Soil Moisture Active Passive (SMAP) Telecommunications

Jim Taylor, William Blume, Dennis Lee, Ryan Mukai

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DESCANSO

**Deep Space Communications and Navigation Systems
Center of Excellence**

Near Earth Design and Performance Summary Series

The Cover

The Soil Moisture Active Passive (SMAP) mission provides global measurements of soil moisture and its freeze/thaw state from a 685−km, near−polar, Sun−synchronous orbit. SMAP was launched January 31, 2015, and began its science mission that April, releasing its first global maps of soil moisture on April 21. The SMAP observatory uses a spinning antenna with an aperture of 6 meters (m), and the SMAP observatory's instrument suite includes a radiometer and a synthetic aperture radar to make coincident measurements of surface emission and backscatter.

SMAP is intended to help scientists understand links among Earth's water, energy, and carbon cycles; reduce uncertainties in predicting climate; and enhance our ability to monitor and predict natural hazards such as floods and droughts. Use of SMAP data has additional practical applications, including improved weather forecasting and crop-yield predictions.

SMAP Mission Status, Mid-2016

On July 7, 2015 SMAP's radar stopped transmitting due to an anomaly involving the radar's high-power amplifier (HPA). Following an unsuccessful attempt on Aug. 24 to power up the radar unit, the project had exhausted all identified possible options for recovering operation of the HPA and concluded that the radar is not recoverable. The radiometer and all engineering subsystems are operating normally.

The start of the SMAP data record is defined as March 31/April 1, 2015. This is the date the SMAP radiometer first started collecting routine science data. The radar was not in its final data configuration until mid-April, and it produced its normal data up to 21:16 UTC on July 7, 2015.

Validated Level 1 radar and radiometer products were released beginning in April 2016, along with beta versions of Level 2 through Level 4 soil moisture and freeze/thaw products. Validated versions of the geophysical products were also released beginning the same month.

Near Earth Design and Performance Summary Series

Article 1

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NEAR EARTH DESIGN AND PERFORMANCE SUMMARY SERIES

Issued by the Deep Space Communications and Navigation Systems
Center of Excellence
Jet Propulsion Laboratory
California Institute of Technology

Joseph H. Yuen, Editor-in-Chief

Articles in This Series

Article 1—**"Soil Moisture Active Passive (SMAP) Telecommunications"**
Jim Taylor, William Blume, Dennis Lee, and Ryan Mukai

Foreword

This Near Earth Design and Performance Summary Series, issued by the Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), is a companion series to the Design and Performance Summary Series and the JPL Deep Space Communications and Navigation Series. Authored by experienced scientists and engineers who participated in and contributed to near-Earth missions, each article in this series summarizes the design and performance of major systems, such as communications and navigation, for each mission. In addition, the series illustrates the progression of system design from mission to mission. Lastly, the series collectively provides readers with a broad overview of the mission systems described.

Joseph H. Yuen

DESCANSO Leader

Near Earth and Deep Space Missions

This article on Soil Moisture Active Passive (SMAP) telecommunications is the first in the Descanso Near Earth series. It is modeled on the deep space telecommunications articles in the Design and Performance and Summary Series

Near Earth and deep space communications differ from each other in several ways. The SMAP spacecraft/Earth station communications links operate at much smaller distances than those deep space missions that communicate with the Deep Space Network. SMAP's commanding and engineering telemetry are at S-band rather than the more common X-band for deep space. The SMAP science data downlink is at 130 megabits per second (Mbps) on X-band, a much higher data rate than the 0.1 to 10 Mbps of typical deep space missions. The low Earth orbiting SMAP communicates with the Near Earth Network of ground stations, some of which have also served deep space missions in their launch phases. Just as with the relay passes between Mars orbiters and landers, SMAP passes with the near-Earth stations are more frequent but of shorter duration than deep space passes. When special or emergency SMAP activities require a longer pass than SMAP geometry with NEN allows, S-band forward and return links are scheduled with geosynchronous Earth orbiting communications satellites operated by the Space Network (SN).

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1. SMAP Mission and Instrument Overview

Completing its commissioning after the January 31, 2015 launch, Soil Moisture Active Passive (SMAP[1]) satellite has been in its science phase since May 2015 [1].

 The SMAP mission is under the NASA Science Mission Directorate, Earth Science Division, and is programmatically managed under the Earth Systematic Missions Program Office at the Goddard Spaceflight Center.

The purpose of the SMAP mission is to establish and operate a satellite observatory in a near-polar, Sun-synchronous Earth orbit and to collect a 3-year soil-moisture data set. The data set is being used to determine the moisture content of the upper soil and its freeze/thaw state. The measurement swath width is 1000 km to provide global coverage within 3 days at the Equator and 2 days at latitudes above 45 degrees (deg) N.

These measurements are being used to enhance understanding of processes that link the water, energy, and carbon cycles, and to extend the capabilities of weather and climate prediction models.

SMAP is one of four first-tier missions recommended by the National Research Council's Committee on Earth Science and Applications from Space [2]. The accuracy, resolution, and global coverage of SMAP soil moisture and freeze/thaw measurements are invaluable across many science and applications disciplines including hydrology, climate, carbon cycle, and the meteorological, environmental, and ecology applications communities. Use of SMAP data can quantify net carbon flux in boreal landscapes and develop improved flood prediction and drought monitoring capabilities.

The SMAP observatory employs a dedicated spacecraft operating in a 685-kilometer (km) near-polar, Sun-synchronous orbit, with Equator crossings at 6 a.m. and 6 p.m. local time. The instrument suite consists of a radiometer and a synthetic aperture radar operating at L-band (1.2 to 1.5 gigahertz, GHz). The instrument is designed to make coincident measurements of surface emission and backscatter, with the ability to sense the soil conditions through moderate vegetation cover.

The SMAP mission design was based on an instrument combining an L-band radar and an L-band radiometer, processing and combining the data from both the active radar and the passive radiometer during simultaneous observation. The active radar failed after providing normal data during April-June of 2015. This article includes details for both the radar and the radiometer of the SMAP science instrument.

Before its failure [3], the radar operated at 1.26 gigahertz (GHz). The radiometer has been successfully operating at 1.41 GHz. The two instruments share a rotating reflector antenna with a 6-meter (6-m) aperture that scans a wide 1000-kilometer (1000-km) ground swath as the observatory orbits the Earth. The L-band frequency enables observations of soil moisture through moderate vegetation cover, independent of cloud cover, and night or day. Multiple polarizations enable accurate soil moisture estimates to be made with corrections for vegetation, surface roughness, Faraday rotation, and other perturbing factors.

The radiometer provides passive measurements of the microwave emission from the upper soil with a spatial resolution of about 40 km, and is less sensitive than the radar to the effects of surface roughness and vegetation. The synthetic aperture radar (SAR) had the capability to make active backscatter measurements from the reflected signal with a spatial resolution of about 3 km acquired over land in its high-resolution mode. Lower resolution radar data was acquired globally [4].

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[1] Acronyms are defined at their first use. See the last section of the article for a list of acronyms and abbreviations and their definitions.

Although there is a loss in accuracy and spatial resolution in not having radar data, the SMAP radiometer measures moisture in the upper 5 centimeters (cm) of soil, with a ground track that repeats every 8 days. The radar data also had the capability to provide information on the freeze/thaw state of the soil, which is important to understanding the contribution of boreal forests northward of 45 degrees (deg) N latitude to the global carbon balance. [5]

1.1 SMAP Science and Mission Objectives

1.1.1 Science Objectives

The SMAP science objectives are to provide global mapping of soil moisture and freeze/thaw state (the hydrosphere state) to:

- Understand processes that link the terrestrial water, energy, and carbon cycles
- Estimate global water and energy fluxes at the land surface
- Quantify net carbon flux in boreal landscapes
- Enhance weather and climate forecast capability
- Develop improved flood prediction and drought monitoring capability

1.1.2 Mission Objectives

The four top-level mission objectives for the SMAP mission are to:

- Launch into a near-polar Sun-synchronous orbit that provides near-global coverage every 3 days.
- Make global space-based measurements of soil moisture and freeze/thaw state with the accuracy, resolution, and coverage sufficient to improve our understanding of the hydrologic cycle.
    Note: Without the radar's 3-km resolution, the resolution of the radiometer alone is 40 km and may be improved to 25 km.
    Note: Spatial coverage that depends on another satellite's radar is sparser than if SMAP's radar had provided the data [6].
- Record, calibrate, validate, publish, and archive science data records and calibrated geophysical data products in a National Aeronautics and Space Administration (NASA) data center for use by the scientific community.
- Validate a space-based measurement approach and analysis concept for future systematic soil moisture monitoring missions.

1.2 Mission Phases

Four mission phases have been defined [5] to describe the different periods of activity during the mission. These are the launch, commissioning, science observation, and decommissioning phases. Time after the liftoff of the launch vehicle ("Launch", abbreviated L) is the reference time used to define activity occurrences relative to one another as well as the boundaries of some of the mission phases. Calendar date, day of year (doy), universal time coordinated (UTC), and Pacific Standard Time (PST) are other date and time references appearing in SMAP project documentation.

1.2.1 Launch

The launch phase is the period of transition that took the observatory from the ground, encapsulated in the launch vehicle fairing, to its initial free flight in the injection orbit.

The launch period opened January 29, 2015 with a launch time of 14:20:42 UTC (6:20:42 a.m. PST at the launch site) and a launch widow of 3 minutes each day. The 8-day launch period included the ability to recycle in 24 hours. A January 29 launch would allow for 100 days of commissioning without eclipse.

Launch dates delayed through March 10, 2015, would still have met a minimum requirement to avoid eclipses during the first 60 days of commissioning.

The actual launch was January 31, 2015 at 14:22 UTC (6:22 a.m. PST) after a launch countdown that began at L minus 6 hours. Figure 1-1 defines the launch ascent profile used for SMAP on the Delta II launch vehicle.
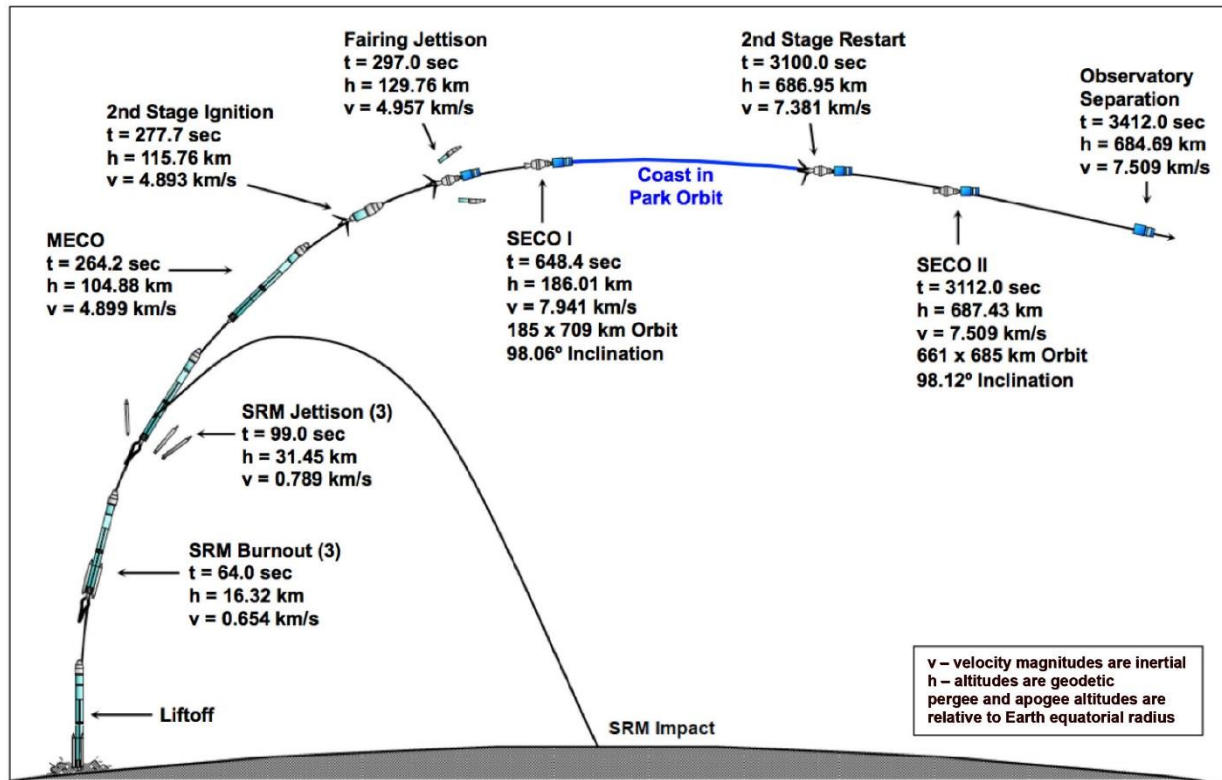
Fig. 1-1. SMAP Delta II ascent profile.
(h = altitude, L = launch (time), MECO = main engine cut off, SECO = single engine cut off,
SEP = separation, SRM = solid rocket motor, t = time, and v = velocity)

Injection by the Delta II upper stage into orbit was off the east coast of Africa at 15:19 UTC; thus, at L + 00:57. A camera on the Delta II upper stage provided a post-separation view of SMAP from SEP through solar array deployment. The Hartebeesthoek, South Africa tracking station had SMAP in view until SEP plus 2.5 minutes (min) to receive transmissions of video from the upper stage.

The S-band transponder (SBT) was powered on at L + 00:56:53, one second after launch vehicle separation. For communications, the first objective was to acquire one-way S-band downlink from the SMAP spacecraft to the project's Mission Operations Center (MOC) via the Space Network (SN). The second objective was to establish an S-band coherent two-way connection with the Near Earth Network (NEN) and play back the recorded launch data. To meet this objective, the spacecraft was launched with the S-band radio in its coherent mode[2]. Initial data rates were planned to be 2 kilobits per second (2 kbps) uplink and 2 kbps downlink, compatible with either SN or NEN.

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[2] Acquisition of signal (AOS) could occur at any time after launch vehicle (LV) separation plus 1 second with a requirement of no later than 20 minutes. The separation attitude had been coordinated to maximize the chances of initial acquisition by the SN. Acquisition by the SN was achieved immediately.

Coverage was scheduled for initial downlink acquisition by two Tracking and Data Relay Satellite System (TDRSS) satellites (named TDZ ("zone")[3] and TDS ("spare")) of the Space Network (SN). Telemetry acquisition through TDZ began at 15:19 UTC, immediately after separation. The two TDRS satellites were scheduled to support SMAP through SEP plus 150 minutes, thus affording the best chance to receive telemetry from the single SMAP S-band low gain antenna (LGA) in a random attitude.

The separation attitude was designed to point the S-band LGA toward TDZ over the Indian Ocean immediately after separation, providing the best chance of receiving the SMAP downlink carrier modulated by 2-kbps real time spacecraft telemetry data. The SN was configured to listen-only (no uplink) for about the first 75 minutes after SEP. The first NEN pass was planned over SG1 at Svalbard at 5 deg elevation angle, about 19 minutes after SEP. The first planned SN forward link to establish two-way communication was not to be transmitted until after the first NEN contacts at MG1 (McMurdo, Antarctica) and TR2 (TrollSat 2 in Queen Maud Land, Antarctica) at separation plus 88 minutes. Telecom logged at 18:21 UTC that the MG1 station had an autotrack problem, but that TR2 achieved good uplink lock. Scheduling both stations provided some overlapping coverage (redundancy) to maximize the capture of onboard configuration and performance data as soon as possible after launch.

The end of the launch phase was defined as L plus 18 hours, or by the completion of the ephemeris load, whichever was later. This was to allow time to establish regular and predictable ground station contacts before the start of the commissioning activities. After ascent and separation from the launch vehicle upper stage, the spacecraft flight software took over control to initiate the telemetry link, stabilize any tip-off rates, deploy the solar array, and establish the Sun-pointed attitude.

The spacecraft was expected to be power positive and to begin rotisserie roll about the sunline no later than L + 01:40:10 hours. Actual results were much better with Sun acquisition and the start of rotisserie mode achieved within less than 15 minutes after separation. With communications established, the ground operations team began monitoring the health of the observatory, collecting data to establish the initial orbit, commanding release of launch restraints on the stowed instrument boom and reflector, and commanding playback of the launch telemetry.

1.2.2 Commissioning

The commissioning phase, sometimes known as in-orbit checkout, is the period of initial operations that includes checkout of the spacecraft subsystems, maneuvers to raise the observatory into the science orbit, deployment and spin-up of the instrument boom and reflector, and checkout of the full observatory. As many as eight commissioning maneuvers, including two calibration burns, were in the plan to raise the observatory to the 685-km science orbit. Commissioning extended from the end of the launch phase until both the ground project elements and the spacecraft and instrument subsystems were fully functional and had demonstrated the required on-orbit performance to begin routine science data collection.

The initial spacecraft checkout, including the tests of the X-band transmitter and the X-band link with the NEN stations, was planned during the first 2 weeks. The first tests were planned before the antenna deployment to characterize X-band performance without multipath from the antenna. Following that was the deployment of the reflector boom assembly (RBA) and the reflector in the third week, and then a second series of X-band tests. The spun instrument assembly (SIA) spin-up was in the seventh week. Initial power-on of the SAR transmitter was deferred to allow adequate venting of the high-power components after launch. Observatory checkout and calibration began in the eighth week to verify instrument thermal stability, activity timing, and radio frequency (RF) background. Routine science operations began with a

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[3] The SN's names for the TDRS satellites are historical with most of them roughly indicating their locations above the Earth. TDZ refers to the exclusion zone longitudes that neither TDE ("east") nor TDW ("west") can reach. The NEN's names for their ground stations indicate the geographical site and antenna number, such as SG1 near Svalbard, Norway and MG1 at McMurdo, Antarctica.

cold-sky calibration 90 days after launch. (A cold-sky calibration for the SMAP instrument uses measurements made when the antenna's main beam does not intersect the Earth's surface.)

1.2.3 Science Observation

The science observation phase is the period of near-continuous instrument data collection and return, extending from the end of the commissioning phase for 3 years. The observatory is maintained in the nadir attitude, except for brief periods when propulsive maneuvers are required to maintain the orbit and for periodic radiometer calibrations that require briefly viewing cold space. During the first year of science acquisition, a period of calibration and validation of the data products has been underway. This has included special field campaigns and intensive in-situ and airborne data acquisitions, data analysis, and performance evaluations of the science algorithms and data product quality. These calibration and validation activities will continue at a lower level for the remainder of the science observation phase, but primarily for the purpose of monitoring and fine-tuning the quality of the science data products.

During science operations, the mission must return an average volume of 135 gigabytes (GB) per day of science data to be delivered to the science data processing facility. SMAP does not have an onboard Global Positioning System (GPS) receiver and the associated ephemeris knowledge because the large instrument reflector in the zenith direction obscures GPS visibility. For this reason, Doppler ground tracking with frequent ephemeris table uploads to the observatory are used to maintain pointing accuracy.

A key aspect to the science phase is achievement of efficient operations with a minimal engineering support staff. Operations in this phase are largely carried out by a few systems engineers and part-time support staff of subsystem experts. Automation plays a major role in spacecraft health monitoring and performance trending, as well as in routine sequence design. Science product data management, ephemeris update, synchronization of instrument look up tables (LUTs), and command loss timer update are all automated. The software and tools used in automation were checked out pre-launch or during commissioning and are under configuration control.

Other routine activities are scripted to minimize manual evaluation; these include communication pass scheduling, the weekly background command sequence generation and review, and spacecraft maintenance. Manual activities include science orbit adjustment (a small maneuver about every 3 months) and conjunction assessment risk analysis (CARA) maneuvers to avoid debris in space that SMAP could collide with as it traverses its orbit.

1.2.4 Decommissioning

At the end of its useful life, expected by 2018 or later, the observatory will be maneuvered to a lower disposal orbit and decommissioned to a functional state that prevents interference with other missions. A primary driver on this end-of-mission (EOM) plan is compliance with NASA orbital debris requirements to mitigate the risk of creating an orbital debris hazard to other spacecraft in low-Earth orbits and the risk that any observatory materials survive reentry and cause any human casualties. The observatory will be maneuvered to the lower disposal orbit to reduce its orbital lifetime and its energy sources passivated (depleted to the extent allowed by the design) to reduce the risk of explosion or fragmentation if struck by orbital debris. As many as 30 days have been allocated for decommissioning to end the active operations of the observatory leading to EOM. A final reprocessing of the science data products using the best understood algorithms and instrument calibration will be completed in this period.

The disposal orbit has been designed to ensure that the observatory will re-enter the atmosphere within 15.5 years as is required to meet orbital debris probability of collision requirements after the observatory is decommissioned.

1.3 Science Orbit Description

The SMAP orbit is a 685-km altitude, near-polar, Sun-synchronous, 8-day exact repeat, frozen orbit, with Equator crossings at 6 a.m. and 6 p.m. local time [5].

- Near-polar provides global land coverage up to high latitudes including all freeze/thaw regions of interest.

- Sun-synchronous provides observations of the surface at nearly the same local solar time each orbit throughout the mission, enhancing change-detection algorithms and science accuracy.

- Consistent observation time with Equator crossing at the 6 a.m. terminator is optimal for science, minimizes effects of Faraday rotation, and minimizes impact on the spacecraft design.

- The exact 8-day repeat orbit is advantageous for radar change-detection algorithms. This orbit with minimal altitude variation during an orbit increases radar accuracy.

- The orbit provides optimum coverage of global land area at 3-day average intervals, and coverage of land region above 45 N at 2-day average intervals.

Table 1-1 gives the mean orbital elements for the science orbit [4]. The Equator crossing times allow soil moisture measurements with the ground at the coldest time of the day near the morning terminator, where ionospheric effects and thermal gradients are also minimized. The 6 p.m. ascending node was selected so that the annual eclipse season (about 12 weeks per year from mid-May to early August, maximum duration ~19 minutes) occurs near the southern part of the orbit, and this minimizes thermal effects on freeze/thaw measurements in the northern hemisphere.

Table 1-1. Science orbit mean elements.

Orbital Element	Mean Element Value
Semi-major axis (a)	7057.5071 km
Eccentricity (e)	0.0011886
Inclination (i)	98.121621 deg
Argument of perigee (ω)	90.000000 deg
Ascending node (Ω)	–50.928751 deg
True anomaly	–89.993025 deg
Earth Space True Equator Coordinate System Time: 31 Oct 2014 15:36:26.5037 ET (node crossing time) Note: SMAP navigators often use Ephemeris Time (ET), which differs from UTC by about 67 seconds: ET minus UTC is ~+67 seconds. [Ref. 7]	

Figure 1-2 shows the pattern of descending (morning) and ascending (evening) ground tracks over North America during one day. The ground track spacing is closer at distances farther away from the Equator, and coverage of boreal forest regions northward of 45 N has an average sampling interval of two days (spatial average). Orbit 16 begins about 24.615 hours after Orbit 1.
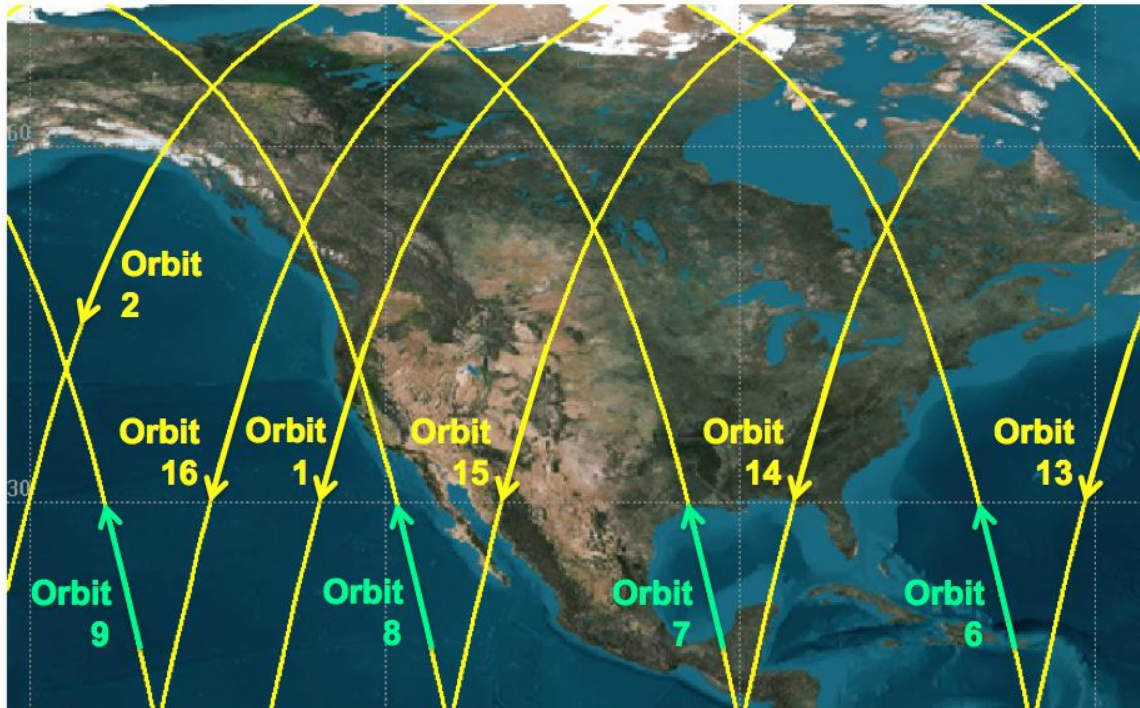
Fig. 1-2. One-day ground track pattern over North America.

1.3.1 Debris Collision Avoidance in Orbit

Overview: The Conjunction Assessment Risk Analysis (CARA) is a process by the Goddard Space Flight Center (GSFC) to monitor for potential close approaches of low Earth orbiting satellites with other space objects in their orbits and an individual project process to mitigate the risk of collisions. SMAP's mitigation is to take evasive action through a propulsive maneuver just large enough to change the orbit enough to avoid the collision. Design of the maneuver by the SMAP navigation team can be done quickly from a pre-canned template that can be executed on board within several hours to about one day and does not require ground testing.

The NASA Robotic Systems Protection Program (RSPP) performs CARA to prevent collisions of NASA satellites with other orbital objects. The CARA team is at the (GSFC). CARA coordinates support with the Joint Space Operations Center (JSpOC) at Vandenberg Air Force Base (AFB) for routine screening analysis that begins within one day after launch.

The SMAP project's role in this is to receive the analysis assessment and to recommend whether to perform a risk mitigation maneuver (RMM) for a high interest event (HIE), which identifies an elevated probability of a collision. Each conjunction event is unique. Based on experience from previous missions, SMAP could expect to design about one RMM per month and to actually execute two or three of these each year. Since launch, one RMM had become required, but OTM-3 in its place served to take SMAP out of danger.

The SMAP project has developed a single, standard magnitude pre-canned maneuver sequence in order to react to short-notice HIE events (with less than 24 hours' notice). All other HIE responses use a time-compressed version of the baseline maneuver development timeline that is also used for the trajectory correction maneuvers performed to maintain the science orbit. The rapid-response timeline takes a day or less to canned-maneuver execution. The baseline maneuver development timeline takes a week or more of planning, including orbit determination by the SMAP navigation team and scheduling the maneuver to occur during a TDRS pass for real time visibility.

1.4 The SMAP Mission Going Forward

The original mission design was to combine the high accuracy of the radiometer and the high spatial resolution of the radar to produce high quality measurements at an intermediate spatial resolution.

SMAP's radar would have allowed the mission's soil moisture and freeze-thaw measurements to be resolved to smaller regions of Earth— about 5.6 miles (9 km) for soil moisture and 1.9 miles (3 km) for freeze-thaw. Without the radar, the mission's resolving power is limited to regions of almost 25 miles (40 km) for soil moisture and freeze-thaw. With the radiometer alone, the mission can continue to meet its requirements for soil moisture accuracy and will produce global soil moisture maps every 2 to 3 days.

The SMAP team currently is working on a new Level 3 freeze/thaw product based on radiometer data that will provide freeze/thaw data for dates after the loss of additional radar data. A beta version of this new product is expected for release in December 2016 with a validated product released by May 2017.

In addition, NASA and SMAP scientists are "auditioning" the radar aboard the European Sentinel-1A and 1B satellites to work in tandem with SMAP to partly replace SMAP radar data [6,8]. The Sentinel orbit is the only one currently close enough (in position and time) to SMAP to gather radar images of the swath of Earth covered by the SMAP radiometer.

2. The Observatory and Launch Vehicle

As shown in Fig. 2-1, the observatory is made up of a rectangular bus structure (spacecraft bus), which houses the engineering subsystems, most of the radar components; and the top-mounted spinning instrument section (including the radiometer hardware, the spin mechanism, and the reflector and its deployment structure). Figure 2-2 shows the observatory in its configurations for launch, with the boom deployed, and with the instrument reflector deployed [9].
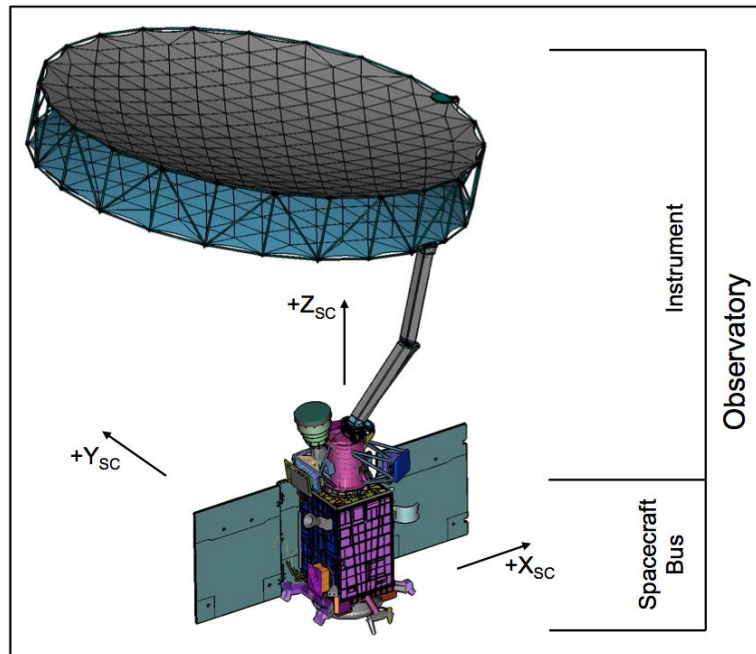
Fig. 2-1. Definition of SMAP spacecraft axes.
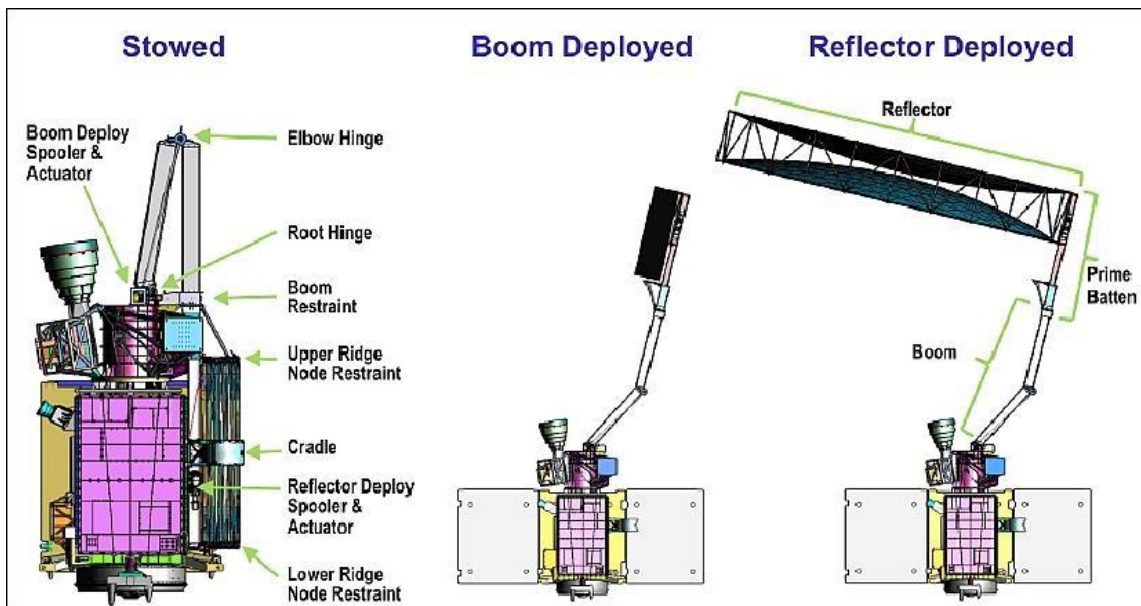
Fig. 2-2. SMAP spacecraft in stowed and deployed configurations.

There were transition periods, with intermediate configurations not shown in the figure, between each major sequence: boom deployment, reflector deployment, and spin-up.

Launch: For launch, the solar array and the reflector boom assembly (RBA) were folded against the spacecraft bus to fit within the launch vehicle fairing, and the instrument section was locked to the spacecraft bus to minimize stress on the spin mechanism.

Partially Deployed: After separation from the Delta II second stage, the launch sequence stored on board the SMAP spacecraft initiated the deployment of the solar array, working with the flight software and a signal produced by the severing of a breakwire between the spacecraft and the launch vehicle. The observatory remained in this configuration for about 2 weeks. During this period the initial engineering checkout was accomplished.

Fully Deployed: Beginning about 15 days after launch, the instrument reflector boom assembly was deployed in two steps. This was followed by a period in which the first commissioning maneuvers were executed to reach the science orbit. About 50 days after launch, the instrument section was released and spun up in two steps to the science rate to 14.6 rotations per minute (rpm) used for science data collection.

