New Horizons REX Instrument Overview

This document is an overview of the New Horizons' Radio Science Experiment (REX) instrument. The REX and DSN (Deep Space Network) descriptions were originally adapted from DeBolt et al. (2005), from DeBoy et al. (2004), from Tyler et al. (2008), from Planetary Data System (PDS) dataset CO-SS-RSS-1-SCC2-V1.0, and from the New Horizons website. During migration to PDS4, this current copy was adapted from the PDS3 REX instrument catalog file, providing light edits to the text, format, and flow.

REQUIRED UNDERSTANDING

The REX and the New Horizons (NH) regenerative ranging tracker (see DeBolt et al. (2005)) are ***separate*** and ***independent*** subsystems that both use the radio frequency (RF) and telecommunications subsystems. Tracking data may not be archived in REX data sets.

Instrument Overview

REX requires the coordinated use of Earth-based transmitters and the New Horizons receiver. The Earth-based 'Ground Element' is made up of the Deep Space Network (DSN) hardware and operations facilities that support the New Horizons (NH) mission. The 'Flight Element' includes the 2.1 m spacecraft high-gain antenna (HGA) and the NH radio receiver that has a REX-specific signal processing board, which sends its output to spacecraft data storage.

Scientific Objectives - REX

The primary purpose of the REX system was to investigate open questions regarding atmospheric and ionospheric structure, surface conditions, and planetary radii of both Pluto and Charon.

The REX encounter with the Pluto system was focused on occultations, by Pluto and Charon, of an Earth-based, uplink radio signal. The New Horizons HGA remained pointed toward Earth for the duration of the occultation events, beginning and ending with the line-of-sight to Earth well above any anticipated sensible atmosphere or ionosphere. This arrangement set up three investigations at each occultation, plus a fourth gravity investigation:

Investigation 1: Atmosphere characterization or detection

As the Earth-spacecraft line-of-sight passed through the atmosphere of Pluto, there was a detectable shift in phase of the 7.2 GHz uplink signal as measured via the heterodyne-, downconversion- and sampling-circuitry that composes REX. These occultation phase shifts provide opportunities for characterization of Pluto's atmosphere and of a possibly sensible ionosphere; a similar encounter allows a search for a sensible atmosphere and ionosphere of Charon.

Investigation 2: Diameter measurement

As the path of the signal approached the limb, there were predicable, detectable changes in signal strength due to diffraction, allowing precise measurement of entry and exit events. The time difference between the entry and exit events, plus knowledge of Pluto-Charon, Earth, and spacecraft ephemerides, provide the length of the occultation chords.

Investigation 3: Front and dark side thermal emission

Just before closest approach, the HGA boresight was swept across Pluto's surface. In one observation (DISKTHERM), the measurement was of sunlit surface thermal emission. In the others (THERMSCAN), 34 m DSN antennas radiated Right- and Left-Circular Polar 7.2 GHz signals timed to arrive at Pluto during the observation. The HGA measured the reflected signal, making this a Bi-Static Radar (BSR) measurement; one scan was directed at the specular reflection point; the other BSR measurement was aimed off of the Earth-Pluto-Spacecraft radiometric equator.

During each occultation (when the uplink signal from Earth was blocked), REX made measurements of radiothermal emissions at 4.2 cm (7.2 GHz). The motion of the spacecraft caused the antenna beam to sweep across the night side of Pluto and Charon while the pointing of the HGA remained fixed in the Earth direction.

Investigation 4: Individual body masses

Away from the limbs and above any atmosphere, perturbations in the measured uplink signal, caused by the gravitational attractions of Pluto and Charon on the spacecraft, may be used to infer their individual masses. However, the reader should note that the proposed gravity investigation is beyond the chosen scope of this data set, and no ranging data will be included here.

Those four investigation descriptions are greatly simplified; see Tyler et al. (2008) for more detail.

Instrument Overview - Flight Element

On-board the NH spacecraft, hardware specific to REX are an analog-to-digital converter and the REX Actel Field-Programmable Gate Array (FPGA). These are on the Radiometrics card within the Integrated Electronics Module (IEM) that is the NH transceiver (see DeBoy et al. (2004)). N.B. There are two redundant IEMs. Note also that the word 'transceiver' is often used when describing REX operations, here and elsewhere, because the REX hardware receives its input signal via the transceiver hardware; such usage does not imply REX has any transmission capability; REX is uplink-only.

Other spacecraft hardware external to the REX hardware, but used by REX, include a digital receiver on the uplink card of the NH transceiver IEM, the 2.1 meter high gain antenna (HGA) and an ultrastable oscillator providing the precision frequency reference necessary for the uplink radio science experiment. N.B. There are two redundant USOs. Refer to Tyler et al. (2008), Fountain et al. (2008), and DeBoy et al. (2004) for further details.

