Analysis of Satellite Radio Occultation Architecture and its Stakeholders

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Global Navigation Satellite System Radio Occultation (GNSS-RO) is a technique that relies on the change of a signal transmitted from a Global Navigation Satellite System (GNSS) as it passes through the planet's atmosphere. This technique is not only suitable to study weather forecasting or climate change, but also offers a low-cost application. This report aims to characterize and parametrize the system architecture of commercial companies pursuing the Commercial Weather Data Pilot (CWDP) contract by the National Oceanic and Atmospheric Administration (NOAA). The approach of the paper will start by explaining the Radio Occultation technique and its potential application to Numerical Weather Prediction (NWP). The paper then identifies the main stakeholders of radio occultation and NWP, and their needs. Some key functional requirements are pinpointed, and the challenges that some of these architectures must overcome is discussed.

I. Introduction

The increase of severe weather in the last decade has led to the need for improvement of U.S. weather forecasting. Severe weather such as hurricanes and flooding causes great economic damage to cities. According to National Oceanic and Atmospheric Administration (NOAA), the cost of economic damage caused by hurricanes was $161 billion for Katrina in 2005, $71 billion for Sandy in 2012, $125 billion for Harvey in 2017, $90 billion for Maria in 2017, and $50 billion for Irma in 2017. The overall cost of hurricanes in the U.S. reached $515.4 billion in insured property losses from 1986 to 2015. One way to mitigate severe weather damage is by collecting weather data that improves forecasting. Recently, there has been a greater need for weather data to augment forecasting capabilities.

The main government organization in the U.S. responsible for providing weather forecasting of severe weather and collecting weather data, NOAA, has predominantly relied on satellite infrastructure and the Radio Occultation (RO) technique, which measures radio frequency signals emitted by Global Positioning System (GPS) and passed through the Earth's atmosphere to derive temperature, pressure, and water vapor of the atmosphere to obtain reliable weather data to create weather forecasts. However, in the past decade, NOAA and Congress have been concerned about data gaps in the NOAA's satellite infrastructure [1]. According to the hearing of Advancing Commercial Weather Data: Efforts to Improve Forecasts in 2015, the chairman, Jim Bridenstine, stated that the weather satellite architecture of NOAA was considered "fragile," meaning that a failure in the satellite infrastructure would cause the lack of critical weather data for forecasting and delays and cost overruns for federal government weather satellite projects. As a result, NOAA released a strategy, called Polar Follow On (PFO) [2], to transition its architecture from "fragile" to "robust." This strategy is in development and would be deployed from 2023 to 2038. Additionally, NOAA has been investigating private sector partnerships as potential sources of weather data to augment weather forecasting capabilities.

Recently, there has also been a rise of commercial satellite infrastructure to collect weather data. This is due to the miniaturization of off the shelf components for subsystems, improvement of small satellite manufacturing, and decrease of launch service cost. According to research by MarketsandMarkets in 2019 [3], the weather forecasting system market is expected to grow up to $3.3 billion by 2025 globally as there are many potential uses for weather data. As a result, several companies have been going to space to acquire weather data.

This paper seeks to pinpoint key factors in the stakeholder architecture that allow RO constellations to supply demand for weather data. Section II below explains the fundamentals of RO technique to obtain atmospheric

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parameters and various applications of this technique. Section III explains how the main stakeholder for weather data, NOAA, uses the weather data in its Numerical Weather Predictions (NWP) and how recently NOAA began relying on the private sector to meet its weather data needs. Section IV explains the rise of other stakeholders providing space-based weather data using RO instruments. This section identifies the function and form of Commercial Weather Data Pilot (CWDP) stakeholders Spire, PlanetIQ, and GeoOptics and explains their space activities. Section V discusses some of the challenges of the commercial partnerships. Lastly, Section VI states the conclusions of this CWDP stakeholders and some aspects that could improve this public-private partnership.

II. Radio Occultation (RO)

Radio Occultation (RO) is a technique to measure temperature, pressure and water vapor in the stratosphere and the troposphere. It is based on utilizing radio signals continuously broadcast by GPS satellites orbiting the Earth in mid-Earth orbit (MEO). This section aims to explain some of the fundamentals of the RO technique.

A. Radio Occultation Basics

The Radio Occultation (RO) technique was first implemented for planetary missions to study the atmosphere of other planets such as Mars [4] or Venus [5]. In 1993, the University Corporation for Atmospheric Research (UCAR) conducted a demonstration project using the Global Positioning System/Meteorology (GPS/MET) satellite [6]. The GPS/MET satellite carried on board a RO instrument to produce limb soundings of the Earth's atmosphere. The project successfully demonstrated proof of concept [7]. Later, with the launch of the COSMIC/ FORMOSAT project in 2006, the European Centre for Medium-Range Weather Forecasts studied the contribution of improvement in short-term weather prediction errors of RO data [8].

The RO technique works by measuring the bending angles of radio signals emitted by GPS satellites and passed through Earth's atmosphere. This physical phenomenon is called refractivity, which is instigated by the vertical gradient of density. From the bending angles measured in RO instruments, refractivity, temperature, water vapor, and pressure of the atmosphere could be derived [9]. The atmospheric profiles obtained with RO instruments are located from the midtroposphere to the mesosphere.

