REX Radiometer Calibration at 4.2 cm on New Horizons

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Abstract

REX is the **R**adioscience **Ex**periment on-board New Horizons. One part of the REX investigation, referred to as REX radiometry, is the measurement of total RF power in two polarizations at X-band for radio frequencies illuminating the spacecraft's 2.1 m high gain antenna (HGA). The conversion of REX samples to physical units of RF power and equivalent temperature incorporates a scaling procedure with coefficients that were determined during pre-launch Integration and Test, as well as the spacecraft's Commissioning after launch in April 2006 and anadditional Calibration Campaign in July 2016.

an additional

also June 2006?

Use of punctuation (especially commas) is unconventional throughout. For example, commas often appear before and/or after terms that have already been set off by parentheses (e.g., captions for Figures 2.0.1a and 2.0.1b).

Is this available? If so, it should be included in the calibration report. It would set a useful lower bound on the in-flight noise temperature.

1.0 Introduction

Radiometric measurement of total X-band power with REX, the **R**adioscience **Ex**periment on-board New Horizons, is performed using the spacecraft's high gain antenna (HGA) with right-hand circular and left-hand circular polarization feeds, the spacecraft's two X-band receivers, with dedicated radiometric channels for each polarization, and dual REX processors. REX digitizes at Nyquist sample rates and computes the total RF power in each of the two polarization channels of the spacecraft's X-band receiver.

The total RF power in REX digitized units is converted to RF power in physical units, such as dBm and an equivalent temperature in K. The coefficients necessary for this conversion process were determined in four calibrations performed over the course of the mission. The first calibration performed before launch measured the HGA's response and the receiver noise temperature without the HGA. The second calibration was performed during the Commissioning of the New Horizons Spacecraft after launch during April and June 2006. An important third calibration occurred during the Pluto Encounter with a serendipitous measurement of the total power from the sun. A fourth, post-Pluto encounter calibration was performed during a dedicated Calibration Campaign, in July 2016. During these calibrations REX measured (a) X-band receiver stability, (b) X-band receiver linearity, (c) the High Gain Antenna (HGA) response, (d) radio sky background, (e) standard radio source power, and (f) total power from the Sun.

Not consistent with Apr 2006 and Jul 2016 in abstract(?)

Check dates

HGA

Section 2.0, describes the overall measurement objectives, and Section 2.1, presents the X-band receiver stability determination, Section 2.2, the X-band receiver linearity, Section 2.3, the HGA response, Section 2.4, determination of the radio sky background, Section 2.5, measurements of total X-band RF power from radio astronomy standard sources, and Section 2.6, measurements of the total power from the sun. Section 3.0, integrates the measurements presented in Section 2, into the determination of the coefficients to convert from REX units to physical units of RF power illuminating the HGA, and Section 4.0, provides an example of the conversion procedure using the calibration constants. This paragraph contains only two sentences, which are very awkwardly punctuated and difficult to understand.

2. Radiometric Characteristics of the REX Receivers

2.0 X-band Receiver Stability

The statistical lower bound for the precision of a REX thermal measurement, with an integration time of one second, is 0.07 K. This derives from the REX 4.5 MHz bandwidth Radiometrics Channel,(with greater than Nyquist sampling of 10 Msamples/sec), and the ~150 K, noise temperature of the New horizon X-band receiver. To realize this lower bound, the gain of the receiver must be stable enough that the effective noise temperature variations of the receiver are significantly smaller than 0.07 K on a time scale of ~1 second.

Channel with

and the ~150 K

Horizons

0.07 K is the theoretical precision of a REX thermal measurement over 1 second. However, the data in Figure 2.0.1 imply that the actual precision is a factor >3 worse (the ratio 2121/642 in RCP and the ratio 2121/578 in LCP). Is it possible that the data in the figure are 0.1 s integrations? If so, that changes a lot of the work in this report and its review.

"[A]t least once per year during … cruise" seems inconsistent with the "four calibrations" listed on page 2 and the two specific months given in the Abstract?

In order to assess the receiver's stability the gain variation was measured regularly, on a cadence of at least once per year, during New Horizons' cruise to Pluto. For this measurement the HGA was pointed to a position on the sky with the lowest X-band brightness temperature. This location, called 'Cold Sky', with coordinates RA 15.2 degrees, and DEC, -8.1 degrees, and an X-band noise temperature of 2.7 K, very near the lower limit afforded by the Cosmic Microwave Background, and over an angular size significantly larger (i.e ~10x), than the 3 dB angular diameter of the HGA (i.e. 1.2°). The spacecraft pointing was controlled within a deadband of 0.1°, when REX acquired radiometric data. The REX data acquisition duration was typically 1000 seconds.

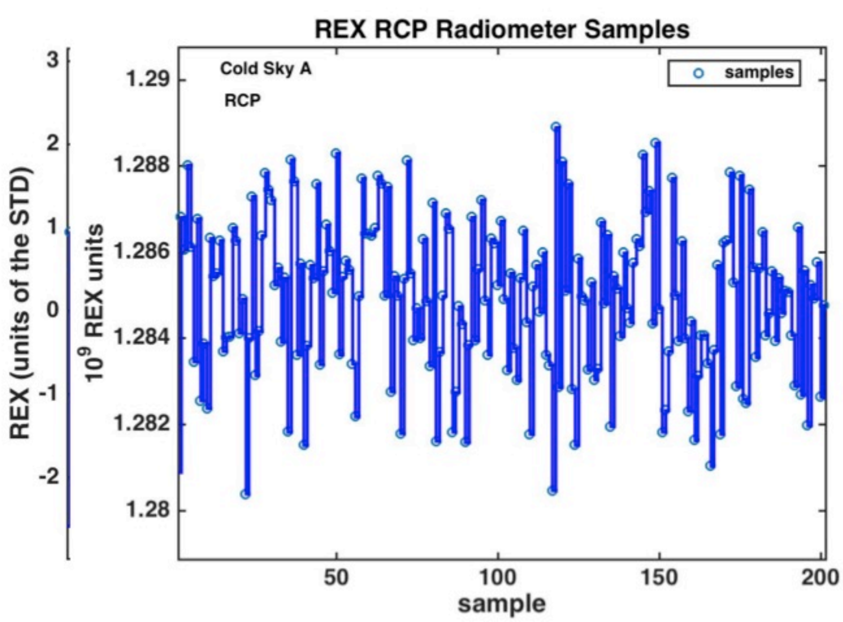
(i.e.,

Other "cold sky" targets — A, B, and C — are mentioned later. But this one is in a completely different part of the sky. When was 'Cold Sky' used and when were A, B, and C used?

The stability of the X-band receiver's radiometrics channel is evaluated from the fluctuation distributions of the REX Cold Sky radiometer data. The shape of the distribution as well as the mean and standard deviation (STD), is computed for dyadically scaled integration times from a single sample to a few 100 seconds.

The variation of REX radiometric power and its fluctuation distribution are illustrated with the set of figures 2.0.1 to 2.0.3. REX computes the square magnitude of Nyquist sampled RF voltages in the X-band receiver's Radiometrics channel. These samples are digitized at 10 Msamples/sec, and accumulated in REX on a 0.1 s cadence. The accumulated sum is recorded 10 times per REX frame. The REX frame rate is one frame every 1.024 seconds. As an example, the first ~200 radiometer samples on a one-second cadence are shown in Figure 2.0.1.a, (RCP channel), and Figure 2.0.1b, (LCP channel).

2.0.1.b



Date/Time of measurements?

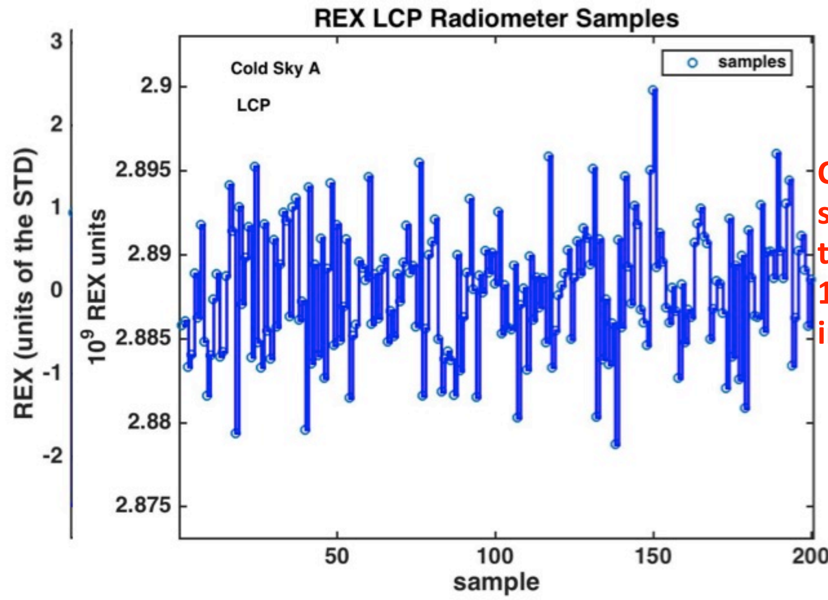
Figure 2.0.1.a. Samples of total power for REX radiometric channel A, (RCP). HGA pointing to Cold Sky. The total power is in 10^9 REX engineering units. An additional

A

Cold Sky A?

scale has been added in units of the standard deviation (STD) of the total power samples. One STD is 0.002 x 10^9 REX units, or 1/642 of the mean total power.

the measured standard deviation



Clarifying that STD is the MEASURED standard deviation is important. The theoretical standard deviation is 1/2121 of the mean for 4.5 Msps in both polarizations.

Figure 2.0.1.b. Samples of total power for REX radiometric channel B, (LCP). HGA pointing to Cold Sky. The total power is in 10^9 REX engineering units. An additional scale has been added in units of the standard deviation (STD) of the total power samples. One STD is 0.005 x 10^9 REX units, or 1/578 of the mean total power.

B

Cold Sky A?

the measured standard deviation

The samples are displayed in "REX units", and scaled by their standard deviation (STD). For the latter, the samples appear to be random samples from an apparent Gaussian distribution with a mean of ~1.285×10^9, for RCP, and ~2.885×10^9, for LCP, and the width of the STD. The approximately 2x difference of the mean power between RCP and LCP is due to a higher gain setting of LCP relative to RCP.

their measured standard deviations

The REX samples are expected to form a normal distribution if the RF power sampled by REX is from the illumination on the HGA of thermal radiation with a black-body spectrum. Further the RF power distribution's STD should scale with the equivalent black-body temperature of the source of the thermal radiation. Thus the shape of the distribution of REX samples of total power in the radiometrics channels should reveal if the combined radiation from Cold Sky and noise from the X-band receiver are consistent as having come from a thermal process with a black-body spectrum. By way of confirmation, the distribution of REX total RF power, formed from samples such as in figure 2.0.1, is presented in Figure 2.0.2.a for the RHC polarization channel, and in Figure 2.0.2.b, for the LHC polarization channel. A best-fit Gaussian is overlaid in each of the plots. The statistical confidence, a chi-squared value is added in red font. The chi-square is the mean of the fit's residuals weighted by the statistical uncertainty of the population of each histogram bin.

RCP

LCP

value,

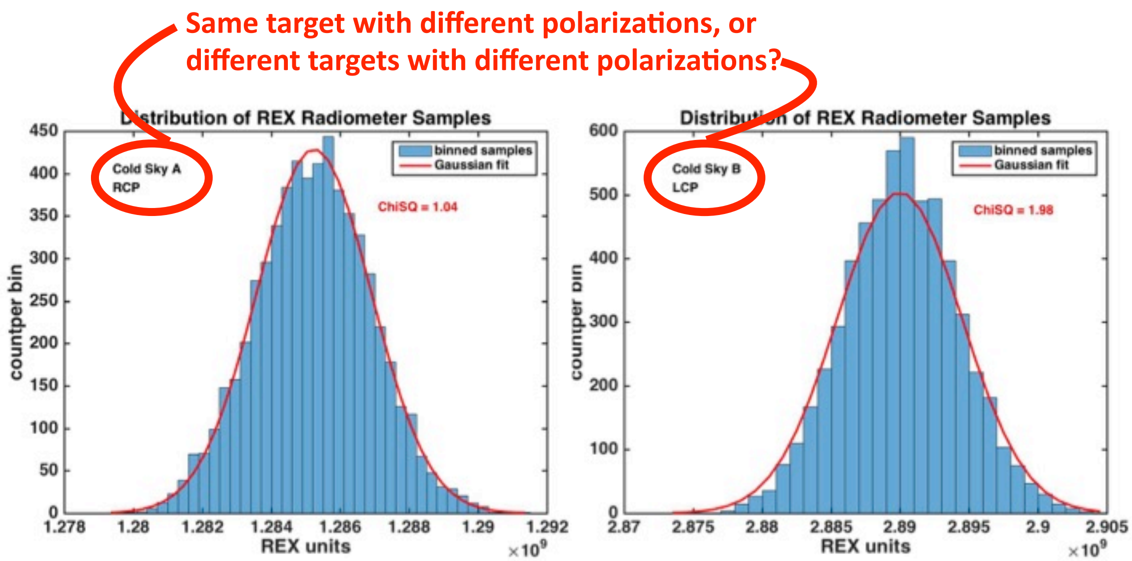


Figure 2.0.2. Distribution of the REX samples of total power with Gaussian fits in the X-band Receiver's radiometric channels.

This chi-square is 1.04, and 1.98, for the RHC and LHC channels respectively in Figure 2.0.2, confirming the assumption of thermal black-body process. Consequently, the mean value of the REX samples is a statistically stable measure of the noise power, and the ratio of the STD to the mean should scale according to the 1/(square-root) of the number of samples used to compute the mean.

