Other GNSS data applications - Status in the US

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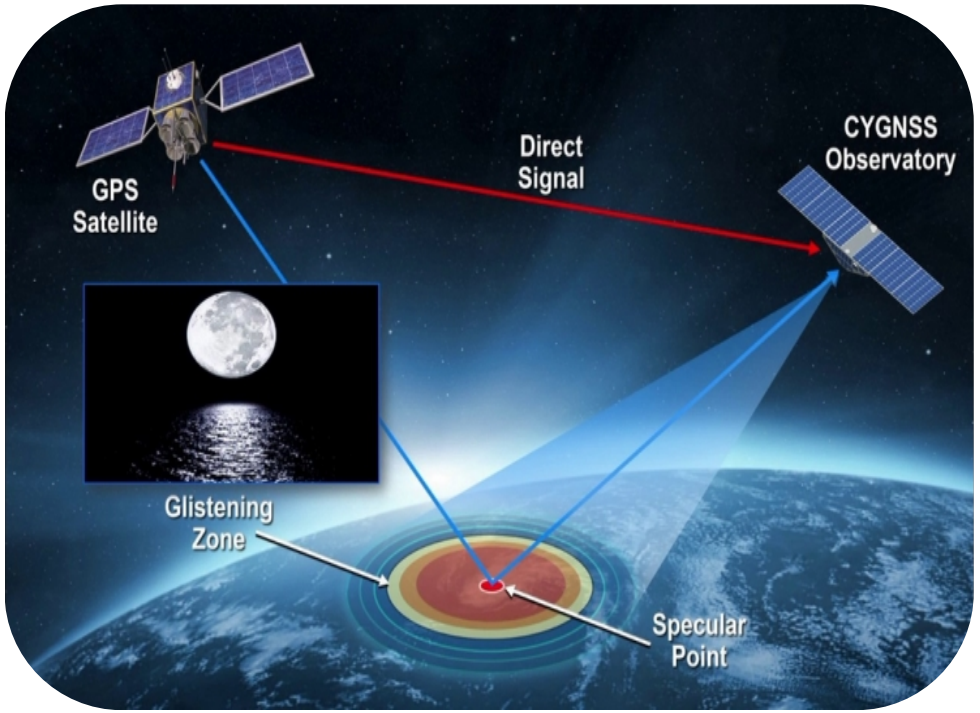
Executive summary

This presentation discusses GNSS data applications beyond Radio Occultation; in particular, we focus on NOAA's use of **GNSS Reflectometry (GNSS-R)**.

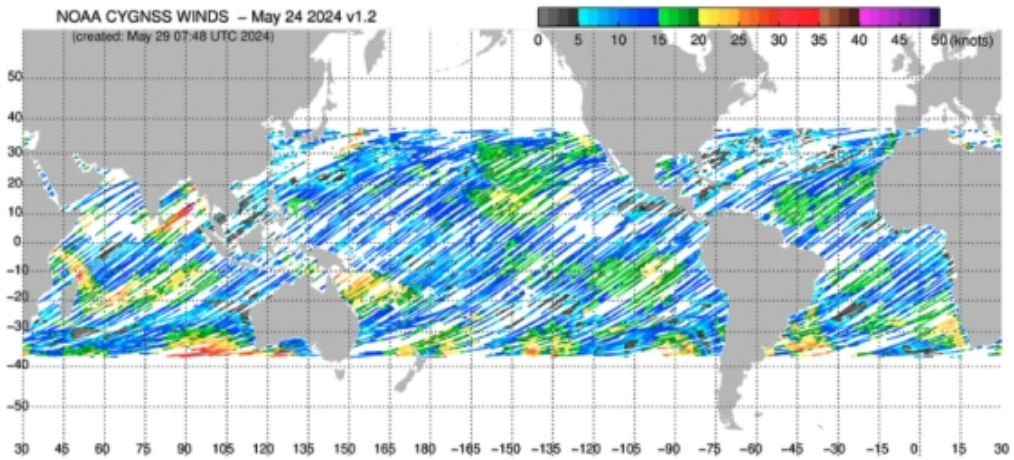
The following presentation will cover:

- Current and upcoming commercial and government GNSS-R systems and products
- Ongoing NOAA OSW Pilot activities



Commercial and Government GNSS-R systems

Today, NOAA utilizes 2 satellite-based GNSS-R systems for environmental monitoring:



1. ***CYGNSS***:
   The NOAA Center for Satellite Operations and Research (STAR) provides GNSS-R derived wind products from the NASA CYGNSS mission.
2. ***Spire***:
   The NOAA Commercial Data Program is currently piloting the use of commercial GNSS-R data from vendor Spire Global:
   - Observation data is used to evaluate ocean surface wind (OSW) measurements and to improve NOAA wind products.
   - Data is also used to evaluate applications including soil inundation, inland water body mapping, freeze/thaw event detection, sea ice detection and characterization, soil moisture monitoring, and water altimetry measurements.