The spacecraft coordinate system, as shown in Fig. 2-2, has its origin in the interface plane between the launch vehicle adapter and the forward separation ring at the center of this circular interface, with the $+Z_{SC}$ axis projecting upward and normal to the interface plane through the center of the bus structure, the $+Y_{SC}$ axis normal to the plane of the solar array, and the $+X_{SC}$ axis completing a right-handed triad. For science data collection, the observatory is oriented to the science orbit reference frame with the $-Z_{SC}$ axis pointed to the geodetic nadir and the $+X_{SC}$ axis coplanar with the nadir direction and the inertial velocity vector in the general direction of orbital motion, so that the $+Y_{SC}$ axis is generally normal to the orbit plane on the sunward side of the orbit. After deployment, the instrument antenna has been spinning about the $+Z_{SC}$ axis at the science rate of 14.6 rpm in a right-handed sense (counterclockwise as viewed from above) with the antenna reflecting the transmitted and received signal 35.5 deg off the nadir.

2.1 Spacecraft Engineering Subsystems

The major characteristics of spacecraft subsystems, *except* for telecom, are described below. The telecom subsystem is detailed in the next section. See the Mission Plan [3] for a fuller description of the subsystems.

2.1.1 Structure

The structural design/implementation provides the integrated physical design of the observatory. The major structural elements of the spacecraft bus include

- Propulsion deck, which mounts the propellant tank and other propulsion hardware and attaches to the launch vehicle adapter
- Reaction wheel assembly (RWA) deck in the middle of the bus, which mounts the reaction wheels
- Instrument deck at the top of the bus, which mounts the spun instrument assembly
- +Y side panel, which provides the attachment for the solar array and the +Y Sun sensor cluster
- −Y side panel, which internally mounts the radar hardware and provides a radiating surface away from the Sun
- +X side panel, which internally mounts control electronics and telecom hardware and externally mounts the cradle holding the furled instrument reflector in the launch configuration

- –X side panel, which internally mounts the avionics hardware and externally mounts the battery and star tracker

- –Y outrigger, which provides attachment for the two low-gain antennas, the three-axis magnetometer, and the –Y Sun sensor cluster

- three-panel solar array with 7.9 m^2 of total area

2.1.2 Guidance Navigation and Control

The guidance, navigation, and control subsystem (GNC) provides spacecraft attitude estimates, three-axis or two-axis attitude control, momentum management, thruster control for propulsive maneuvers, and control modes for instrument spin-up. The attitude sensors include two coarse Sun sensor units (CSS) for defining the Sun-relative attitude, primarily after separation from the launch vehicle and in anomaly situations; a star tracker (stellar reference unit [SRU]) for defining the inertial attitude; two miniature inertial measurement units (MIMUs) for sensing angular rates, and a three-axis magnetometer (TAM) for sensing the Earth magnetic field vector. These sensors feed data to the GNC component of the flight software, which determines the current attitude and commands actuators to maintain the desired attitude. Pointing control over most of the mission is accomplished by four reaction wheels making up the reaction wheel assembly (RWA), and three magnetic torque rods (MTRs) provide torques to continuously desaturate the RWAs and maintain the wheel speeds within a specified range.

2.1.3 Power and Pyro

The power and pyro subsystem provides for generation, storage, and distribution of electrical energy to the spacecraft equipment. The major components of the subsystem are the three-panel solar array, four lithium-ion batteries, a single power bus, the power control assembly, the power distribution assembly, and the pyro firing assembly. The solar array uses gallium-arsenide triple-junction solar cells with a cell area of about 7 square meters (m^2), a packing factor of about 80 percent, and a beginning-of-mission (BOM) output of about 2 kilowatts (kW) (direct pointing to Sun). The batteries provide energy during launch and eclipses, and for infrequent propulsive maneuvers where the array cannot be pointed at the Sun.

Switches in the power distribution assembly distribute energy to the instruments and spacecraft loads, and the pyro firing assembly contains the pyro firing circuitry.

2.1.4 Propulsion

The propulsion subsystem uses a blowdown hydrazine design to provide thrusting for orbit correction maneuvers and for attitude control, primarily to initiate and maintain a Sun-pointed attitude after separation from the launch vehicle and to provide greater control authority in anomaly situations. A single pressurized propellant tank provides the capacity for 80 kg of usable hydrazine with a 3:1 blowdown ratio. Eight 4.5-newton (N) thrusters are located on four brackets off the propulsion deck and directed to provide roll, pitch, and yaw control, with four of the eight providing thrust in the +YSC and –YSC direction for yaw control. The remaining four thrusters provide thrust in the +ZSC direction for orbit correction maneuvers and roll and pitch control.

2.1.5 Command and Data Handling

Part of the avionics subsystem, the command and data handling (CDH) subsystem provides the hardware for the central computational element of the observatory; for the storage of science and engineering data; and for the necessary interfaces to receive commands and data from the ground, to receive sensor data on the state of the observatory, to send actuation commands to modify the state of the observatory, to receive and store instrument data, and to format science and engineering data for transmission to Earth. The CDH hardware includes components of the Jet Propulsion Laboratory (JPL) multimission system architecture

platform (MSAP), including some Mars Science Laboratory (MSL) components. Major elements of the subsystem include

- The system flight computer (SFC) is a RAD750 radiation-hardened single-board computer that hosts the observatory flight software.

- The non-volatile memory card (NVM), which provides 128 GBs of not and (NAND) flash memory for storing radiometer (RAD) and SAR data and engineering files.

- The MSAP/MSL telecom interface card (MTIF) provides the interface for engineering telemetry and commands with the S-band transponders. The T-zero umbilical, generates and broadcasts spacecraft time.

2.1.6 Flight Software

Also part of the avionics subsystem, the flight software (FSW) provides the primary computational control of the observatory functions. Hosted in the CDH spaceflight computer board (a BAE Enhanced RAD750), the software uses the WindRiver VxWorks operating system. Substantial portions of the code are inherited from MSAP and the Mars science laboratory (MSL) project. The MSAP-inherited software includes basic uplink, downlink, commanding, telemetry, file system services, spacecraft health, and timing and software support functionality. The MSL inherited software supports the power, pyro, propulsion, and GNC functionality. The remainder of the software is developed to meet unique SMAP requirements, including functionality required for commanding, monitoring, and data handling of the radar and radiometer. There are also power control, thermal control, spin mechanism control, and fault protection functions required by the flight software to support specific instrument needs.

An element of the flight software, the mode commander, manages transitions between observatory system modes. At each transition into a different system mode a configuration table is used to enforce a pre-defined observatory state. This limits the reconfiguration that is required by the operations team.

Fault protection (FP) is the overall approach to minimizing the effect of observatory faults, but most often refers to the autonomous monitoring and response capabilities of the observatory implemented in flight software. With mostly single-string architecture, FP for SMAP is focused on providing protection against a set of credible faults and reasonable protection against operator error. System fault protection (SFP) is implemented in the FSW and coordinates the operation of onboard subsystems making up the overall flight system. In addition to SFP, the instrument and some of the observatory subsystems have internal FP implemented in their hardware. The instrument's FP provides limited diagnostic engineering telemetry for ground assessment.

The higher level FP logic implemented in flight software is intended to detect any fault, isolate each fault, and/or recover from that fault if recovery is an available option. For most faults, a transition into a fault mode interrupts the sequenced observatory activities and waits for intervention by the operations team. Fault detection occurs in various error monitors that detect anomalous system performance, which is marked in telemetry and passed to a fault engine if a given threshold and persistence is exceeded.

2.1.7 Thermal Subsystem

The thermal subsystem provides the hardware and design approach to measure and manage the temperatures of the spacecraft bus components. Passive thermal control is utilized wherever possible with the use of surface coatings, multi-layer insulation, radiators, and thermal doublers. Electronic boxes are conductively coupled to the outside structural panels, which function as radiating surfaces. Active heating is used under control of mechanical thermostats where it is necessary to maintain components at operating temperatures (for example, propulsion tank, lines, and thrusters) or above minimum flight-allowable temperatures (for example, survival heaters for the radar electronics when powered off). Temperatures are

measured and reported from many locations (as many as 162) on the observatory using platinum resistance thermometers (PRTs).

Significant variations in the thermal environment must be accommodated during regular tracking passes for S- and X-band downlinks, seasonal eclipse periods as long as 19 minutes per orbit, out-of-plane propulsive maneuvers, and safing events when the instruments are powered off and survival heating must be applied.

2.2 The Science Instrument (RF Payload)

The radiometer and radar components of the SMAP instrument measure microwave energy focused by the spinning reflector, which allows a 1000-km swath to be built up as the conical scan is carried across the Earth by the orbital motion of the observatory.

The instrument components are required to meet the Level 1 requirements. These requirements are summarized in the SMAP Handbook [10] from the SMAP Level 1 Requirements and Mission Success Criteria document. The requirements document is essentially a contract with the Jet Propulsion Laboratory, California Institute of Technology to design, build, deliver, and operate a science mission to produce science products with the following Level 1 requirements[4].

The science requirements for SMAP as defined pre-launch were to provide estimates of soil moisture in the top 5 cm of soil with an error of no greater than 0.04 cm^3 cm^{-3} volumetric (1-sigma) at 10-km spatial resolution and 3-day average intervals over the global land area, excluding regions of snow and ice, frozen ground, mountainous topography, open water, urban areas, and vegetation with water content greater than 5 kg m^{-2} (averaged over the spatial resolution scale). The mission is additionally required to provide estimates of surface binary freeze/thaw state in the region north of 45ºN latitude, which includes the boreal forest zone, with a classification accuracy of 80% at 3 km spatial resolution and 2-day average intervals.

The baseline science mission is required to collect space-based measurements of soil moisture and freeze/thaw state for at least three years to allow seasonal and interannual variations of soil moisture and freeze/thaw to be resolved. The document required SMAP to conduct a calibration and validation program to verify that it is delivered data meet the requirements.

2.2.1 Reflector Boom Assembly

As seen in Fig. 2-3, most of the instrument components are part of the spun instrument assembly (SIA), with only the radar electronics and the active radar RF components located in the spacecraft bus. The SIA includes the reflector boom assembly (RBA) and the spun platform assembly (SPA). The instrument spins in a positive right-handed sense with respect to the $+Z_{SC}$ axis (counterclockwise as viewed from above) at rates from 12.3 rpm (minimum for 30 percent radiometer overlap) up to the planned science rate of 14.6 rpm.

The bearing and power transfer assembly (BAPTA) supplied by Boeing Corporation's Space and Intelligence Systems, spins the SIA and allows power and digital telemetry transfer across the spinning interface on slip rings. The BAPTA includes the rotary joint assembly (RJA), which passes radar RF signals across the spinning interface [5].

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[4] The pre-launch SMAP spacecraft and mission design Level 1 requirements are defined in [Refs. 10 and 11] and presume an operable radar and radiometer and have been retained in this article for historical documentation. Since the failure of the radar [8], ongoing SMAP radiometer-only resolution capabilities have been refined. Further, resolution capabilities assuming the SMAP radiometer with radar support from another satellite have been estimated [6].
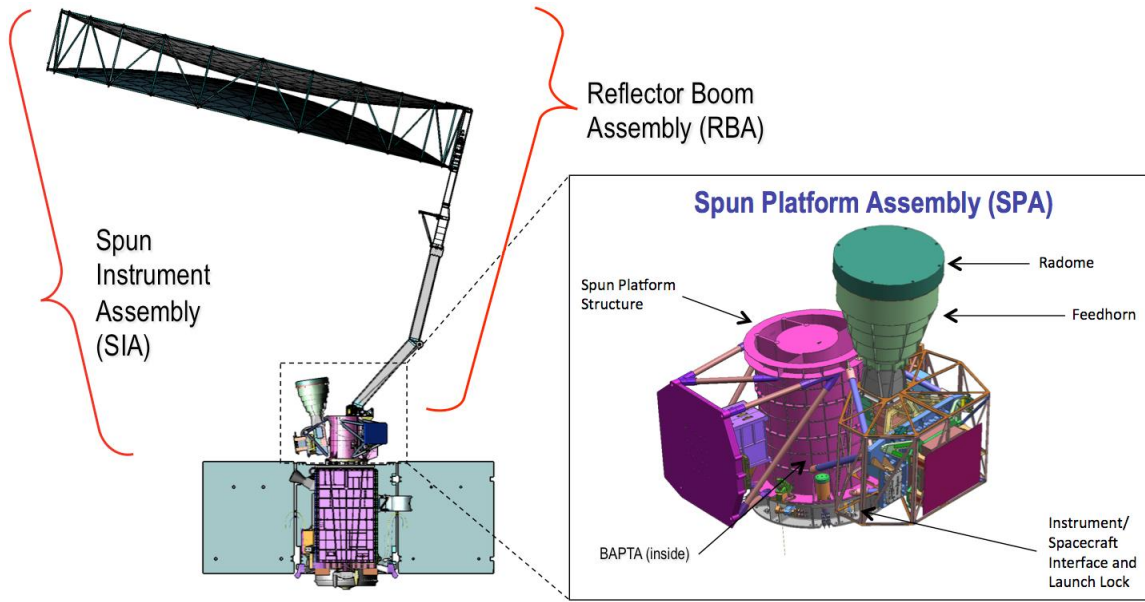
Fig. 2-3. SMAP instrument configuration.

The RBA, supplied by Astro Aerospace, a unit of Northrop Grumman Aerospace Systems (NGAS), consists of the reflector, its positioning boom, and all the supporting structure and mechanisms necessary to hold the furled antenna against the spacecraft bus during launch and to then deploy it to the correct position and shape to accurately focus microwave energy to and from the instrument feed horn. RBA deployment (and to a lesser degree spin-up) represents a significant driver to the mission and observatory design.

Figure 2-4 is a sketch of the RBA reflector deployment steps.
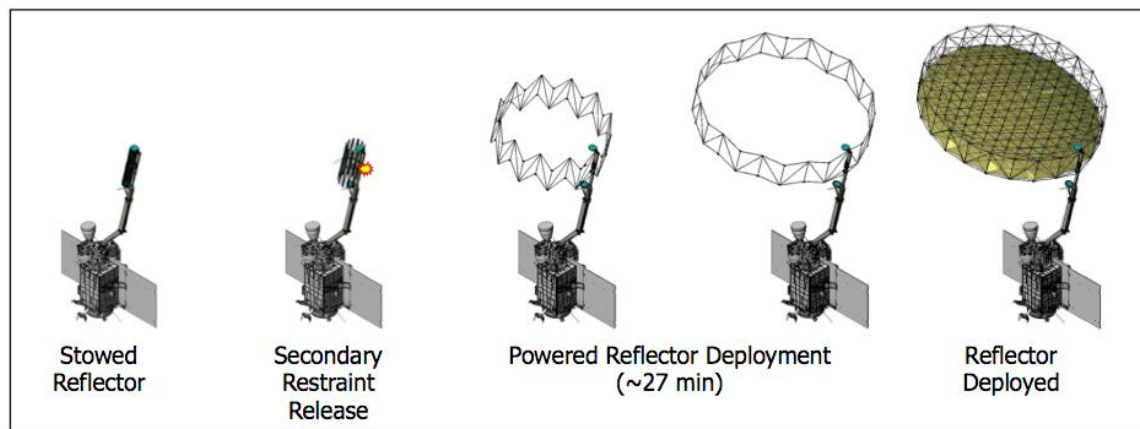
Fig. 2-4. RBA reflector deployment steps.

The reflector has an offset paraboloid shape with a 6.55-m major diameter, a 6.17-m minor diameter, and an effective circular aperture of 6.0 m directed 35.5 deg off the $-Z_{SC}$ axis.

The integrated feed assembly (IFA) is made up of the feed assembly that transmits and receives the RF signal to and from the reflector, the radiometer front-end assembly, and the necessary supporting structure. The feed assembly includes the conical feed horn (which is covered by a Styrofoam radome to prevent large thermal swings between sunlit and eclipse conditions), a thermal isolator waveguide component, an orthomode transducer (which separates/combines the horizontally and vertically polarized RF signals), and waveguide-to-coaxial adapters to interface to the instrument electronics.

2.2.2 Radar

The radar is the active component of the SMAP instrument, operating as both a scatterometer and an unfocused (non-imaging) synthetic aperture radar. It transmits in the Earth Exploration Satellite Service (EESS)[5] active frequency band 1215–1300 MHz in two polarizations and makes both co-polarized and cross-polarized measurements of the reflected signal.

The radar hardware is primarily located on the spacecraft bus in four main boxes on the –Y panel, which house the digital electronics, the RF transmit and receive-chain assemblies, the high-power solid-state amplifier for the transmit pulse, and the RF and digital power converters. The digital electronics handles commanding and passes the down-converted (video) echoes to the NVM on the spacecraft. The RF back-end generates the radar chirps, and it amplifies and transmits the chips to the rotary joint assembly that passes the RF signal to the feed horn and the antenna. The radar operation is synchronized with the rotation of the reflector through its interfaces with the integrated control electronics (ICE) and the flight software.

Radar measurement accuracy is sensitive to the presence of anthropogenic terrestrial radio frequency interference (RFI), which is prevalent over most land regions. Design features have been incorporated into the radar and science data system, including frequency hopping within the transmit band, to allow RFI present in the radar data to be detected and corrected. The frequency hopping is necessary to mitigate the effects of the terrestrial RFI in order for the measurements to meet SMAP's Level 1 science requirements [10]. The radar must also insure that it operates in a way to reduce potential interference with terrestrial Federal Aviation Administration (FAA) and Department of Defense (DOD) aircraft navigation radars to accepted levels. Accepted levels are defined in frequency license agreements. In order to comply with these provisions, the radar changes its transmit frequency about once every 12 seconds. This insures that any potential interference to terrestrial navigation radars is limited to one narrow sector of one navigation radar rotation (and thereby avoids interference to consecutive ground radar rotations, which becomes a concern for navigation radar).

2.2.3 Radiometer

The radiometer (RAD) is the passive component of the SMAP instrument, measuring the microwave emission from the Earth's surface in the EESS passive frequency band of 1400–1427 MHz. The radiometer design uses experience gained during the Aquarius radiometer development.

The hardware is located on the SIA. Microwave energy is received through the shared feed horn and split between radar and radiometer signals in two diplexers that provide horizontally and vertically polarized signals to the radiometer front-end electronics. Subsequent processing in the RF back-end electronics provides two signals to the radiometer digital electronics (RDE) where analog and digital processing takes place and engineering and science telemetry are formatted. The RDE also receives commands from the FSW to synchronize its operation with the radar and to determine whether high-rate or low-rate data is collected.

The footprint of the radiometer (approximately 40 km) is defined by the frequency and the size of the antenna. The requirement that adjacent footprints overlap by 30 percent drives the rotation rate of the antenna (overlap in the along-track direction between successive rotations) and the size of the swath (overlap in the cross-track direction between adjacent ground-tracks).

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[5] As defined in the SMAP context by NASA, Earth Exploration Satellite (EES) Service is between Earth stations and one or more space stations in which information relating to the characteristics of the Earth and its natural phenomena is obtained from active or passive sensors on Earth satellites. From [Ref. 12]:
1215–1300 MHz Space Research Services (SRS)/Earth Exploration Satellite (EES) – Active
1370–1427 MHz Space Research Services (SRS)/Earth Exploration Satellite (EES) – Passive

In a manner similar to the radar accuracy, the radiometer measurement accuracy is sensitive to the presence of terrestrial RFI. Design features in the radiometer and science data system allow RFI present in the radiometer data to be detected and corrected. Mitigation of the terrestrial RFI effects is necessary to achieve measurements that meet the Level 1 science requirements. [10].

2.3 Launch Vehicle

SMAP was launched from the Vandenberg Air Force Base on a Delta II launch vehicle. The launch system consisted of the launch vehicle and all the associated ground processing facilities at the launch site (also referred to as SLC-2W) and tracking assets used to capture launch vehicle telemetry.

The Delta II was provided by the United Launch Alliance (ULA)[6] under the NASA Launch Services II contract. SMAP flew on the 7320-10C configuration of the Delta II [13] with two liquid stages, three solid strap-on solid rocket motors, and a 3-m (10 feet) diameter composite payload fairing as shown in Fig. 2-5. SMAP was the 153rd Delta II flight, rising from launch site SLC-2W [14].
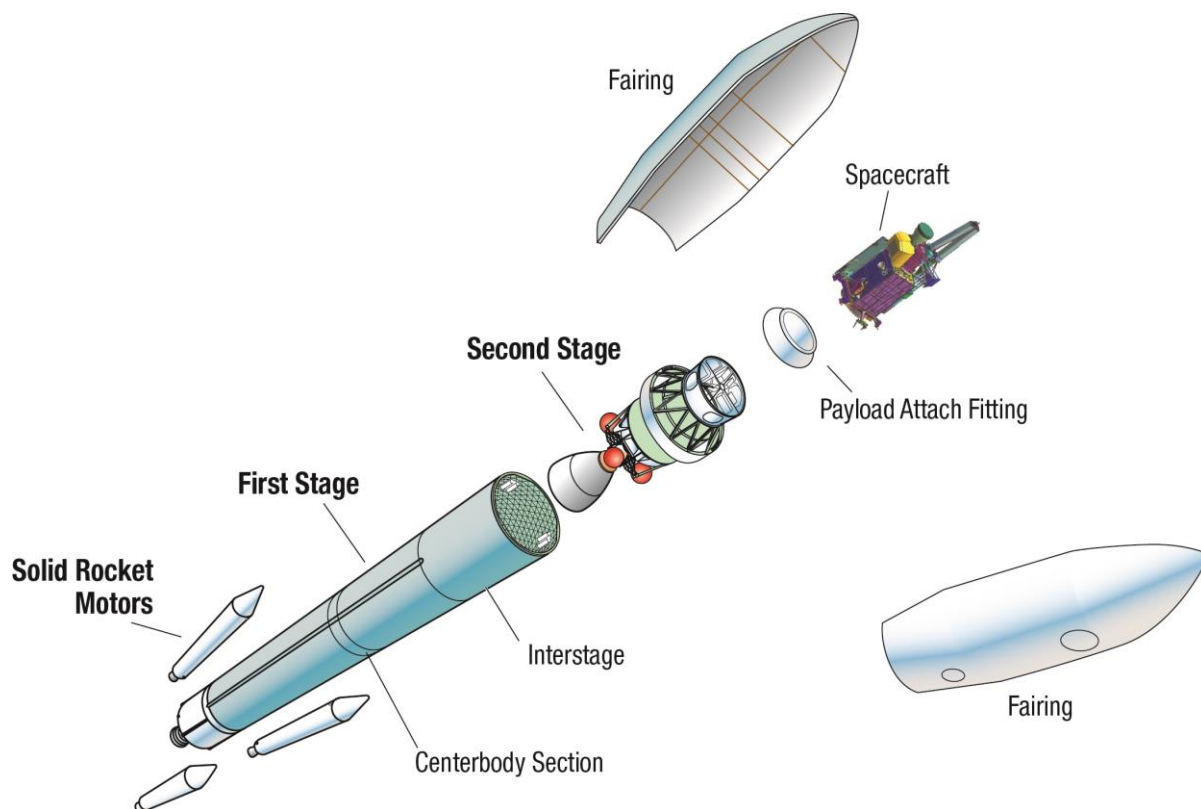
Fig. 2-5. Exploded view of Delta II 7320-10C launch vehicle configuration.

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[6] ULA is a 50-50 joint venture between Lockheed Martin and The Boeing Company formed in 2006 [Ref. 15]. ULA launch operations are located at Cape Canaveral Air Force Station, Florida, and Vandenberg Air Force Base, California.

3. Telecommunications Subsystem

3.1 Overview

The telecommunications subsystem provides a single uplink (forward link) at S-band and a downlink (return link) at S-band, X-band, or both. In the science phase, S-band and X-band systems are normally operated together, though engineering activities may be S-band only. The uplink receives commands and data to control the observatory activities. The downlink returns observatory engineering and instrument data. Used together and with the radio in coherent mode, the S-band uplink and downlink can also provide accurate Doppler tracking data for navigation.

Figure 3-1 summarizes the SMAP communications links and the data rates. Commands in the science phase originate from the SMAP Mission Operations Center (MOC), and they are modulated onto the uplink by a ground station of the NASA Near-Earth Network (NEN) in a bent-pipe manner. The NEN stations (excluding McMurdo Ground Station, MGS) collect two-way S-band Doppler tracking data [16]. Due to the polar orbit of SMAP, the stations at the highest latitudes (Svalbard (Norway, SG1), Alaska (Alaska Satellite Facility, Fairbanks, ASF), McMurdo (MGS), and Trollsat (Troll, Antarctica) have the most passes.
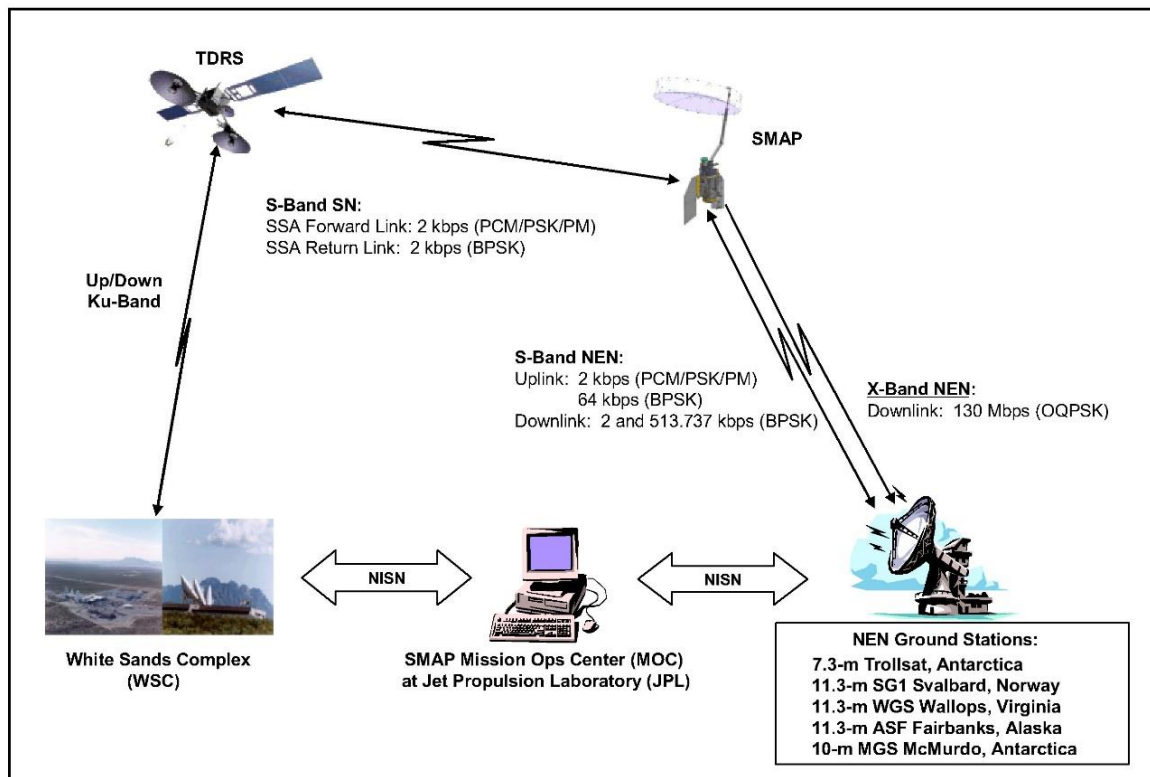
Fig. 3-1. SMAP communication links and data rates.
(BPSK = binary phase shift keying, Mbps = megabits per second, NISN = NASA Integrated Services Network, OQPSK = offset quadrature phase shift keying, PCM = pulse code modulation, PM = phase modulation, PSK = phase shift keying, SSA = S-band single access,

The S-band side of the subsystem is used to receive commands at a data rate of either 2 or 64 kbps and to return engineering telemetry at an information data rate of either 2 or 513.737 kbps. The X-band side is downlink only and returns instrument data at an information data rate of 130 Mbps. Data return at both

frequencies is typically scheduled with NEN stations once or twice on most orbits. Ground station contact durations are typically 5 to 11 minutes.

For launch and major events during commissioning and for anomaly situations, S-band command and telemetry can also be scheduled through the NASA Space Network (SN), using Tracking and Data Relay Satellites (TDRS); these allow coverage over most of the SMAP orbit. TDRSS communication uses the S-band single access capability, and data rates are limited to 2 kbps for both uplink and downlink. Margins are smaller with SN than NEN due to the ~45,000 km maximum TDRS–SMAP range, as compared with ~2,500 km NEN–SMAP slant range.

Table 3-1 summarizes the S-band and X-band signal parameters from [Refs. 17 and 18].

Table 3-1. SMAP telecom signal parameters.

Parameter	Value
S-band carrier frequency	2094.25125 MHz (forward) 2274.3 MHz (return)
X-band carrier frequency	8180 MHz (return)
LGA polarization	Left-hand circularly polarized (LCP) (S-band and X-band)
S-band forward and return data rates	2 kbps and 64 kbps (forward) 2 kbps and 513.737 kbps (return)
X-band return data rate	130 Mbps (return) – no X-band forward link
Forward error correction (FEC) coding	(7,1/2) convolutional + Reed-Solomon (RS) encoded (2 kbps S-band return & 130 Mbps X-band return) Reed-Solomon only (513.737 kbps S-band return)
Forward link modulation	PCM/PSK/PM 16 kHz subcarrier (2 kbps) BPSK (64 kbps) from the NEN only
Return link modulation	BPSK (S-band return) OQPSK (X-band return)
Data format	Non-return to zero level (NRZ-L) (S-band forward and X-band return) NRZ-M (S-band return)

The S-band telecommunications hardware includes two redundant S-band transponders (5-watt (W) output), a single S-band low-gain antenna (LGAS), and a coaxial switch to select the active transponder. The X-band telecommunications hardware includes redundant X-band transmitters (8-W output), a single X-band low gain antenna (LGAX), a bandpass filter, and a coaxial switch to select the active transmitter. Both the LGAS and the LGAX are located on an outrigger, projecting below the spacecraft bus and away from the solar array to maximize the unobstructed field of view (FOV). LGAX is boresighted in the –Z direction (nadir) and has an unobstructed FOV to the Earth horizon (out to about 65 deg off nadir). LGAS is canted 30 deg up from nadir and away from the solar panels in the Y–Z plane to improve TDRSS communication in the –Y hemisphere and specifically in a cone at least 30 deg about the –Y axis where longer contacts are possible when a TDRS is broadside to the SMAP orbit.

Table 3-2 summarizes the S-band and X-band configurations during the four mission phases of launch, commissioning, science observation, and decommissioning.

Table 3-2. Telecom configurations in SMAP mission phases.

Phase	Timeline	Description	Telecom Configuration
Launch	L to L + 3 days	Spacecraft checkout Initial S-band return link acquisitions by SN and NEN Initial lock-up of S-band forward links from NEN and SN Initial estimate of spacecraft orbit	Configured for initial acquisition • 2 kbps forward and return link to SN Coherent mode, to enable near-continuous 2-way S-band Doppler measurements from NEN and SN needed for orbit determination
Commissioning	L + 3 days to L + 90 days	Deployment of 6-m radar antenna Instrument checkout and calibration Adjust orbit to planned science orbit using orbit correction maneuvers Radar reflector spin up At least two S-band passes from NEN stations per orbit for subsystem commissioning events	Continuous 2 kbps forward/return link to SN during selected propulsive maneuvers, radar reflector deployment and spin-up Checkout of X-band transmitter and link performance with NEN Two-way S-band Doppler required
Science observation	3 years	Continuous radar and radiometer measurements Periodic orbit trim maneuvers (OTMs) for orbit maintenance Average data volume return on X-band of about 135 GB per day X-band passes with 5-minute minimum duration starting at 10 deg elevation; S-band passes with 4-minute minimum starting at 5 deg elevation	513.7 kbps S-band return link to NEN 2 kbps S-band forward link 2-way S-band Doppler required X-band 130 Mbps return link to NEN 2 kbps forward and return links with SN when SMAP is in safemode
Decommission-ing	30 days after end of the science observation phase	Maneuver SMAP to lower the perigee so that the orbit can decay safely and more quickly 1 to 3 passes per orbit	Engineering data via S-band link to confirm maneuvers and final configuration.

Using RS 422 standards[7] via universal asynchronous receiver/transmitter (UART) interfaces [19], the onboard FSW transmits commands to and receives health and status from both the S-band transponder (SBT) and the X-band transponder (XBT).

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[7] RS-422, also known as TIA/EIA-422, is a technical standard originated by the Electronic Industries Alliance that specifies electrical characteristics of a digital signaling circuit. RS is an abbreviation for recommended standard [20]. RS-422 is the common short form title of American National Standards Institute (ANSI) standard ANSI/TIA/EIA-422-B Electrical Characteristics of Balanced Voltage Differential Interface Circuits. The standard only defines signal levels; other properties of a serial interface, such as electrical connectors and pin wiring, are set by other standards [21].