According to the UCAR COSMIC Data Analysis and Archive Center (CDAAC), some of the advantages of RO data include: global coverage; profiles of the ionosphere, stratosphere, and troposphere; high accuracy (equivalent to 0.5 K with 0.1 K average accuracy); high precision (0.02-0.05 K); high vertical resolution (0.1 km near surface and 1 km at tropopause); only space system to profile atmospheric boundary layer; and not affected by aerosols, clouds, or precipitation. Furthermore, according to Kursinski et al., "with 24 GPS satellites, a single GPS receiver in a near-polar orbit at 800 Km will observe 500 occultations per day, distributed fairly uniformly around the globe. This number could be doubled if the Russian Global Navigation System (GLONASS) is added." [9] Additionally, "20 GPS/GLONASS receivers could provide approximately 25,000 daily occultations yielding an average of one profile every 150 Km square."

B. RO Application: Understanding Hurricane Formation

The RO measurements provide accurate atmospheric parameters and are useful for predictions of tropical storm such as hurricanes. These predictions have provided valuable insights about this weather phenomenon. Since this is one of the main subjects to be characterized using RO data, this section has been allocated to discuss some of the underlying principles about how a tropical storm forms near the U.S. coast.

The global weather behavior is determined by the rotation of Earth and the heat exchange between the north pole and the moist air in the equator [10]. Tropical storms are powered by unstable air, moisture, and the warm oceans. The oceans located in equatorial regions normally accumulate heat from the sun during the summer season. After the summer season, the heat taken in the oceans is released that, combined with moisture, triggers the process of tropical storms.

First, moist air starts rising upwards caused by the released heat taken in the ocean and eventually condenses in the sky, forming clouds. Second, since the air next to the ocean rises, this area becomes a low-pressure area, which pulls air from high pressure areas in its surroundings. This is the genesis of the low-pressure system, which pulls or attracts clouds from its surroundings. Lastly, the rotation of the hurricane is determined by the location of the low-pressure system in Earth's hemisphere and the rotation of Earth.

For instance, imagine two opposite clouds and one low-pressure system as illustrated in Fig. 1 (left). The cloud closer to the equator moves towards the low-pressure system with a higher tangential speed than the cloud closer to the North Pole. As a result, the cloud closer to the equator moves with a higher speed with respect to the low-pressure system, allowing the cloud to move ahead the low-pressure system and eventually the same cloud is pulled back by the low pressure as illustrated in Fig. 1 (right). On the other hand, the cloud closer to the North Pole moves towards the low-pressure system with a lower tangential speed than the cloud closer to the equator. As a result, the cloud closer to the North Pole falls behind the low-pressure system and is eventually pulled towards the low-pressure system as illustrated in Fig. 1 (right).

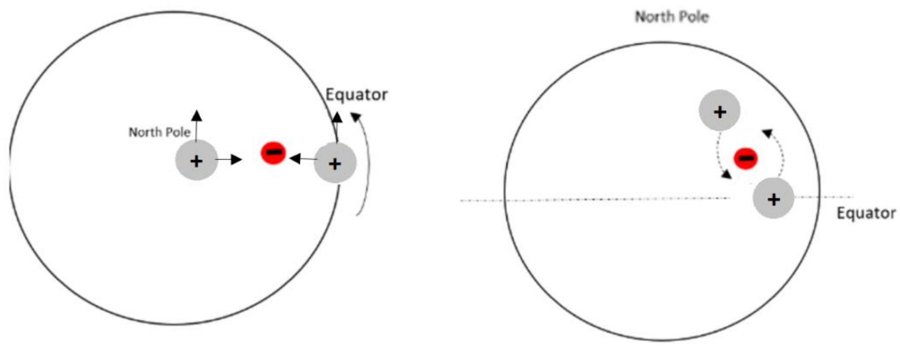

Fig. 1 Hurricane Formation

This difference of speed from clouds to the low-pressure systems coming from the North and South determines the direction in which the hurricanes rotate. If the hurricane is in the Northern hemisphere, then the hurricane rotates counterclockwise. However, if the hurricane is in the Southern hemisphere, then the hurricane rotates clockwise. Overall, the combination of warm, unstable air, and moisture is the genesis of tropical storms that when the wind speed reaches 39 mph is called a tropical storm and when the wind speed reaches 74 mph is called a hurricane.

C. Radio Occultation Measurements and Hurricanes Predictions

As mentioned in the last section, some of the drivers for hurricane formation are temperature and water vapor. The distribution of these parameters over the hurricane region is what determines some important characteristics such as path and intensity of hurricanes. Given that the RO measurements offer high vertical resolution of these parameters, the RO technique offers a big advantage of measuring the temperature and water vapor around hurricanes. For this reason, RO data is valuable for hurricane forecasting.

According to Liu et al. [11], RO data was assimilated into numerical models to predict hurricane Ernesto in 2006. In the study, numerical weather predictions without using RO data were not able to predict the formation of Ernesto. However, when RO data (observed with COSMIC constellation) was assimilated into the numerical weather prediction system, the results showed the formation of Ernesto. Moreover, this result was helpful to estimate the path of this hurricane, which enable NOAA to provide severe weather warnings for the U.S. East coast. Perhaps, a contributor to the accuracy of predicting hurricanes is that the RO constellation offers more measurements of distributed vertical temperature not only over the land, but also over the oceans, the principal contributor to hurricane formation.

