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
EDP	Electron Density Profiles
FDMA	Frequency Division Multiple Access
FEEP	Field-Emission Electric Propulsion
GNOMES	GNSS Navigation and Occultation Measurement Satellites
GNSS	Global Navigation Satellite System
IF	Intermediate Frequency
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
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
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 an SSE experimental satellite and engage in market trials with the atmospheric data obtained from the experiment, as permitted under the Commission's rules.[1] This satellite will eventually be a part of the SSE constellation of "GNSS Navigation and Occultation Measurement Satellites" (GNOMES) for which SSE 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
Uplink	S-band	2.081 GHz	450 kHz
Downlink	X-band	8.260 GHz	20 MHz

1.2 Background

The vision of SSE 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, SSE 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 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 sun-synchronous orbits (SSO) to provide pole to pole coverage. The satellite's

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

solar panels deliver power sufficient to acquire all RO acquisition opportunities continuously and downlink at every opportunity. Data is downlinked over each pole, yielding 50-minute maximum latency to the ground with an average latency of approximately 25 minutes. All occultation measurements will be downlinked at the next downlink opportunity. Each satellite carries a propulsion system to achieve the desired final 800 km altitude, optimal phasing between satellites, and 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.

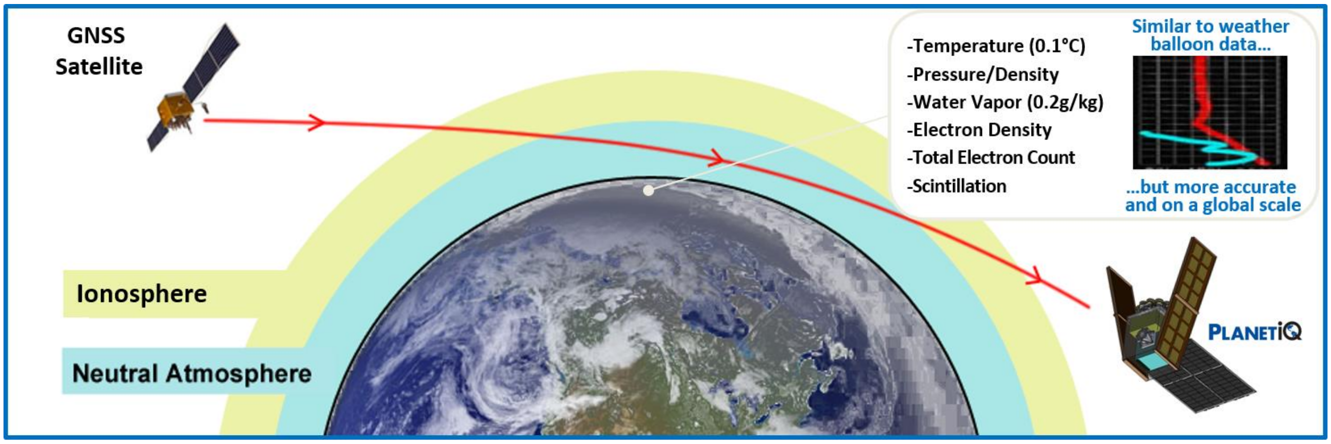

Figure 1.2-1. Geometry of a typical GNSS-RO event and resulting data products derived from the technique

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

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

2 Mission Description

2.1 Mission Expectations

The Pyxis instrument onboard each SSE 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 will 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, SSE 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 23 functional MEO satellites on orbit by mid-2019, we predict that our receivers will track 89 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 approximately 2,600 occultations per day per receiver 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
Q3 2019	89	2160
2020	96	2330
2021	101	2451
2022	107	2597

Polar orbits provide pole-to-pole coverage, and our fully-populated constellation's ascending nodes are dispersed to sample all local times for full diurnal coverage. The GNOMES-1 will be launched into SSO at initial injection orbit of 630 km and will have a nominal operational altitude of 800 km, shown in Figure 2.1-1a. The ascending node times will be separated to diversify coverage by separate launches and with the on-board ion propulsion system. Our final, operational constellation will consist of twenty GNOMES in ten, equally-spaced orbital planes, with large overlap of the swath widths of adjacent satellites for higher coverage and built-in redundancy, shown in Figure 2.1-1b.