Current and Future Commercial and Government GNSS-R systems

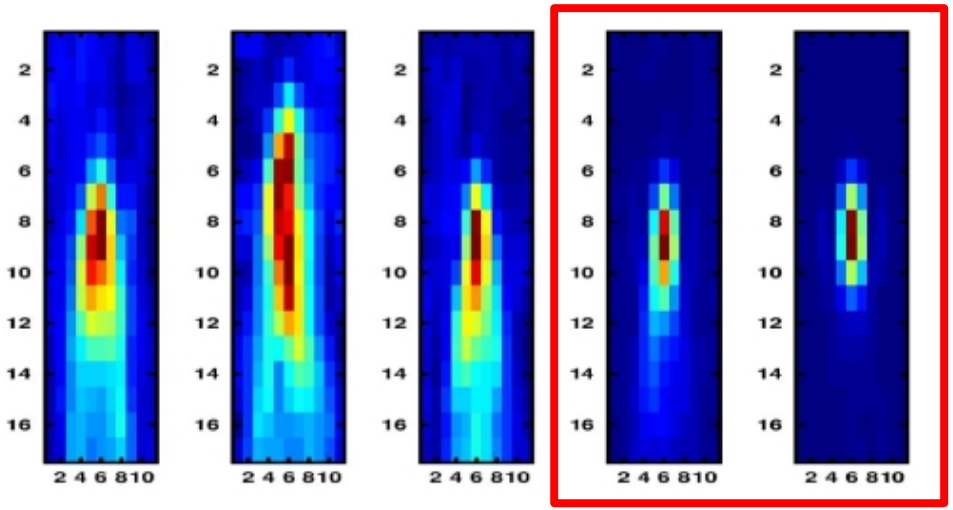
System	Data Products	Operational Satellites	Antennas	Availability
CYGNSS	L1, L2 Science Data L2, L3 Climate Data UCAR L3 Soil Moisture NOAA CYGNSS L2 Wind Speed	8 CYGNSS satellites launched 2016, on extended mission status. Mid-latitude +-37 degree orbit with no high-latitude or polar coverage.	Delay Doppler Mapping Instrument (DDMI), 2 nadir and 1 zenith antennas, 4 simultaneous observations per antenna.	Public distribution: - Available through NASA (PO.DAAC)
TASA Triton	Planned products include: ocean surface wind speed, soil moisture/inundation, sea ice characterization.	FORMOSAT-7R, launched 10/2023. TASA plans to manifest the GNSS receiver on 4 missions, with >5-year lifespans: - FORMOSAT-9A, launching late 2027 - FORMOSAT-8E, launching 2029 - FORMOSAT-9B, launching 2029 - FORMOSAT-8F, launching 2030	Dual-frequency RHCP zenith antenna for GNSS signals, high-gain dual-frequency LHCP nadir antenna for reflected signals.	- Data beginning in Q2, 2024
Spire	Grazing angle GNSS-R: Lev1: Reflectivity and phase Lev2: Altimetry Lev2: Ice extent & classification Near-nadir GNSS-R (20-90deg): Lev1: Reflectivity Lev2: Soil Moisture Lev2: Ocean wind and mean square slope	Total constellation of ~90 satellites Grazing angle GNSS-R: 4 satellites (2024 OSW Pilot) Near-nadir GNSS-R: Up to 25 satellites	STRATOS GNSS Radio Occultation instrument Grazing angle GNSS-R: RHCP fore and aft. Near-nadir GNSS-R: Near nadir 20-90deg using deployable nadir-pointing antennas	NOAA OSW Pilot: - Near real-time data - Data beginning in 1/25/2024 - Available for government, academic, non-commercial use NASA CSDA: - Data from 2019 (L1)/ 2020 (L2) - Available for U.S. Government
Muon Space	Planned products include: surface soil moisture, ocean surface wind speeds, sea ice properties. Muon OSW product trained on CYGNSS data.	MuSat-2 launched on April 3. 2024. MuSat-3,4,5 launches planned starting in 2025.	Dual polarization multiple band, 32 simultaneous observations High-gain beamforming GNSS-R antenna starting with MuSat-4.	USAF pilot: - Data beginning in 3Q 2024 - Available for U.S. Government
PlanetIQ	Products to be developed under contract.	Gnomes-4 launched on December 1, 2023 (grazing angle GNSS-R). Gnomes-5,6 launch late 2024 (near nadir).	Dual linear polarization antennas for measuring surface reflections.	Near nadir: - Capability beginning in 4Q 2024
HydroGNSS	Primary products: soil moisture, freeze-thaw state over permafrost, inundation and biomass. Secondary products: ocean wind speed and sea-ice extent.	Launch planned for November 2024; 2 Satellites planned.	Surrey Sat Delay Doppler Mapping Receiver, dual polarization dual frequency.	- Data beginning in 1Q 2025