III. Main Stakeholder: NOAA

NOAA's mission and vision is "to understand and predict changes in climate, weather, oceans and coasts, to share that knowledge and information with others; and to conserve and manage coastal and marine ecosystems and resources" [12]. The functions of NOAA, and the form they take, are explained below.

A. NOAA's Functions

NOAA performs Numerical Weather Prediction (NWP) and collects global observations to provide warnings of severe weather to U.S. residents. With the advent of supercomputers, NWP has improved significantly, resulting in more accurate weather predictions [13]. The NWP model represents the atmosphere as a three-dimensional grid across the globe. Each grid in the model influences physical properties from one grid to the surrounding grids. Since the atmosphere is treated as a mixture of gasses, the physical properties that grids influence one over others are heat transfer, solar radiation, humidity, convection properties, chemistry, thermodynamics, and fluid motion. All these properties are expressed as linear, non-linear, and differential equations in each grid of the model, increasing the computing resources needed to solve these equations over the 3D model and in time. Additionally, the resolution of the model depends upon the size of each grid in the model. Higher resolutions have smaller grid sizes and lower resolutions have larger grid sizes. Consequently, higher resolution forecasts require additional computational resources than lower resolution forecasts.

Models vary grid sizes depending on the region and type of phenomena being analyzed. For instance, according to NOAA/National Centers For Environmental Information (NCEI) [14] [15], the NWP is composed of several models such as the Nested Grid Model (NGM), Global Forecast System (GFS), North American Regional Reanalysis (NARR), and Global Data Assimilation System (GDAS). The NARR is structured with a grid size of 32 km in latitude. The NGM receives its data from the Regional Analysis and Forecast System (RAFS) [16] whose analysis component is the Regional Optimum-Interpolation (ROI) grid [17]. The ROI grid has different grid sizes over different regions of the Earth, illustrated in Fig. 2. The grid A has a grid size of 365.8 km and the grid B 182.9 km.

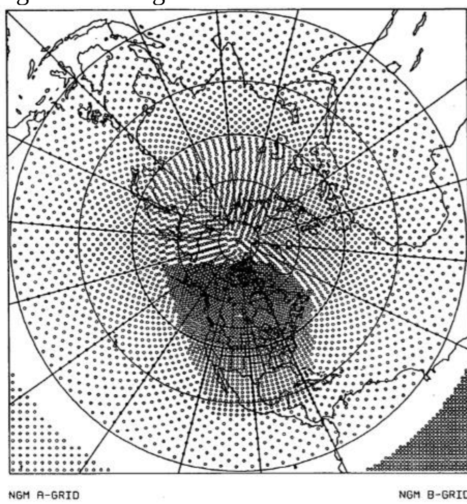

Fig. 2 ROI Grid [17]

The fine mesh over the U.S. enables the model to produce the most accurate outcomes in this region of interest. Having a fine mesh like this one globally would, demand excessive computing resources.

Furthermore, the GFS model uses a different grid size that depends on the forecasting time. The GFS model uses a grid size of 28 km horizontally when performing predictions up to 16 days in the future. Meanwhile, the GFS model uses a grid size of 70 km when performing predictions for one to two weeks. The variables needed to run the GFS model come from temperature distribution, winds, precipitation, and atmospheric concentration. The GFS model is divided into four models: the atmospheric, ocean, land, and sea ice models, using a mesh depicted in Fig. 3.

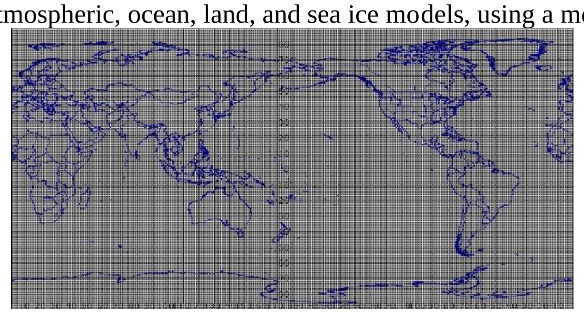

Fig. 3 NCEP Grid 4 GFS

To get accurate predictions, NOAA also performs data assimilation which continuously ingests observations into NWP and creates forecasts based on the observations collected by different sources such as weather satellites, radiosondes, ships, ocean buoys, and surface measurements [14]. NOAA needs two principal systems to forecast weather in the future: the above-mentioned NWP and the initial conditions that NWP needs to run the simulations. The initial conditions are determined based on the observations collected daily. In addition, since errors in the initial condition propagate exponentially throughout the simulation in time [18], NOAA performs corrections of the initial conditions periodically, a process called data assimilation. Inherent errors in the initial conditions increase with time that in a forecast of days could indicate severe weather in the near future. For instance, the GFS has models that have a data assimilation of three, six, and twelve hours, which means that the NPW gets updated with new initial conditions (collected observations) every three, six, and twelve hours, to create a six-hour analysis cycle illustrated in Fig. 4.

