NOAA/NESDIS

Commercial Data Pilot
GNSS-R Ocean Surface Winds Pilot
Executive Summary

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1. Executive Summary

1.1 GNSS-R Reflectometry and NOAA's Mission

Global Navigation Satellite System Reflectometry (GNSS-R) is a remote sensing technique that utilizes signals from positioning, navigation, and timing (PNT) service satellites, such as GPS and Galileo, to measure and study various properties of the Earth's surface. NOAA has performed significant scientific work on investigating the utility of GNSS-R for addressing mission needs including measuring ocean wind speeds, soil moisture, flooding extent, and sea ice characterization

A key NOAA mission need is for accurate and comprehensive measurements of global ocean surface wind (OSW) speed and direction. Wind speed measurements are important to meteorologists and oceanographers in the preparation of marine weather forecasts for hurricanes, winter storms, and high seas. Retrieving OSW speeds is a highly promising application of GNSS-R. OSW speed can be determined by analyzing how wind-induced ocean surface roughness changes the characteristics of the reflected GNSS signals.

Key rationale for purchasing commercial GNSS-R observations to derive environmental variables such as OSW, soil moisture, sea ice, and flooding inundation include:

The use of GNSS-R for OSW speed retrievals has the potential to allow for regular monitoring of surface winds at a relatively low cost. Commercial small satellite constellations demonstrate that cost-effective alternatives exist for providing Earth observations. An affordable commercial constellation of GNSS-R satellites could fully sample and quickly revisit the Earth's surface.

GNSS-R can complement existing observation systems and has the potential to improve forecast accuracy.

GNSS-R ocean surface wind speed observations agree well with other data types and allow wind speed measurements in hurricanes.

A reliable, long-term government source of GNSS-R observations does not exist. However, commercial vendors such as Muon Space (Muon) and Spire Global (Spire) already operate satellite constellations with GNSS-R payloads.

Commercial technology is improving rapidly. For example, commercial satellite vendor Muon's newest GNSS-R demonstration satellite offers an upgraded high-gain antenna. This satellite is the prototype for a new constellation and can be used to test improved retrieval of tropical cyclone winds.

1.2 NESDIS CDP GNSS-R OSW Pilot Overview

The NESDIS Commercial Data Program (CDP) conducts commercial data studies to help NOAA meet its terrestrial weather mission objectives. Starting in 2024, NOAA conducted a GNSS-R Pilot Study (GNSS-R OSW Pilot) to assess the quality and impact of available commercial GNSS-R observations as a viable, cost-effective means of ocean wind monitoring. As an ancillary part of the Pilot Study, NOAA assessed the quality and impact of commercial GNSS-R observations for soil moisture characterization, land surface flooding/inundation, freeze/thaw events, and sea ice characterization.

1.2.1 Pilot Participants

The major pilot participants included the NESDIS Center for Satellite Applications and Research (STAR), the University Corporation for Atmospheric Research (UCAR), the Joint Center for Satellite Data Assimilation (JCSDA), the Quantitative Observing System Assessment Program (QOSAP), and the National Weather Service (NWS) National Centers for Environmental Prediction Environmental Monitoring Center (EMC).

1.2.2 Vendor Selection

Spire Global was selected as the Pilot data vendor based on its mature satellite constellation, its GNSS-R collection and processing system, a proven delivery history to NOAA since 2017, and its demonstrated compliance with IT security and data specification requirements.

1.2.3 Pilot Execution

The pilot followed a structured 12-month vendor contract, including a 3-month technical preparation period, a 6-month data delivery period, and a 3-month vendor support period. Technical evaluation and analysis also continued beyond the vendor support period.

Spire successfully delivered all required data and met or exceeded the minimum daily observation thresholds throughout the delivery period, demonstrating resilience in its constellation despite a minor satellite loss. This successfully confirmed the commercial sector's technical and logistical capability to supply high-volume, compliant GNSS-R data.