Overview – GNSS-R Applications

- The GNSS-R measurement technique relies on bi-statically reflected signals transmitted from global navigation satellites.
- The unique range coded modulation of the GNSS signals allows for the mapping of received power as a function of both time-delay and Doppler frequency across the Earth's surface.

GNSS-R is suitable for both ocean and land observations:

- Ocean surfaces exhibit more coherent reflections due to smooth surfaces. **Ocean applications include ocean wind speed retrievals, swell and altimetry, and sea ice concentration and extent.**
- Land surfaces exhibit diverse distributions of reflecting surfaces; therefore, signals are a mixture between both coherent reflection and incoherent scattering. This make land calibration of the GNSS-R signal more complex. **Land applications include soil moisture, vegetation opacity, and wetland detection and monitoring, flood inundation, and snow height**.



Coherent reflection

Potential Commercial GNSS-R Vendor Applications

NOAA data requirements addressed by commercial vendors	Muon Space	PlanetiQ	Spire Global
Atmosphere			
• Atmospheric Composition and Air Quality (Hi Priority)			
• Greenhouse Gases (Hi Priority)			
• Atmospheric Temperature (Hi Priority)	RO	RO	RO
• Atmospheric Water Vapor (Hi Priority)	RO, PRO, MWS	RO, PRO	RO, PRO
• Clouds (Hi Priority)	IR		
• Lightning			
• Precipitation (Hi Priority)	PRO, MWS	PRO	PRO, HyMS
• Radiation Budget			
• Tropical Cyclone Characteristics (Hi Priority)	REF, RO, PRO, MWS	REF, RO, PRO	REF, RO, PRO, HyMS
• Volcanic Eruption Characteristics			
• Winds (Hi Priority)	REF	REF	REF
Cryosphere			
• Lake and Sea Ice (Hi Priority)	REF	REF	REF
• Snow Glaciers (Hi Priority)			
Land and Surface Hydrology			
• Fires (Hi Priority)	IR		
• Flood	REF	REF	REF
• Surface Moisture	REF	REF	REF
• Surface Temperature	IR		
• Vegetation	REF, IR		
Oceans, Freshwater, and Coasts			
• Biology and Biogeochemistry			
• Surface Height (Hi Priority)			
• Topography and Bathymetry	REF	REF	REF
• Water Pollution			
• Water Temperature and Salinity	REF, IR		

NOTE: Data-as-a-Service (DaaS) Vendors only, focused on CY 2024-2025 offerings, longer term not included
Instruments:
HyIR = Hyperspectral Infrared
HyMS = Hyperspectral Microwave Sounder
IR = Infrared Spectrum Imager
REF = GNSS/SoOp Reflectometry
RO = GNSS Radio Occultation (non-polarized)
PRO = Polarimetric GNSS Radio Occulation
VIS = Visible Spectrum Imager

Ongoing NOAA OSW Pilot activities

The NOAA GNSS-R Ocean Surface Wind Pilot is ongoing, with a number of activities underway at NOAA and pilot partners. Current activities include:

- Evaluating Spire GNSS-R Level 1 data in comparison with other satellites (i.e., CYGNSS, ASCAT-B/C, AMSR2, OceanSat3) and numerical models (i.e., GDAS and ECMWF).
- Analyzing Spire L2 Ocean Wind Speed Product data.
- High latitude (Alaska) underflights of Spire GNSS-R orbital tracks by the STAR Ocean Winds Team.
- Establishing an end-to-end assimilation system for Spire data.
- Using Spire GNSS-R data to study recent atmospheric river (AR) events
- Estimating surface soil moisture content using Spire reflection data.
- Using GNSS reflections to map extent and height of inland water bodies.