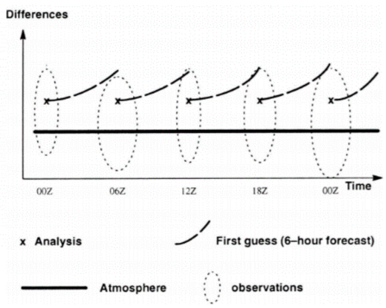

Fig. 4 Analysis Cycle

From all the models used at NCEP, the GFS model assimilates data from RO measurements from COSMIC observations in which a study of refractivity and bending angle measurements were ingested [19]. The study states that unexpected refractivity measurements of RO produce better outcomes than ingesting bending angles. Furthermore, the GFS ensembled with the Kalman Filter system (EnKF) is used to reduce the track of the tropical cycle (TC) [20].

B. NOAA's Forms

The NOAA National Environmental Satellite Data and Information Service (NESDIS) currently provides environmental data and information from satellites for further data assimilation into numerical weather models. The mission of NESDIS is "to provide secure and timely access to global environmental data and information from satellites and other sources to promote and protect the Nation's security, environmental, economy, and quality of life [21]." Furthermore, NESDIS manages the satellites described below.

- **GOES-S**: Geostationary satellite that provides remote sensing capabilities to predict Pacific storms systems, severe storms, fog, wildfires, and cyclones in the eastern Pacific Ocean, including Hawaii.
- **Jason-3**: Low Earth orbit satellite that measures the height of the ocean's surface and rate of sea-level rise using a radiometer to support NOAA's National Weather Service in tropical storms forecasting.
- **Suomi NPP**: Earth-observing satellite that collects data for long-term climate change and short-term weather conditions.
- **Deep Space Climate Observatory (DSCOVR)**: The DSCOVR mission is located at Lagrange point 1 (L1) and monitors solar wind to alert about potential harmful radiation levels that could damage key infrastructures on Earth.
- **NOAA 20:** Polar-orbiting satellite that maps temperature, water vapor, precipitation, snow and ice cover every day. Mapping global patterns of temperatures will help identify climate changes and locate cold areas in the atmosphere. These cold areas could pose hazards for commercial flights. Additionally, NOAA 20 also provides microwave measurements for up to seven-day weather forecasts.

C. Key Form: RO Constellation Deployment

NESDIS also manages one satellite constellation that uses RO. This constellation, called Constellation Observing System for Meteorology, Ionosphere and Climate-2 (COSMIC-2), was designed by the U.S. and Taiwan, and it is comprised of six satellites. The COSMIC-2 constellation was deployed into its desired orbit through the insertion of a parking orbit and the implementation of orbit precession to the desired orbit. Ultimately, the COSMIC-2 constellation was located on an orbit of inclination 40° and altitude of 520 km.

The mission's purpose is to improve capabilities of global weather forecasting, space weather, climate, ionospheric, and geodetic research. The constellation carries three instruments on board. The first is the TriG (third generation) GNSS-RO receiver payload, which measures signals of the upper and lower atmosphere in a region near the Equator where most of the global moisture accumulates. The second payload is the Ion Velocity Meter (IVM), whose main purpose is to provide measures of ion velocity in the upper atmosphere for space weather predictions. The third instrument is the Radio Frequency (RF) Beacon whose purpose is to measure the total electron content in the Earth's upper atmosphere.

The COSMIC-2 RO constellation collects data of the temperature, density, water vapor content, and pressure over the equatorial region. Collecting data around the equatorial region is important because "most of the moisture that drives global weather patterns is located around the equator" [22]. Overall, this data feeds computer models for medium to long-term weather forecasting. The RO measurements in the tropical regions would improve the predictions of some severe weather events such as hurricanes, typhoons, or variation of Earth's climate. According to UCAR, which is the organization responsible for disseminating COSMIC-2 data, the COSMIC constellation downlinks its observational data within about 30 minutes to ground stations in Hawaii, Tahiti, Honduras, Cuiaba (Brazil), Ghana, Kuwait, Mauritius, Taiwan, Guam, and Darwin (Australia).

Moreover, the COSMIC-2 constellation has a (threshold) capacity of 8,000 profiles per day with a goal of 10,000 profiles per day and compatibility to operate with the GPS, GALILEO, and GLONASS systems [23].

Additionally, UCAR also manages other RO missions in Table 1. RO instruments are relatively small in comparison with the size of the spacecraft and consume low power. Table 2 shows the mass and power of some missions and their respective RO instruments.

Table 1 RO Missions Managed by UCAR

Mission	Total Atmospheric Occultations	Total Ionospheric Occultations
CHAMP	468,029	306,318
C/NOFS	152,610	0
COSMIC-1 (6 s/c)	6,957,937	4,648,581
GPS MET	5,002	0
GPSMETAS	4,577	0
GRACE	565,148	260,561
KOMPSAT-5	565,089	0
METOP-A	2,599,361	0
METOP-B	1,424,379	0
PAZ	86,925	0
SAC-C	353944	0
TerraSAR-X	831,634	0
Total	14,014,635	5,215,460
As of October 28, 2019 Source: https://www.cosmic.ucar.edu/		