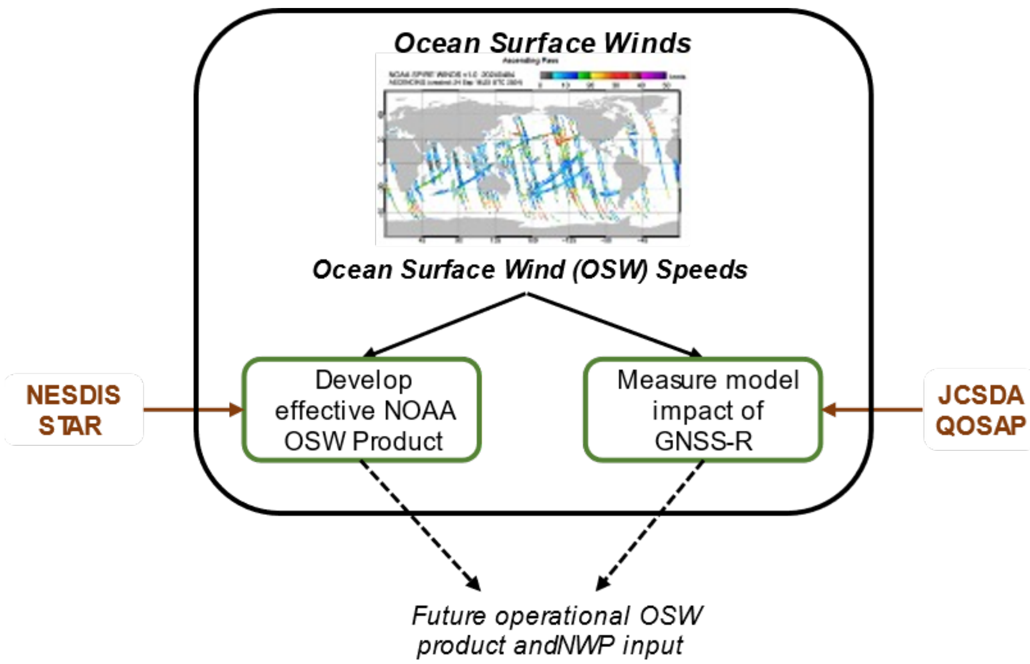
The pilot also successfully integrated data ingestion and evaluation efforts across the NOAA enterprise, involving organizations including STAR, UCAR and the University of Colorado, JCSDA, and EMC.

1.2.4 OSW Impact Assessment

The utility of commercial GNSS-R data for OSW applications was investigated by STAR, JCSDA, and QOSAP and EMC. STAR conducted an evaluation of GNSS-R OSW products to determine their suitability for enhancing NOAA's operational weather forecasting and warning capabilities. JCSDA investigated the impact of the Spire OSW product in the Joint Effort for Data assimilation Integration (JEDI) data assimilation system and conducted observing system experiments (OSEs) designed to accentuate the new data sources and identify problems and systematic issues.

The OSW related activities and participating organizations are illustrated in Figure 1-1.