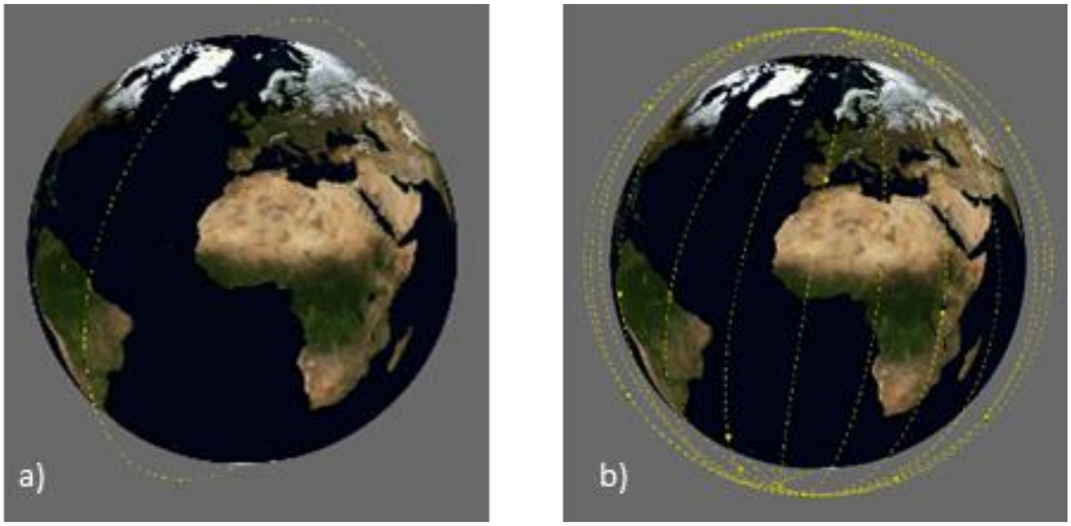

Figure 2.1-1. SSE satellite orbit configuration for a) the first satellite registered under the Part 5 license and b) the final twenty-satellite constellation under the eventual Part 25 license(s)

Figure 2.1-2 shows the daily global coverage of the approximately 2,160 occultations per day from our first satellite. Figure 2.1-3 shows the daily coverage over the Arctic region.

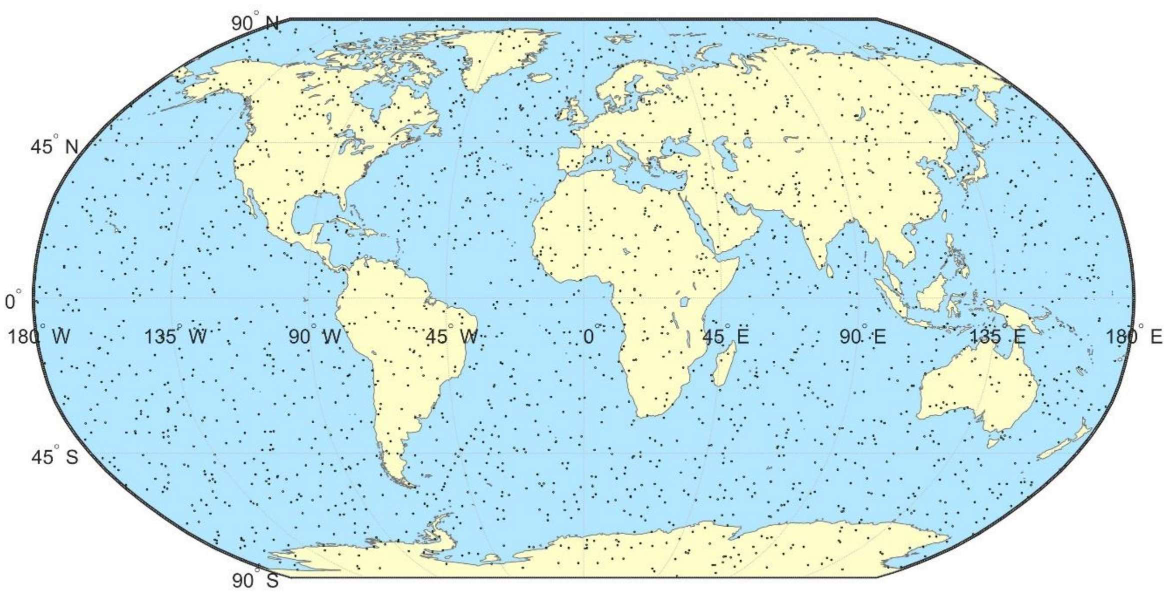

Figure 2.1-2. Worldwide daily coverage from the first SSE satellite from 89 GNSS satellites

