IMPACT ASSESSMENT OF ESA EARTH OBSERVATION EARLY R&D ACTIVITIES

Commercial GNSS-Radio Occultation Data

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FINAL

January 2025

Climate change mitigation necessitates reliable and timely information to increase resilience …

Effective weather forecasting and wider climate change mitigation efforts rely on the availability of reliable, timely, and precise information. The impacts of climate change in particular are evidenced by the growing frequency of significant weather events in Europe. Such events include record-breaking heatwaves across southern Europe in 2023 which resulted in wildfires, as well as significant flooding events in Germany, Belgium, and Spain in 2024 which caused significant loss of life and damage to property. The European Environment Agency reports that extreme weather events have caused economic losses of assets estimated at approximately €162 billion between 2021 and 2023.[1] A 2024 research study, meanwhile, suggests that there were 46,960 excess deaths within Europe because of heat in 2023.[2] These examples highlight the importance of accurate weather forecasting, and the need for real-time, actionable data.

The impact of reliable operational weather forecasting and early warning systems cannot be overstated, and such systems depend on accurate models to inform governments, industry, and communities of weather events threats, allowing time for pre-emptive measures. For example, flood risk management depends on precise precipitation data and modelling to issue alerts and design adaptive infrastructure, temperature forecasts help energy providers manage spikes in demand during heatwaves, while enhanced storm prediction and tracking enables early evacuation. By enhancing the data available to understand these activities, effective weather forecasting can reduce risk to life and property through enhanced preparedness and early-response, as well as reducing the potential financial costs associated with disaster response and recovery.

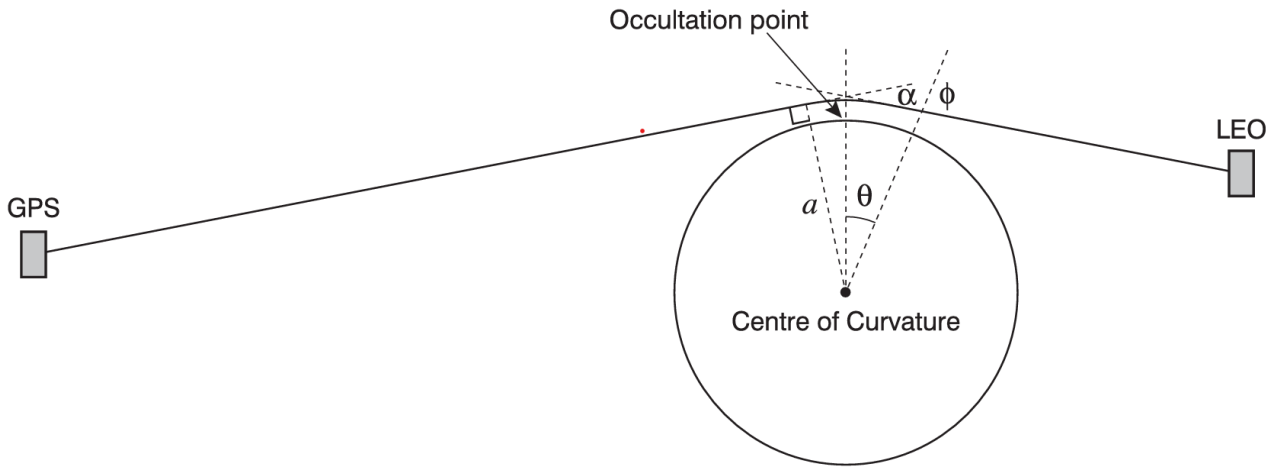
Satellite data is key to observing Earth's atmosphere, oceans, and surface. In Europe, organisations such as the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the European Centre for Medium-Range Weather Forecasts (ECMWF) leverage satellite systems to support climate research and operational meteorology. One of the most valuable tools in this effort is Global Navigation Satellite System - Radio Occultation (GNSS-RO), which measures the bending of radio signals as they pass through the atmosphere to provide highly accurate data on temperature, pressure, and humidity.

