M. Larson, M.W. Williams, F. G. Nievinski, and V. Zavorotny, "Snow measurement by GPS interferometric reflectometry: an evaluation at Niwot Ridge, Colorado," *Hydrol. Process.*, 2012, and other publications on GNSS multipath interferometry technique.

A Concept of Delay-Doppler Mapping for Measuring Ocean Winds and Other Multiple Applications





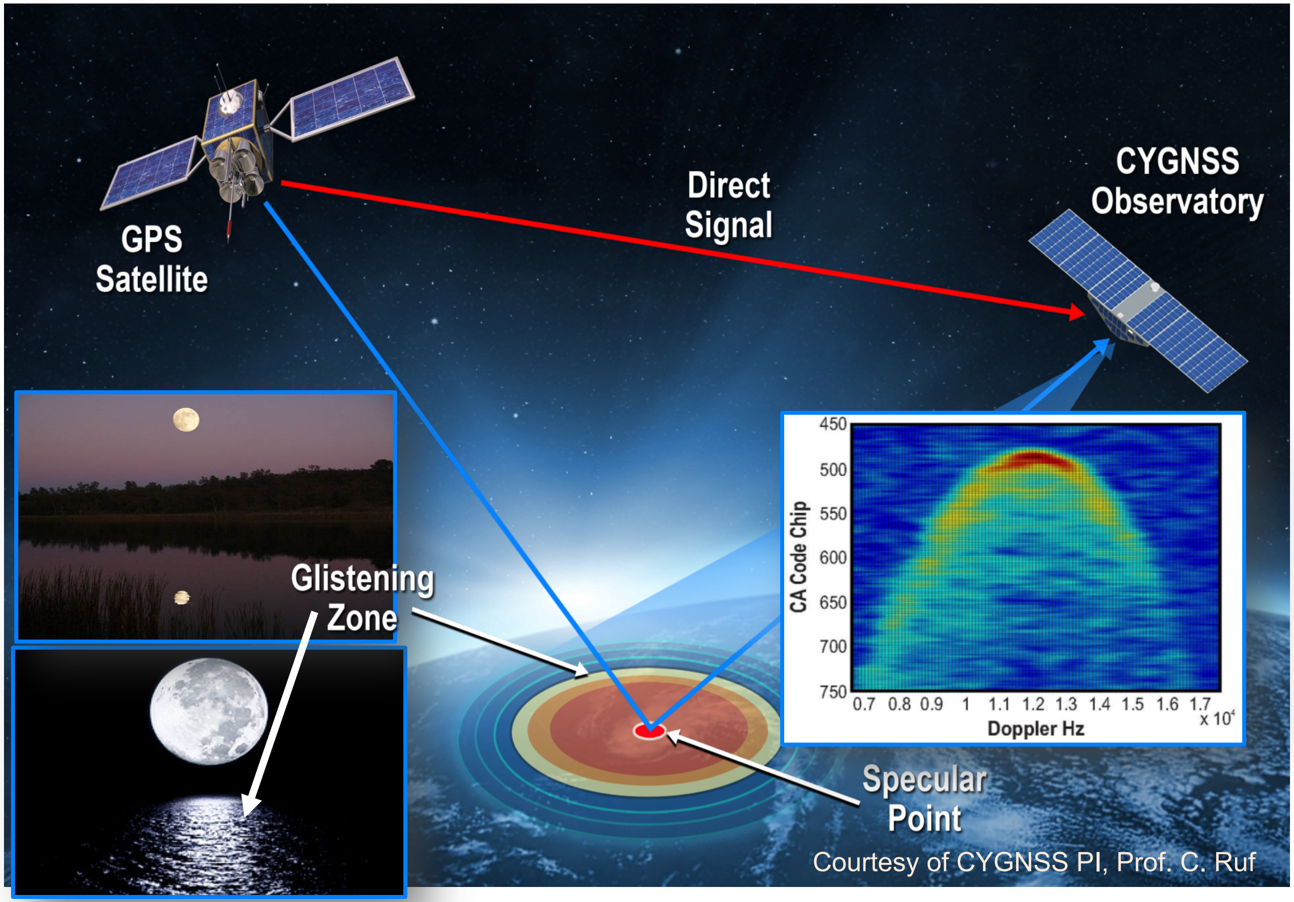
Delay-Doppler Mapping (DDM) creates an image of the scattering coefficient of the surface roughness in the delay-Doppler domain similar to Synthetic Aperture Radar.