Figure 2.1-3. Arctic view of occultations from the first satellite on orbit, producing 2,160 occultations per day worldwide

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, SSE 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 polar, sun-synchronous at approximately 800 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) C47, scheduled for launch between July-September 2019. The spacecraft will be sun-synchronous, in an orbital plane dictated by its launch characteristics (630 km altitude, 10:30 LTDN (to be refined once Antrix determines the launch characteristics))). Orbital maneuvers, such as altitude adjustments and station keeping, will be done with the on-board ion propulsion system.

As GNOMES-1 is a secondary payload onboard PSLV C47, the injection altitude and inclination are not the planned final orbit. SSE 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 for the first month of operation (July 2019). After the contractual period of performance, the satellite will perform altitude and inclination maneuvers with its propulsion system for approximately three months to reach its final operational orbit, with periodic satellite telemetry check-ups during the orbit raise. 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 a separate Exhibit: Exhibit A Orbital Debris Assessment Report (ODAR).

The lower injection altitude of PSLV C47 serves to help SSE adhere to the Commission's deorbit rules in case of propulsion failure. As shown in Table 2.2-1, the orbit lifetime of GNOMES-1 will be within the 25-year deorbit time span limit from natural orbit decay.

Table 2.2-1. Injection and final orbit characteristics calculated using the NASA DAS v.2.1.1 software*****

Mission	Launch	Altitude (km)	Inclination (°)	LTDN	Lifetime (yrs)
GNOMES-1	PSLV C47	Initial: 630x630	98.0	10:30	25.0 (max)
		Operational: 800x800	98.7		7 (planned)
		Deorbit: 800x200	98.7		<1 month

***Assuming an area to mass ratio of 0.009 m^2/kg (without the solar array)**

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 2.5 Watts. This data will be transmitted to polar and near-polar ground stations approximately 28 times per day per satellite. Commands and software updates will be uplinked via S-band radio from the same ground-stations at a rate of 128 kbps.

For purposes of the operating frequency for the two experimental GNOMES, SSE 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 450 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. SSE 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

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

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 SSE to cross-check and validate the accuracy of its data observations.

Observations of 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 with a launch mass of 26 kilograms, and 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.

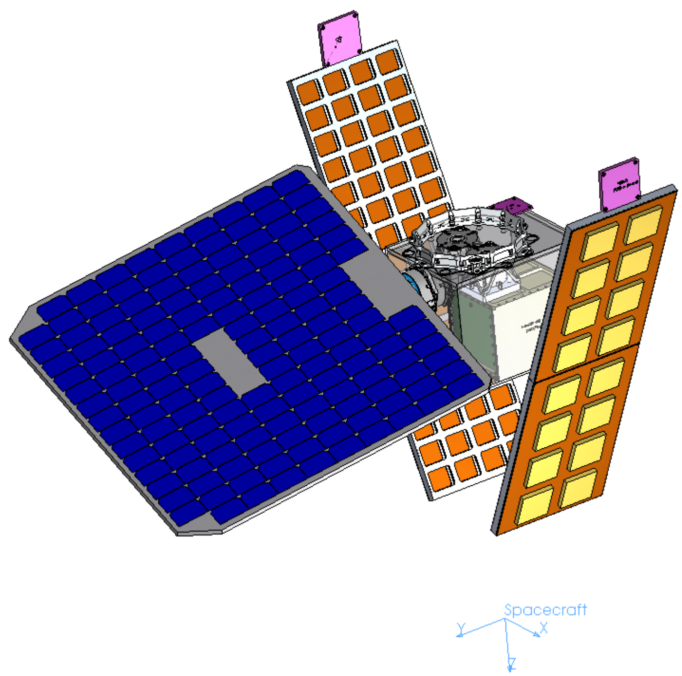

Figure 2.3-1. The GNOMES spacecraft in its deployed state

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 de-orbit after end of mission. Further description of re-entry disposal, orbital debris mitigation plan, and specialized thruster can be found in a separate exhibit: Exhibit A Orbital Debris Assessment Report (ODAR).