Signals captured by the HGA are downconverted and passed through a 4.5 MHz filter before entering the REX signal conditioning unit. Outputs from this unit are: (1) in-phase (I) and quadrature (Q) 16-bit integer samples at 1250 sample pairs (complex) per 1.024 seconds -- i.e., approximately 1220.7 I samples per second and 1220.7 Q samples per second; and (2) the radiometer output, consisting of 40-bit accumulating samples at a rate of 10 samples every 1.024 seconds.

REX is part of the redundant spacecraft telecommunication subsystems and signal paths that use the single HGA in common. The two REX cards are designated as Sides A and B (also Channels A and B). REX Side A always received RCP (Right Circular Polarization) uplink signal from the DSN; Side B always received LCP (Left Circular Polarization) uplink signal from the DSN. This is unaffected by the switching described in the next paragraph. See [REX Use of the DSN] topic below for a description of uplink signal polarity sent during REX observations.

Sides A and B can be operated simultaneously, to increase SNR, using uplink signals with RCP and LCP, respectively. Normally Side A communicates with spacecraft CDH1 (Command and Data Handling), and B with CDH2, but that can be switched if required by spacecraft events; as of the end of 2015, this switch has never occurred. There are two USOs, and each REX side is referenced to a separate USO, and that must be considered when using the data. The USOs are also cross-strapped so either can provide timing to both sides in the event of a single USO failure. Execution of the command to do so would be a one-time, irreversible event, and as of the end of 2015 that has not occurred.

Specifications

NAME:	REX (Radio Science Experiment)
DESCRIPTION:	Local oscillator vs. uplink signal phase comparator
PRINCIPAL INVESTIGATOR:	Ivan Linscott, Stanford University
WAVELENGTH RANGE:	4.2 cm
FIELD OF VIEW:	20 mRad
ANGULAR RESOLUTION:	20 mRad
FREQUENCY RESOLUTION:	3E-13 (delta-f/f)
POWER CONSUMPTION:	1.6 W (per-side; see Note 1)
MASS:	160 g (per-side; see Note 1)
VOLUME:	520 cm^3 (per-side; see Note 1)

Note 1: Resource usage values include those for the following components: Analog-to-Digital Converter (ADC), Field-Programmable Gate Array (FPGA), and Integrated Circuit (IC) buffers.

Instrument Calibration - REX

HGA Beam Pattern Calibration

The REX commissioning test on July 20, 2006 was dedicated to mapping the beam pattern of the NH spacecraft high gain antenna. The REX science team obtained the beam pattern by tuning the frequency of an unmodulated uplink signal of constant power from the DSN to arrive at the NH spacecraft with a constant frequency; the signal served as a calibration source. At the same time, the team varied the spacecraft attitude with respect to the direction to Earth, thus implementing a scan of the HGA beam over a small range of angles about the Earth direction, centered approximately on the beam maximum. The initial offset of the scan was set at the upper left corner of a 2 deg x 2 deg angular box. The beam direction then was made to 'nod and step' parallel to the box edges so as to perform a raster scan about the Earth direction. During the scan, REX processed the uplink signal from the transceiver, with the REX output recorded and time-tagged on-board. At the same time the spacecraft body vectors were logged and time-tagged. The combination of these two time sequences allowed the team to map estimates of the uplink signal power to the spacecraft pointing direction.

Sample Calibration

Raw 16-bit I and Q samples are scaled to Volts based on the assumed-stable reference voltage of the 12-bit ADC, plus the design of the digital filter implemented within the FPGA. The net result is a gain-independent, direct scaling factor, which value is in the Science Operation Center (SOC) Instrument Interface Control Document (ICD).

> **N.B.** the IQ data calibration is present only to satisfy a PDS requirement; it is more or less meaningless as it provides no additional information not already in the raw data, because the purpose of the IQ data is the signal phase relationship encoded in the Q:I ratio of each IQ pair. The calibrated IQ data provide no additional insight into that ratio not already present in the raw data. The noise inherent in any single measurement swamps any error in the calibration (e.g. fluctuation in the ADC reference voltage). Statistically, the radiometry values, by both intent and design, will be more useful in evaluating signal strength in scientific units.

The 40-bit radiometer samples are scaled to temperature values in Kelvin, using a reference temperature calibrated from the noise figure of the New Horizons radio receiver and a gain setting (AGC or AGCGAIN).

Note that the acronym AGC comes from the nomenclature of the RF Uplink hardware, which is separate from REX, and which uses Automatic Gain Control as part of its carrier tracking loop. For REX there is no automatic gain control and REX gain is manually set by commands from the ground based on the expected uplink power, or radiometry, in the REX band.

Radiometer Calibration

Summary: The System Noise Temperature of the REX instrument is 146 K.

System Noise Temperature (SNT) is typically measured by injecting known amounts of noise power into the signal path and comparing the total power with the noise injection 'on' against the total power with the noise injection 'off.' That operation is based on the fact that receiver noise power is directly proportional to temperature. Normally, measuring the relative increase in noise power due to the presence of an absolutely calibrated thermal noise source allows direct calculation of SNT.

However, for the NH radio subsystem, without an absolutely calibrated thermal noise source, it is possible to calculate the SNT using multiple standard radio sources and Cold Sky: 'on' is when the HGA is pointing at a standard radio source; 'off' is when the HGA is pointing at Cold Sky.