[1] European Environment Agency (2024). *Economic losses from weather- and climate-related extremes in Europe.* Available at: www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related

[2] Gallo, E, Quijal-Zamorano, M., Méndez Turrubiates, R.F. et al. (2024). "Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health," *Nat Med* 30, 3101-3105. Available at https://doi.org/10.1038/s41591-024-03186-1

GNSS-RO data offers two key benefits for forecasting in comparison to other data types. It provides precise, high-resolution vertical profiles of the atmosphere, and the data is immune from calibration drift, ensuring consistency and reliability for long-term climate trend analysis. Unlike many other satellite-based observation systems that rely on visible or infrared radiation, GNSS-RO can operate independently of weather conditions, and is unaffected by clouds, precipitation, or other phenomena that might interfere with traditional sensing methods. Though EUMETSAT's own assets already provide GNSS-RO data, the inclusion of commercial datasets, such as those provided by Spire, improve forecasting abilities and overall resilience through the provision of larger, more diverse datasets to complement existing approaches.

Figure 1: The geometry of the GNSS-RO measurement technique



Source: Final Technical Note of "Impact assessment of commercial GNSS-RO data"

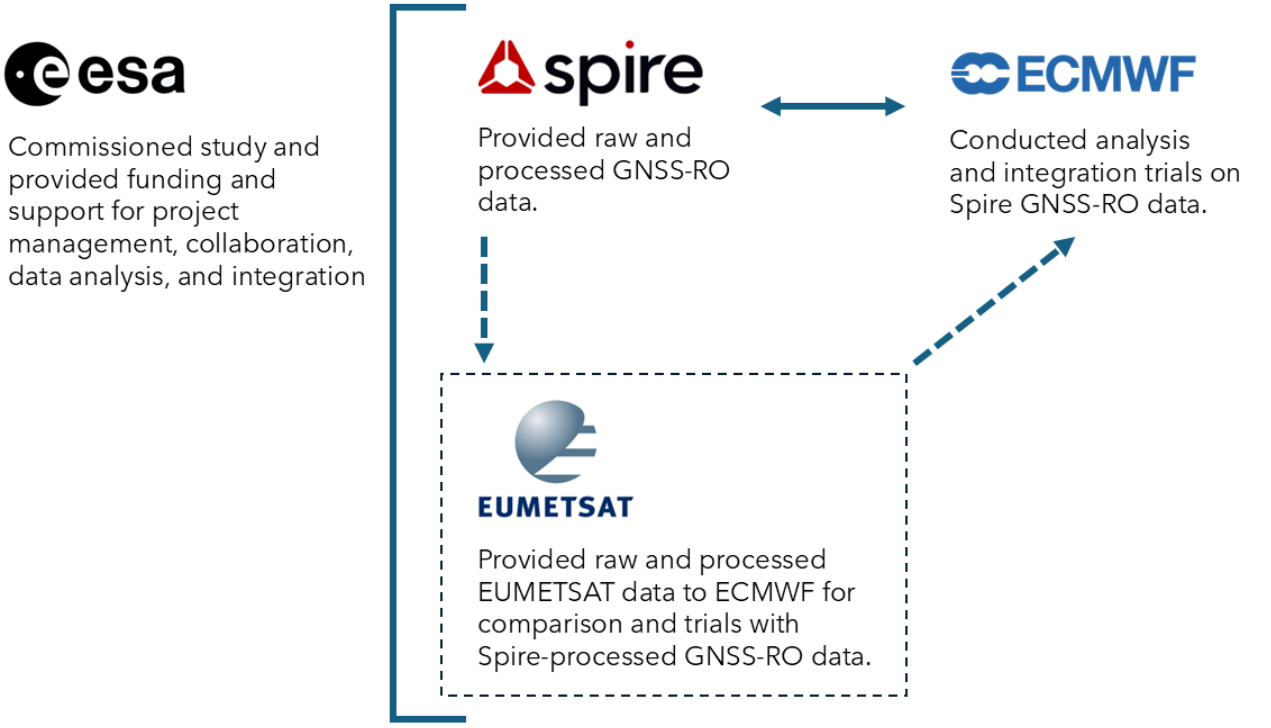
GNSS-RO also has applications that extend beyond meteorology. In ionosphere research, for example, it analyses delays in GNSS signals to monitor electron density, and GNSS-RO data has been used to detect pressure waves from volcanic eruptions, demonstrating its utility in geophysical and disaster preparedness. Spire also reported that the same payloads can be used for dual-use purposes, such as GNSS jamming detection, highlighting the versatility of these assets to both civil and defence users.