Table 2 Mass and Power of Selected RO Missions

Mission	Mass [Kg]	Power [W]	Instrument	Mass instrument [Kg]	Power instrument [W]	Data Rate instrument [Mbps]
Formosat-5	525	280	RSI	5	5	1
CHAMP	522	150	BlackJack	3.2	15	0.017
C/NOFS	384	260	Coriss	3	10	0.0005
Komposat-5	1400	1400	AOPOD	5	22	
Metop-A	4085	1810	GRAS	30	30	0.027
PAZ	1282		ROHPP	4.6	16	0.017
TerraSAR-X	1152	800	IGOR	4.6	16	0.017
Source: Observing Systems Capability Analysis and Review Tool (OSCAR)						

D. NOAA's Commercial Partnerships

To address the possibility of weather data gaps and to augment forecasting capabilities, NOAA frequently seeks to partner with the private sector by issuing Request for Quotations (RFQ). One RFQ issued in 2010 solicited commercial companies to assess the feasibility of future partnerships to collect commercial weather data using the GPS-RO instruments [24]. From this RFQ, two companies were awarded funds ($25,000) to study the validation of price and technical viability of GPS-RO measurements: GeoOptics LLC of Pasadena, California and ORBCOMM Inc. of Fort Lee, New Jersey. In addition, President Trump signed the Weather Research and Forecasting Innovation Act 2017 which includes in NOAA's mission research to improve weather forecasting such as predicting the track and intensity of hurricanes. This law formally allowed NOAA to purse commercial weather data partnerships.

Considering the availability of weather commercial data and the National Space Policy (NSP) [25] enacted on June 28, 2010, NOAA is requesting, through the Commercial Weather Data Pilot (CWDP) [26], that private companies provide weather data in order to explore and validate assimilation of commercial RO weather data into its meteorological models in order to support NOAA's mission. The CWDP has been conducted in two rounds; the first was awarded in 2016 to the companies Spire Global and GeoOptics. In this round, Spire Global delivered timely RO data to NOAA. However, GeoOptics could not deliver data within the timeframe established. The second round was awarded to Spire Global, GeoOptics, and PlanetIQ in September 2018.

IV. The Rise of Commercial Stakeholders

This section seeks to explain the simultaneous rise of commercial stakeholders going to space to acquire RO data. These stakeholders (Spire, PlanetIQ, and GeoOptics) are also competing for CWDP contracts. This section describes the functions and forms of the stakeholders.

The rapid growth of nanosatellites in the industry and the frequent and affordable access to space have allowed for the rise of commercial space companies such as OneWeb, Planet Labs, PlanetIQ, Spire, Global World, and others. Some space companies leverage the NASA Commercial Orbital Transportation Services (COTS) [27] program, which allows private companies to launch services through the International Space Station (ISS). Moreover, the advent of non-expendable rockets, such as the Falcon 9 or Electron rocket, has decreased the price of launching satellites to Low Earth Orbit (LEO). For instance, during the 2000s the launch services were mainly done through expendable rockets. As a result, the cost to launch to space was approximately $8,000 to $10,000 per pound. However, launching with non-expendable launch vehicles, the price per pound has dropped to $1,000 to $2,000 per pound. This is a significant reduction in price that is allowing space companies to profit from their operations.

Furthermore, the rise in commercial satellite infrastructure to collect weather data is in response to the need for more weather data but also the increasing awareness that there are many potential uses of weather data. According to research by MarketsandMarkets in 2019, the weather forecasting system market is expected to grow to $3.3 billion by 2025 globally [3]. For instance, the renewable energy industry is increasingly interested in wind forecasting to estimate potential energy generation in some regions of the world.

A. Spire

Spire Global is a data and analytics company that relies on their Lemur satellites to provide services to the weather, maritime, and aviation industry. Spire's constellation is deployed across high and low inclination orbits and multiple planes to maximize global coverage. The large constellation aims to not only maximize coverage, but also the number of measurements taken in the atmosphere. Spire uses a globally distributed ground station network on Earth to provide low-latency data downlink. This network is also operated by the same company.

1. Functions

There are three pillars that define Spire. First, Spire uses software-defined instruments that can be programmable or re-programmable to change capabilities while on orbit. Second, the value of the data is driven by the number of sensors rather than the size of the sensor. The last pillar is to collect data from everywhere in world.

The services that Spire provides are: Maritime data and Analytics (sensor AIS), Weather Data (GNSS RO, R, and Weather Model), and Aviation (ADS-B data), and payload host (1U available). Additionally, considering the substantial amount of data that Spire's constellation gathers on orbit, Spire offers APIs to customers to visualize the data needed using geographic information systems (GIS). To provide these services, Spire carries three instruments on board of its LEMUR-2 satellites, which are the satellites that comprise the Spire constellation.

One of these instruments that uses RO sensors is the STRATOS, which provides weather data to run their weather models. The STRATOS is composed of GNSS RO instrument, GNSS-R (reflectivity) or GNSS Bistatic Radar, and the Precise Orbit Determination (POD). STRATOS also enables atmospheric and ionospheric measurements, which derive parameters including electron density, total electron content, and scintillation events. The GNSS RO instrument detects measurements of bending angles emitted by GPS, GLONASS, Galileo, Quasi-Zenith Satellite System (QZSS), and BeiDou (BDS) signals. The atmospheric parameter derived from RO are temperature, pressure, and water vapor. The process of RO measurement is as follows [28]: measure raw phases and amplitude of two signals (L1 and L2), correction of clock and orbit determination, determine the bending angles of the two signals, calculate neutral bending angles, calculate refractivity (N), and lastly calculate temperature, pressure, and water vapor. Furthermore, the GNSS-R allows for the determination of soil moisture, ocean wind/waves, sea ice, and wetlands/flood inundation.