There are three Cold Sky locations chosen for NH REX, where the sky temperature is within a few tenths of a Kelvin of the Cosmic Microwave Background (CMB) over a section of the sky larger than several times the half-power beam width of the HGA.

Using the ratios of radiometry measurements of multiple standard radio sources to radiometry measurements of Cold Sky allows indirect calculation of the SNT, as long as the relative power ratios between the standard radio sources are known and are not unity, and with the following assumptions:

1. We assume that the REX radiometry system response is linear with power.
2. We assume that the maximum signal when the HGA scans across a standard radio source is proportional to the X-band radio flux from that source. The peak in the HGA beam pattern is a significant fraction of a degree, which is much broader than the pointing deadband of 0.1 deg used for these observations, so this assumption is reasonable.
3. We assume that the Standard radio sources chosen for this calibration are 'thermal', i.e., they possess blackbody radiation spectra that are constant, or at least interpolable, across the REX band.

Refer to the REX Radiometer Calibration at 4.2 cm document found within the PDS for more details. On 29 June 2006, the team obtained a series of five crossed scans of radio astronomy sources together with dwells on cold sky. The spacecraft HGA was initially commanded to point at an offset from the source direction of -1 degree along the NH body X coordinate, and then scanned across the source at 1E-4 rad/s to X = +1 degree, a maneuver that required approximately 350s. Similar scans were performed for the vertical, or Z coordinate, but with a dwell of 300 s at the origin X = Z = 0.

Two of the targets were positioned on the sky where the galactic synchrotron background was very low, and within a few tenths of a kelvin of the Cosmic Microwave Background (CMB). These two targets were called the Cold Sky Cals. The other targets were standard radio sources with known radio fluxes. The calibration procedure then mapped the SNR's of the targets (the signal was characterized by the radio sources; the noise was characterized by the Cold Sky Cals) against the expected radio fluxes, and produced a log-log linear relationship with a 1% standard deviation.

One-second samples of power in a 4.5 MHz bandwidth were smoothed using a 10s sliding window; the standard deviation of the 10s averages indicates that the NH transceiver is radiometrically stable at a level of approximately 5 parts in 10,000, and thus adequate for measuring radiometric temperature to a one-sigma uncertainty of about 0.1K (1 part in 1000). Again, refer to the REX Radiometer Calibration at 4.2 cm document found within the PDS for the latest information regarding how the REX calibration was performed.

Gain Linearity tests

The gain setting (AGC or AGCGAIN) is designed to produce linear results in the radiometry calibration formula in units of dBm (the formula is available in the SOC Instrument Interface Control Document). These tests varied the gain setting (steps of two in the gain setting, equivalent to ~1dB) while measuring a single target source, i.e., an unmodulated, constant-strength signal sent from the DSN. The results indicated that the instrument performs as designed.

Note that the acronym AGC comes from the nomenclature of the RF Uplink hardware, which is separate from REX, and which uses Automatic Gain Control as part of its carrier tracking loop. For REX there is no automatic gain control and REX gain is manually set by commands from the ground based on the expected uplink power, or radiometry, in the REX band.

As of 2017, a link analysis is in process to verify the amplitude stability of the gain over the length of the mission. Please contact the instrument representative or the SOC for more details if needed.

Instrument characterizations

In addition to instrument calibration, the following activities were performed as part of commissioning during the Launch mission phase.

Some of these tests were also performed during the Pluto Cruise mission phase as part of spacecraft Annual CheckOut (ACO) activities to monitor instrument functionality and stability.

Spur tests/Spurious signal tests/Find weak tones, no uplink

The test for spurs in the REX band is part of the Annual Checkout activities for New Horizons. The test involves setting the open-loop AGC to near the upper end of its range and acquiring REX data with no uplink. A spur is a narrowband frequency, revealed as a narrow spectral line in the time-integrated spectrum of the REX band.

Interference tests

During encounter, multiple instruments on-board New Horizons operated simultaneously. Tests were performed during Commissioning to verify that simultaneous operation of these instrument suites did not cause mutual interference. For REX, both REX and Alice operated simultaneously to observe the occultations of the Earth and Sun by Pluto and Charon. At Pluto Encounter, the Earth and Sun are separated by 1.5 degrees, and Earth occultations for REX and the Solar occultation for Alice by Pluto and Charon occurred very close together in time. The mutual interference test for REX and Alice had both instruments on, i.e. both REX and Alice were acquiring data, REX without an uplink and Alice without the Sun in its aperture. Neither instrument found any artifacts during these tests.

Uplink simulates multi-tones to assess intermodulation distortion

Two uplinks, close in frequency in the REX band, were transmitted to New Horizons in each of Right-hand and Left-hand Circular Polarization (RCP and LCP), to assess the incidence of intermodulation distortion. None was found at a level of less than -60 dBc.

