12.   REX INSTRUMENT DESCRIPTION

12.1   Overview

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

The REX instrument is unique among the suite of instruments comprising the New Horizons payload in that it is physically and functionally incorporated within the spacecraft telecommunications subsystem. REX consists of both a 'Flight Element' carried on-board the New Horizons spacecraft, and a 'Ground Element' comprising the existing Earth-based NASA Deep Space Network transmitting and operations facilities, which radiate an uplink signal that is sampled and measured by REX on-board the spacecraft.

REX is designed to fulfill the mission objectives by performing the following distinct experiments:

1. A radio occultation experiment, designed to detect and measure the atmosphere, ionosphere and size of Pluto, and of Charon where detectable. The spacecraft will be maneuvered so that Pluto, and then Charon, pass through the line of sight from Earth to the spacecraft. That line of sight is coincident with the uplink signal path from the Ground Element, and so Pluto and Charon will effect changes in the signal received and measured by REX. The experiment will detect phase differences between the uplink signal as measured by REX, and a modeled signal which would be expected if there were no occultations. Subsequent analysis of the behavior of those phase differences over time, combined with knowledge of the ephemerides of Pluto, Earth and the spacecraft, will be used to deduce atmospheric temperature and pressure profiles down to the surface of Pluto (and of Charon, should it be found to have a sensible atmosphere), as well as electron and ion densities of Pluto's (and possibly Charon's) ionosphere. Analysis of the on-board-measured uplink signal strength as the spacecraft goes in and out of occultation will be used to deduce the chord lengths of the line of sight path across the disks of Pluto and Charon.

2. A gravity experiment, designed to measure the independent gravitational fields of Pluto and possibly of Charon. Around the time of the occultation experiment, but with the line of sight to Earth well away from the limbs of Pluto and Charon and above any atmosphere or ionosphere, accurate tracking of Doppler shifts in the received frequency of the uplink signal, again compared to a model of what would be expected if there were no body-induced gravity fields nearby, will be used to deduce gravitationally-induced changes in velocity along the spacecraft's flight path.

3. A radiometry experiment, designed to measure the spatially averaged surface emission brightness at a wavelength of 4.2 cm (7.182 GHz, the nominal operating frequency of the New Horizons radio) of Pluto and of Charon. The dark-side emissions will be measured during the occultation interlude. The day-side emissions will be measured as is operationally feasible.

In those first two experiments the on-board REX system hardware downconverts and samples an uplink signal from the Ground Element (Earth-based Deep Space Network; DSN) for the purpose of analyzing the frequency and phase behavior of that signal compared to an on-board oscillator. In the third experiment the on-board hardware measures (integrates) the radiometric emission of a source.

Note that this section's focus, and the PDS archive data sets produced from REX data, comprise samples taken and measurements made *on-board* the spacecraft *by REX* either of a one-way uplink signal from the Ground Element (DSN), or of 4cm-wavelength (7.2GHz) radiation from a planetary surface, from an astronomy source, or from cold sky.

Further note that, at the time this is being written, about a year before the Pluto Encounter, almost all REX observations using one-way uplink data to-date have been instrument functional tests, instrument characterizations, and instrument calibrations. As such, there is *no need* for tuning profiles of the one-way uplink data to analyze those observations. The only exceptions are Lunar Occultations in May of 2011 and January of 2012; Tracking and Navigation Files (TNFs; TRK-2-34 files) with uplink tuning profiles will not be covered here, but will be delivered with PDS data sets containing the lunar occultation data; these data are described by PDS labels and by DOCUMENT/TNFSIS.LBL in those data sets.

Finally note that Earth-spacecraft-Earth non-coherent (a.k.a. one-way mode) tracking data, with measurements made *at the Ground Element (DSN)* of signals sent from REX, are *not processed* by the SOC pipeline, are *outside the scope* of this document, and are *not included* in any REX PDS data sets. At the time this is being written, about a year before the Pluto encounter, there have been no non-coherent tracking data taken for science, only for navigation. The disposition and archiving of non-coherent tracking data to be taken around the Pluto encounter for gravity investigations is TBD.