RCP and LCP
of a thermal

The extent of the scaling of the STD with (no. of samples)$^{-0.5}$ tests an additional assumption of the statistical independence of the REX samples. Hence, if the X-band receiver's gain is not constant, but varies perhaps slowly and by a small amount, then the REX samples will not be strictly independent, but possess a correlation on the time scale of the gain variation.

scaling of the STD with averaging interval, samples' standard deviations,

To evaluate the scaling the STD of the mean, the sample's standard deviation, σ_{STD}, of the REX radiometer samples from the cold sky targets are averaged over contiguous blocks of time. The REX samples are segmented into M sets of equal time intervals τ_a. where typically τ_a = 0.1 sec, the length of the Mth interval. The mean power is computed in each interval τ_a. and the STD of the means is computed over the set M. The length of the time interval is increased by a factor of two, and the process is repeated, for as long as the number of intervals M, is large enough for M to be statistically significant (i.e. M ≥ 4). The scaling of σ_{STD} with τ_a, for the Cold Sky data is shown in Figure 2.0.3.

noise, ,

From the behavior seen in Figure 2.0.3, REX's radiometer noise σ_{STD},, decreases with increasing integration time τ_a , as $1/\sqrt{\tau_a}$ for time intervals up to ~100 seconds. For longer time intervals the decrease no longer follows this scaling law, but decreases at a slower rate. The change of slope at ~100 s, indicates there is a transition from statistical independence to partial interdependence, i.e. the onset of sample to sample correlation. Hence the gain of the New Horizons X-band receiver is sufficiently stable for integrating radiometer power for time intervals of up to 100 s to a precision of 0.07 K/$\sqrt{\tau_a}$. At the sample rate of 10 Msamples/sec, and an integration time of 100 seconds, the statistical decrease in the STD of the power is 1/$\sqrt{10^9}$samples, or 0.33 x 10^{-4} for a 100 s integration. However, the REX radiometrics channels are 4.5 MHz, and at 10 Msamples/s, the samples are not sample-to-sample statistically independent. The decrease in STD with integration is then expected to be 1/$\sqrt{4.5\text{x}10^8}$, or 0.47x10^{-4}. At a noise temperature ~150 K, for the X-band receiver, the resultant precision of a REX radiometer power measurement is 0.007 K, for a 100 s integration. **See comment at beginning of Section 2.0**

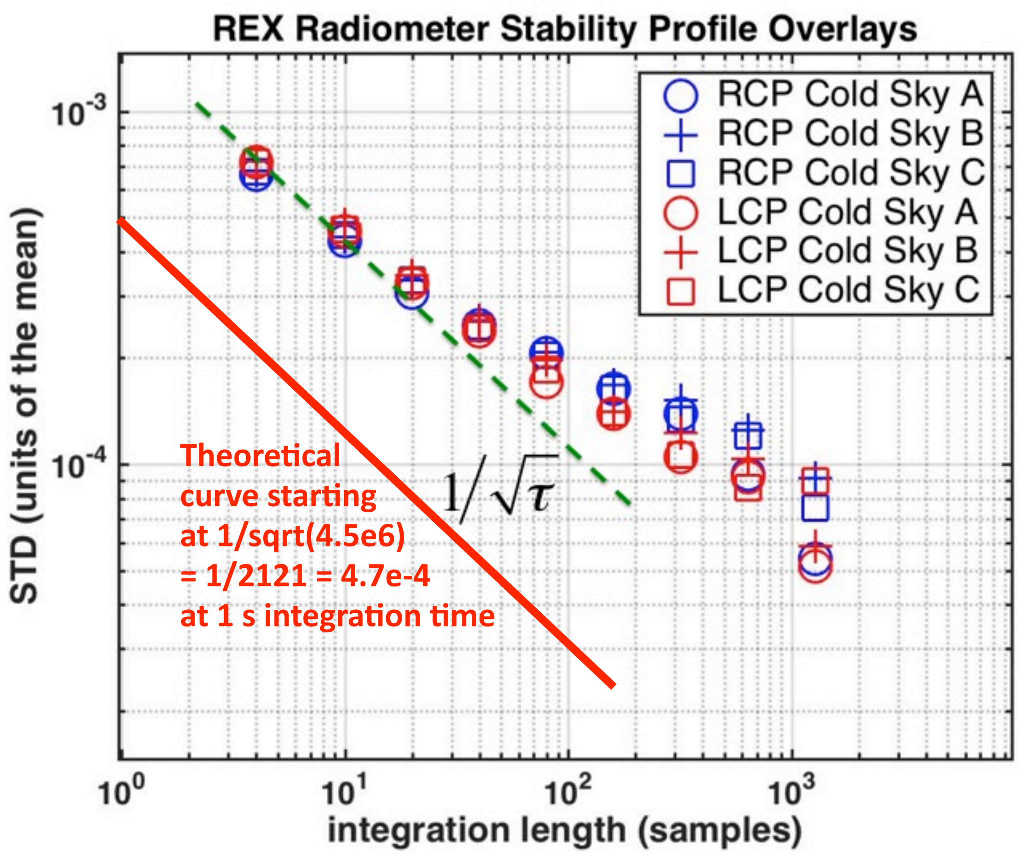


Figure 2.0.3. The standard deviation (STD) of REX total power samples, evaluated over the range of integration times appropriate for the radiometer measurement objectives. Profiles are shown for three cold sky locations and two polarizations each.

What is the stability over years? Since gain was measured "at least once per year" (page 3), a table showing Cold Sky power for each polarization annually would be a useful addition to this document. The year-to-year gain stability is important since Pluto encounter measurements were calibrated using measurements taken throughout the mission.

2.1. X-band Receiver Linearity

In addition to stability, the radiometer power produced by REX must be a linear response to the RF power illuminating the receiver's antenna. The end-to-end response of the X-band receiver was measured post-launch during spacecraft commissioning, and at every annual checkout. The gain of the receiver was stepped in intervals 2 x 0.48 dB, (twice the minimum gain step), while REX recorded radiometer power and narrowband waveforms of high power uplink transmission from earth. Uplink CW signal were transmitted by NASA's Deep Space Network (DSN) antennas, radiating up to 20 kWatts from 34-m and 70-m antennas. The radiated power was adjusted to produce an RF illuminating power on the spacecraft a nominal -112 dBm. This illumination increased the REX radiometric channel power by ~10%, and produced a narrow-band signal in the REX band with an SNR of ~55 dB/Hz. The uplink's power afforded measurements were found to have a precision of ~0.025 dB for each gain step of ~1 dB, thereby providing the capability to assess the end-to-end linearity of the power measurement from earth transmission to REX data samples.

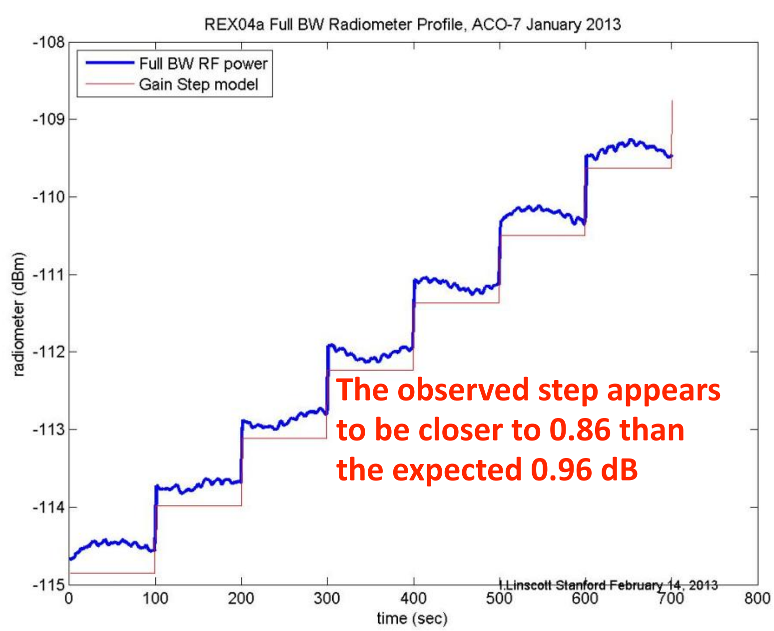
signals

at a

that were

An example of the REX radiometer power profile obtained while the gain stepped in ~1 dB increments is shown in Figure 2.1.1. The 'staircase' of expected power change thus confirming the linearity of the REX power with the selected gain. The variation of the power in the REX band within each of the gain steps is attributed to the variation in the uplink power due to both small variations in transmitted power at the source and propagation effects along the ~30 AU radio path from earth to the spacecraft. **DSN and HGA pointing may also be factors.**

REX radiometry channel



Would checking linearity with a broadband (natural) radio source have been better? The variations in carrier power seem to limit the usefulness of these measurements. Of course, the natural source data may have been collected using a different gain setting. Which would have been more appropriate for Pluto calibrations?

Figure 2.1.1

Figure 2.2.1. Steps in the received X-band power with the HGA pointed to Earth, while a nominal uplink was transmitted to the spacecraft.

There is no Section 2.2

2.3 High Gain Antenna (HGA) response

The response of the High Gain Antenna's (HGA) to far-field RF illumination was measured both before launch. These measurements were used to produce a 2D response and gain profile. During the pose-launch spacecraft commissioning, the HGA response was re-measured by slewing the spacecraft's HGA in a raster scan across across an uplink from the DSN. REX acquired the uplink waveform in the REX band and by downconverting to baseband resolved the uplink power to a frequency resolution of 1 Hz. The SNR at this resolution was ~60 dB, suitable for resolving the HGA's sidelobes. Figure 2.3.1, shows the HGA's response obtained from the pre-launch measurements. Figure 3.3.2, shows the comparison with the HGA's post-launch measurements for both REX radiometric channels.

measured

post-

across

Figure numbers and/or descriptions need correction.

polarization?

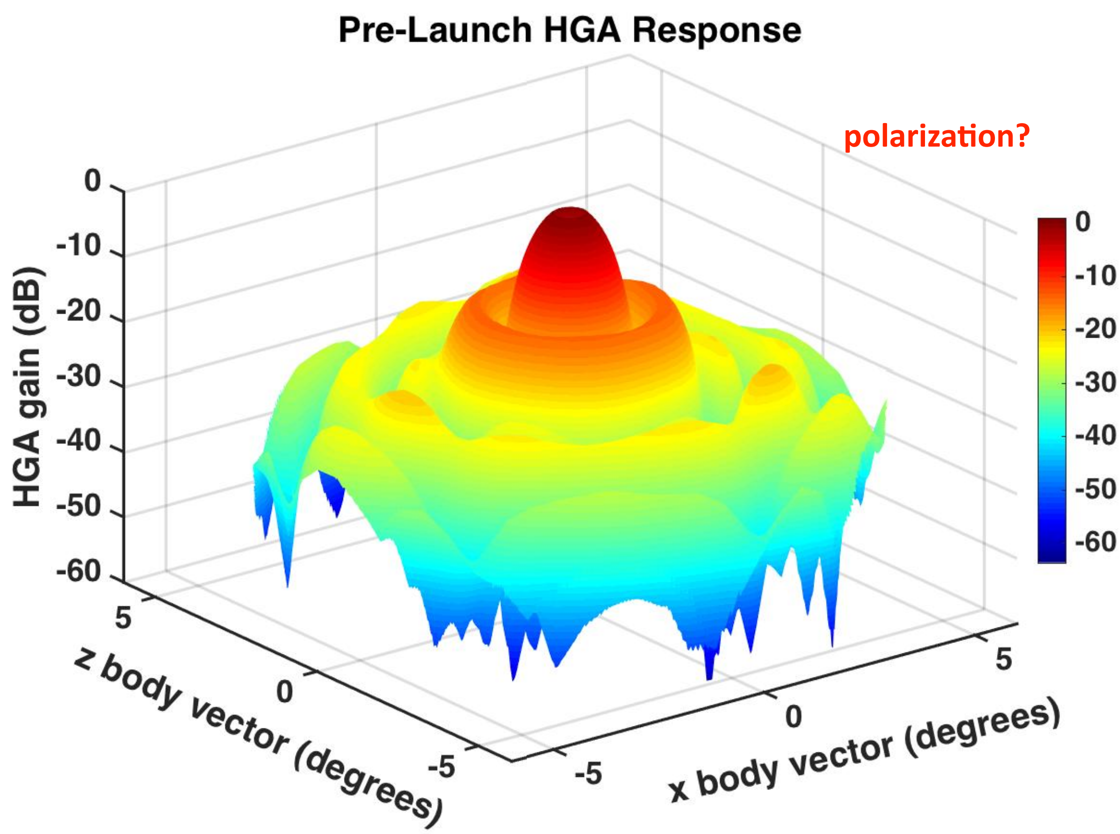
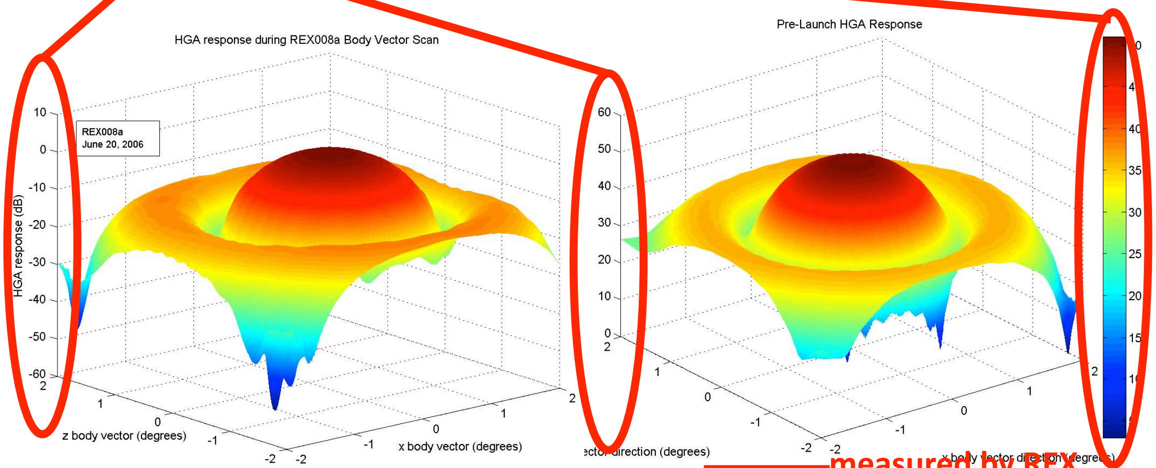


Figure 2.3.1 Pre-launch response of the HGA out to 5° elongation from the boresight.

Inconsistent scales, unlikely to be relative to boresight.

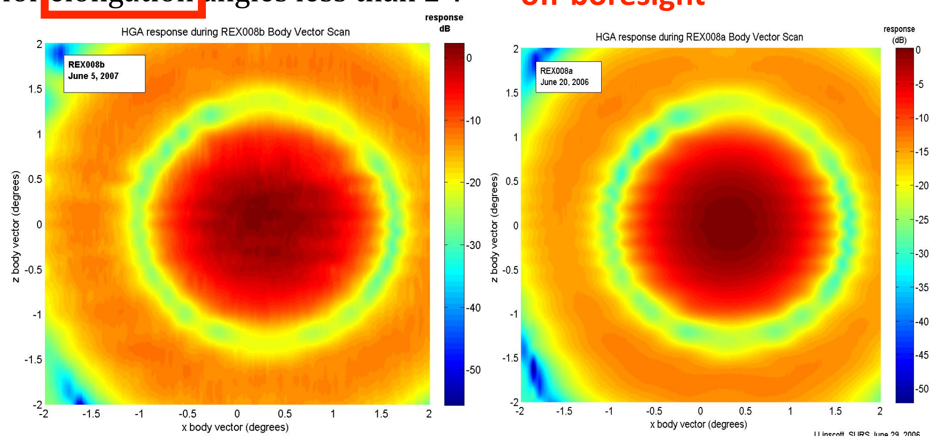


measured by REX

nominal boresight

Figure 2.3.1. Left hand figure is the HGA's response in REX. Right hand figure is the HGA's response as measured before launch. The gain relative to boresight is shown for elongation angles less than 2º.

off-boresight



These are normalized, to what?

