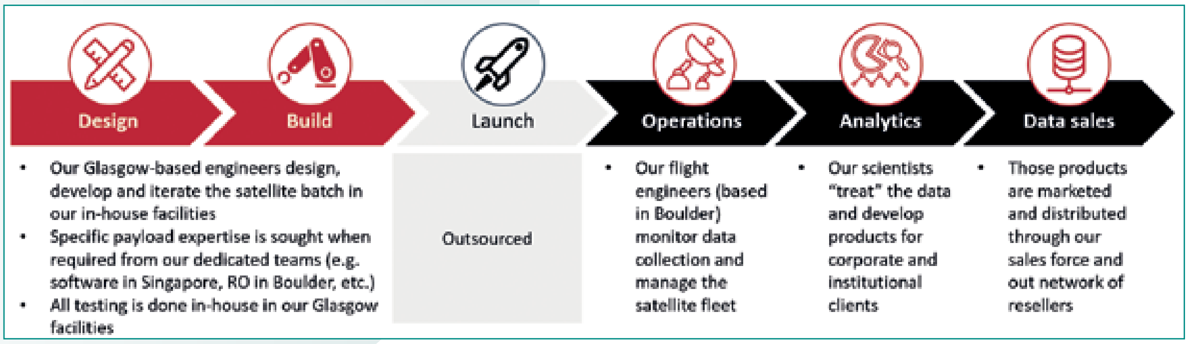
GNSS Radio Occultation in Advanced Numerical Weather Prediction Models

by Guillermo Bosch



Radio Occultation (RO) is a well-proven technique that goes back to the mid 1960's, when the satellite Mariner IV transmitted data while it was approaching Mars. In the moments as it disappeared behind the Red Planet, the transmitted signal, as viewed from Earth, passed through the thin Martian atmosphere, from its upper layers down to its surface. This represented history's first inter-planetary atmospheric and ionospheric radio occultation experiment. Minutes later, as the signal reappeared on the other side of Mars, the first rising radio occultation was observed from Earth.

After the Mars experiment, several other planets, as well as many bodies of the solar system, were studied through RO, until GPS-RO was used to study the Earth's atmosphere. Many experiments and proofs-of-concept followed, such as GPS/MET (April 1995), and NASA-sponsored international missions from 1998 through 2005 (SAC-C of Argentina, SUNSAT of South Africa, Oersted of Denmark, CHAMP of Germany, and GRACE of US and Germany). In April 2006, COSMIC-1 (Constellation Observing System for Meteorology, Ionosphere, and Climate), a fleet of six Low-Earth-Orbit (LEO) satellites mission, sponsored primarily by Taiwan's National Space Organization and managed in the U.S. by the University Corporation for Atmospheric Research (UCAR), become the first dedicated constellation for assessing the operational use of GPS-RO data in NWP models. When COSMIC-1 RO profiles were first used as a data source for NWP - they were providing about 150 occultations per day (eventually it would reach 3000 per day), several other small constellations or single satellites were launched for the same purpose. Today, METOP (3 satellites) are contributing with circa 600 ROs per day, KOMPSAT-5 with about 350 ROs/day and GNOS-FY3D with an estimated 800 ROs/day.

Spire's Technology, expertise and value chain

Spire Global is a company that started operations in 2012, with the mission to collect and to analyze advanced datasets from space. With almost complete control over its value chain, from the design of its satellites to the creation of innovative products that are designed from the data constantly generated by its growing satellite constel-

lation, it is one of the only two non-government companies in existence to manage a fleet of more than eighty satellites, and constantly relay their data to its cloud infrastructure through its integrated network of ground stations.
Manufacturing capacity is close to one satellite per week at its facilities. Spire has built on this hardware base an extensive series of key software and services, offering its clients a set of strong assets and differentiators based on global, straight-from-space data. This suite of products is analyzed and maintained by teams of scientists, distributed across our global offices, that have an ability to build unique, differentiating products, and to leverage unique data sets and decades of fundamental research in their given scientific field of expertise.