Figure 1-1: Reported OSW Pilot Activities



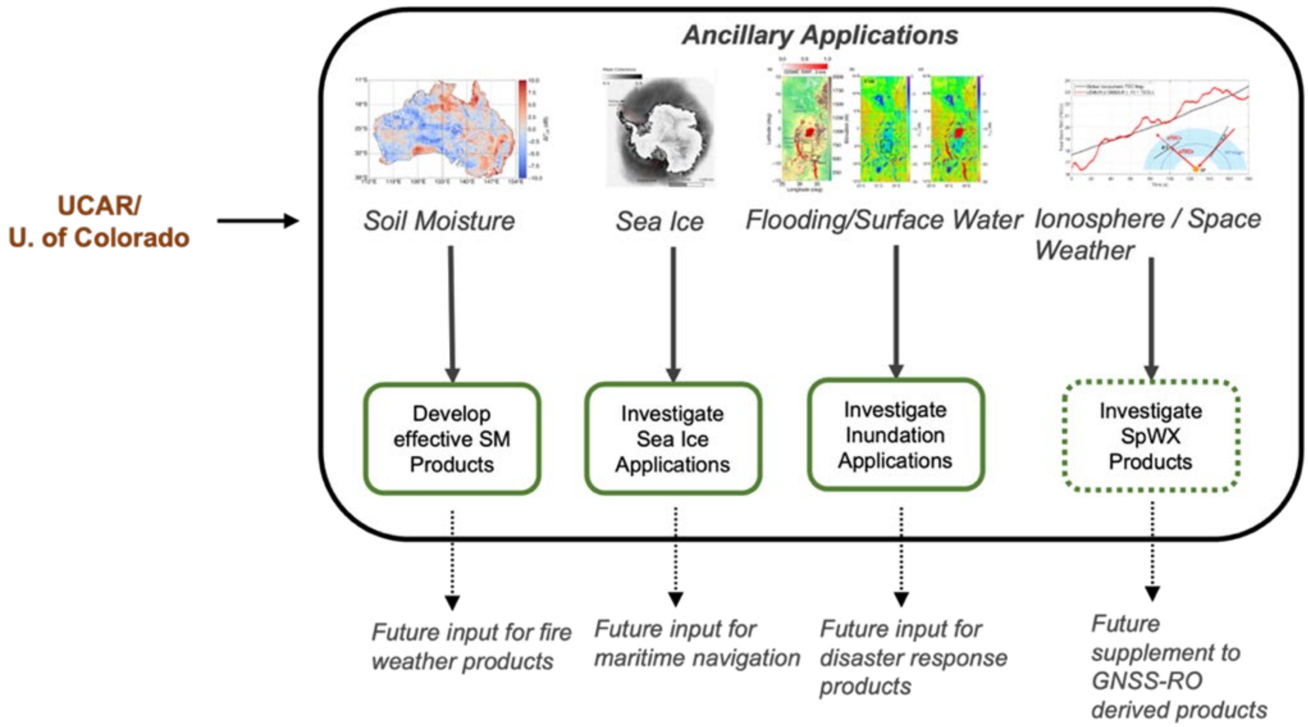
1.2.5 STAR OSW Product Development

The STAR team evaluated and fully characterized the Spire GNSS-R Level 1 (L1) data and Level 2 (L2) OSW product. STAR discovered that for Spire L2 OSW products, wind speed biases lead to inconsistent performance, resulting in loss of product confidence. As a result, the STAR team decided to adapt the NOAA CYGNSS wind retrieval algorithm to the Spire dataset. In support of STAR, the JCSDA also examined the characteristics of the NOAA L2 Spire OSW product in comparison to the Spire L2 OSW product.

1.2.6 UCAR Ancillary Product Development

The utility of commercial GNSS-R data for ancillary applications was investigated by UCAR and the University of Colorado. Figure 1-2 illustrates the ancillary Pilot activities, participating organizations, and potential operational products.

Figure 1-2: Reported Ancillary Pilot Activities



1.3 STAR Summary

1.3.1 STAR Analysis Objective

STAR evaluated GNSS-R Ocean Surface Wind (OSW) products from the context of supporting NOAA’s operational weather forecasting and warning mission: if GNSS-R OSW product is of sufficient quality and consistency and positively impact NOAA’s weather mission, then satellite-based GNSS-R measurements could potentially augment the measurements provided by dedicated OSW satellite systems at a relatively low cost.

1.3.2 STAR Pilot Product Development Activities

The STAR team evaluated and fully characterized the Spire GNSS-R Level 1 data and Level 2 OSW product. STAR discovered that for Level 2 OSW products, wind speed biases associated with satellite antennas lead to inconsistent performance, resulting in loss of product confidence. As a result, the STAR team decided to adapt the NOAA CYGNSS wind retrieval algorithm to the Spire dataset. STAR successfully adapted the wind retrieval algorithm, resulting in much higher wind speed retrieval from the NOAA Spire wind product compared to the Spire derived ocean wind speed product. In late December 2024, a final version was released and daily map images of the NOAA Spire wind product including wind speed biases and relevant monitoring plots were made available on the STAR website.

1.3.3 STAR Pilot Conclusions and Recommendations

The initial commercial data pilot using data from Spire confirmed the technology's potential (similar to the NASA CYGNSS mission) but highlighted a primary technical challenge: accurate retrieval becomes more difficult at high wind speeds due to reduced signal reflection.

The initial CWDP data from Spire was of limited quantity, and the team’s analysis revealed similar challenges and potential utility as previously observed in NASA CYGNSS data. Despite its challenges, GNSS-R ocean winds speed retrievals have value in being able to fill in the temporal and spatial gaps of the existing satellite ocean wind observing system supporting the operational weather mission. The initial CWDP did not overlap the hurricane season or winter storms season, which hindered the team’s ability to quantify the impact of these data to the operational weather mission. Additionally, there are now GNSS-R receivers with high gain antennas, which will improve the quality and consistency of retrievals at higher wind speeds.