… and the inclusion of commercial satellite data sources, supported by ESA funding, can help to meet this requirement …

The '*Impact Assessment of Commercial GNSS-RO data*' study was designed to assess and demonstrate the quality and value of commercial GNSS-RO data provided by Spire for operational numerical weather prediction (NWP).

This study, led by ECMWF, received funding through the ESA FutureEO programme[3] and successfully demonstrated - via independent GNSS-RO experts between July 2020 and July 2021 - the feasibility and value of integrating commercial GNSS-RO data into short- and medium-range operational weather forecasting models.

Figure 2: Overview of partner organisations, and relationships, involved in the Impact Assessment Study



The study was undertaken by ECMWF, a global leader in NWP, who provide global medium- to long-term weather forecasts and climate data to its member states and partners.[4] Spire, meanwhile, is a satellite-powered data company with a presence in the United Kingdom, Luxembourg, Germany, and the United States, which operates a constellation of multi-payload nanosatellites to collect near real-time data. It is currently the only commercial provider of GNSS-RO data in Europe. EUMETSAT, with over two decades of experience in GNSS-RO data processing through the MetOp programme, was also affiliated to this study

[3] The ESA FutureEO programme is a long-term initiative aimed at developing innovative EO technologies, missions, and applications. It focuses on developing research, including promoting the use of new observation techniques. By supporting early-stage research and development projects, and exploring novel mission ideas, FutureEO seeks to maintain European leadership in EO.
[4] ECMWF is an independent intergovernmental organisation supported by 23 Member States and 12 co-operating States. Member States include Austria, Belgium, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Serbia, Slovenia, Spain, Sweden, Switzerland, Türkiye, and the United Kingdom. Co-operating States are Bulgaria, Czech Republic, Georgia, Hungary, Israel, Latvia, Lithuania, Montenegro, Morocco, North Macedonia, Romania, and Slovakia.

and processed Spire GNSS-RO raw data (level 0) to further validate the Spire processing chain. It is important to stress the importance of independent expert assessment of data, which is separate from the data suppliers (i.e. Spire) own processes. It is worth noting that the UK MetOffice also analysed parts of the data in parallel with ECMWF, as part of separate assessment efforts, to enable comparative analysis and integration activities for the study.

This ECMWF-led *Impact Assessment* study, funded by the FutureEO programme, built upon three ESA precursor activities, conducted with Spire, related to GNSS-RO data provision and utilisation. These included a technical baseline study through the ESA Advanced Research in Telecommunications Systems (ARTES) programme where RO observations were delivered as part of the project, alongside a precursor integration assessment by the UK Met Office of the impact of Spire GNSS-RO data. Building on this, the second activity - funded through the FutureEO programme - was a verification and operational testing study to assess the quality of 30,000 RO observations provided by Spire including undertaking comparisons to MetOp and GNOS[5] datasets to evaluate quality, with the final result being assessed as 'promising'. The third activity was undertaken at the European Space Research Institute, where they conducted an Earthnet Data Assessment Pilot (EDAP) project with a view to providing a framework for integrating non-ESA (Third Party Missions) into the overall ESA EO strategy.[6]

The ECMWF-led impact study also built on an existing, and exceptional, operational use of Spire GNSS-RO commercial data during the COVID-19 pandemic. The provision of this commercial data helped to bridge a significant gap which had emerged in spring 2020 in the wake of global air-traffic reductions due to the pandemic, reflecting the fact that a large proportion of meteorological data is provided by aircraft in-flight. In response to this, Spire provided, free-of-charge, datasets to ECMWF. These datasets were subsequently integrated into the existing operational forecasting models. The success of this rapid operational integration meant that, though formal testing and validation was still required to assess the potential of long-term use of the data – the purpose of this project – the project team (ECMWF, UK MetOffice and EUMETSAT) were familiar with the data (including processing and quality) and had confidence in the suitability of the data for NWP purposes.