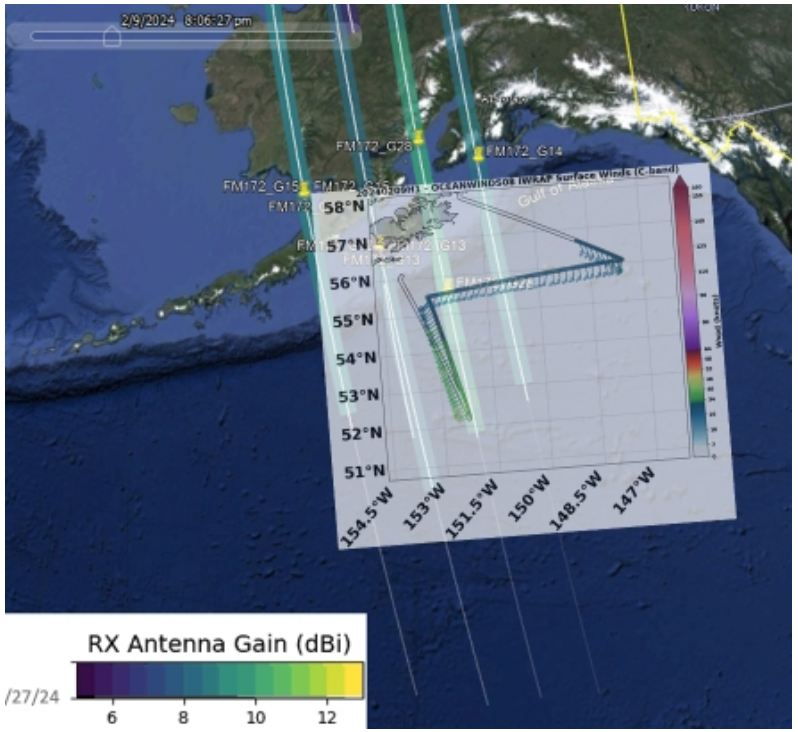


Illustration showing NOAA STAR underflight of SPIRE GNSS-R satellites on 2/9/2024.

Upcoming activities include:

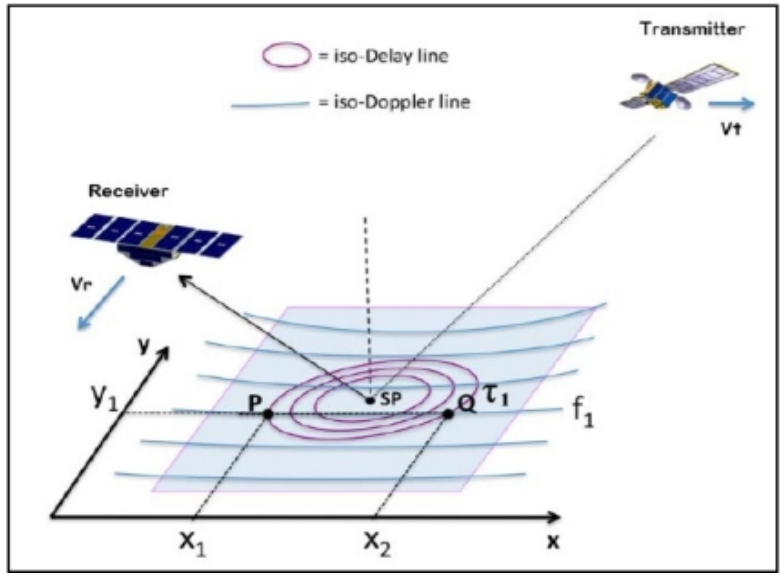
- Establishing an efficient product delivery system to deliver calibrated Level 1 data and derived OSW products to NOAA data centers.
- Developing NOAA OSW products from Level 1 Spire data.

Thank you.

