Space Sciences & Engineering LLC, d/b/a

PlanetiQ

CRITICAL DATA FOR A SMARTER PLANET

Exhibit C – Technical Annex

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Acronyms

BCT	Blue Canyon Technologies
DAS	Debris Orbit Software
DSN	Deep Space Network
FDMA	Frequency Division Multiple Access
GNOMES	GNSS Navigation and Occultation Measurement Satellites
GNSS	Global Navigation Satellite System
ITU	International Telecommunication Union
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
ALB	Advanced Lightband
NWP	Numerical Weather Prediction
PFD	Power Flux Density
PSLV	Polar Satellite Launch Vehicle
RF	Radio Frequency
RO	Radio Occultation
SDR	Software-Defined Radio
SNR	Signal-to-Noise Ration
SSO	Sun-Synchronous Orbit
STK	Systems Toolkit (formerly Satellite Toolkit)
TT&C	Telemetry, Tracking, and Control

1 Scope

This Exhibit contains technical and other information regarding the GNOMES-4 satellite.

2 General Description

2.1 Theory of Operations

PlanetiQ plans to perform system commissioning and RO data collection at the injection altitude. The commissioning period is expected to be less than 1 month. The satellite will resume data collection and transfer to the ground after the orbit transition.

Because data latency is vital for the value of the atmospheric measurements, frequent data downloads to the ground are necessary. Occultation observation data from GNOMES-4 will be downlinked via X-band radio at a nominal rate of 10 Mbps and maximum output power of 2.0 dBW. This data will be transmitted to globally distributed ground stations. Commands and software updates will be uplinked via S-band radio from a subset of ground-stations at a rate of 100 kbps.

Based on prior pre-coordination discussions with federal operators, PlanetiQ is applying for center frequencies of 8.260 GHz (downlink) and 2.081 GHz (uplink). GNOMES-4 will transmit in a single 20 MHz channel for downlink and another single 200 kHz channel for uplink. Telemetry, tracking and command (TT&C) will also be provided within those frequency bands.

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 1575.42 MHz and B2 at 1207.14 MHz) constellations, as shown in Table 2.1-1.

Table 2.1-1. RO signal source for each constellation

	GPS	**GLONASS**	**Galileo**	**BeiDou**
1st frequency	L1C/A	L1OF	E1	B1C
2nd frequency	L2C	L2OF	E5b	B2a

Dual-frequency measurements from the 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.

2.2 Spacecraft Description

The GNOMES-4 is a microsatellite-style satellite. Once separated from the launch vehicle, the satellite will deploy the solar panel and specialized Pyxis-RO antennas. The spacecraft is three-axis stabilized and nadir following.

2.2.1 Orbital Parameters

The GNOMES-4 spacecraft is expected to be launched into the orbit listed in Table 2.2-1.

Table 2.2-1 GNOMES-4 Orbital Parameters

Orbit	Spacecraft	Apogee	Perigee	Inclination	RAAN	Period	LTDN
1	GNOMES-4	525 km	525 km	97.6°	0°	5708s	07:00:00

2.2.2 Frequency Plan

PlanetiQ proposes operating GNOMES-4 using the same frequency characteristics previously pre-coordinated and approved for GNOMES-2 and GNOMES-3, as shown in Table 2.2-2.

Table 2.2-2. 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

2.2.3 Telemetry, Tracking and Control (TT&C)

GNOMES-4 will carry the SDR-X X-band transmitter/S-band receiver. 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. The transmission characteristics are described below in Table 2.2-3.

Table 2.2-3. X-band transmitter description

	Non-geostationary
Action frequency	8.260 GHz
Maximum output power	2.0 dBW
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 nearly hemispherical in their gain patterns and are nadir-pointed. For both antennas, the gain is generally constant and varies between 0 and 6 dBi over Earth coverage angles.

A link budget can be formed from the transmitter characteristics shown in Table 2.2-3 and the expected X-band antenna coverage.