3.2 Telecom Block Diagram

Figure 3-2 is a block diagram of the S-band and X-band telecommunications subsystems. The S-band subsystem consists of two redundant S-band transponders (SBTs) with integrated diplexers and a coaxial switch to select the operating transponder, and an S-band low gain antenna. The X-band subsystem consists of two redundant X-band transmitters (XBTs), a coaxial switch to select the operating transmitter, a bandpass filter, and an X-band low gain antenna.
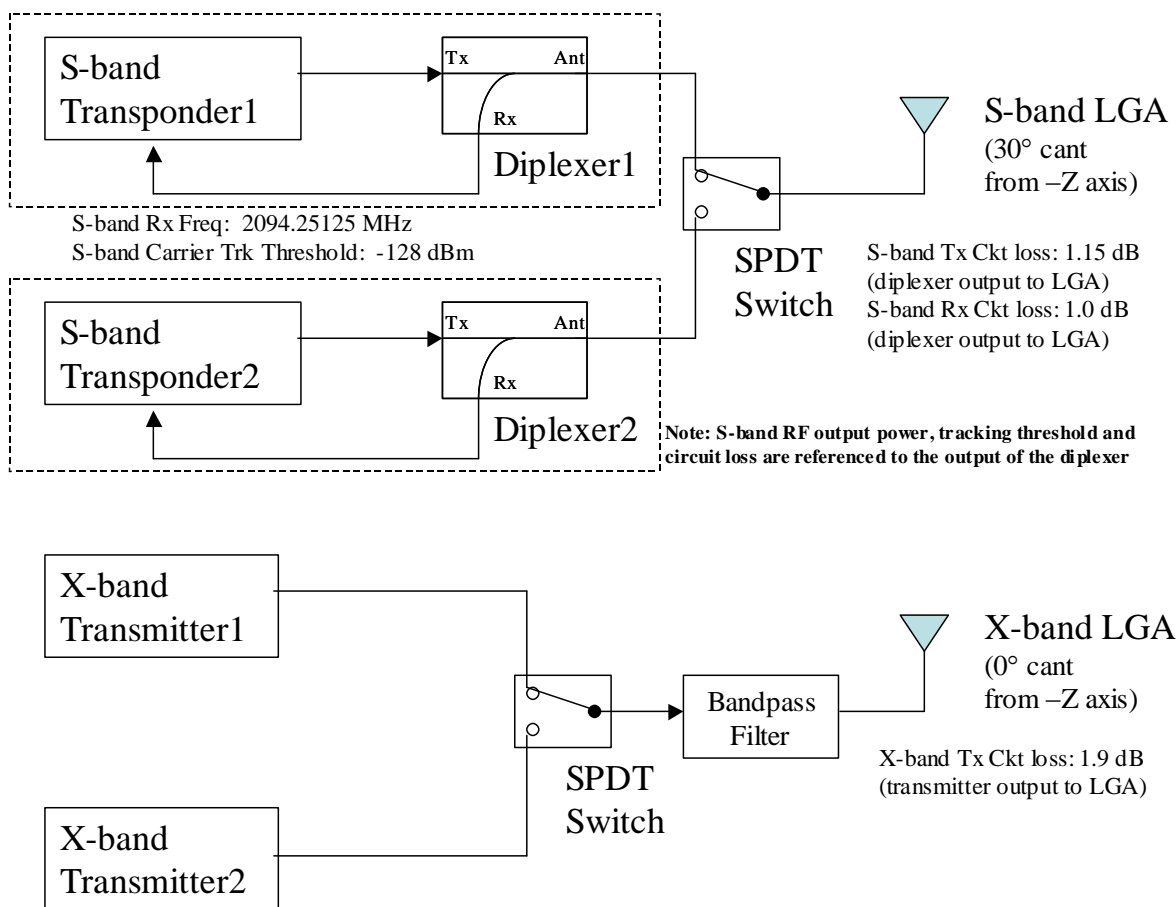
Fig. 3-2 Telecom subsystem block diagram.
(Ant = antenna, Ckt = circuit, Rx = receiver, SPDT = single pole double throw, Tx = transmitter)

3.3 Telecom subsystem design

Figure 3-3 shows the locations of the telecom panel and the LGA outrigger relative to the rest of the spacecraft when the solar arrays and the 6-m reflector have been deployed. (See Fig 2-1 for a definition of the spacecraft axes.)

Figure 3-4 shows the mounting location of the telecom components on the +X–Z panel. These include the LGAS, the LGAX, the redundant S-band transponders, and the redundant X-band transmitters. Only one S-band transponder can be powered on at a time, and similarly only one X-band transmitter can be powered on at a time. Furthermore, there is a thermal constraint expressed as a flight rule that limits the XBT transmitting time to a maximum of 30 minutes per any 98.5-minute period (one orbit).
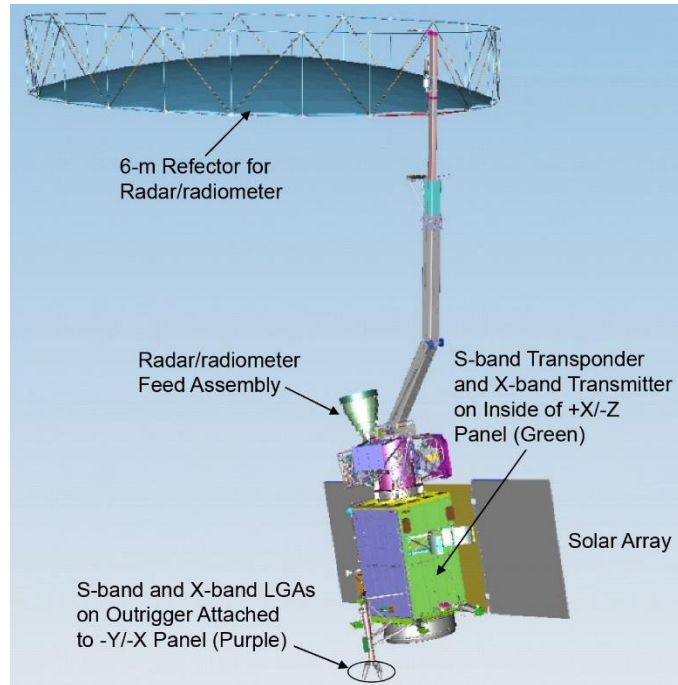
Fig. 3-3. Location of telecom panel and LGA outriggers (after deployment).
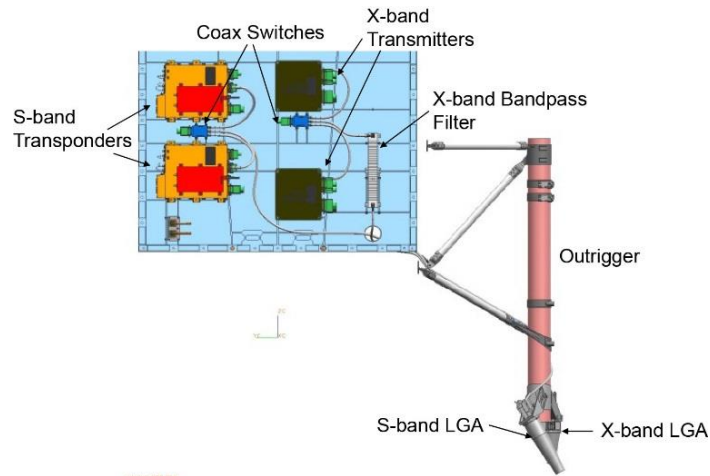
Fig. 3-4. Location of telecom components on +X/–Z panel.

3.4 S-band and X-band Antennas

The S-band LGA and X-band LGA are both quadrifilar helix antennas made by RUAG Space AB in Sweden [22].

The length of the S-band LGA is 285 mm (about 11.2 inch) total, with the helix portion 204 mm (8 in.). The X-band LGA (Fig. 3-6) measures 240 mm (9.4 inch) long, with 148 mm (6 in.) for the helix portion.

3.4.1 S-Band LGA

Table 3-3 shows some of the relevant characteristics of the S-band LGA as provided by the vendor. Figure 3-5 shows the predicted S-band receive and transmit antenna gain patterns. The red curves are for the intended LCP, and the blue ones for right-hand circular polarization (RCP).

Table 3-3. Characteristics of S-band low-gain antenna.

S-band LGA Characteristic	Value
Frequency passband	2.0–2.15 GHz (receive) 2.2–2.3 GHz (transmit)
Beamwidth	±95 deg
Voltage standing wave ratio (VSWR)	1.22:1 (typical)
Power handling	10 W
Mass	250 g
Polarization	LCP
Axial ratio (within ±95 deg beamwidth)	< 4.5 dB (receive) < 5.5 dB (transmit)
Minimum gain (within ±95 deg beamwidth)	–2 dBi (receive) –3 dBi (transmit)
Operating temperature	–85° to +80° C
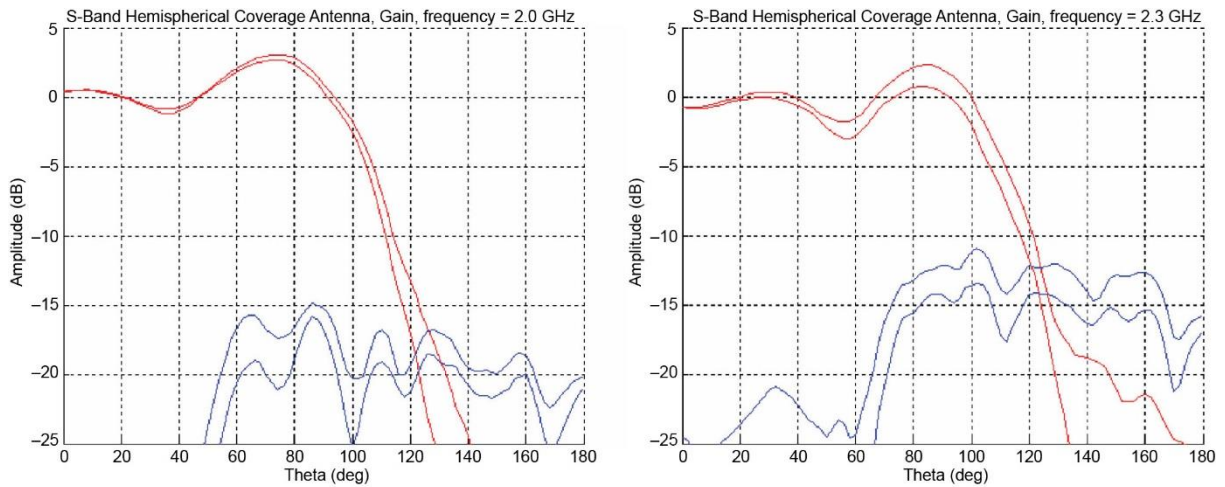
Fig. 3-5. S-band LGA patterns

Fig. 3-5 S-band LGA patterns: at receive (left) and transmit (right) frequencies.

3.4.2 X-Band LGA

Fig. 3-6 is a photograph of the X-band LGA, and Table 3-4 shows some of the relevant characteristics of its downlink-only performance.

Fig. 3-6 RUAG X-band quadrifilar helix LGA.

Table 3-4. Characteristics of X-band low gain antenna.

X-band LGA Characteristic	Value
Frequency range	8180 ± 150 MHz (transmit)
Beamwidth	Defined in the minimum gain below
VSWR	Return loss < −15 dB
Power handling	> 10 W
Mass	< 400 g
Polarization	LCP
Axial ratio (within ±62 deg beamwidth)	< 4.55 dB (RCP/LCP < −10 dB)
Minimum gain	> −1.5 dBi @ 0° to 30° > 0.167*θ − 6.5 dBi for θ between 30 and 60 deg > 3.5 dBi between 60° to 70 deg
Operating temperature	−85° to +80° C

Figure 3-7 shows the predicted X-band LGA transmit gain pattern. Like the S-band antenna, the X-band polarization is LCP (red curve). The blue curve is the RCP pattern.
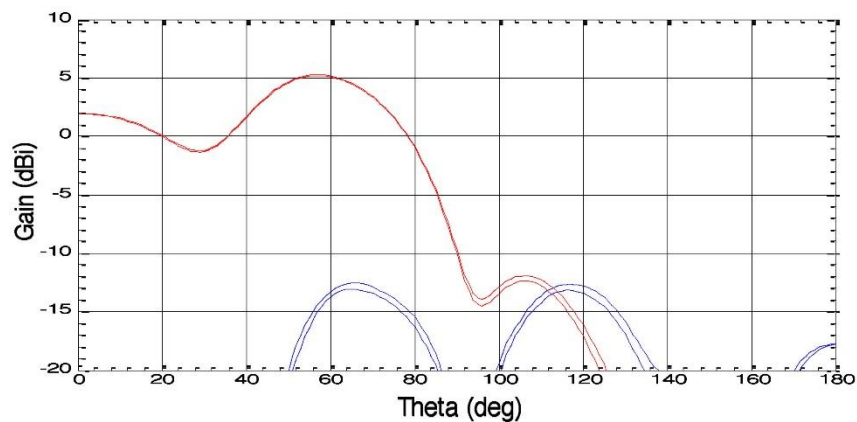
Fig. 3-7 X-band LGA pattern (at transmit frequency).

3.5 S-Band Transponder (SBT)

The two S-band transponders (Fig. 3-4 shows their location) were provided by L-3 Cincinnati Electronics. Each SBT [23] has a receiver, a transmitter, and a diplexer that provides simultaneous receiving and

transmitting capability. The SBT heritage is the transponder used by the Magnetospheric Multiscale (MMS) Mission. Table 3-5 summarizes some of the relevant characteristics of the SBT.

Depending on the commanded configuration, the transponder receives either a 2 kbps PCM/PSK/PM signal modulated on a 16 kHz subcarrier or a 64 kbps BPSK signal modulated directly on the S-band carrier. In transmit mode, the SBT either encodes and transmits a rate ½ convolutional signal or bypasses the encoder and transmits a 513.7 kbps BPSK signal.

The SBT has two interfaces with CDH: For telemetry tracking and command (TT&C), the interface is with the MSAP Serial Interface Adapter (MSIA), for the clock and telemetry data, the interface is with the MSAP telecom interface (MTIF).

Table 3-5. S-band transponder characteristics.

SBT Characteristic	Value
Transmit carrier frequency	2274.3 MHz
Transmit FEC encoding	(k = 7, r = 1/2) convolutional or bypass
Transmit RF output power	+5 W (end of life, EOL min), 6.3 W (nominal)
Transmit data rates	2 kbps and 513.737 kbps
Transmit data format	Non-return to zero-mark (NRZ-M)
Transmit modulation index	90 deg
Receive carrier frequency	2094.3 MHz
Command modulation index	1.35 rad (2 kbps), 1.57 rad (64 kbps)
Command data rate	2 kbps and 64 kbps
Receiver noise figure (at the diplexer input)	< 4 dB
Receiver maximum input level	+10 dBm
Receiver acquisition frequency range	±60 kHz
Receiver acquisition carrier level range	-124 dBm to –50 dBm
Receiver acquisition time	< 8 sec
Receiver command threshold	–122 dBm (2 kbps) –106 dBm (64 kbps)
DC power consumption	6.9 W (receive only) 38.5 W (receive and transmit)
Operating temperature	–20° to +40° °C
Dimensions	0.24 m (L) x 20.6 m (W) x 11.9 m (H)

3.6 X-Band Transmitter (XBT)

The dual X-band transmitters are also provided by L-3 Cincinnati Electronics. The XBT [24] has heritage from transmitters used for the GeoEye I, WorldView I and II, and ICESat spacecraft. The transmitter is made up of four slices: the digital interface slice which contains the command/telemetry interface with the CDH, the OQPSK modulator, and the field-programmable gate array (FPGA) for FEC encoding; the dielectric resonant oscillator (DRO) slice to generate the 8180-MHz downlink carrier; the driver amplifier slice; and the power amplifier slice. Table 3-6 shows some of the X-band transmitter characteristics.

The XBTs interface with the CDH subsystem is with the NVM for TT&C, clock, and data.

Table 3-6. X-band transmitter characteristics.

XBT characteristic	Value
Transmit carrier frequency	8180 MHz
FEC encoding	Reed-Solomon and convolutional; or bypass
RF output power	8 W (typical), 6 W (minimum)
Transmit data rate	130 Mbps
Data modulation	Offset QPSK
Input direct current (DC) voltage	16–40 VDC
Input DC power	61.7 W (nominal), 69.0W (maximum)
Operating temperature	−10° to +40° C
Dimensions	0.178 m x 0.173 m x 0.121 m

3.7 S-Band and X-Band Microwave Components

3.7.1 S-Band and X-Band Coaxial Switches

The S-band coaxial switch is a single pole, double throw (SPDT) switch. Dow-Key provided the flight coaxial switches. The RF connectors on the switch are SMA-type.

The X-band coax switches are single pole, double throw (SPDT) switches inherited from the Gravity Recovery and Interior Laboratory (GRAIL) project. The input/output connectors to the switch are also sub-miniature version A (SMA).

Except for the working frequencies, both switch types share the characteristics in Table 3-7.

Table 3-7. S-band and X-band coaxial switch characteristics.

Coaxial Switch Characteristics (S-band and X-band)	Value
Frequency range (S-band switch)	2.0–2.3 GHz
Frequency range (X-band switch)	8.0–8.4 GHz
Insertion loss	0.2 dB maximum
VSWR	1.25:1 maximum
Isolation	50 dB minimum
Operating temperature	−20° to + 55° C

Two flight rules apply to use of the coaxial switches:

1. No RF output can be present at the switch when switching.
2. Do not energize either switch more often than once per 30 minutes.

3.7.2 X-Band Bandpass Filter

The X-band bandpass filter (BPF) is used to prevent the SMAP X-band transmitted spectrum from interfering with the adjacent Deep Space frequency band (8400–8450 MHz), as defined by the International Telecommunication Union (ITU) [25]. The BPF, provided by Delta Microwave, is a cavity-coupled, folded waveguide filter with TNC-type coax input/output connectors.[8]

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[8] The Threaded Neill–Concelman or TNC connector is a threaded coaxial cable quick connect/disconnect mechanism used particularly for microwave connections.

Table 3-8 shows the characteristics of the bandpass filter.

Table 3-8. X-band bandpass filter characteristics.

Parameter	Value
Frequency passband	8180 ± 150 MHz
Insertion loss	0.5 dB max
VSWR	1.2:1 max
Rejection band attenuation (from 8400 to 8450 MHz)	40 dB min
Operating temperature	−10° to + 40°C

3.8 Telecom Subsystem Mass and Power Input

Table 3-9 summarizes the mass and power consumption of the SMAP telecom subsystem [26].

Table 3-9. SMAP telecom subsystem mass and power input.

Component	Number of Units	Mass per Unit (kg)	Total Mass (kg)	Spacecraft Power (W)	Notes
S-band LGA	1		0.2		
X-band LGA	1		0.3		
SBT	2	4.8	9.5	7 39	receive only receive/transmit
XBT	2	3.8	7.7	62	transmitter on
S-band switch	1		0.1		
X-band switch	1		0.1		
X-band BPF	1		0.3		
Coaxial cables & connectors	not applicable		0.5		
Total			**18.7**		

3.9 Communication Behavior

Communication behavior [19] is a spacecraft FSW function that configures the hardware and software elements required to provide S-band uplink and downlink. Communication behavior is limited to configuring the S-band radio for commanding and engineering data return because of the need for the spacecraft to autonomously initiate communication in anomaly scenarios. Science data downlink, which is routed exclusively via the X-band radios, is not required in contingency scenarios and is manually managed by the mission operations team via standardized blocks of ground commands.

Communication behavior performs the following functions:

- Manage power of the SBT

- Configure hardware required for uplink and downlink (SBT, MSAP telecom interface (MTIF))

- Start/stop of downlink data flow

- Ensure spacecraft is always "command receptive"

- Ensure communication is active during anomaly scenarios

The System Mode Manager initializes the communication window state to a known state in any flight mode that the spacecraft can boot into. This configures the spacecraft to receive properly formatted commands and files from the ground. Commanded communication windows reconfigure the downlink settings and transmit data. These windows are scheduled via time-tagged commands in a sequence. Contingency communications provides a state of continuous communication based on predefined settings. It is entered via command or as an autonomous action (that is, fault protection response or mode transition) and persists until commanded otherwise by the mission operations team.

3.9.1 S-Band Communication Windows

Each S-band communication window (Fig. 3-8) is initiated via a FSW command. Only a single S-band window can be active at one time, and commands to initiate a new S-band window when one is already active are rejected and an event record (EVR) generated[9]. The radio and MTIF settings are then configured based on the arguments provided in the communication window command. Once the window ends, the hardware and software are reconfigured to a standard background configuration to ensure that the spacecraft is command receptive (with predictable settings).
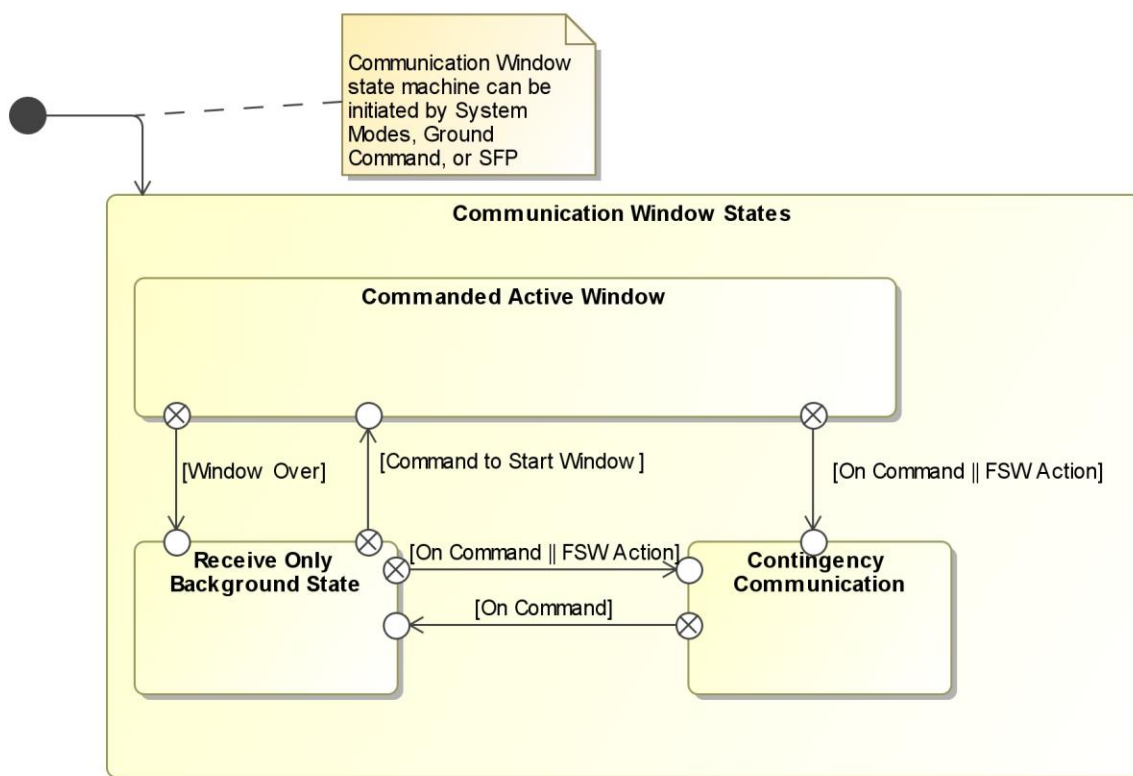
Fig. 3-8. S-band communication window states. (SFP = system fault protection)

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[9] An EVR is a type of telemetry that communicates discrete events in the flight system. An EVR outputs the time of occurrence, the FSW subsystem involved, a standard brief text description of the event, and a category including activity (high or low), a diagnostic, and a warning (high or low).

3.9.2 S-Band Contingency Communication

Contingency communication state (Fig. 3-8) effectively acts as an S-band communication window that can be used in anomalous situations. It relies on hardcoded configuration information to govern its behavior so the S-band configuration can be stable and predictable. Onboard autonomy by either SFP or system mode management can enforce the contingency communication state. Contingency communication takes priority over any active communication window (including another contingency window) and overrides the existing window. Contingency communication is not based on a particular duration or window start time. It is a state, and the only way to leave that state is via ground command.

3.9.3 X-Band Behavior

No communication behavior for the XBT and science data downlink is required. The mission operations team executes science downlink via a series of ground commands (usually in a background sequence) that manages the XBT on/off state and the solid state power amplifier (SSPA) on/off state. Other X-band configuration (modulation, encoding) states do not need to be individually commanded as they are established by the XBT power-on-reset (POR). The background sequence controls the starts/stops of the science data downlink to occur within the periods of SSPA on/off.

4. Tracking Networks and Data System

SMAP communicates with two networks operated by the NASA Goddard Space Flight Center. These are the Space Network (SN) [27] and the Near Earth Network (NEN) [16,28]. For the SN and NEN, SMAP is a customer.

Figure 4-1 is a map showing the location of the SN's TDRSS satellites and the NEN ground stations that communicate directly with the SMAP. The satellites (identified as F-1 through F-7) are first generation[10]; the ones identified as F-8 through F-10 are second generation; and F-11 and later are third generation. The primary satellites used by SMAP are [27]:

    F-10   TDRS West at 174 deg West longitude (TDW)

    F-11   TDRS at 171 deg west longitude (TD171)

    *F-12   TDRS East at 41 deg West longitude (TDE), replacing F-9 in February 2015

    F-7   TDRS at 275 deg West longitude (TDZ)

    F-6   TDRS Spare at 46 deg West longitude (TDS)

    (*)   At SMAP launch, Figure 4-1 shows that F-9 was designated TDE.

The vertical red bars in Fig. 4-1 show how the satellites move north or south of the Equator in equatorial geosynchronous orbit. The north-south excursion affects their viewperiods with SMAP.

The NEN stations are at Wallops, Virginia; Fairbanks, Alaska; Poker Flats, Alaska; Svalbard, Norway; and McMurdo and TrollSat in Antarctica.

The following two subsections (4.1 and 4.2) further detail the SN and NEN networks and their functional capabilities.

4.1 The Space Network (SN)

The Space Network (SN) is a data communication system comprised of a constellation of Tracking and Data Relay Satellites (TDRSs) and several ground terminal complexes employing high-gain microwave antennas. The combination of elements comprising the SN provides telecommunication services for telemetry, tracking, and command between low-Earth orbit (LEO) spacecraft and customer control and data processing facilities.

The space segment of the SN consists of as many as six operational TDRS spacecraft in geosynchronous orbit at allocated longitudes. The spacecraft are deployed in geosynchronous orbits to provide the broadest possible coverage to customers. Each TDRS provides a two-way data communications relay between customer spacecraft and the White Sands Complex (WSC) or the Guam Remote Ground Terminal (GRGT) for data transfer and tracking.

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[10] The TDRS started in the early 1970s, and the three generations of satellites refer to spans of launch dates. The first generation satellites that SMAP has communicated with include TDRS-6 (launched January 13, 1993) and TDRS-7 (launched July 13, 1995). The second generation included TDRS-9 (launched March 8, 2002). The third generation include TDRS-11 (launched January 30, 2013) TDRS-12 (launched January 23, 2014, and replacing TDRS-9 in February 2015). Because SMAP uses only the S-band single access mode, services provided by all three satellite generations are the same. [Ref. 29] describes the differences between the generations.
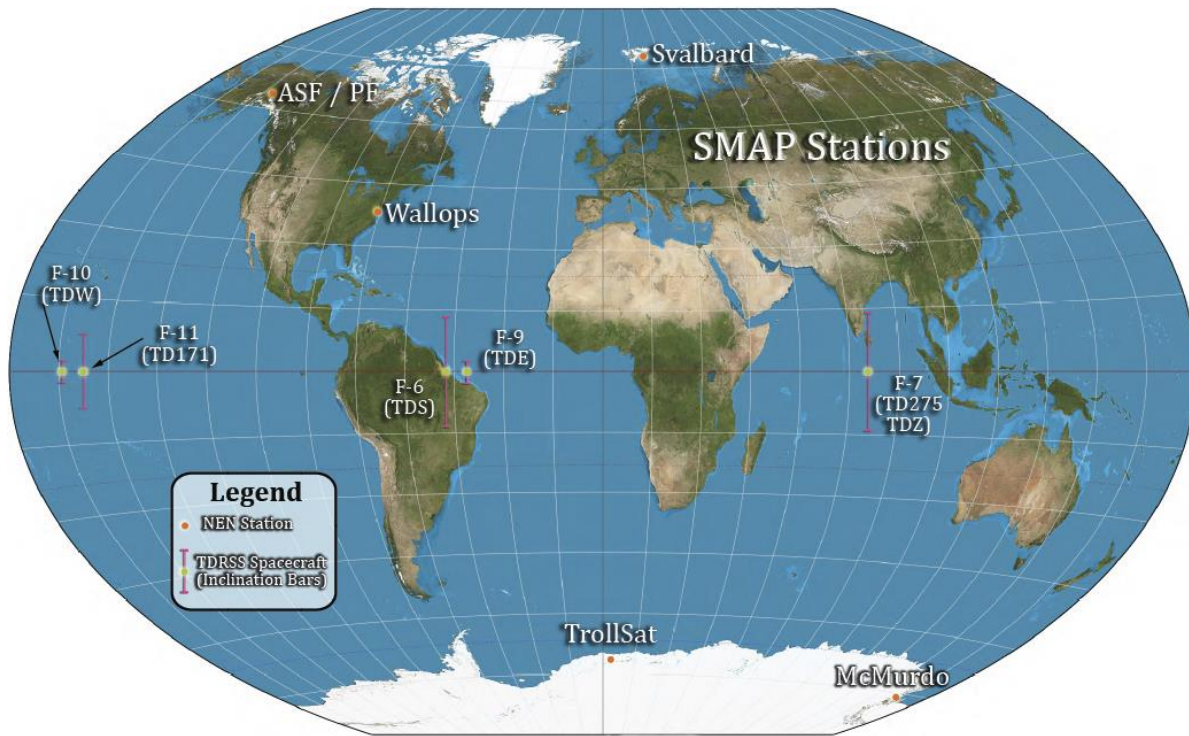
Fig. 4-1. Map of TDRS satellites and NEN stations supporting SMAP at launch.

The space segment of the SN consists of as many as six operational TDRS spacecraft in geosynchronous orbit at allocated longitudes. The spacecraft are deployed in geosynchronous orbits to provide the broadest possible coverage to customers. Each TDRS provides a two-way data communications relay between customer spacecraft and the White Sands Complex (WSC) or the Guam Remote Ground Terminal (GRGT) for data transfer and tracking.

The SN works with the SMAP links in the TDRS single S-band access (SSA) mode when the SMAP uplink and downlink are at 2 kbps. (The NEN, 4.2, works with the SMAP S-band at both the 2-kbps rates and at higher uplink and downlink rates and the X-band downlink.)

Figure 4-2 is a functional diagram for the SSA SN to SMAP forward link at 2 kbps. All three TDRS generations of satellites have identical capabilities for the SSA mode used by SMAP. The NRZ-L data command starts at the WSC interface. The TDRS ground terminal generates a subcarrier frequency of 16 kHz. The modulated subcarrier is phase modulated on a forward link carrier. The modulated carrier is uplinked to the TDRS from WSC at Ku-band. The WSC Ku-band transmit frequency together with the frequency translation on board TDRS produce the nominal 2094.25 MHz S-band forward link frequency transmitted by the TDRS satellite to SMAP.

Figure 4-3 is a functional diagram for the SSA SMAP-to-SN return link at 2 kbps. This link consists of a carrier modulated with telemetry data. On board SMAP, the S-band NRZ-L data stream is RS encoded, Consultative Committee for Space Data Systems (CCSDS) randomized, with ASM added [30]. The NRZ-L data is converted to NRZ-M data format and then rate ½ convolutionally (K = 7) encoded. The carrier is BPSK modulated. SMAP transmits the return link via the S-band LGA with LCP.

The link from SMAP to SN is either coherent data group DG2 Mode 1 or noncoherent Mode 2 [31][11]. For coherent Mode 1, the return link operation requires forward link acquisition and tracking by SMAP. The

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[11] TDRS return link services are divided into two data groups: DG1 and G2. DG1 signal parameters are further subdivided into three operating modes. Mode 1 is used for 2-way Doppler and range measurements. The DG2

carrier frequency is 240/221 times the received uplink carrier frequency. Two-way Doppler tracking is provided in Mode 1. For noncoherent Mode 2, the SMAP transmitter maintains the return link transmit frequency at a nominal value of 2274.3 MHz.

