The Radioscience Experiment on New Horizons

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Abstract

REX is the Radioscience Experiment in the payload on the New Horizons spacecraft en-route to its encounter with Pluto in July of 2015. REX will obtain the temperature and pressure profiles of Pluto's tenuous atmosphere while measuring radiometric temperature, gravitational moments and ionosphere structure. Additional targets of opportunity, at lower priority, include the search for an atmosphere at Charon, improved gravity precision and a bistatic surface scattering on Pluto. For all but radiometry, these measurements take advantage of a high-power, X-band uplink transmitted from the earth, received on the spacecraft with the aid of a high-gain antenna, a low-noise X-band receiver and an ultrastable oscillator (USO), as a frequency reference. This combination enables REX to sense Pluto's atmosphere with precision of ~ 0.1 Pa (1 μbar), and ~ 3 K, and a neutral number density of $4 \times 10^{19}/m^3$. Critical measurement techniques will be validated using results from the May 20, 2011, Lunar Occultation of New Horizons spacecraft.

1. Introduction

New Horizons is a NSAS mission to Pluto launched on January 2006, with a nine year cruise and intended encounter with Pluto on July 14, 2015. The spacecraft payload comprises a high resolution imaging camera, a visible, infrared and ultraviolet imaging spectrometer, particle instruments for both solar wind and energetic ions, a student built dust detector and a radioscience experiment, REX. The arrangement of these instruments on the spacecraft is illustrated in Figure 1.

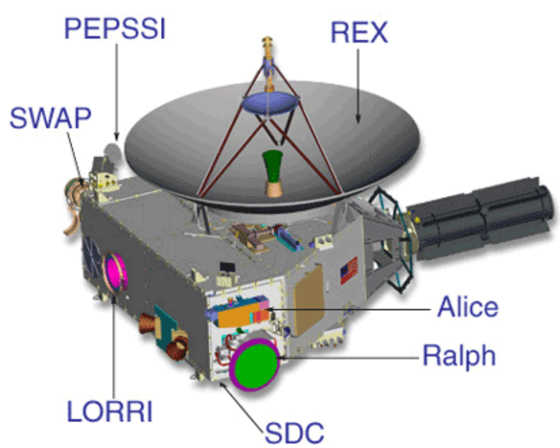

Figure 1. The New Horizons Spacecraft. The payload configuration of the principal instruments: REX – represented by the high gain X-band antenna; LORRI – the long range optical telescope; Alice and Ralph – the ultraviolet, optical and infrared imaging spectrometers; SWAP – the solar wind detector, PEPSSI – the energetic ion detector; SDC the student dust counter. [image courtesy NASA/APL]

In July of 2015, New Horizons will fly through the Pluto system. The encounter date was chosen to occur at a time of solar opposition, when the radio path from the Earth to the spacecraft possesses a minimum in the density

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fluctuations of interplanetary plasma and the uplink signal is accordingly the least perturbed in amplitude and phase [1]. The encounter with Pluto is organized into phases, (a) Approach, (b) Near, and (c) Departure, where REX is active in all three. The experiment with the highest priority for REX is the occultation of Pluto to obtain the profile of the refractivity of Pluto's atmosphere. Further, in each phase, REX will measure the radiometric temperature of Pluto and Charon. In the Near phase, REX will observe an additional occultation, that of Charon, to search for an atmosphere. During the fly-by, REX will measure the change in the spacecraft's velocity vector to separate the masses of Pluto and Charon. These experiments, with the exception of the radiometry, involve a seldom used uplink protocol, where high power, high stability, CW X-band signals are transmitted from Earth in both LHC and RHC polarizations and received on the spacecraft [2].

The uplink configuration affords REX a substantial improvement in sensitivity due to a higher signal to noise ratio (SNR), of the uplink protocol versus the more traditional downlink. The SNR improvement between uplink and downlink is canonically the ratio of the respective transmitter powers to the receiver noise figures. For REX where uplink power from NASA's Deep Space Network (DSN), stations is three orders of magnitude greater than the spacecraft's transmitter power, the SNR improvement makes possible the measurement of a very tenuous atmosphere at the great distance to Pluto.

2. Experimental Method

The spacecraft's velocity has a small transverse component on the plane of the sky as seen from earth. Thus the occultations occur after closest approach as the spacecraft departs and flies behind Pluto and Charon. From the spacecraft's point of view the uplink signal is occulted first by Pluto and then by Charon. The spacecraft high-gain antenna is pointed toward earth and REX records oppositely polarized uplink signals from independent transmitters during the entire interval of both occultations. REX captures the moments of ingress and egress for both Pluto and Charon and the fly-by has been designed to cut the object's discs at a near diametric chord. During the 'dark' intervals when the spacecraft is in the object's shadow, REX continues to record and thus obtains the backside radiometric temperatures.