Miscellaneous characterizations and tests; see Tyler et al. (2008) section 6

- Functional Verification
- Uplink Signal Acquisition (minimum SNR)
- USO Stability
- REX Passband Response

Summary

All calibration and characterization activities indicate the REX instrument operates as expected.

See section 6 of Tyler et al. (2008) for more details of the REX instrument performance, as well as the REX Radiometer Calibration at 4.2 cm document found within the PDS.

Operational Considerations - REX

Controls

The primary controls for REX are its power, the allocation of memory to store REX data on the Solid State Recorder (SSR) via Command and Data Handling (C&DH), and the gain setting (AGC). REX generates In-phase, Quadrature-phase and Radiometry values whenever it is on, although the memory allocation determines when and whether those values are stored in the SSR. Configuration of the spacecraft telecommunications subsystem for use by REX (Haskins & Millard (2004); Tyler et al. (2008); DeBoy et al. (2004)), allocation of memory on the Solid State Recorder to store REX data, and telemetering stored data to Earth are all necessary but outside the scope of this document.

The intersection of the periods when REX was on (time) and data allocations (data volume) can be inferred from the existence of time-contiguous files of REX data in the archived data set.

The AGC settings are provided as state tables, REX AGC History Data for Side A and REX AGC History Data for Side B files in the PDS.

Note that the acronym AGC comes from the nomenclature of the RF Uplink hardware, which is separate from REX, and which uses Automatic Gain Control as part of its carrier tracking loop. For REX there is no automatic gain control and REX gain is manually set by commands from the ground based on the expected uplink power, or radiometry, in the REX band.

REX data compression and Time Tag anomalies

REX writes data to the SSR as a series of frames at 1 frame per 1.024s, from the first 1PPS (One Pulse Per Second spacecraft timekeeping signal) encountered after both the instrument is powered on and an SSR allocation goes active, until either the instrument is powered off or the SSR allocation is filled. For this reason, it is possible for the first frame written to the SSR (due to the wait until the first 1PPS) and last frame written to the SSR (due to a power off asynchronous with frame boundaries) to be incomplete.

When REX data are stored to the SSR using compression, C&DH processing logic assumes complete frames. Thus, when C&DH tries to compress REX data with incomplete frames, it logs an error. Once this behavior was recognized (after 05 March 2007) REX data were always downlinked in packetized formats (Application Process Identifiers. ApIDs - 0x7b1 or 0x7b3) rather than compressed formats (ApIDs 0x7b0 or 0x7b2). N.B. ApIDs are case insensitive.

REX Time Tags are used to keep track of REX Output Frames (ROFs) by incrementing ten times within each frame and continuing to increment once between consecutive frames. Inconsistencies in the Time Tags can be used to locate errors due to the REX data compression issue and any other corrupt frames. Any such frames are listed in file ERRATA.TXT in the PDS3 data set. All current data set versions do not contain any. Such frames are rare, so ignoring those frames will not significantly affect REX data analysis.