GNSS-RO. The Key to precise atmospheric Measurementes

Figure 1 shows a conceptual diagram of the principles of GNSS-RO. A GNSS satellite generates an L-band radio signal that is received by Spire's Low Earth Multi Unit Receiver (LEMUR) Satellites from the opposite side of the Earth. Both satellites need to have descending orbits relative to each other to be able to 'slice' the atmosphere as they reciprocally disappear over the horizon. Due to the refractivity of the atmosphere, radio waves experience bending during propagation from the GNSS satellite to Spire's LEMUR. Since atmospheric refractivity depends on temperature, pressure, and water vapor, measurement (called "soundings") of the bending angle (an absolute measurement, with no need for calibration), GNSS-RO allows us to retrieve accurate atmospheric profiles that are used in advanced NWP models. Once the bending angle and other geometric parameters are measured in a specific point in the atmosphere, data is pre-processed on-board and downloaded to Spire's proprietary current ground network of 32 stations. Once data is available for further processing, a climatology model is used to compensate for ionospheric effects and to calculate the ionosphere's Total Electron Content (TEC). At this point in the process, the refractivity profile and the associated temperature profile at the specific sounding point is obtained. While by their very nature and reach, other constellations or single satellites contribute to different NWP models with a smaller numbers of RO profiles, Spire's unique fleet of more than eighty LEMURs is currently measuring about 4000 RO profiles/day, with increasing numbers as Spire launches more satellites and uses the satellites of additional GNSS fleets. Today, Spire performs RO though the GPS and Galileo fleets. Incidentally, Spire is the only company in the world that preforms RO soundings using Galileo. Spire's GNSS-RO capability provides vertical profiles with high vertical resolution of 100m and 0.1oc temperature accuracy from the Mesopause (about 70 kilometers in the atmosphere) down to near the surface of the earth. This unique data set has been proven, according to studies by the European Centre for Medium-Range Weather Forecasting (ECMWF), to have a high impact on forecast accuracy and is a data set that Spire collects globally, including all land masses, oceans, poles, and extremely remote areas. The quality, accuracy and resolution of Spire's RO soundings are a new key dataset for any NWP. The two diagrams in Figure 2 below, show the quality of Spire's GNSS-RO temperature profiles (measured in K) taken by two independent Spire satellites at nearly the same location (mid-Pacific). Both show that there is an error in the National Weather Service (NWS) Global Forecast Service (GFS) model analysis in

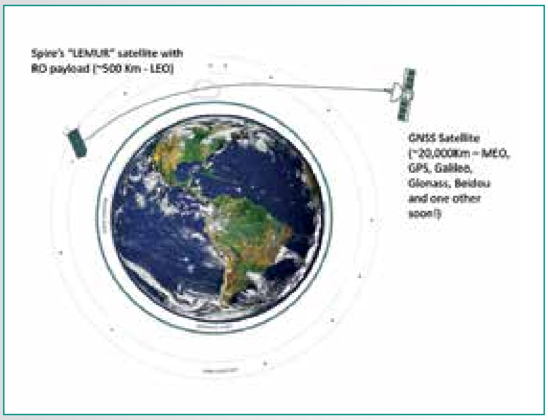


Fig. 1 - Conceptual diagram of the principles of GNSS-RO.

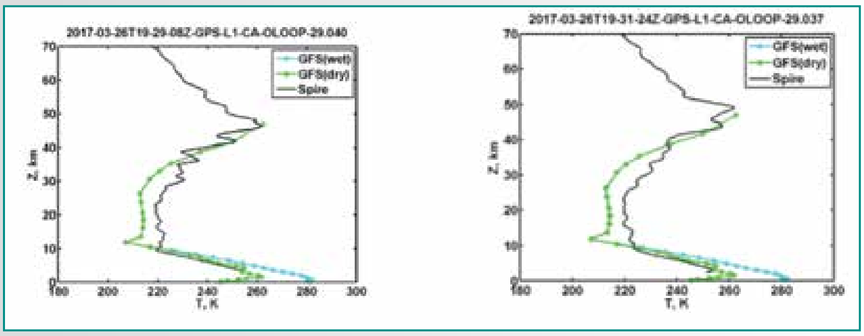


Fig. 2 - Quality of Spire's RO profiles.

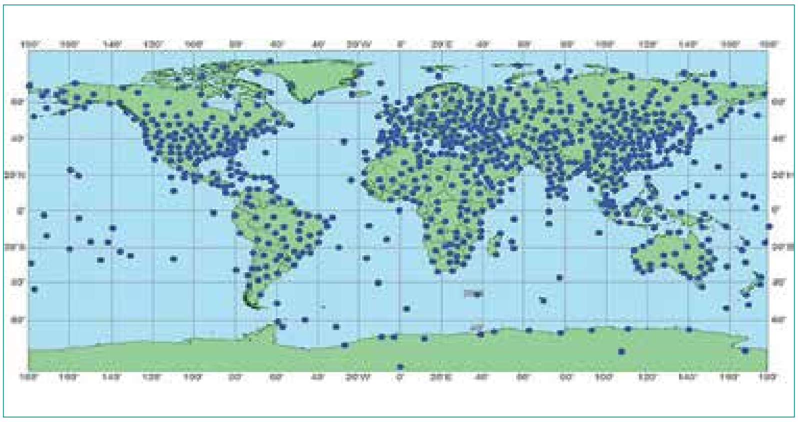


Fig. 3 - Global Network of radiosondes.