These precursor activities are beyond the scope of this particular case study but are mentioned to highlight the range of projects that enabled the *Impact Assessment of GNSS-*

[5] MetOp is the European Meteorological Operational Satellite Programme, a series of weather satellites operated by EUMETSAT in collaboration with ESA. GNOS is the GNSS Occultation Sounder from China, an instrument designed for atmospheric and ionospheric sounding using signals from the GNSS system.
[6] ESA published a new EO Science Strategy, *Earth Science in Action for Tomorrow's World* in September 2024. Though the three precursor activities, including the EDAP project, predated the publication of this strategy, these early activities contribute to the overarching objective to harness satellite data to develop "our collective understanding of the Earth system as a whole".
The new strategy is available at: www.esa.int/Applications/Observing_the_Earth/ESA_releases_new_strategy_for_Earth_observation

RO data study. The remainder of this report focuses on the benefits and impacts of the ECMWF-led impact assessment study.

… by helping improve weather forecasting …

The *Impact Assessment* study established that the inclusion of commercial Spire RO observations into the NWP system was beneficial to the quality and accuracy of forecasting models. The final assessment noted in particular an overall improvement in forecasting, pointing towards specific improvements in temperature, humidity, and wind forecasting in some geographic areas, particularly in the Tropics, and in the Southern Hemisphere. For example, the ECMWF assessment demonstrated an 11% improvement in temperature observations in the Tropics.[7] In the same region, wind forecast scores improved by approximately 2% between forecast days 1 and 4 at altitudes of between 5-6 km and 16-20 km. Such improvements are cumulative, and any improvements in forecasting abilities and accuracy are welcomed, as is the increased resilience that is offered by multiple data sources. The overall conclusion was that both ECMWF and the UK Met Office would assimilate the Spire GNSS-RO data operationally if, and when, it becomes available for use.[8] This impact assessment, funded by FutureEO, supports European space ambitions by demonstrating the value of public-private collaboration in advancing EO capabilities. This study - and the first integration of commercial observations into ECMWF NWP models - provides a pathway for future partnerships and collaborations and highlights the opportunity for commercial providers to have their data evaluated with a view of delivering high-precision, operationally relevant datasets. This continued improvement reinforces the perception of European forecasting as amongst the best in the world and underscores its commitment to harnessing cutting-edge technologies and partnerships to deliver resilient and timely services to its people.

… delivering valuable socio-economic benefits

Notwithstanding the observed improvements in forecasting, this study also produced important human capital and knowledge benefits, as well as laying the foundations for potential future collaborations and partnerships.

[7] This improvement relates to radiosonde temperature observations at 100 hPA; typically associated with the stratosphere, a layer of Earth's atmosphere at an altitude of roughly 16–20 km (10–12 miles) above sea level. The improvement is based on the addition of Spire and COSMIC-2 data to NWP systems. The UK MetOffice reported the improvement at 15% based on their own evaluation.
[8] ECMWF does not purchase observational data directly. Instead, it receives data from EUMETSAT, which either acquires the data from their own satellites, or procures it from third parties. EUMETSAT processes and disseminates this data to ECMWF for use in NWP systems and related applications.

Harnessing existing technologies to improve data, forecasting and resilience

GNSS-RO leverages existing technologies to enhance weather forecasting, climate monitoring, and terrestrial decision-making processes.