Detector & Electronics - Flight Element

The amplifier chain is a conventional heterodyne design (see the figure below). The noise performance of the receiver has been improved over previous implementations by locating the leading low-noise amplifier (LNA) close to the antenna to reduce the effective temperature of the wave guide connecting the LNA to the high-gain antenna (HGA). The various mixing frequencies, fLO, for the intermediate frequency (IF) amplifier stages are derived from the USO, as are the clock reference frequencies used to drive the analog-to-digital converter. The REX portion of the system, which follows the 4.5 MHz buffer and anti-aliasing filter, is made up of an analog-to-digital converter (ADC) which feeds a triply redundant programmed gate array (FPGA). This gate array implements the two data processing functions required by the REX experiment. These are i) calculation of the total power in the 4.5 MHz bandwidth containing the uplink signal that enters the antenna, and ii) processing of the 4.5 MHz data stream to isolate the 1 kHz portion of the frequency spectrum containing the occultation signals in order that these can be returned to the ground efficiently. The output of both processes is passed to the NH on-board data memory for later transmission to Earth.

```
 ____________________________NH Receiver___________________________
/                                                                  \

 HGA
\             _    +---------+   _   +-------------------> To NH Command
 \   +---+   / \   |  IF     |   / \  |                     & Tracking
+-)--|LNA|-->|X|-->|Amplifier|-->|X|--+
 /   +---+   \_/   | Chain   |   \_/  |   +-------------+
/             ^    +---------+   ^   +-->|4.5MHz Filter|--> To REX
 7.2Ghz       |f                  |f      +-------------+
 from DSN     | LO                | LO
              |   1               |   final
              |     +---+         |
              +-----|   |---------+
                    +---+
                      ^
 ____________________ | _____REX Signal Conditioning____________________
/                     |                                                 \
                     ~~~

           ==========REX Hardware==========================
           [                                              ]
           [              = = =FPGA = = = = = = = = = = = ]
           [                                              ]
           [              [                             ] ]
           [                      +----------+            ]
           [              [       |4MHz Power|          ] ] 10 samples/1024ms
f  =2.5MHz [  +--------+       +-->|Integrator|--(/40)-+   ] @ 5 bytes/sample
 IF        [  |  ADC   |  [   |   +----------+        | ] ]
from  ------->|(T ,f )|-(/12)-+                       +--------> To NH SSR
4.5MHz     [  |  s  s |  [   |   +----------+        | ] ]
Filter     [  +--------+       +-->|~1kHz I&Q |--(/16)-+   ] 1250 complex
           [              [       |Digital   |        | ] ] samples/1024ms
           [                      |Filter    |--(/16)-+   ] @ 2*2 bytes/sample
           [              [       +----------+          ] ]
           [                                              ]
           [              = = = = = = = = = = = = = = = = ]
           [                                              ]
           ================================================
                ^
                |    ~~~
                |     |
 ______________ | ___ | _____USO Frequency Distribution_______
/               |     |                                       \
  =====         |     |
 ( USO )--------+-----+----> to Transceiver
  =====
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See also the description above and Tyler et al. (2008), which contains a better figure than can be achieved by the ASCII graphics used above.

Operational Modes - REX

There are three controls on the REX hardware: the power; the input signal source; a gain control. REX generates 1250 IQ sample pairs and 10 cumulative radiometry values per ROF any time it is powered on. In addition to the HGA signal, REX can also be commanded to process any of a set of internal test patterns stored in the REX signal processor: impulse response; three square waves of different frequencies; two pseudo-random number sequences of different amplitudes; all zeros. The gain control is an integer value that is kept track of via monitoring of uplink commanding; there is no feedback of the gain setting in the data downlink. The gain control affects the radiometer calibration only; it does not affect the IQ calibration.

The phrases 'REX mode' and 'Radiometry mode' are used in several documents; they do not refer to specific instrument modes or configurations, but rather to specific types of observation and whether the IQ pair or the radiometery values are the focus of the observation. Although they are not strictly operational modes, they are defined here for convenience.

1) REX mode for occultation studies.

Returns 16-bit In-phase and Quadrature (I&Q) ADC value pairs from the input signal. The input signal is normally from the HGA by way of the receiver electronics, but the input select command can make REX use any of seven internally generated signals, for which the results can be compared with deterministic results to ensure consistent operation of REX.

2) Radiometry mode for surface temperature measurement.

At those times when the New Horizons spacecraft high gain antenna (HGA) points toward Pluto or Charon, the REX instrument, operating in a 'radiometry mode,' will receive 7.2 GHz thermal radio emission from the two bodies. Opportunities to observe radio thermal emission occur during the several minutes of radio occultation measurements when the disks of Pluto and Charon obscure the Earth. The REX instrument will detect radiation from the obscuring body as an increase in the radio system noise level in the radiometry channel and also an increase in the noise floor of the occultation channel. These observations will be used to derive the nightside emission temperatures of Pluto and Charon. Similar observations will be taken of the day side emission temperatures on approach for comparison.

See Tyler et al. (2008) for further details.

Measured Parameters - REX

1) Instantaneous strength of

- uplink baseband signal, heterodyned by the Intermediate Frequency (IF) amplifier, a conventional design, to an intermediate frequency of 2.5MHz, and passed through a 4.5Mhz filter,
- sampled at 10 Msample/s,
- downconverted and output as I&Q value pairs
- at a rate of 1250 I&Q value pairs per 1.024s.

The process of down conversion from 10 Msample/s is accomplished by digitally shifting to zero frequency the uplink carrier signal centered initially at the 2.5MHz IF center frequency, followed by use of time-invariant baseband filters to reduce the bandwidth. The details are too extensive to include here, but are explained in detail in Tyler et al. (2008).

2) Integrated power

- cumulative over 1.024 seconds,

- reset every 1.024 seconds,
- at 10 samples per 1.024 second.

The REX power integrator (see the figure above) follows the conversion of the uplink NH transceiver signal to 10 bit digital samples. These data are passed to the REX processor at a rate of 10 Msample/s, where they are processed to extract the total power in the input stream. This is accomplished by squaring and averaging input samples over 102.4ms for each output sample, as

$$P_{UP}(k) = \sum_{i=1}^{kN} s(i)^2$$

where

```
  s(i)     = one input sample (12 bit register, 10Ms/s)