DDM theoretical model: Zavorotny-Voronovich bistatic radar equation → Forward modeling of Delay-Doppler Maps → Wind speed retrieval; Wind direction retrieval; Altimetry, soil moisture, snow, ice, other applications

This model has proven successful in aircraft GNSS reflection experiments. Currently it is used to interpret data from recent space-based TechDemoSat-1 experiment simulations for future satellite GNSS reflection missions such as CYGNSS mission and others.

V. Zavorotny and A. Voronovich, "Scattering of GPS Signals from the Ocean with Wind Remote Sensing Application," *IEEE Trans. Geosci. Remote Sens.*, 2000.

CYGNSS: Cyclone Global Navigation Satellite System - 2016 Measuring Surface Wind Speed in the Inner Core of Hurricanes from Space



Courtesy of CYGNSS PI, Prof. C. Ruf

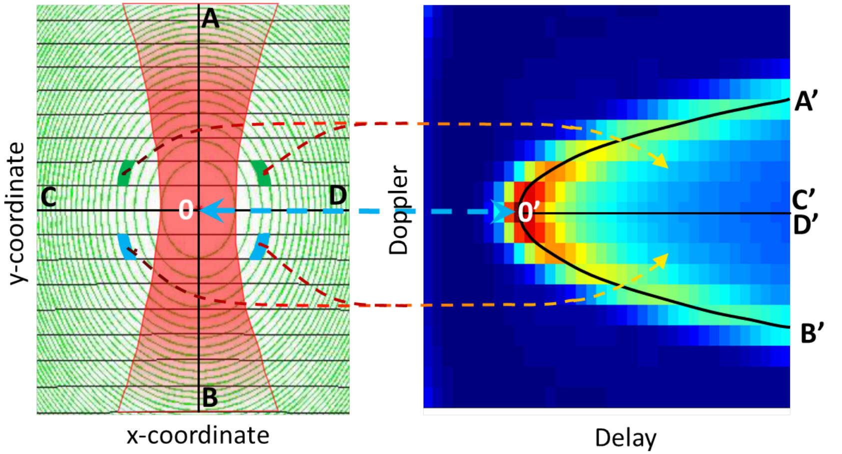
- CYGNSS uses a constellation of eight microsatellites to measure signals scattered by the ocean from existing GPS satellites.
- Those signals contain information about the wind speed at the surface.
- 24-hr coverage provides nearly gap free spatial sampling within +/- 35 deg orbit inclination.
- Frequent measurements by the constellation of wind structure in the inner core will advance forecasting of the storm track, intensity and surge.

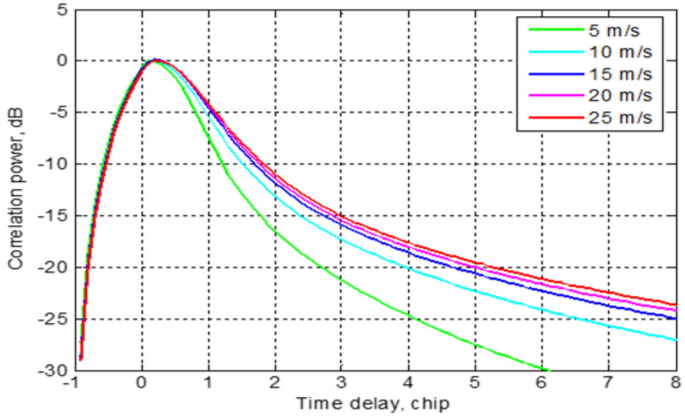
Summary and Conclusions

- The cost-effective technique of GNSS multipath interferometry was tested for soil moisture, snow depth, vegetation measurements.
- This technique together with other techniques employed by NOAA and discussed today should help to close two biggest gaps in hydrological observations of soil moisture an snow water equivalent/cover area.
- Measurements of ocean wind speed and direction using airborne GNSS bistatic radar of opportunity were demonstrated.
- The CYGNSS constellation mission is underway with an objective to measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification.
- Future works include experimental and theoretical studies of GNSS reflectometry for measurements of vegetation, wetlands, permafrost and Arctic ice.
- Possibility to use other signals of opportunity (such as from communication satellites, TV, etc.) for remote sensing purposes should be explored further.