On the ground, the TDRSS terminal BPSK demodulates the carrier. The demodulated data stream goes to the symbol synchronizer and Viterbi decoder. The NRZ-M data is converted to NRZ-L. The data stream is frame synchronized, de-randomized, and RS decoded at the gateway to the NASA Integrated Services Network (NISN). The SMAP return data is sent to SMAP facilities via the SN Gateway (not part of this figure).
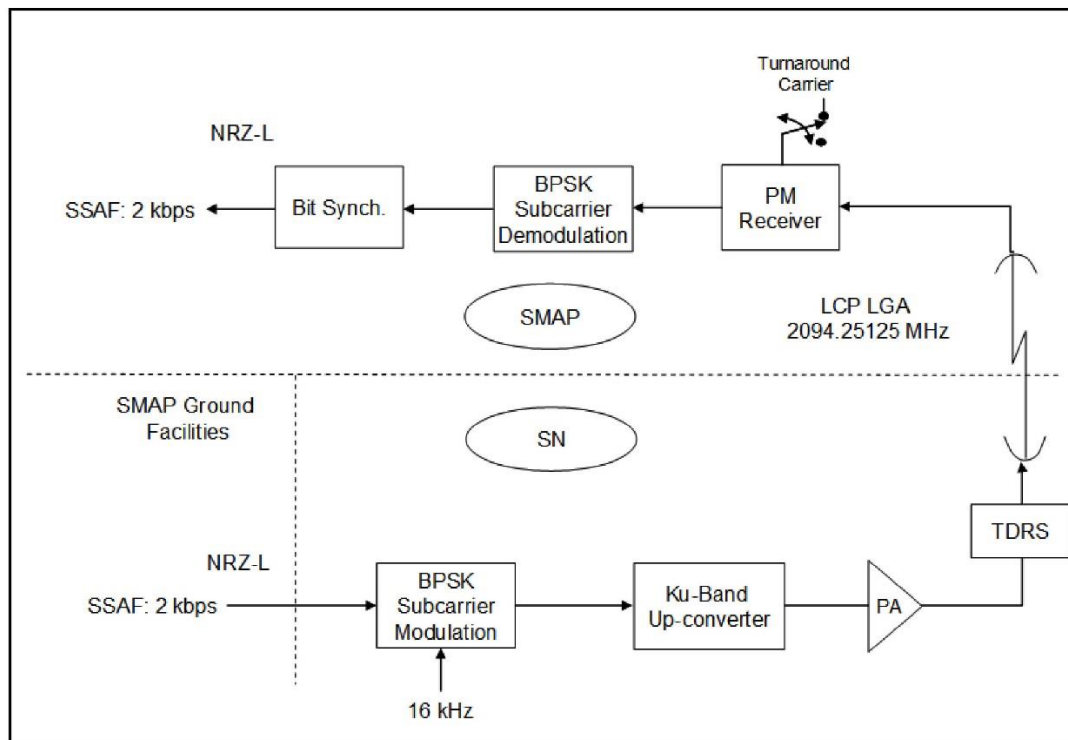
Fig. 4-2 SN to SMAP SSA forward link diagram (2 kbps command).
(LCP = left-hand circularly polarized, NRZ-L = non return to zero, level, PA = power amplifier)

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carrier can be either coherently related to or independent of the forward link carrier frequency. Two-way Doppler can be provided if the DG2 carrier is coherently related to the forward link carrier frequency. Data Group is a parameter value in the SN service specification as described in Section 5 (Table 5-1).

Mode 2 is used when return ink acquisition is desired without a prior forward link acquisition; it uses short, easily acquired PN codes. Mode 3 is used when 2-way range and Doppler measurements are required simultaneously with high-rate telemetry data. Mode 3 is available only when supported by the SSA service. The Mode 3 return link PN code length is identical to and time-synchronized with the forward link PN code received from the TDRSS [29].
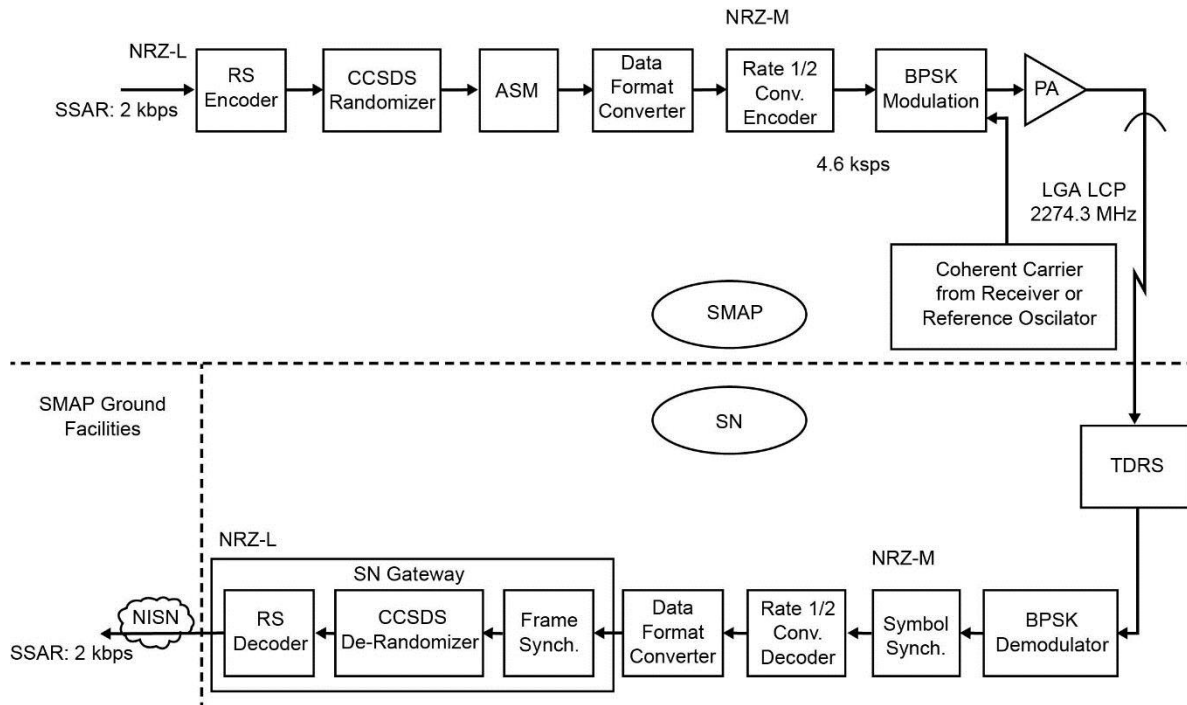
Fig. 4-3. SMAP to SN SSA return link diagram

Fig. 4-3. SMAP to SN SSA return link diagram (2 kbps telemetry).
(ASM = attached synchronization marker, CCSDS = Consultative Committee for Space Data Systems,
ksps = kilosymbols per second, SSAR = SSA return)

4.2 NEN—Near Earth Network

The NEN includes a diverse collection of antenna assets located around the world, as well as centralized operation and control from facilities operated by NASA GSFC. The NEN provides TT&C services for orbital missions, including missions like SMAP that are in low Earth orbit. Many of the NEN sites are located at high latitudes, north or south, to provide service to high-inclination polar-orbiting spacecraft. Because SMAP passes over the Earth's poles each orbit, stations in Norway, Alaska, and Antarctica have SMAP in view every orbit and can provide frequent services as scheduled.

Some NEN stations are NASA owned and maintained and dedicated to NASA customer missions. The NASA owned stations that SMAP uses include the 11-m Wallops ground station in Virginia (WGS), the 10-m McMurdo Ground station (MG1) at McMurdo base in Antarctica, and the 11-m AS1 and AS3 stations of the Alaska Satellite Facility (ASF) near Fairbanks Alaska. Figure 4-4 shows the AS3 and AS1 stations [16].

Fig. 4-4. NEN Alaska stations AS3 (foreground) and AS1.

In addition, NASA provides a significant portion of its space communications services by contracting commercial ground station providers to support NASA missions. The commercial apertures provided by these contractors are available to NASA's NEN customers through existing contracts. Commercial stations supporting SMAP include SG1 and SG2, which are 11-m stations operated by Kongsberg Satellite Services station (KSAT) at 78 deg N latitude in Svalbard, Norway and the 7.3-m TR2 and TR3 TrollSat stations at 72 deg S latitude in Queen Maud Land, Antarctica, also operated by KSAT [28]. The 10-m PF2 station operated by SSC/Universal Space Network (USN at Poker Flat, Alaska has provided SMAP backup for AS1 and AS3. During the science mission, SG2, also an 11-m station in Svalbard has provided backup to SG1.

Figure 4-5 is a functional diagram for the NEN-to-SMAP S-band uplink at 64 kbps. For the high rate uplink most often used, 64 kbps command data in the non-return to zero-level (NRZ-L) format is provided to the station at the NEN interface. The data stream is binary phase shift key (BPSK) modulated directly onto the uplink carrier. The NEN transmits with LCP towards SMAP at a nominal frequency of 2094.25 MHz, the same as the SN (TDRS).

Figure 4-5 shows the standard 64 kbps uplink rate. There is not a separate diagram for the seldom-used 2 kbps uplink. For 2 kbps, the command data in NRZL format is provided to the station instead of 64 kbps. The station generates a subcarrier frequency of 16 kHz and modulates the subcarrier rather than the RF carrier with the BPSK data stream. The modulated subcarrier phase modulates the uplink carrier.
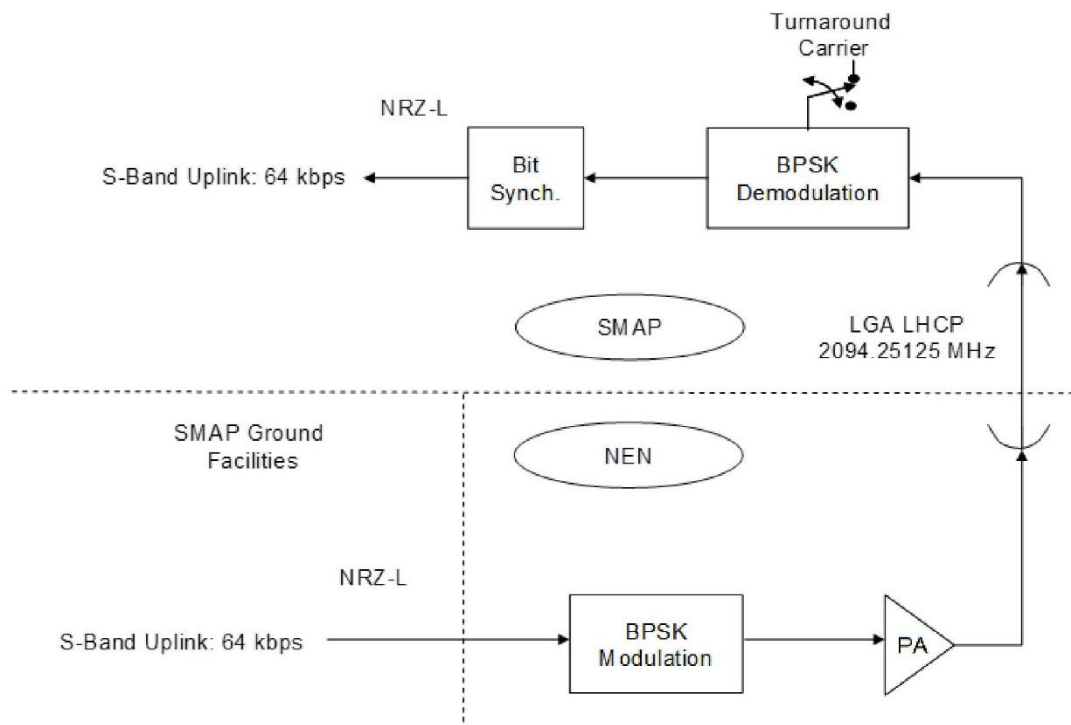
Fig. 4-5 NEN to SMAP S-band uplink diagram (64 kbps command).

Figure 4-6 is a functional diagram for the SMAP-to-NEN high rate S-band downlink at 513 kbps. This link contains a single channel with telemetry only. The S-band downlink is transmitted from SMAP via the LCP S-band LGA. The NEN provides S-band downlink service on a scheduled basis during intervals during which NEN-SMAP line-of-sight exists, the supporting station antenna elevation angle to SMAP is greater than 5 deg above the horizon, and SMAP is above the supporting station's local antenna mask.

For coherent mode, the carrier frequency is 240/221 times the received uplink carrier frequency (nominally 2274.3 MHz). Two-way Doppler tracking is provided. For noncoherent mode, the SMAP transmitter transmits at a frequency of 2274.3 MHz.

As shown in the figure, the SMAP NRZ-L data stream is RS (255,223) encoded, it is CCSDS randomized, an attached synchronization marker (ASM) is inserted, and then the stream is converted to NRZ-M data format. The BPSK modulated signal is transmitted to the NEN station where the receiver BPSK demodulates the downlink signal. The demodulated signal is output to a symbol synchronizer. The NRZ-M data stream is converted to NRZ-L, frame synchronized, de-randomized, and then RS decoded at the station prior to being sent to the SMAP Mission Operations Center (MOC).

When the SMAP telemetry is 2 kbps low data rate as defined in the transmit and receive (TR) code, the spacecraft encodes the data with Reed-Solomon (255,223), randomizes it, adds the ASM, and converts the stream from NRZ-L to NRZ-M. Unlike the 513-kbps data, the 2-kbps NRZ-M stream is (k = 7, r = 1/2) convolutionally coded. The NEN station receiver BPSK demodulates the downlink signal. The demodulated signal is sent to a symbol synchronizer and then a Viterbi decoder. The NRZ-M data stream is converted to NRZ-L, frame synchronized, de-randomized, and then RS decoded.)
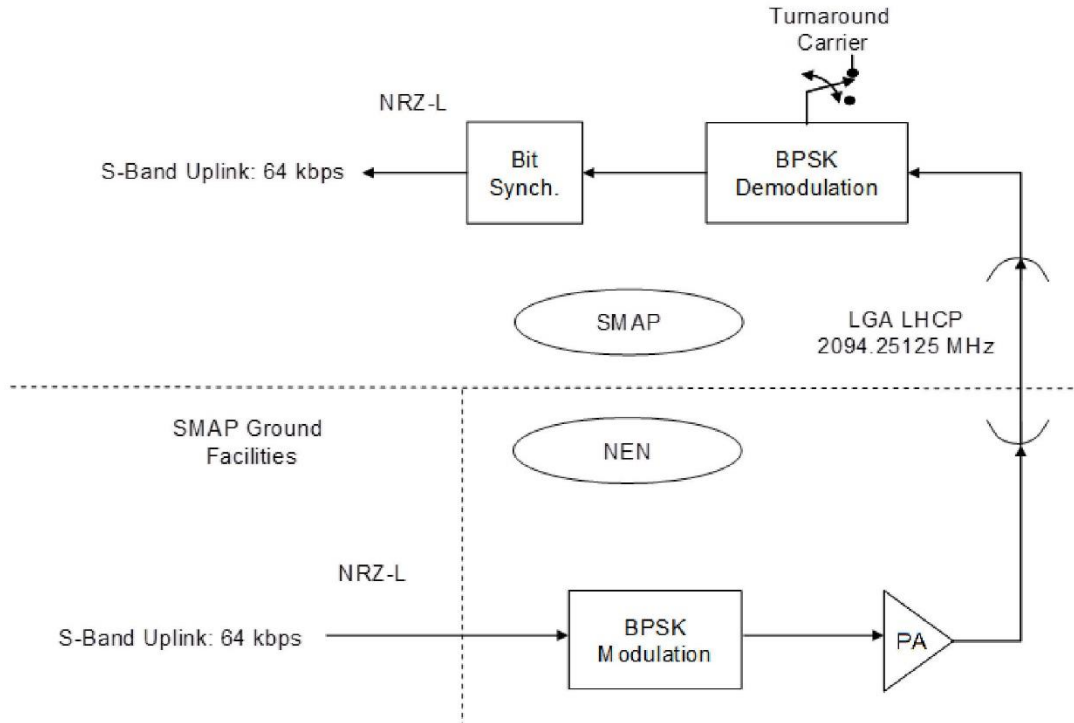
Fig. 4-6. SMAP to NEN S-band downlink diagram (513 kbps telemetry).

Figure 4-7 is a functional diagram for the SMAP-to-NEN X-band downlink.

The SMAP X-band transmits science data having a total information rate of 130 Mbps. This NRZ-L information data stream is RS (255,223) encoded, CCSDS randomized, and ASM added, producing a symbol stream at 151.32 Msps. This is applied alternately to the I and Q channels with the I and Q channels individually convolutionally encoded (rate ½, k=7)[12]. The offset quadriphase shift keying (OQPSK) modulated signal is transmitted to NEN with an I/Q channel power ratio of 1:1. SMAP transmits the OQPSK modulated downlink signal at 8180 MHz to the NEN through the LCP X-band LGA.

The NEN X-band service can be scheduled for periods when NEN-SMAP line-of-sight exists, the supporting antenna elevation angle to SMAP is greater than 10 deg above horizon, and SMAP is above the station's local antenna mask.

The NEN ground station receiver provides both I and Q channels to the OQPSK demodulator. The in-phase and quadrature components of a signal (I and Q) channels are delivered to the symbol synchronizers and Viterbi decoders. The two NRZ-L data streams are multiplexed to form a single stream. The data stream is frame synchronized, de-randomized, and RS decoded by the NEN station and sent to the project via the NASA Integrated Services Network (NISN) and the Earth Observing System (EOS) Data and Operations System (EDOS) [32].

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[12] Figures 4-6 and 4-7 introduce a number of signal generation and detection terms. The CCSDS provides an overview of space communications protocols using these terms [25] and specifies encoding, randomization, and ASM bit patterns [33]. The SMAP-NEN/SN interface document [7] specifies the encoding, modulation formats, and the I- and Q-channel (I-CH, Q-CH) contents, and the SMAP-NEN/SN compatibility test report [Ref. 34] defines the specific 32-bit ASM pattern as 1ACFFC1D (hexadecimal).
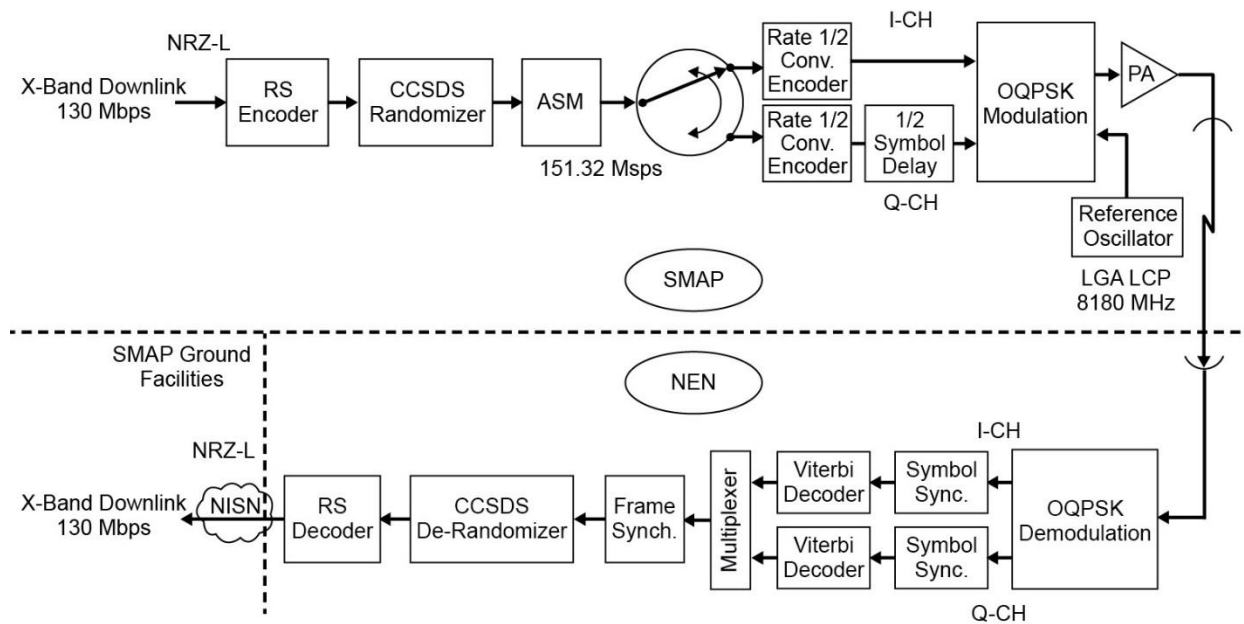
Fig. 4-7. SMAP to NEN X-band downlink diagram (130 Mbps science data).

4.3 SMAP Ground Data System (GDS)

The project command, telemetry, tracking and science data interfaces with the NISN are defined in terms of functions in Fig. 4-8 and in terms of facilities in Fig. 4-9.

Figure 4-8 is a functional flow diagram of the SMAP ground data system [35]. At a top level, it illustrates the major GDS facilities that support the SMAP mission system. The GDS includes facilities in the MOC and supporting services and interfaces with external facilities such as the tracking networks (NEN and SN) and facilities and services provided by GSFC. These include the Data Services Management Center (DSMC) at the White Sands Complex (WSC), the Flight Dynamics Facility (FDF) at GSFC and the Level-0 Processing Facility (LZPF).

The SMAP physical infrastructure and the Mission Operations Center (MOC) are housed in existing facilities, which provide network access and both network and physical security. The project's navigation function includes orbit determination (OD), maneuver design (MD), and ephemeris generation (Eph Gen).

Some architecture and inheritance highlights of the SMAP GDS design [36] are as follows:

- Antenna Sites and Services

    o Existing GSFC SN and NEN and services

    o Updated receivers at some sites to handle Viterbi codes

    o McMurdo high-rate telemetry relay

    o SN (TDRSS) and NEN

- Engineering Telemetry and Command Processing

    o Adapted the core tool-set of the (Advanced Multi-Mission Operations System) AMMOS Mission Processing and Control System (AMPCS) [37] of the Multimission Ground Systems and Services (MGSS)

- o   New MGSS command capability for flight
- Spacecraft health & performance
  - o   Adapted MGSS AMPCS display, query, plotting, and reporting tools
  - o   Adapted MGSS TFP for telecom prediction and analysis
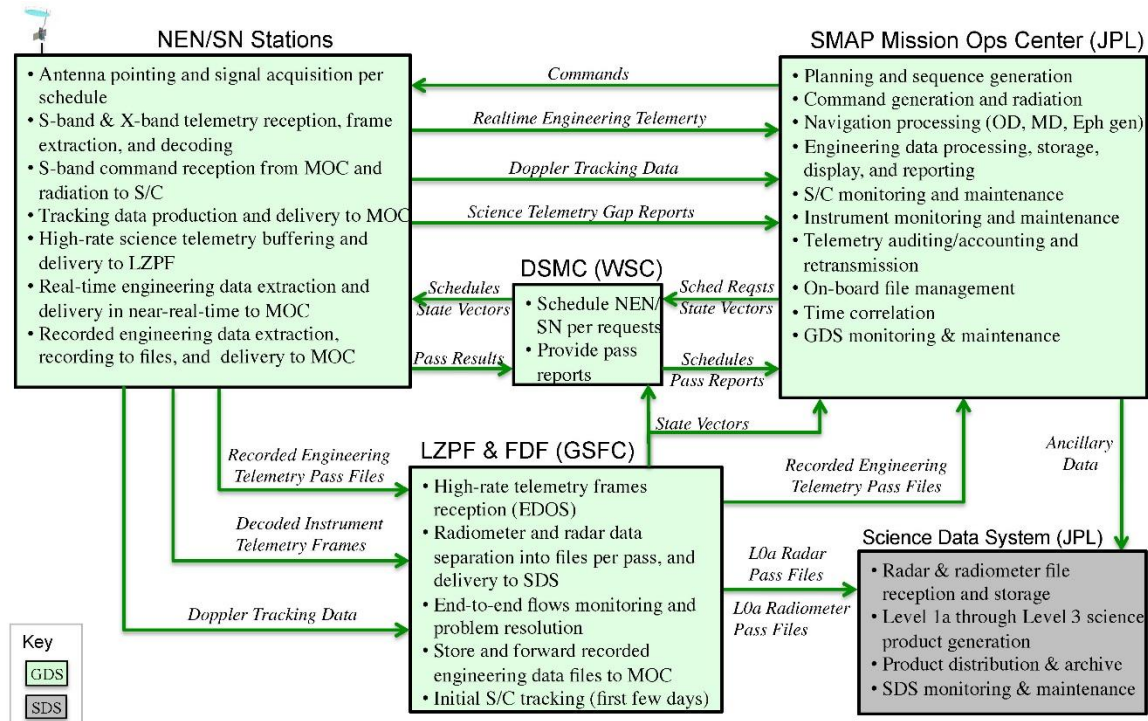
Fig. 4-8. SMAP ground data system functional flow.

Figure 4-9 is another view of the ground data system, from the point of view of the services provided by different organizations.

The GSFC provides the tracking networks (SN and NEN), which provide the processing and transmission of uplink (command); the reception and processing of downlink telemetry (science data and engineering data), and the processing and the generation of tracking data (one-way and two-way Doppler).

The Mission Operations Center (MOC), located at JPL with a backup MOC (BMOC) at GSFC, provides the creation of sequences and command products from the mission plan and science inputs, real-time data monitoring of spacecraft telemetry and detection of problems (anomalies), the non-real time analysis of spacecraft performance and resolution of anomalies, and the navigation of the spacecraft using the tracking data. The science instrument data goes directly to the Science Data System (SDS), not to the MOC.

Real-time and recorded engineering data comes down during the scheduled NEN/SN station passes. Real-time telemetry is bent-piped by the station to the MOC via a socket interface. Recorded telemetry is collected into files to be transferred to the MOC after the end of the pass.
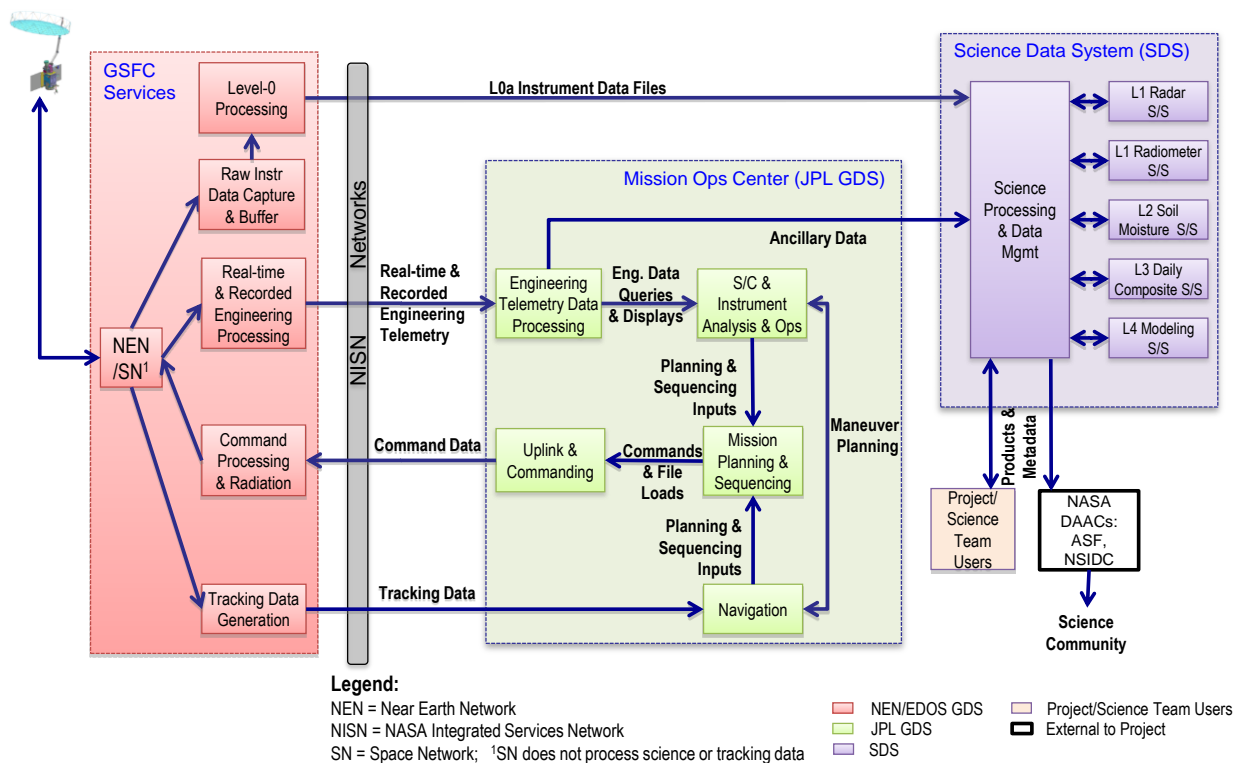
Fig. 4-9. Ground Data System services.

Science data capture and level 0a processing services are provided by the GSFC Earth Science Mission Operations (ESMO) organization using the EDOS [32]. This multi-mission service is configured to be always running, and it automatically captures and processes high-rate science data received at the NEN stations. The service also includes 24 × 7 monitoring and service restoration. The EDOS system produces files that are pushed to the SDS system at JPL after each pass. The SDS system detects and automatically processes these files into higher-level science products. The EDOS includes the Level-0 Processing Facility (LZPF) at GSFC for delivery of Level-0a products to the SDS and delivery of near-real-time and post-pass frame accountability statistics to the GDS at JPL.

SMAP has a requirement that the science data be delivered to the SDS within one hour of a pass end-of-track. To achieve this for data received at McMurdo, the McMurdo TDRS Relay System (MTRS) provides a high-speed path from McMurdo to White Sands via a TDRS satellite relay.

5. S-Band and X-Band Link Performance

5.1 NEN Transmit Receive (TR) Codes and SN SSC Codes

5.1.1 SN Service Specification Codes (SSC)

The TDRS provides the S-band single access (SSA) mode for SMAP scheduled passes. The SN defines one SSC for the SSA forward link, three possible SSCs for the SSA return link, and three SSCs for tracking (Doppler). These codes, shown in Table 5-1, identify SMAP as spacecraft 0430.

Table 5-1. SN service specification codes for SMAP.

Forward Codes

SSC	Service	Data Rate Max	Data Rate Initial	FREQ (Hz)	PN Mod	Pol.	Doppler Comp
H01	SSAF	2000	2000	209425125	N	LCP	Y

Return Codes

SSC	Service	Data Source	Polarization	Coherency	Data Group	DG1	FREQ
I01	SSAR	Single Identical	LCP	Coherent	2	1	2274.3 MHz
I02	SSAR	Single Identical	LCP	Non-coherent	2	1	2274.3 MHz
I12	SA	Single Identical	LCP	Non-coherent	2		2274.3 MHz

Track Codes

SSC	Service	Ranging	Doppler	Forward SSC	Return SSC	Sample Rate	
T01	SSA	N	2 way	H01	I01	1/1	
T02	SSA	N	1 way		I02	1/1	
T12	SSA	N	1 way		I12	1/1	

5.1.2 NEN Transmit Receive (TR) Codes

The station configuration for each scheduled pass is determined from the TR code. SMAP uses five codes for MOC operations and has four more for backup MOC operations, as defined in Table 5-2. They define

- whether the SBT coherency is enabled or disabled

- the uplink command rate

- the S-band downlink telemetry rate

- whether the SBT transmitter is on or off

- whether the XBT is on or off (if on, downlink rate is always 130 Mbps)

- whether the SMAP mode is contingency communication (comm) or normal windows (routine operations)

Table 5-2. NEN Transmit Receive (TR) codes for SMAP (spacecraft ID 0430).

Mode ID	Coherent or Non-Coherent	Command	S-Band Real Time	S-Band	X-Band 302.64Msps	Principally Used for
TR1	Coherent	ON 2.0 kbps	4.588 ksps (2.294 kbps	ON	OFF	Contingency (prime MOC)
TR2	Noncoherent	ON 2.0 kbps	4.588 ksps (2.294 kbps	ON	OFF	Contingency (prime MOC)
TR3	Coherent	ON 2.0 kbps	589.270 kbps	ON	ON	Routine ops (prime MOC)
TR4	Coherent	ON 64.0 kbps	589.270 kbps	ON	ON	Routine ops (prime MOC)
TR5	N/A	No	589.270 kbps	ON	ON	Listen only (prime MOC)
TR6	Coherent	ON 2.0 kbps	4.588 ksps (2.294 kbps	ON	OFF	Contingency (backup MOC)
TR7	Noncoherent	ON 2.0 kbps	4.588 ksps (2.294 kbps	ON	OFF	Contingency (backup MOC)
TR8	Coherent	ON 2.0 kbps	589.270 kbps	ON	OFF	Routine ops (backup MOC)
TR9	N/A	No	589.270 kbps	ON	ON	Listen only (backup MOC)

Notes: 1. Codes TR1 and TR2 (and TR6 and TR7 for the backup MOC) are SN compatible.
2. Code TR4 (and TR8 for the backup MOC) is primary for routine science return.
3. The listen-only Codes 5 and 9 are for the second station with overlap for generic scheduling.

5.2 Spectrum Considerations

5.2.1 Maximum Levels into the Deep Space Bands

SMAP is required to comply with applicable spectrum regulations of the ITU, the National Telecommunications and Information Administration (NTIA), and the Space Frequency Coordination Group (SFCG) of the FCC.

In particular, ITU-R SA.1157 [30] specifies protection criteria for S-band and X-band Deep Space[13] frequencies. It limits the spectral interference to the 8400–8450 MHz band from transmitters not in the Deep Space band (such as SMAP's) to less than –220.9 dBW/Hz, as measured by a 70-m diameter antenna. Similarly, it limits spectral interference to the 2290–2300 MHz Deep Space band from out-of-band transmitters such as SMAP's to less than –222 dBW/Hz, as measured by a 70-m diameter antenna.

5.2.2 SMAP X-Band Spectrum and Signal Level at Deep Space Stations

The X-band protection criterion, the output power and spectrum of the SSPA, and the orbit altitude of SMAP make an XBT output bandpass filter necessary. Figure 5-1 shows the spectrum of the 130-Mbps modulated downlink carrier at the input to the bandpass filter. Without a BPF, the calculated power spectral density (PSD) at the 70-m antenna LNA input would be about –184 decibels referenced to watts per hertz (dBW/Hz), exceeding the protection criterion by 37 dB. The X-band BPF was verified to attenuate the signal by 40 dB or more anywhere in the 8400–8450 MHz frequency band.