  P  (k)   = one output power sample @ 40 bits
   UP

  k        = the index of one output sample, 1 to 10
  i        = the index of the input samples
  N        = the number of input samples included in 102.4ms
```

See Tyler et al. (2008) for further details.

Absolute time of Time Tags and Radiometry (10 samples per ROF)

The Time Tags are absolute counters, starting at 0 for the START_TIME from PDS label of the first ROF in a run of ROFs, and increment every 102.4ms.

The raw radiometer values accumulate squared ADC measurements over each ROF, with the first raw radiometer value, in any ROF after the first ROF, representing the accumulation for the preceding ROF. So the midpoint of the time period represented by each raw radiometer value is halfway between the time of the corresponding time tag and the previous START_TIME. This means the midpoint for the first accumulated value, in any raw or calibrated (cal) ROF after the first ROF, is 512ms before START_TIME i.e. in the middle of the previous ROF. The midpoint of the time period of the calibrated radiometer values, except the first in each ROF, is 51.2ms before the time of the corresponding time tag value.

The items above are spelled out in the following table indicating the absolute timestamp for each of the column values in the ten rows of the EXTENSION_RAD_TIME_TAGS_TABLE OBJECT of the data files, where

S0 = START_TIME (in the PDS label)

Index	Time Tag time	Raw radiometer time	Cal radiometer value
0	S0 + 0.0ms	S0 - 512.0ms	S0 - 512.0ms
1	S0 + 102.4ms	S0 + 51.2ms	S0 + 51.2ms
2	S0 + 204.8ms	S0 + 102.4ms	S0 + 153.6ms
3	S0 + 307.2ms	S0 + 153.6ms	S0 + 256.0ms
4	S0 + 409.6ms	S0 + 204.8ms	S0 + 358.4ms
5	S0 + 512.0ms	S0 + 256.0ms	S0 + 460.8ms
6	S0 + 614.4ms	S0 + 307.2ms	S0 + 563.2ms
7	S0 + 716.8ms	S0 + 358.4ms	S0 + 665.6ms
8	S0 + 819.2ms	S0 + 409.6ms	S0 + 768.0ms
9	S0 + 921.6ms	S0 + 460.8ms	S0 + 870.4ms

Absolute time of IQ pairs (1250 sample pairs per ROF)

The timestamp apropos the first IQ pair in a ROF is (1024/1250)ms before the START_TIME of that ROF; the timestamp of any other IQ pair is (1024/1250)ms after the previous IQ pair.

Instrument Overview - DSN

Three Deep Space Communications Complexes (DSCCs) (Barstow, CA; Canberra, Australia; and Madrid, Spain) compose the Deep Space Network (DSN). Each complex is equipped with several antennas, associated electronics, and operational systems. Transmission and reception are possible in several radio frequency bands; REX uses X-band (7100-8500 MHz, or 4.2-3.5 cm).

The DSN is managed by the Jet Propulsion Laboratory (JPL), California Institute of Technology, for the U.S. National Aeronautics and Space Administration (NASA).

For more information on the DSN and its use in Radio Science see Asmar & Renzetti (1993). For design specifications on DSN subsystems see [DSN810-5].

REX Use of the DSN

When REX measures signals transmitted by the DSN, the transmitted frequency is corrected for station motion (e.g., Earth orbit and rotation) and spacecraft motion so that the signal received at the spacecraft is within a narrow fraction (a few hundred Hertz) of the 2.5 MHz IF.

For REX occultations, the DSN provides a frequency ephemeris (a description of the transmitted frequency as a series of linear ramps) in Tracking and Navigation Files (TNFs). REX radiometry observations do not require DSN signals. Hence, Tracking and Navigation Files (TNF) are not required prior to arrival at Pluto, other than for Lunar occultations in 2011 and 2014.

In general, any time REX was using DSN uplink signals, the DSN transmitted the polarization of uplink signal(s) apropos the REX Sides (A and/or B) that were in operation at that time. That is, when only Side A was on, the DSN transmitted RCP uplink signal; when only Side B was on, the DSN transmitted LCP uplink signal; when both Sides A and B were on, the DSN transmitted both RCP and LCP uplink signals.

The DSN also provides troposphere and spacecraft-specific ionosphere calibration files in TRK-2-23 file format. Each file contains calibrations for one month. Troposphere calibration files cover 24 hours per day, while ionosphere calibration files cover every possible tracking pass throughout the month. Station (antenna) coordinate information is available in DSN Telecommunications Link Handbook document 810-005, module 301. Refer to the TRK-2-23 media calibration guide for further details and usage.

Subsystems - DSN

The DSCCs are an integral part of Radio Science instrumentation. The following paragraphs describe the functions performed by individual subsystems of a DSCC. For additional information, consult [DSN810-5].

Each DSCC includes a set of antennas, a Signal Processing Center (SPC), and communication links to JPL. The following table lists some of the DSN antennas available to REX. The Deep Space Station (DSS) nomenclature has been carried over from earlier times when antennas were individually instrumented.

Antenna	GOLDSTONE SPC 10	CANBERRA SPC 40	MADRID SPC 60
34-m HEF	DSS 15	DSS 45	DSS 65
34-m BWG	DSS 24	DSS 34	DSS 54
	DSS 25	DSS 35	DSS 55
	DSS 26	DSS 36	
34-m HSB	DSS 27		
	DSS 28		
70-m	DSS 14	DSS 43	DSS 63
Developmental	DSS 13		

