Space Sciences & Engineering LLC (dba)

FCC Form 442 – Narrative Statement

Application for New or Modified Radio Station Under Part 5 of FCC Rules-

Experimental Radio Service (Other Than Broadcast)

Federal Communications Commission

445 12th Street, SW

Washington, DC 20554

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Acronyms

BCT	Blue Canyon Technologies
DAS	Debris Orbit Software
DSN	Deep Space Network
EDP	Electron Density Profiles
FDMA	Frequency Division Multiple Access
GNOMES	GNSS Navigation and Occultation Measurement Satellites
GNSS	Global Navigation Satellite System
HDRM	Hold Down and Release Mechanism
ITU	International Telecommunication Union
JPL	NASA Jet Propulsion Laboratory
JSPOC	Joint Space Operations Center
L1	1575.42 MHz
L2	1227.60 MHz
L5	1176.45 MHz
LEO	Low Earth Orbit
LTDN	Longitude of the Descending Node
MEO	Medium Earth Orbit
MLB	Mark II Motorized Lightband
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PFD	Power Flux Density
PSLV	Polar Satellite Launch Vehicle
RF	Radio Frequency
RFP	Request for Proposal
RO	Radio Occultation
SDR	Software-Defined Radio
SNR	Signal-to-Noise Ration
SSO	Sun-Synchronous Orbit
STK	Systems Toolkit (formerly Satellite Toolkit)
S4	Amplitude Scintillation
TEC	Total Electron Count
TT&C	Telemetry, Tracking, and Control
UCAR	University Corporation for Atmospheric Research
V/V	Volts/Volt

1 Narrative Statement

1.1 Introduction

Space Sciences & Engineering LLC (SSE), a subsidiary of Global Weather & Climate Solutions, Inc. and doing business as PlanetiQ, seeks authority to conduct Earth weather observation via Radio Occultation (RO) from a PlanetiQ experimental satellite and engage in market trials with the atmospheric data obtained from the experiment, as permitted under the Commission's rules.[1] PlanetiQ plans to sell data products collected from the experimental spacecraft to both the Department of Commerce, pursuant to the Commercial Weather Data Pilot Radio Occultation project, and a limited number (less than 100) interested commercial parties. Assessment of the market for the data products, including price and commercial interest, will inform our ability to launch and operate a commercial satellite system.

This satellite will eventually be a part of the PlanetiQ constellation of "GNSS Navigation and Occultation Measurement Satellites" (GNOMES) for which PlanetiQ will seek separate FCC Part 25 authorization, and is the first of two experimental satellites (GNOMES-1 and GNOMES-2).[2] The experimental GNOMES will operate under the frequency characteristics shown in Table 1.1-1.

Table 1.1-1. Desired frequency characteristics

	Frequency Band	Center Frequency	Maximum Bandwidth	Data Rate
Uplink	S-band	2.081 GHz	200 kHz	100 kbps
Downlink	X-band	8.260 GHz	20 MHz	10 Mbps

1.2 Background

The vision of PlanetiQ is to significantly improve weather forecasting, numerical weather prediction (NWP) models, and space weather forecasts and analyses by dramatically increasing the number and quality of Global Navigational Satellite System (GNSS) occultations that are available to be assimilated. To achieve this vision, we have designed a new GNSS-RO instrument, Pyxis, which delivers the highest level of performance while flying on a microsatellite-style spacecraft. This approach enables a large number of satellites carrying state of the art instrumentation to be placed into and operate in low-Earth orbit (LEO) and will dramatically increase the combined quality and quantity of GNSS occultations assimilated in each NWP and space weather update cycle. Our well-engineered system ensures that commercial RO will move the needle by supplying accurate, high vertical resolution, global atmospheric profile data to NWP centers.

To achieve this level of performance on a microsatellite, PlanetiQ drew upon on our knowledge of previous generations of receivers and instruments and used modern radio frequency (RF) and digital hardware. To maximize the number of occultations acquired, our Pyxis receiver tracks dual-frequency signals from all four major GNSS constellations (GPS, GLONASS, Galileo and BeiDou, see Section 3.2 for further description of reception from

[1] 47 C.F.R. § 5.602; *see also infra* Section 1.3 (discussing the pilot Department of Commerce weather data contract).
[2] PlanetiQ will submit a separate experimental application for the second experimental satellite.

foreign GNSS satellites) and will eventually acquire over 2,500 occultations per day per satellite. It acquires the signals via open loop tracking in the troposphere and lower stratosphere and tracks rising and setting occultations with equal performance.

Each GNOMES spacecraft will carry a Pyxis instrument. The GNOMES will be launched into orbits of at least 500 km altitude and varying inclinations. The nominal orbit configuration is a sun-synchronous orbit (SSO) at 650 km altitude to provide pole to pole Earth coverage; however, the satellite design is capable of operation at other inclinations and altitudes. The satellite's solar panel delivers power sufficient to acquire all RO acquisition opportunities continuously and downlink at every opportunity to globally distributed commercial ground stations. Each satellite carries a propulsion system to maintain altitude, optimal phasing between satellites, and accelerated de-orbit at end of mission. See Figure 1.2-1 for an example of the GNSS-RO geometry and descriptions of the derived data products.