When the REX data are later downlinked to the ground, the occultation data sets will be processed to first remove effects of limb diffraction and obtain the profile of refractivity [2]. The refractivity profiles are then transformed to profiles of atmospheric pressure and temperature. An especially high sensitivity is required for these measurements since the expected pressure on the surface of Pluto is in the range of 1-10 μbar (0.1 - 1 Pa), with a surface temperature of the order of 10's of K. With the Allen deviation of the USO's better than 3×10^{-13}, and the SNR of the uplink better than 55 dB/Hz, the accuracy of the REX measurements in pressure temperature, and neutral number density are respectively ~1 μbar (0.1 Pa), 3 K, and $4 \times 10^{19}/m^3$, which is adequate for measuring atmospheric pressure and temperature with scientifically useful precision.

Thermal radiation at 7.2 GHz, (4.2 cm wavelength), is readily detected by REX. The spacecraft's high gain antenna has a 3 dB beamwidth of 1.2 degrees (21 mrad), and the X-band receiver's noise temperature is 150 K. Thermal radiation illuminating the antenna and falling within the beamwidth appears in the radiometrics channel as additional noise power. REX processes the full bandwidth of 4.5 MHz of the radiometrics channels and forms total power averages at a rate of 10/sec, that are included in the REX data output. Thus thermal temperature of any object fully illuminating the high gain antenna can be measured from the REX total power averages with a temperature resolution limited by the integration time and the gain stability of the X-band receiver. Measurements both before launch and in cruise demonstrate this temperature resolution to be 70 mK on time intervals of one second. During closest approach the HGA will scan Pluto's disk to profile the temperature at 4.2 cm. During this scan the geometry is favorable for catching bistatic scattering from Pluto's surface.

3. REX Design and Implementation

The spacecraft high-gain antenna has a dual polarization feed, RCP and LCP, and in the X-band receiver the uplinks are heterodyned in separate polarization channels using the USO's as frequency references. The uplink's frequency is ramped at the transmitter to compensate for Earth and spacecraft motion-related Doppler shifts, maintaining the uplink signals within 600 Hz of the center of the radiometrics channel. Both channels are sampled in parallel, with the USO reference, at the Nyquist rate, and input to REX where each polarization is digitally downconverted in parallel REX channels, or "sides" to a 1.2 kHz total, 0 Hz centered baseband and resampled. The functional organization of the REX signal processing is shown in Figure 2.

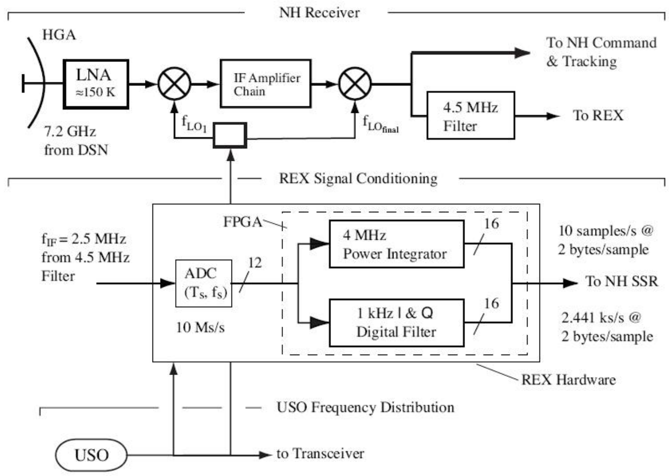

Figure 2. Block Diagram of the signal processing in the REX Instrument contained in the X-band Receiver. Only one side of REX is illustrated. REX consists of two identical subsystems, one associated with the RHC polarization and the other associated with the LHC polarization.

The frequency references on the spacecraft used for heterodyning, and sampling are derived from ultrastable crystal oscillators (USO's). The two side of the REX radio system are referenced by separate USO. The frequency stability at launch of the USO's exhibited Allen Deviations of ~3 x 10^{-13}, on intervals of one second, while post-launch the stability has improved to ~2 x 10^{-13}, on the same interval. The stability of the received and processed uplinks possess this same reference stability and thus phase shifts and frequency perturbations in excess of this amount are measureable contingent on adequate strength of the uplink signal. By taking advantage 10-20 kw transmitters operated by NASA's Deep Space Network (DSN), the uplink signal strength relative to the noise power density in New Horizons X-band Receiver at the distance of Pluto is at least 55 dB/Hz. An example of the frequency spectrum of the uplink signal as captured in REX during the CY 2010 Annual Checkout (ACO), is shown in Figure 3.