SMAP Unfiltered SQPSK PSD at 70m Aperature, 300 Msps (130 Mbps with Rate 1/2 Conv+RS)
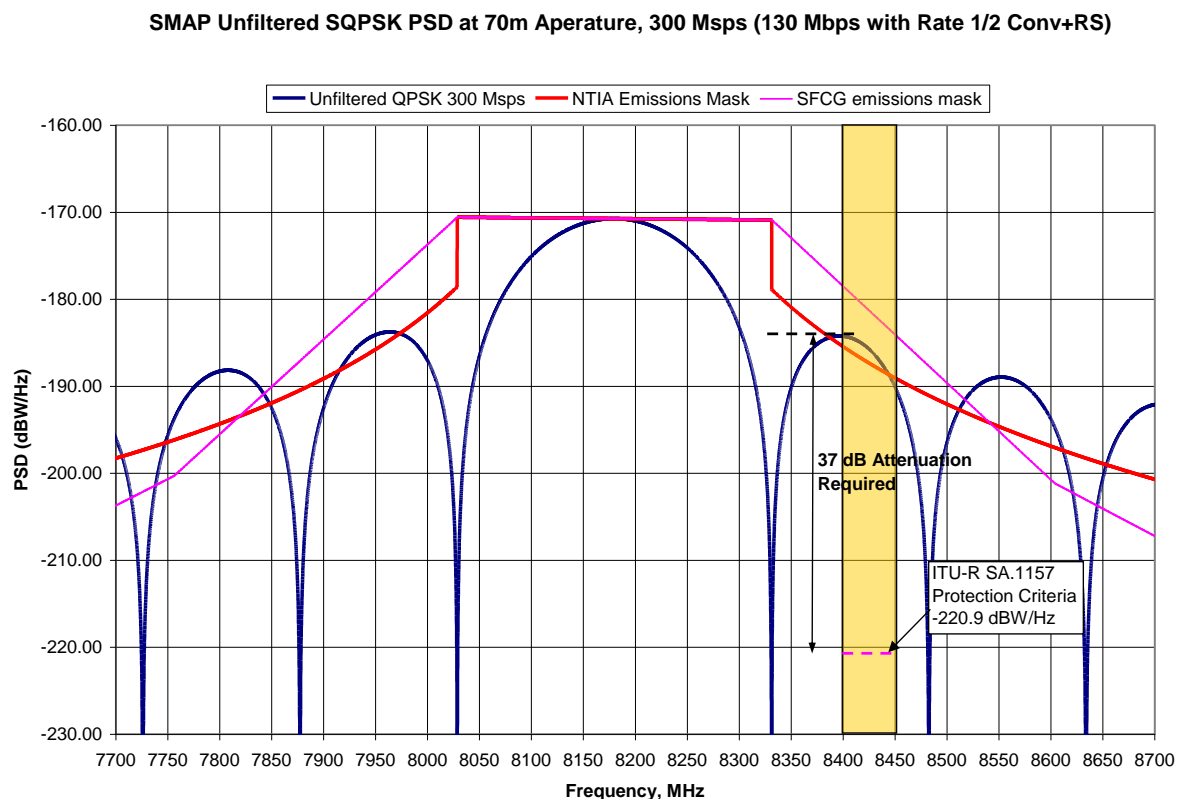
Fig. 5-1. 130 Mbps X-band spectrum at a 70-m station without bandpass filter.

The figure is a worst-case plot because it assumes that the Deep Space Network (DSN) 70-m diameter antenna boresight is pointed at SMAP and that SMAP is the minimum possible distance away. SMAP only transmits at X-band when above 10 deg elevation to one of the NEN ground stations. The minimum possible distance of about 1641 km occurs at Goldstone when SMAP is transmitting to WGS.

The NTIA also specifies a power flux density (PFD) limit measured at the Earth's surface. The PFD limit is given as a function of angle of arrival. The limit value is –154 dBW/m² arriving at a 5 deg. elevation

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[13] This article uses Deep Space (initial caps) for the specific bands or frequencies allocated by the ITU to spacecraft operating beyond lunar distance.

angle at S-band and −150 dBW/m^2 at a 10 deg. elevation angle at X-band. The SMAP downlink is less than the required envelope at all elevation angles, with a minimum margin of about 6 dB.

5.3 Link Performance with the SN

SMAP has used the SN (TDRS satellites) to support initial acquisition post-separation, instrument deployment (in particular, the reflector deployment and spin-up), and orbit determination during the launch phase. The TDRSS link has also been used for emergency communications during spacecraft anomalies and safing events. Due to the larger distance from SMAP to a TDRS satellite as compared with a NEN station, the SN link margins are considerably smaller than the NEN link margins.

The data rates for the TDRSS forward and returns links are both 2 kbps. The same SMAP S-band antenna is used for the SN and NEN links, and it is canted 30 deg off-nadir. The cant angle improves the SN link margin to TDRSS somewhat, which increases the link availability. The TDRS SSA mode allows SMAP to use the same modulation scheme, modulation index, and coding for both the SN and NEN 2 kbps links.

Table 5-3 compiles the factors involved in link margin design for the SN initial acquisition of SMAP [17]. The SMAP link design is required to maintain 0.5-dB margin for the return link using the SN. There is no similar margin requirement for the SN forward links. The SN maintains internal margin on the TDRS effective isotropic radiated power (EIRP) and ratio of antenna gain to receiver noise temperature (G/T), which enables it to guarantee service down to 0 dB margin. Based on their SMAP link analysis before launch, the SN committed to providing forward link service (with 0 dB margin) whenever the SMAP LGA could provide more than −4 dBi antenna gain in the direction of the transmitting TDRS. To be more conservative, the SMAP project link budgets for the SN forward link assume a minimum LGA gain of −3 dBi.

In order to close the forward link, the SN configures the TDRS transmitter in high power mode, which provides 2.7 dB additional EIRP (46.3 dBW versus 43.6 dBW in normal mode for the first generation TDRS (F1–F7) satellites. Though the second generation (F8–F10) and third generation (F11 and beyond) satellites provide 48.5 dBW in high power mode, the more capable satellites may not be available to SMAP at a given time due to geometry or schedule. Hence, the SN-to-SMAP forward link budget is computed assuming 46.3 dBW EIRP [5].

During initial acquisition, the SN ground station receiver was configured for an extended frequency search range in order to acquire the first S-band noncoherent return carrier frequency. The first S-band carrier frequency received from SMAP had a large uncertainty due to thermal changes in the S-band transponder after turn-on, and initial orbit Doppler uncertainty.

An extended frequency search range results in a higher receiver threshold. To balance uncertainty versus threshold, the SN developed a new frequency search range, ±6.5 kHz, for SMAP initial acquisition. This frequency search range allowed the SN to acquire the signal for SMAP LGA gain of at least −5 dBi. This covers as much as 95 deg LGA FOV. The standard SN expanded frequency search range is ±40 kHz, which has an 8.2-dB higher threshold. This would have severely limited the antenna FOV available for initial acquisition of the first SMAP return link.

Table 5-3. Summary of SN link margins (2 kbps up/2 kbps down).

Link Description	Modulation / FEC	Link Margin	Comments
2 kbps S-band forward link	16 kHz subcarrier/ uncoded	**0.9 dB**	LGA gain = –3 dBi; assuming TDRS high power mode forward service (46.3 dBW)
Carrier only S-band forward link	None	**1.6 dB**	LGA gain = –5 dBi; For Doppler tracking via SN
S-band 2 kbps return link	BPSK / (7,1/2)+RS	**5.0 dB**	For emergency communications and during deployment

5.4 Link Performance with the NEN

SMAP schedules support from NEN ground stations during nadir-pointed telecom operations. The telecom modes are as follows:

(1) a 64-kbps S-band uplink for command;

(2) a 513.737-kbps S-band downlink for engineering telemetry;

(3) a 2-kbps S-band uplink and downlink for emergency mode; and

(4) a 130-Mbps X-band downlink for science data return.

Of the five NEN sites, the best ground-station coverages of the SMAP polar orbit in terms of the longest passes are from Svalbard and McMurdo/Trollsat, followed by Alaska, and then Wallops. Most station antennas are 11.3 m in diameter, except for the 10-m antenna at McMurdo and the 7.3-m antenna at Trollsat. The smaller antennas have less link margin at a given range to SMAP and a given SMAP configuration.

A telecom link margin summary table for SMAP S-band telecom is shown in Table 5-4, using McMurdo as the receiving and transmitting station. The margins are computed at 5 deg, the NEN minimum for S-band. As the table shows, the S-band uplink and downlink margins with the NEN greatly exceed the SMAP requirements.

Table 5-4. Summary of S-band link margins to NEN (based on McMurdo).

Link Description	Modulation / FEC	Link Margin	Comments
2 kbps Forward Link	16 kHz subcarrier / uncoded	**40.4 dB**	Normal command rate
64 kbps Forward Link	BPSK / uncoded	**27.8 dB**	File uploads
2 kbps Return Link	BPSK / (7,1/2) convolutional + RS	**40.2 dB**	Emergency communications
513.737 kbps Return Link	BPSK / Reed-Solomon	**14.1 dB**	Normal playback rate

In Table 5-5, the X-band link margins to the five NEN station types are shown, computed at an elevation angle of 10 degrees, the NEN minimum for X-band. Although considerably smaller than the S-band link margins, with Trollsat the smallest,[14] the X-band margins still meet the SMAP requirement.

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[14] The table names the NEN sites. Three sites have two stations (antennas). NEN defines the antennas at a given site as having identical EIRP and G/T performance, though the elevation angle masks and exact locations are defined individually. SMAP has used SG1 and SG2 at Svalbard, WPS at Wallops, AS1 and AS3 at Alaska, MG1 at McMurdo, and TR2 and TR3 at Trollsat.

Table 5-5. Summary of 130-Mbps X-band link margin to NEN.

Ground Station Antenna	Modulation / FEC	Link Margin
11.3-m SGS (Svalbard)	OQPSK / (7,1/2)+RS	6.9 dB
11.3-m WGS (Wallops)	OQPSK / (7,1/2)+RS	4.5 dB
11.3-m ASF (Alaska)	OQPSK / (7,1/2)+RS	7.6 dB
10-m MGS (McMurdo)	OQPSK / (7,1/2)+RS	3.7 dB
7.3-m TRL (Trollsat)	OQPSK / (7,1/2)+RS	2.5 dB

6. Flight Operations

6.1 Telecom Planning

Compared with many deep space missions, SMAP telecom planning is fairly simple.

- Communications behavior limits the S-band transponder (SBT) to two primary data-rate and modulation schemes (contingency comm and normal windows)

- Normal comm windows are repetitive and are primarily intended for NEN operations only. Coherency is a window parameter with values of enabled or disabled, but it is normally set to enabled for all windows in a sequence. It would be set to disabled only for windows that support critical engineering activities with telemetry data having higher priority than the two-way Doppler tracking that the coherency-enabled mode provides.

- Contingency comm can be compared with a single comm window that lasts until the mode returns to receive-only or to normal windows.

- The contingency comm SBT coherency state (enabled or disabled) is established a mode parameter that tends to remain the same for long periods of time.

- The XBT has a single downlink mode and no uplink.

6.2 Flight Rules

The project flight rules [38] govern the safe sequencing and operation of all spacecraft subsystems during flight.

Table 6-1 states the telecom rules (and idiosyncrasies) that govern the use of the SBT, the X-band transponder (XBT), and the switches that select between side A and side B of each. As the header in the rightmost column of the table indicates, some rules can be checked by the Seqgen (sequence generation) software used to build sequences. Depending on the criticality of a rule violation and project policy, Seqgen can issue an error or a warning. Other rules need to be checked manually or may simply document an equipment idiosyncrasy. Violations of two telecom rules (one criticality A and the other criticality C) produce Seqgen warnings, while the rest are either checked manually or define idiosyncrasies.[15]

6.3 Telecom Monitor, Query, Analysis, and Trending

6.3.1 Real Time Monitoring (Telecom Perspectives)

The flight team monitors high-importance activities in real time in the Mission Operations Center (MOC). Telemetry in the form of engineering, housekeeping and accountability (EHA) channel values versus time, or as event records (EVRs) can be displayed on the workstation screen as a perspective. Perspectives can have a variety of digital telemetry (channel title, latest value, and time

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[15] Each flight rule is assigned a Criticality Rating [39] that defines the potential severity of a violation. Criticality A rule violation could result in an inability to meet primary mission objectives up to and including mission failure. Criticality B violation could result in degraded mission return, such as permanent degradation of an instrument or loss of functional redundancy. Criticality C is other than Crit A or Crit B, for example violation that could result in temporary degradation or loss of an engineering subsystem or instrument, degradation of non-mission-critical data, or loss of flight consumables. An Idiosyncrasy defines an existing characteristic of a subsystem that not rise to the level of a Flight Rule.

tag) in a table format, or they can be displayed as plots that provide one or several channels with EHA values on the Y-axis and time on the X-axis, or as formatted sentence-like event records (EVRs).

Table 6-1. Telecom related flight rules.

Flight Rule ID	Operational Category	Criticality	Title	Seqgen Disposition
CB-A-0001	Comm behavior	A	Do not energize the X-band or S-band single pole double throw (SPDT) switch more than once per 30 minutes	Warning
CB-C-0002	Comm behavior	C	Use comm behavior commands versus lower level commanding	None (manual check)
CB-C-0004	Comm behavior	C	No RF transmission during switch changes (that is: no "hot switching"	Warning
CB-I-0003	Comm behavior	I	X-band command and event counter discrepancy may result from CDH power cycle	None (idiosyncrasy only)
CB-I-0005	Comm behavior	I	S-band digital telemetry temperature below –25 °C is considered invalid	None (idiosyncrasy only)
CB-I-0006	Comm behavior	I	Subtract 1.4 V from the 9-V telemetry value reported to get the correct voltage	None (idiosyncrasy only)
THRM-A-0009	Thermal	A	Maximum allowed X-band transmit time is 24 minutes in any 98.5 min period (~1 orbit)	None (manual check)

Figure 6-1 shows a typical SMAP telecom real-time monitor table page. When the SMAP telecom analyst is on console in the MOC or logs in remotely to view telemetry data, this single page provides the latest SBT and XBT data at a glance. Between passes, the latest available data remains on screen, with the time tags remaining static in the three columns to the right remaining unchanged until new data replaces the old.

Column 1 of Fig. 6-1 displays the unique channel number for each telemetry point in the display. Channels that begin with the letter E are the responsibility of the telecom subsystem. Those beginning with letter D are from the data management subsystem, and those with letter P are from the power subsystem. Column 2 displays the unique channel name assigned to the measurement. Most channel names are abbreviated, with the abbreviations defined in the list of abbreviations and acronyms at the end of the article. For example, channel E-0008, CB_SBAND_A_COHON is an abbreviation for "communications behavior S-band, SBT-A coherency on", with the current value shown in third column as a data number or "raw" value ("1" in this example) and in the fourth column as an engineering unit or state value ("coherent" in this example).

File View Utilities Advanced Help

| Status | Product Status | EVR | Command | Channel List | Custom Grid ✕ |

ID	Title	Raw	Value	ERT	SCLK	SCET
E-0051	CB_STATE	3	CONTINGENCY	21:35:07.112	0472019756.	2014-350T16:34:4
SBT-A						
E-0004	CB_SBAND_SPDT_POS_1	1	Active	22:52:36.975	0472024406.	2014-350T17:52:1
E-0030	CB_SBAND_A_RECEIVER_7V	6.96080017016	6.960800170898	21:35:07.112	0472019756.	2014-350T16:34:4
E-0022	CB_SBAND_A_IF_SIG_PWR	0	-430.2409998815	22:52:36.975	0472024406.	2014-350T17:52:1
E-0025	CB_SBAND_A_FREQ_OFFSET	0	0.0	22:52:36.975	0472024406.	2014-350T17:52:1
E-0033	CB_SBAND_A_RECEIVE_DATA_RATE	4	2kbps	22:52:36.975	0472024406.	2014-350T17:52:1
E-3011	CB_SBAND_A_TXON	1	ON	22:52:36.975	0472024406.	2014-350T17:52:1
E-0032	CB_SBAND_A_TRANSMITTER_PWR	38.17903137:	38.17903137207	22:52:36.975	0472024406.	2014-350T17:52:1
D-1610	DMD_DWN_MODE_RATE	0	RS_2K	21:45:20.679	0472020356.	2014-350T16:44:4
E-0034	CB_SBAND_A_XMIT_DATA_RATE	3	4.6kbps	21:35:07.112	0472019756.	2014-350T16:34:4
E-3008	CB_SBAND_A_COHON	1	Coherent	22:52:36.975	0472024406.	2014-350T17:52:1
E-0065	CB_SBAND_A_EVENT_COUNTER	0	0	22:52:36.975	0472024406.	2014-350T17:52:1
E-0027	CB_SBAND_A_PA_TEMP	103	26.89948356162	22:52:36.975	0472024406.	2014-350T17:52:1
E-0028	CB_SBAND_A_TCXO_TEMP	100	25.5394	22:52:36.975	0472024406.	2014-350T17:52:1
XBT-A						
E-0006	CB_XBAND_SPDT_POS_1	1	Active	21:35:07.112	0472019756.	2014-350T16:34:4
N-3000	SFP_PRIME_XBAND	0	A	22:52:36.975	0472024406.	2014-350T17:52:1
P-3238	PWR_XBT_A_SENSED	0	OFF	22:52:36.975	0472024406.	2014-350T17:52:1
E-3048	CB_XBAND_A_SSPA	0	OFF	21:35:07.112	0472019756.	2014-350T16:34:4
E-0014	CB_XBAND_A_RF_POWER	32.81863784:	32.81863784790	21:35:07.112	0472019756.	2014-350T16:34:4
E-0020	CB_XBAND_A_10V	9.80069923416	9.800699234008	21:35:07.112	0472019756.	2014-350T16:34:4
E-0010	CB_XBAND_A_EVENT_CNT	0	0	21:35:07.112	0472019756.	2014-350T16:34:4
E-0000	CB_XBAND_A_OCS_TEMP	1170.0	28.48357376970	21:35:07.112	0472019756.	2014-350T16:34:4
E-0002	CB_XBAND_A_AMP_TEMP	1177.0	28.10112908378	21:35:07.112	0472019756.	2014-350T16:34:4

Fig. 6-1. Typical telecom real time monitor table page.

6.3.2 Post-Pass or End-of-Day Querying (via chill_get_chanvals)

At the end of a shift or end of the day, the telecom analyst runs a script on the workstation to produce three output files: a set of "digitals", a query output file, and a query output summary file. The Python query script accesses data for a user-specified span of time

The digitals output is a *.html file for viewing in a browser. Figure 6-2 is an example of the first page of a displayed digitals file. This page defines successive configurations for SBT-A. The page organizes the data into a set of formatted columns of EHA channels to show changes in configurations or states over the time span. Columns 1 and 2 are time tags expressed in spacecraft event time (SCET) and spacecraft clock (SCLK). Column 3 is a session number or session ID. The session number provides a means of separating out data from different tests that may have the same span of SCET as was common during pre-launch. In flight, the time spans are unambiguous, and session numbers are not needed. The remaining columns across the page each represent one telemetry measurement, for example Col 4 has in its header the channel number (E-0004) and the channel name (CB SBAND SPDT POS1), The successive values down that column indicate whether that switch's POS1 is selected ("active") or not selected ("inactive") from which the analyst can determine which SBT has been selected at any given time within the span. See the list of abbreviations and acronyms for other terms used in the column headers of Figure 6-2.

The csv output file is time-ordered and formatted to be read into a spreadsheet template that produces a set of plots of voltages, powers, temperatures, and other values over the time span. The

text file provides a column containing the average of the data values over the query span for each channel organized for paste-in to a point-per-day spreadsheet.

SBT A Receiver/Transmitter configuration

SCET	SCLK	SESS ID	E-0004 CB SBAND SPDT POS 1	N-3001 SFP PRIME SBAND	P-3244 PWR SBT A RCVR SENSED	P-3174 PWR SBT A XMTR SENSED	E-3011 CB SBAND A TXON	E-3008 CB SBAND A COHON	E-3064 CB SBAND A CONV
2014-313T17:05:19	0468824786	2472	Active	A	ON	ON	ON	Non-Coherent	ENCODING ENABLED
2014-313T17:13:40	0468825287	2472	-	-	-	OFF	OFF	-	-
2014-313T17:14:02	0468825309	2472	-	-	-	ON	-	-	-
2014-313T17:14:04	0468825311	2472	-	-	-	-	-	Coherent	ENCODING BYPASSED
2014-313T17:14:08	0468825315	2472	-	-	-	-	ON	-	-
2014-313T17:46:14	0468827241	2472	-	-	OFF	OFF	-	-	-
2014-313T17:46:20	0468827247	2472	-	B	-	-	-	-	-
2014-313T17:46:26	0468827253	2472	Inactive	-	-	-	-	-	-
2014-313T18:00:57	0468828125	2472	-	A	-	-	-	-	-
2014-313T18:01:01	0468828129	2472	-	-	-	ON	-	-	-
2014-313T18:01:07	0468828135	2472	Active	-	ON	-	-	-	-
2014-313T18:03:21	0468828268	2472	-	-	OFF	OFF	-	-	-
2014-313T18:03:26	0468828273	2472	-	-	ON	ON	-	Non-Coherent	ENCODING ENABLED
2014-313T18:08:01	0468828548	2472	-	-	-	OFF	OFF	-	-
2014-313T18:08:11	0468828558	2472	-	-	-	ON	-	-	-
2014-313T18:08:16	0468828563	2472	-	-	-	-	-	Coherent	ENCODING BYPASSED
2014-313T18:08:21	0468828568	2472	-	-	-	-	ON	-	-

Fig. 6-2 SMAP telecom query "digitals" report PDF, first page.

Figure 6-3 shows a plot, produced by the csv file being read into an Excel template. This plot shows the temperatures in the SBT-A transmitter during a pre-launch assembly, test and launch operations (ATLO) test. The SBT was powered on about 20 min before the end of the time span shown.
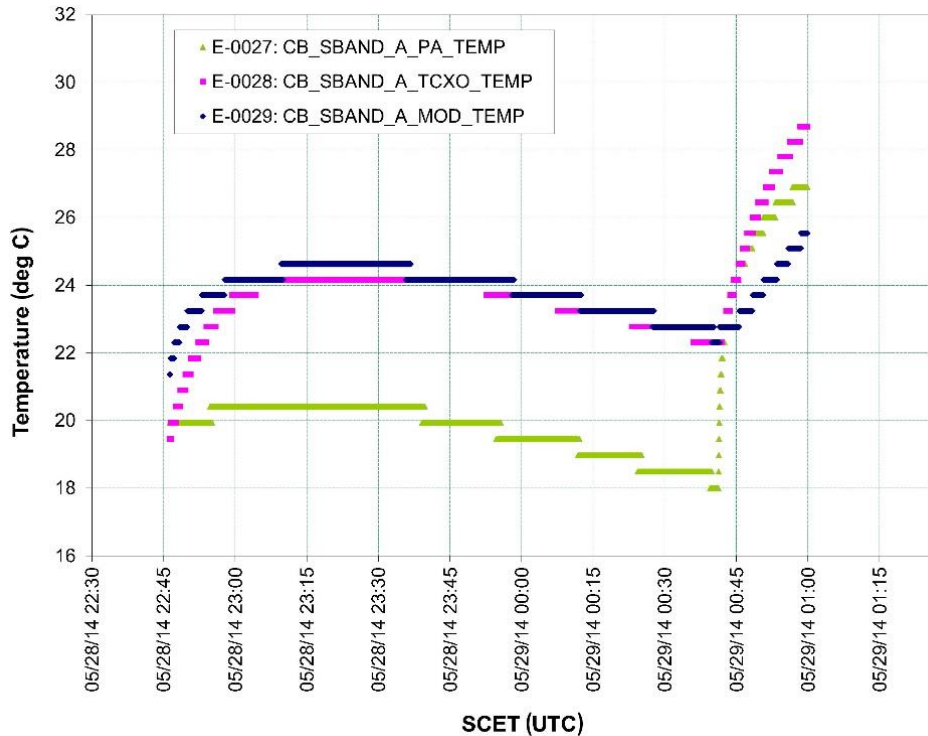
Fig. 6-3 SBT-A temperatures from pre-launch ATLO test.

6.3.3 Longer-Term Trending (Point-per-Day)

Both an Excel spreadsheet process and a dashboard tool have been implemented for SMAP telecom trending. The first, the point-per-day Excel spreadsheet, is unique to telecom, has been used from launch through commissioning, and continues into the science phase. By the end of commissioning, a more automated web-based "dashboard" system[16], SmapDash, became available for all subsystems to produce on-the-fly user-defined plots of channels of interest.

The point-per-day plot is spreadsheet-based and its use has been adapted for SMAP from the same process on the Dawn and Mars Science Laboratory deep space missions. See [Ref. 40] for Dawn and [Ref 41] for MSL telecommunications design and operations. The average value of each channel from the EHA chill_get_chanvals query represents the "point" for that day's query. A year-long point-per-day plot would have a few hundred data points and would readily show trends in the telemetry for voltages, currents, RF powers, and temperatures of the SBT and XBT.

Figure 6-4 shows a point-per-day plot of the SBT RF output, the SBT baseplate temperature, and the SBT power amplifier temperature. Temperatures are on the left hand scale, and the RF output (0.1 dB per grid marker) is on the right-hand scale.

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[16] In the SMAP analysis context, a dashboard is a particular user interface that pulls together and presents information SMAP subsystem telemetry information to the user in a way analogous to presentation of automobile operating information on the car's dashboard. The SMAP dashboard accesses large databases of subsystem telemetry data from launch to the present time, and in some cases starting before launch.
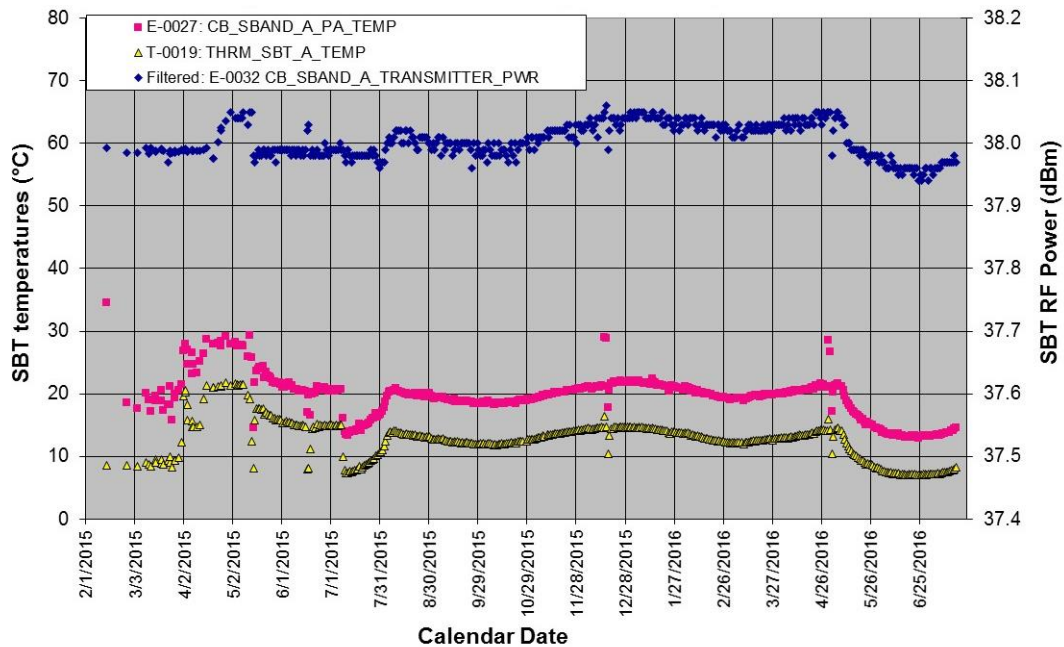
Fig. 6-4. Point-per-day of SBT RF output and temperature averages.

6.4 Sequence Review

SMAP sequences of commands are generated using the multi-mission Seqgen software, tested on a test bed (if they have not been used before), and approved for uplink transmission. SMAP subsystem and system approval is documented and audited by accessing via a web browser an uplink summary generation (Ulsgen) link. Each analyst, including telecom, receives notice when the sequence is ready for signature "signs" the uplink summary form separately. Clicking "approve" signifies review of either the command sequence products themselves or the results of running the sequence on a testbed.

6.4.1 Sequence Review

Telecom verifies a planned sequence by verifying the telecom-related spacecraft commands and the pass list. (Systems and other subsystems review other aspects of the sequence.) Almost all telecom commands have the prefix CB_. The telecom consistency check requires that:

- X-band science playback is enclosed within an interval with XBT and SSPA power-on.

- Science playback is also enclosed within the 10-deg elevation points of a NEN pass.

- S-band data playback is enclosed within the start time and end time of a comm window.

- In turn, the comm window start and end times are enclosed within the 5 deg elevation time points of a NEN pass. The 5-deg elevation at rise is defined as begin of track (BOT) and the 5-deg elevation at set is defined as end of track (EOT) times.

- Finally, to avoid an out-of-lock gap in data, the S-band playback start is delayed to the end of the NEN uplink transmitter sweep that begins at scheduled 5 deg elevation BOT.

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6.4.2 Testbed Results Review

The flight team activity lead runs the sequence on a testbed. The activity lead announces the completion of the run and provides data to the subsystems via e-mail. A subsystem analyst can review EHA and EVR data using chill_* queries similar to those used to analyze in-flight data post-pass, accessing the data by start/end time or Session number. The analyst also can review the test conductor's experiences from the Activity Report on the /trac software[17], and can review a standardized combined output of EHA data and EVRs in the Session Report (a spreadsheet file) in /trac.

Testbed sequence and command review was most intense pre-launch and for the contingency plans that were completed during commissioning. The review focused on configuration changes.

6.5 Contingency Plans (Loss of Signal)

Figure 6-4 is a top-level flow diagram for responding to the absence or degradation of the S-band downlink at the expected BOT or during a scheduled NEN or SN pass. The process is to isolate the problem to a NEN tracking station, an SN TDRS satellite, the GDS from station to MOC, or on board the spacecraft. In addition to the failure types shown, "rotisserie" mode antenna pointing must be considered in working with loss of signal (LOS). An LOS on the uplink may result in a commandability problem. A downlink LOS causes loss of telemetry data or two-way Doppler data.

In the two spacecraft safemodes (Sys_Safe_Rwa and Sys_Safe_Rcs), as well as during the intentional safemode used for a few days after launch, the antenna pointing is not 3-axis oriented. In these rotisserie modes, GNC control points the spacecraft +Y axis in the direction of the Sun line and spins the spacecraft about +Y at a rate of –0.03 deg/s, which corresponds to approximately 180 deg per orbit. The S-band antenna has a field of view (FOV) of almost 2π steradian centered at the antenna boresight, canted 30 deg off $-Z_{SC}$ toward $-Y_{SC}$. As the spacecraft rotates about the Sun line, the telecom FOV may point away from a ground station, causing scheduled passes with a NEN ground station to be missed. In rotisserie mode, it is possible that it may take as much as a full orbit before a ground station pass occurs when the telecom FOV is pointed in the correct direction.

Figure 6-5 shows at top level the process for isolating an S-band communications failure to the spacecraft, the NEN or TDRS telemetry (TLM) function, or the link between the MOC and the NEN or the TDRS space ground link terminal (SGLT). In this figure, the logic term for "exclusive or" (xor) near the bottom is used to distinguish the action taken "resume nominal" operations) if either SN or NEN is now receiving a signal from that taken (resolve an "S-band failure" on board) if neither SN nor NEN is now receiving a signal.

Figure 6-6> shows in more detail the process for re-establishing communications that have been deemed or suspected to be caused by problems on board the spacecraft. In the figure, the blocks from top-left to lower-right represent successively more significant commanded changes on-board. The term SUROM refers to the start-up read-only memory in the FSW. There is also the option of "doing nothing" and letting the command loss timer (CLT) fault protection (FP) software attempt to restore the downlink.

Figure 6-7 shows how the ground and spacecraft contingency plans can interact. Terms introduced in this figure for the SN facilities include

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[17] Trac is an open source wiki and issue tracking system for software development projects and is used on SMAP. It provides an interface to the Subversion version control and reporting system, called svn on SMAP. http://trac.edgewall.org/ and http://subversion.apache.org/ [both accessed August 2, 2016]

EBOX = EDOS box

GRTS = Guam remote tracking station

WSGT = White Sands ground terminal)

The NEN sites referenced in the figure are Wallops (WPS), Svalbard (SGS), Alaska (ASF), and McMurdo (MGS). With support from both SN and NEN, for the SMAP MOC to accomplish its activities, CMD (command), TRK (tracking data) and TLM (telemetry) flow through input-output networks (IONet) of the NISN.

The ground-commanded process for re-establishing the downlink by command must assume that the command reception capability is unimpaired. The Fig. 6-6 block numbers, such as LOS 3.1, summarize step-by-step activities in the SMAP *Loss of Signal / Telecom Contingency Plan* [42]. The CLT is reset periodically to a specified value by a particular command from the ground. The CLT then begins counting down. If the CLT reaches zero before being reset again, a fault protection (FP) monitor is tripped, in turn calling a response. The response is similar to the normal ground-to-SMAP commanding process except that it is autonomous on board and, therefore, does not require commandability through the SBT.

The response has three tiers of actions that attempt to put the spacecraft in a stable state and repair the telecom system. To give the flight team time to evaluate and respond the problem, the onboard actions of the complete command loss response are intentionally not rapid. The first tier actions safe the vehicle and attempt to swap the prime SBT; the tier also resets the command loss timer to 12 hours. The second tier resets the CDH as an attempt to clear any avionics problems associated with loss of signal; the command loss timer is again reset to 12 hours. Finally, the third tier power-on-reset (POR) resets the CDH hardware, providing a more complete reset of the system; CLT is again set to 12 hours. After the CDH POR, the tier count is reset. After that, for each repetition of the CLT expiration, the same three tiers are repeated.

Loss of Signal

Yes — Station see RF? — NEN — SN or NEN? — SN — SN SGLT see RF? — Yes — Locked on Data? — Yes

No — Locked on Data?