The LEMUR-2 satellites deorbit once they have reached their lifecycle, avoiding the increase of space debris. The Spire constellation is replenished every two years. Hardware is updated on a two-year basis.

The LEMUR-2 satellites are also inter-linked among each other, so each satellite can send or receive data from other LEMUR satellite [29]. This approach was adopted to improve communication with ground stations, aiming to downlink the observed data in the shortest timeframe possible. This is critical for weather observations since wind patterns change suddenly within few tens of minutes, influencing new weather behavior on Earth. There are a few setbacks by implementing inter-link satellites into their architecture such as power demand and physical size [30].

Spire Global builds and operates its own ground network, aiming to support near real time connectivity.
Having a constellation is advantageous from the reliability standpoint since there are several satellites in operations. Furthermore, the data is stored in an Amazon Web Services cloud for redundancy [31].

2. Form

Spire's goal is to collect 100,000 profiles per day [32] which is approximately 10 times more than the COSMIC-2 constellation provides. Spire strives to reach this rate because this amount of profiles could halve the weather forecast error. Additionally, Spire launches four to eight satellites every six weeks, and the satellite communications is done using UHF and S-band (downlinking data).

The Spire constellation offers a high revisit time due to its large number of satellites, observing each point on Earth 100 times per day, every day. This ensures complete global coverage, including the polar regions at horizontal resolution of 1/8th degree global (~ 12 Km or 7.5 miles) everywhere on Earth. The Spire's constellation is composed with LEMUR-2 satellites, which comply with the 3U CubeSats (10x10x30 cm) standard [33].

3. Constellation Deployment

The Spire constellation has been continuously deployed in batches as secondary payload since 2013. Table 3 shows the history of the Spire constellation deployment. Some of the launched satellites have failed either for deployment, launch, or have reached the end of their lifecycle. After the launch service, the satellites are placed in a parking orbit. Eventually, the satellites reach a desired orbit by implementing a technique called differential drag, which leverages perturbations caused by drag to move across the orbits.

Table 3 Spire Constellation Deployment

Launch date	Vehicle	Number of satellites	Orbit
03/08/2013	H-IIB		International Space Station (ISS)
09/01/2014	Antares		ISS
19/06/2014	Dnepr		Sunsynchronous Orbit (SSO)
28/09/2015	PSLV-XL	4	Equatorial
22/03/2016	Atlas-5	9	ISS
17/10/2016	Antares	4	ISS
09/12/2016	HIIB	4	ISS
14/02/2017	PSLV	8	SSO
18/04/2017	Atlas-5	4	ISS
23/06/2017	PSLV	8	SSO
14/07/2017	Soyuz	8	SSO
11/11/2017	Antares	8	ISS
28/11/2017	Soyuz	10	Failed
12/01/2018	PSLV	4	SSO
20/01/2018	Electron	2	83º
01/02/2018	Soyuz	4	SSO
21/05/2018	Antares	4	ISS
11/11/2018	Electron	2	
29/11/2018	PSLV	4	
27/12/2018	Soyuz	8	
01/04/2019	PSLV	4	
05/07/2019	Soyuz	8	
Reference: Gunter's Space Page			

B. PlanetIQ

PlanetIQ is a relatively new company with a mission to provide high volume of RO measurements for weather forecasts. The company states that its RO sensors are more sensitive in comparison with other versions of RO instruments and that the data latency of collected measurements is about three minutes, which is the fastest downlink data from space.

1. Functions

The PlanetIQ constellation will deliver over 50,000 profiles per day and provide real-time data delivery. PlanetIQ also provide space weather data such as total electron content, scintillations, ionosphere and region state, local neutral winds, local charged particles, and local magnetic fields.

2. Form

The PlanetIQ constellation will rely on a relay communication system in Geosynchronous orbits to improve data latency and to reduce cost of ground stations. The PlanetIQ constellation will carry on-board a fourth-generation radio occultation sensor, which will be compatible to receive signals from GPS, GLONASS, Galileo, and Beidou.

3. Constellation Deployment

The PlanetIQ constellation will deploy 2 satellites in January 2020. It is expected that PlanetIQ will deploy 18 satellites later. The satellites will be launched on-board the Polar Satellite Launch Vehicle (PSLV) as a secondary payload. The final orbit for PlanetIQ's constellation is located an altitude between 750 to 800 kilometers and an inclination of 72 degree.

C. GeoOptics

GeoOptics is a California-based company whose mission is to provide the best and timely data available for their customers and users around the world. The company's goal is to deploy 100 satellites (6U CubeSat) called Community Initiative for Continuing Earth Radio Occultation (CICERO) in LEO [34]. GeoOptics aims to deliver weather and ion age data from RO observations. The CICERO data will be free for users who need RO data for research purposes. Additionally, GeoOptics is planning to incorporate in the future a new payload to measure Earth's gravity field to track reservoirs of water and their risks.