The heart of the REX instrument is an Actel Field Programmable Gate Array (FPGA) that takes samples of the downconverted & digitized intermediate frequency (IF) receiver output and generates wideband radiometer and narrowband sampled signal data products. The REX hardware also includes an analog-to-digital converter (ADC) and other direct interface components, and by extension all of the RF telecommunications system hardware along the uplink (receive) path from the High Gain Antenna (HGA) to the input to the ADC.

Stanford is responsible for the FPGA design and system analysis. APL is responsible for the design of the telecommunications system and incorporating the REX FPGA system therein.

The interfaces to the REX FPGA (see Figure 12-1) include a 30 MHz clock signal from the Ultra-Stable Oscillator, (USO), the secondary power connections, the command and telemetry data interfaces to the Uplink Card, the high-speed data interface to the Instrument Interface Card, a 1 PPS signal for data framing, and the interface to the ADC, where the wideband IF signal from the Uplink Card is sampled.
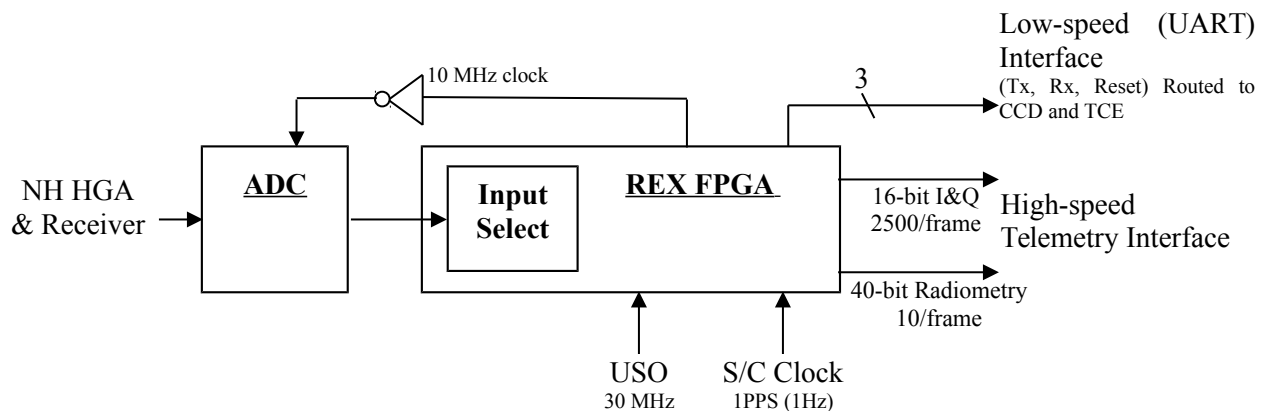

Figure 12-1: Electrical Interfaces to the REX FPGA

The input to the REX FPGA is normally the uplink signal from the DSN after being filtered by a 4.5 MHz bandpass filter (not shown) and digitized by the ADC at a sample rate of 10 Msamples/s. The Input Select function, commandable via uplink, allows the FPGA to process any of seven predetermined digital signals for testing the FPGA functionality (see the ROF Status Byte section below).

12.2   Raw Data Specifics

After REX receives a power-on command, on the next 1PPS strobe from the spacecraft clock the REX FPGA starts generating a continuous stream of data containing In-Phase & Quadrature-Phase value pairs as well as integrated radiometer values. This stream of data is divided into fixed-length units called REX Output Frames (ROFs) at a rate of one ROF per 1.024s (s implies seconds on the spacecraft clock in this section). The ROFs are stored on the spacecraft solid state recorder (SSR), and eventually played back via the High-Speed Telemetry interface to the DSN and arrive at the SOC as raw telemetry packets.

REX continues to generate ROFs until turned off. Each ROF also contains Time Tags that may be used to verify that a sequence of ROFs is a contiguous set. If REX is turned off while writing data to the SSR, the data at the end of the last ROF in a contiguous sequence of ROFs *may* comprise random bits. It is up to the user to assess where this has occurred; in general the last ROF of a sequence can be ignored.

The In-Phase, Quadrature-phase, Radiometer, and Time Tags are all multi-byte values, and the individual bytes for all quantities are interleaved throughout the ROF.

12.2.1   Raw Data Format

The SOC Raw pipeline decommutates each ROF from telemetry and places it into the Primary Data Unit (PDU) of an individual FITS file. Each PDU is stored as a one-dimensional image of 5088 bytes: the first 5082 bytes are the ROF; the last 6 bytes in the PDU are spare.