LCP peak response is offset to about x = 0.3 deg.

Figure 2.3.2. HGA response as measured by scanning the HGA across an uplink. Left hand figure is HGA response for Left Hand Circular polarization (LCP), and the right hand plot is the HGA's response for Right Hand circular polarization (RCP)

3. Calibration of REX using Standard Radio Sources

Not 40-bit?

kelvins

REX produces samples of the RF power in the New Horizons X-band Receiver's Radiometrics Channel, a heterodyned representation of the radio frequencies in a 4.5 MHz band centered at 7.18 GHz, The REX power values are in "REX units", unscaled 32-bit representations of the squared-and-accumulated digitized samples from the Radiometrics Channel. The conversion of REX units to physical units such as temperature in degrees Kelvin or RF power in watts (or more likely dB relative to a milliwatt (dBm)), is a linear scaling using a single conversion constant and knowledge of the receiver's noise figure, (or noise temperature), for both RCP and LCP. Additional knowledge of the HGA's gain is needed as well. The peak gain determined from pre-launch testing was found to be 41.8±0.2 dBi (R. Schulze, priv. comm.) This value for the gain yields an effective HGA area of A_{HGA} = 2.098 m^2 and an aperture efficiency of 0.61.

Omit mention of dBm, which is not a linear scaling.

Use commas or parentheses but not both.

The corresponding conversion factor is thus given by:

$$[K/Jy] = A_{HGA}/2\ k_B = 7.598E\text{-}4.$$

The calibration determines two unknowns for both RCP and LCP (a) the receiver noise figure (i.e. temperature), and (b) the conversion constant from REX units to Kelvin. The determination of these two unknowns requires a minimum of two constraints per polarization with additional constraints to afford robustness of the measurements. Thus the calibration of the REX process used seven targets on the sky that are radio source standards where the RF flux in X-band is either well known or can be estimated to greater than the precisions of the observations. The seven targets were two galactic and one extra-galactic source, three positions on the 'coldest' part of the sky, and the sun. The next sections discuss the observing strategy, the observations and calibration results.

kelvins

Was the 'Cold Sky' (unlettered) region mentioned on page 3 ever used?

3.1 Calibration of REX using Thermal Emission from Jupiter

New Horizons was launched on January 19, 2006, and on February 28, 2006, received a gravity assist from Jupiter. The proximity to Jupiter was an opportunity to record Jupiter's thermal emissions using REX. Four days before Jupiter closest approach, the spacecraft's High Gain Antenna (HGA), scanned diametrically across Jupiter's equator, and four days after closest approach the HGA scanned again diametrically, from pole to pole. At the time of the scans Jupiter's size, seen from the spacecraft (1.15 deg for the arrival scan, and 0.89 deg for the departure scan), was slightly smaller than the beamwidth of the HGA. This proximity was especially significant, for at no other time in the Mission – other than at the Pluto Encounter itself – would a thermal radio source fill nearly all of the beamwidth of the HGA, and present as high a radiometric temperature for the purposes of calibration.

The scan profiles from the REX Radiometric samples, (at a cadence of 1 samples/1.024 seconds) are in Figures 3.1.1. From the perspective of New Horizons, the first (equatorial) scan, Jupiter was against the background sky close to the Galactic plane, while for the second (polar) scan, Jupiter's background was well above the Galactic plane and in Cold Sky.

sample

The scan specifics are here.

JREXCAL Scans
JREXCAL01 Done on February 24, 2007, start at 02:55:56 SC UTC, MET 0034591678
Scan from -x to +x (SC coords), and -3 deg to +3 deg Note: SC HGA boresight is in +Y Jupiter at: RA 251.5 deg, dec -18.75 deg, (16:45, +17.0)
Galac1c: 0 deg, +15 deg (close to Galac1c Plane) Jupiter target angle: 19.563 mrad (full)

According to Zarka and Kurth (SSR, 116, 1, pp 371-397, 2005; Fig 3) Jupiter's synchrotron radiation dominates thermal over 0.1-10 GHz.

JREXCAL02 Done on March 05, 2007, start at 12:08:00 SC UTC, MET 0035402400 Scan from -z to +z (SC coords), and -3 deg to +3 deg Note: SC HGA boresight is in +Y Jupiter at: RA 49.25 deg, dec +17.0 deg, (03:15, +17.0)
Galac1c: 170 deg, +35 deg (well above Galac1c Plane) Jupiter target angle: 15.594 mrad (full)

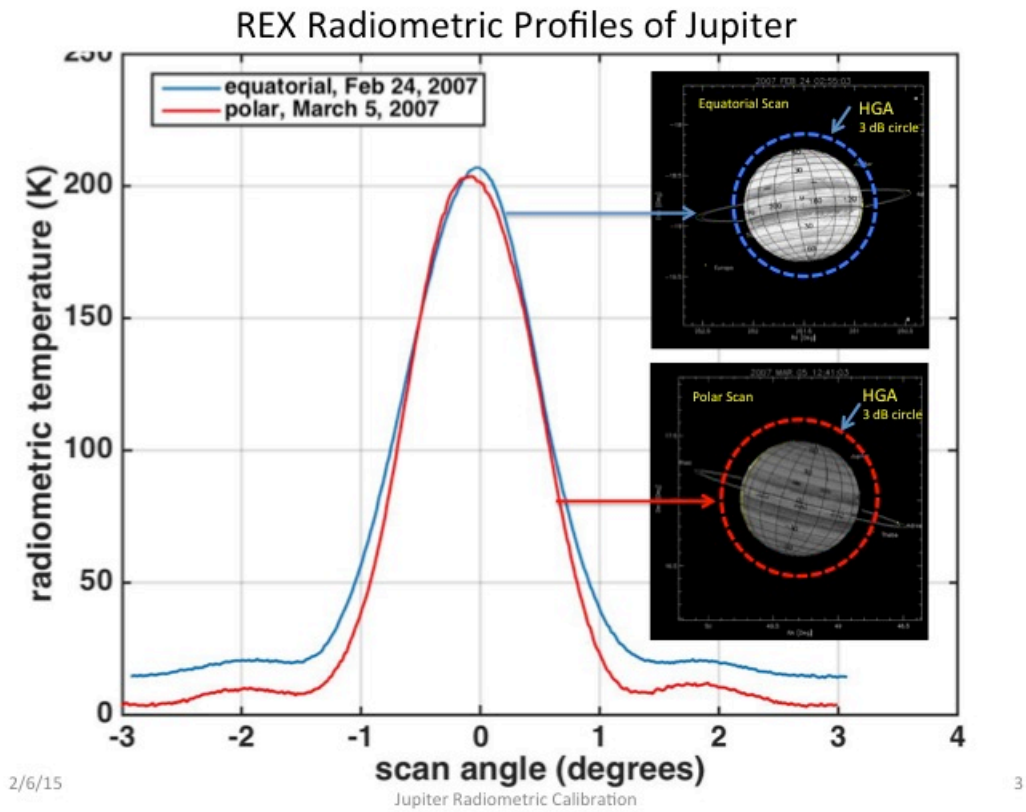


Figure 3.1.1. Radiometric scans of Jupiter with REX and the HGA.

Section 3.1 is an interesting exercise, but I am troubled by the lack of any external controls on the solution for receiver temperature and conversion factor. Does the solution make sense when compared against the results from Cold Sky observations, for example?

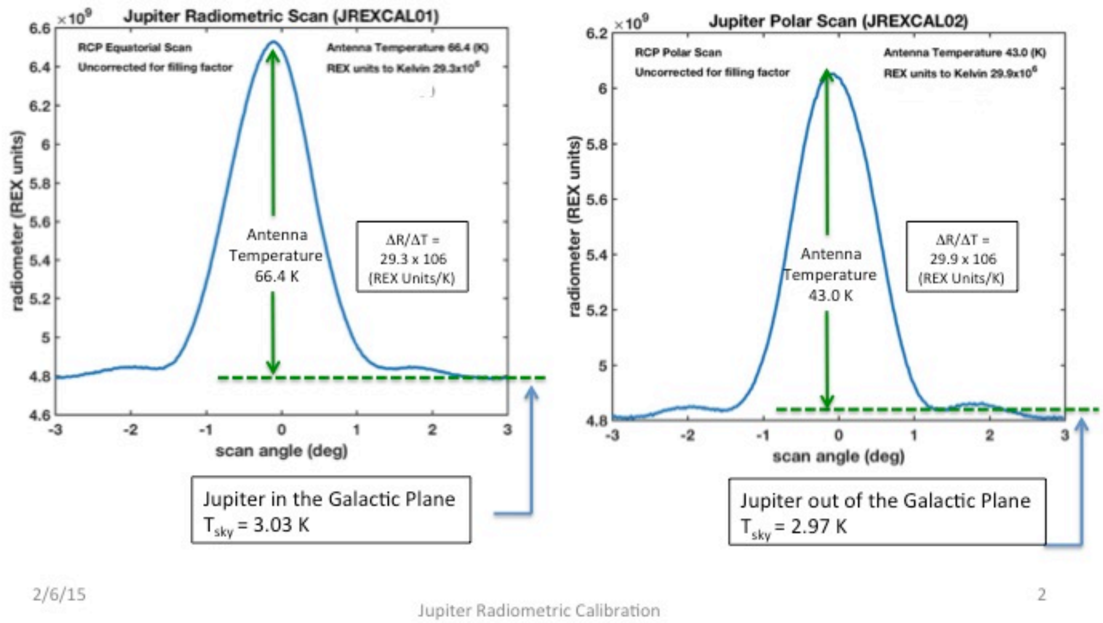


Figure 3.1.2. Radiometric scans of Jupiter with REX and the HGA

The gain of the HGA, or alternatively, the response of the HGA as a function of illumination direction, represented in Figure 2.3.1, is approximately circularly symmetric. The HGA gain is not constant from the central direction (the central direction will be called the HGA's boresight). The illumination of radio frequency power on the HGA is the integration of the radio brightness as a function of illumination direction multiplied by the response of the HGA in that direction. This expressed integration is express compactly as the convolution of the HGA's gain response $H(\theta,\phi)$ with the target's radio brightness angular distribution $T_J(\theta,\phi)$, in this case it is Jupiter.

$$T_{ant} = H * T_J \qquad 3.1.1$$

If Jupiter was larger than the beam size of the HGA, then the HGA's antenna temperature would be Jupiter's radio brightness temperature. Jupiter was somewhat smaller than the HGA's beam size. It would be convenient if the HGA's gain response were constant out to some critical angle Θ_{beam}, and then zero at angles larger than that. Then the HGA's antenna temperature would be the sum of the fraction of the HGA's beam occupied by Jupiter, η, at Jupiter's temperature T_J, plus the remaining fraction of the HGA's beam not occupied by Jupiter $(1-\eta)$, at the temperature of the background sky T_{sky}, as expressed in Eq'n 3.1.2.

$$T_{ant} = \eta\, T_J + (1-\eta) T_{sky} \qquad 3.1.2$$

The filling fraction, η, is the fraction of the HGA's beam area occupied by Jupiter as the radiometric target. Since the convolution in Eq'n 3.1.1, is a linear operator, it can be reorganized in terms of Θ_{beam}, under the assumption T_J, is uniform over its projected surface.

questionable assumption

$$
\begin{aligned}
I(\theta,\varphi) &= \int_0^{2\pi} H(\theta,\varphi)T(\theta,\varphi)\,d\varphi \int_0^{\pi} \sin(\theta)\,d\theta \\
&= \left[\int_0^{2\pi} H(\theta,\varphi)\,d\varphi \int_0^{\pi} \sin(\theta)\,d\theta\right]\left[\int_0^{2\pi} T(\theta,\varphi)\,d\varphi \int_0^{\pi} \sin(\theta)\,d\theta\right] \\
&= \left[\int_0^{\Theta_{beam}} \tilde{H}(\theta)\sin(\theta)\,d\theta\right]\bar{T} \\
&= \pi\,\Theta_{beam}^2\,\bar{T}
\end{aligned}
\qquad 3.1.3
$$

Here Jupiter's temperature distribution is replaced with the average over the projected surface, and the integral of the HGA's gain is replaced by the area of a circle whose radius is the equivalent angular width of the HGA's gain, using the equivalence,

$$
\begin{aligned}
G &= \int_0^{2\pi} H(\theta,\varphi)\,d\varphi \int_0^{\pi} \sin(\theta)\,d\theta \\
&= \int_0^{\Theta_{beam}} \tilde{H}(\theta)\,\sin(\theta)\,d\theta \\
&= \pi\,\Theta_{beam}^2
\end{aligned}
\qquad 3.1.4
$$

Where,

$$\tilde{H} = H/H(0,0)$$

Both the beam shape of the HGA and the shape of Jupiter are very nearly circular, hence η is well represented by the ratio of the area of two circles with angular diameters Θ_{beam}, and Θ_J. for the HGA and Jupiter respectively.

$$\eta = \left(\frac{\pi\Theta_J^2/4}{\pi\Theta_{beam}^2/4}\right) = \left(\frac{\Theta_J}{\Theta_{beam}}\right)^2 \qquad 3.1.5$$

Meaning the radio diameter of Jupiter is assumed to be the same as the optical diameter?

Jupiter size was determined from the navigation solution for the spacecraft's trajectory, giving the distance to Jupiter at the time of the radiometric scans, and correspondingly Jupiter's angular diameters for both scans.

The effective angular area of the HGA beam is a circle whose angular diameter is 1.60 degrees, the asymptotic limit of the integral in Eq'n. 3.1.4. This integral is shown in Figure 3.1.3. as a function of the upper integration limit.

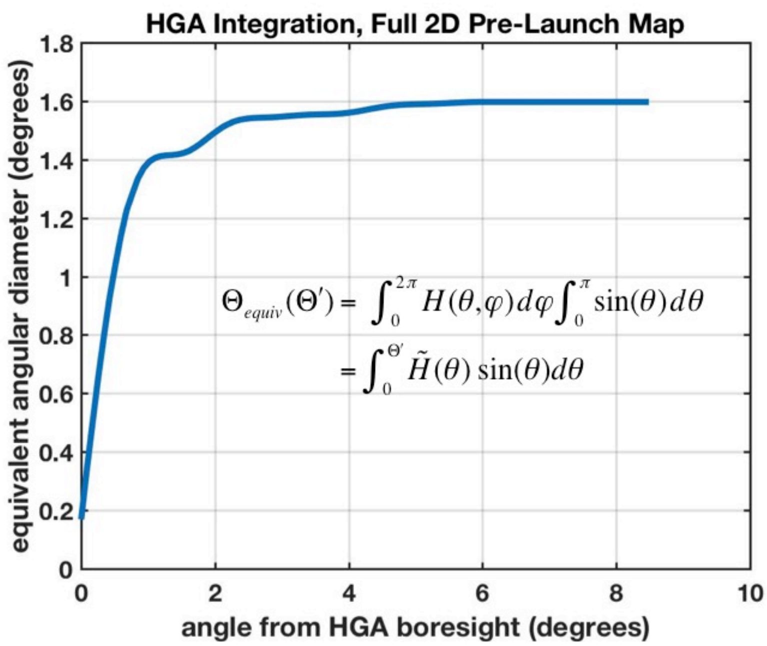


Figure 3.1.3. Equivalent HGA angular diameter integral.