No — NEN TLM failure

No — SN TLM failure

No — GDS failure

Yes — GDS failure

Re-attempt on next pass

Attempt to reacquire

Resume nominal ← No (NEN xor SN) — Signal Received?

No (NEN and SN)

S-Band failure
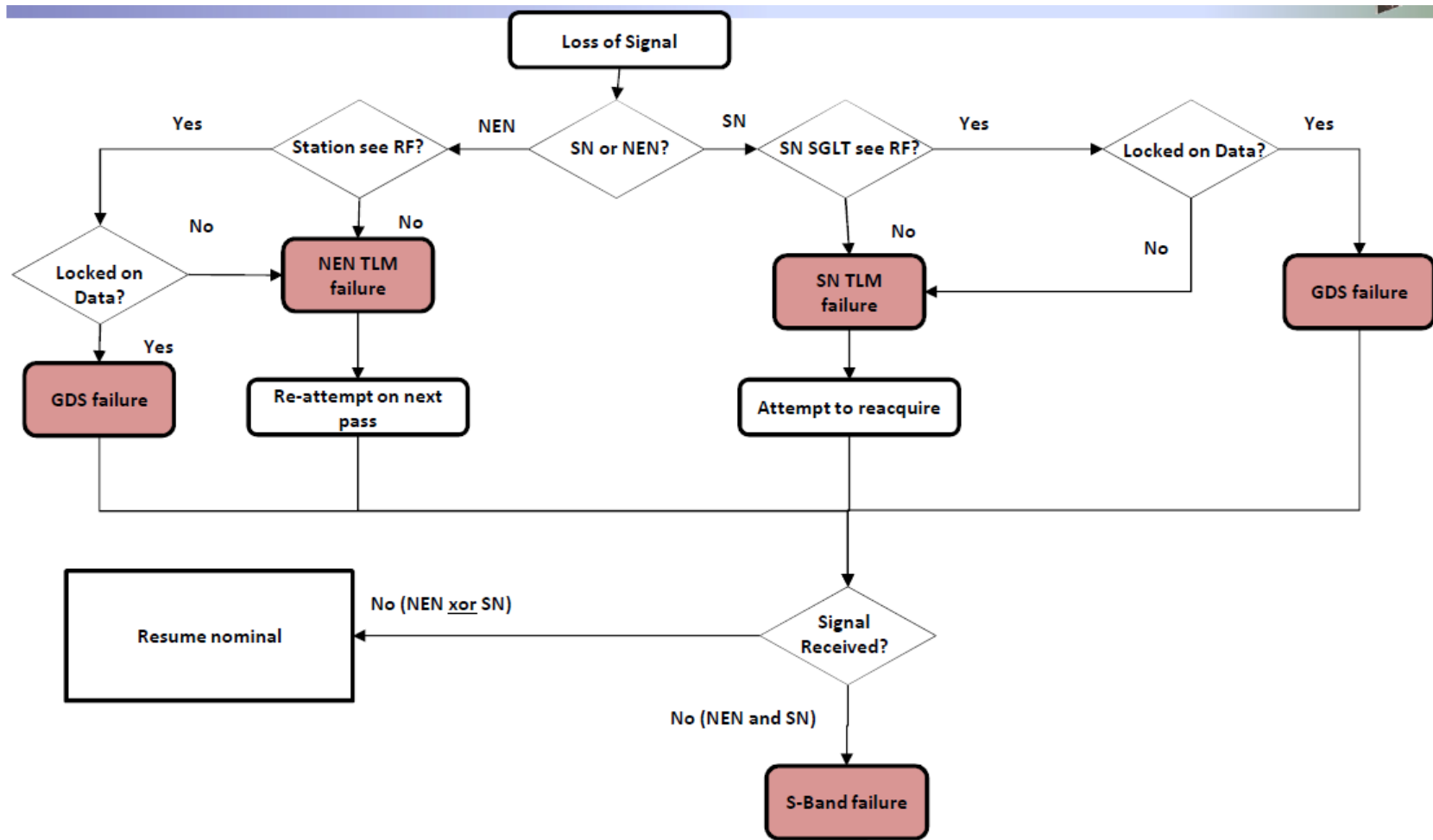
Fig. 6-5. Top level flow diagram for loss or degradation of S-band downlink.

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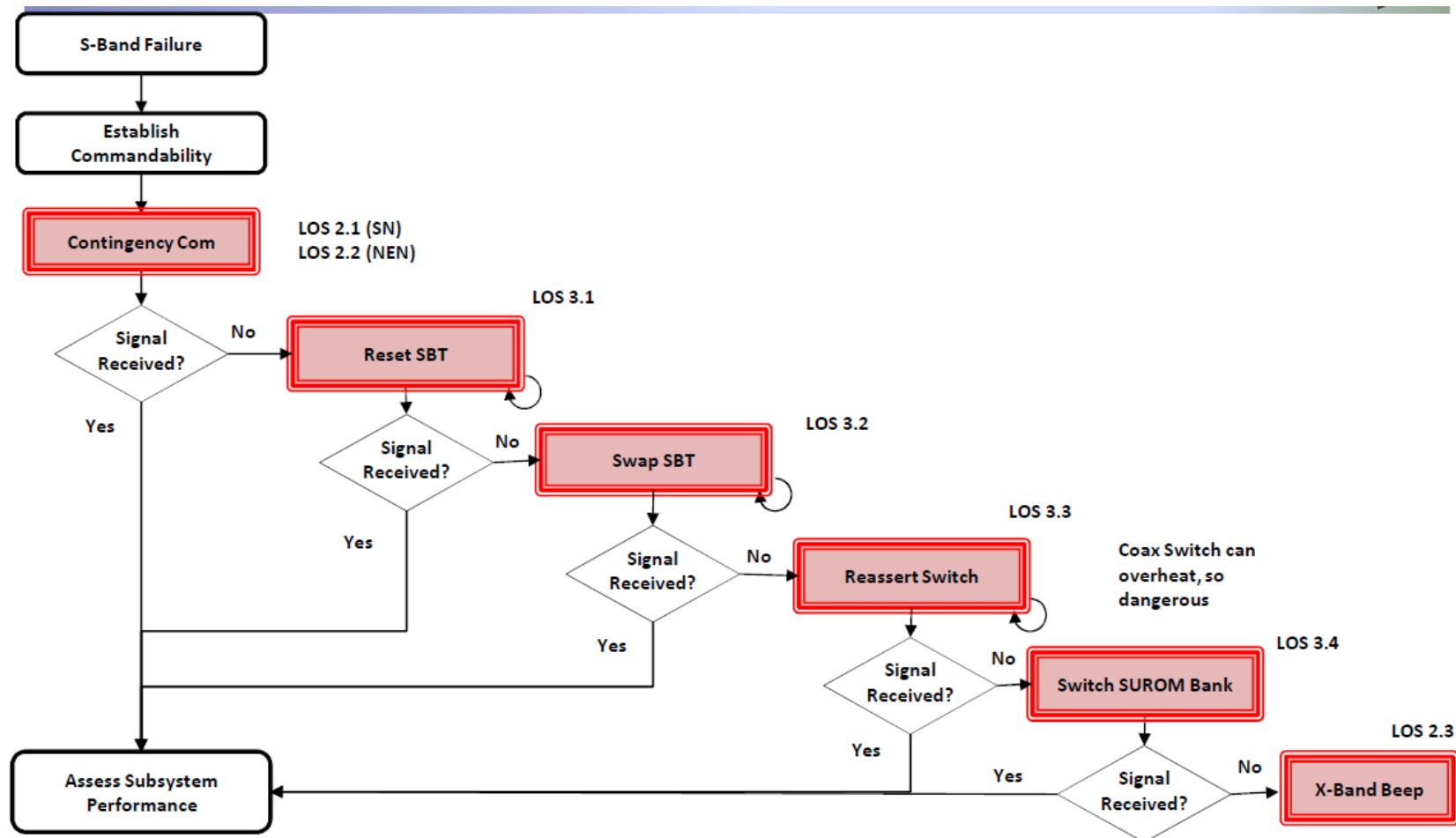
Fig. 6-6. Flow diagram for determining and correcting an onboard S-band fault.
(SUROM = start-up read-only memory)
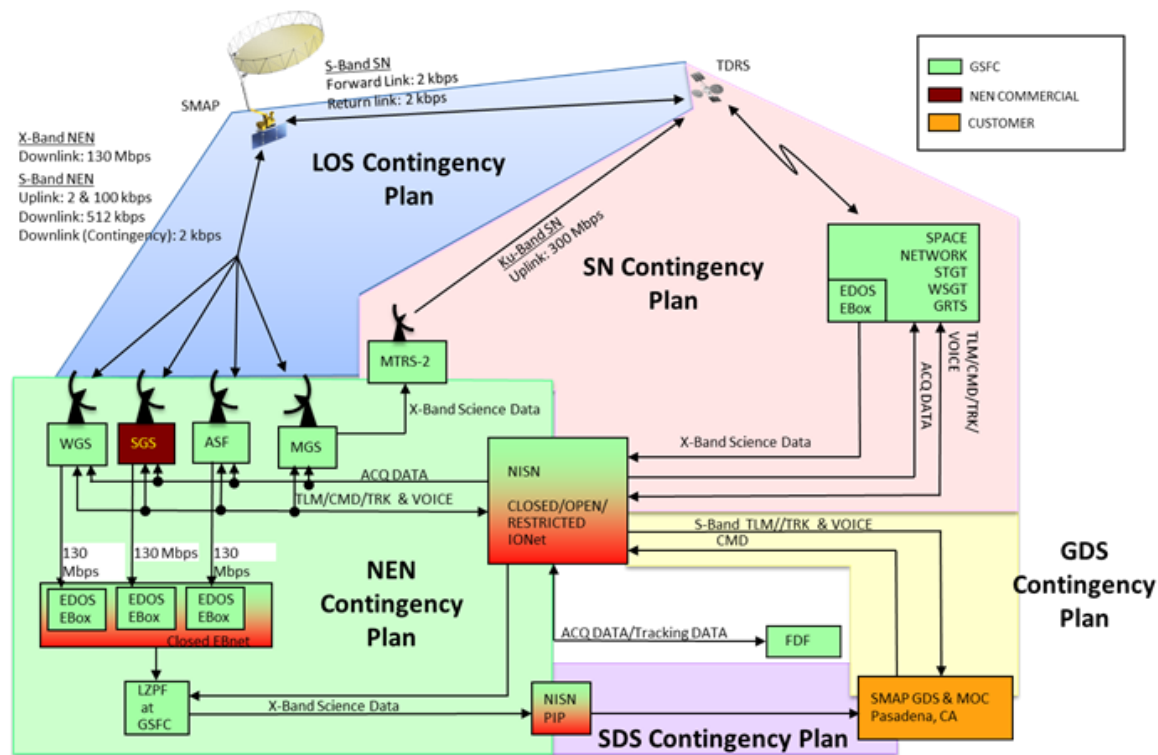
Fig. 6-7. SMAP communications links and contingency plans.

6.6 Telecom Prediction (TFP and predictMaker)

Prediction of the spacecraft links with the NEN and the SN are made with separate adaptations of the multi-mission Telecom Forecaster Predictor tool that continues in use on numerous deep space missions supported by the DSN. The NEN adaptation is most like the previous versions in that communications are modeled between the orbiting spacecraft and a network of stations on the surface of the Earth. The SN adaptation has some similarities with the Generalized Telecom Predictor (GTP) [43] used for predictions between moving rovers and orbiters around Mars. In the case of the SN, communications are at S-band only and between the SMAP spacecraft and any of several TDRS satellites. Both SMAP and each TDRS are in distinct orbits around Earth.

Both adaptations use kernel files generated by the navigation team (Nav) and GNC. The kernels are in NAIF format [44]. The Nav files are called spacecraft position kernel (SPK) and establish the position and velocity of the spacecraft. The GNC files are called CK and establish the orientation of the spacecraft. "Frame" kernels define the locations of antennas relative to the spacecraft coordinates and the ground stations with respect to the Earth. (The TDRS antenna in the SSA mode points directly toward SMAP.) Nav produces 30-day planning SPK files that characterize the SMAP orbit and 63-day planning SPK files for each TDRS. The TDRS files go out 63 days, but they are updated daily. Because SMAP is in a "frozen" orbit, there is also a planning SPK file that goes out to the end of mission, with reasonable accuracy.

The tool uses a graphical user interface (GUI) for consistency of inputs, generally with pull-down menus for individual items such as tracking station or satellite, downlink data rate and modulation index. Figure 6-8 shows the GUI for NEN predictions and Fig. 6-9 for SN predictions.

An additional GUI permits the user to define a custom spacecraft attitude, such as the safemode rotisserie. Prediction outputs may be specified as either standard or customized tabulated quantities versus time, plotted quantities, or design control tables. The TFP allows the user to rescale the value axis or the time axis and to annotate the plot outputs.

A batch mode script, predictMaker, can generate standard TFP tabulated outputs for each of several standard cases that are predefined in terms of uplink and downlink data rate pairs, S-band or X-band, NEN or SN, and attitude pointing mode (standard nadir-point or CK file). The two most used NEN cases are S-band at 64 kbps uplink and 513 kbps down and X-band at 130 Mbps downlink. The single SN standard case is 2 kbps uplink and 2 kbps downlink.

The predictMaker_nadir and predictMaker_nadir_query versions of the script requires one user input, the name of the Pass List file. The pass list is a text file in which each row defines the BOT, EOT, NEN or TDRS number, S-band or X-band, and the SMAP orbit number. The predictMaker script produces one prediction set for each row.

In addition to standard tabulated outputs, a second version predictMaker_ck (and predictMaker_ck_SN) requires the name of a CK filename as input. That version incorporates two other scripts (smapPass and sortPass) to provide an output that defines above-threshold start/end times for each planned or potential pass in time order, and lists the above-threshold duration of each pass to the nearest 30 seconds. These additional outputs are useful for on-console support to schedule additional tracks, either NEN or SN (a new pass every few tens of minutes, with a duration of the order of 10 minutes.

Fig. 6-8. SMAP TFP graphical user interface for nadir-point NEN predictions.

Fig. 6-9. SMAP TFP GUI for CK-file pointing SN predictions.

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7. In-Flight Events and Telecom Performance

7.1 SMAP Launch and Commissioning Phase Activities

7.1.1 Launch, Injection and Initial Orbits

SMAP was launched on January 31, 2015 at the third launch opportunity. The lift-off occurred at 14:22 UTC (06:22 PST), about a minute into the 3-minute launch window. The delay was to allow time to process final weather-balloon data.

The spacecraft was injected as expected at 15:19 UTC. The post-injection video in conjunction with the onboard telemetry indicated a successful solar array deployment.

Initial downlink acquisition occurred immediately after separation at 15:19 UTC. SN-TDR275 (aka TDZ) reported solid acquisition on SBT-A with listen only mode. TDS (TDRSS Spare) also reported a successful signal acquisition 12 minutes after the initial acquisition.

The spacecraft went through detumble and Sun search smoothly. The rotisserie attitude was established shortly after the Sun acquisition at about 15:32 UTC.

Two orbits after separation, the NEN stations were experiencing about 4 seconds of timing offset relative to predicted station pointing. JPL Navigation confirmed this and informed the Flight Dynamics Facility (FDF) to generate an improved inter-range vector (IIRV) for updating the station antenna predicts. The initial orbit size was 651 by 687 km, with a period of 98 minutes, and 98.2 deg inclination.

7.1.2 Orbit Control

On February 3, 2015 (Mission Day 4) after the stellar reference unit (SRU, star tracker) was read out, SMAP was commanded into the RCS nadir-down attitude.

On March 5, the first calibration maneuver with a 1.3-m/s burn duration, was successful. The objective of this periapse-raise maneuver (69-s burn time centered at apoapsis) was to increase the periapsis altitude by 5 km and to add 3 seconds to the orbital period. Near real-time navigation Doppler residuals showed a post-burn orbit of about 654 by 691 km.

On March 11, the first inclination maneuver was performed. The objective of the burn was to adjust the local mean solar time (LMST) trending to a favorable direction and rate such that even after many years SMAP would still not require another inclination maneuver to meet the science LMST requirement of 6 a.m./p.m. ± 5 minutes.

On March 16, SMAP established its science orbit by successfully executing its two largest in-plane maneuvers, INP1a (4.7 m/s with a burn near the South Pole and INP1b (1.1 m/s with a burn near the North Pole). These executions also eliminated the need to perform a Conjunction Assessment Risk Analysis (CARA) maneuver the following day[18]. Given the precise executions of these maneuvers, SMAP met the science orbit requirements of 6:00 p.m. ± 5 min (ascending node) Sun synchronous and polar frozen orbit with a repeat-ground-track pattern. Post-burn orbit was 671 × 688 km, with the ascending node at 6:02 p.m. LMST, a 5900.5-s orbital period and a 98.1-deg inclination. Once a reference trajectory defining the 8-day-repeat cycle was released in late March,

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[18] Through September 2016, no CARA debris avoidance maneuvers have been required [45].

orbit trim maneuvers (OTMs) to maintain the science orbit requirements began, with the first one on April 14, 2015.

On March 23, the reference orbit characteristics were defined as follows, based on a reference trajectory delivered on March 19. The design location, "0" ground-track error, was defined at 20:13 UTC on April 15. The average equatorial geodetic altitude is 685 km with a 674 by 691 km mean orbit size. Four eclipse seasons (obscured by the Earth) will occur during the 3-year primary phase, with an average maximum Earth shadow of about 19 minutes. The first eclipse season was expected to start on May 10, 2015 and the first shadowing actually was observed May 6. The deepest eclipse occurred on a few hours after the summer solstice on June 21, with almost 20 minutes that the Sun sensors did not see the Sun. Eclipses also ended gradually. They were 5 minutes long on August 3, but by August 6, there was only lingering effects of atmospheric eclipse seen in Sun sensor data.

Figures 7-1 through 7-4 define the ground track pattern, the solar eclipse seasons, and the pattern of local mean and local true solar times for the "frozen orbit that has been achieved. All three figures are for the planned 3-year science mission that began in May 2015.
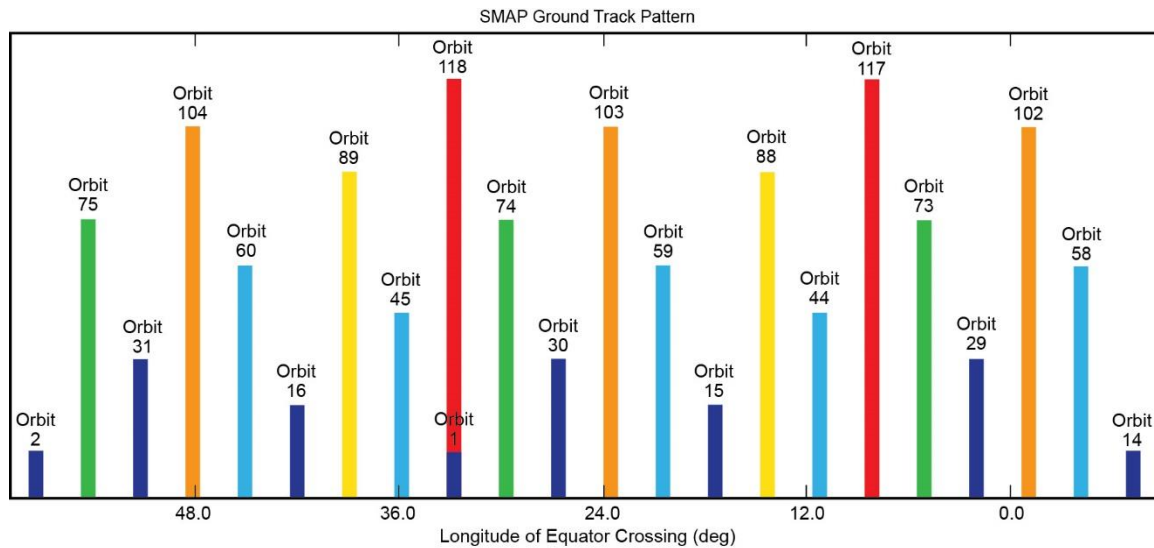
Fig. 7-1. SMAP repetition of ground tracks.
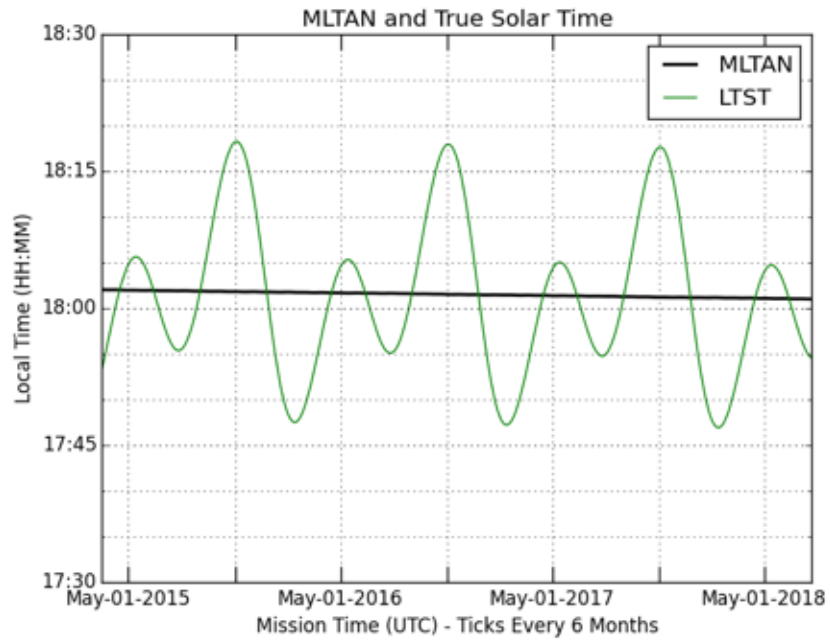
Fig. 7-2. Mean local time of ascending node (MLTAN) and local true solar time (LTST).
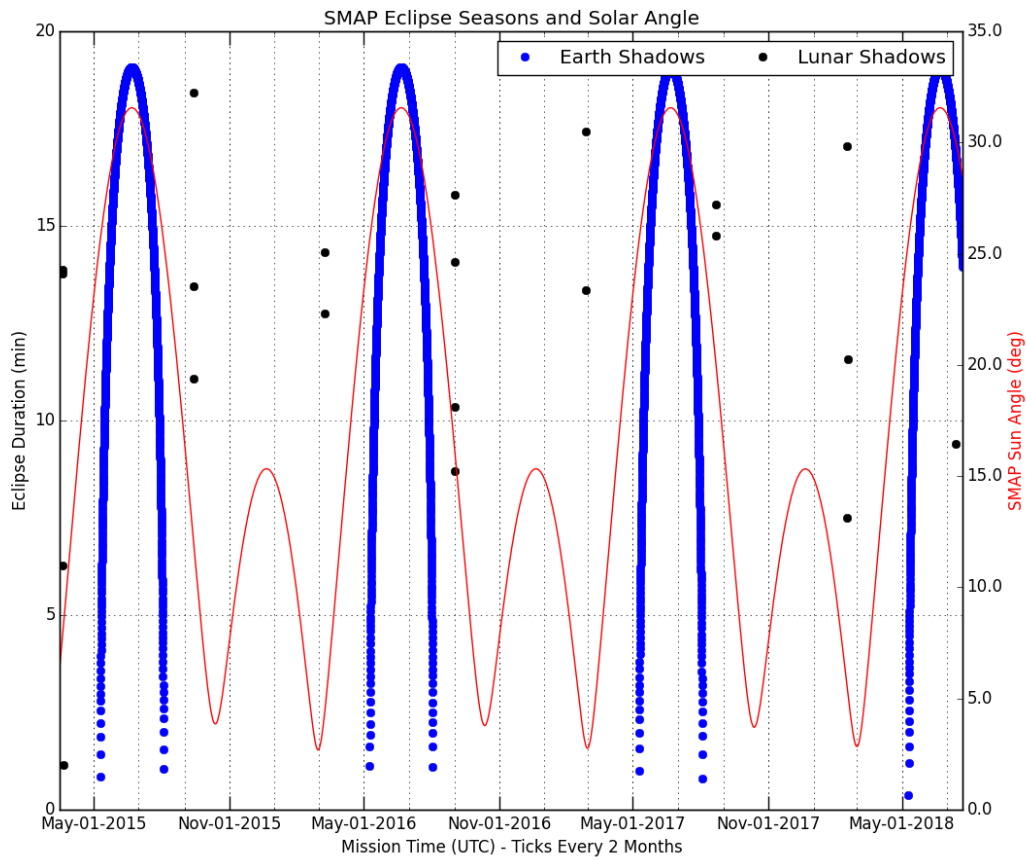
Fig. 7-3. Earth and lunar shadow eclipse seasons.

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On April 14, the first Orbit Trim Maneuver (OTM-1) was completed with a magnitude of about 21 cm/s. The main objective of this burn was to maintain the 20-km ground track requirement with respect to the science reference trajectory. The maneuver execution was centered at the perigee. OTM-1 was the first maneuver in the 14.6-rpm spin configuration. It served as a calibration maneuver to improve execution accuracy for subsequent OTMs. OTM-2, -3, and -4 occurred on July 30, 2015, January 7, 2016 and May 25, 2016, respectively [45].

7.1.3 Safemode

(1) On February 6, 2015, SMAP entered safemode due to an SRU anomaly. The spacecraft's fault protection achieved a stable GNC mode called Sun-Point-RWA, using the reaction wheel assembly. Safemode, also used at launch, configured the S-band mode for 2 kbps uplink and downlink to work with both the SN and the NEN. The spacecraft went to rotisserie mode using Sun orientation only. In this mode, the S-band antenna points favorably to NEN stations about half of each orbit and unfavorably in between. The first detection of this anomaly came from the Wallops operations center. WSC instructed McMurdo to initiate the contingency response plan. MG1 immediately switched to a configuration compatible with the 2-kbps up/down telecom configuration, which also initiated the project's autonomous notification/response system. Depending on their driving distances and circumstances, all "first responders" (key subsystems on the Flight Operations Team (FOT), a flight director and a mission manager) were able to call in or report to the MOC at JPL in about 30 minutes. Those calling in viewed telemetry data remotely and were patched into the voice net.
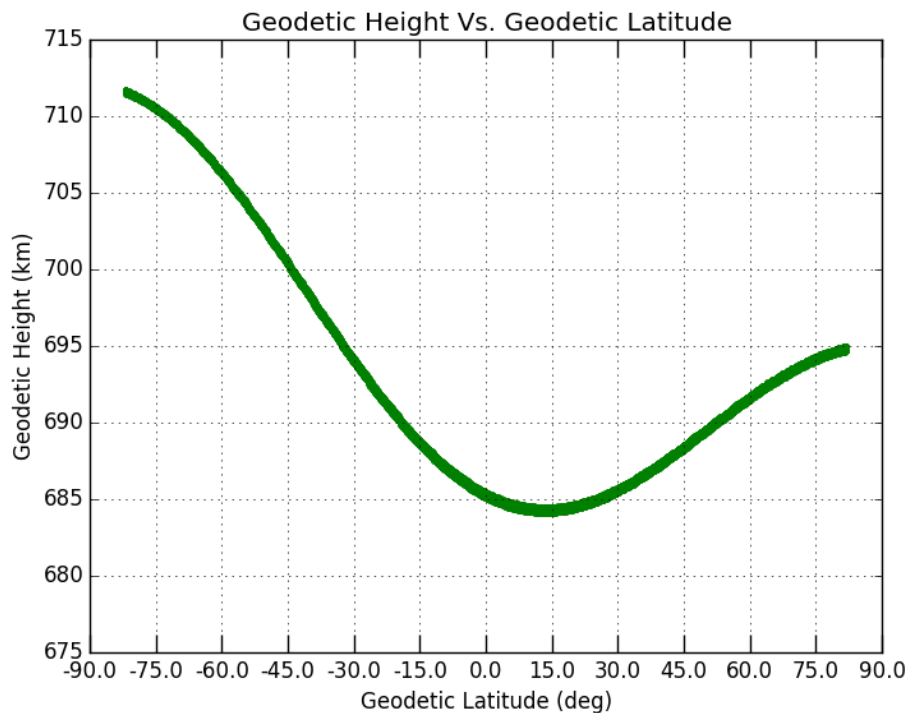
Fig. 7-4. Geodetic height versus geodetic latitude for science orbit.

At the time the anomaly occurred, the command loss timer time-out was 70 hours. This gave the FOT time to develop and test a recovery plan over the weekend. On Monday February 9, SMAP exited safemode and re-established the nadir attitude, with normal 64 kbps up/513 kbps down to NEN. The root cause for entering safemode had not been fully determined by the time recovery

from it was accomplished. Based on evidence from telemetry at the time of safing, the suspected cause was an SRU fault induced by radiation as SMAP passed over the South Atlantic Anomaly (SAA). Recovery files have been reviewed and tested on the ground to keep on hand through the science mission for the more likely SRU faults as well as for some other subsystem faults.

(2) On February 19, SMAP was determined to have gone into safemode around 4:46 PST. The next scheduled NEN station at Svalbard detected the loss of signal (LOS) at 5:45 PST. The delay between safemode and its detection was due to a tracking gap prior to the pass start. The LOS triggered the contingency response actions. The FOT was on console shortly after the automated alarm notification system went off. This time safemode was due to an inertial reference unit (IRU) "monitor reply timeout" trip. Recovery was performed according to the contingency plan.

(3) On May 12, which was early in the science mission phase, SMAP went into safemode. GNC verified the safing was due to an SRU reset that tripped the fault system FP and most likely was induced by a single event upset) event in a region of galactic cosmic rays near the South Pole. The observatory was returned to routine science operations about 2-1/2 days later, on May 14. This was the first safe-mode recovery accomplished by a much smaller FOT. They made heavy use of the mature contingency response plan and safe-mode recovery procedures. Further improvements in safemode recovery efficiency and robustness may be made through the mission, but verification of such improvements would require more onboard safemode "opportunities". Onboard executions are required because the testbed lacks sufficient fidelity to confirm the SRU update sequences integral to recovery.

7.1.4 Space Weather

On March 17, GNC observed a small trend of the onboard spacecraft-Y momentum (atmospheric drag direction) starting around midnight the previous day. Navigation independently reported an increase of more than 50% in their estimates of atmospheric drag effects starting at about the same time. The spaceweather.com[19] site also had issued a warning of a severe solar storm hitting the Earth earlier in the day [46]. Once the situation was assessed, no concerns remained regarding the spacecraft health.

On March 20, the FOT updated the SAA polygon based on a combination of flight data trendings and a SMAP specific study performed by JPL Natural Space Environments Group. The size of the polygon as of March 20, 2015 was slightly larger and had moved 8 deg northward relative to its size and position at launch. Figure 7-5 shows these changes.

The onboard Activity Master was updated to incorporate these changes to reduce the likelihood of future single event upsets.

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[19] The site http://www.spaceweather.com/ is the NASA space weather bureau, providing information and news about natural processes in space that can affect satellites, including solar flares and the resulting geomagnetic storms. On March 17, 2015, the site reported the strongest geomagnetic storm of the solar cycle that began in 2008 was underway. The ongoing storm began with the arrival of a coronal mass ejection (CME) at 0430 UTC. In a matter of hours a severe G4-class storm was underway.

Note, per the NOAA space weather prediction center site (http://www.swpc.noaa.gov/noaa-scales-explanation), the geomagnetic storm scales have a range of G1 (minor) through G5 (extreme). A G4 storm is severe. The definition of G4 includes "Spacecraft operations may experience surface charging and tracking problems, and corrections may be needed for orientation problems." (both sites accessed August 2, 2016)
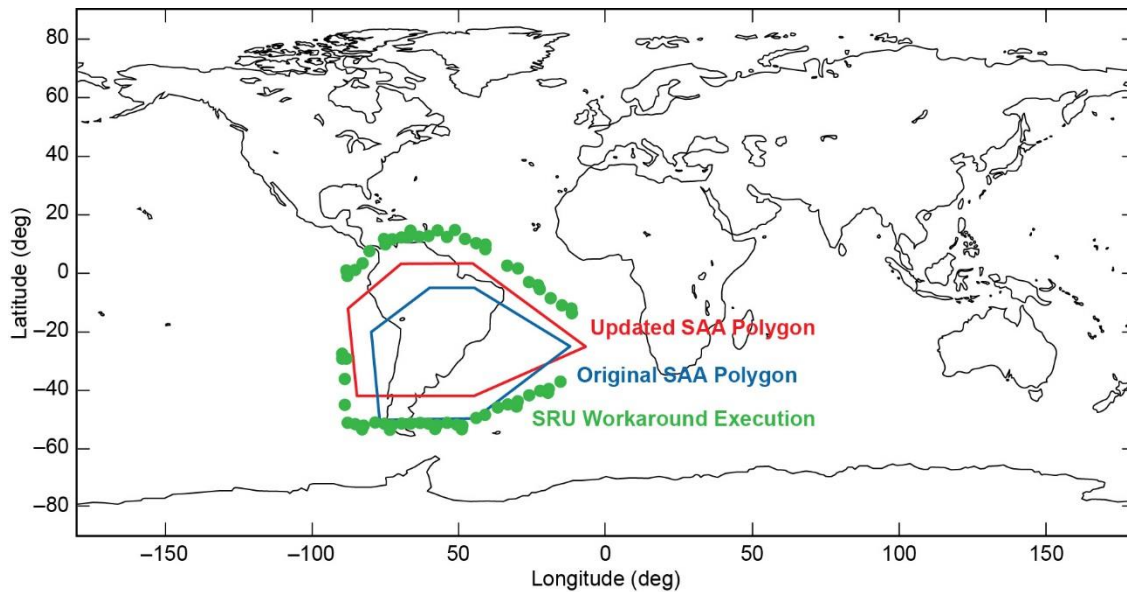
Fig. 7-5. South Atlantic anomaly (SMAP single-event upsets).