The SOC Raw pipeline also looks in the telemetry for packets corresponding to the time of the ROF, and places them in Extension Data Units (EDUs). Specifically, data from spacecraft housekeeping ApIDs (packet Application Process IDentifiers; also Application IDs) 0x004, 0x016, 0x084 and 0x096 as well as from Thruster packets are placed in EDUs 1 through 5, respectively, of the Raw FITS files.

12.2.1.1 PDU Content

Each ROF contains the items listed in Table 12-1, with the individual bytes in an interleaved format:

Item	Item Description	Count/ROF	Bytes/item	Total bytes
ID byte	ROF Identifier = 0xB7	1	1	1
Status byte	Input select	1	1	1
Radiometry	40-bit integrated power; reset each ROF	10	5	50
Time tag	24-bit accumulator	10	3	30
I&Q value pair	In-phase & Quadrature @ 16 bits	1250 (pairs)	(2 + 2 =) 4	5000

Table 12-1: REX Output Frame Contents

12.2.1.1.1   ROF ID byte

The ID byte is the first byte in the ROF and should always have the same value; see Table 12-2:

Unsigned Decimal	Hexadecimal	Binary
183	B7	1011 0111

Table 12-2: REX Output Frame ID byte value

12.2.1.1.2 ROF Status byte

The ROF Status byte is the fourth byte in the ROF. In bit positions 6, 5 & 4 (bit position 7 is the most significant bit = $128 = 2^7$; bit position 0 is the least significant bit = $1 = 2^0$) it contains the three bits that make up the Input Select setting for the ROF; all other bits are normally zero, otherwise corruption should be suspected. When Input Select is set to any of its non-zero values, the ADC output is replaced as the FPGA input with a predetermined 10Msample/s signal as described in Table 12-3. In that case, the ouptut of the REX FPGA should be deterministic and known, and may be compared bit-for-bit against the expected ouput as a limited check on the health of the FPGA as well at that of the Input Select system.

Input Select (binary)	Status Byte (binary)	Input Select description
000	0000 0000	ADC output from NH receiver system (default)
001	0001 0000	Impulse: 2 samples (200ns) of value 128 at the start of each ROF, followed by zeroes
010	0010 0000	Low-Frequency Square Wave: +/-256 @ 610.3515625 Hz
011	0011 0000	Mid Frequency Square Wave: +/-256 @ 19.53125 KHz
100	0100 0000	Pseudo-Random Number (PRN) of value +/-1 @ 10 MHz
101	0101 0000	Pseudo-Random Number full scale @ 10 MHz
110	0110 0000	Hi Frequency Square Wave: +/-256 @ 78.125 KHz)
111	0111 0000	All zeroes

Table 12-3: REX Input Select & Status Byte values

12.2.1.1.3 Integrated Radiometry values

The details of how incoming power is used as radiometry are given in Tyler et al., 2008.

The FPGA integrates the incoming power from its input signal by squaring and summing the ~10Msamples/s that compose its input. Ten accumulating radiometry values are stored in each ROF, and the FPGA resets the value to zero at the start of each ROF. Each radiometry value comprises 40 bits, or 5 bytes, as an unsigned integer, and the bytes are in MSByte-first order, interleaved with I&Q values.

The time interval between radiometry values is one-tenth of a ROF or 102.4ms. In each ROF, REX stores a integrated radiometry value at the start time of that ROF (and not 102.4ms after its start), so the tenth, or last, radiometry value of associated with a ROF (i.e. the one that represents a full 1.024s of integration time) is actually stored as the first radiometry value in the following ROF.

12.2.1.1.4 Time Tag values

REX places ten incrementing time tags in each ROF. The first time tag of the first ROF after a start command is zero, and following time tags increment by one. The time tag is not reset at the start of each ROF. Each time tag value comprises 24 bits, or 3 bytes, as an unsigned integer, and the bytes are in MSByte-first order, interleaved with I&Q values. Each increment of the time tag represents 102.4ms. The rollover time is about a fortnight and a half (16.7Ms) and will never be reached in practice.

The time tags can be used both to identify any breaks in a sequence of ROFs, and to determine the time between any two ROFs within a sequence.