this geographic area. The GFS has a tropopause of about 12 km, and a colder stratosphere, whereas Spire RO measurements show that the actual low is much deeper, with characteristic lower tropopause at 10 km, and a warmer stratosphere. Such theoretical model errors can amplify into large errors in prediction downstream.

Comparison of capabilities of GNSS-Radio Occultation to Radiosondes

Currently the main source of accurate atmospheric data is a network of about 1,300 radiosondes that are launched twice a day (Figure 3). They are expensive to operate, and they provide a poor coverage over the oceans and unpopulated areas. On the other hand, a single Spire LEMUR satellite is capable of producing from a number of 500 to 1000 RO-based atmospheric profiles (based solely on the GPS constellation) per day with a global distribution. If we multiply the number of ROs per satellite by the number of Spire's LEMUR satellites available today and scheduled in the near future, and we also take in consideration other GNSS fleets (e.g. Galileo), we obtain a number close to 120,000 atmospheric profiles per day (Figure 4), thus contributing immensely to the atmospheric data available to NWS models. In Figure 5 are depicted a radiosonde and a three-unit (measuring 3 dm3) LEMUR GNSS-RO enabled satellite.

Operational use of GNS-RO in NWP models

As previously discussed, GNSS-RO is a dependable source of high-quality real time data for global and regional weather models. Previous academic programs like COSMIC, demonstrated the high quality of RO atmospheric profiles and their value for weather forecasts. Spire has taken the COSMIC experience to the next level, by operating a current fleet of more than eighty LEO satellites (increasing in number every three months) with unique atmospheric sounding capabilities.
Figure 6 below depicts the conceptual block diagram of a generic advanced NWP weather model that takes advantage of RO data. From left to right, data is collected from many existing atmospheric standard sources, as well as many RO profiles as they become available. Both RO data and standard atmospheric data are ingested into a data assimilation filter that generates very precise initial conditions of the atmosphere at a specific moment in time. Such initial conditions are the input to the advanced NWP model that, at a certain number of times per day, and more typically as often as possible, outputs a certain number of Forecast Products. Such products are then stored in a data server and cloud services that are the basis for delivery of the final forecast (Output Data) to Customers, under the form of GRIB2 files and APIs. Optional fully customized products for specific vertical markets may also be provided.
Apart from being specifically designed to assimilate RO data and other weather data available from third-party sources, advanced NWPs core features are often based upon the following underlying principles:

- They are non-hydrostatic models (featuring a dynamic core) that resolves weather below 10 miles.
- Have a higher vertical and horizontal resolution by virtue of highly efficient computing

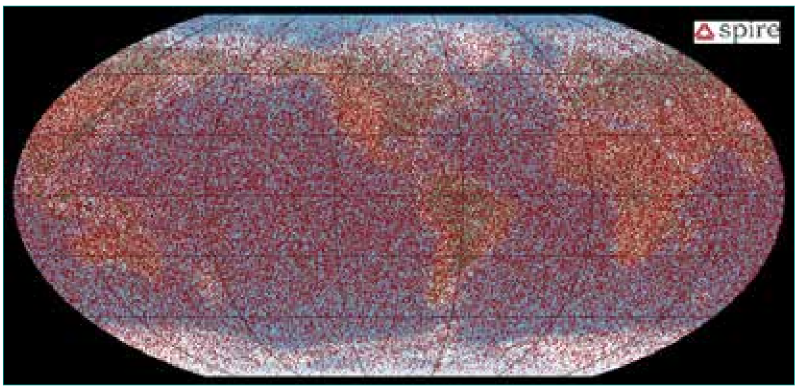


Fig. 4 - Spire's ROatmospheric profiles at full constellation.

Fig. 5 - A radiosonde features a balloon and a payload capable of one vertical atmospheric profile/launch (right) and a LEMUR satellite (above) is capable of measuring 1000 atmospheric profiles/day.

there are plans to implement operational short-range weather models in the near future. They will have an inherent advantage against other options because no national center currently runs a global short-range model. Many countries use regional models (WRF) over their area of the world, but there is compelling evidence that these limited domain models are not as accurate as global models in producing short-term weather forecasts.