Fig. 3.1.3, ?

kelvins

Using the equivalent HGA angular aperture from Fig. 3.3.3., the conversion constants of RX units to Kelvin and the X-band Receiver's noise temperature are detetmined for the two Jupiter radiometric scans. The determination uses a parameterized, 4D optimization that allows the two sky temperatures to vary slightly near 3K, and the filling fractions to vary slightly within a few percent. The metric is the square of the Rx noise temperature difference added to the square of the REX-to Kelvin difference. A weight is included penalizing large changes in the search parameters. The optimizer finds good solutions for the HGA equivalent aperture diameter, with sky temperatures differing only 0.03 K from 3.0 K, and filling fractions larger by ~10%, implying Jupiter was either larger by 5% diameter, or the HGA equivalent angular size was smaller by 5%, or both a lesser amount.

kelvin

This seems a little suspicious since the nominal background is 2.7 K for the polar scan rather than 3.0 K.

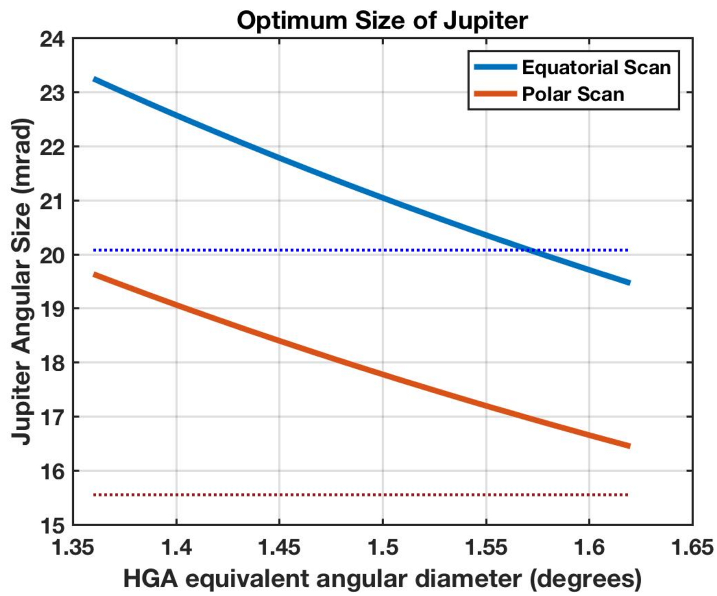


Figure 3.1.4. The size of Jupiter using the 4D optimization, where the two background sky temperatures and the two HGA filling fractions are optimized. The equivalent angular diameter of the HGA was variable, i.e. the optimization was run for each choice of the HGA equivalent angular diameter as a means of validation. The dotted lines are the values of Jupiter's size from the spacecraft's trajectory. The optimization with an HGA equivalent angular diameter of 1.6 degrees, from the pre-launch gain map, produces Jupiter sizes in good proximity to the spacecraft trajectory's values, a good indication that both the HGA gain map and the sizes of Jupiter are trustworthy.

kelvins

The X-band Receiver's noise temperature and the conversion constants from REX units to Kelvin are the two additional values from the optimization. Figure 3.1.5, is a plot of these values for the same range of choice of the HGA's equivalent angular diameter.

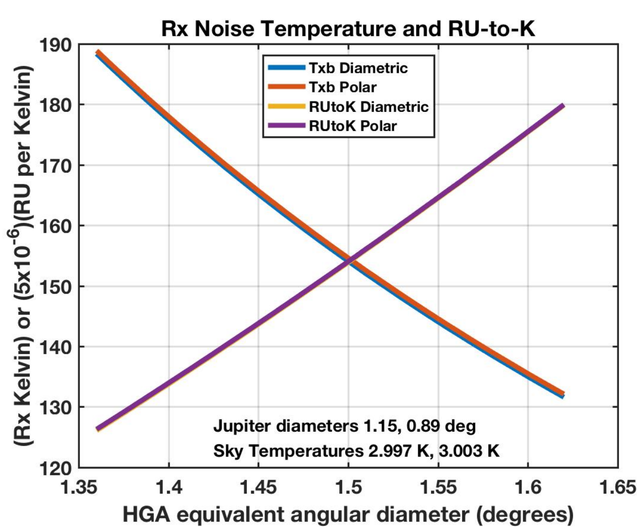


Figure 3.1.5. X-band Receiver Noise Temperature and REX units to Kelvin conversion constants for the Jupiter Equatorial and Polar Radiometric Scans. The plot pairs representing the two Jupiter scans are nearly coincident, indicating the success of the optimizations. As in Figure 3.1.4, the equivalent angular diameter of the HGA was variable, i.e. the optimization was run for each choice of the HGA equivalent angular diameter as a means of validation.

kelvins

An equivalent angular diameter of 1.60 degrees, for the HGA, results in an X-band Receiver noise temperature of 135 K, and a conversion constant of 35.2 x 10^6. Unfortunately, the conversion constant changed during the course of the mission when with other choices of the receiver's gain. The receiver gain during the Pluto Encounter was nine gain steps, or 4.3 dB, higher than for the radiometric scans of Jupiter. However, the receiver noise temperature has evidenced great stability and therefor this value of 135 K, is expected for the results of the calibrations performed later in the mission, and in particular in close proximity to the Pluto Encounter.

when used with

But 135 K does not seem to compare well with other estimates, including the pre-launch value of 152 K. Also, why should receiver temperature vary with the gain setting?

3.2 The Sun as a Calibrator

During the radio occultation of Pluto four uplinks were transmitted from Earth and recorded by REX as Pluto crossed the line of sight from the spacecraft to Earth. The Earth was near-solar opposition during the Pluto Encounter as seen by the spacecraft. The angle between the Earth and the Sun was 0.23 degree. The uplink signal was recorded well before occultation ingress, and recording continued between occultation ingress and egress even though the uplink was absent in the receiver. The recording continued additionally well after egress. Just before egress, with the uplink still occulted by Pluto, the Sun appeared from behind Pluto's limb and was within the beam of the HGA for about one 1 minute before earth and its four uplinks appeared. Accordingly, the sun presented itself as a serendipitous calibrator. The REX radiometer power profile during Pluto Occultation is shown in Figure 3.2.1, with a zoomed-in version in Figure 3.2.2. Here the appearance of the sun is evident against the decreasing power from Pluto's dark side.

near solar inferior conjunction

one minute

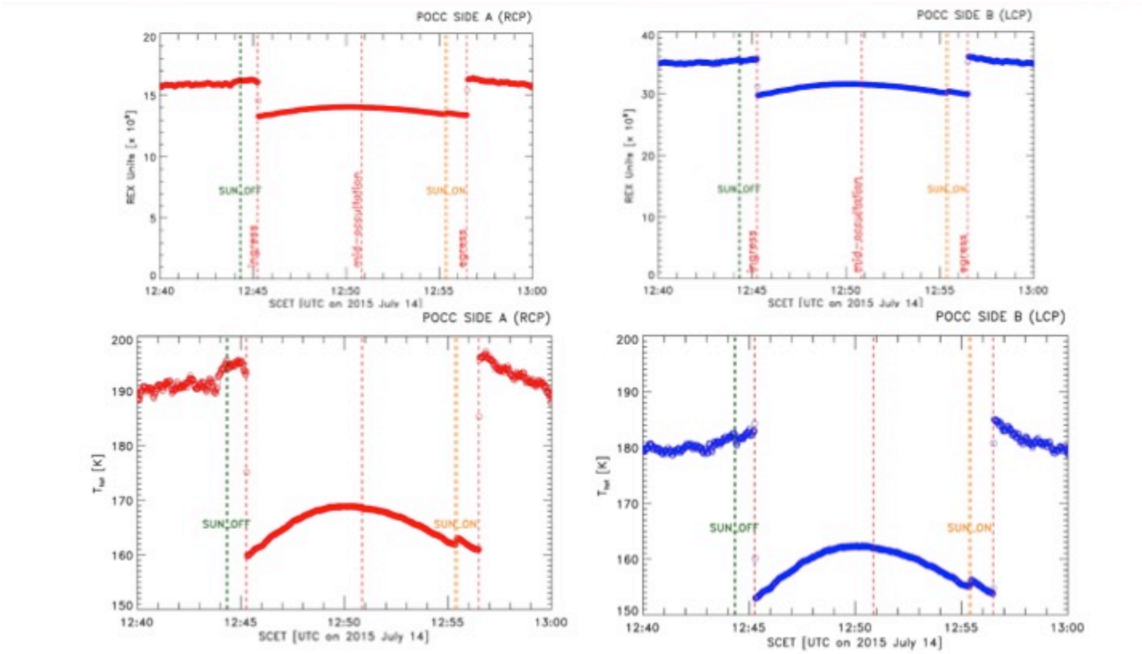


Figure 3.2.1. REX Radiometer Power during Pluto Occultation. Upper panels: Total recorded power in REX units (left: RCP; right: LCP). Lower panels: Total recorded power converted to kelvin (left: RCP; right: LCP).

But we don't know how to do this yet, correct?

kelvins

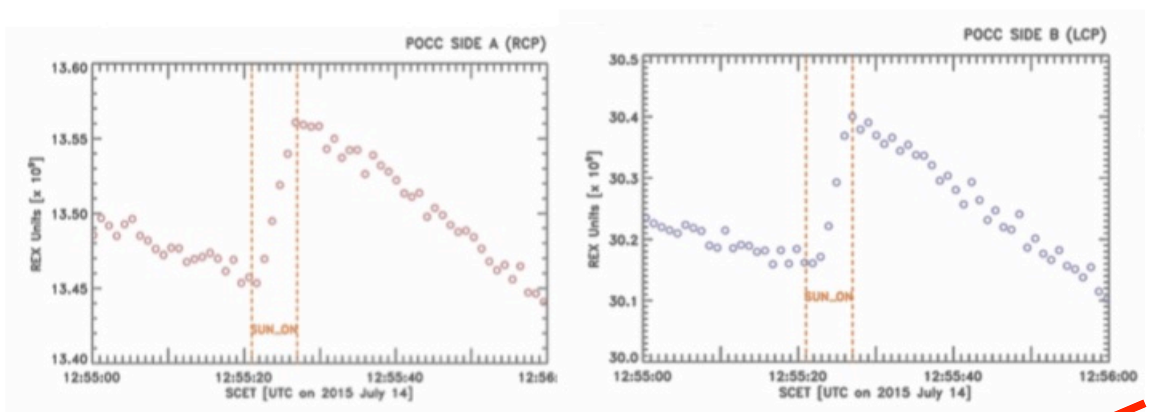


Figure 3.2.2. REX Radiometer Power During Pluto Occultation. The sun's increase in the power just after egress. (detail for the time 12:55 to 12:56 UTC). The power increases abruptly as the Sun emerges from behind the Pluto disk just before radio occultation egress.

This sentence should be omitted.

before

over 5-6 seconds

The Sun in X-band as seen from the earth is a strong radio source (1.5 Mjy), but at the distance to Pluto of 32.91 AU, the sun is much weaker, and estimated at 1759 jy. Even so, the sun's power in X-band is ~1.3 K comparable to only a few other radio sources on the sky. The sun's radio power is not stable, but the solar variation is very well monitored from Earth. The variation is on timescales of hours to days.

1.5 MJy at 32.91 AU is 1385 Jy, not 1759 Jy. Then Tsun is ~1.05 K, not ~1.3 K.

Radio Astrophysical Observatory

Dominion

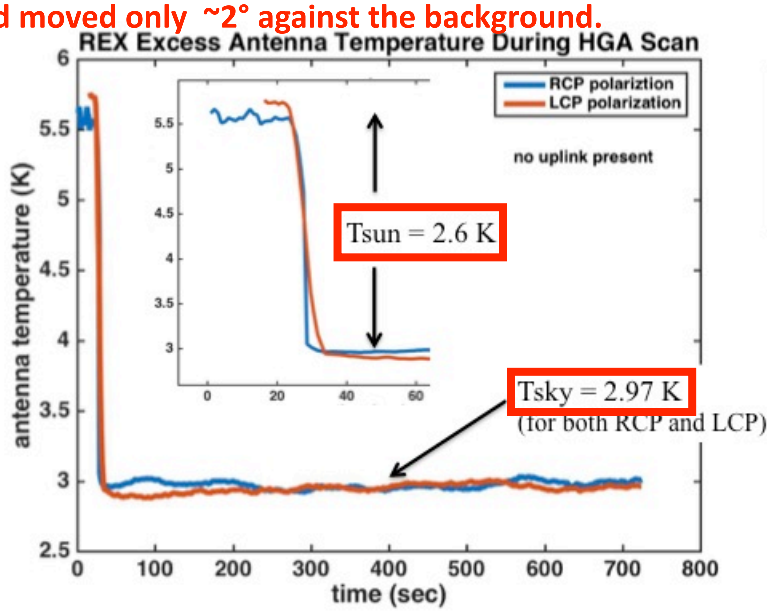
The solar intensity at New Horizons was determined from daily observations at 10.7 cm wavelength (2800 MHz) at the Dominican Radio Observatory (DRAO) in British Columbia. Using a model of solar power variation, the solar flux density at X-band was determined for the time of the Pluto occultation. Using this high fidelity model of solar power variation, scaled to X-band frequencies, the sun's temperature was estimated at the time of Pluto occultation egress.

when

A post-Pluto Encounter Calibration Campaign was performed in July 2016, a year after Pluto Encounter, where an additional scan across the sun was obtained. This time, the earth was again near solar opposition, but the background sky was very cold ~3 K, close to the Cosmic Microwave Background's lower temperature limit 2.7 K. This scan is shown in Figure 3.2.3.

Was background significantly colder in 2016 than 2015? From simple geometrical considerations the Sun had moved only ~2° against the background.

Why not plot as REX Units? Then we should be able to derive both the REX-to-K multipliers and the Tsys baselines for each polarization.



Why 2.6 K in 2016 when it was 1.3 K in 2015?

Should this be 1.485 K?