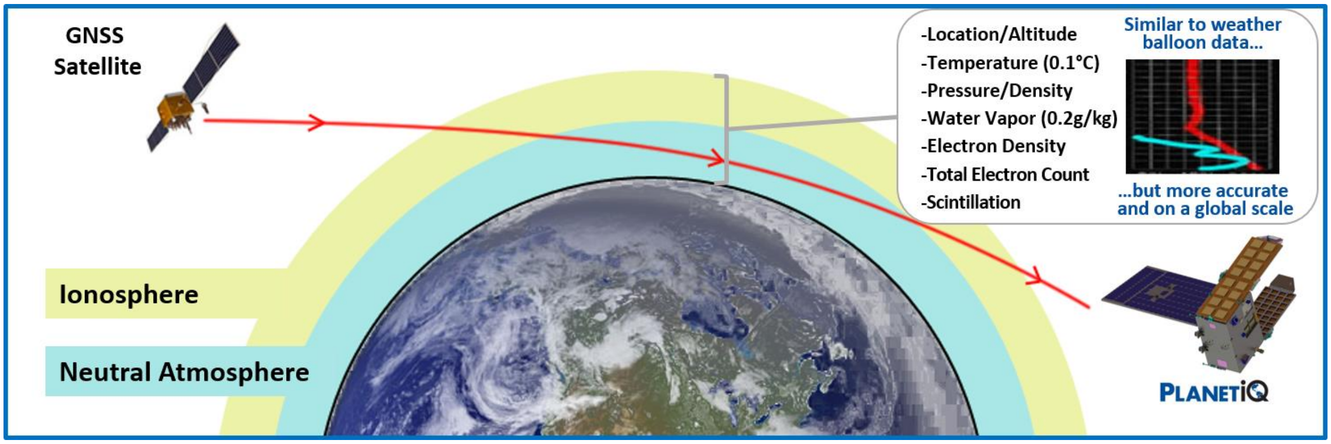

Figure 1.2-1. Geometry of a typical GNSS-RO event and resulting data products derived from the technique

1.3 Government Contract

With regard to Section 4 of FCC Form 442, this frequency authorization application is to be used to fulfill the following government contract:

Government Project: **Commercial Weather Data Pilot (CWDP) Radio Occultation (RO)**
Agency: **Department of Commerce**
Contract Number: **1332KP18CNEEB0012**[3]

The contract is part of a Department of Commerce initiative to "pursue demonstration projects to validate the viability of assimilating commercially provided environmental data and data products into NOAA meteorological models and add value to the forecast. Data

[3] The contract is available online. *See* https://www.fbo.gov/index?s=opportunity&mode=form&id=919a17d831c31a26a50eae5282056289&tab=core&_cview=1.

demonstration and validation will precede operational procurement of commercial data by NOAA."[4]

2 Mission Description

2.1 Mission Expectations

The Pyxis instrument onboard each PlanetiQ satellite tracks dual-frequency signals from GPS, Galileo, GLONASS, and BeiDou GNSS satellites. Pyxis tracks both rising and setting occultations to double the numbers of soundings. With our design for a future operational system, the GNOMES aim to track with a 100% duty cycle, each and every orbit, as all operational weather satellites do.

Daily occultation counts are dependent upon the number of functional GNSS satellites on orbit as well as the signals that they broadcast. Although the GPS constellation is fully populated, PlanetiQ collects signals only from the Block IIR-M and more recent GPS blocks, which broadcast the L2C signal. We also collect data from all 24 GLONASS satellites, and all the available Galileo and BeiDou satellites (see Table 2.1-1 for the signal sources from each constellation). All signals collected are freely available to civil users.

Table 2.1-1. RO signal source for each constellation

	GPS	**GLONASS**	**Galileo**	**BeiDou**
1st frequency	L1C/A	L1OF	E1OS	B1
2nd frequency	L2C	L2OF	E5b	B2

Since BeiDou is expected to only have 25 functional MEO satellites on orbit in late-2019, we predict that our receivers will track 92 GNSS satellites on orbit in that timeframe. As shown in Table 2.1-2, this number will increase over time such that our receivers will acquire nearly 2,600 occultations per day per satellite in 2022.

Table 2.1-2. Number of expected occultations per GNOMES, based upon the number of available GNSS satellites and signals

Timeframe	# GNSS	Occ/GNOMES
Q4 2019	92	2,233
2020	96	2,330
2021	101	2,451
2022	107	2,597

Our final, fully-populated constellation of mixed sun-synchronous and lower inclined orbits will provide pole-to-pole coverage and sample all local times for full diurnal coverage. The on-board ion propulsion system allows for minor adjustments to altitude, inclination, and right ascension of the ascending node to diversify coverage.

[4] *See* Original Synopsis, at 5 (Apr. 25, 2018), available at https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=41d99f5a205b9f03e7f3151f92bd0302&_cview=0.

GNOMES-1 will be launched on one of three possible launches scheduled for Q4 2019. The initial injection orbit altitude will be between 500 km and 750 km, with a nominal operational altitude of 650 km planned, as shown in Figure 2.1-1a. Our final, operational constellation will consist of twenty GNOMES, in sun-synchronous or a combination of sun-synchronous and lower inclined orbits, shown in Figure 2.1-1b.