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

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	2.5 W
ERP	3.85 W
Mean/Peak	Peak
Frequency Tolerance	0.001%
Emission Designator	20M0G1D
Modulating signal	10000000 baud QPSK

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. The X-band antenna gain pattern for all elevation and azimuthal angles in Figure 2.4-1. The x-axis in Figure 2.4-1 represents the azimuthal spread and the y-axis is the elevation, with boresight at 0° and spacecraft nadir at -90°. The gain pattern that impacts the Earth's surface for a satellite at 800 km altitude (e.g. GNOMES) is highlighted[7].

[7] A spreadsheet with the numeric values at one degree fidelity for this same gain pattern is available upon request.

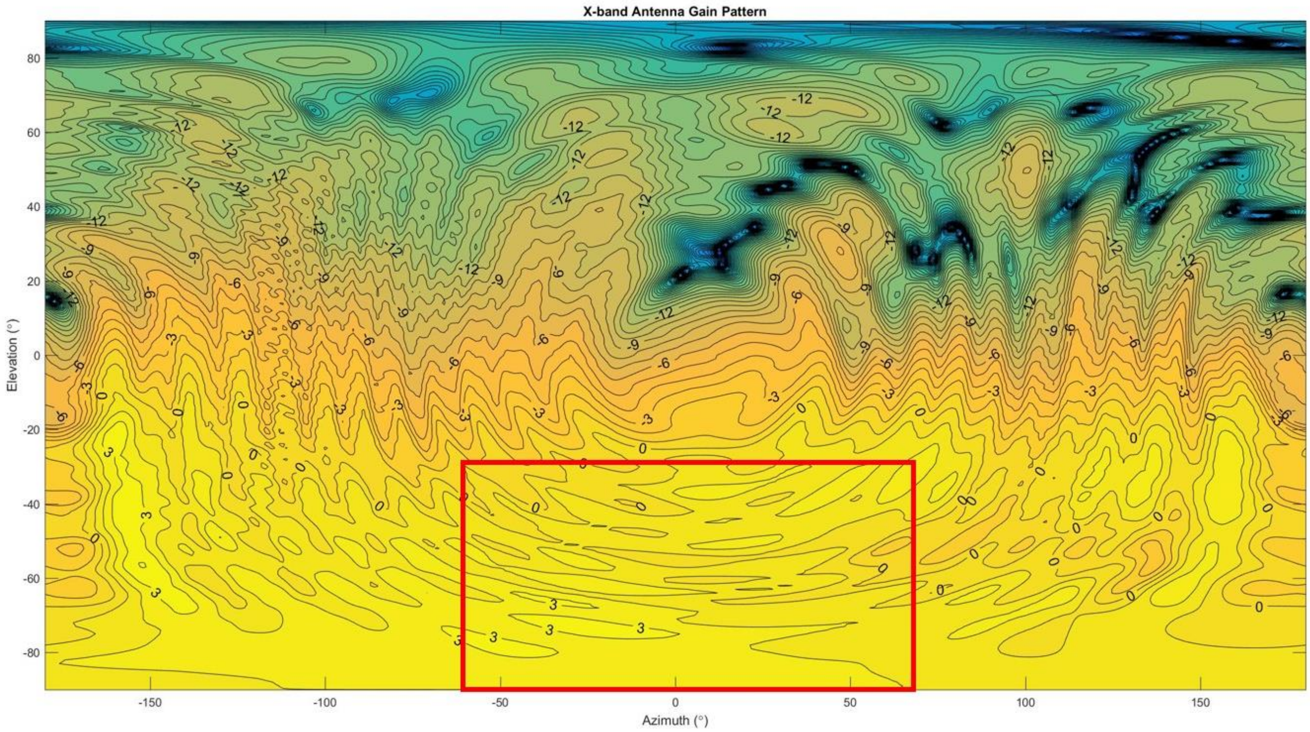

Figure 2.4-1. X-band antenna gain pattern for SSE's GNOMES. The highlighted region represents the approximate Earth coverage.