1. Functions

The CICERO communications link between the satellite and ground stations uses relay geostationary satellites to ensure continuous communications with ground stations. GeoOptics estimates to downlink approximately 10,000 atmospheric profiles within three-hour data collection. The CICERO constellation must contain 100 spacecrafts to provide global coverage and a replenish rate of 20 spacecraft per year.

The payload (GNSS-RO) of the CICERO satellite also performs the spacecraft avionics functions by adding software to the payload. For example, the payload could provide accurate position and altitude determination. Additionally, the CICERO constellation also carries on board a GNSS-Reflection (R) instrument to provide remote sensing data of the Earth's surface.

2. Form

The CICERO satellite has a mass less than 30 kilograms and 5 kilograms of hydrazine propellant. This propellant is used for orbit insertion and maintenance. Moreover, the CICERO solar arrays provide at least 50 watts of power on average to support its operation.

The data latency is less than 100 minutes for weather data, and less than 5 minutes for space weather data. The estimated volume data rate is more than 10 megabits per orbit per craft. The payload data downlink is through the X-band, and the telemetry data is through UHF band. The ground stations for CICERO's communications are made through the Inmarsat network. The constellation has compatibility to receive GNSS signals from GPS and Galileo systems.

3. Constellation Deployment

The designed orbit for the CICERO constellation is between 500 kilometers to 750 kilometers at 72 degrees. It is expected that the CICERO constellation will be deployed across 18 orbit planes with two satellites in each one, aiming for an optimized distribution to provide global coverage.

GeoOptics like the other low-cost companies, leverages the secondary payload service to launch its satellites to space. In 2017, the CICERO-6 was launched as a secondary payload on board of the Polar Satellite Launch Vehicle (PSLV-C38) to an altitude of 505 kilometers and 97.44 degrees inclination. Additionally, according to Celestrack, there currently are four CICEROs numbers 6,7, 8, and 10 in orbit.

V. Discussion

This section discusses some aspects of the commercial weather data, technology and approach of companies, as well as potential future issues related to weather forecasting for NOAA.

A. 5G Network Interference

NOAA is concerned that the spectrum used for 5G networks will cause interference with spectrum that weather satellites use to collect crucial observations for weather forecast. The U.S. Department of Commerce and NOAA have expressed their concern about a future interference of 5G networks spectrum to the Federal Communication Commission (FCC) after the intentions of FCC to free-up spectrum in the 24Ghz band to 5G carriers. NOAA alleged that its weather satellite measurements could be compromised if 5G spectrum operates near the spectrum in which its weather observations are made, leading to inaccurate weather observations and thus inaccurate weather forecasts. It is estimated that about 90% of the data collected by weather satellites is used for weather forecasting. However, the 5G mobile carriers disagree with NOAA's claim, arguing that the 24 GHz band for 5G network will not interfere with any of NOAA's weather satellites and that NOAA's proof of 5G spectrum interference is flawed.

B. Issues with CWDP

While investigating commercial partnerships to support NOAA's NWP, there are two issues that NOAA has encountered with the CWDP. As mentioned previously, the first round was granted to GeoOptics and Spire Global, but GeoOptics suffered problems launching its constellation and could not deliver data to NOAA. Spire Global delivered data to NOAA but this data did not meet the observation requirements of NOAA or was not accurate enough [35]. Since these problems emerged, NOAA decided to issue the second round of the CWDP, allowing these companies to improve their measurements. Additionally, NOAA also reported that price of RO data provided by these companies is higher than expected, making the commercial partnerships more difficult.

Furthermore, the second issue that NOAA encountered is within the context of weather data sharing with international organizations such as the World Meteorological Organization (WMO) and public services in the U.S. Under an international agreement with WMO via Resolution 40, NOAA is committed to sharing its weather collected data with the WMO. This agreement has provided benefits to both parties since the vast amount of observations required for weather forecasting is economically impossible for only one organization to gather. However, with the advent of the CWDP, this exchange of data has been controversial because one member finances the commercial weather data benefiting other members of the WMO. Congress requested NOAA to investigate and reconcile a better agreement of Resolution 40 for cases in which the weather data is purchased from the private sector. NOAA is still in trials of commercial weather data to request a change of Resolution 40 to WMO although the purchased RO data from round one was shared with the WMO. Even the director of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) expressed skepticism for the CWDP and he is waiting to see if this commercial partnership works in the U.S. Furthermore, NOAA must share the weather data with the public in the U.S., but this data should not be used for commercial purposes, leading NOAA to license its data. Perhaps, the cloud based the Big Data Project (BDP) would allow more control over what data is distributed to the public and what data is delivered for commercial purposes [36].

C. Technology Improvement

The improvement of RO technology has led to the reduction of mass and power of the RO instruments. As an example of this decrease of mass and power consumption, consider the following two instruments: TRIG, carried onboard COSMIC-2 and CION, designed for the CICERO satellite. Table 4 below compares the specifications for each instrument. The newer instrument, Cion, consumes significantly less power compared with the Trig instrument. This is due to, among other reasons, the Cion instrument weighing significantly less than Trig. The reduction of instrument mass and size also leads to decreased costs, such as launch cost.