The provision of GNSS-RO data is not new, and several satellite missions already provide GNSS-RO data for weather forecasting, climate monitoring, and atmospheric research. Notable missions include Metop's GPS-Based Atmospheric Sounder (GRAS), the six satellites of the US-Taiwanese COSMIC-2 mission, Spire's own constellation of Lemur satellites equipped with GNSS-RO payloads, and PlanetIQ's GNOMES satellites which provide over 2,200 GNSS-RO profiles per day to support the US National Oceanic and Atmospheric Administration's Commercial Weather Data Program.

Commercial GNSS-RO is a cost-effective solution to data provision, as it leverages existing GNSS-RO institutional infrastructure. The compactness of GNSS-RO, with inexpensive receivers can be hosted on small satellites, reducing development and launch costs. By using small-satellite constellations, for example, GNSS-RO collects substantial datasets at a fraction of the cost of traditional systems, making it a high-value tool for weather forecasting and climate monitoring. Its precision and (relative) cost-effectiveness position it as a key enabler of improved forecasting, helping to address the challenges posed by climate change and enabling better decision-making and responses.

The Impact Assessment study demonstrated that the NWP improvements were possible thanks to the significantly larger number of GNSS-RO measurements coming from the nanosatellites in the Spire constellation. Important system questions for future Earth Observation systems could finally be answered. The combination of GNSS-RO instruments in one or two large satellites works well with the miniaturised and cost-effective measurements from nanosatellites because the greater temporal sampling of the very dynamic atmosphere is more important than the slightly degraded quality in each individual smaller satellite. This study also demonstrated that the quality of data obtained via Spire's satellites was very similar to that of larger satellites (such as COSMIC-2), and that degradation of data was deemed to be less of an issue. Whilst larger platforms offer the opportunity for longer orbital lifespans, they are expensive to design, manufacture and deploy; nanosatellites have demonstrated an ability to provide cost-effective and high-quality datasets. Although this cannot be generalised to non GNSS-RO measurements, a methodology has been established: more impact assessment studies will be needed to prove that commercial data can bring value and complement expensive missions.

Utilising commercial data also aligns with a broader ambition within Europe to foster faster innovation and utilise space-based capabilities to find solutions to global challenges. In this sense, the integration of commercial data sources, such as Spire's GNSS-RO data, contributes to the wider effort to address climate change by improving atmospheric monitoring, and contributing to the accuracy of information used to inform decisions related to disaster relief and, more broadly, long-term environmental policies. The study, though specific to Spire's GNSS-RO data, exemplifies how existing technologies can be harnessed to create more robust and adaptive EO systems.

Fostering public-private collaboration

The collaboration between Spire, ECMWF, EUMETSAT and ESA showcased the potential of public-commercial partnerships to integrate commercial data in NWP, developing trust, processes, and new frameworks for collaboration, while addressing global challenges to ensure mutual benefit and long-term sustainability.

As previously highlighted, during the COVID-19 pandemic, Spire demonstrated the potential value of public-private sector collaboration by providing GNSS-RO data to ECMWF for 3 months in the spring of 2020 free of charge. This initiative demonstrated not only the technical and operational viability of commercial data integration, in exceptional circumstances, but also highlighted the willingness and ability of the commercial sector to support critical public services, and a willingness from ECMWF to integrate new data sources.

In addition to the COVID-19 efforts, a more scientifically rigorous Impact Assessment study funded under FutureEO was needed between July 2020 and July 2021. The success of this Impact Assessment enabled EUMETSAT, as the principal customer of meteorological data, to have confidence in the viability of Spire's GNSS-RO data, but also to develop the inter-organisational relationships and contacts that are central to the development of future commercial partnerships. The success of these relationships is also evidenced by Spire's emergence as the first European, and currently only, commercial supplier of meteorological data to EUMETSAT.