Figure 3.2.3. Scan away from the sun during Calibration Campaign.

during 2016

Comparing the REX radiometer power between Figures 3.2.2 and 3.2.3, the change in REX radiometer power is consistent with an increase in power due to the sun of $380x10^6$ REX units. Attributing this increase solely to the 3.1 K RF temperature of the sun, and apportioning the RF power equally between the two X-band polarizations, the scaling between REX units and Kelvin is:

kelvins, Gp, is:

REX RCP: 90.04 x 10^6 REX units per degree K
REX LCP 207.20 x 10^6 REX units per degree K

This makes no sense. From Figure 3.2.2 the Sun is worth ~117E6 REX Units in RCP and ~269E6 REX Units in LCP — not 380E6 (total) REX Units. Why is the Sun 3.1 K, when Figure 3.2.3 shows it clearly to be 2.6 K (or 1.3 K when split between the two polarizations)? With these corrections, I get 90E6 REX Units per K (RCP) and 207E6 REX Units per K (LCP) — the values shown.

3.3 Radio Sky Background

Having now the conversion constant between REX units and Kelvin the receiver's noise temperature can be found using additional radio sources, such as the Cosmic Microwave Background (CMB), and radio source standards. kelvins

Using sky maps from all-sky radio surveys, locations were found on the radio sky where the sky temperature is within a few tenth's of a Kelvin of the Cosmic Microwave Background (CMB) for a region large with respect to the HGA's beam. tenths of a kelvin
The HGA is a 2.1-m diameter dish, and for the X-band receiver wavelength of 4.2 cm,
3 the -3 dB beamwidth of the HGA is 1.2 degrees. Three suitable location were found, locations
and are detailed in Figure 3.3.1.

Radio Source Standards

Cass-A: RA $23^h 23^m 26^s$, dec +58° 48′
350.8583, +58.8000

Taurus-A: RA 5° 34' 32" | Dec 22° 0.870'
83..6333, +22.0167

Cygnus-A: RA $19^h 59^m 28.3566^s$, dec +40° 44′ 02.096″
299.8667, +40.7339

Cold Sky Positions

	S	AZIM RA	ELEV Dec	X	Y	Z
Position A		91.20	17.9	-0.0199287	0.95138570	0.3073566
Position B		88.62	13.4	0.02342757	0.97249373	0.2317479
Position C		93.80	13.4	-0.0644697	0.97063720	0.2317479

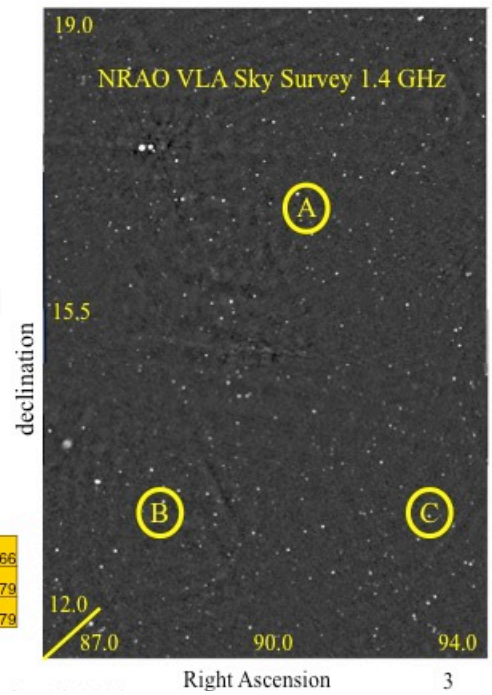


Figure 3.3.1. Cold Sky Locations used for REX Calibration.

Since the CMB temperature is 2.725 K, and only half of its power is added to the receiver's own noise temperature, is was necessary to run long acquisitions of REX to attain the precision needed for determining the receiver's noise temperature. Thus observations of several hundred seconds were done. In addition to achieving high precision of the radiometer power the stability of the X-band receiver was verified as well. The REX radiometer power sequences from each of the Cold Sky
3.3.2 locations are in Figures 3.2.2 though 3.3.4.

How is "antenna temperature" on the vertical axis known?
Isn't that one of the parameters being sought?

Are these one second integrations? Explain red vs blue in captions.

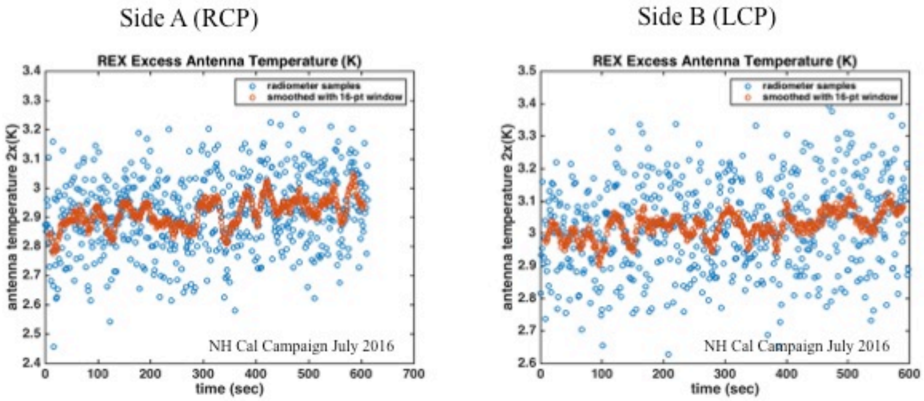


Figure 3.3.2. Cold Sky Location A, RA 91.20 deg, dec 17.9 deg. Note: the first 200 samples are Figure 2.1.1

Figure 2.0.1?

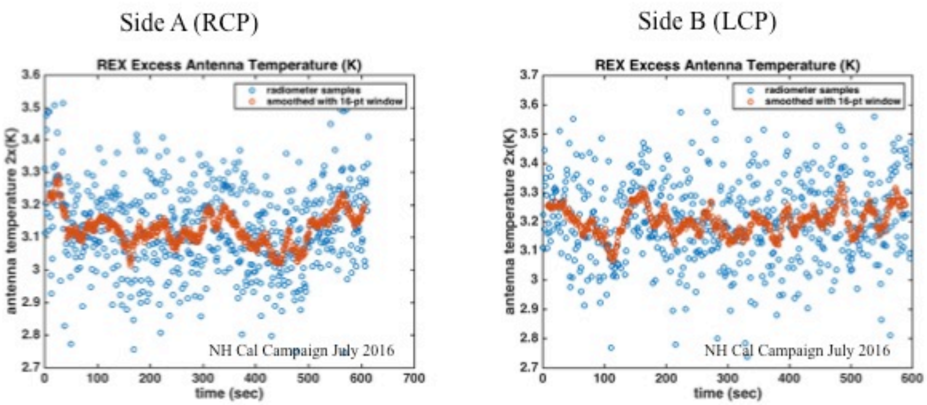


Figure 3.3.3. Cold Sky Location B. RA 88.62 deg, dec 13.4 deg.

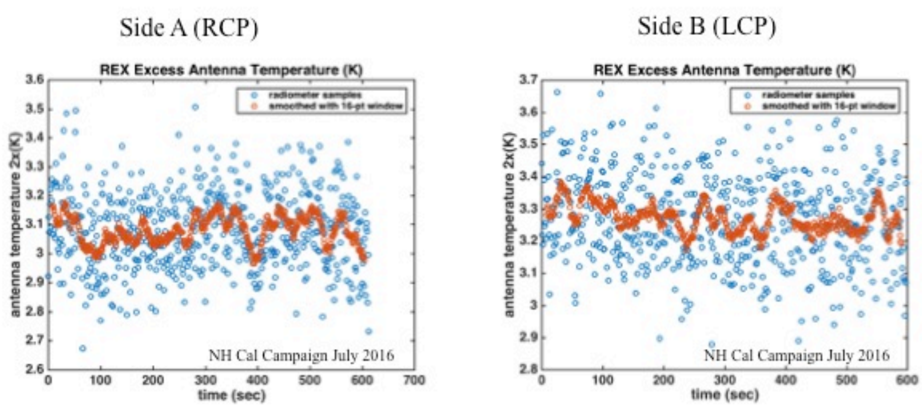


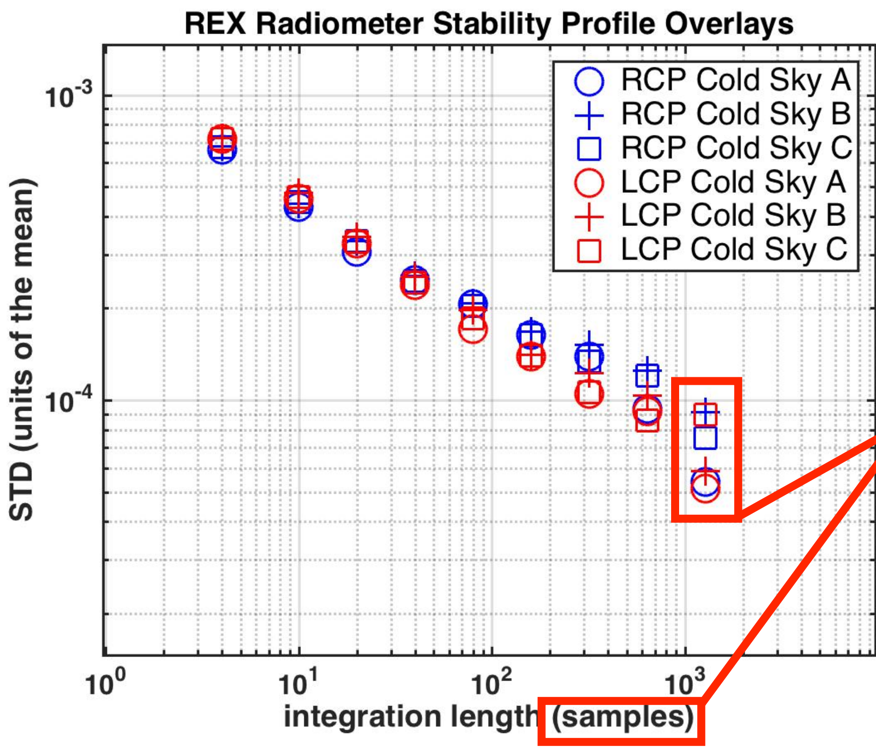
Figure 3.3.4. Cold Sky Location C. RA 93.80 deg, dec 13.4 deg.

The power fluctuations in these six sequences form Gaussian distributions near identical for those in Figure 2.1.2. The scaling of their STD's follows the trends in Figure 2.2.2, as well. The six STD scaling, as a function of integration length, is

Poorly constructed sentences and incorrect figure references.

Please provide a table of mean values in REX Units for each location for each date/time and polarization a measurement was conducted. Include gain settings. Table 3.3.1 is a start; but there is no information on when those data were acquired.

included in Figure 3.3.5, to confirm that the X-band receiver is sufficiently stable that the mean of the entire sequence for each location is a reliable and stable measure of the REX radiometer power from each cold sky location.



How much time per sample? The source data (Figures 3.3.2 through 3.3.4) appear to be one second averages and are plotted versus time over 0-600 seconds. There appear to be no data supporting an integration length >1000 samples, as shown in Figure 3.3.5.

Figure 3.3.5. STD Scaling vs integration time. The six cold sky STD scaling profiles are overlaid.

sky for each polarization,

Even though there are three distinct and arguably independent measurement of radiometric power from cold sky, the temperatures are so very near identical that the three locations do not qualify as three independent constraints for purposes of solving for the calibration constants. Rather the three locations are just one constraint on solving for the second calibration constant, namely the receiver's noise temperature. But, these are three independent total power integrations, and they do produce three statistically independent samples of power. Thus there is an opportunity to check if the three are statistically consistent, and if the gain variations are small, and if the temperature of the three cold sky locations is indeed the same.

measurements nearly

... consistent and, if the gain variations are small, whether the temperatures at the three cold sky locations are indeed ...

Assuming then the conversion from REX units to Kelvin that, obtained from the observation of the sun, is trustworthy, the temperature $T_{Cold\ Sky\ NP}$, associated with each of the $N = 3$, cold sky locations is found by dividing each of the cold sky mean power values $P_{REX\ units\ NP}$, by the conversion constant G_N, computed for the two polarizations, $P = 2$.

that observations

kelvin,

Gp, computed for the corresponding polarization.

There is a complete disconnect between derivation of the equations and the results presented in Table 3.1.3. In the equations P_REXunitsNP is the raw measured value from REX, T_CMB is assumed to be 2.725/2, Gp is the conversion constant from the solar measurements, and T_XBP is the (unknown) receiver noise temperature. In the table Gp is the unknown.

$$T_{Cold\,Sky\,NP} = P_{REX\,units\,NP} / G_P$$

Assuming further that the temperatures determined this way are the total of the sum of the X-band receiver $T_{XB\,P}$, and the CMB T_{CMB},

$$T_{Cold\,Sky\,NP} = T_{XB\,P} + T_{CMB}$$

$T_{CMB}/2$

Then the noise temperature of the X-band receiver is, **each**

$$T_{XB\,P} = T_{Cold\,Sky\,NP} - T_{CMB}$$

$$= \frac{P_{REX\,units\,NP}}{G_P} - T_{CMB} \qquad (3.3.1)$$

Is this supposed to be an equation number? If so, which equation?

Table 3.3.1, contains the conversion constants determined by this method for the three cold sky locations and the two receiver polarizations.

I don't understand. You just solved for Gp on page 18. Here you don't know T_XBP; how can you solve for Gp using the cold sky data?

RCP	Cold Sky A	Cold Sky B	Cold Sky C	Sun
Radiometer (10^9 REX units)	12.852	12.861	12.859	
STD (10^6 REX Units)	1.315	1.757	1.468	
REX to Kelvin **kelvins** (10^6 REX units/°K) **/K**	82.149 +/- 0.008	82.208 +/- 0.012	82.195 +/- 0.009	82.15 +/- 0.015

LCP	Cold Sky A	Cold Sky B	Cold Sky C	Sun
Radiometer (10^9 REX units)	28.883	28.901	28.907	
STD (10^6 REX Units)	2.705	3.0216	2.585	
REX to Kelvin **kelvins** (10^6 REX units/°K) **/K**	192.492 +/- 0.018	192.607 +/- 0.020	192.649 +/- 0.016	192.49 +/- 0.030

These are not the values shown at the bottom of page 18; they differ by almost 10%. Where did they come from and why are the error bars so small?

Table 3.3.1. REX Radiometer Conversion from Cold Sky Measurements. Tables are separated by RCP and LCP. Errors in the table are the combined statistical STD's **STDs** of the mean radiometer power and the uncertainty introduced by the two solar calibrations. **Again, I don't understand. Where did the solar calibrations come in?**

Comparing the values in the last row of Table 3.3.1, for statistical consistency, the conversion constant for Cold Sky A is within 1 sigma of the constant derived for the sun. Further, the three cold sky locations are not within 1 sigma of each other

It's true that Gp for Cold Sky A is close to Gp for the Sun; but where did the Sun values come from? These are not the values shown on page 18. It's true that the values for Cold Sky A are not within one sigma of the values for B and C; but the B and C values appear to be consistent with each other.