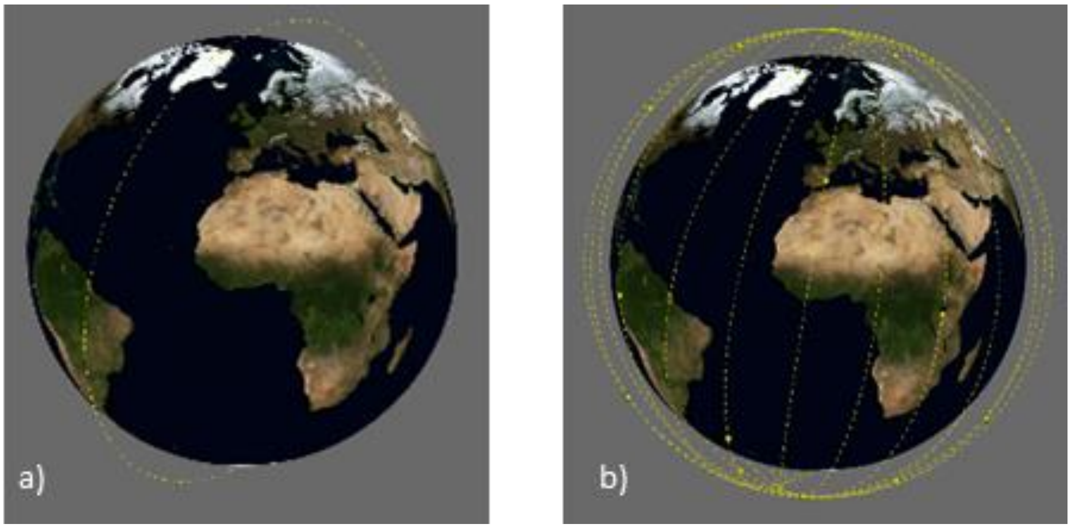

Figure 2.1-1. PlanetiQ satellite orbit configuration for a) the first satellite registered under the Part 5 license and b) the final twenty-satellite constellation under the eventual Part 25 license(s)

The fundamental goal of the Pyxis-RO instrument and GNOMES mission is to provide as many high-quality GNSS occultations as possible to maximize its impact on NWP forecasts, and space weather and climate predictions. To accomplish this task, PlanetiQ must:

- Demonstrate a high signal-to-noise ratio (SNR) (~ 2000 V/V) GNSS-RO instrument to provide all-weather atmospheric data from the surface of the planet to the top of the ionosphere.
- Demonstrate the ability to detect and track GNSS signals during super refraction conditions, and to derive data from the lower troposphere in all cases and conditions.
- Deliver high impact/high value data to NWP centers and demonstrate forecast accuracy improvements.

2.2 Theory of Operations

To achieve global coverage for full atmospheric and ionospheric sampling, our target orbit for the Pyxis spacecraft is at 650 km altitude. The first experimental spacecraft (GNOMES-1) will be launched as a secondary payload on-board the Antrix Corporation Polar Satellite Launch Vehicle (PSLV), on a launch scheduled in the 4th Quarter of 2019. The spacecraft will be in an orbital plane dictated by its launch characteristics, and could be sun-synchronous or at a lower inclination, but will be bounded between 500 and 750 km altitude. Orbital maneuvers, such as altitude adjustments and station keeping, will be done with the on-board ion propulsion system. Further analysis of the possible orbital characteristics and their implications to de-orbit operations can be found in Exhibit A - Orbital Debris Assessment Report.

As GNOMES-1 is a secondary payload onboard the PSLV, the injection altitude and inclination are not equivalent to the planned final orbit. PlanetiQ plans to perform system validation and RO data collection at the injection altitude for GNOMES-1 to fulfill our data contract obligations to the Department of Commerce, as well as to verify satellite functionality. It is planned to keep GNOMES-1 at its injection altitude for up to 18 months, then shift to operational status at 650 km. The satellite will perform altitude and inclination change maneuvers with its propulsion system for several months to reach 650 km altitude, with periodic satellite telemetry check-ups during the orbit maneuvers. The satellite will resume data collection and transfer to the ground after the orbit transition. The satellite contains sufficient propulsion for orbit raise, inclination adjustments, station keeping, and deorbit operations (details described in Exhibit A - Orbital Debris Assessment Report).

Table 2.2-1 shows the orbit lifetime of GNOMES-1 for each of the three potential launch scenarios for Q4 2019. GNOMES-1 will carry propulsion regardless of the chosen launch, to adjust to a 650 km circular orbit, and to allow for perigee lowering to accelerate deorbit by atmospheric reentry. The planned orbit lifetime for any of the possible orbit injection options adheres to the Commission's 25-year deorbit time span limit.

Table 2.2-1. Injection and operational orbit characteristics and planned mission lifetime. The orbital altitude and inclination will be maintained by the onboard propulsion system.

Mission	Launch	Altitude (Perigee x Apogee)	Inclination	LTDN	Lifetime
GNOMES-1	PSLV-C50	Injection: 530 km x 530 km	97.6°	06:00	<18 months
		Operational: 650 km x 650 km	98.0°		5½-7 years
	PSLV-C49	Injection: 555 km x 555 km	37.0°	N/A	<18 months
		Operational: 650 km x 650 km	37.0°		5½-7 years
	PSLV-C53	Injection: 730 km x 730 km	98.4°	12:00	<18 months
		Operational: 650 km x 650 km	98.0°		5½-7 years

Because data latency is vital for the value of the atmospheric measurements, frequent data downloads to the ground are necessary. Occultation observation data from the first GNOMES will be downlinked via X-band radio at a nominal rate of 10 Mbps and maximum output power of 2.0 Watts. This data will be transmitted to globally distributed ground stations at least 27 times per day per satellite. Commands and software updates will be uplinked via S-band radio from a subset of the ground-stations at a rate of 100 kbps.

For purposes of the operating frequency for the two experimental GNOMES, PlanetiQ is applying for center frequencies of 8.260 GHz (downlink) and 2.081 (uplink) GHz. The satellites will transmit in no more than a 20 MHz channel for downlink and a 200 kHz channel for uplink. Telemetry, tracking and command or TT&C will also be provided within those frequency bands.