STAR strongly recommended that a follow-on study is warranted to fully ascertain the value and capability of GNSS-R for NOAA’s satellite ocean wind observing system portfolio. This next phase should include:

1. **Coverage of major storm seasons.**
2. **Evaluation of newer high-gain GNSS-R antennas designed to improve data quality and consistency at higher wind speeds.**

1.4 UCAR Summary

A team from the UCAR COSMIC Program and University of Colorado Aerospace Engineering Sciences Departments (CU) participated in the Ocean Surface Winds Data Pilot to evaluate and validate science products for applications including ocean surface winds, sea ice, inland water bodies, soil moisture, and soil inundation.

The vendor data utilized included both near nadir (NN) reflection observations from Earthward facing antennas as well as grazing angle (GA) reflection observations collected on limb-viewing radio occultation antennas. NN delay Doppler map (DDM) observations were used to retrieve soil moisture, map inland water bodies and flood inundation, and detect sea ice. GA reflection carrier phase measurements, a different type of observation than DDMs, were used to map inland water bodies and conduct case studies of inland lake altimetry retrieval and observation of ionospheric scintillation effects.

1.4.1 UCAR Pilot Conclusions

UCAR found that the Spire GNSS-R data provided for this data pilot, with appropriate quality control, are in general of high quality and suitable for multiple land, inland water body, and sea ice applications relevant to NOAA.

Key results from the UCAR analyses are:

- Based on engineering assessments, Spire provided sufficient numbers of observations per satellite to sample up to ~30% of the Earth's surface per day at 36km resolution. This fraction is lower with higher resolution grids and is simply a function of the number of satellites participating and the number of GNSS-R observations each satellite collects per day.

- Soil moisture retrievals using NN reflection observations over Australia agree well with independent NASA Soil Moisture Active Passive (SMAP) data. The level of agreement is comparable to using active radar backscattered signals to measure soil moisture.

- Inland water body mapping and retrieval of surface water fraction was demonstrated using NN reflection observations in multiple case studies of the Tibetan Plateau and East Africa. Comparison to a standard independent surface water fraction database indicates very good performance for water detection using the Spire GNSS-R data.

- Spire GNSS-R data was used to map soil inundation dynamics in East Africa through monthly reflectivity maps and identifies soil inundation (flooding) events in areas that are not typically covered by water. Reflectivity maps also illustrate the drainage processes at two sites, consistent with Sentinel-2 optical results.

- Relatively sparse GNSS-R observations can be interpolated to higher 3km resolution with the aid of SMAP data and the Previously Observed Behavior Interpolation technique. When applied to soil moisture retrieval using Spire data in the Southeastern US, this approach achieves average agreement with CYGNSS and average agreement with in-situ soil moisture sensors.

- Spire DDM based sea ice detection was demonstrated to map sea ice extent and seasonal evolution in the polar regions. Monthly 25 km resolution maps generated for both poles for Jan-Jul 2024 show expected seasonal trends. UCAR also found typically ~90% ice presence detection agreement compared to independent AMSR-2 observations.

- GA reflection observations were used for an altimetry case study at Tonle Sap Lake (Cambodia). Results from the Spire data are in close agreement with the NASA Surface Water Ocean Topography mission and accurately retrieved water level changes between 2023 and 2024.

- GA reflection data were also used to map small lakes in Northwestern Canada using a deep learning model, and achieved an accuracy score of ~90% compared to Landsat truth data.

- GA reflection carrier phase observations provided insight into ionosphere scintillation affecting the measurement link. Scintillation amplitude and phase indices were examined for the May 9-12, 2024 solar storm event and clearly track disturbed conditions during the onset and main phases of the event. The observed trends agree with ground receiver scintillation indices. GNSS-R based scintillation information could complement traditional ground- and space-based GNSS scintillation observations

1.4.2 UCAR Pilot Recommendations

As NOAA considers a future GNSS-R data pilot involving one or more vendors, UCAR recommended:

- If possible, **obtain data from more than one vendor** and design the data collection requirements such that statistically significant volumes of collocated observations are available from certain regions representing open ocean, sea ice, and different land types, on timescales of one day to one week. This would enable both intercomparison/intercalibration of results between contributing constellations and production of combined environmental data records. This would also provide a benefit from improved spatiotemporal coverage.

- Evaluate **reflection observations from higher gain antennas** to demonstrate benefits for retrievals of stronger ocean surface winds and land parameters.

- **Increase the number of daily observation tracks** required in total per constellation and per spacecraft. This could significantly improve global coverage and refresh to enable production of lower latency global monitoring products.