A link budget can be formed from the transmitter characteristics shown in Table 2.4-1 and the X-band antenna coverage shown in Figure 2.4-1. The power flux density (PFD) at the maximum gain (3 dB) is calculated to be -122 dB(W/m^2) over the total bandwidth of the transmitter. Therefore, the largest PFD resulting from the X-band transmitter on the GNOMES will be -135 dB(W/m^2·MHz) at the sub-satellite point, 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.

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

[8] Rec. ITU-R SA.1810

[9] ITU Radio Regulations Table 21-4

The PFD profile as a function of elevation angle from the Earth's surface are shown in Figure 2.4-2 for GNOMES-1. The PFD produced by GNOMES-1 satisfies the ITU PFD limits at all angles of arrival with over 10 dB of margin. In addition, the BCT X-band radio is adjustable on orbit, allowing SSE to control the PFD levels during all phases of the mission.

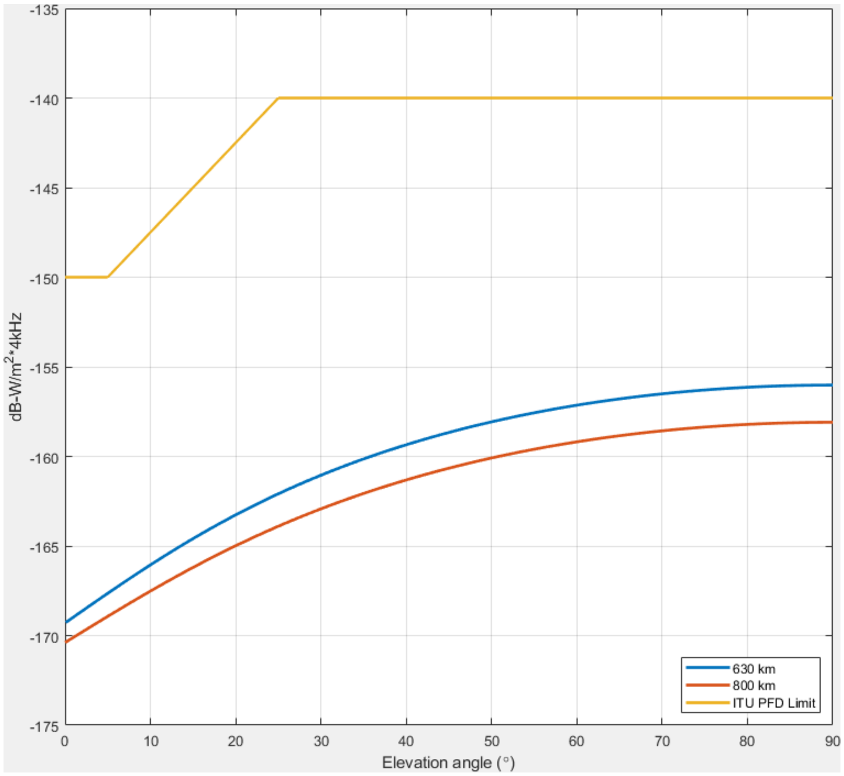

Figure 2.4-2. PFD at the Earth's surface produced by the X-band downlink radio for GNOMES-1 at initial and operational altitudes.

Finally, the ITU specifies a maximum allowable interference power spectral flux-density at Earth's surface of -255.1 dB(W/(m^2Hz)) to protect earth-station receivers in the deep-space research band of 8.40-8.45 GHz[10]. The chosen data rates and center frequency 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 we can avoid any sort of downlink transmission while within sight of a DSN station.

2.4.2 Ground Stations

The atmospheric soundings measured by the GNOMES will be downlinked via commercial ground station network. SSE 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].