12.2.1.1.4.1 *Time tag anomalies in ROF sequences*

The normal sequence for time tags is to start at zero in the first ROF and increment ten times per ROF, so first time tag of the second ROF is 10, that of the third ROF is 20, etc. The time tags continue to increment until either REX is turned off or the high-speed allocation for the observation in the Solid-State Recorder (SSR) is full. In practice, the first and last ROFs in a sequence do not always show simple zero starts and clean finishes, respectively; the first time tag may be 10, or it may continue from the previous ROF sequence before resetting to zero; the time tags in the last ROF often start correctly for the first few but then drop to zero for the final values. This can be due to the compression issue mentioned elsewhere, but has also been observed with uncompressed data. These time tag anomalies indicate data corruption in just those starting and ending ROFs, but there is no indication of corruption elsewhere within ROF streams. REX commanding ensures there are always adequate ROFs before and after any observation, so discarding starting and ending ROFs in a sequence based on simple inspection of time tags is the way to handle this issue.

12.2.1.1.5 I & Q value pairs

Each ROF contains 1250 pairs of In-Phase (I) & Quadrature-Phase (Q) values. Each I value and each Q value comprises 16 bits or two bytes as a twos-complement signed value.

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

12.2.1.2 Method 1 - values' bytes' layout within ROF: Interleaving

In each ROF, the bytes of the ID, Status, Radiometry and Time Tag values are interleaved with the I&Q value pairs, but none of the values start or end on other than a byte boundary. There are two methods to describe such an arrangement: describe the layout of the bytes of the data values as a sequence bytes from the ROF; describe the layout of the ROF as built out of a sequence of bytes extracted from the de-interleaved data values (ID, Status, Radiometry, Time Tag, I&Q). Both methods will be described here, the former first as it lends itself more easily to writing computer code to build the data values by extracting bytes from the ROF. Indeed, IDL(tm) and Python routines to de-interleave ROF data exist each with less than two dozen statements.

Item, Item Size (bytes), Item Count	First (MSB) byte of first value (1-based)	Offset to succeding byte(s) within an Item	Byte Offset(s) to successive Items	First (MSB) byte of first value (0-based)
ID byte, 1, 1	1	N/A	N/A	0
Status byte, 1, 1	4	N/A	N/A	3
Radiometry, 5, 10	7	3	508	6
Time Tag, 3, 10	22	3	508	21
I, 2, 1250	2	1	6 & 4	1
Q, 2, 1250	5	1	6 & 4	4

Table 12-4: Data values' bytes' positions and offsets within an ROF. For example, there are 10

Radiometry values, each comprises 5 bytes (1st column, Radiometry row). The first Radiometry value comprises the 7th (2nd column), then 10th, 13th, 16th, and 19th bytes (3rd column) of the ROF. The second Radiometry value comprises the 515th (7+508; 4th column), then 518th, 521st, 524th, 527th bytes of the ROF.

The following sections use the notation in Table 12-5 to and/or locate the various quantities' bytes within the ROF (Method 1), or vice versa (Method 2):

ROF[N]	Nth byte of ROF (N=1 to 5082), interpreted as an unsigned integer (Range is 0 to 255)
R[I]	Ith Radiometry value; I=1 to 10
T[J]	Jth Time Tag value, J=1 to 10
I[K] or Q[K]	Kth In-phase (I) or Quadrature-phase (Q) value, K=1 to 1250
X[M:N]	Bits M through N of multi-byte quantity X. E.g. R[10][31:24] second byte of R[10]
Y[MSB]	The MSByte, as an unsigned integer, of a 16-bit signed IQ value Y; Y[MSB] = Y[15:8]
Y[LSB]	The LSByte, as an unsigned integer, of the a 16-bit signed IQ value Y; Y[LSB] = Y[7:0]
Oi	A useful offset quantity equal to (508 * (i-1))

Table 12-5: Notation used in this section

12.2.1.2.1 Method 1 - Layout of ID & Status bytes

The ID and Status bytes are the first and fourth bytes in the ROF, respectively, and can simply be obtained from the ROF as such as there are no following bytes or values:

ID byte = ROF[1]

Status byte = ROF[4]