Backup slides

Delay-Doppler map and 1-D delay waveform





Delay-Doppler map emerges as a convolution of the Woodward Ambiguity Function with the Bistatic Radar Cross Section function within the antenna footprint described by its gain pattern. In a sense, delay-Doppler mapping creates an image of the scattering coefficient in the delay-Doppler domain:

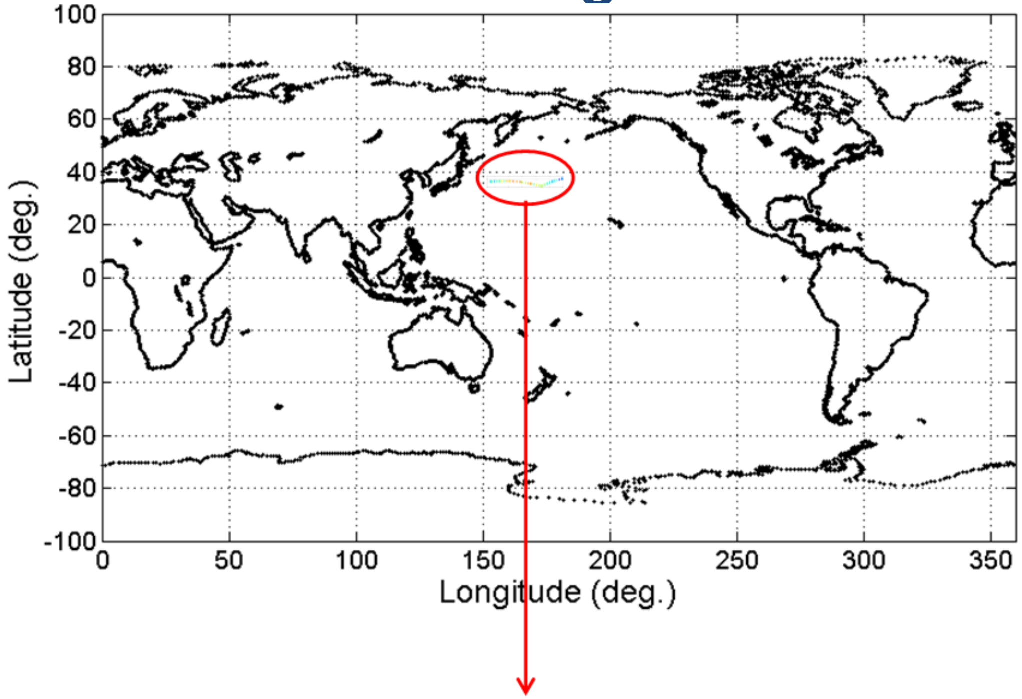
$$DDM(\tau, f_{dop}) = \frac{P_T G_T \lambda^2 G_R}{(4\pi)^3 kT^\circ B_D} \iint \frac{F(\vec{\rho})\Lambda^2(\tau,\vec{\rho})\left|S(f_{dop},\vec{\rho})\right|^2}{R_0^2 R^2}\sigma_0(\vec{\rho})d^2\rho;$$

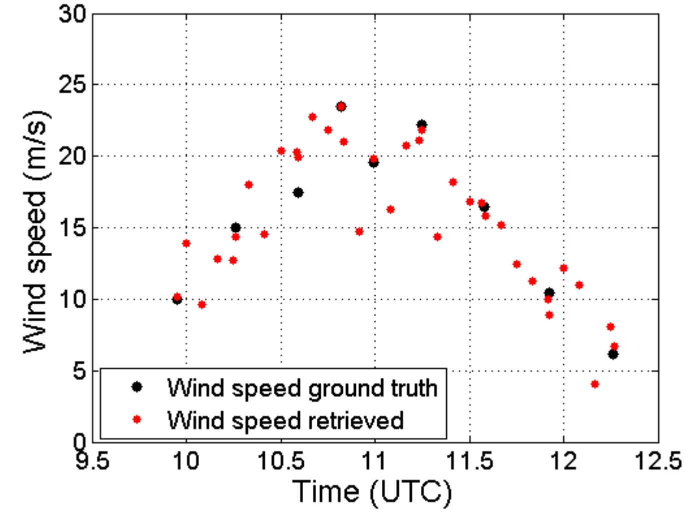
Equi-Doppler lines are separated by:

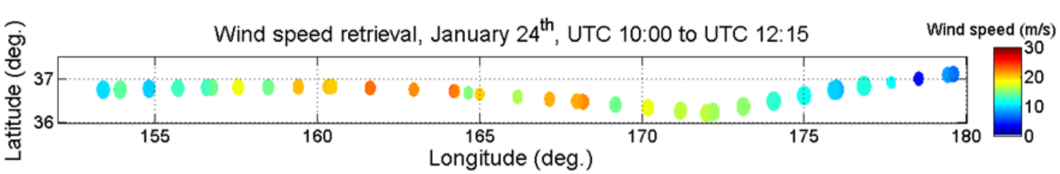
$$\Delta f \equiv f_c \pm \frac{1}{2T_{coh}} = \left[\vec{V}_{TX}\cdot\vec{m}(\vec{r}) - \vec{V}_{RX}\cdot\vec{n}(\vec{r})\right]/\lambda.$$

For a detailed description see: V. Zavorotny, S. Gleason, E. Cardellach, and A. Camps, “Tutorial on remote sensing using GNSS bistatic radar of opportunity,” *IEEE Geosci. Remote Sens. Magazine*, 2014.