At a practical level, the project sustained the role of one scientist (A2) grade at ECMWF for one year, supported by a senior scientist who aided in managing the project based on their existing skills and experience. A noted benefit of this collaboration was the communication and management skills that were developed as part of working with new partners, particularly between scientists in different organisations. This is particularly relevant given the different ways of communicating – driven by different priorities – that often exist between commercial and institutional organisations. The partnership between Spire and ECMWF / UK MetOffice / EUMETSAT scientists, and the specific focus on validating and integrating Spire GNSS-RO

data also led to the continuous improvement of data and processes in both organisations, adapting to the requirements of a public-commercial partnership and ensured that data was of the correct standard and fidelity to enhance existing forecasting models.

Acting as a bridge between institutional and commercial partners, ESA has enabled a new framework for collaboration. This framework specifically enables the inclusion of third-party missions (such as Spire's) to be included in institutional and eventually operational (subject to data validation and verification) NWP. These efforts have helped to develop and foster trust, align goals, and create opportunities for collaboration by leveraging the unique strengths of both sectors. These experiences include ESA's project management and facilitation experience, ECMWF's world-class forecasting reputation, EUMETSAT's provision of high-quality datasets, and Spire's globally deployed satellite constellation and experience of commercial data provision in the US.

As these partnerships evolve, new ways of working, and new processes, will emerge. Lessons will also continue to be identified and learnt through addressing potential challenges, including around differences in standards, potential data integration challenges, and divergences in priorities. By establishing and refining processes, such as public-commercial collaboration, data processing standards, and requirements and methods of integration, this study has established a baseline for a more integrated and effective approach to leveraging commercial capabilities in support of European institutional, and global, missions.

Enabling future commercial involvement in European forecasting

The integration of commercial data into European forecasting systems demonstrates the potential for commercial data to enhance operational NWP systems, foster innovation, and stimulate competition, while establishing a pathway for expanding the role of commercial contributions.

The integration of commercial data into European forecasting systems represents a step forward in enhancing operational NWP systems. Whilst such inclusion will always be on a case-by-case basis, with each data provider and data type being subject to rigorous evaluation, this particular Impact Assessment study (of Spire GNSS-RO data) under FutureEO acted as a proof-of-concept where data was acquired for assessment, with a view of potentially deploying it within an operational system.

This project also demonstrates an openness within Europe to explore commercial data solutions, fostering a more inclusive and innovative approach to data sourcing. It also represents a milestone which highlights the potential value, and viability, of commercial data services to augment and enhance existing institutional meteorological observation systems.

This project establishes a clear and proven pathway for data validation and integration into institutional NWP systems, encouraging companies to invest in and develop GNSS-RO and other related or adjacent technologies. This not only increases competition within the commercial sector but has the potential to stimulate innovation in GNSS-RO, leading to more diverse and potentially cost-effective solutions for atmospheric observations. Furthermore, the success of this project creates a foundation for assessing commercial data, expanding the scope of commercial-sector contributions to European forecasting systems. In doing so, it paves the way for an ecosystem where public and commercial partnerships drive advancements in meteorological science, and operational capabilities.

Enhanced reputation and visibility

The validation of Spire's data enhances its reputation and visibility as a trusted GNSS RO data provider, while strengthening ESA, ECMWF, and EUMETSAT's standing as reliable institutional and commercial partners.

The validation of Spire's GNSS-RO data by ECMWF demonstrates that Spire can successfully fulfil the stringent technical and project delivery requirements that are necessary to ensure accurate and timely forecasts. Through its participation in this study and building on its previous collaborations with ESA and ECMWF, Spire has established itself as a credible and trustworthy commercial partner with the capability to provide high-quality GNSS-RO data that can contribute to operational forecasting.

ESA, ECMWF, and EUMETSAT also benefit from these new commercial partnerships, such as that with Spire, not only through the enhanced accuracy and credibility of forecasting models due to additional data, but also as a result of access to a broader range of skills and experiences.

Future contracts for commercial data provision

The success of integrating Spire GNSS-RO data into ECMWF forecasts highlights the viability of commercial data services in operational meteorology.