Table 4. Comparison of TRIG and CION RO Instruments

Specification	Trig	Cion
Mass	6 kg	1.2 kg
Power	65 W	8 W

Additionally, the size of the instruments has also decreased, making the RO instruments suitable for remote sensing applications. Leveraging the reduction of instrument mass and size, some companies such as PlanetIQ and Spire Global may utilize other weather instruments that measure important weather data for NWP. For instance, both companies' constellations will carry on board two additional instruments to complement their RO instruments. The first instrument is the GNSS-R (reflectivity), which is used for land surface monitoring. The second instrument is a magnetometer, which measures Earth's magnetic field.

D. Crosslink Communications

Crosslink communication is feasible for the Spire constellation due to its large size. According to Wiley J. Larson and James R. Wertz (third edition), crosslink constellations typically require more than 20 satellites to have a high link availability. As large constellations have short distances between satellites, crosslink would not require a lot of power to transmit data to adjacent satellites, and thus large equipment to support crosslink power is not required. This also could be another advantage of having a large constellation which is strictly constrained by the mass and dimensions of satellites. Furthermore, the CubeSat Laser Infrared Crosslink (CLICK) project led by NASA explores a promising technology that would support crosslink communication by miniaturizing optical transceivers. Perhaps, in the near future, with the increase of data observed and constraint by volume, constellations could use technology such as the optical laser to support more data rate crosslink or the usage of crosslink data for navigation purposes.

E. After the First Round of CWDP

The CWDP might be a suitable contract to enter the commercial weather industry for Spire, GeoOptics, and PlanetIQ, but this commercial weather data contract may not be issued for a long period of time. Presumably, once NOAA deploys its Polar Follow On (PFO) strategy by 2023, proving a fault-tolerant weather satellite architecture, NOAA would not primarily rely on commercial weather partnerships. This does not mean the government will completely stop all commercial partnerships. Nonetheless, even if NOAA is not a primary customer for weather data companies, weather companies still have a private sector market that is demanding weather data. Weather data demand will likely increase in the coming years since industries such as aviation, energy, oil and gas, agriculture, insurance, and shipping are demanding forecasts for safety or efficiency-operation purposes. This demand will increase with the frequency of severe weather due to climate change. In fact, there are companies (including Spire Global) that are investing in numerical weather prediction models and could potentially demand weather data. Additionally, in 2016 Panasonic claimed to have the best weather model in the world, outperforming the GFS model of NOAA and the ECMWR model. Panasonic uses weather observations collected by airplanes to feed its NWP. Although Panasonic uses airplanes to collect observations collected observations of the atmosphere, with the rise of RO private constellations, Panasonic could potentially require services from RO constellations companies in the future.

F. Results of the Second Round of CWDP

After the testing and evaluation from the second round of CWDP, NOAA concluded that the proposed commercial weather data products met the requirements for data assimilation, which would result in future weather data purchases from these companies. NOAA performed evaluations with delivered data based on the standard deviation against a model climatology, signal-to-noise ratio for each GNSS frequency, and comparison of measurements between the commercial data and radiosondes and other satellite measurements. The evaluation of this data revealed that Spire Global and GeoOptics data products not only improved weather forecasts over the one to three-day forecast, but also improved NOAA's space weather predictions. This was possible because the competing companies also provided quality total electron content (TEC) measurements. It is worth noting that these TEC measurements were taken in normal space weather conditions and did not include measurements under severe space weather.

Furthermore, the competing companies, Spire Global and GeoOptics, complemented weather data sources for operating systems such as COSMIC-2. The companies deployed their constellations at high inclination in sun synchronous orbits, which resulted in more measurements per day over high latitudes. These high latitude measurements are important to compliment measurements at mid-low latitudes provided by COSMIC-2. Although sun synchronous orbits offer benefits over high altitudes, the local time coverage of this kind of orbit is not well distributed. For example, the constellation offers more measurements per day over a specific period during the day. More distributed measurements during the day are advantageous to monitor drastic change over different regions.

VI. Conclusions

Overall, there are some advantages and disadvantages that allow these companies to provide weather data. On the one hand, Spire seems to have expertise manufacturing CubeSats rapidly up to the point that they can launch between four to six CubeSats every six months. However, the accuracy of their RO measurements did not meet high standards such as those imposed by NOAA for its NWP models, given that Spire's delivered data in the first round of the CWDP was not "comprehensive" or accurate enough for NOAA. Although Spire had this mishap, the CEO of Spire claimed that after the first round of the CWDP, Spire has diligently worked on improving RO observations for the second round of the CWDP.

On the other hand, PlanetIQ and GeoOptics might not have as much experience manufacturing CubeSats in short periods of time as Spire, but these companies have experienced resources in their designing teams who have worked on previous RO constellations such as COSMIC. This is advantageous because they have more experience in designing systems that meet NOAA's high standard requirements.

NOAA is still disseminating the delivered data in the CWDP second round and until a new update of this analysis, we cannot conclude yet about the potential success of future commercial partnerships. Nonetheless, improvements of technology in the future could potentially make the partnership beneficial in future rounds. For instance, better sensors would obtain measurements that meet NOAA's requirements, and low-cost and highly distributed ground stations would allow for downlinking more data and decrease data latency. Such improvements in technology would augment NOAA's capability for more accurate weather forecasting.

Acknowledgments

This work was completed as a part of J. Tapia Tamayo's SYS 800 master of engineering capstone project at Stevens Institute of Technology, advised by P. Grogan.

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