The criterion for whether A, B, and C have the same temperature should be the Radiometer values in REX Units with their standard deviations, not the derived Gp values.

indicating the sky temperature differed from location to location. This is the case for both polarizations. Most likely the sky temperature of location A, was the 2.7 K expected for the temperature of the CMB, but for the other two locations the temperature was higher by ~0.3 K. **How do you get 0.3K? The difference between A and B is only 0.07%. If the total temperature is ~150 K, the difference between A and B is ~0.1 K.** The statistical consistencies are further illustrated in Figure 3.3.5, where the three Cold Sky locations are plotted along with their respective 1 sigma error bars. The **kelvins** REX units to Kelvin conversion constant derived from the solar calibration is included for additional comparison.

The very close agreement with the solar derived conversion constant for location Cold Sky A, is a confirmation that the estimate of the sun's brightness temperature is correct, as well as the assumption the sky temperature at location A, is the CMB's temperature of 2.7 K. Of particular significance, the noise temperatures of the X-band receiver, as determined using the sun and used to compute the conversion constants for the cold sky locations, are self consistent within the statistical precision of the REX radiometer measurements. The corresponding receiver noise temperatures are 153.7 K for RCP, and 148.5 K for LCP. **Impossible to confirm from the data in this report because of the confusion over Gp.**

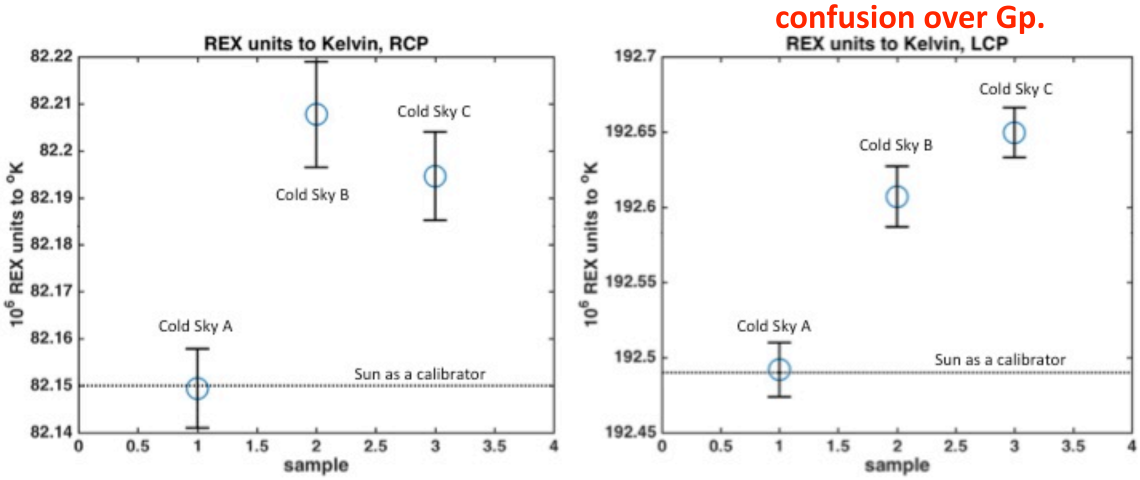


Figure 3.3.5. Comparison of the REX units to Kelvin estimates for the three Cold Sky locations with the REX units to Kelvin determination using the sun as a calibrator. Only location A, is statistically consistent with the solar calibration. Locations B and C, are statistically consistent with each other, but not location A, or the sun's calibration result. **kelvins** **kelvins**

3.4 Standard Radio Source Power Measurement

Four additional radio source standards have been scanned by New Horizons and REX for the purpose of radiometric calibration. These scans were performed both during spacecraft commissioning in 2007 and thee of the four during the July 2016 Calibration Campaign. The scans consisted of cross-hair scans of the HGS from

observed **observations** **performed** **2006?** **three of the four were repeated during**

Replace sentence with: Each observation consisted of an HGA cross-hair scan of the source extending ±2 degrees from its center in orthogonal directions.

approximatel2 degrees on either side of the radio source's center. The four standard radio sources are (1) Cass-A, (2) Taurus-A, (3) Cygnus-A, and (4) Virgo-A, and are among the brightest radio sources on the sky. Their radio flux in X-band is low, but still strong enough to constrain estimation of the REX calibration constants. Figure 3.3.1, shows the radio flux expected from these standard sources over a wide range of radio frequencies using radio flux models from published archival observations. The supernova remnant Cass-A, flux decays with an index that was used to predict the radio flux at the time of the REX measurements during commissioning in 2007

The standard radio sources distinguish themselves from the cold sky locations in that the radio sources are nearly point sources on the sky, and do not fill the beam of the HGA. On the other hand, the cold sky locations are broad, beam-filling regions at ~2.7 K. To obtain an equivalent temperature for the point sources, the RF flux from the radio source Φ_S, is presumed to uniformly illuminate the HGA, and either (or both) the gain of the HGA, or the HGA's equivalent aperture A_{HGA}, is needed to find the RF power, $P_{RF\,S}$ in the X-band receiver from the RF flux illuminating the HGA. The RF power in the X-band receiver can be represented by an equivalent temperature T_S , chosen such that , $P_{RF\,S} = k\,T_S$, k is Boltzmann's constant. Then the RF power in the X-band receiver is the integrated radio flux over gain of the HGA, or alternatively, the product of the radio flux and the equivalent aperture of the HGA.

$$kT_S = A_S \Phi_S + T_{sky} \qquad (3.3.2)$$

A_HGA has already been defined to be effective antenna area. Its value is 2.098 sq m (bottom, p.9)

Knowing T_S, the equivalent temperature of the radio source, and using the process outlined in Section 3.3, and with an equation similar to (3.3.1), the REX radiometer calibration constants can be independently determined. This independent determination enables the calibration constants to be optimized for consistency and robustness with respect to both statistical and systematic variations in the measurement process. In particular, a total of eight radio sources have been measured and used to solve for the three calibration constants. The measurements constitute an over-constrained solution, and as such allow for optimization. Optimizations can be tuned to optimize metrics such as residuals, robustness, and physical reasonableness. Each of these metrics are evaluated for their impact on the REX radiometer constants, the Rex units to Kelvin conversion constant G_P , the X-band receiver's noise temperature $T_{XB\,P}$, and the HGA's effective aperture A_{HGA}. .

The eight sources are Cold Sky A, Cold Sky B, Cold Sky C, Cass-A, Cyg-A, Tau-A, Vir-A, and Sun?

Three? I can only think of two (per channel): the REX to power conversion and the receiver noise temperature.

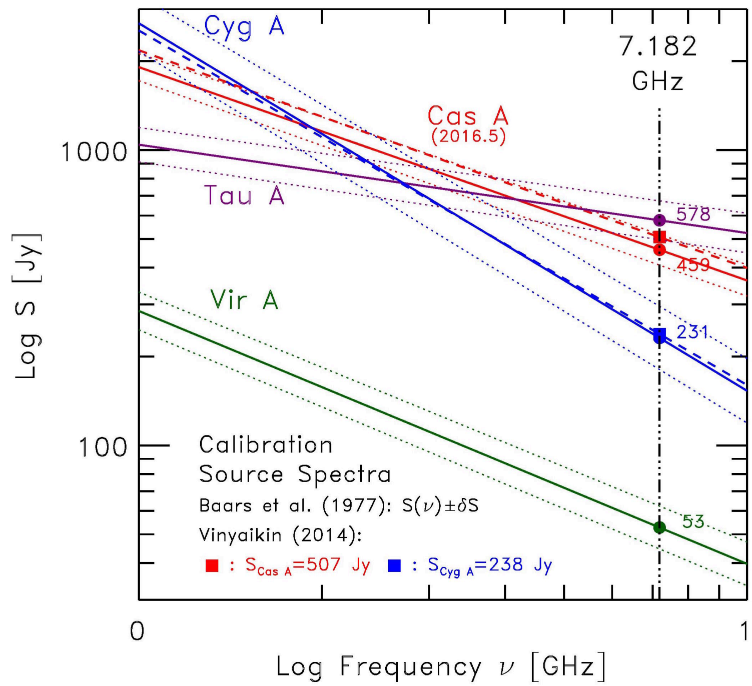


Figure 3.4.1. Radio Flux Models of Standard Radio Sources. The more recent flux densities for Cyg A and Cas A determined by Vinyaikin (2014) were used in this work.

for Solutions of the REX radiometer calibration constants uses REX radiometer power use estimates from scans of the HGA across the radio source standards. The radiometric power measured with REX for the standard sources chosen for calibration is shown in Figures 3.4.2 to 3.4.4. Typically, the radio source is not a point-source imbedded in a uniform background. The scans, on orthogonal cross-hairs, oriented using published radio sky images, are used to estimate the peak RF power relative the relative to the background power. The scans in Figures 3.4.2 to 3.4.4 show radiometric power in REX units.

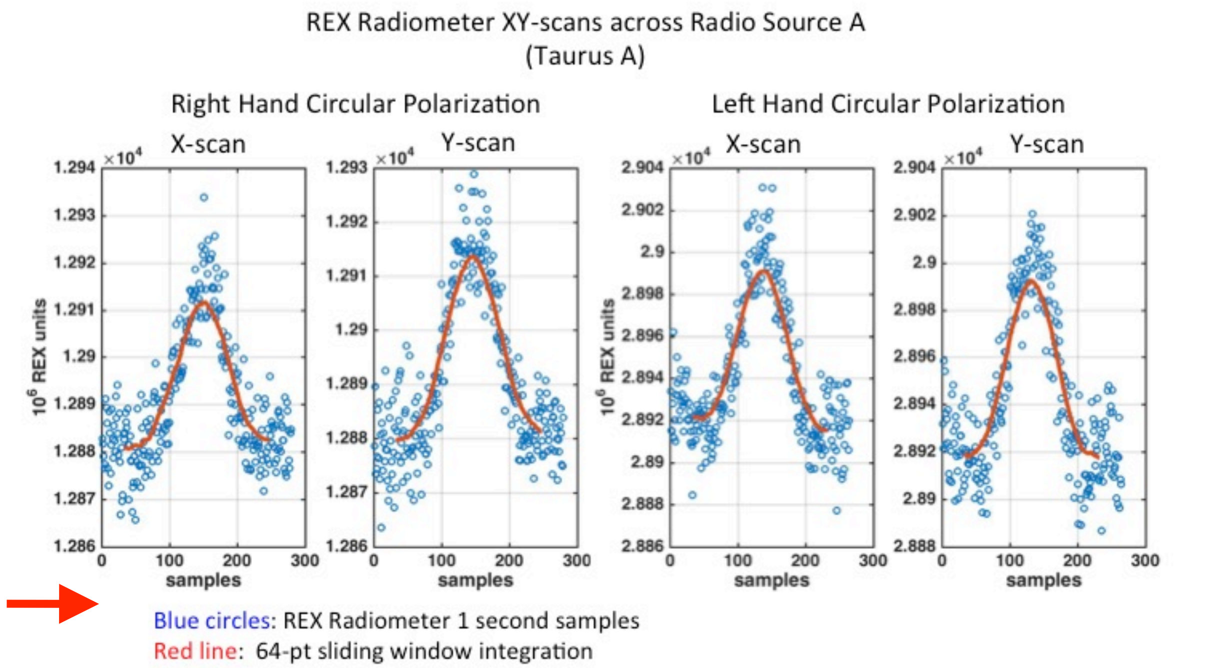


Figure 3.4.2. Scans Across Standard Radio Source Taurus-A.

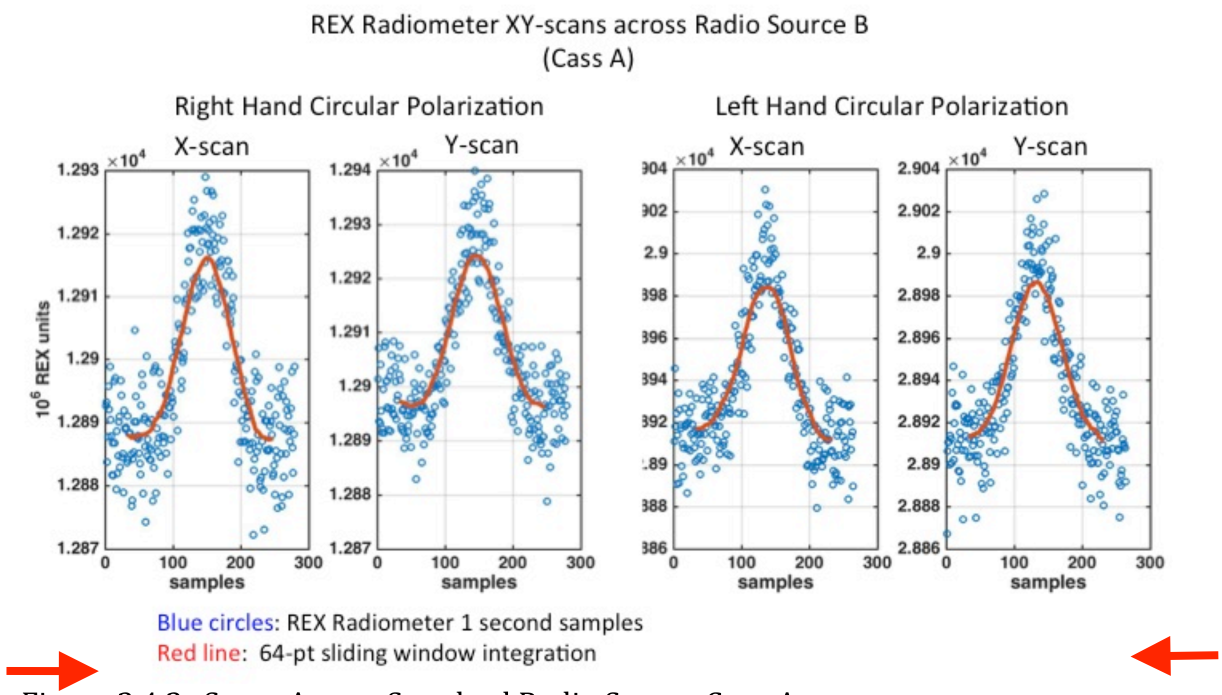


Figure 3.4.3. Scans Across Standard Radio Source Cass-A.