Due to the success of this study, and the conclusion that Spire GNSS-RO data fulfils the quality and reliability required to be integrated and included within ECMWF forecasts, Spire have been awarded in July 2021 a three-year contract worth up to a maximum of €9 million to provide GNSS-RO data to EUMETSAT (extended to mid-2026).[9] This data is for

[9] EUMETSAT (2021). *In a first, EUMETSAT will buy meteorological data from a commercial supplier*. [Press Release]. Available at: www.eumetsat.int/first-eumetsat-will-buy-meteorological-data-commercial-supplier

operational use, and is used by a number of meteorological centres including ECMWF, the UK MetOffice, Météo-France, and Deutscher Wetterdienst (DWD, the German Weather Service). Whilst the award of this contract is specific to Spire, and to the provision of the assessed GNSS-RO datasets, it also demonstrates a potential entry route for other providers of commercial data. This contract is the first of its kind in Europe, representing the first time ever that EUMETSAT has purchased data from a commercial supplier.

ECMWF also reported that – building on this project – they are also investigating the potential integration and use of data obtained from other observation types, including new NWP applications with GNSS Reflectometry for sea winds or land moisture, and Polarimetric RO for precipitation.

Would these benefits have been realised without ESA?

It is unlikely that the benefits achieved would have been realised without the involvement of ESA and its funding of this study. The operational focus of EUMETSAT means that it is not in a position to undertake speculative or exploratory studies into the suitability of commercial datasets, recognising that the sheer volume of commercial providers makes this impractical. Similarly, ECMWF does not buy data directly, instead utilising that with which it is provided by EUMETSAT. The initiation of this Impact Assessment study under FutureEO was crucial to complementing, scientifically, the GNSS-RO data from Spire provided via ESA's Earthnet EDAP, and in enabling the subsequent analysis by independent end-users and partnerships that were required to see this project to successful completion.

ESA also played a pivotal role as a facilitator, not only through financial support to the study, but also by fostering collaboration between project partners and interested parties. ESA's involvement helped to establish new ways of working between these organisations, bridging industry-institutional gaps and helping to develop understanding. In doing so, ESA facilitated the alignment of objectives, and the exploitation of expertise from all involved parties. This facilitative role was as critical as the funding itself, ensuring that the benefits were realised in a coordinated, timely, and impactful manner.

> *"Activities from ESA in this area were extremely useful because it gave the European science community the opportunity to look at the data and see if it was valuable. That would not have been possible without ESA taking the lead and funding the study".* - EUMETSAT

ESA funding, therefore, was instrumental in enabling ECMWF to undertake the independent evaluation of the data, ultimately providing robust data validation for EUMETSAT's operational environment.