Results of wind speed retrieval using GNSS-R data from G-IV high-altitude experiment in 2010

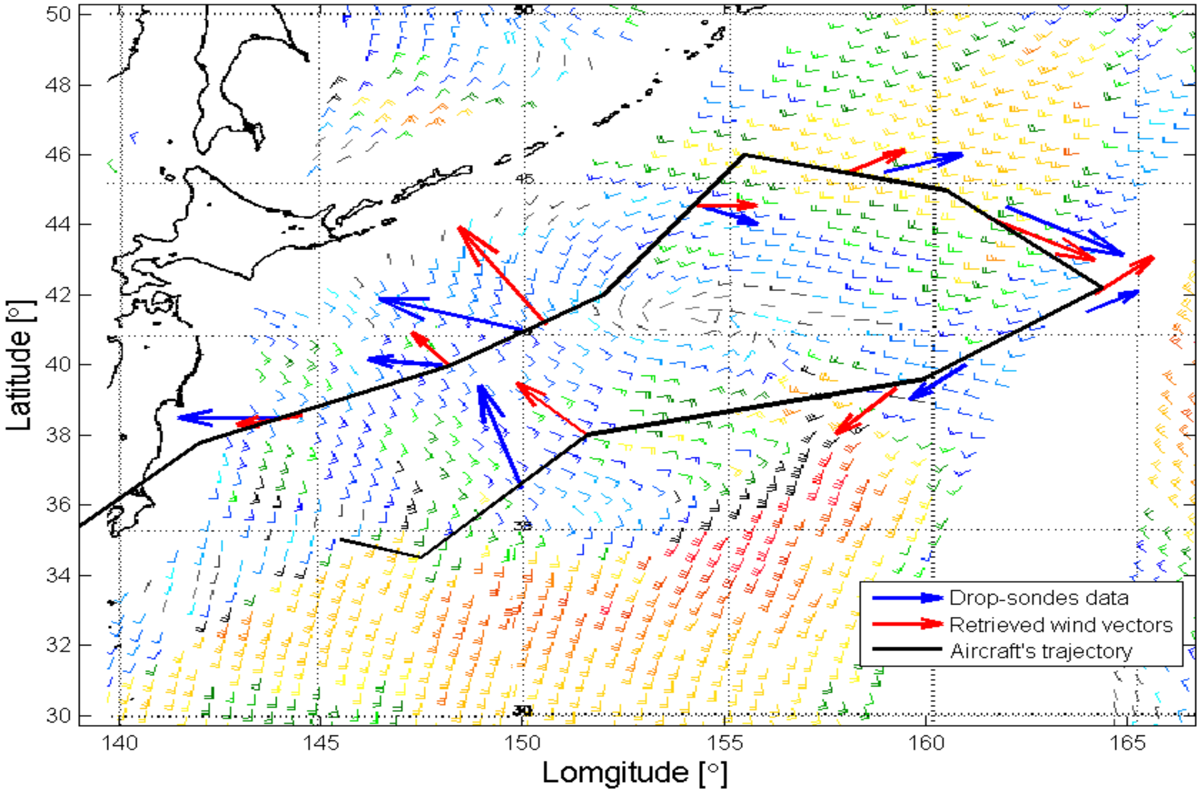






N. Rodriguez-Alvarez, D.M. Akos, V.U. Zavorotny, J.A. Smith, A. Camps, and C.W. Fairall, "Airborne GNSS-R wind retrievals using delay-Doppler maps," *IEEE Trans. Geosci. Remote Sens.*, 2013

Wind direction retrieval



- Retrieved wind vectors were superimposed to an OceanSAT wind vectors map as measured 10 hours before the flight.
- Both wind vectors' sets show an anticyclonic circulation feature over which the aircraft was flying.

E. Valencia, V. U. Zavorotny, D. M. Akos, and A. Camps, "Using DDM asymmetry metrics for wind direction retrieval from GPS ocean-scattered signals in airborne experiments," *IEEE Trans. Geosci. Remote Sens.*, 2014.