The first two experimental GNOMES will anchor a larger satellite constellation after sufficient demonstration of the Pyxis-RO technology is established. PlanetiQ will seek the applicable Part 25 authorizations at the appropriate times.

The Pyxis-RO instruments are designed to receive the publicly available GNSS signals from the GPS (L1 at 1575.42 MHz and L2 at 1227.6 MHz), Galileo (E1 at 1575.42 and E5 at 1207.14 MHz), GLONASS (FDMA signals centered at L1 at 1602 MHz and L2 at 1246 MHz), and BeiDou (B1 at 1561.1 MHz[5] and B2 at 1207.14 MHz) constellations, as shown previously in Table 2.1-1. Dual-frequency measurements from each occulting satellite are necessary to resolve the ionospheric contribution to the signal path delay. Additionally, the reception of multiple GNSS signals will allow PlanetiQ to cross-check and validate the accuracy of its data observations.

Observations of GNSS signal Doppler frequency and carrier phase amplitude will be collected and stored on-board before periodic transfer to the ground for further processing. Linking the observations to post-processed orbital geometry information will identify the bending angle unique to each occultation event, which is then translated to a vertical refractivity profile at a given location. The use of post-processed orbits also ensures that the weather products are not derived from spoofed or inaccurate signals, especially from the foreign GNSS satellites. Further discussion of reception of foreign GNSS signals is found in Section 3.2.

2.3 Spacecraft Description

The GNOMES are a microsatellite-style satellite that are installed on the Planetary Systems Corporation's 8 inch Mark II Motorized Lightband (MLB) separation system for launch[6]. See Figure 2.3-1 for a conceptual drawing of the satellite's deployed configuration. Once separated from the launch vehicle, the satellite will deploy the solar panel and specialized Pyxis-RO antennas. The spacecraft are three-axis stabilized and nadir following.

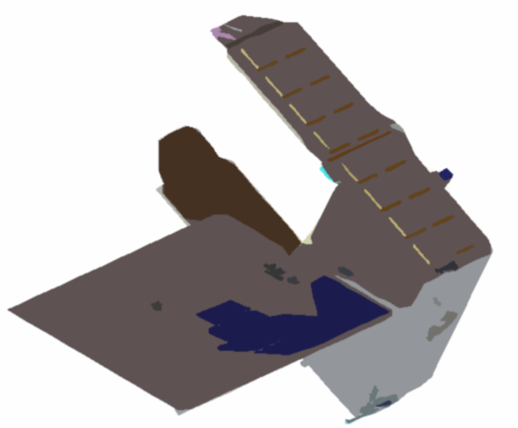

Figure 2.3-1. The GNOMES spacecraft in its deployed state

The on-board ion propulsion system will allow for precise orbit insertion after launch vehicle separation, with sufficient fuel to lower the satellite perigee and accelerate de-orbit after end of mission. Further description of re-entry disposal, orbital debris mitigation plan, and

[5] Also eventually at 1575.42 MHz with BeiDou Phase 3 B1C signal.

[6] Further information on the MLB can be found at http://www.planetarysystemscorp.com/product/mark-ii-motorized-lightband/

specialized thruster can be found in a separate exhibit: Exhibit A - Orbital Debris Assessment Report[7].

2.4 Data Transfer

2.4.1 Space Stations

The GNOMES will carry a single X-band transmitter to downlink data and conduct telemetry, tracking, and command (space-to-Earth). This transmitter is the SDR-X model supplied by Blue Canyon Technologies (BCT), with transmission characteristics described by Table 2.4-1 and in Form 442.

Table 2.4-1. BCT SDR-X X-band transmitter description

	Non-geostationary
Action frequency	8.260 GHz
Maximum output power	2.0 W
ERP	3.85 W
Mean/Peak	Peak
Frequency Tolerance	4 ppm
Emission Designator	20M0G1D
Modulating signal	10000000 baud OQPSK

The X-band and S-band antennas are designed and supplied by Haigh-Farr Inc. Both are nearly hemispherical in their gain patterns and are nadir-pointed. For both antennas, the gain is generally constant and varies between 0 and 5 dBi over Earth coverage angles.

A link budget can be formed from the transmitter characteristics shown in Table 2.4-1 and the expected X-band antenna coverage. The power flux density (PFD) at the maximum gain (5 dB) is calculated to be -117 dB(W/m^2) over the total bandwidth of the transmitter at the worst case injection altitude of 530 km and -119 dB(W/m^2) at the nominal operational altitude of 650 km. Therefore, the largest PFD resulting from the X-band transmitter on the GNOMES-1 will be -130 dB(W/m^2·MHz) at the sub-satellite point from 530 km, a value that is well below the recommendation given by the ITU[8].

The ITU also recommends the following limits of PFD from space stations as received at the Earth's surface[9]. These limits relate to the PFD obtained only under free-space path loss conditions and a 4 kHz bandwidth.

[7] Information regarding the on-orbit performance of the propulsion system is found in: Krejci, David & Reissner, Alexander & Seifert, Bernhard & Jelem, David & Hörbe, Thomas & Friedhoff, Pete & Lai, Steve. (2018). DEMONSTRATION OF THE IFM NANO FEEP THRUSTER IN LOW EARTH ORBIT.