12.2.1.2.2 Method 1 - Layout of Radiometry bytes

The first byte of the first radiometry value is the seventh byte of the ROF, and the following four bytes of that first radiometry value are each offset by three bytes from the previous byte. The order is MSByte-first. So, the first radiometry value of a ROF may be calculated from the following formula:

```
R[1] = ( ( (ROF[7] * 256 + ROF[10]) * 256 + ROF[13]) * 256 + ROF[16]) * 256 + ROF[19]
```

The following radiometry values' bytes in the same ROF are each offset 508 bytes from the previous radiometry value's bytes. So, more generally:

```
R[i]=(((ROF[7+Oi]*256 + ROF[10+Oi])*256 + ROF[13+Oi])*256 + ROF[16+Oi])*256 + ROF[19+Oi]
```

12.2.1.2.3 Method 1 - Layout of Time Tags' bytes

The first byte of the first time tag value is the 22nd byte of the ROF, and the following two bytes of that first radiometry value are each offset by three bytes from the previous byte. The order is MSByte-first. So, the first time tag value of a ROF may be calculated from the following formula:

```
T[1] = (ROF[22] * 256 + ROF[25]) * 256 + ROF[28]
```

The following time tag values' bytes in the same ROF are each offset 508 bytes from the previous radiometry value's bytes. So, more generally:

```
T[i] = ( ROF[22+Oi] * 256 + ROF[25+Oi] ) * 256 + ROF[28+Oi]
```

12.2.1.2.4   Method 1 - Layout of I & Q values' bytes

The bytes that are used to store the I & Q values alternate in sequence (I[1], Q[1], I[2], Q[2], I[3], Q[3], ..., I[1250], Q[1250]) as 16-bit MSByte-first two's complement signed integers, that cover all of the bytes not used by the other values (ID, Status, Radiometry, Time Tags) above.

Specifically, Table 12-6 describes how ROF bytes are used to calculate I[K] and Q[K] for K=1 to 1250:

KMOD	KMOD = (K+123) MOD 125
j	j = (K+123-KMOD) / 125
Oj	Oj = 508 * (j-1)
K=1	I[K] = IQ(ROF[2], ROF[3]) Q[K] = IQ(ROF[5], ROF[6])
K>1 & KMOD<4	I[K] = IQ(ROF[8+KMOD*6+Oj], ROF[9+KMOD*6+Oj]) Q[K] = IQ(ROF[11+KMOD*6+Oj], ROF[12+KMOD*6+Oj])
K>1 & KMOD>3	I[K] = IQ(ROF[15+KMOD*4+Oj], ROF[16+KMOD*4+Oj]) Q[K] = IQ(ROF[17+KMOD*4+Oj], ROF[18+KMOD*4+Oj])

Table 12-6: I & Q values from ROF

Where Function IQ(MSByte,LSByte) is defined as (with MSByte & LSByte interpreted as unsigned 8-bit - i.e. 1-byte - integers)

```
IQ(MSByte,LSByte) = 256 * MSByte + LSByte
```

if MSByte is between 0 and 127 inclusive. Otherwise, it is defined as

```
IQ(MSByte,LSByte) = 256 * MSByte + LSByte - 65536
```

12.2.1.3 Method 2 - Layout of ROF

The tables below have one cell per ROF byte, and indicate which data values (ID, Status, Radiometry, &c) each byte contributes to. The order of bytes in these table is left-to-right and down i.e.

ROF[1]	ROF[2]	ROF[3]
ROF[4]	ROF[5]	
ROF[6]	ROF[7]	
...	...	

The first six ROF bytes contain the ID & Status bytes and the first I&Q pair:

ID	I[1][MSB]	I[1][LSB]
Status	Q[1][MSB]	Q[1][LSB]

The next 508-byte "chunk" (again, ROF byte order is left-to-right then down) contains one Radiometry value, one Time Tag, and 125 I&Q pairs:

R[1][39:32]	I[2][MSB]	I[2][LSB]
R[1][31:24]	Q[2][MSB]	Q[2][LSB]
R[1][23:16]	I[3][MSB]	I[3][LSB]
R[1][15:8]	Q[3][MSB]	Q[3][LSB]
R[1][7:0]	I[4][MSB]	I[4][LSB]
T[1][23:16]	Q[4][MSB]	Q[4][LSB]
T[1][15:8]	I[5][MSB]	I[5][LSB]
T[1][7:0]	Q[5][MSB]	Q[5][LSB]
I[6][MSB]	I[6][LSB]	
Q[6][MSB]	Q[6][LSB]	
I[7][MSB]	I[7][LSB]	
Q[7][MSB]	Q[7][LSB]	
I[8][MSB]	I[8][LSB]	
Q[8][MSB]	Q[8][LSB]	
...	...	
I[126][MSB]	I[126][LSB]	
Q[126][MSB]	Q[126][LSB]	