Arrows denote approximate Cold Sky levels

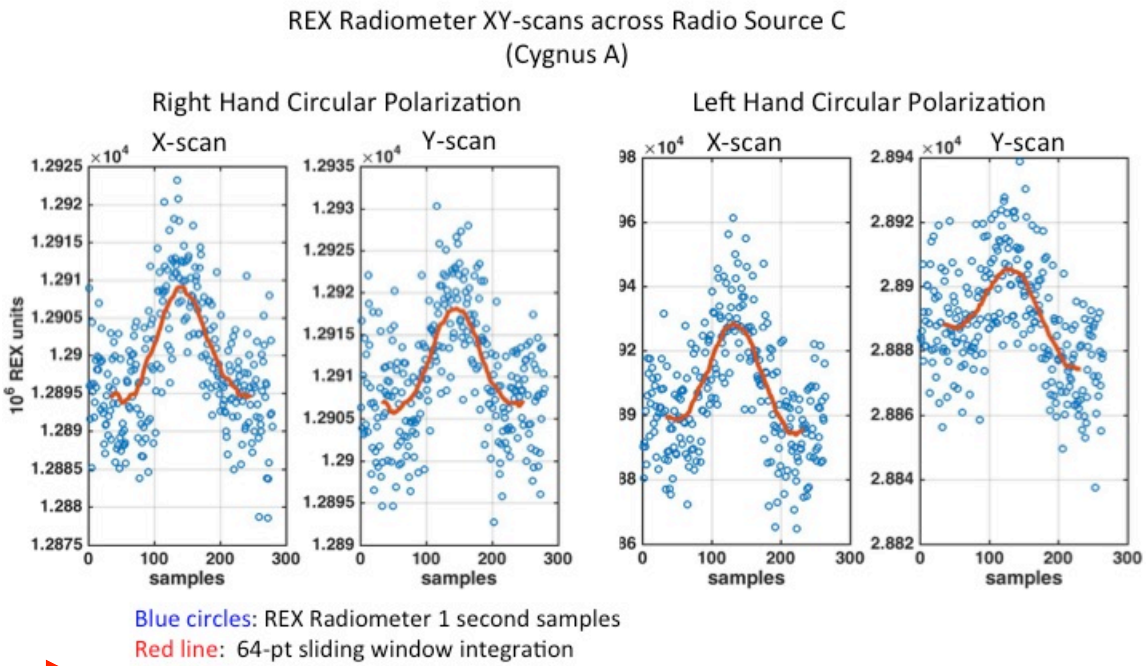


Figure 3.4.4. Scans Across Standard Radio Source Cygnus-A.

desired scaling

To obtain an equivalent temperature for the point sources, the increase in the recorded power at the maximum of the scan is determined in REX units. This may be compared with the known flux density in Jy. Each source yields its own estimate of [REX units/Jy], which, from knowledge of the effective HGA area A_{HGA}, may be converted to the desired the scaling factor [REX units/K]. The radio flux recorded for each source is plotted in Fig. 3.3.5. as a function of the known flux density.

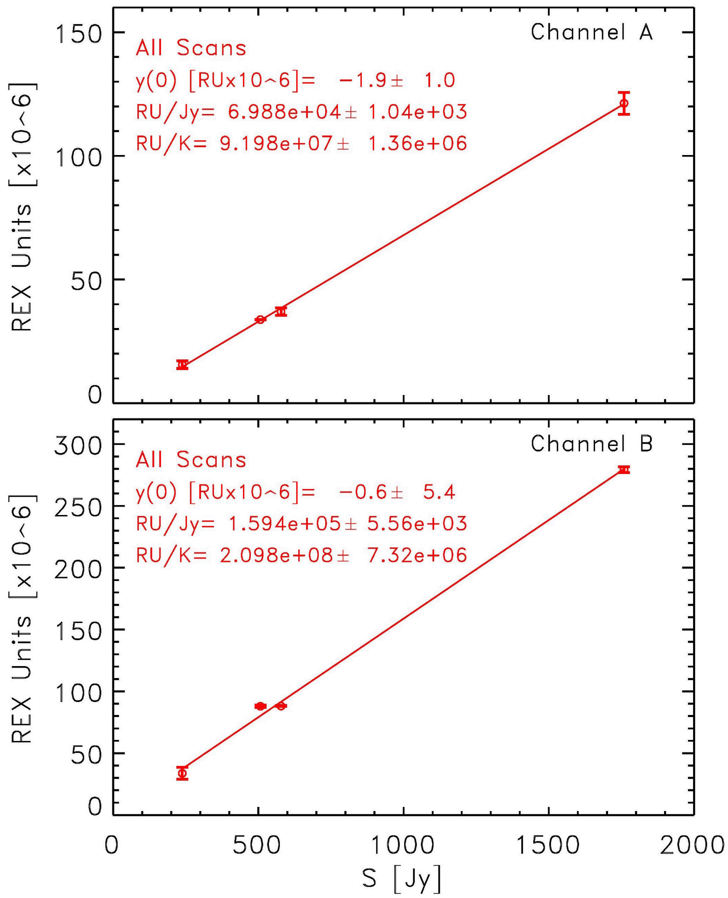


Figure 3.4.5. REX observed power for four known radio sources (upper plot: Channel A; lower plot: Channel B) The points from left to right are for Cyg A, Cas A, Tau A, and the Sun, respectively. The observed increase in radio power (REX units) is plotted versus the known flux density of each source. In Jy. The slope of each least-squares fit to the observations, shown in each panel, is the scaling factor for RU/K

source in Jy.

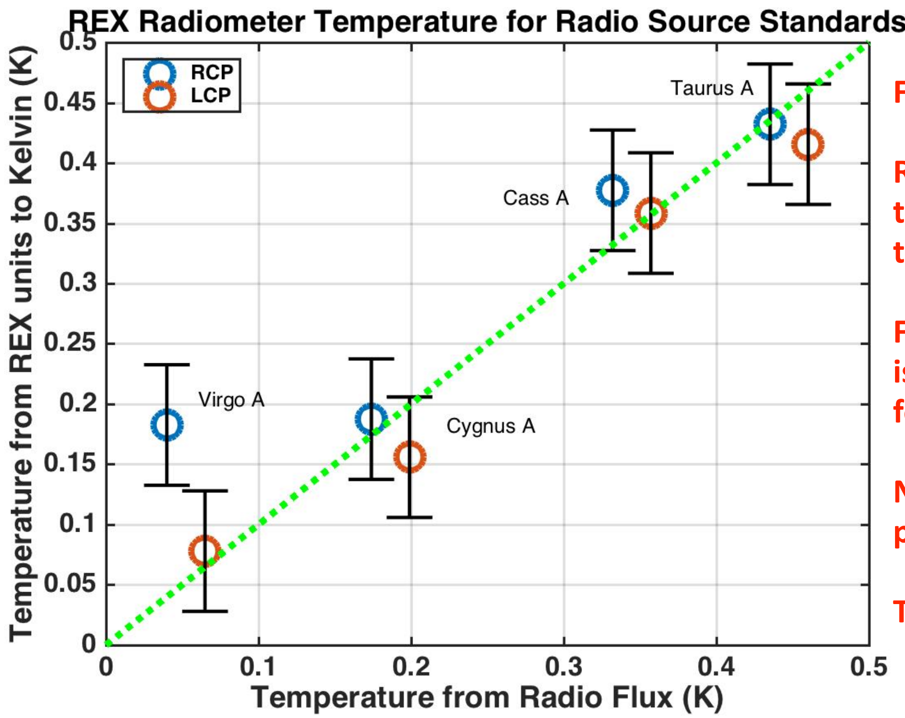


Figure 3.4.6 is puzzling.

RCP and LCP points should have the same abscissa for each target.

From my analysis RCP for Cas-A is less than LCP while RCP~LCP for Cyg-A and Tau-A.

No Vir_A data have been presented.

The error bars are unexplained.

Figure 3.4.6. Temperature to Temperature Comparison for Standard Radio Sources. The radio brightness temperature estimated from the radio source standard's flux is the horizontal coordinate. The vertical coordinate is the radio brightness temperature extracted from the REX radiometer X and Y scans across the radio source using the REX units to Kelvin conversion. The blue markers are for the Right Hand Circular polarization measurements (RCP), and the red markers are for the Left Hand Circular polarization measurements (LCP).

kelvins

No such equation. If you meant (3.3.2), note that T_SKY would be set to zero.

The antenna temperature estimates on the horizontal coordinate of Figure 3.4.6, are computed using Eqn (3.4.2). Adjusting the effective aperture of the HGA to obtain the best agreement between the REX radiometric brightness and the effective antenna temperature of the standard radio sources, finds the best agreement for an effective aperture of 0.6, for the HGA. Effective aperture or aperture efficiency? If the former, this is far from the value at the bottom of p. 9.

The REX radiometer measurements of the eight calibration sources is summarized in Table 3.4.2. The calibration constants were determined (a) by using of the sun to find the conversion from REX units to Kelvin (b) using the Cold Sky Locations to find the noise temperatures in the X-band polarization channels, and (c) using the radio source standards to find the effective aperture of the HGA.

are

kelvins

	Right Circular Polarization	Left Circular Polarization
Convert REX units to Kelvin	82.149 +/- 0.008	192.492 +/- 0.018

kelvins

These are not the values that resulted from the Sun calibration (page 18).

They are also missing factors of 10^6.

Receiver Noise Temperature	138.43 K +/- 0.6 K	136.36 K +/- 0.6 K

Table 3.4.2. REX Radiometer Calibration Constants

These values do not appear anywhere previously in the document. They do appear again near the bottom of page 31.
If they came from the cold sky calibrations, it is not clear how.

3.5 Calibration Using X-band Uplinks from Earth

Over the course of the New Horizons mission unmodulated X-band uplinks were transmitted from Earth using DSN stations to the New Horizons spacecraft. These uplinks were received in the spacecraft's X-band Receiver and recorded using REX. The REX process shifted the uplink signal to a 1.25 kHz baseband in both in-phase and quadrature channels, and Nyquist sampled those channels at 1250 samples per 1.024 seconds. The uplink frequencies were offset from band center (i.e. DC), by +/- 100 Hz, such that the uplink's cross-polarization's locations in their respective polarizations were separated in frequency by 100 Hz.

receiver

Figs. 3.5.1 and 3.5.2 imply 200 Hz spacings of up to 4 carriers and 400 Hz tuning offset between RCP and LCP.

The X-band power in the uplink signal at the spacecraft was determined using a link analysis. The power monitor in the X-band receiver on the spacecraft was calibrated before mission launch, and has agreed with the power values from the link analysis to within +/-0.1 dB, over the duration of the mission.

Did this work with multiple uplinks?

With knowledge of the uplink's X-band power, and the uplink recordings produced by REX, an alternative estimate of the spectral power density of the X-band receiver's noise can be obtained. For example, by taking FFT's of successive 1250-sample sequences of the in-phase (I) and quadrature (Q) samples, the mean spectral power density of both the uplink and the X-band receiver's noise is estimated to good statistical precision. These estimates are obtained for every uplink recorded by REX during the New Horizons mission. An example of this process is shown in Figure 3.5.1, for both RCP and LCP uplinks recorded two days after the Pluto Encounter. Notice that the SNR of the RCP uplink is 4 dB stronger than for the LCP. This is due to the RCP uplink transmitted from DSS-43, a 70-m antenna in Canberra, while the LCP uplink is from DSS-34, a 34-m antenna in Goldstone, CA. Both stations transmitted at 20 kW transmitter power.

Were the RCP and LCP data acquired simultaneously? If so, I'm surprised that the DSS-34 signal in RCP is 35 dB weaker than in LCP while the DSS-43 signal in LCP is only 25 dB weaker than in RCP (when compared against the noise baseline). This suggest that the end-to-end cross-polarization is not symmetrical (albeit with different antenna combinations). I usually figure 20 dB of isolation is nominal for combinations of DSN and spacecraft antennas.

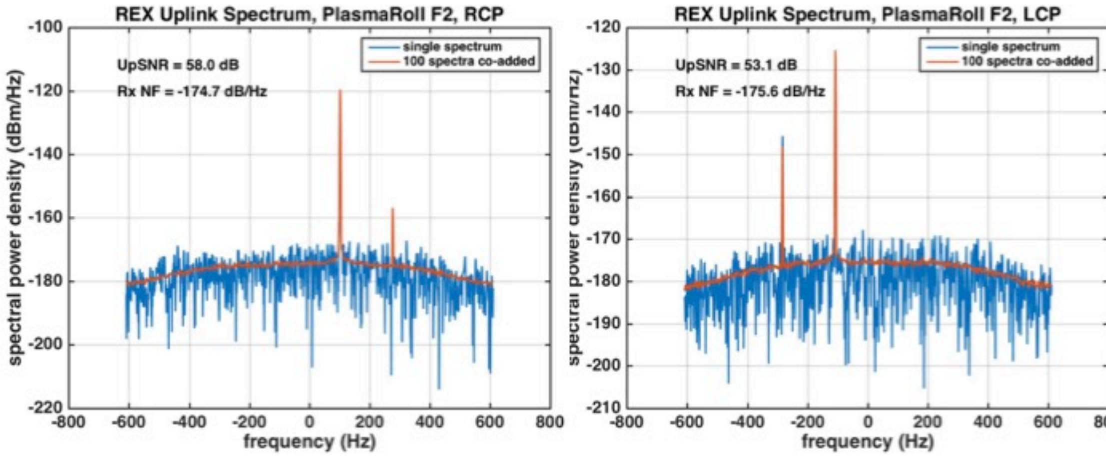


Figure 3.5.1. REX Uplink Spectra from PlasmaRoll F2. The PlasmaRolls were measurements spacecraft measurement made of the solar wind by rolling the spacecraft along an around earth-pointed axis. Uplinks were transmitted and received on the spacecraft during the spacecraft roll. Using a link analysis the uplink's power is registered to the peak was of the uplink spectral line, and the power spectral density of the X-band receiver's was noise floor is then scaled by the uplink to noise floor SNR.

The link analysis the uplink's power provides the means to register the peak of the analysis provides a means uplink spectral line. This registration is determined by integrating the power PSD? spectral density (psd), of the uplink under the spectral line. Because the spectrum of the uplink was computed using the FFT of the 1250-samples REX I's and Q's, windowed by a Hamming-type window (e.g. a Parzen window), The spectral width the of the uplink is ~5 FFT bins wide. The integral of the uplink's spectral samples is scaled to the uplink power from the link analysis. The shape of the impulse response of the window, is fit to the spectral samples, and the shape's peak is the registration value. The psd of the X-band receiver's noise floor is scaled from the uplink's registration by the signal-to-noise ratio (SNR) from the spectral peak to the noise floor near baseband center. The 1.25 kHz bandwidth of REX's baseband channel is tapered toward band edge to suppress aliasing. toward the band edges

The psd of the X-band receiver's noise expected in the REX baseband spectra is,

$$P_N = k\, T_{XB}\, B$$

As defined here, P_N is the total power in the bandpass, not the PSD. The PSD could be calculated by setting B=1.

where Where k is Boltzmann's constant, T_{XB} is the noise temperature of the X-band receiver's polarization channel and B is the channel's bandwidth. With B = 1250/1.024 Hz, and the receiver noise temperatures 138.4 K for RCP, and 136.4 K for LCP, the psd's as determined by the above process are,

$S_{XB}(RCP)$ = -176.73 dBm/Hz
$S_{XB}(LCP)$ = -176.88 dBm/Hz

These values are not correct. The Boltzmann constant is 1.38e-23. For RCP and B=1, the noise power is k*T_XB = 1.38e-23*138.4 = 1.91e-21 watts/Hz. Expressed in log form, this value is -207.19 dB/Hz or -177.19 dBm/Hz. The LCP value is -177.25 dBm/Hz. Why this simple calculation leads to errors of 0.3-0.5 dBm/Hz is not clear.