[8] Rec. ITU-R SA.1810

[9] ITU Radio Regulations Table 21-4

Table 2.4-2. ITU PFD limits at the Earth's surface

Frequency band	Service	Limit in dB(W/m^2) for angles of arrival (δ) above the horizontal plane			Reference bandwidth
		0°-5°	5°-25°	25°-90°	
8025-8500 MHz	Earth exploration satellite (space-to-Earth) Space research (space-to-Earth)	-150	-150 + 0.5(δ-5)	-140	4 kHz

The PFD profile as a function of elevation angle from the Earth's surface are shown in Figure 2.4-1 for GNOMES-1. The PFD produced by GNOMES-1 satisfies the ITU PFD limits at all angles of arrival and possible altitudes, with over 10 dB of margin. In addition, the BCT X-band radio is adjustable on orbit, allowing PlanetiQ to control the PFD levels during all phases of the mission.

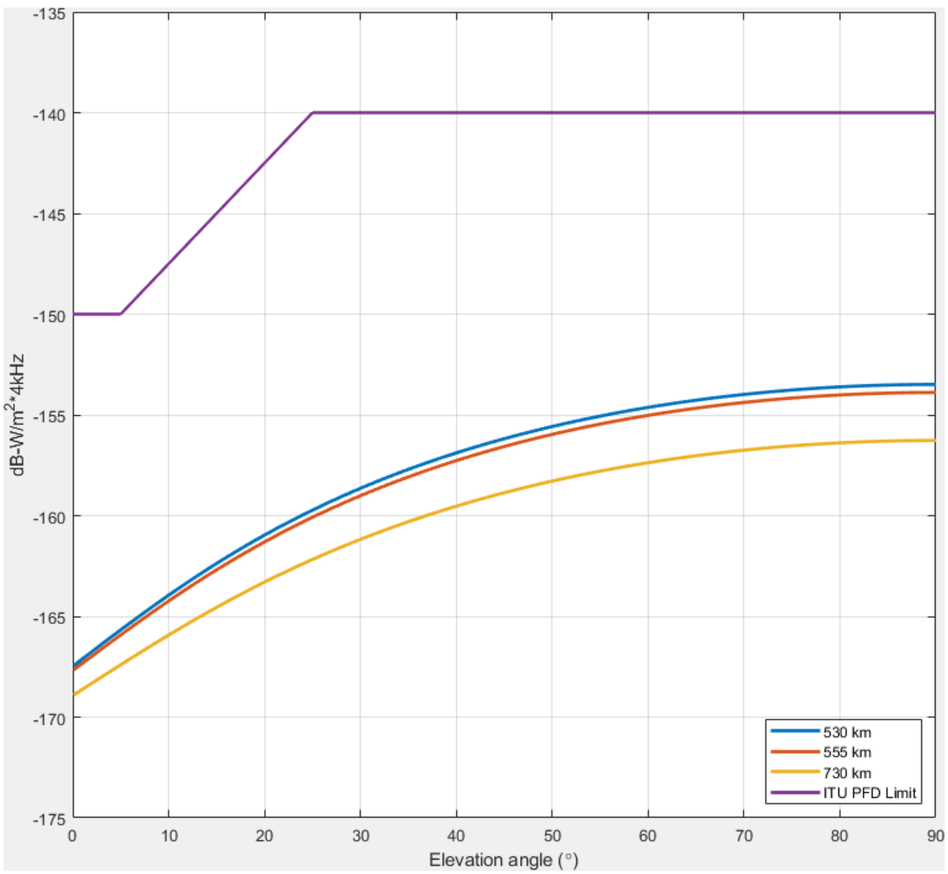

Figure 2.4-1. PFD at the Earth's surface produced by the X-band downlink radio for GNOMES-1 at all possible injection altitudes.

Finally, the ITU specifies a maximum allowable interference power spectral flux-density at Earth's surface of -255.1 dB(W/m^2·Hz) to protect earth-station receivers in the deep-space research band of 8.40-8.45 GHz[10]. The chosen data rate and center frequency for the X-band transmission on GNOMES should guarantee that no close-in side lobes are within the deep space band. Additionally, the chosen ground stations, described in Section 2.4.2, are sufficiently far from Deep Space Network (DSN) stations that the GNOMES can avoid downlink operations while within sight of a DSN station (see Figure 2.4-2).