Back-Up Slides

NOAA GNSS-R OSW Pilot Objectives:

1. To conduct studies to improve upon GNSS-Reflectometry (GNSS-R) derived ocean wind speed products previously developed by NOAA and investigate the utility of wind speed products developed by vendors.
2. To assess the quality and impact of commercial GNSS-R observations for additional environmental measurements.
   - Provide L1 & L2 grazing angle GNSS-R observations for sea ice and altimetry measurements.
   - Produce calibrated Delay Doppler Maps and Specular reflection point location estimates.
   - NESDIS & NWS will compare the commercial GNSS-R measurements with other more traditional satellite measurements.
   - Leverage past reflectometry research with the NASA-led Cyclone GNSS (CYGNSS) mission.
   - Investigate insights into other parameters (e.g. sea ice, soil moisture, flood mapping).



NOAA GNSS-R OSW Pilot Member Organizations:

Agency	*Role*
• **NOAA/NESDIS Commercial Data Program**	• Pilot project management.
• **STAR**	• Statistically analyze and characterize pilot GNSS-R data including OSW products in comparison to satellite and numerical model data. • Quantify the impacts of pilot GNSS-R derived OSW and GNSS RO Data for topical cyclone prediction. • Assess ancillary GNSSR Level 2 products generated by UCAR.
• **UCAR/University of Colorado**	• Develop, improve, and validate data products including soil inundation, detection and mapping of inland water body boundaries, detection and characterization of sea ice, precision altimetry over calm ocean, sea ice, and inland water bodies. • Utilize correlative datasets to validate and compare GNSS-R pilot datasets.
• **JCSDA**	• Determine methods for ocean surface wind product ingest and assimilation. • Determine OSW data impact on global numerical weather prediction using JEDI Skylab system. • Quality control, error assignment, and systematic bias examination for vendor GNSS-R data.
• **QOSAP**	• Conduct impact assessment and optimization for the assimilation of Ocean Surface Winds (OSW) data. • Evaluate OSW vendor data quality against CYGNSS products.
• **NWS NCEP**	• Data assessment, impact analysis & data assimilation plan, timeline development for utilization.
• **OSPO**	• Evaluation of GNSS-R products.
• **NCCF and NCEI**	• Data ingest, dissemination, and archive.
• **EUMETSAT, ESA, ECMWF, IEEC and ICE-CSIS (Spain), UKMET and UKNOC, NCMRWF (India)**	• International participants • Pilot data evaluation and data product development

Data Rights and Security Requirements (SOW)

Data Rights

NOAA will retain all data purchased under this contract for non-operational use, including, but not limited to, analysis related to the CWDP or space weather research and modeling. The Contractor shall grant NOAA a Limited License, allowing it to provide free access to data upon delivery to NOAA, not for further dissemination for commercial purposes, to U.S. Government agencies, WMO-designated National Meteorological and Hydrological Services, Regional Specialized Meteorological Centers, and members of the Coordination Group for Meteorological Satellites.

Security Requirements

The Contractor shall comply with CAR 1352.239-72, section (i). The Contractor may request COR approval of alternate security accreditation methodologies for compliance with section (i) including: information security assessment methodology promulgated by the U.S Federal Government (specifically, National Institute of Standards and Technology (NIST) Special Publication (SP) 800-37 and NIST SP 800- 53), or internationally recognized private industry information technology (IT) security frameworks (such as International Standards Organization (ISO)/International Electrotechnical Commission (IEC) 27033, 27001, 27006 and 27002, or Control Objectives for Information and Related Technology (COBIT)). The Contractor will provide an analysis for alternative methodologies compared to SP 800-53 high impact baseline identifying any gaps. The Contractor shall deliver files to NOAA ingest using either Hypertext Transfer Protocol Secure (HTTPS) (preferred) or Secure File Transfer Protocol (SFTP). The Contractor shall use a data integrity method compliant with the NCCF ICD and approved by NOAA.

OSW Pilot Observation Requirements:

- **Data Processing & Evaluation:**
  - NESDIS will assess the quality and impact of available commercial GNSS-R observations for the determination of ocean surface wind characteristics.
    - STAR & UCAR will jointly process and distribute the derived L-2 data products
    - STAR, NWS & AOML will evaluate and assess the research product and conduct impact analysis
- **GNSS-R Observation Requirements*:**
  - **Spatial Resolution:** 25 km x 25 km or better
  - **Duty Cycle:** 80%
  - **Wind speed dynamic range:** 25 km x 25 km resolution of 3- 35 m/s
  - **Retrieval uncertainty for winds:** >than 20 m/s is less than 10%
  - **Retrieval uncertainty for winds:** <than 20 m/s is less than 2 m/s
- **Quantity*:**
  - Greater than 500 daily GNSS-R observations, when averaged over any 30-day period
- **Performance Schedule:**
  - Phase 1: Preparation. 3 months (includes 24-hours of sample data)
  - Phase 2: Data Delivery. 6 months
  - Phase 3: Evaluation. 3 months