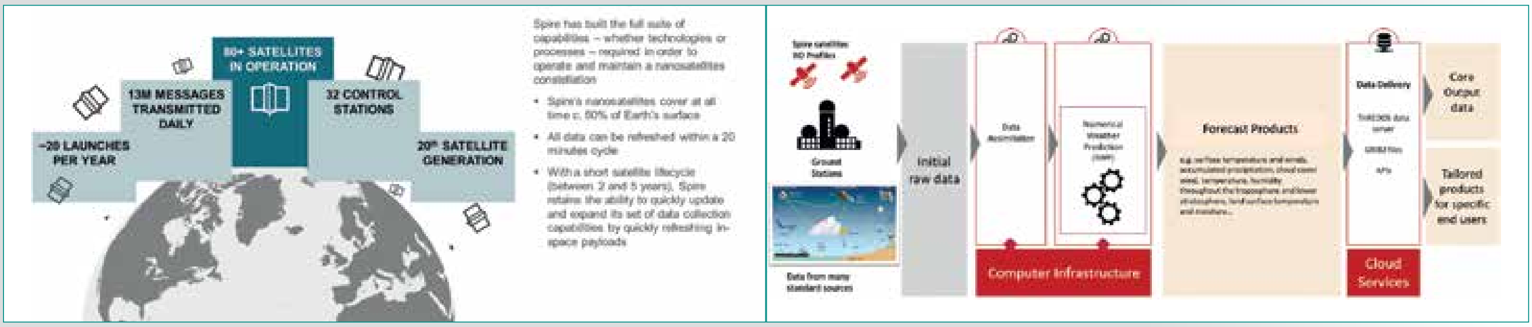


Fig. 6 - Weather Prediction System block diagram.

- They are optimized for short-term (0-36 hour) predictions with frequent assimilation that often allows for prediction up to 7 days.

From a study published by Carla Cardinali et al. [CAR1], in Figure 7 is shown the importance of Spire's GNSS-RO as a contributing dataset to NWP models, in terms of comparison of the performance percentage increase of weather models depending on the data source in use against cost. Most datasets shown in the picture are provided by missions that cost hundreds of millions of dollars. For example, datasets provided by the MetOP program (e.g. through the IASI Infrared sounder) cost 756 M Euros, while the Aqua satellites with AIRS infrared sounder run over 900 million dollars.

While most available soundings datasets are inefficient in terms of NWP model percentage performance increase against mission cost, Spire's GNSS-RO soundings contribute enormously to NWP models performance, at a mere fraction of the cost of other options.

In terms of forecasting capabilities,

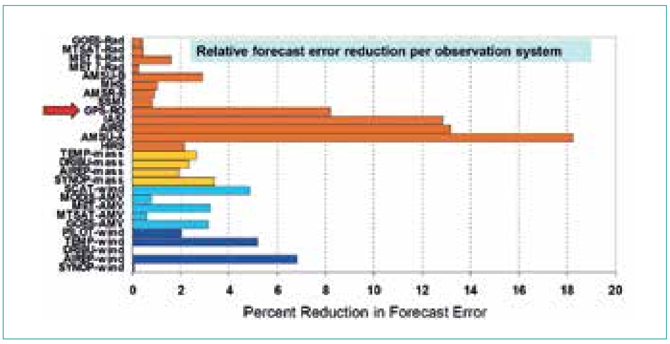


Fig. 7 - RO contribution to performance increase of NWPs.

REFERENCES

[CAR1] Carla Cardinali and Sean Healy. "Impact of GPS radio occultation measurements in the ECMWF system using adjoint based diagnostics." Q.J.R Meteorol. Soc. 140(684), 2315-2320, doi:10.1002/qj.2300

KEYWORDS

Spire; GNSS Radio Occultation; smallsats; cubesats; LEO; TEC; NWP

ABSTRACT

GPS-Radio Occultation (GPS-RO), and generally, Global Navigation Satellite System Radio Occultation (GNSS-RO), is a technique that measures the refractivity of the Earth's atmosphere as a Low Earth Orbit (LEO) satellite listens to the radio signal of a GNSS satellite. As the signal between the two satellites travels through the different levels of the Earth's atmosphere, temperature and water vapor content can be derived at each occultation point, allowing for a new weather dataset to be available to meteorologists.

In this article we describe the benefits of large-scale GNSS-Radio Occultation (GNSS-RO) as a method of gathering large amounts of extremely accurate atmospheric data that exceptionally contributes to the performance of advanced numerical weather prediction (NWP) models.

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