Antennas are grouped above by diameter and design. HEF is high efficiency, BWG is beam waveguide, and HSB is high-speed BWG.

DSCC Receiver-Exciter Subsystem

The receiver-exciter subsystem is split into the exciter component (UPL for Uplink Subsystem) and a separate receiver component, not used by REX. The UPL comprises the Exciter, the Command Modulation, the Uplink Controller, and the Uplink Ranging assemblies. The exciter generates a sky-level signal, which is provided to the Transmitter Subsystem (TXR) for transmission to the spacecraft. It is tunable under command of a Digitally Controlled Oscillator (DCO).

DSCC Transmitter Subsystem

The Transmitter (TXR) Subsystem accepts a sky-level frequency signal from the Uplink Subsystem exciter. This signal is routed via the diplexer through the feed horn to the antenna, where it is then focused and beamed to the spacecraft.

The Transmitter Subsystem power capabilities range from 18 kW to 400 kW, for S- and X-band uplink. Power levels above 20 kW for NH REX operations were supplied only from 70-m stations.

DSCC Monitor and Control Subsystem

The DSCC Monitor and Control Subsystem (DMC) is part of the Monitor and Control System (MON) which also includes the ground communications Central Communications Terminal (CCT) and the Network Operations Control Center (NOCC) Monitor and Control Subsystem. The DMC is the center of activity at a DSCC. The DMC receives and archives most of the information from the NOCC needed by the various DSCC subsystems during their operation. Control of most of the DSCC subsystems, as well as the handling and displaying of any responses to control directives and configuration and status information received from each of the subsystems, are done through the DMC. The effect of this is to centralize the control, display, and short-term archiving functions necessary to operate a DSCC. Communication among the various subsystems is done using a Local Area Network (LAN) hooked up to each subsystem via a network interface unit (NIU).

The DSCC Monitor and Control (DMC) subsystem operations are divided into two separate areas: the Complex Monitor and Control (CMC) and the Network Monitor and Control (NMC). The primary purpose of the CMC processor for Radio Science support is to receive and store all predict sets transmitted from the Network Operations Control Center (NOCC) -- such as antenna pointing, tracking, receiver, and uplink predict sets -- and then, at a later time, to distribute them to the appropriate subsystems via the LAN. The NMC processor provides the operator interface for monitor and control of a link -- a group of equipment required to support a spacecraft pass.

DSCC Tracking Subsystem

All Tracking Subsystem (DTK) functions are incorporated within the UPL and the Downlink Tracking and Telemetry Subsystem (DTT). The primary functions of the DTK are to acquire and maintain communications with the spacecraft and to generate and format radio metric data containing Doppler, range, and uplink frequency ramps. Only the ramps are used for REX.

In addition, the Tracking Subsystem receives from the CMC uplink tuning predicts (used to program the DCO). From the (NMC, it receives configuration and control directives, as well as configuration and status information on the transmitter, microwave, and frequency and timing subsystems.

DSCC Frequency and Timing Subsystem

The Frequency and Timing Subsystem (FTS) provides all of the frequency and timing references required by the other DSCC subsystems. It contains four frequency standards, of which one is prime and the other three are backups. Selection of the prime standard is done via the CMC. Of these four standards, two are hydrogen masers followed by clean-up loops (CUL) and two are cesium standards.

Allan Deviations of the signals sent to REX (derived from FTS) are:

Integration Time (seconds)	Allan Deviation
1	2E-13
10	8E-14
100	2E-14
1000	4E-15

Optics - DSN

X-Band performance of the DSN ground stations depends primarily on the size of the antenna and capabilities of the electronics.

Antenna Performance

Performance of antennas is summarized in the following table. Beamwidth is half-power full angular width. Polarization is circular; X-Band can transmit either left or right circular polarization (LCP or RCP, respectively).

DSS X-Band Characteristics

Transmit	70-m	34-m BWG	34-m HEF
Frequency (MHz)	7145-7190	7145-7190	7145-7190
Wavelength (m)	0.042	0.042	0.042
Ant Gain (dBi)	73	67	67
Beamwidth (deg)	0.038	0.077	0.077
Polarization	L or R	L or R	L or R
Tx Power (kW)	>=20	20	20

Although some 34-m antennas were either upgraded or in the process of being upgraded during Pluto Encounter, only 70-m antennas were used to transmit at powers above 20kW for NH REX operations.

Antenna Pointing

Pointing of DSCC antennas may be carried out in several ways. In conscan mode antenna pointing is offset slightly, following a conical path around the nominal direction during routine uplink commanding and telemetry reception. The slight signal degradation during one time interval is used to correct the pointing for the next. In planetary mode, the system interpolates from three (slowly changing) RA-DEC target coordinates; this is 'planetary' pointing since there is no feedback from a detected signal. In sidereal mode, the antenna tracks a fixed point on the celestial sphere. In precision mode the antenna pointing is adjusted using an optical feedback system. REX uses only planetary pointing.