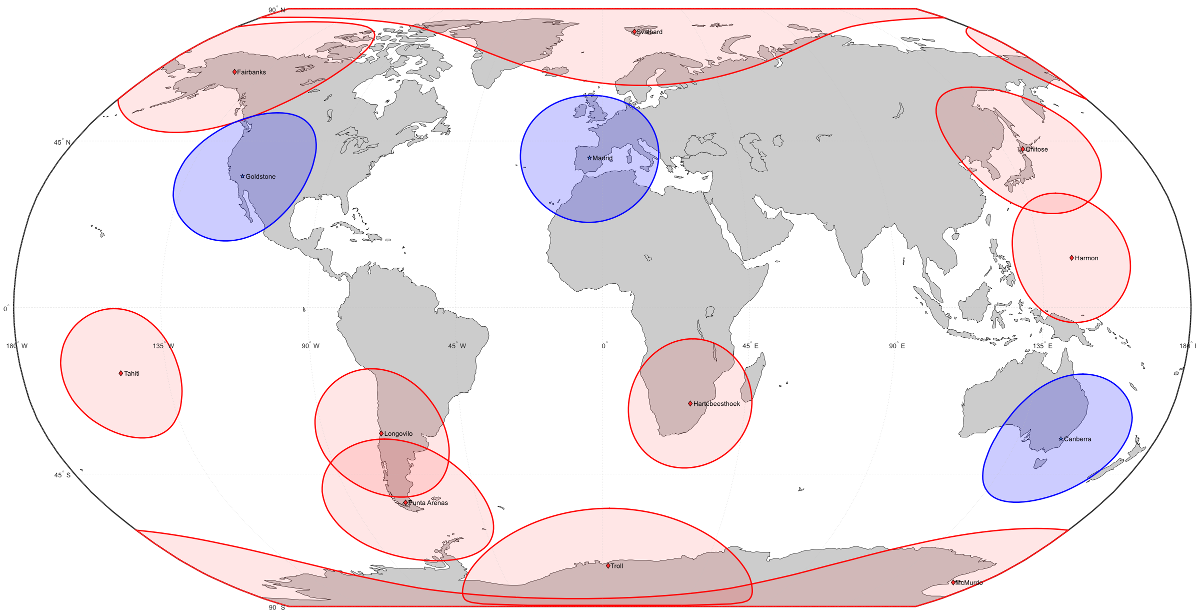

Figure 2.4-2. Transmission footprints for the possible ground stations for GNOMES-1 (in red) and their overlap with DSN station (in blue).

Under contingency operations, the downlink data rate for GNOMES-1 will drop to 200 kbps, causing the power spectral flux density to approach the interference protection level of -255.1 dB(W/m^2·Hz) at the closest possible slant ranges to the DSN stations. Under these uncommon conditions, PlanetiQ plans to lower the X-band radio transmit power to abide by ITU recommendations.

2.4.2 Ground Stations

The atmospheric soundings measured by the GNOMES will be downlinked via commercial ground station networks. PlanetiQ is in negotiations with Kongsberg Satellite Services (KSAT) for use of their ground station network as specified in Table 2.4-3. For S-band uplink and X-band downlink, KSAT supplies a network of 3.7 meter antenna dishes[11]. PlanetiQ also plans to use ground stations of various sizes (3.4 m to 9.1 m) from ATLAS Space Operations, specified in Table 2.4-4, for X- and S-band communications.

The ground stations shown in Table 2.4-3 and Table 2.4-4 represent a superset of possible ground stations under consideration from KSAT and ATLAS. The ultimate set of ground stations will depend on the injection inclination of GNOMES-1: a sun-synchronous launch will dictate the use of the polar ground stations at Svalbard, Fairbanks, Troll, Hartebeesthoek, Punta Arenas, and eventually McMurdo, while a lower inclined launch will employ stations at

[10] ITU-R SA-1157

[11] https://www.ksat.no/en/news/2016/january/ksat%20lite-network/

Hartebeesthoek, Longovilo, Chitose, Harmon, and Tahiti. Combinations of the ground stations shown in Table 2.4-3 and Table 2.4-4 allow for at least 27 opportunities for data transfer per day for each of the GNOMES. Further information regarding the transmission and reception characteristics for all antennas to be used by PlanetiQ can be found in Exhibit B – National Telecommunications and Information Administration Space Record Data Form.

Table 2.4-3. KSAT ground station locations (uplink and downlink)

	Svalbard, Norway	**Troll, Antarctica**	**Hartebeesthoek, South Africa**	**Punta Arenas, Chile**
Latitude	78°13'46"N	72°00'40"S	25°53'08"S	52°56'06"S
Longitude	15°24'28"E	2°33'14"E	27°42'20"E	70°52'14"W
Elevation above sea level	480 m	1365 m	1543 m	22 m

Table 2.4-4. ATLAS ground station locations (uplink and downlink)

	Fairbanks, Alaska	**McMurdo, Antarctica**[12]	**Longovilo, Chile**	**Chitose, Japan**	**Harmon, Guam**	**Tahiti, French Polynesia**	**Dubai, United Arab Emirates**
Latitude	64°47'37" N	77°51'00"S	33°57'19"S	36°31'55"N	13°30'45"N	17°38'08"S	24° 56' 31.57"N
Longitude	147°32'10"W	166°40'00" E	71°24'00"W	140°22'23"E	144°49'29"E	149°36'35"W	55° 20' 51.57"E
Elevation above sea level	144 m	10 m	168 m	55 m	45 m	12 m	65 m

PlanetiQ and its subcontracted ground station suppliers will seek the appropriate licenses for all ground stations deemed necessary for the chosen orbit for GNOMES-1 under the agreements with the ground station providers. PlanetiQ may subscribe to other ground stations within the KSAT and ATLAS networks, as needed, to decrease latency and avoid transmission overlap with other missions and will amend this application and coordinate all such operations, as necessary.

2.4.3 Ground Station Access

To facilitate with spectrum use coordination, the technical capabilities of the GNOMES system is described here. The GNOMES carry the SDR-X X-band transmitter/S-band receiver, produced by BCT. The radios are software defined, and have an adjustable data rate up to a maximum 25 Mbps. PlanetiQ plans to use 10 Mbps for nominal operations on-board the GNOMES. During a station pass, the GNOMES must downlink the accumulated atmospheric measurements from the previous fraction of an orbit while in range of the ground station. With the broad distribution of ground stations around the Earth, the GNOMES will have frequent telecommunications opportunities. GNOMES-1 is designed to downlink roughly half an orbit's worth of scientific data and satellite telemetry (165 MB) at each pass. The time to downlink 165

[12] Expected availability in 2021

MB of data given a 10 Mbps data rate is approximately 140 seconds. Including an estimated 10 seconds for framing overhead, 150 seconds is needed at each pass to downlink the necessary data.

A simulation of GNOMES-1 in its possible anticipated orbits was conducted using the orbital software package Systems Toolkit (STK) from Analytical Graphics, Inc. The length of time of the line-of-sight radio access between GNOMES-1 and the set of ground stations most applicable for its particular orbit (equatorial for 37° inclined, polar for sun-synchronous orbits) was recorded for one year's worth of orbits at the nominal operational altitude of 650 km. An elevation mask of 5 degrees or more was be imposed at each of the ground stations to limit data transfer to elevations above the surrounding foliage and structures, as well as to ensure our link budget supports our data rates.