The rest of the ROF comprises 9 more chunks of 508 bytes per chunk, essentially identical to the one above, incrementing the R[] & T[] indices by one per chunk, and incrementing the I[] & Q[] indices by 125 per chunk. Each chunk except the last contains 125 I&Q pairs; N.B. the tenth chunk ends after its 504th byte and after its 124 I&Q pair which is the 1250th, and last, I&Q pair of the ROF.

12.2.2   Data Sources (High/Low Speed, CCSDS, ITF)

REX data are in the high-speed stream and come to the SOC in CCSDS (Consultative Committee for Space Data Systems) packets.

12.2.3   Definition of an "Observation"

One REX Output Frame (ROF), as defined above, is an observation.

12.2.4   Data and housekeeping in Raw FIT files' PDU and EDUs

The Raw pipeline puts the raw ROF into the Primary Data Unit (PDU; a.k.a. EDU "0"), and puts ROF-derived information (I/Q pairs, Radiometry, Time Tags), plus several types of housekeeping (HK) packets, as FITS binary tables (BINTABLEs) into Extension Data Units (EDUs) 1 through 8 (see Table 12-7). The pipeline attempts to find the closest HK packet to the observation time. If no packet is available, the

EDU data are not present and the corresponding Extension Header Unit (EHDU) will indicate a zero-sized EDU.

#	EXTNAME	Cal	Description
0	N/A	No	Raw ROF (REX Output Frame)
1	I AND Q VALUES	Yes	1250 (In-, Quadrature-phase) value pairs
2	RADIOM. AND TIME	Yes	Radiometer and Time Tag values (10 each)
3	HOUSEKEEPING_0X004	No	Phase Locked Loop HK from ApID 0x004
4	HOUSEKEEPING_0X016	No	REX HK from ApID 0x016
5	HOUSEKEEPING_0X084	No	Phase Locked Loop HK from ApID 0X084
6	HOUSEKEEPING_0X096	No	REX HK from ApID 0x096
7	THRUSTERS	No	Thruster HK from ApID 0x124
8	SSR_SECTOR_HEADERS	No	SSR sector header information (Note 1)

Table 12-7: REX RAW (AND CALIBRATED; see Section 12.3.2 below) FITS PDU (a.k.a. EDU 0 or DU 0) and EDU Numbers, Names, Calibration relevance, & Descriptions. Extension with calibration-relevant have "Yes" in the "Cal" column. Extensions 3-8 are irrelevant to PDS users.

12.2.4.1 FITS keywords added to PDU (a.k.a. EDU 0 or DU 0)

The Status byte is added to the PHDU (FITS header of PDU).

12.2.4.2 FITS BINTABLE specifics

12.2.4.2.1 Extension Data Unit (EDU) 1 - I & Q values

The In-phase and Quadrature-phase values are each combined from two ROF bytes as described above and stored as signed 16-bit values n their respective columns (TFORMn = I; TFORMn is a keyword in EDU BINTABLE header and declares the format of table column n; a value of I indicates a 16-bit integer; refer to FITS reference given in Section 3 for more detail).

The BINTABLE comprises 1250 rows, and each row comprises two columns laid out over four bytes.

12.2.4.2.2 EDU 2 – Radiometry and Time Tags

The Radiometry values are each combined from five ROF bytes as described above, and stored within signed 64-bit integers in the first column of the BINTABLE (TFORM1 = K).

The Time Tag values are each combined from three ROF bytes as described above, and stored within signed 32-bit integers in the second column of the BINTABLE (TFORM2 = J).

The BINTABLE comprises 10 rows, and each row comprises two columns laid out over twelve bytes.

12.2.4.2.3   EDUs 3 through 8 – Housekeeping

The remaining BINTABLES contain housekeeping information and are there for historical reasons and for diagnostics performed by the science team, and will not be described here. PDS users may safely ignore them.