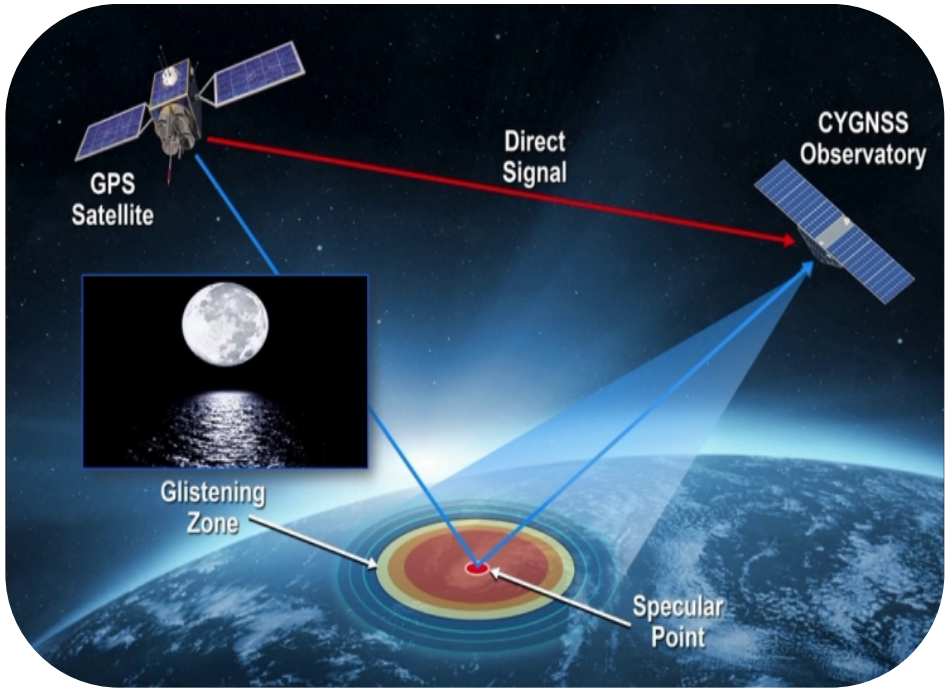
** A number of requirements in the SOW were listed as Objective (desired) and not Baseline (required) in order to encourage vendor participation.*

Spire Purchase Summary

Feature	*Description*
Observations	500 unique Ocean Wind observations daily.
Latency	Near real time, < 180 minutes.
Antenna Technology	• Antenna beamforming and signal processing technology to meet the sensitivity requirements specified in the NOAA RFP. • GNSS-R software defined radio receiver operates in “beamforming” mode to achieve the higher radio sensitivity required to meet the NOAA requirement of high ocean surface winds up to 35 m/s. The beamforming mode coherently combines two antennas for a 3 dB sensitivity increase in the direction of the specular reflection. • 15 Spire satellites measure grazing angle GNSS-R events in areas of high-coherence • 5 satellites measure reflections at near nadir (NN-GNSS-R) between 20 - 90 degrees elevation. These use deployable nadir-pointing antennas and process delay- Doppler maps (DDMs) of reflection power. • RHCP for grazing angle. LHCP nadir observations supporting digital beamforming.
Unique Data	“NOAA will be the only organization that will have access to the operational near real-time data with the sensitivity enabled using beamforming technology at the required quantity.”
OSW Products	L1 (Ocean and Land), L2 all Ocean Winds
Ancillary Products	L2 Soil moisture product, L1 and L2 sea ice extent and classification

GNSS-R Overview

- GNSS Reflectometry is an innovative technique that leverages reflected GNSS signals to study the Earth's surface and atmosphere. This method has gained significant attention due to a wide variety of possible environmental monitoring applications.
- The GNSS-R field is now experiencing exponential growth in applied research and has captured the attention of researchers and government agencies.



- GNSS-R is being considered by a growing number of commercial satellite data-as-a-service (DaaS) vendors for use in bespoke environmental monitoring products and to supplement government observing systems.