- **Include additional end users in the evaluation and develop data product pipelines** to these users. An obvious candidate would be the National Ice Center, which synthesizes ice information from different observing systems. The Ice Center could evaluate how GNSS-R ice observations complement their analysis products. Another end user evaluation focusing on the use of Earth surface models applied in global NWP would also be insightful. This could potentially have relevance to the Coordination Group for Meteorological Satellites International Earth Surface Working Group that focuses on surface-atmosphere interactions for Earth system models.

- Investigate how GNSS-R ionosphere observations may complement traditional ground and space radio occultation scintillation observations. This could be explored together with NOAA's Space Weather Prediction Center.

- **Finally, a second GNSS-R data pilot should aim to develop some routine operational paths from observation delivery to processing to end user applications**. This could be done similarly to the 2023-2024 Space Weather Data Pilot, where product development/assessment was done in parallel with developmental near real-time processing and product delivery. Although products were continually refined and reprocessed during the pilot, implementing developmental, quasi-operational processing resulted in established data paths and end user ingest procedures that were straightforward to promote into operations after the pilot. Promising near real-time product pipelines to develop could be for ocean surface wind, sea ice, and scintillation monitoring.

1.5 JCSDA Summary

1.5.1 JCSDA Data Assimilation Testing

Through the pilot project, JCSDA demonstrated and established a positive impact of the Spire OSW product in the Joint Effort for Data assimilation Integration (JEDI) data assimilation system. JEDI is a unified, modular, and community-driven data assimilation framework designed to enable advanced, flexible assimilation of Earth observation data across NOAA, NASA, the Navy, Air Force, and international partners. This allows JCSDA to deliver direct guidance and configuration instructions to those at NOAA and their partners with similarly JEDI-based systems. JCSDA has conducted observing system experiments (OSEs), which are not designed to replicate an operational environment, but rather to accentuate the new data sources, helping to identify problems and systematic issues.

1.5.2 JCSDA Pilot Conclusions

Overall, the Spire GNSS-R OSW shows a positive impact on the OSE. The greatest impacts are on the zonal wind and temperature, and are larger outside the tropical regions. The impact on temperature will be greatly reduced in a full observing system, particularly one containing satellite radiances. The GNSS-R OSW Spire product and generation of receivers employed in this pilot were sensitive to relatively low wind speeds, typically less than 15 m/s. These observations, by their nature, would generally not have as significant an impact as a sensor that provides profiles or is sensitive to a wider range of wind speeds. The ability of the Spire receivers to track multiple transmitters simultaneously allows a greater number of GNSS-R reflection tracks per receiver compared to CYGNSS. However, the volume of the data would likely need to be greatly increased to provide a more significant impact for the current range of OSW speeds retrieved. We find the Spire OSW to be a reliably delivered and high-quality GNSS-R based product, with a moderate to low overall impact on average.

Unique orbits or sampling would increase the impact of the offering. However, it is important to note that there are examples of the Spire data providing unique observations in regions not covered by programs of record, and could be situationally of greater importance.

The JCSDA has also examined the NOAA Level 2 (L2) Spire OSW product. The NOAA L2 product appears to harmonize treatment of CYGNSS and Spire data and this product also offers characteristics, like reduced correlation between observations and an overall better fit to background forecasts, that are suitable for operational assimilation. The GNSS-R technology overall is proving viable for OSW retrieval and ready for promotional testing by NOAA operations and their partners.

1.6 QOSAP and EMC Summary

1.6.1 QOSAP Contributions

The Quantitative Observing System Assessment Program and EMC provided contributions to the CDP Pilot/Ocean Surface Winds (OSW) including:

1. Tuned data assimilation (DA) algorithms for OSW observations using NOAA-derived Cyclone Global Navigation Satellite System (CYGNSS) OSW retrievals as a testing dataset.

2. Quantified the impact of CYGNSS OSW retrievals on global weather forecasting using NOAA's global numerical weather prediction system (e.g. GFS).

3. Quantified the impact of Spire OSW retrievals on hurricane weather forecasting using NOAA's hurricane numerical weather prediction system (e.g. HAFS).

1.6.2 QOSAP Observations

The impact of the assimilation of Spire OSW was evaluated for a 1.5-month period (1 June – 15 July, 2024). OSW observations were assimilated using the quality controls developed for CYGNSS, while observation errors were adjusted according to the Spire data. The impact of Spire OSW in GFS was neutral, likely due to the low number of available observations.