Because of the polar nature of the sun-synchronous orbits, the optimal ground stations are near the Earth's poles. Table 2.4-3 shows the ground stations sites under consideration from KSAT. For data transmission on GNOMES-1, use of the Svalbard and Troll stations from KSAT will be baselined. Because of visibility constraints due to geometry, Troll only provides

[10] ITU-R SA-1157
[11] https://www.ksat.no/en/news/2016/january/ksat%20lite-network/

access to the GNOMES-1 13 out of 14 passes per day. Therefore, other southern hemisphere stations within the KSAT network are being considered to supplement for the missing passes. Combinations of the ground stations shown in Table 2.4-3 allow for at least 28 opportunities for data transfer per day for each of the GNOMES.

Table 2.4-3. KSAT ground station descriptions

	Svalbard, Norway	**Troll, Antarctica**	**Hartebeesthoek, South Africa**	**Punta Arenas, Chile**	**Awarua, New Zealand**
Latitude	78°13'47" N	72°00'41"S	25°53'08" S	53°09'17"S	46°31'41"S
Longitude	15°24'28"E	2°32'06"E	27°41'03" E	70°54'41"W	168°28'54"E
Elevation above sea level	450 m	1270 m	1416 m	34 m	444 m
Half-power beamwidth	1.31°				
Action frequency	2.081 GHz				
Output power	50 W				
ERP	42.65 dBW				
Mean/Peak	Peak				
Frequency Tolerance	0.000250%				
Emission Designator	450KG1D				
Modulating signal	128000 baud BPSK				

Because the ground stations to be used by the GNOMES are not located in the United States, SSE has not specified them in the Form 442. SSE may subscribe to other ground stations within the KSAT network, 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. SSE 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 orbit while in range of the ground station. With two ground stations located on opposite sides of the Earth, the GNOMES will downlink roughly half an orbit’s worth of scientific data and satellite telemetry (160 MB) at each pass. The time to downlink 160 MB of data given a 10 Mbps data rate would be 130 seconds. Including an estimated 20 seconds for framing overhead, 150 seconds is needed at each pass to downlink the necessary data.

A simulation of the GNOMES in their 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 the GNOMES and the Svalbard and Troll ground stations was recorded for one year's worth of orbits and the injection and final orbital altitudes. An elevation mask of 5 degrees will be imposed at each of the ground stations to limit data transfer to elevations above the surrounding foliage and structures.

The distributions of pass times for each of the stations are shown in Figure 2.4-3 for GNOMES-1. The majority of GNOMES-1 pass times for data transfer are over 600 seconds for each ground station at either the injection or final orbit altitudes. Only 1-2% of passes are less than 150 seconds for the Troll station, at any orbit altitude.