The GNOMES-4 spacecraft will use a sufficiently unique telemetry marker at deployment to assure that its telemetry stream can be unambiguously identified.

Contact details for the control center are provided below:

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2.2.4 Satellite Antennas

The GNOMES-4 spacecraft receives S-band Earth-space communications with a patch antenna with peak gain of 6 dBi and sidelobe patterns as illustrated in Figure 2.2-1. The GNOMES-4 spacecraft employs 3-axis stabilization to keep the Nadir panel pointing towards earth and allow for continuous scientific data collection.

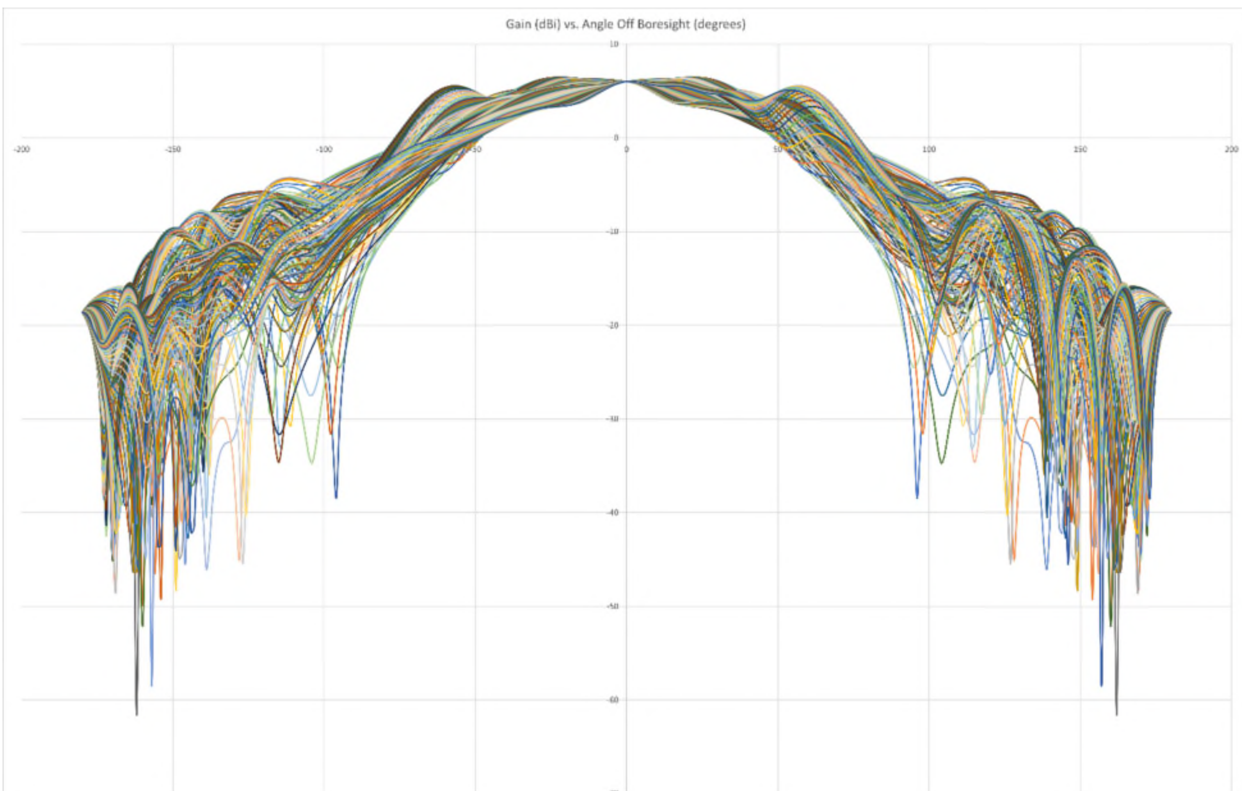


Figure 2.2-1 S-band Earth-space Spacecraft Antenna Pattern

The GNOMES-4 spacecraft transmit X-band space-Earth communications with a patch antenna with peak gain of 6 dBi and sidelobe patterns as illustrated in Figure 2.2-2.