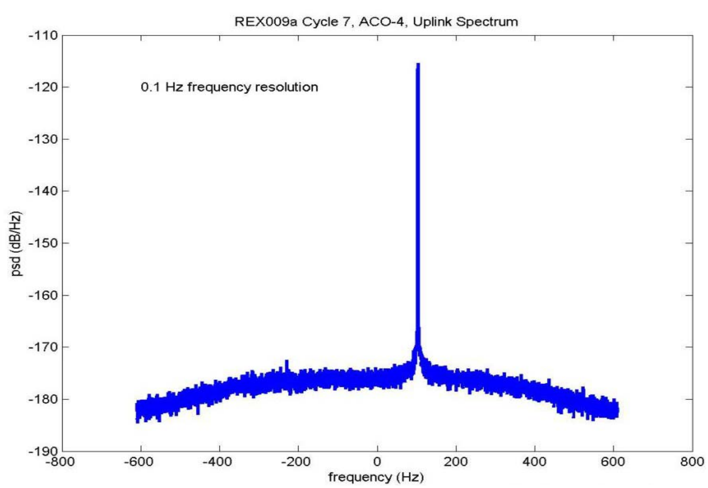

Figure 3. Uplink signal frequency spectrum. The X-band uplink, received in New Horizon receiver is downconverted to baseband in REX, sampled at the Nyquist rate of 1250 samples/sec, with 16-bit precision for multiple epochs of 100 seconds. The samples are stored in the spacecraft's solid state recorder and subsequently downlinked to Earth. For this spectrum, multiple 10 second intervals of samples were Fourier transformed and averaged producing a power spectral density profile. The uplink power is contained within a few 0.1 Hz resolution bins, and the noise floor is smooth at ~70 dB below the uplink peak in the 0.1 Hz bins.

The Annual Checkouts for New Horizons verify functionality and performance of the payload. During the ACO's, REX receives, samples and stores multiple epochs, typically 100 seconds each in duration, to provide the basis for evaluating uplink signal integrity, USO stability, and the character of the radio path from the earth. An example of the Allen deviation formed from frequency estimates of the uplink signal is in Figure 4.

At X-band, the USO stability effects the uplink's signal estimated frequency with changes of ~1.5 x 10^{-3} Hz (1.5 mHz), or 0.01 radians of phase shift in one second, which is commensurate with the uplink SNR. This affords at Pluto a precise measurement of the bending angle of the uplink ray path in Pluto's tenuous atmosphere. For example, with the spacecraft travelling at 14 km/sec (3.5 km/sec, plane of the sky), a 1.5 mHz frequency shift would be the consequence of bending the uplink rays by an angle of 16×10^{-9} radian.

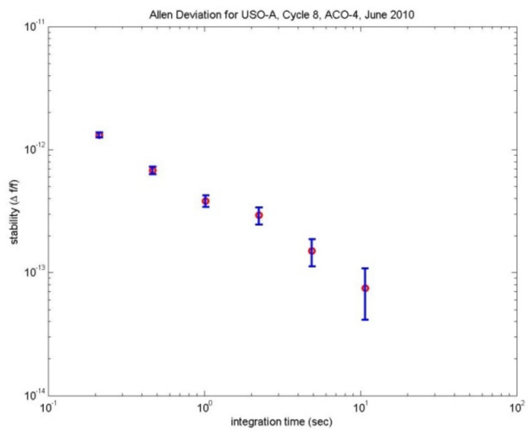

Figure 4. Allan deviation for USO-A. Estimates of the uplink frequency are determined from the REX samples and standard deviations (STD's) of the estimates, relative to the uplink's frequency, are formed over a set of time intervals (i.e. integration times, τ). At short integration times the STD's exhibit the expected 1/sqrt(τ) behavior.

4. Lunar Occultation

In its nine year journey to Pluto, New Horizons has encountered only Jupiter and its moons. The path to Pluto excluded any favorable geometry for an occultation, and a commensurate opportunity to validate the methods and occultation performance for REX. Fortuitously, the Earth's moon will occult the spacecraft three times between March 2011, and January 2012. On May 20th, 2011, one such occultation will occur and operations coordinated between the New Horizons Mission Operations Team and NASA's DSN station in Madrid. A high power uplink will be transmitted to the spacecraft in both polarizations, with REX operating and the spacecraft recording during the entire interval from ingress to egress of the lunar occultation. REX data downlinked from the lunar occultation will be processed to validate REX performance, diffraction compensation and occultation inversion and transformation methods. Example results will be available at the time of presentation.

This work is support by NASA's Office of Space Science. Much appreciation and gratitude goes to Johns Hopkins Applied Physics Laboratory, particularly the Radio Receiver Group, and the New Horizons Mission Operations Team, as well as Southwest Research Center, Boulder, CO, and Director Alan Stern.

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