The distributions of pass times for each grouping of stations are shown in Figure 2.4-3 for GNOMES-1. The majority of GNOMES-1 pass times for data transfer are over 400 seconds for the ground stations for either polar or equatorial orbits. Less than 5% of passes are less than 150 seconds for either sets of ground stations, at any orbit inclination.

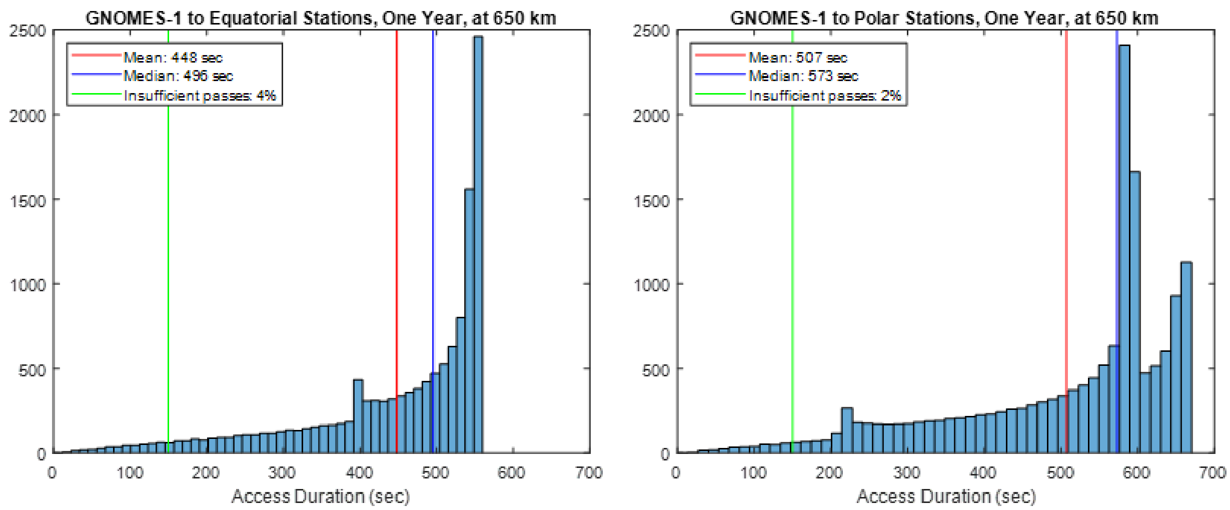

Figure 2.4-3. Pass lengths for GNOMES-1 at 650 km 37° inclined orbit (labeled "Equatorial") and 650 km sun-synchronous orbit (labeled "Polar").

With a data downlink rate of 10 Mbps, there is temporal flexibility within the satellite-station pass for data downlink for the majority of passes. The ground stations within the KSAT and ATLAS networks, shown in Table 2.4-3 and Table 2.4-4, also give geographic diversity for downlink opportunities. The GNOMES also have on-board data storage sufficient for multiple passes without downlink. For every pass, there is time for data transmission, plus additional time and storage to mitigate against concurrent transmission with other high priority missions.

2.4.4 Potential Interference

PlanetiQ plans to actively engage in pre-coordination and coordination activities with other S-band/X-band spectrum users to avoid potential interference during transmission. The scheduling of ground station use for either uplink or downlink transmissions will be coordinated by KSAT and ATLAS for each pass.

3 Utility of Data

3.1 Improvement to Numerical Weather Prediction

Current weather forecasts from the NWP centers are based on data that is insufficient in both quality and quantity. Much of the current data is produced by orbiting infrared cameras and microwave instruments. These infrared cameras cannot penetrate through clouds (which regularly cover 70% of the Earth), and microwave instruments have poor vertical resolution, the inability to discern tropospheric boundary layer conditions, and are ineffective over land. PlanetiQ aims to fix this shortfall of global atmospheric data with the demonstration of our Pyxis-RO instrument on-board the two GNOMES platforms. The experiment will be capable of collecting global measurements of the atmosphere through all possible conditions from the Earth's surface, through the boundary layer, the troposphere, and finally, up through the stratosphere.

The Pyxis-RO mission will demonstrate the highest capability GNSS-RO atmospheric sounder to date. Its observations of precise temperature, water vapor, atmospheric pressures, and wind data will be sent to and processed by the NWP centers to create more accurate and timely weather forecasts. High frequency sampling of the occultation signal allows for improved vertical resolution, as dense as 100 meters (see Figure 3.1-1 for ray path geometry). The higher quality measurements of the atmosphere's current conditions collected by the Pyxis-RO sensor will enable even better forecasting ability by the NWP centers on a global scale.