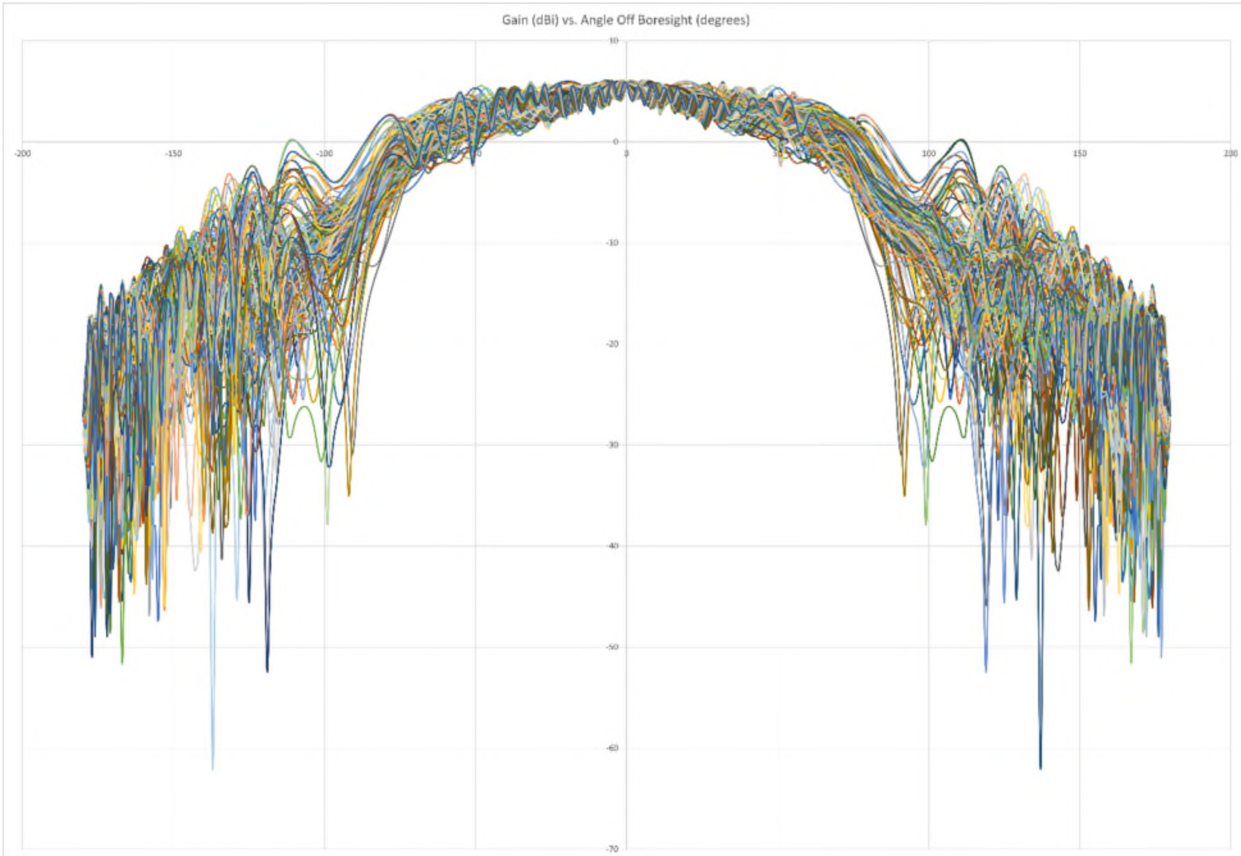


Figure 2.2-2 X-band space-Earth Spacecraft Antenna Pattern

2.2.5 Antenna Beam Projections

Included in the Schedule S (repeated here for convenience) are Nadir-pointing antenna beam projections for the S-band Earth-space beam, Figure 2.2-3, and the X-band space-Earth beam, Figure 2.2-4, when the GNOMES-4 sub-satellite point is just east of Ecuador. The provided GXT files (in a GIMS container) are actually geostationary footprints. However, the contours reflect the beam projection from an orbital altitude of 525 km (the nominal orbit for the GNOMES-4 spacecraft). Because these antennas are nearly omni directional, the contours below -6 dB are beyond the horizon and are not illustrated.