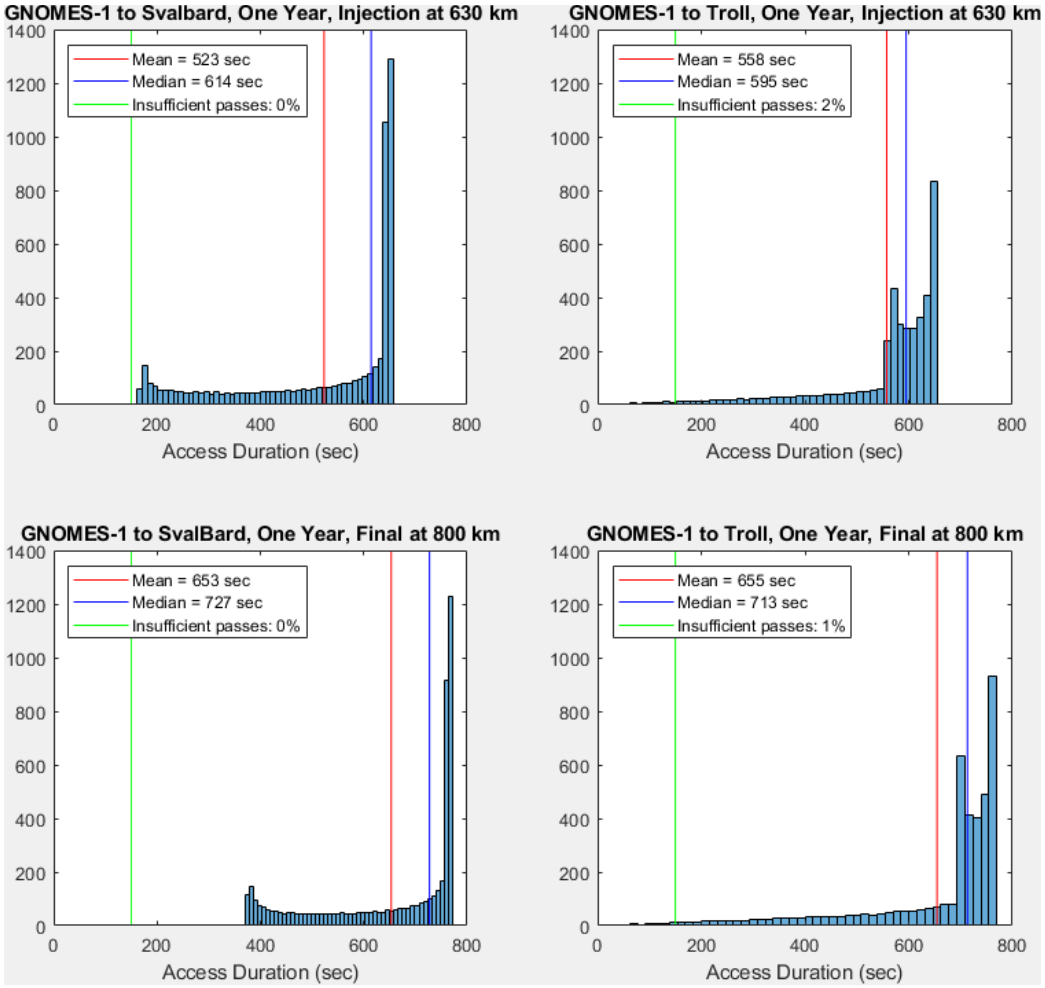

Figure 2.4-3. Pass lengths for GNOMES-1 at 630 km sun-synchronous orbit with 10:30 LTDN and 800 km sun-synchronous orbit with 10:30 LTDN.

With a data downlink rate of 10 Mbps, there is temporal flexibility within the satellite-station pass for data downlink for all Svalbard passes and the majority of Troll passes. For the Troll passes that are less than 150 seconds, other southern hemisphere ground stations within the KSAT networks are being explored. 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

SSE plans to actively engage in pre-coordination and coordination activities with other S-band/X-band spectrum users to avoid potential interference during transmission.

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. SSE 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.

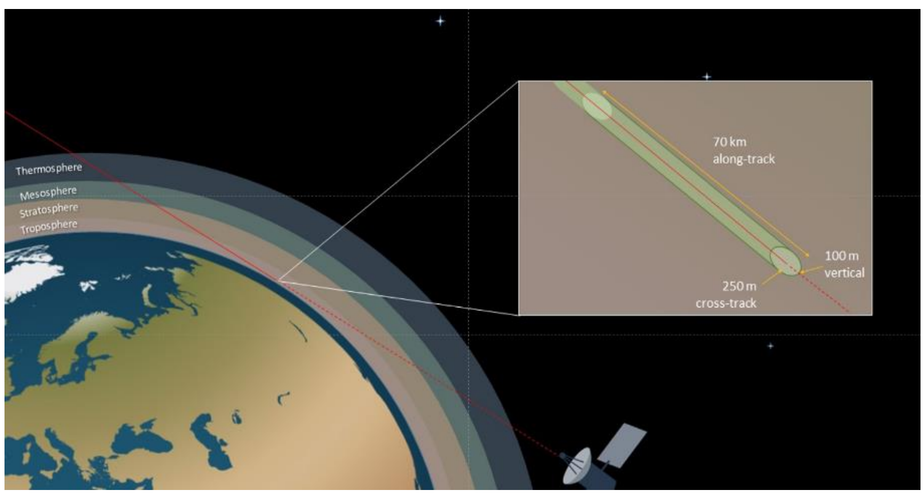

Figure 3.1-1. Dimensions of the occulting GNSS signal ray path

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 SSE 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[12]. 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.

SSE 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[13]. NOAA has recently awarded contracts for commercially obtained space-based

[12] 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.

[13] 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.

radio occultation data with no limitations on the signal source[14]. 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[15]. The Pyxis-RO 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.

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

[15] 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.