Figure 3.5.1?

The noise floor psd values in Figure 3.4.1 are -174.7 dBm/Hz, and -175.6 dBm/Hz, are 2.0 dB and 1.2 dB larger respectively then expected. This discrepancy is likely due to the assumption in the link analysis that the uplink power was 20 kW, while the actual power transmitted by the station typically varies during the duration of the transmission.

dBm/Hz; they

But Section 3.5, paragraph 2 states that the on-board power monitor agrees with the link analysis to ±0.1 dB for the entire mission. Can't this 1-2 dB discrepancy be checked?

An additional recording by REX of uplinks occurred during the Pluto and Charon encounters, where four uplinks were transmitted by the DSN, two in RCP, and two in LCP. The spectrograms of these recordings are shown in Figure 3.5.2, where the two uplinks in each polarization are the strongest spectral lines, while the two uplinks from the cross polarization are the weaker cross-pol lines.

encounters when

DSN — two in RCP and

weaker lines

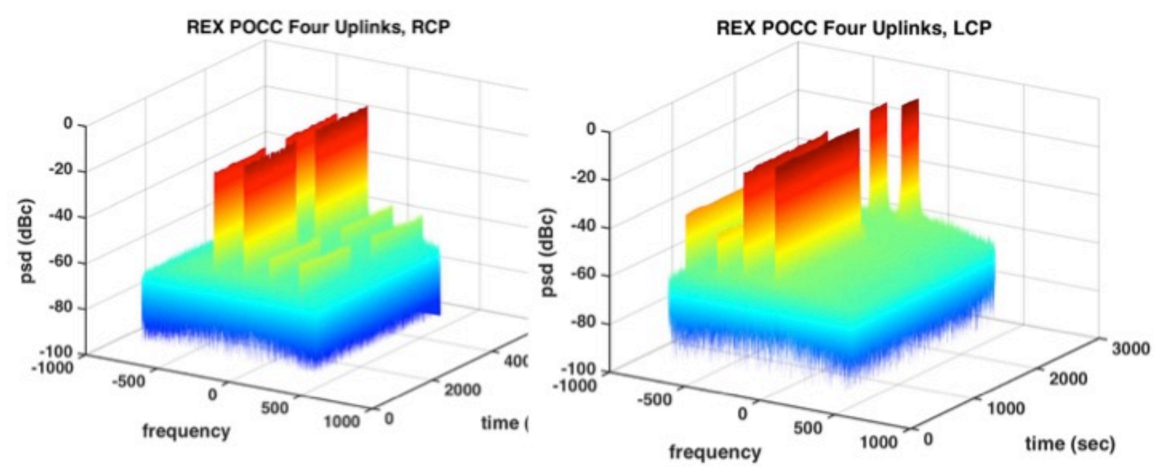


Figure 3.5.2. REX spectrograms of uplinks during the Pluto and Charon occultations. Four uplinks were transmitted to REX by the DSN during the occultations. Two uplinks in RCP, and two uplinks in LCP. The weaker spectral lines in the spectrograms are the cross-polarization signals.

Both polarizations of the REX recordings of the I and Q samples were low-pass filtered to isolate each of the four uplinks from each other. The complex representation I + iQ samples were frequency shifted to 50 Hz from DC and the I and Q sequences were separately digitally bandpass filtered in a 40 Hz band centered at 50 Hz. This separation was because the digital filter was a real-only process. The parallel I and Q filtered sequences were then recombined as I + iQ, into a complex representation. This process created two narrow band segments in the REX band, one containing just one of the uplinks, the other segment containing only the X-band receiver's noise. The power in the uplink is estimated from the segment containing the uplink and some of the receiver noise, and the spectral noise floor is estimated from the segment with only the noise. The SNR of the uplink is determined by summing the uplink's power spectral densities in the few spectral lines and subtracting the product of the noise floor psd time the number of bins

times

Replace third sentence by: "The two higher frequency uplinks were LCP, and the two lower frequency uplinks were RCP." Add a fifth sentence: "Note that the LCP receiver was tuned ~400 Hz higher than the RCP receiver because of differences in their USO frequencies."

From Figures 3.5.1 and 3.5.2 there don't appear to be any signals at DC; the closest are at ±100 Hz.

Replace sentence by: "Figures 3.5.4 and 3.5.5 illustrate the processing to obtain SNR and noise power with four uplinks and two polarizations."

used in the spectral line sum for the uplink power. Figure 3.5.4, and Figure 3.5.5, are the plots illustrating the result of the SNR's and psd's of the receiver noise.

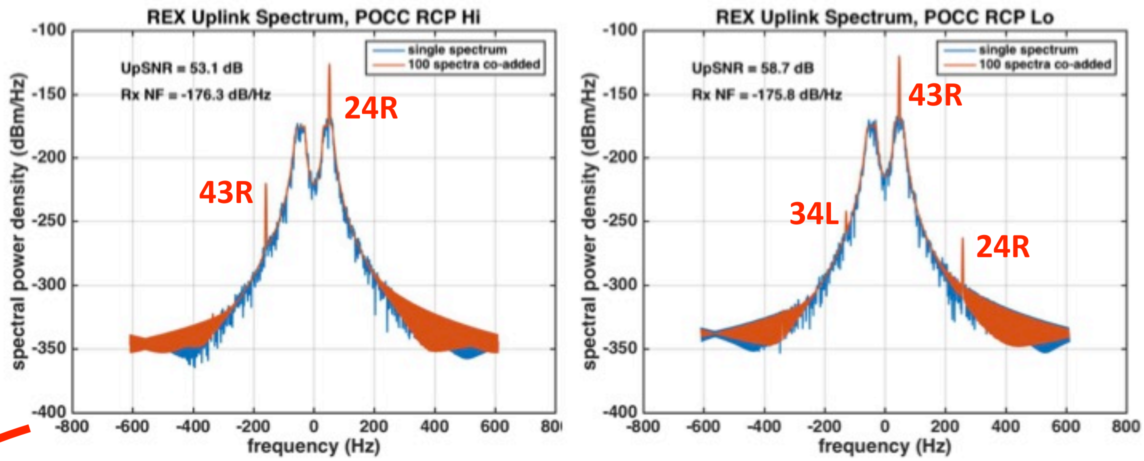


Figure 3.5.4. REX spectra of uplinks in RCP during Pluto and Charon Occultations. The two uplinks in each polarization have been isolated using a combination of frequency shifting and bandpass filtering. Consider combining Figures 3.5.4 and 3.5.5 into panels a, b, c, and d of a single figure. Label the uplinks that can be identified by DSS number. Note that -50 Hz is the noise window.

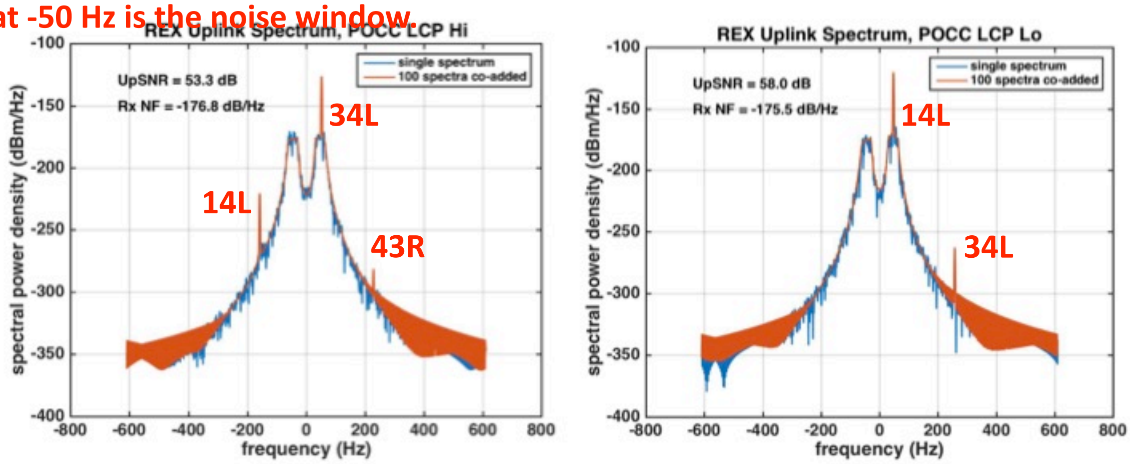


Figure 3.5.5. REX spectra of uplinks in LCP during Pluto and Charon Occultations. The two uplinks in each polarization have been isolated using a combination of frequency shifting and bandpass filtering.

The power radiated by the DSN stations was logged for the Pluto and Charon occultations and used in the link analysis for an accurate estimate of the uplink power at REX. The registration and scaling of the power spectral density using this more accurate uplink power estimate improves the agreement between the resultant and expected receiver noise psd's. The agreement is within a few tenths of a dB. The residual uncertainties likely reside in the losses the heterodyne process incurs converting the RF in the X-band antenna and feed down to the Radiometrics Channel's band and then to REX.

Are frequencies in Figures 3.5.4 and 3.5.5 reversed from Figure 3.5.2? UpSNR values (and locations and SNR values of neighboring spikes) only make sense if negative and positive frequencies have been swapped. Annotations on figures (e.g., "43R") show inferred DSS numbers and uplink polarizations from Hinson et al. (2017).

Replace first two sentences (and correct many small errors) with: "The constants in Table 3.4.2 may be used to convert radiometric power in each REX channel (in REX Units) to equivalent temperatures in kelvins."

4.0 Conversion of REX units to Physical Units

The constants in Table 3.3.2, will convert REX units to degrees Kelvin. Doing so gives the radiometric power in the REX channel as a temperaturein units of Kelvin. The radiometric power was sampled and recorded in the X-band receiver's 4.5 MHz bandwidth Radiometric Channel. Using Boltzmann's constant the temperature in Kelvin can be converted to the total received power in the radiometrics channel in watts:

kelvins

$P_{tot}(W) = kBT$

where, k = Boltzmann's constant = 1.3807×10^{-23} J/K
B = predetection bandwidth = 4.5 MHz
$T\ (K) = T_{sys} + T_{ant}$

with, T_{sys} = system temperature
T_{ant} = antenna temperature

For example to convert REX units to power in dBm, where:

dBm: Decibels relative to 1 mWatt
dBm = $10 \log_{10}(\text{Power} \cdot 1000)$, (Power in watts)

A logarithmic form of Eqn 3.3.1 is useful:

$$\log_{10}(kT_{XB\,P}) = \log_{10}\left(k\frac{P_{REX\,units\,NP}}{G_P}\right)$$

The total power does not depend on T_sys; omit this term. If receiver noise goes up or down, that change is reflected in RU. Omit R_G from the equation.

For the two polarization channels, RCP and LCP, while accounting for the gain setting of the receiver, and in units of dBm, dBm/Hz

$$P_{dBm} = R_G + 10\log_{10}(RU) + g_{Step}(G_{AGC} - G_0) + R_0 \quad + 30 \quad (4.1)$$

P_dbm/Hz

P+dBm/Hz is the radiometric power density in dBm/Hz

where, P_{dBm}, is the radiometrics total power in dBm
R_G, is the radiometrics channel power due to receiver noise alone
RU, are the REX units of the samples
g_{Step}, is the receiver's gain step (equal to 0.475 dB) See comments regarding Figure 2.2.1
G_{AGC}, is the gain setting, also called the *gain word*
G_0, is the reference gain word, fixed at 167 for RCP and 163 for LCP
R_0, is the REX units to Kevin calibration constant scaled by the Boltzmann constant

is the Boltzmann constant divided by the REX-to-K coefficient (logged and multiplied by 10)

In particular, for the two X-band receiver polarizations, Eq'n. 4.1, becomes,

For RCP: $dBm_{RCP} = -176\ dBm + 10\log_{10}(R_{REX\_RCP}) - 0.475\ (G_{AGC\_RCP} - 167) + R_{0\_RCP}$

Sign is "+" in equation (4.1)

and for LCP: $dBm_{LCP} = -176\text{ dBm} + 10\log_{10}(R_{REX\_LCP}) - 0.475\,(G_{AGC\_LCP} - 163) - R_{0\_LCP}$

$R_{0\_RCP} = -106.2$, $R_{0\_LCP} = -104.2$ and G_{AGC_A}, G_{AGC_B}, are the REX gain words, with reference values of 167,and 163, respectively.

-311.44

different values; but neither is correct

Note: The power values dBm_{RCP}, dBm_{LCP} are not for the 4.5 MHz bandwidth of the REX Radiometrics Channel, but rather for a 1 Hz bandwidth. The power conversion is thus in dBm/Hz. To obtain the Radiometrics power in the 4.5 MHz bandwidth of the Radiometrics Channel, an additional term of $R_{RC} = 10\log_{10}(4.5\text{x}10^6) = 66.532$, should be added into the above formulas.

omit this paragraph; (4.1) now given in dBm/Hz

Note: The REX radiometer samples have a cadence of 10 samples per REX frame. The first sample in each frame is the total accumulated power from the last frame (due to an idiosyncrasy of the REX processor implementation). The REX radiometer accumulator is then cleared and next sample, is the integrated power for the 1st time interval Δt, of the frame ($\Delta t = (1/10)1.024$ sec). For the following samples, the sample value increments by the accumulated integrated power from the preceding time step. The power samples from the second to the last appear as a staircase set of steps.

This note must be consistent with ICD equation.

As an example, from the cold sky radiometer measurements,

$R_{REX\_RCP} = 1.289 \text{ X } 10^{10}$
$G_{AGC\_RCP} = 167$
$R_{0\_RCP} = -106.6$

Giving, $dBm_{RCP} = -176.89$ dBm

and

$R_{REX\_LCP} = 2.892 \text{ X } 10^{10}$
$G_{AGC\_LCP} = 163$
$R_{0\_LCP} = -104.2$

not correct

Converting to, $dBm_{LCP} = -176.41$ dBm

These are both smaller powers than the receiver noise power, which was given as -176 dBm on page 34. Using the input values here and the equation at the bottom of page 34, I get dBm_RCP = -181.50 (not -176.89), which is even smaller. Using the values given here and the equation at the top of this page (with the sign correction), I get -175.59, not -176.41.

Note that not all REX radiometer data, if converted to physical units will produce physically reasonable values since not all REX Radiometer data was taken with an external radiometric source in the beam of the HGA. For example, a typical REX measurement consists of first switching REX to an internal set of test patterns where REX produces data that can be bit-by-bit compared to the expected response. The REX Radiometer power will not be physically reasonable for any of the test pattern data.

True; but is this really televant?