Figure 2.2-3 S-band Earth-space Antenna Beam Projection

Figure 2.2-4 X-band space-Earth Antenna Beam Projection

2.3 Spectrum Sharing

2.3.1 Power Flux Density

The power flux density (PFD) at the maximum EIRP (8 dBW) is calculated to be -115.6 dB(W/m^2) over the total bandwidth of the transmitter at the lowest operational altitude of 430 km. Therefore, the largest PFD resulting from the X-band transmitter on GNOMES-4 will be -152.7 dB(W/m^2·4kHz) at the sub-satellite point from 430 km, a value that is well below the recommendation given by the ITU[1].

[1] Rec. ITU-R SA.1810

The power flux density (PFD) as the Earth's surface and the GSO arc are calculated as follows:

EIRP Densities at transmit antenna

At the Source: EIRP Density = EIRP - 10*$\log_{10}$(Occupied Bandwidth in Hz)

EIRP Density(Hz) = 8 dBW – 10*$\log_{10}$(20,000,000 Hz) = 8 - 73 = -65 dBW/Hz

EIRP Density(4kHz) = -65 dBW/Hz + 10*$\log_{10}$(4000) = -29 dBW/4kHz

Power Flux Densities

Power Flux Density (PFD) (525km) = EIRP Density – spreading loss

PFD (dBW/m^2/4 kHz) = EIRP Density (dBW/4 kHz) - 10*$\log_{10}$ (4*pi*distance*distance)

PFD = -29 dBW/4 kHz – 10 * 10*$\log_{10}$(4*π*$525{,}000^2$) = -29 – 125.4 = -154.4 dBW/m^2/4 kHz

(Note, convert km to meters)

Power Flux Density per 4 kHz 525km) = -154.4 dBW/m^2/4 kHz

Worst Case PFD at GSO, is if we pitch up and point our downlink antenna up to point at GSO's

Power Flux Density GSO (35241 km above 545km)

PFD = -29 dBW/4 kHz – 10 * 10*$\log_{10}$(4*π*$35{,}241{,}000^2$) = -29 – 161.9 = -190.9 dBW/m^2/4 kHz

(Note, convert km to meters)

Power Flux Density per 4 kHz 525km) = -190.9 dBW/m^2/4 kHz

The ITU also recommends the following limits of PFD from space stations as received at the Earth's surface.[2] These limits relate to the PFD obtained only under free-space path loss conditions and a 4 kHz bandwidth.

[2] ITU Radio Regulations Table 21-4.