7.1.5 Eclipse Season

On May 3, the 3-year-long science mission phase began.

On May 6, the GNC analyst noted that the first eclipse season had begun. Sun sensor telemetry data showed the first clear indication that the Earth's atmosphere had begun to diminish the sunlight reaching the sensors. The first signs of the eclipses began when the center of the Sun was ~1.3 degrees from the Earth's horizon. Because the Sun is about 0.5 deg in diameter, this meant that the lower limb of the Sun was still about 1 degree above the horizon when the atmospheric effect first became visible. Full occultations began several days later.

7.2 Activities Supported by S-band and X-band Communications

The S-band link initially provided a return link for initial acquisition and launch data playback through the SN and NEN. Then both forward and return S-band links were configured by a background sequence. The X-band link provided a return link to the NEN to check out instrument configuration and downlink (return link) data flow.

On January 31, 2015, launch-day, the S-band support during post launch events was via links with both SN and NEN. On launch day, the performance of the S-band 2-kbps uplink (aka forward link) and 2-kbps downlink (aka return link) with SN was verified. Also achieved on the same day were a 64-kbps uplink command verification test from the NEN and an initial 513-kbps downlink performance assessment test with the NEN.

On February 1, during several NEN passes SMAP transmitted all of the onboard recorded data files, and they were received on the ground. This was a challenge given the difficulty of managing the station lockup uncertainty caused by spacecraft orientation uncertainties, including phasing of the rotisserie mode plus deadbanding. To mitigate these uncertainties, a retransmission sequence was used to improve the data downlink robustness.

On February 3, the first background sequence went active. The background sequence autonomously manages and executes the telecommunication configurations for ground contacts. After that first one, weekly background sequences created by use of a script, reviewed on Fridays, sent up on the weekend, and going active on Mondays became the norm.

The same day, JPL navigation assumed the responsibility of generating and delivering IIRV for NEN and SN antenna pointing predicts.

7.2.1 Boom Deployment

On February 18, SMAP successfully conducted the boom deployment activities. Out of 500 plus cases that the deployment team had tested and drilled over the preceding months, the flight deployment was the smoothest one. Everything worked as scripted, without a single glitch.

Preparation the day before included the FOT sending commands from the MOC and monitoring activities that oriented the solar array normal to the Sun, confirming the integrated control electronics (ICE) baseline and controller parameters had been modified as planned, and ensuring fault protection state and thresholds were in place. The preparation also optimized the deployment temperature environment and activated a momentum bias sequence.

Post-deployment clean-up activities included momentum bias removal, background sequence re-activation, and enabling of the bake-out heaters. After deployment, the telecom subsystem was on background sequence control, in receive only mode between scheduled NEN passes, but with the onboard communications behavior producing 64 kbps uplink / 512 kbps downlink windows synchronized with the passes.

7.2.2 Antenna Deployment

On February 24, as a critical flight team activity, the 20-foot (6-m) reflector deployed with no problems. Telecom expected the effective LGAS and LGAX antenna patterns to be somewhat different from their pre-deploy state, and potentially some multipath effects. Telecom did note some transient signatures in the coherent signal power and downlink signal power during deployment activities, but these never became an issue during subsequent operations, before or after spin-up.

On March 3, Reflector initial detensioning activities were completed. The objective was to retain adequate tension for the cone/clutch assembly (CCA) engagement activity later in March. After the final tension adjustment, the reflector team estimated the deploy cable tension to be ideal for this activity.

On March 20, final boom and reflector detensioning activities were completed. This marked the completion of the instrument-deploy operation.

7.2.3 Spin-up (Low-Rate and High-Rate)

On March 23, the low-rate spin-up was completed. The spacecraft was configured for 2 kbps up and downlink rates at S-band, suitable for NEN or SN support. SMAP took 63 seconds to spin-up to 5 RPM, close to the previous tested mean value.

On March 26, the high-rate spin was completed. As had been done 3 days previously for the low-rate spin-up, the contingency comm. mode (2 kbps up and 2 kbps down) was configured on board, then the high-rate spin sequence was initiated. It took about 80 minutes to slowly spin-up the observatory from 5 rpm to 14.6 rpm. This was to minimize dynamic disturbances of the spin mechanism and the GNC control system.

The spin-up activities did not cause any noticeable changes in the S-band and X-band uplink or downlink performance.

7.2.4 Commanding Process Enhancements after Launch

On March 1, the flight teams demonstrated an end-to-end "AUTO" capability using "no-op" and "Command Lost Timer (CLT)" commands. The "AUTO" process includes automatic product/sequence generations, verification and validation, uplink, and execution for routine activities [15]. The tested "AUTO" process also successfully shadowed ephemeris and data product management activities. In shadowing efforts, the end products are manually reviewed for a command approval meeting (CAM), radiated, and executed. This capability was intended to help SAMP to perform the science phase of the mission with a reduced workforce.

On March 31, "AUTO" successfully performed command loss timer (CLT) and data management activities. It automatically generated uplink products, performed verification, checked the validity of the command window start time and duration, and uplinked and executed the sequences.

On April 15, SMAP successfully conducted the Backup Mission Operations Center (BMOC) live test. Two commands, a no_op and a command loss timer reset, were executed via the BMOC located at GSFC's EDOS facility [32]. In case of catastrophic events occurring at JPL, the BMOC can be activated remotely to monitor spacecraft health and maintain basic flight operation activities.

7.3 X-Band Test Purpose and Plan

The purpose of these tests was to verify that the major events of deployment of the 6m reflector and the spin-up did not result in significant changes to the X-band link performance. The tests basically consisted of downlinking a standard set of stored science data (created in ATLO prior to launch) before the deployment, after the deployment, and after the spin-up. The downlinks for each test occurred over a series of scheduled NEN passes, each test taking most of a day.

7.3.1 Results Prior to Reflector Deployment

Initial Instrument Operation and Data Processing

On February 12–13, the flight teams, including the radiometer team at GSFC, conducted a 2-day instrument checkout, with both the synthetic aperture radar (SAR) and the radiometer (RAD) being powered on and then powered off. The science data team also received the Level 0A data and produced Level 0B data[20] [47]. They determined the robustness and completeness of the Level 0 data and went through their processing of it within a week of the test.

On February 27, the SMAP radiometer was powered on, and about 50 minutes later the SAR was powered on in the transmit mode. (The SAR had been powered in the receive-only mode the previous day.) Telemetry showed healthy performance. The X-band data looked excellent. Returned data showed significant changes in radiometer counts as it transitioned from land to water and vice versa. The transmit-related radar telemetry also looked excellent with SAR echo power levels reacting as predicted to ocean and land transitions. Preliminary analysis of the observed return pulse envelope appeared to be an excellent match to the predicted pulse envelope as derived from the beam pattern expected of a fully deployed and functional reflector.

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[20] The Earth Observing System Data and Information System (EOSDIS) is a major core capability within NASA's Earth Science Data Systems Program. EOSDIS data products are processed at various levels ranging from Level 0 to Level 4. Level 0 products are raw data (reconstructed but unprocessed instrument and payload data at full instrument resolution.) Level 0 data has communications artifacts (e.g., synchronization frames, communications headers, or duplicate data) removed. At higher levels, the data sets are converted into more useful parameters and formats. See [Ref. 47] for brief descriptions of Level 1 through Level 4, representing successively more refined data products. All EOS instruments must have Level 1 products. Most have products at Levels 2 and 3, and many have products at Level 4.

X-Band Testing.

On February 11, 2015, the first X-band checkout was completed over five NEN stations (AS3, SG1, WPS, MG1, and TR2). A small number of frame drops occurred on some of the stations. Telecom started a spreadsheet to compile the number of Reed-Solomon frame errors and total frame numbers in virtual channel 1 (VC-1) data[21] [T], from sequenced data sessions conducted during the nadir-down normal spacecraft attitude.

On February 25, an X-band retransmission sequence was activated to downlink SAR/RAD data during the first X-band session at TR2. The retransmitted data from ATLO testing had been stored on board prior to launch. Preliminary results indicated 99.998% data completeness.

On February 27–28, a total of 31 NEN X-band passes were sequenced during the 2-day non-spin test. Post-test statistics verified that all science data was transferred to JPL via EDOS from each station within 30 minutes after scheduled LOS of the pass. The average latency was 16.8 minutes, which is a significant leap forward comparing with the previous checkout experience (the mean latency requirement is 60 minutes). The average per-pass data volume was ~50% more than the previous checkout activities. In terms of data completeness, the total data loss was about 0.27%. This is a more than 10-fold improvement over the previous test.

7.3.2 Results after Reflector Deployment

Initial Science Checkout

On March 31, 2015, 2 months into the 3 months of commissioning, the spacecraft went into "Science Mode" and began producing observatory/science checkout data. The first activity was to perform timing tests to evaluate the instrument interfaces.

Science Calibrations

By April 14, the Instrument Operation Team (IOT) successfully completed RAD/SAR timing and Radio Frequency Interference (RFI) survey tests over a 12-day period. The overall instrument pointing and LUT (look up table) control looked excellent. The activity included implementing a small onboard nadir pointing bias, about 75 millidegrees. The needed bias was estimated by the GNC dynamic & control (D&C) function, using the data collected from the timing test. Subsequent verification of the nadir bias was based on the SAR echo telemetry.

During a 9-day RFI survey, the IOT executed 48-, 12-, and 5-frequency sequences as planned. The survey collected abundant receive-only frequency data for all likely transmit frequencies. The database allows the optimization of SAR frequency selection for the science mission phase.

7.4 Telecom Display and Reporting Tools in the SMAP MOC

During the commissioning phase, operations were largely conducted in real time in the MOC. Coordination and reporting were "on the net" using the voice operational communications

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[21] SMAP and other spacecraft define virtual channels (VC) for data storage on board and transmission to the ground. From [T], virtual channels are a feature of all CCSDS Space Data Link Protocols. The Virtual Channel concept allows one Physical Channel (a stream of bits transferred over a space link in a single direction) to be shared among multiple higher-layer data streams, each of which may have different service requirements. A single physical channel may therefore be divided into several separate logical data channels, each known as a virtual channel. Each transfer frame transferred over a physical channel belongs to one of the virtual channels of the physical channel. Often V0 refers to real time data, while higher VC numbers refer to recorded engineering data and science data from different downlink frequencies and within that, from different instruments or different activity types.

assembly (VOCA)[22], with team members following a timeline display (named "Timely") on the workstation, and monitoring data from perspectives also displayed on the workstation.

Telecom MOC operations primarily rely on standard displays of telemetry channel tabulations in numeric form and a set of plots of key quantities versus time. Initially these were produced as AMPCS perspectives [35,36] that had been developed during pre-launch operations readiness tests (ORTs). As commissioning continued, telecom began to rely more on similar tabulated and plot displays developed in SmapDash from the AMPCS perspectives.

Figure 7-6 shows the tabulation, and Fig. 7-7 shows the plots during a calibration activity late in commissioning, both from SmapDash. Figure 7-8 is a page from the shift log that documents MOC activities. The shift log includes systems and subsystems sections. The reports are searchable by activity (example: DEPLOY1, or SAFEMODE), by mission phase or by user-chosen keywords.

7.5 Link Performance: Predicted and Achieved

The onboard telecom system, the SN, and the NEN have provided excellent communications, in most respects as predicted and with little data loss. In several cases, anomalous performance was resolved by the NEN altering internal station configurations or optimizing software-controlled parameters such as receiver bandwidths for SMAP communications.

7.5.1 S-band and X-band Communications with the SN and NEN

The next section describes the normal operations. The section following that describes the results of mismatched uplink polarization exacerbated by multipath at the spacecraft.

Three of the NEN sites (Alaska, McMurdo, and Wallops) provide monitor data that can be used to compare the actual downlink performance during a pass with what has been predicted by TFP. The remaining NEN sites (Svalbard and Trollsat) and the SN do not provide monitor data, though they have provided verbal reports of downlink bit-energy-to-noise spectral-density ratio (E_b/N_0, commonly pronounced ebb'no on the voice nets) during critical passes. Spacecraft telemetry includes two forms of SBT received signal levels that can be monitored in real time or queried after the fact and compared with predictions. These telemetry values apply to uplinks from any NEN station or TDRS satellite.

Generally, the downlink signal received at a NEN station is many decibels (dB) above threshold. The received signal level has units of decibels referenced to one watt (dBW), and the E_b/N_0 has units of decibels. Both quantities are saturated (meaning that a 1-dB change in received signal level displays as less than a 1-dB change in reported signal level) and therefore are 10 or more dB lower than would be indicated by the predictions. For this reason, detailed analysis of actual and predicted signal levels is not emphasized on SMAP as it is with deep space links that have much smaller margins.

Because there are routinely numerous NEN passes per day and no SN passes, telecom assessment initially was on a spot-check basis for a few representative passes per day. By the end of commissioning, the query tool for NEN data had been made more capable and its use more automated. Predicts came from predictMaker_nadir_query using a passlist input file. The following describes the capabilities at the end of commissioning.

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[22] The VOCA system appears to the analyst on console as a wireless or wired headset connected to a control unit. The control unit provides buttons to select various groups of functional positions for talk/listen, listen only or not selected. It also provides, via a menu system on the control unit, the ability to control the volume, use a speaker for listening, and other functions for each of the selected nets, as well as receive and make telephone calls.

For NEN passes, the actual data is queried using a Python script (one for spacecraft telemetry and one for NEN monitor data) and was initially processed (analyzed) using Excel templates that could display predictions and the actual data on the same axes. Figure 7-9 shows a plot of predicted quantities output from TFP, this one of predicted P_t/N_0 for one SMAP pass with the TDRS7 satellite, the return link from SMAP (labeled "DL") at the top and the forward link to SMAP ("UL") at the bottom. The computer-generated title above each of the two plots identifies the station (in this case SNTDR7 refers to the SN, TDRS 7) and the spacecraft ID (SCID, in this case 205 is the identifier for SMAP in the NAIF trajectory files.). Thresholds for the 2-kbps downlink and uplink data rates appear in the figure as horizontal lines labeled 2000 BPS.

Figure 7-10 shows an Excel plot of the predicted and actual monitor data quantities for one pass over Alaska (station AS3), with the smooth curve at the top being the predicted LGAX offpoint angle from the station, the middle curve the predicted 130-Mbps E_b/N_0, peaking near 20 dB, and the bottom curve the actual E_b/N_0, peaking near 10 dB.

File Edit View History Bookmarks Tools Help

SmapDash Telecom Perspective

https://smapweb.jpl.nasa.gov/smapdash/#tool=persp   Google

SMAP Dash

| OPS | SCET | 2015-064T00:00:00 | Mar 05 | Testbit | 0 |

Telecom   Main NEN

Mar 05 2015-064T23:59:59

MOC Side A FULL (latest)

ID	Title	Value	SCET
TELE FULL (latest)			
E-0051	CB_STATE	ACTIVE_WINDOW	2015-064T18:10:20.221
SBT-A			
E-0004	CB_SBAND_SPDT_POS_1	Active	2015-064T18:09:52.221
E-3004	CB_SBAND_A_CARLOCK	Locked	2015-064T18:10:20.221
E-3006	CB_SBAND_A_SUBCARLOCK	Unlocked	2015-064T18:10:20.221
E-3007	CB_SBAND_A_DETLOCK	Locked	2015-064T18:10:20.221
E-3008	CB_SBAND_A_COHON	Coherent	2015-064T18:09:52.221
E-0033	CB_SBAND_A_RECEIVE_DATA_RATE	64kbps	2015-064T18:10:20.221
E-0022	CB_SBAND_A_IF_SIG_PWR	-80.3422893048338	2015-064T18:10:20.221
E-0023	CB_SBAND_A_COH_SIG_PWR	41	2015-064T18:10:20.221
E-0025	CB_SBAND_A_FREQ_OFFSET	-38124.710073821996	2015-064T18:10:08.221
E-0030	CB_SBAND_A_RECEIVER_7V	6.9156002998352	2015-064T18:09:52.221
E-0031	CB_SBAND_A_TRANSMITTER_9V	10.4160003662109	2015-064T18:09:52.221
E-0032	CB_SBAND_A_TRANSMITTER_PWR	37.9933090209961	2015-064T18:09:52.221
E-3011	CB_SBAND_A_TXON	ON	2015-064T18:09:52.221
D-1610	DMD_DWN_MODE_RATE	RS_512K	2015-064T18:09:52.221
E-0034	CB_SBAND_A_XMIT_DATA_RATE	589.3kbps	2015-064T18:09:52.221
E-0063	CB_SBAND_A_CMD_COUNTER	9802	2015-064T18:09:52.221
E-0065	CB_SBAND_A_EVENT_COUNTER	43629	2015-064T18:09:52.221
E-3002	CB_SBAND_A_EEPROM_ERROR	No Error Detected	2015-064T18:07:46.221
XBT-A			
E-0006	CB_XBAND_SPDT_POS_1	Active	2015-064T18:09:52.221
N-3000	SFP_PRIME_XBAND	A	2015-064T18:10:20.221
P-3238	PWR_XBT_A_SENSED	OFF	2015-064T18:09:52.221
E-3048	CB_XBAND_A_SSPA	OFF	2015-064T18:09:52.221
E-0014	CB_XBAND_A_RF_POWER	32.8186378479004	2015-064T18:09:52.221
E-0020	CB_XBAND_A_10V	0.0092285303399	2015-064T18:09:52.221
E-0010	CB_XBAND_A_EVENT_CNT	7	2015-064T18:09:52.221
Side A temps			
T-0019	THRM_SBT_A_TEMP	10.6891860961914	2015-064T18:09:52.221
E-0028	CB_SBAND_A_TCXO_TEMP	25.082518166267	2015-064T18:09:52.221
E-0027	CB_SBAND_A_PA_TEMP	23.700951460352	2015-064T18:09:52.221
T-0015	THRM_SLGA_TEMP	-9.4453067779541	2015-064T18:09:52.221
T-0017	THRM_XBT_A_TEMP	5.2113652229309	2015-064T18:09:52.221
E-0000	CB_XBAND_A_OCS_TEMP	10.6188468412501	2015-064T18:10:20.221
E-0002	CB_XBAND_A_AMP_TEMP	8.599574916167	2015-064T18:10:20.221
T-0016	THRM_XLGA_TEMP	-11.6903629302979	2015-064T18:09:52.221
Side A FP mon			
E-0053	CB_MON_XBAND_A_OVERTEMP_STAT	Black	2015-064T18:09:52.221
E-0057	CB_MON_XBAND_A_OVERVOLT_STAT	Black	2015-064T18:09:52.221
E-0062	CB_MON_SBAND_CONFIG_ERR_STAT	Green	2015-064T18:09:52.221
E-0055	CB_MON_XBAND_A_OVERTEMP_PER	0	2015-064T18:09:52.221
E-0059	CB_MON_XBAND_A_OVERVOLT_PER	0	2015-064T18:09:52.221
E-0061	CB_MON_SBAND_CONFIG_ERR_PER	0	2015-064T18:09:52.221

MOC Side B FULL (latest)

Fig. 7-6. Telecom SmapDash tabulation display during MOC activity.

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Fig. 7-7. Telecom SmapDash summary and plot display during MOC activity.

SMAP ShiftLog   🏠 Home   ☰ Logs ▾   🔍 Search   🏷 Tags   Francis

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Ryan Mukai / Telecom / edit / rev 1   29 minutes ago / 2015-064T17:29:45 UTC

Beautiful TD275 = TDRSS-7 link throughout our engine burn! Getting ready to go back to the nadir attitude. Note we LOSE TD275 signal about 17:44:10 due to exiting contingency comm to go back to receive only.

MANEUVER

Ryan Mukai / Telecom / edit   1 hour ago / 2015-064T16:22:06 UTC

G. Thomas is on console, and R. Mukai is shadowing/helping her. This is to help her gain experience. She's pulled up the SNAS interface for the upcoming TD275 pass on the workstation.

MANEUVER

Ryan Mukai / Telecom / edit   3 hours ago / 2015-064T14:58:02 UTC

EVRs show successful activate of maneuver CAL1 sequence at 064T14:48:17. Sequence has begun!

MANEUVER

Ryan Mukai / Telecom / edit   4 hours ago / 2015-064T13:27:12 UTC

Also, will need to perform some TFP runs for +/- 40 deg rotations about the X and Y axes for X-band (Z-axis shouldn't yield a significant difference, but we'll do it anyway after the X and Y axes).

MANEUVER

Ryan Mukai / Telecom / edit   4 hours ago / 2015-064T13:24:08 UTC

No unusual EVRs for UPL, SBM, or XBM so far. SmapDash checks reveal normal voltages and temperatures and RF output power for SBT-A and also XBT-A. The plots in SmapDash need to be adjusted and scaled, which is something we will work on with the SmapDash development team, as we are are this can often be done by simply adjusting a few JSON entries.

MANEUVER

Ryan Mukai / Telecom / edit   4 hours ago / 2015-064T13:21:08 UTC

R. Mukai on console. Glad to see Ling Su (developer for SMAP Telecom) has delivered a script for generating SN predicts from a CK file. Will test this morning after checking spacecraft health.

MANEUVER

Francis Taylor / Telecom / edit   17 hours ago / 2015-064T00:39:52 UTC

SMAP console telecomers:

In her 3:30 pm e-mail today, Ling Su delivered the long-awaited predictMaker_ck (SN). This is just in time for the early-start of CAL-1 sequence uplinking and monitoring tomorrow morning. Ling's instructions are as follows.

To run predictMaker_ck (SN), per Ling's 03/04/2015 e-mail

1. Copy C-kernels file to /home/smaptel/tfp_smap/kernels/smap_sn
2. cd /home/smaptel/bin
3. predictMaker_ck_SN C-kernels-filename   # need only filename, not path
4. sort file will generate under bin directory.

MANEUVER

Fig. 7-8 Telecom shift log to document console activities.

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Fig. 7-9 TFP prediction of SMAP return link P_t/N_0 and TDRS forward link P_t/N_0.

Fig. 7-10. LGAX offpoint and predicted/actual E_b/N_0 to NEN station AS3.

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More recently, use of Excel has been de-emphasized, replaced by standardized listings of averages of the queried quantities produced directly by the Python query script. The script also produces a PDF file of standardized plots to attach to the telecom "Shift Log".

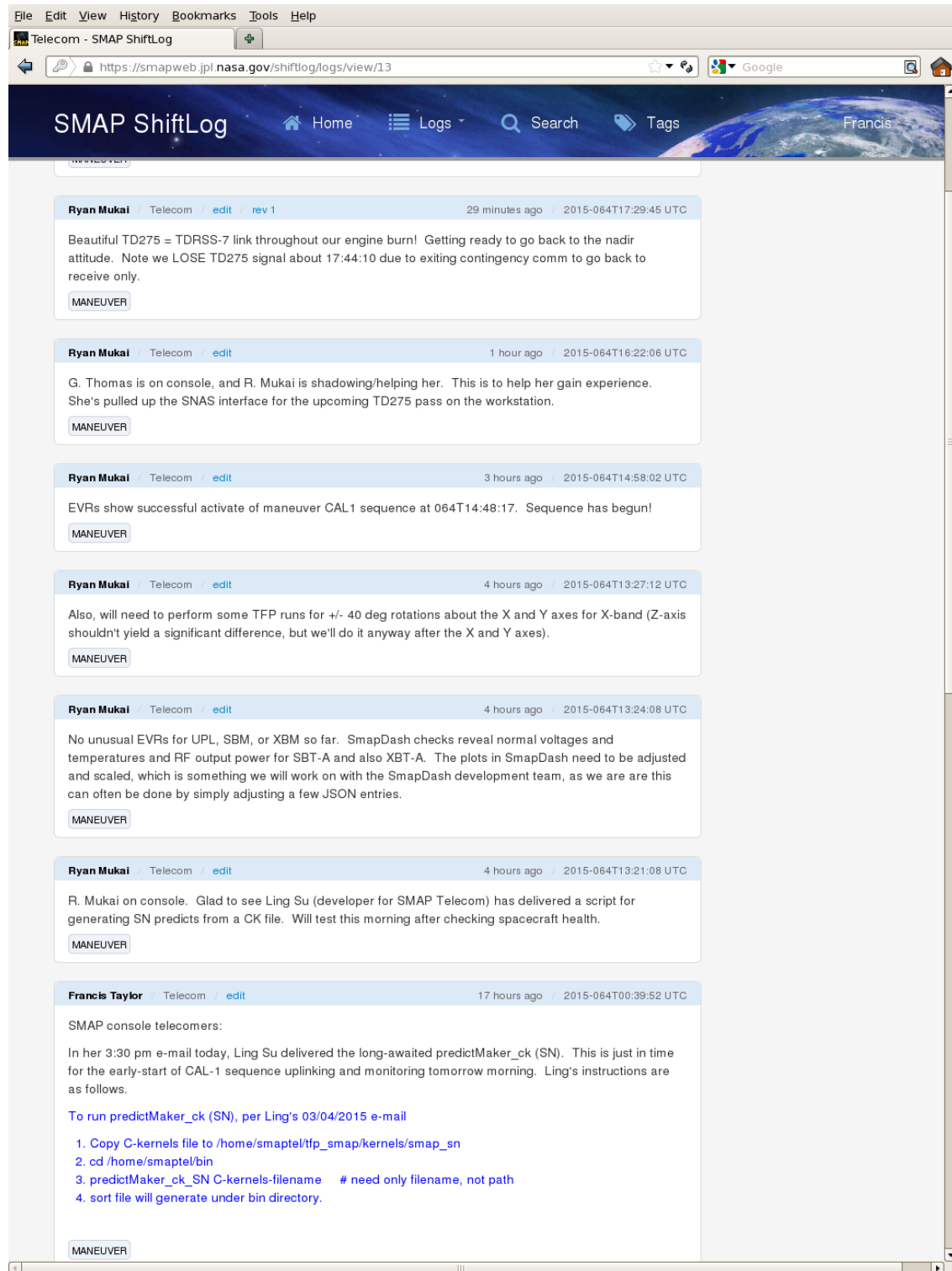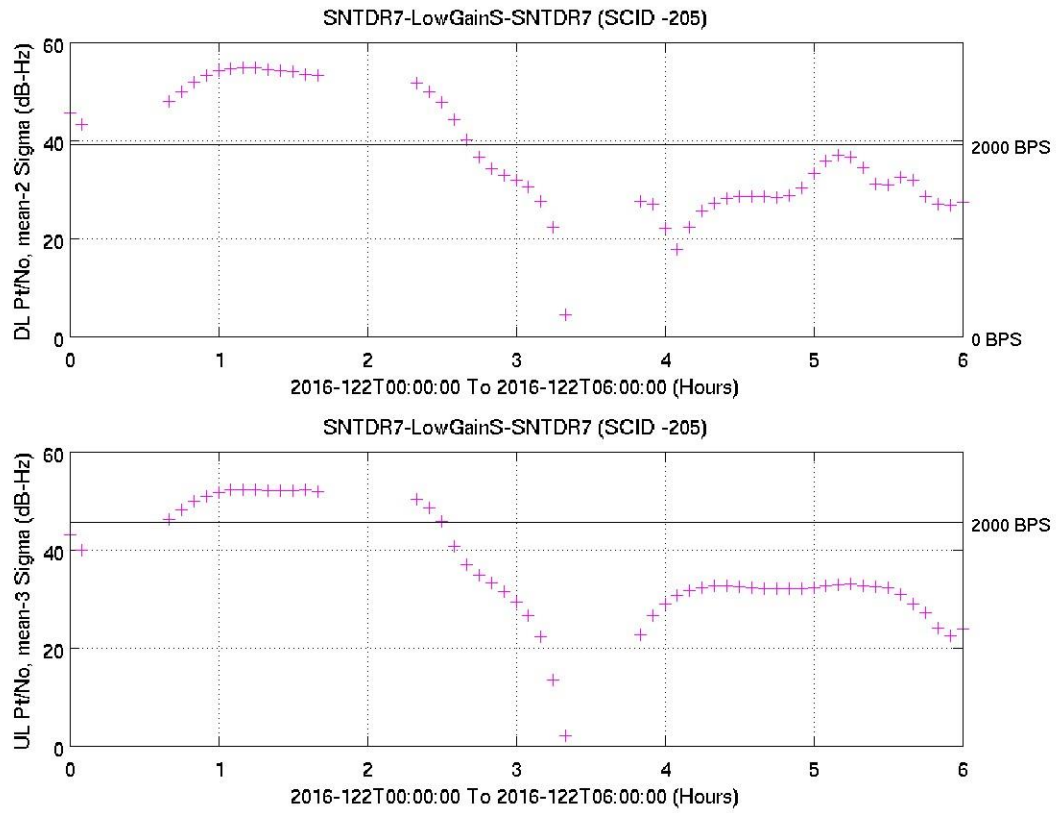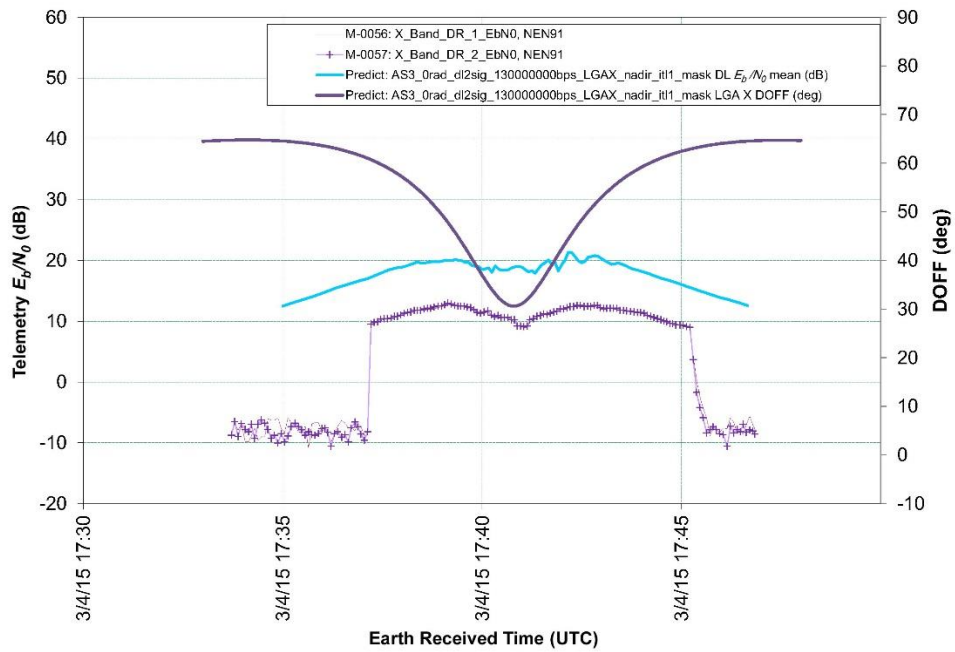Figure 7-11 summarizes SBT performance over 24 hours and about the same number of individual passes on May 20, 2015. The four plots in the figure include the signal level (in dBm), the frequency offset (in Hz) from best lock frequency (NEN does not Doppler compensate the uplink), and two counters. The unit label DN stands for data number, meaning the row telemetry value has not been converted. Figure 7-12 summarizes XBT performance over the same period, including the voltages (typically very constant) and the oscillator and SSPA temperatures against a 15°C baseline when the XBT is powered off between passes, and 25–30°C when it is powered on.

7.5.2 S-Band Uplink Polarization Mismatch and Multipath

This problem was caused by the uplink being transmitted RCP due to a stuck polarization switch at the NEN McMurdo station MG1 and received predominantly LCP by the SMAP LGAS). Because the uplink signal level margin from NEN is so large, commanding only dropped below threshold occasionally. Troubleshooting of these occasions showed large variations in the uplink signal level received at the SBT, as telemetered in engineering telemetry. Further, the passes in which the variations were largest were separated by 8 days, the repetition of the ground tracks. This suggested multipath might also be involved, either near the station or near the spacecraft. Troubleshooting analysis included modeling of the LGAS pattern which is not perfectly LCP, especially at large angles off boresight.

Figures 7-13 and 7-14 show the SBT signal level as queried and processed in the Excel template on doy 2015-078 and exactly 8 days later on doy 2015-086.

Figures 7-15 and 7-16 compare the signal levels received at MG1 and SG1. The two polar plots are of SBT IF coherent signal power over all the uplinks with the spacecraft nadir down. The radial coordinate, labeled 10 to 70 deg, is LGAS theta or angle from boresight; the circumferential coordinate labeled 0 to 360 deg is the LGAS phi or "clock" angle. Each pass becomes an arc starting at a large angle from boresight, decreasing closer to boresight, and then increasing again. An arc is how the spacecraft sees the station moving through its reference frame. Each plot contains arcs representing hundreds of individual 64-kbps uplink passes at the site. The figure is a superposition of the passes in spacecraft coordinates.

The redder portions of an arc are higher signal levels, and the bluer portions are weaker signal levels. Comparing the figures, only MG1 shows deep fades (the blue "lakes" in Figure 7-15) scattered over so much of the circle. SG1 in Fig 7-14 and other stations also have deep-fades but only near the edges of the LGAS pattern. At MG1 some bluer portions are at small LGAS off-Earth angles. The SG1 data shows mostly red, except at large LGAS off-Earth angles. This is very highly consistent with significant multipath with the MG1 uplink and negligible multipath with the SG1 uplink. The behavior at MG1 is highly repeatable, and the SG1 behavior is typical of other NEN sites.

Downlink patterns for the same passes showed no significant signal level or E_b/N_0 variability. The report from NEN that the MG1 transmit polarization switch had been stuck in the RCP position since before launch was key to understanding the problem.