Calibration - DSN

Calibrations of hardware systems are carried out periodically by DSN personnel; these ensure that systems operate at required performance levels - for example, that antenna patterns, receiver gain, and propagation delays meet specifications. Additional information may be available in [DSN810-5].

Location - DSN

Accurate analysis of REX occultation data requires knowledge of the locations of the DSN tracking stations. The coordinate system in which the locations of the tracking stations are expressed should be consistent with the reference frame definitions used to provide Earth orientation calibrations.

The International Earth Rotation Service (IERS) has established a terrestrial reference frame for use with Earth orientation measurements. The IERS issues a new realization of the terrestrial reference frame each year. The definition of the coordinate system has been changing slowly as the data have improved and as ideas about how to best define the coordinate system have developed. The overall changes from year to year have been at the few-cm level. Refer to [DSN810-5] section 301 or the Navigation and Ancillary Information Facility (NAIF) at JPL SPICE kernels (Steffel et al. (2007)) for the latest locations; the values provided here are only provided as examples.

The DSN station locations have been determined by use of VLBI measurements and by conventional and GPS surveying.

The DSN Station Locations in ITRF1993 Cartesian reference frame at the epoch noted (assuming subreflector-fixed configuration) are as follows:

Antenna	**x (m)**	**y (m)**	**z (m)**	**Epoch**
DSS 13	-2351112.491	-4655530.714	+3660912.787	1993.0
DSS 14	-2353621.251	-4641341.542	+3677052.370	1993.0
DSS 15	-2353538.790	-4641649.507	+3676670.043	1993.0
DSS 34	-4461146.720	+2682439.296	-3674393.517	1993.0
DSS 35	-4461273.0838	+2682568.9220	-3674152.0885	2003.0
DSS 36	-4461170.2358	+2682816.0240	-3674085.9737	2003.0
DSS 43	-4460894.585	+2682361.554	-3674748.580	1993.0
DSS 45	-4460935.250	+2682765.710	-3674381.402	1993.0
DSS 63	+4849092.647	-0360180.569	+4115109.113	1993.0
DSS 65	+4849336.730	-0360488.859	+4114748.775	1993.0

Acronyms And Abbreviations - DSN

ACS Antenna Control System
ADC Analog-to-Digital Converter
AGC Automatic Gain Control N.B. REX gain is not automatic

ATDF	Archival Tracking Data File
AUX	Auxiliary
BPF	Band Pass Filter
bps	bits per second
BVE	Block V Exciter
BVR	Block V Exciter
BWG	Beam WaveGuide (antenna)
CCT	Central Communications Terminal
CDU	Command Detector Unit
CMC	Complex Monitor and Control
CRG	Coherent Reference Generator
CSO	Compensated Sapphire Oscillator
CUL	Clean-up Loop
DANA	a type of frequency synthesizer
dB	deciBel
dBi	dB relative to isotropic
dBm	dB relative to one milliwatt
DCO	Digitally Controlled Oscillator
DEC	Declination
deg	degree
DMC	DSCC Monitor and Control Subsystem
DOD	Differential One-Way Doppler
DOR	Differential One-way Ranging
DSCC	Deep Space Communications Complex
DSN	Deep Space Network
DSS	Deep Space Station
DTK	DSCC Tracking Subsystem
DTT	DSCC Downlink Tracking and Telemetry Subsystem
E	east
EL	Elevation
FTS	Frequency and Timing Subsystem
GHz	Gigahertz
GPS	Global Positioning System
HEF	High-Efficiency (as in 34-m HEF antennas)
HGA	High-Gain Antenna
HSB	High-Speed BWG
I	In-phase
IERS	International Earth Rotation Service
IF	Intermediate Frequency
IVC	IF Selection Switch
JPL	Jet Propulsion Laboratory
K	Kelvin
kbps	kilobits per second
LCP	Left-Circularly Polarized

LGA	Low-Gain Antenna
LMC	Link Monitor and Control
LNA	Low-Noise Amplifier
LO	Local Oscillator
Ms/s	Million samples per second
m	meters
MCA	Master Clock Assembly
MDA	Metric Data Assembly
MHz	Megahertz
MON	Monitor and Control System
MSA	Mission Support Area
N	north
NH	New Horizons
NMC	Network Monitor and Control
NOCC	Network Operations and Control System
NRV	NOCC Radio Science/VLBI Display Subsystem
NSS	NOCC Support Subsystem
OCI	Operator Control Input
PDS	Planetary Data System
Q	Quadrature
RA	Right Ascension
REC	Receiver-Exciter Controller
REX	Radio Science Experiment (a New Horizons instrument)
RCP	Right-Circularly Polarized
RF	Radio Frequency
RFE	(Probe) Receiver Front End
RFIS	Radio Frequency Instrument Subsystem
RFS	Radio Frequency Subsystem
RMS	Root Mean Square
SPC	Signal Processing Center
sps	samples per second
SRA	Sequential Ranging Assembly
SSR	Solid State Recorder or Space Science Reviews, (publication journal)
TBD	to be determined
TDDS	Tracking Data Delivery Subsystem
TID	Time Insertion and Distribution Assembly
TLM	Telemetry
TLP	Telemetry Processor
TNF	Tracking and Navigation File
TWM	Traveling Wave Maser
TXR	Transmitter (subsystem)
UNK	unknown
UPL	DSCC Uplink Subsystem
USO	UltraStable Oscillator

UTC	Universal Coordinated Time
VLBI	Very Long Baseline Interferometry
X-band	approximately 7800-8500 MHz

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