Table 2.3-1. 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

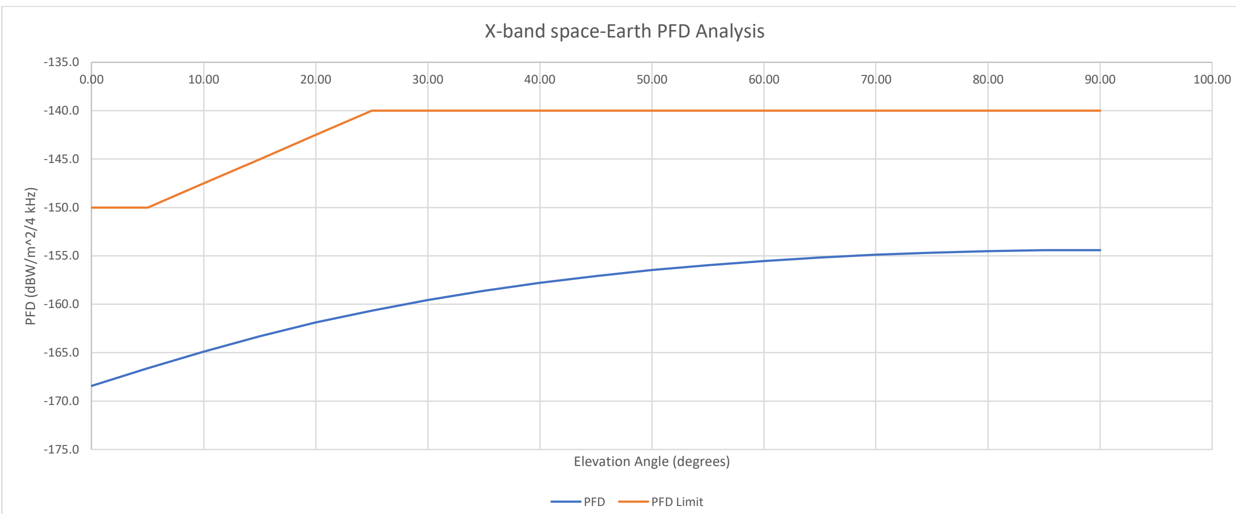


Figure 2.3-1 X-band PFD vs Elevation Angle at Insertion Orbit (525 km x 525 km)

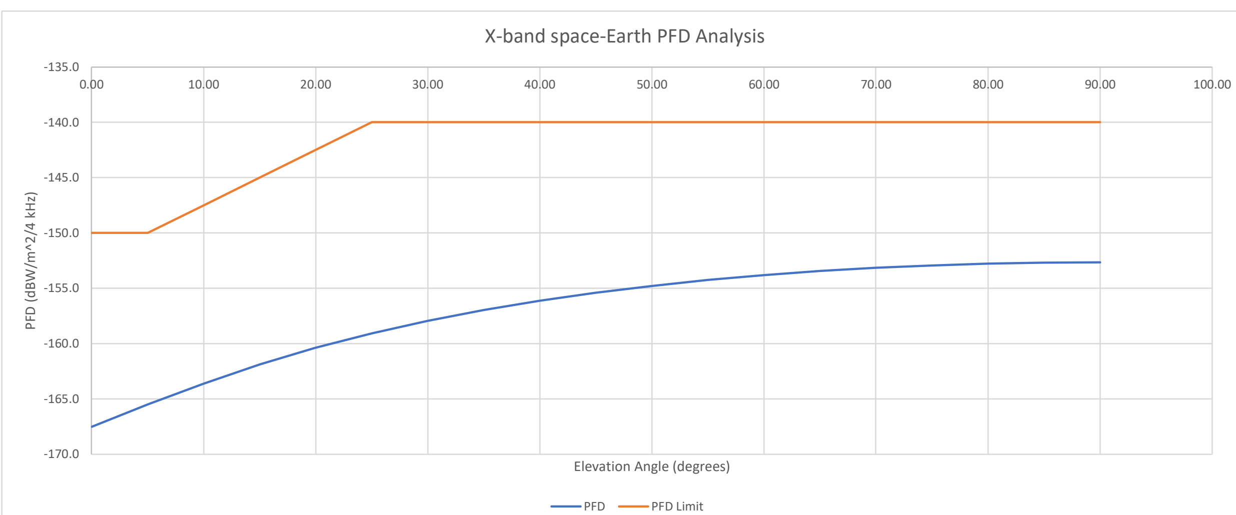


Figure 2.3-2 X-band PFD vs Elevation Angle at Minimum Operational Orbit (430 km x 430 km)