12.2.5   Note for PDS users reading FITS files

There are many FITS libraries that render trivial the reading of data from any PDU or EDU in a FITS file.

If however the PDS user, for whatever reason, still desires to write their own access routines, then we recommend they should instead use the detached PDS labels as a data map. PDS labels provide, in both machine- and human-readable form, a simple arithmetic path to interpret the bytes in these FITS files.

12.2.6   Raw Science Data and/or Housekeeping Requirements

Radio receiver housekeeping (ApIDs 0x004 and/or 0x084 noted above).

12.3   Calibration Specifics

12.3.1   Calibration Algorithms

The conversion of RAW REX data to Calibrated data is concerned with three data streams from REX:

(1) the REX filter output, comprising 16-bit samples at 1250 samples (complex) per ROF, i.e., 1250 In-phase samples per ROF and 1250 Quadrature-phase samples per ROF, and

(2) the Radiometer output, comprising 40-bit samples at a rate of 10 samples per ROF, and

(3) the Time Tags, 10 per ROF.

12.3.1.1 Calibrating the REX filter output: In-phase & Quadrature-phase values

The conversion of the I/Q samples from the raw DN to calibrated physical units (milliVolts) involves applying a gain-independent scaling, since the FIR process producing the samples has no adjustable parameters.

The algorithm takes each I or Q raw **FilterValue** that represent a single filter output value and does the following:

- Scale the filter value by the ratio of the ADC input range ($\pm$ 1V = $\pm$ 1000mV) to its ouput range ($\pm$ 2^{13}; the ADC output values are 14-bit, twos-complement integers):

    - mV_{IorQ} **= (1000 / (2^{13})) * FilterValue**

12.3.1.2 Calibrating the REX Radiometry

The formula for converting the Raw REX radiometer data to power, in units of dBm, is as follows:

dBm = –172 + 10 * log10(4.5e6 * deltaSamp)   + Ro

– (16 * AGC – AGCoffset) / dBstep + ant_dBm

where

deltaSamp = Increase in raw (40-bit) 64-bit integer value from ROF (raw FITS BINTABLE)

- – There are ten raw (accumulating) values stored in column 1 of EDU 2 in the raw file. The equation above applies to the delta of each raw value from the previous one.

- – The increase corresponding to each raw value is the difference between it and the previous raw value, with two exceptions:

  - – If the first raw value in the column is greater than the second, then that first raw value is actually the tenth accumulating raw value from the previous ROF. In order to confine the calibration to the current FITS file, the pipeline uses the expedient of dividing such accumulated raw first values by ten and using the result as a proxy for the increase from the last raw value from the previous ROF/raw FITS file.

  - – In that case (1st > 2nd), nothing is subtracted from the second value.

Ro   = Constant: -93.170

AGC   = AGC setting from whichever REX Side, A or B, generated the data being calibrated.

- – A state table of commanded, per-Side AGC settings as a function of time, derived from SeqGen SSF output files, is stored in the Uplink DataBase (UplinkDB) on the SOC, and in TABLEs AGCGAINA and AGCGAINB for PDS data sets, and

- – when creating the raw FITS file, the pipeline retrieves the appropriate value based on the observation time of the FITS file and the side (ApID: 0x7b0 and 0x7b1 are side A; 0x7b2 and 0x7b3 are side B), and puts it into the FITS header as keyword AGCGAIN. For observations before the state table, use 167 or 163 for Side A or B, respectively.

- – The calibration code retrieves the value from the FITS header when calibrating the data.

Name	Description	Side A Value (0x7b0; 0x7b1)	Side B Value (0x7b2, 0x7b3)
AGCoffset	REX Side-dependent constant; AGC setting offset	2512	2304
dBstep	REX Side-dependent constant; size of AGC setting increase for a decrease of 16 in the dBm	32.5	34
ant_dBm	REX Side-dependent constant	1.33	1.23

12.3.1.2.1 Radiometry calibration

The Ro dBm offset constant was set based on Cold Sky and radio source radiometer observations taken in June, 2006 and elsewhere throughout the mission. The gain-related coefficients are based on gain linearity tests where the gain is stepped through several values while receiving a fixed-amplitude signal from the DSN.