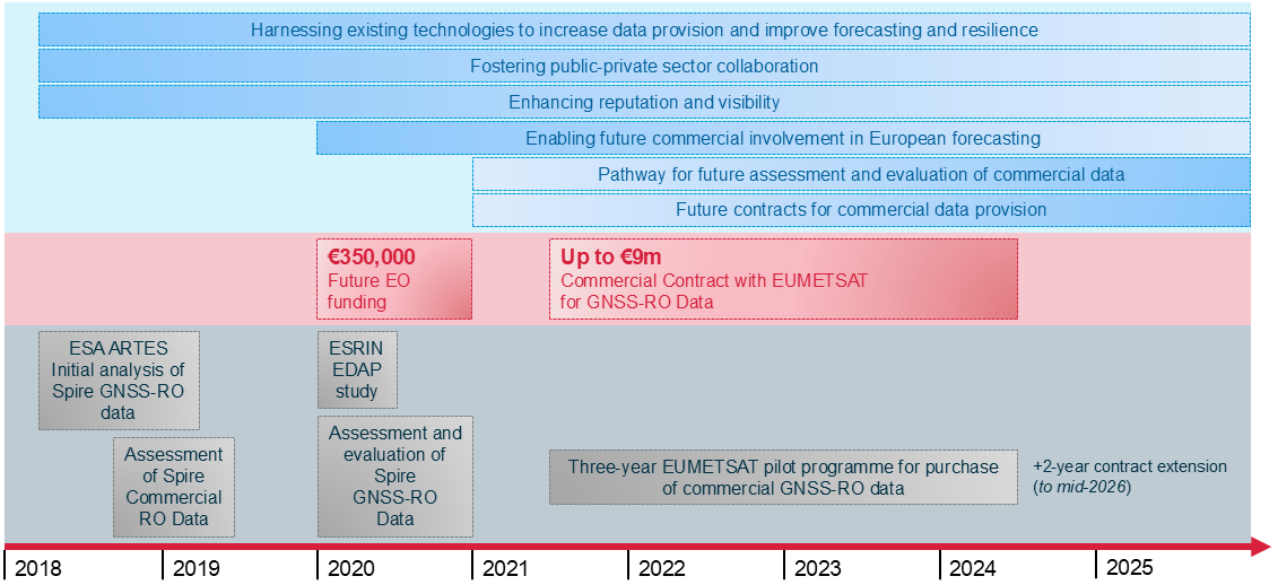
As mentioned earlier, the UK Met Office undertook its own assessment of Spire GNSS-RO data. While the UK Met Office's forecasts are also considered world leading, any data purchased by EUMETSAT and used by ECMWF must be validated according to EUMETSAT's own standards. It was noted that, naturally, national weather centres may approach data verification and validation in different ways, subject to their own needs, but that ultimately this provides an additional and independent layer of evidence. In this sense, the UK Met Office study findings reinforced the findings of the ECMWF study, thereby increasing overall confidence surrounding the integration of data into the NWP system.

Next steps: further development, further benefits

With commercial data proving its utility in enhancing NWP accuracy, the success of this project could act as a catalyst to encouraging other commercial providers to engage with institutional stakeholders like ESA, ECMWF, and EUMETSAT. This success could lead to new contracts, not only for GNSS-RO data but also for complementary commercial observational datasets; Spire in particular have developed satellites which are capable of producing GNSS Reflectometry (GNSS-R) data for ocean winds and soil moisture. Other potential datasets that may be generated, with appropriate equipment, include microwave soundings, hyperspectral imagery, and air quality measurements.

Whilst these new data types would be subject to rigorous evaluation and validation processes, their integration into operational forecasting systems could unlock additional benefits. These include improved forecasting of extreme weather events, better climate monitoring, and enhanced situational awareness for sectors like agriculture and transportation services. Furthermore, developing and growing the European commercial meteorological satellite data market may stimulate innovation – driving satellite operators to develop and deploy novel data collection tools and systems.

Figure 3: Overview of the timeline of the progress, and subsequent benefit realisation, of the commercial GNSS-RO data study



Source: know.space based on Spire, ECMWF, EUMETSAT and ESA data

An increase in satellite operators providing GNSS-RO data in Europe could also reduce costs as a result of greater competition, economies of scale, and common infrastructure. More operators would also increase data availability. For suppliers, such as Spire, an increase in market size will likely open up new commercial partnerships, as well as increasing demand for their products. More broadly, a diversified commercial base mitigates dependency on single sources, enhances market resilience and fosters cost-effective solutions for the end user (in this case, EUMETSAT and ECMWF), ultimately making high-quality weather and climate data more readily accessible.

Key priority indicators

Programme	FutureEO
Country	See ECMWF member states
Activity cost	-
Duration	12 months
Lead contractor	European Centre for Medium-Range Weather Forecasts (ECMWF) and Spire Global
Sub-contractors	In-kind support from EUMETSAT, and UK Met Office
TRL progression	-
Spin-in into the space sector	-
Jobs supported	1 (A2 grade scientist) at ECMWF
New collaboration with ESA	-
Partnerships created	Spire and EUMETSAT
Follow-on funding applied/secured	Three-year contract (2021-2024) worth up to a maximum of €9 million for Spire to provide GNSS-RO data, with an extension to mid-2026.