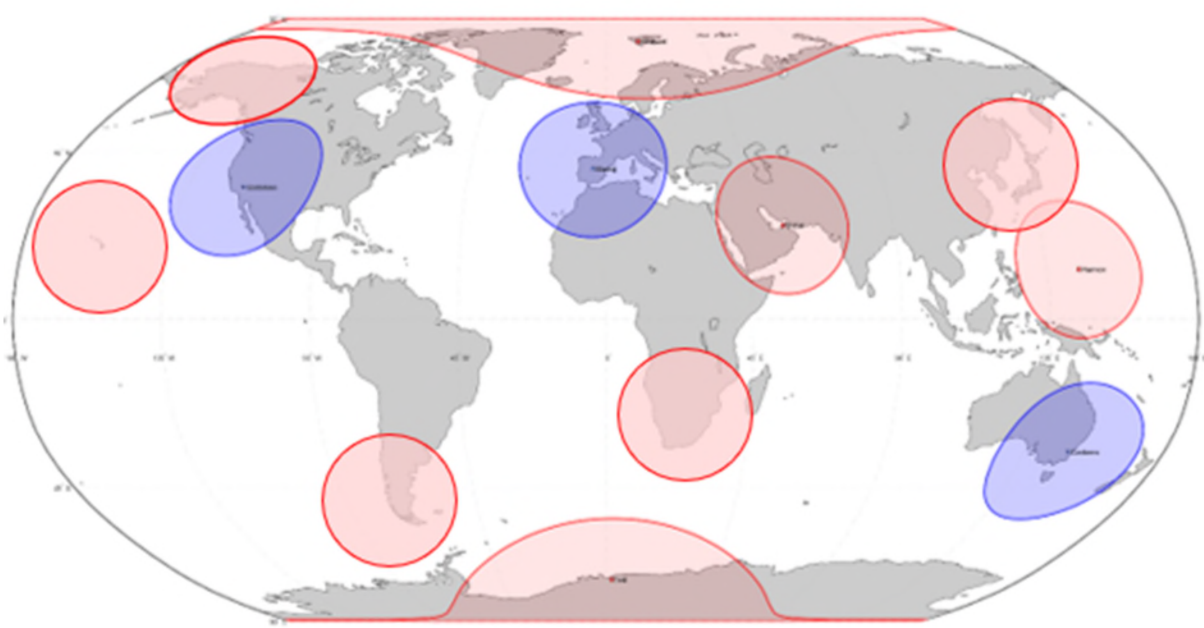
Table 2.3-3 GNOMES-4 Peak Power Flux Density from 525 km to Earth, and from 525 km to GSO (if pointing up vs. pointing to the Earth).

	430km (worst-case) to Earth	**545km (worst-case) to GSO**
EIRP (dBW)	8 dBW	8 dBW
EIRP Density/4kHz	-29 dBW/4 kHz	-29 dBW/4 kHz
Peak Power Flux Density (4kHz)	-152.7 dBW/m^2/4kHz	-190.9 dBW/m^2/4kHz
Peak Power Flux Density - Limit (4kHz)	-140 dBW/m^2/4kHz	-174 dBW/m^2/4kHz

The PFD produced by GNOMES-4 satisfies the ITU PFD limits at all angles of arrival and possible altitudes, with over 10 dB of margin. In addition, the X-band radio is adjustable on orbit, allowing PlanetiQ to control the PFD levels during all phases of the mission.

2.3.2 Deep Space Network

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.[3] The chosen data rate and center frequency for the X-band transmission on GNOMES-4 should guarantee that no close-in sidelobes are within the deep space band. Additionally, the chosen ground stations, described in Section 2.4.7, are sufficiently far from Deep Space Network (DSN) stations that the GNOMES-4 spacecraft can avoid downlink operations while within sight of a DSN station (see Figure 2.3-3).



[3] ITU-R SA-1157

Figure 2.3-3. Transmission footprints for the possible ground stations for GNOMES-4 (in red) showing no overlap with DSN station (in blue).