The impact of assimilating Spire OSW data for Hurricane Beryl (June 29-July 9, 2024) was investigated with Hurricane Analysis and Forecast System (HAFS). Due to the limited number of observations in the tropical region and the relatively smaller HAFS inner domain, most of the Spire OSW benefits on tropical cyclone forecasts came through the initial and boundary conditions from GFS. QOSAP found positive impact in tropical cyclone (TC) track forecasts from the assimilation of Spire OSW, with the largest improvement (between 10-20%) seen for shorter lead times. A smaller improvement (up to 5%) was found for the longer lead times. Finally, the assimilation of Spire OSW observations resulted in more accurate surface wind fields at longer forecast lead times, leading to TC maximum wind speed forecast values closer to the observed values

1.7 Overall Summary and Recommendations

1.7.1 Pilot Results

The GNSS-R OSW Pilot succeeded in determining that **available commercial GNSS-R observations are a viable means of ocean wind monitoring, soil moisture characterization, land surface flooding/inundation, freeze/thaw events, and sea ice characterization.**

The Pilot's evaluation of Spire data confirmed the potential of commercial GNSS-R for ocean surface wind monitoring:

- STAR successfully evaluated the quality of commercial GNSS-R observations and adapted the NOAA CYGNSS wind retrieval algorithm to the Spire data, resulting in much higher wind speed retrieval from the NOAA OSW product compared to the Spire OSW product.

- **JCSDA demonstrated and established a positive impact of the Spire OSW product** in the Joint Effort for Data assimilation Integration (JEDI) data assimilation system. JCSDA determined that overall, Spire GNSS-R OSW data shows a positive impact on observing system experiments.

- QOSAP and EMC adapted data assimilation algorithms for OSW observations, quantified the impact of CYGNSS OSW retrievals on global weather forecasting, and quantified the impact of Spire OSW retrievals on hurricane weather forecasting. **QOSAP found that the assimilation of Spire OSW data contributed to improved tropical cyclone forecasts** in NOAA's Hurricane Analysis and Forecast System (HAFS). Spire OSW data provided a 10–20% improvement in short-lead track forecasts and yielded more accurate surface and maximum wind speed predictions.

- JCSDA examined the NOAA L2 Spire OSW product and **determined the product offers characteristics that are suitable for operational assimilation.**

- The JCSDA determined that the **GNSS-R technology overall is proving viable for OSW retrieval and ready for promotional testing by NOAA operations and their partners.**

UCAR and the University of Colorado determined **that commercial GNSS-R data is suitable for multiple land, water, and ice applications relevant to NOAA**. These include soil moisture monitoring, sea ice characterization, and inland water body and flooding evaluation.

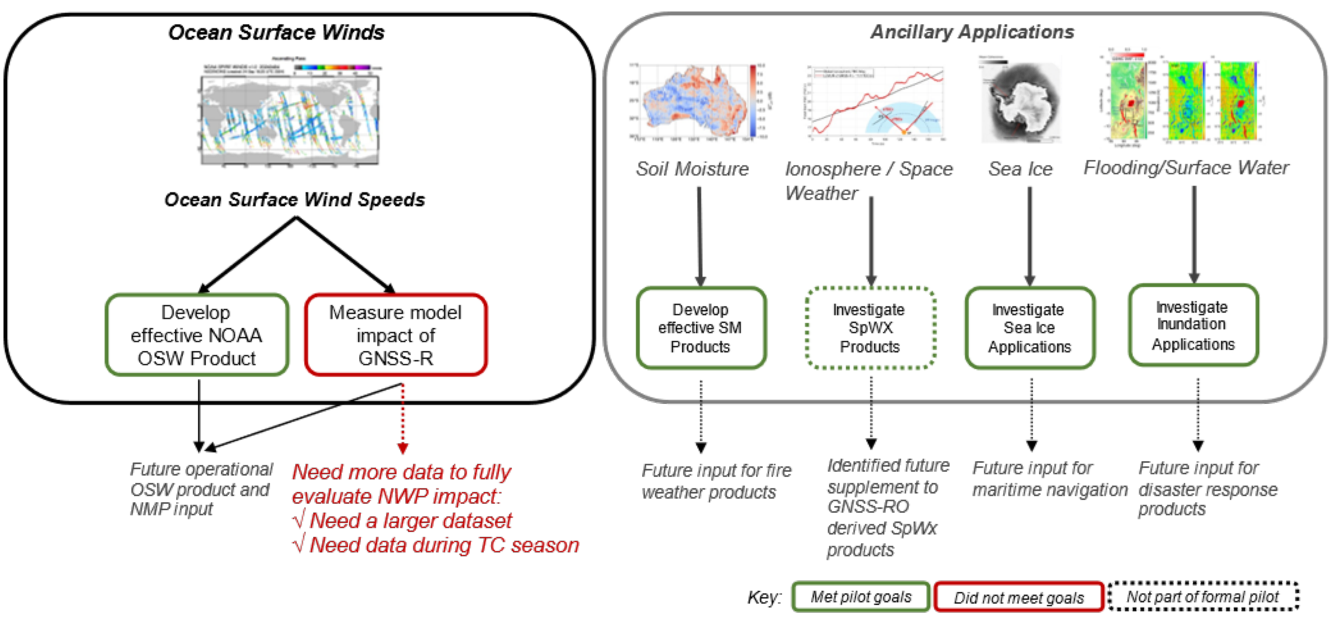
- Soil moisture retrievals agree well with independent NASA Soil Moisture Active Passive (SMAP) satellite data. GNSS-R data complements SMAP data and relatively sparse GNSS-R observations can be interpolated to higher resolutions with the aid of SMAP data.