Fig. 7-11. SBT 24-hour performance from all NEN passes on May 20, 2015.
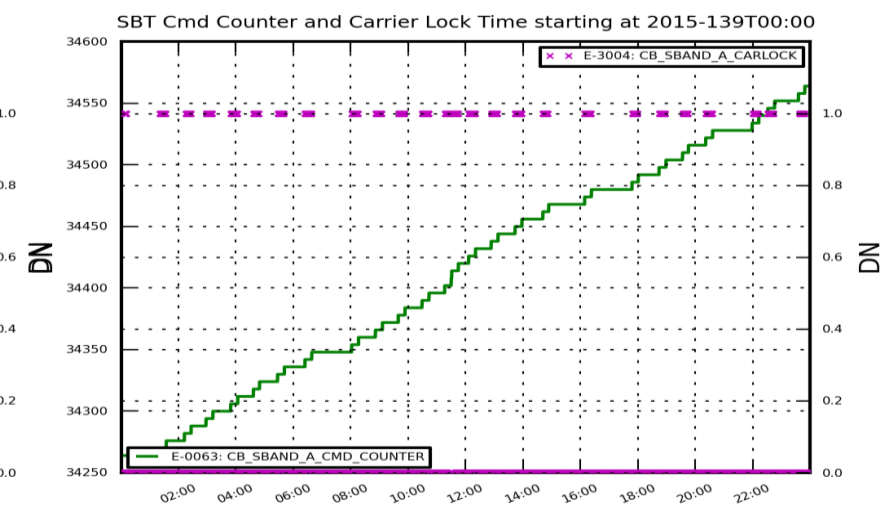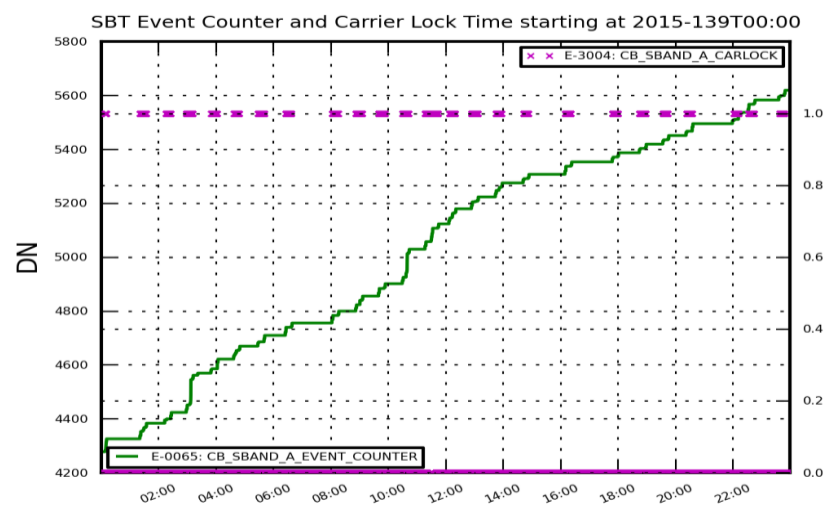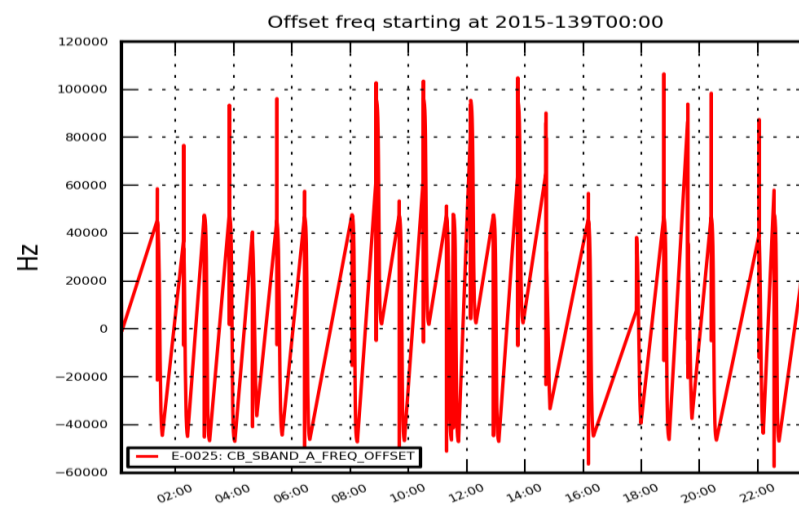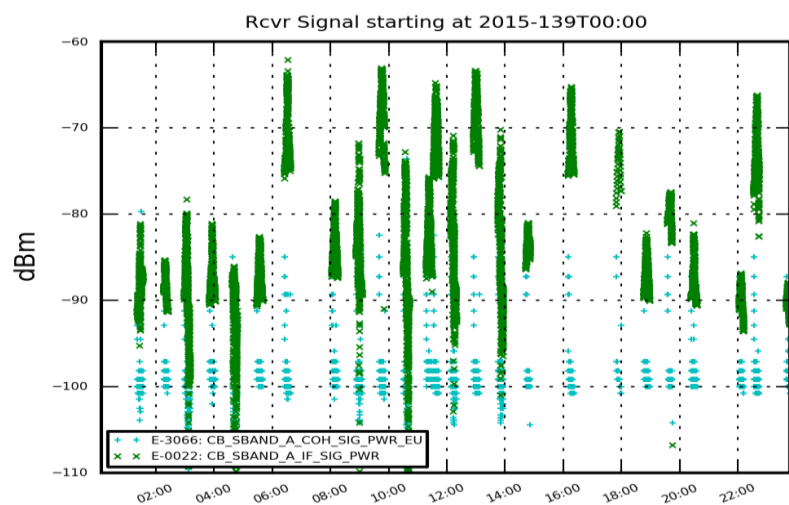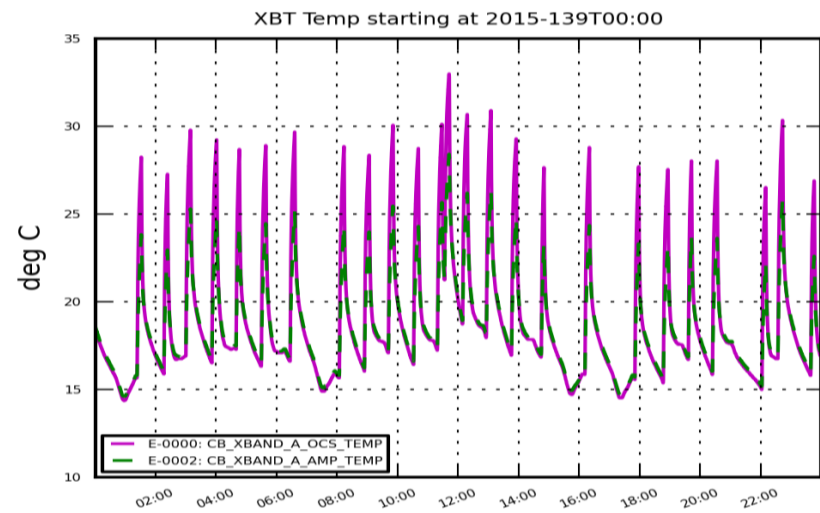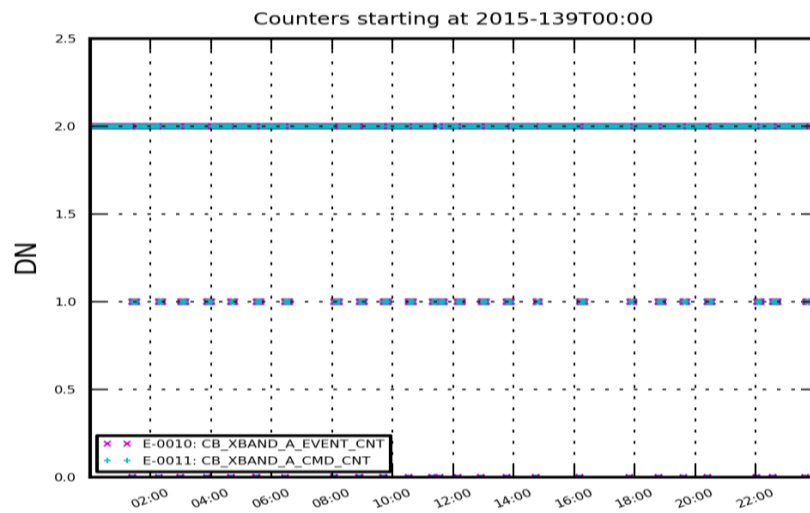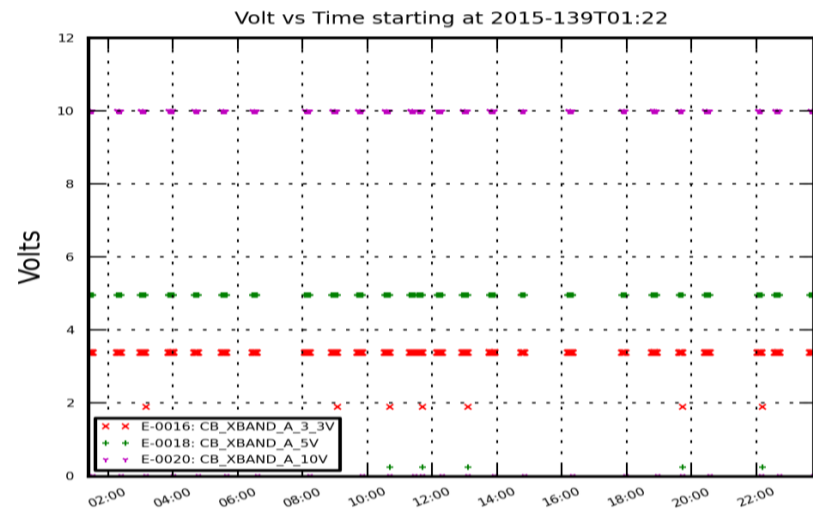
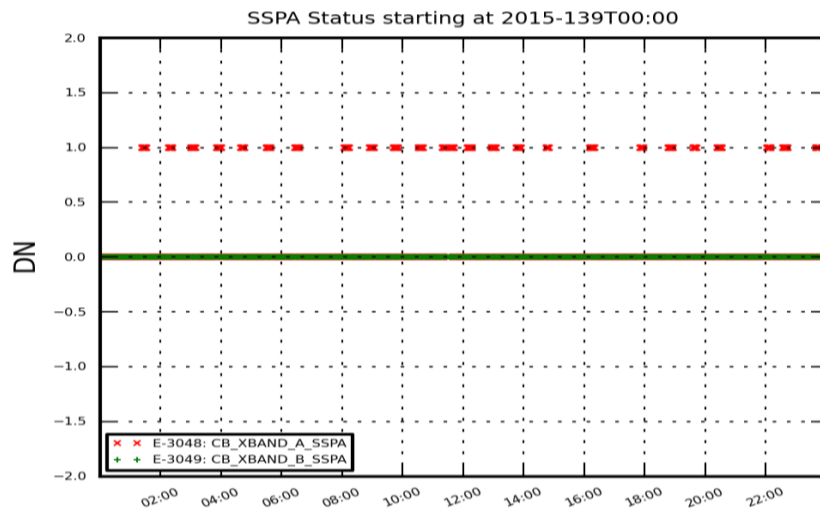**Fig. 7-12. XBT 24-hour performance from all NEN passes on May 20, 2015.**
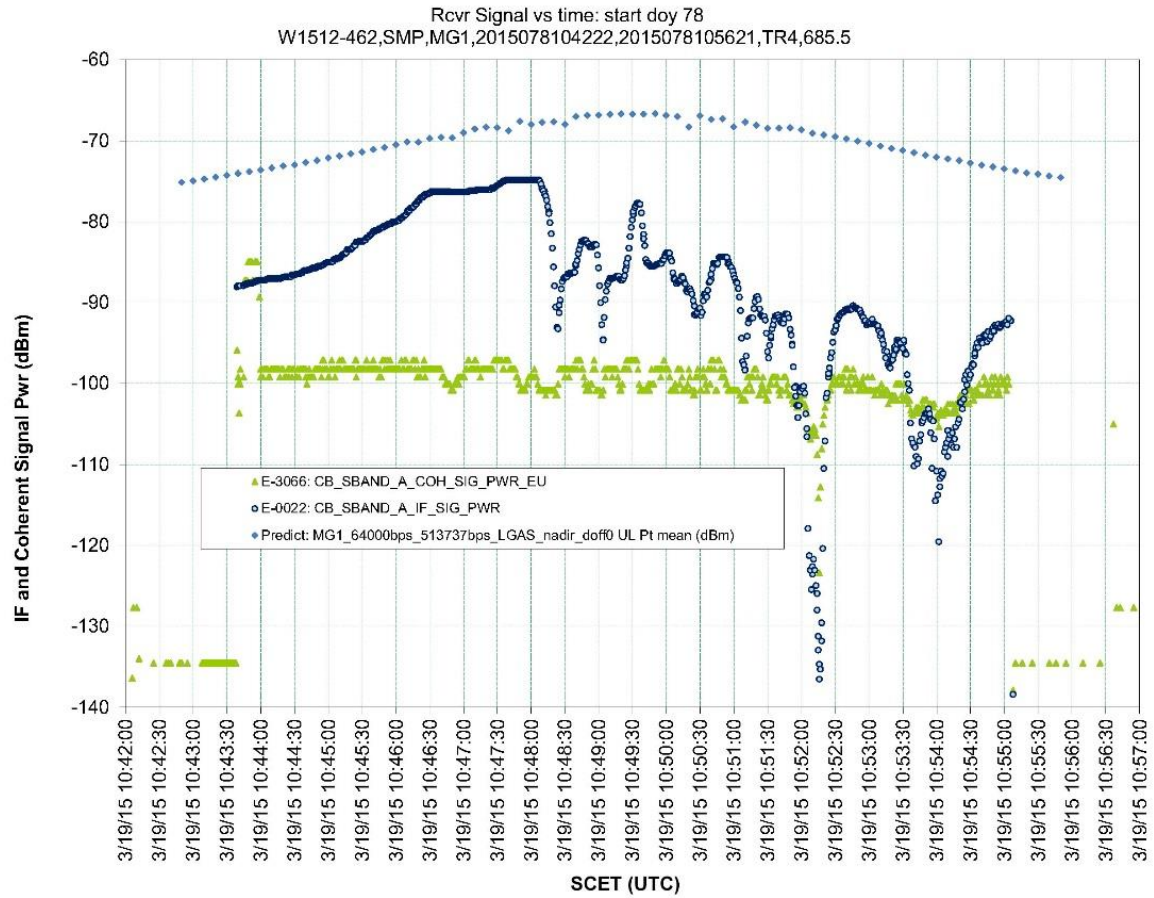
Fig. 7-13. SBT received S-band signal from McMurdo (MG1) on doy 2015-078.
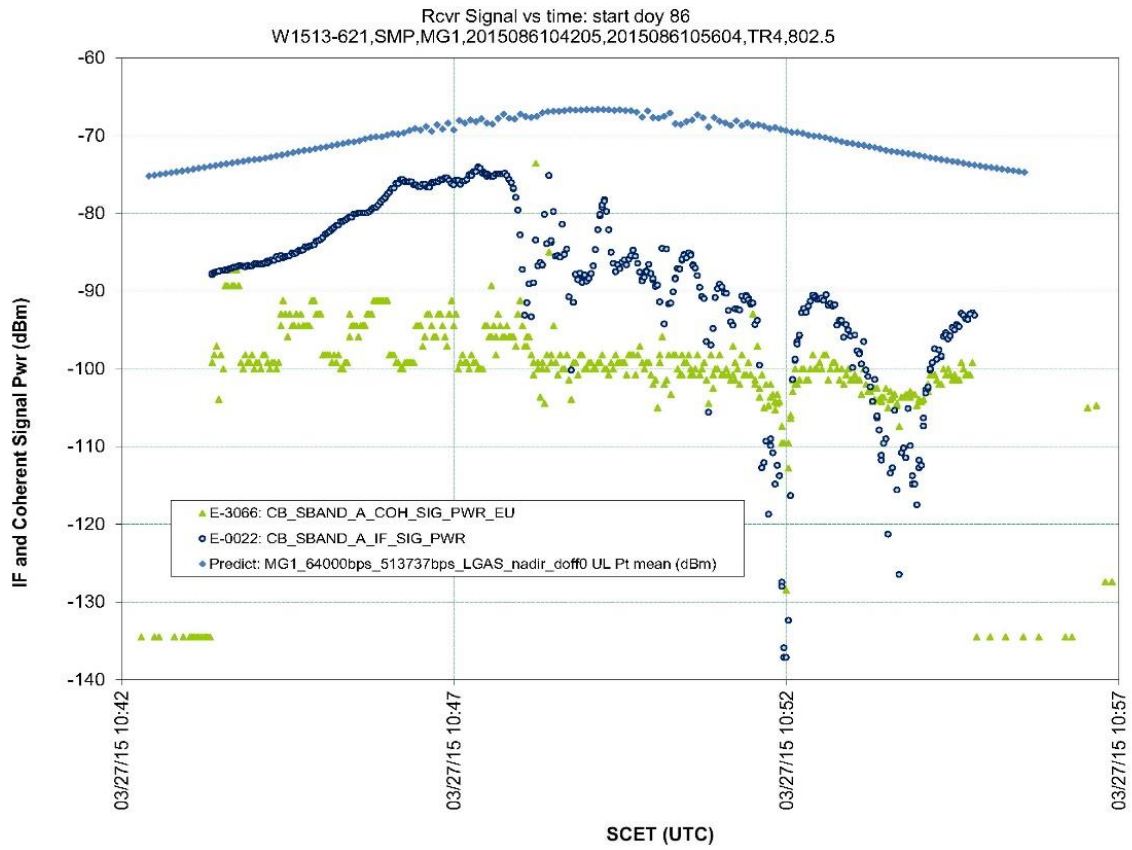
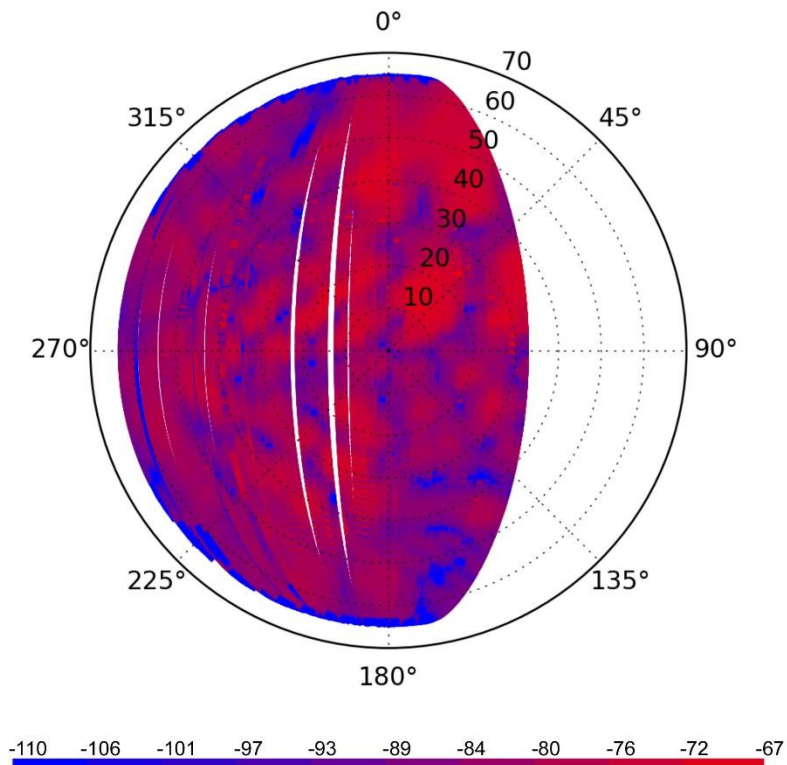**Fig. 7-14. SBT received S-band signal from MG1 on doy 2015-086.**

Fig. 7-15. Composite nadir-down SBT signal levels from McMurdo (MG1).
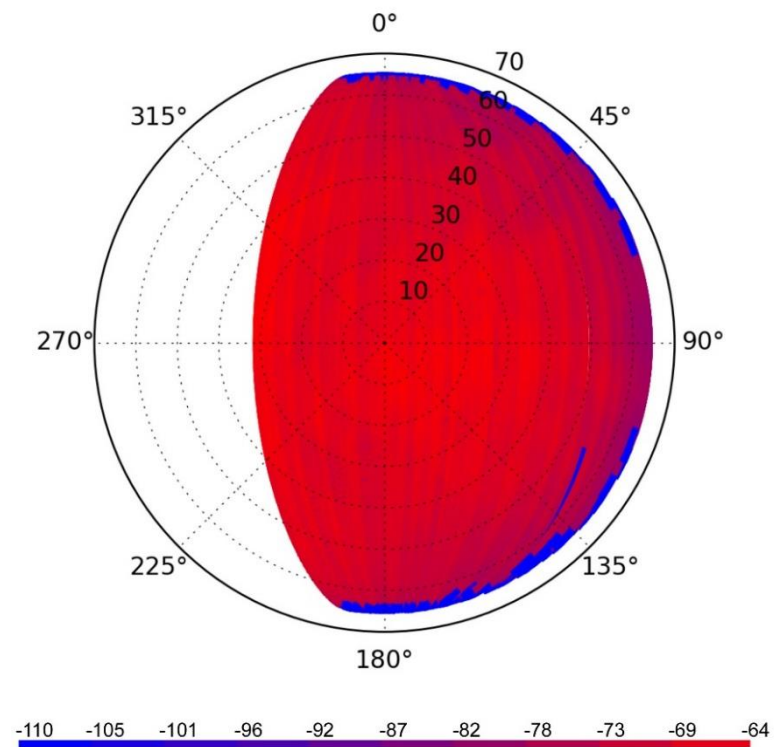

Fig. 7-16. Composite nadir-down SBT signal levels from Svalbard (SG1).

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9. Abbreviations, Acronyms, and Nomenclature

ACQ, Acq	acquisition
AFB	Air Force Base
aka	also known as
a.m.	ante meridiem, Latin meaning "before noon"
AMMOS	Advanced Multi-Mission Operations System
AMPCS	AMMOS Mission Processing and Control System (name used by SMAP)
ANSI	American National Standards Institute
Ant	antenna
AOS	acquisition of signal
AS1, AS3	11-m Near Earth Network (NEN) stations at Alaska Satellite Facility (ASF) near Fairbanks, Alaska
ASF	Alaska Satellite Facility (near Fairbanks, Alaska)
ASM	attached synchronization marker
Astro Aerospace	unit of Northrop Grumman Aerospace Systems
ATLO	assembly, test, and launch operations
BAE	British Aerospace Engineering Systems Inc., a subsidiary or BAE Systems Plc
BAPTA	bearing and power transfer assembly
BMOC	Backup Mission Operations Center
BOM	beginning of mission
BOT	beginning of track
BPF	bandpass filter
BPS, bps	bits per second
BPSK	binary phase shift keying (PSK)
CAM	command approval meeting
CARA	conjunction assessment risk analysis
CB	communications behavior
CCA	cone/clutch assembly
CCSDS	Consultative Committee for Space Data Systems
CDH	command and data handling (subsystem)
CK	C kernel in SPICE; guidance, navigation, and control subsystem
Ckt	circuit
CLT	command loss timer
CMD	command
cnt	count (abbreviation)

coax	coaxial
cohon	coherency on (abbreviation)
comm	communication (abbreviation)
conv	convolutional (abbreviation)
CSS	coarse Sun sensor
csv	comma separated values (file type)
DAAC	distributed active archive center
D&C	dynamic and control
dB	decibel
dBi	decibel with respect to isotropic antenna
dBm	decibel with respect to 1 mW
dBW	decibels referenced to watts
dBW/Hz	decibels referenced to watts per hertz
DC	direct current
deg	degree
DG	data group
DESCANSO	Deep Space Communications and Navigation Systems Center of Excellence
DL	downlink (return link from SMAP)
DN	data number
DOD	Department of Defense
Dow-Key	(provided the flight coaxial switches)
doy	day of year
DRO	dielectric resonator oscillator
DSMC	Data Services Management Center
DSN	Deep Space Network
dwn	down (abbreviation)
E_b/N_0	bit-energy-to-noise spectral-density ratio
EBOX	EDOS box
EDOS	EOS [Earth Observing System] Data and Operations System
EESS	Earth Exploration Satellite System [Google has Earth Exploration Satellite System]
EHA	engineering, housekeeping and accountability
EIA	Electronic Industries Alliance
EIRP	effective isotropic radiated power
EOL	end of life
EOM	end of mission
Eph Gen	ephemeris generation
EOS	Earth Observing System
EOSDIS	EOS Data and Information System

EOT	end of track
ERT	Earth received time
ESMO	Earth Science Mission Operations
ET	ephemeris time
EVR	event record
f	frequency
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDF	Flight Dynamics Facility
FEC	forward error correction
FK	frame kernel
FOT	Flight Operations Team
FOV	field of view
FP	fault protection
FPGA	field-programmable gate array
freq	frequency (abbreviation)
FSW	flight software
G4	Geomagnetic storm level 4 ("severe"); part of storm levels 1 through 5__
GB	gigabyte
GDS	ground data system
GHz	gigahertz
GNC	guidance, navigation, and control subsystem; also called CK in SPICE
GPS	Global Positioning System
GRAIL	Gravity Recovery and Interior Laboratory (project)
GRGT	Guam remote ground terminal
GRTS	Guam remote tracking station
GSFC	Goddard Space Flight Center
G/T	ratio of antenna gain to receiver noise temperature
GTP	Generalized Telecom Predictor
GUI	graphical user interface
h	altitude
HIE	high interest event
I	the in-phase component of a signal
I-CH	in-phase channel
ICD	interface control document
ICE	integrated control electronics

I-CH	In-phase channel
IF	intermediate frequency
IFA	integrated feed assembly
IIRV	improved inter-range vector
InPla	in-plane (maneuver) a
InPlb	in-plane (maneuver) b
IONet	input output network
IOT	Instrument Operations Team
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
JSpOC	Joint Space Operations Center
k	constraint length of a convolutional code
kbps	kilobits per second
km	kilometer
KSAT	Kongsberg Satellite Services
ksps	kilosymbols per second
Ku-band	frequency band that carries the SMAP forward link to TDRS (15 GHz)
kW	kilowatt
L	launch (reference date/time of liftoff of the launch vehicle)
L	data processing level (as in L0, L1, …)
L-band	frequency band that includes SMAP instrument frequencies (1.2 to 1.5 GHz)
LCP	left-hand circularly polarized
LEO	low Earth orbit
LGA	low gain antenna
LGAS	S-band LGA
LGAX	X-band LGA
LHCP	left-hand circular polarized
LMST	local mean solar time
LNA	low noise amplifier
LOS	line of sight
LTST	local true solar time
LUT	look up table
LV	launch vehicle
LZPF	Level-0 Processing Facility
m	meter
m^2	square meter

Mbps	megabits per second
MD	maneuver design
MECO	main engine cut off
MG1	10-m Near Earth Network (NEN) station (also known as MGS) at McMurdo, Antarctica
MGS	McMurdo Ground Station
MGSS	Multimission Ground Systems and Services
MIMU	miniature inertial measurement unit
min	minute(s)
MLTAN	mean local time of ascending node
MMS	Magnetospheric Multiscale (Mission)
MOC	(SMAP) Mission Operations Center
MPCS	Mission Processing and Control System (name used MSL, see AMPCS)
MSAP	multimission system architecture platform
MSIA	MSAP serial interface adapter
MSL	Mars Science Laboratory (project)
Msps	megasymbols per second
MTIF	MSAP telecom interface
MTR	magnetic torque rod
MTRS	McMurdo [Tracking and Data Relay Satellite] TDRS Relay System
N	newton
NAIF	(NASA) Navigation and Ancillary Information Facility
NAND	not and
NASA	National Aeronautics and Space Administration
Nav	navigation, Navigation Team
NEN	Near Earth Network
NGAS	Northrup Grumman Aerospace Systems
NISN	NASA Integrated Services Network
NRZ	non return to zero
NRZ-L	non return to zero -level
NRZ-M	non return to zero -mark
NSIDC	National Snow and Ice Data Center
NTIA	National Telecommunications and Information Administration
NVM	non-volatile memory
osc	oscillator
OD	orbit determination
OQPSK	offset quadrature phase shift keying
ORT	operational readiness test
OTM	orbit trim maneuver

PA	power amplifier
PCM	pulse code modulation
PDF	portable data file (file type)
PFD	power flux density
PF2	11-m station operated by Universal Space Network (USN) at Poker Flat, Alaska
PM	phase modulation
p.m.	post meridiem, Latin meaning "after noon"
POR	power on reset
pos	position (abbreviation)
predictMaker	batch mode script that generates standard TFP tabulated outputs
PRT	platinum resistance thermometer
PSD	power spectral density
PSK	phase shift keying
PST	Pacific Standard Time
pwr	power (abbreviation)
Q	The quadrature component of a signal
Q-CH	Quadrature channel
QPSK	quadrature phase shift keying
r	ratio of information bit rate to channel symbol rate in a convolutional code
RAD	radiometer
RAD750	a radiation-hardened single board computer made by BAE Systems
RBA	reflector boom assembly
RBE	(radio frequency) RF back-end electronics
RCP	right-hand circular polarization
RCS	reaction control subsystem (thrusters)
rcvr	receiver (abbreviation)
RDE	radiometer digital electronics
RF	radio frequency
RFI	radio frequency interference
RJA	rotary joint assembly
RMM	risk mitigation maneuver
rpm	rotations per minute
RS	recommended standard (as in RS-422)
RS	Reed-Solomon (coding or encoded)
RSPP	Robotic Systems Protection Program
RUAG	(originally Rüstungs Unternehmen Aktiengesellschaft) Space AB, Sweden RWA reaction wheel assembly

RX	receive or receiver
S-band	(also "SBAND" in some computer-generated figures) frequency band that includes S-band transponder (SBT) receive/transmit frequencies (2090 to 2280 MHz)
SAA	South Atlantic Anomaly
SAR	synthetic aperture radar
SBT	S-band transponder
S/C	spacecraft
SCET	spacecraft event time
SCID	spacecraft ID
SCLK	spacecraft clock
SDS	Science Data System
SECO	second engine cut off
SEP	separation
Seqgen	sequence generation
sess	session (abbreviation)
SEU	single event upset
SFC	system flight computer
SFCG	space frequency coordination group (of the Federal Communications Commission))
SFP	system fault protection
SG1, SG2	11-m NEN stations at Svalbard, Norway
SGLT	space-ground link terminal
SGS	Svalbard ground station
SIA	spun instrument assembly
sig	signal (abbreviation)
SMA	sub-miniature version A
SMAP	Soil Moisture Active Passive
SmapDash	an automated web-based system for telecom trending
SN	Space Network (NASA network that supports spacecraft communications near Earth [orbits of roughly 73 to 3000 km])
SPA	spun platform assembly
SPDT	single pole double throw
SPK	spacecraft position kernel
SRM	solid rocket motor
SRU	stellar reference unit
S/S	subsystem
SSA	S-band single access
SSAF	SSA forward
SSAR	SSA return

SSC	service specification code
SSPA	solid state power amplifier
STGT	Second TDRSS ground terminal
SUROM	start-up read-only memory
Svn ™	Subversion version control system used by SMAP (Apache Software Foundation)
T	time (as in T-zero, SCET, etc.), most often expressed as UTC
TAM	three-axis magnetometer
tcxo	temperature compensated crystal oscillator (abbreviation)
TDE	TDRS East
TDRS	Tracking and Data relay Satellite
TDRSS	Tracking and Data Relay Satellite System (part of the Space Network [SN])
TDS	TDRS Spare
TDW	TDRS West
TDZ	Tracking and Data Relay Satellite System 275; SN TDR275
TFP	Telecom Forecaster Predictor
TIA	Telecommunications Industry Association
TLM	telemetry
TNC	Threaded Neill–Concelman
TR	transmit receive (as in TR code)
TR1 – TR9	the NEN transmit receive codes
TR2, TR3	7.3-m Near Earth Network (NEN) stations in Queen Maud Land, Antarctica
Trac	project management wiki and issue-tracking system, used by SMAP (Edgewall software)
Trk	track
TrollSat	Troll Satellite Station, Troll, Antarctica
TT&C	telemetry tracking and command
Tx	transmit or transmitter
txon	transmitter on (abbreviation)
UART	universal asynchronous receiver/transmitter
UL	uplink (forward link to SMAP)
ULA	United Launch Alliance
Ulsgen	uplink summary generation
USN	Universal Space Network
UTC	Universal Time Coordinated
V	volt
VC1 – VC4	Virtual channel 1 through Virtual channel 4 (data streams in the GDS)
VOCA	Voice operational communications assembly

VSWR	voltage standing wave ratio
VxWorks	real time operating system by Wind River Systems
WG1	11-m Near Earth Network (NEN) station (aka WPS or WGS) in Wallops, Virginia)
WGS	Wallops Ground Station
WPS	11-m Wallops Ground Station (call sign on voice net)
WSC	White Sands Complex
WSGT	White Sands Ground Terminal
X-band	(also "XBAND" in some computer-generated figures) Frequency band that includes the XBT transmit frequency (8180 MHz)
XBT	X-band transmitter
xor	exclusive OR (Boolean operator)
$+X_{SC}$	Spacecraft +X reference axis
xmt	transmit (abbreviation)
xmtr	transmitter (abbreviation)
$+Y_{SC}$	Spacecraft +Y reference axis
$+Z_{SC}$	Spacecraft +Z reference axis