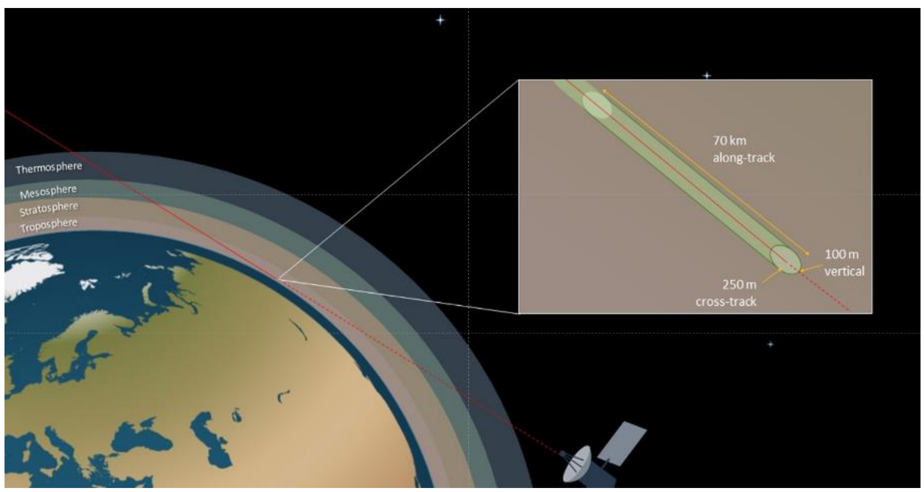

Figure 3.1-1. Dimensions of the occulting GNSS signal ray path

Additionally, the Pyxis-RO instrument will assess the state of the ionosphere by obtaining the total electron count (TEC), electron density profiles (EDP), and scintillation characteristics (S4) through dual-frequency atmospheric sounding. These measurements are important to ionospheric models used to monitor space weather and ionospheric conditions affecting communication and navigation signals.

3.2 Receipt of Foreign GNSS Signals

The Pyxis-RO receivers are designed to detect dual-frequency signals from the four major GNSS constellations (GPS, GLONASS, Galileo, and BeiDou). However, any concern over the use of foreign GNSS signals is unwarranted, as any possible deliberate falsification or "spoofing" of foreign GNSS signals will be detected by the GNOMES and known well before PlanetiQ releases any weather data products, described in the following section.

The GNSS satellites are ideal transmitters, as their on-board atomic frequency standards provide a precise and accurate reference for the carrier waves collected by the Pyxis-RO instrument. The high accuracy of these signals makes it possible to derive key characteristics of the atmosphere. The addition of signals from foreign GNSS constellations provides a greater number of sources from which to obtain viable occultation measurements.

The characteristics of the lowest layers of the atmosphere are found by calculation of the navigation signal's unique bending angle, which is obtained via open-loop tracking. During open loop tracking, the occultations are found by differencing the measured amplitude and Doppler of the carrier phase from accurate models based on geometry and observed atmospheric conditions. This requires resolving the relative velocity between the GNOMES and GNSS satellites (where a satellite in LEO has a typical velocity of 7 km/sec and a GNSS satellite at 26,000 km altitude is approximately 3 km/sec) to 0.15 to 0.2 mm/sec[13]. This level of orbital accuracy requires post-processed orbits and clock performance for the GNSS satellites, as well as fine-tuned orbital and clock information for the GNOMES in LEO. On-board scheduling and orbit determination for the GNOMES are performed by a navigation engine using only GPS observations. The GNSS orbit and clock data used to derive the atmospheric characteristics will be obtained from reputable post-processing facilities, such as NASA Jet Propulsion Laboratory (JPL) or University Corporation for Atmospheric Research (UCAR). Any false observations will be detected well before atmospheric products are made.

Typical GNSS spoofing is performed by recreating false GNSS signals from a local transmitter. However, a space-based receiver makes this scenario highly unlikely. Falsifying the satellite ephemeris/almanac message could also possibly cause receiver issues; however, because the Pyxis-RO instrument is directed to collect Doppler and phase measurements from values obtained directly from the particular satellite's ephemeris, a false ephemeris will lead to no measurements.

PlanetiQ will not be the only RO data provider to use foreign GNSS signals, as the NOAA led RO mission, COSMIC-2/FORMOSAT-7, is equipped with the Tri-GNSS (TriG) receiver built by NASA JPL and intends to collect signals originating from GPS, GLONASS and Galileo for its occultations[14]. NOAA has recently awarded contracts for commercially obtained space-based radio occultation data with no limitations on the signal source[15]. In fact, they specifically state the need for GNSS-RO measurements. The RFP language for the contract from NOAA contemplates that data would be provided from foreign GNSS satellites[16]. The Pyxis-RO

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[13] Schreiner, William, Rocken, Chris, Sokolovskiy, Sergey, Hunt, Douglas, "Quality assessment of COSMIC/FORMOSAT-3 GPS radio occultation data derived from single- and double-difference atmospheric excess phase processing," GPS Solutions, 14(1), 2009, pp. 13-22, doi: 10.1007/s10291-009-0132-5.

[14] Turbiner, Dmitry, Young, Larry E., Meehan, Tom K., "Phased Array GNSS Antenna for the FORMOSAT-7/COSMIC-2 Radio Occultation Mission," Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012), Nashville, TN, September 2012, pp. 915-916, *available at* http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/44928/1/12-4880_A1b.pdf.

[15] See https://www.fbo.gov/index.php?s=opportunity&mode=form&id=919a17d831c31a26a50eae5282056289&tab=core&_cview=1.

[16] Attachment 6 GNSS High Rate Binary Format (v1.9) under Requisition Number NEEP0000-18-00419, see https://www.fbo.gov/index?s=opportunity&mode=form&id=919a17d831c31a26a50eae5282056289&tab=core&_cview=1.

instrument, and subsequent data processing, will be able to validate the foreign GNSS signals as viable sources for atmospheric sensing.

Both government-lead and commercial RO missions contribute to numerical weather prediction and forecasts, and are desired in near real-time. However, post-processing of the GNSS orbits and clocks will always be necessary to derive the atmospheric characteristics, and any spoofing will be detected in this post-processing. Therefore, the weather products obtained via RO are resistant to false signals.