12.3.1.3 Calibrating the REX Time Tags

The time tags are 24-bit integers, stored as 32-bit integers in the FITS BINTABLE, that increment ten times per ROF frame of 1.024s and represent the time since the first contiguous ROF frame in a sequence

(or, in the unlikely case of REX taking data for more than about a fortnight and a half, from the last Time Tag rollover), so the formula to convert from the 24-bit Time Tag value TTraw to seconds is

```
Ts = TTraw * 0.1024      *** N.B. relative spacecraft seconds
```

12.3.2   *Calibrated FITS file data format*

The calibrated data from each ROF are stored in a single FITS file. The data layout in the PDU and EDUs is similar to that of a raw data FITS file (see Table 12-7); the PDU containing the raw ROF data and BINTABLES in EDU 3 through 8 containing HK data are identical; the only differences are that

- in the EDU 1 BINTABLE, the I&Q, pairs the Radiometry and the Time Tags have been calibrated to units of mV, dBm and s, respectively, and
- in the EDU 2 BINTABLE, the radiometry power values are derived from rates – differences between successive accumulating values - instead of the accumulating values themselves, and
- all values are converted to scientific units (see section 12.3.2.3) stored in the FITS file as 32-bit floating point values.

12.3.2.1 Extension Data Unit (EDU) 1: I & Q values

The first extension of the Calibrated FITS file is a FITS BINTABLE, containing the calibrated I&Q value pairs in units of milliVolts.

The BINTABLE comprises 1250 rows, and each row comprises two columns laid out over eight bytes.

12.3.2.2 EDU 2: Radiometry & Time Tags

The second extension of the Calibrated FITS file is also a FITS BINTABLE, containing two columns: Radiometry values in dBm; Time Tags in seconds.

The BINTABLE comprises 10 rows, and each row comprises two columns laid out over eight bytes.

12.3.2.3 Scientific Units

The units of the calibrated values, after applying the scaling factors if present, are as follows:

```
Filter outputs (IQ pairs):      Voltage (mV)
Radiometry:                     Power (dBm)
Time Tag:                       Relative spacecraft time (s)
```

12.3.2.4 Additional FITS and PDS Keywords

12.3.2.4.1   Keywords added to raw Raw and Calibrated PHDUs
```
 FSTATUS = '0x00    '              / Raw status byte from TLM
 AGCGAIN =                    158 / AGC Gain
 AGCSRC  = 'ULCMD   '              / Source of AGC Gain info
 AGCPROV = '06361.ssf:CORX04b_01_GainLin$2REX_50CMD,158' / Provenance
```

12.3.2.4.2   Provenance added to Calibrated PHDU
```
 RADRAD__= '*** Radiometry formula and coefficients:'
 RADRADIO= 'dBm=-172+10*log10(4.5e6*RAW)+RO-(16*AGC-AGCOF)/DBSTP+ANTDB'
 RADRO   =              -96.8700
 RADAGC  =              158.0000
 RADAGCOF=             2304.0000
```

```
RADDBSTP=              34.0000
RADANTDB=               1.2300
RADIQ___ = '*** I&Q formula:'
RADIANDQ= 'mV = (1000 / (2^13)) * RAW = KIQ * RAW'
RADKIQ  =               0.1221
RADTT___ = '*** Time Tag formula:'
RADTIMTG= 's = 0.1024 * RAW = DT * RAW'
RADDT   =               0.1024
```

12.3.3   Hardware/OS Development Platform

PC/Linux

12.3.4   Language(s) Used

Python (Telemetry to Raw); C (Raw to Calibrated)

12.3.5   Third Party Libraries Required

cfitsio (where C used) or Pyfits (where Python used)

12.3.6   Calibration Files Needed (with Quantities)

AGC gain table, in the UplinkDB on the SOC, and in DOCUMENT/AGCGAIN{A,B}.* in PDS data sets. All other calibration factors are in the source code and listed above.

12.3.7   Memory Required

< 128MB

12.3.8   Temporary File System Space Needed

None.

12.3.9   Predicted Size of Output File(s)

< 70 Kbyte

12.3.10   Predicted Execution time

Less than a second per ROF

12.3.11   Contact/Support Person(s)

Ivan Linscott

12.3.12   Maintenance Schedule (Code/Data Updates, Documentation)

None planned; something may come out of the PDS review.