- Inland water body mapping and retrieval of surface water fraction was demonstrated in multiple case studies and indicates very good performance for water detection using commercial GNSS-R data. GNSS-R observations were used for an altimetry case study with results in close agreement with the NASA Surface Water Ocean Topography mission. Reflection data were also used to map small lakes with results in close agreement with Landsat data.

- Sea ice detection using Spire GNSS-R data was demonstrated to map sea ice extent and seasonal evolution in the polar regions. Studies found high ice presence detection agreement compared to independent satellite radiometer observations.

- Ionosphere scintillation from GNSS-R was investigated and could complement traditional ground and space-based GNSS scintillation observations. Scintillation amplitude and phase indices were examined and observed trends agree with ground receiver scintillation indices.

Figure 1-3: The OSW Pilot results illustrated



The OSW Pilot was unable to fully achieve its objective of measuring the impact of GNSS-R OSW products for numerical weather prediction due to the following reasons:

The Spire Pilot data yielded insufficient tropical cyclone coverage within the Atlantic and Eastern Pacific ocean basins as the data collection period did not overlap the hurricane season. This hindered the team's ability to quantify the impact of OSW data to the operational weather mission.

The initial CWDP data from Spire was of limited quantity as Spire's constellation of GNSS-R satellites was intended for evaluation and not for full operational capability.

Due to the limited observation volume, QOSAP found that the assimilation of Spire OSW data had a neutral impact in the Global Forecast System (GFS).

1.7.2 Pilot Recommendations

All Pilot participants strongly recommended that a follow-on study is warranted to fully ascertain the value and capability of GNSS-R for NOAA's observing system portfolio and to develop a path for future operational data purchasing.

The follow-on Pilot should:

- Obtain coverage of major storm seasons.
- Obtain data from more than one vendor if possible.
- Obtain observations from new commercial high-gain GNSS-R antenna systems designed to improve data quality and consistency at higher wind speeds.
- Increase the number of daily observation tracks to improve global coverage.
- Include additional end users in the evaluation and develop data product pipelines to these users.
- Develop operational paths from observation delivery to processing to end user applications. Recommend creating near real-time product pipelines for ocean surface winds, soil moisture, flooding/inundation, sea ice, and scintillation monitoring.

Rationale for a follow-on Pilot designed to lead to operational data purchasing were considered and are summarized in the following table:

Table 7.1-1 Pilot Recommendations Table

Rationale	Pilot Activity	Path to Operational Purchasing
Seasonality	Collect data during the Atlantic and East Pacific tropical cyclone season	Better evaluation of high wind speeds and impact of GNSS-R OSW data on TC characterization and modeling
Data Volume	Collect larger quantities of data from multiple vendors	Better evaluation of impact of GNSS-R OSW data on weather models, quantify impact of commercial data in global weather forecasting and in hurricane forecasting
Additional Vendors	Collect data from new vendors	Develop ability to assimilate wider variety of vendor data for future operational purchases
SNR	Examine impact of improved signal to noise from high gain antennas	Evaluation of impact of better GNSS-R OSW data on TC winds and weather models
Timeline	Start timeline towards operational data buys	Reach goal of operational-ready data products for OSW

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