2.3.3 Coordination

PlanetiQ has already commenced pre-coordination activities with federal S-band/X-band spectrum users.

2.3.4 Frequency Tolerance

The frequency tolerance requirements of section 25.202(e) that the carrier frequency of each space station transmitter be maintained within 0.002% of the reference frequency will be met.

2.3.5 Out of Band Emissions

The out-of-band emission limits of section 25.202(f)(1), (2), and (3) will be met.

2.3.6 Frequency Reuse

The GNOMES-4 spacecraft does not operate in any frequency bands where section 25.210(f) applies.

2.3.7 Cessation of Emissions

All downlink transmissions can be turned on and off by ground station telecommand, thereby achieving cessation of emissions from the satellite, as required by section 25.207. All GNOMES-4 transmissions will be initiated by ground command and not scheduled. The GNOMES-4 spacecraft will always be listening for commands from the ground and transmit only when a transmit command is received. This "failsafe" mechanism assures that the GNOMES-4 spacecraft does not regularly or constantly transmit in a scenario where a command to cease transmission cannot be received.

2.3.8 Ground Stations

The atmospheric soundings measured by the GNOMES-4 spacecraft will be downlinked via commercial ground station networks. PlanetiQ has contracts with Kongsberg Satellite Services (KSAT) and ATLAS Space Operations for use of their ground station network as specified below. For S-band uplink and X-band downlink, KSAT supplies a network of 3.7-meter antenna dishes,[4] while ATLAS maintains a network of ground stations of various sizes (3.4 m to 9.1 m).

The ground stations shown in Table 2.3-2 and Table 2.3-3 represent a superset of possible ground stations under consideration from KSAT and ATLAS.

Table 2.3-2 KSAT ground station locations

Ground Site	Latitude	Longitude	Antenna
Svalbard, Norway	78°13'46"N	15°24'28"E	3.7m S U/L, SX D/L
Troll, Antarctica	72°00'40"S	2°33'14"E	3.7m S U/L, SX D/L
Inuvik, Canada	68.2° N	133.3° W	3.7m S U/L, SX D/L
Hartebeesthoek, S. Africa	25.8° S	27.7° E	3.7m S U/L, SX D/L
Punta Arenas, Chile	53.0° S	70.0° W	3.7m S U/L, SX D/L
Jeju, S. Korea	33.5° N	126.8° E	3.7m S U/L, SX D/L

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

Maui, Hawaii	20°49'2.1" N	156°27'16.1" W	3.7m S U/L, SX D/L

Table 2.3-3 ATLAS ground station locations

Ground Site	Latitude	Longitude	Antenna
Harmon, Guam	13°30'45"N	144°49'29"E	3.7m S U/L, SX D/L
Dubai, UAE	24°56'32"N	55°20' 52"E	3.7m S U/L, SX D/L
Chitose, Japan	42.77° N	141.62° E	3.4 m S U/L, SX D/L
Utqiagvik (Barrow), AK	71.27° N	156.8° W	3.7m S U/L, SX D/L

2.3.9 Ground Station Access

During a station pass, the GNOMES-4 spacecraft will downlink the accumulated atmospheric measurements since the previous ground contact. With the broad distribution of ground stations around the Earth, the GNOMES-4 spacecraft will have frequent telecommunications opportunities. PlanetiQ has baselined a 5-minute contact time for each station pass to conduct commanding and downlink operations, although with our 10 Mbps data rate, the necessary communication time is likely less.

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 2.3-2 and Table 2.3-3, also give geographic diversity for downlink opportunities. GNOMES-4 also will have on-board data storage sufficient for multiple passes without downlink.

CERTIFICATION OF PERSON RESPONSIBLE FOR PREPARING ENGINEERING INFORMATION

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 25 of the Commission's rules, that I have either prepared or reviewed the engineering information submitted in this application and that it is complete and accurate to the best of my knowledge and belief.

/s/

____

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