REX Thresholding: Algorithm and Computation

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1.0 Introduction

REX is the Radio Science Experiment on board New Horizons. The science and engineering objectives are primarily (a) radio occultation, (b) radiometry, (i.e. radiometric thermal measurement), and (c) Doppler gravity. These objectives are well described in (Tyler, et. al., 2008). REX is a digital signal processor instantiated in Field Programmable Arrays (FPGA's), inside the Radiometrics Channel of the New Horizons X-Band Receiver. Additional detail for REX's functionality and its integration in the X-Band Receiver is in (Deboy, et.al., 2004 "The RF Telecommunications System for the New Horizons Mission to Pluto").

REX produces both a low-speed data stream and high-speed data stream. The low-speed data is the Housekeeping and is imbedded in the X-band Receiver's Housekeeping data. REX's high-speed data is exported from REX to the Solid Sate Recorders (SSR's). REX processes both RF polarizations: Right-Hand Circular (RHC), and Left-Hand Circular (LHC), using separate and independent FPGA processors. Additional detail is as well in (Deboy, et.al., 2004).

The X-Band Receiver have Radiometrics Channels for each polarization with bandwidths of 4.5 MHz. The RF voltages in these channels are sampled at 10 Msamples/sec. These samples are input to their respective REX processors, where they are digitally filtered to baseband with bandwidths of 1.25 kHz. The baseband filter outputs are voltages represented by 16-bit integers In-phase and Quadrature samples, at a rate of 1250 samples per 1.024 seconds. Additional detail of this process is in (Deboy and Funk, 2004).

In a typical REX experiment, a high-power, CW, X-band signal (an 'Uplink'), is transmitted from earth to New Horizons and received by the X-Band radio system and sampled by REX. The uplink is Doppler compensated to locate its frequency in REX's narrowband, 1.25 kHz baseband filter outputs. An example REX narrowband output with an EMP dust impact candidate is shown in Figure 1.

2.0 REX RF Power Computation for the Narrowband Data

The narrowband filter in the REX processor outputs a sequence consisting of in-phase (I) and quadrature (Q) samples. Let these samples be designated as:

$$V_n = \{v_{real}, v_{imag}\}$$

Here *n*, is the sample index number. The subscript *real*, identifies the in-phase (or I) component, and *imag*, the quadrature (or Q) component. The REX processor outputs the I/Q pairs sequentially. The output sample sequence is enumerated below in Table 1 and its formatting and reconstruction to voltage samples will be discussed in detail later.

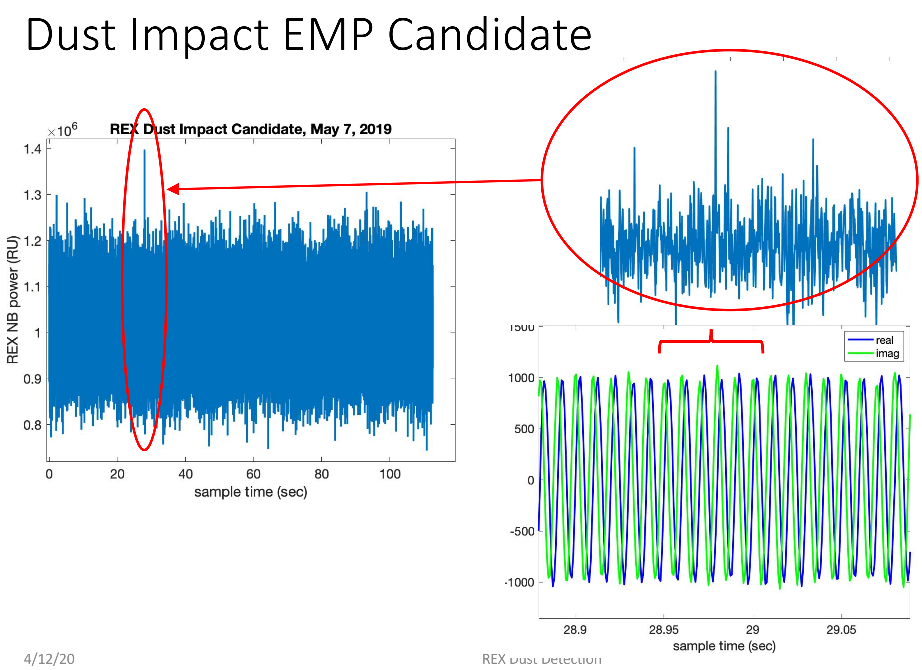

Figure 1. REX Narrowband filter data. Left hand side shows 112 seconds of signal power in 'REX units', fixed-point integer sample values produced by the REX processor. The dust impact EMP candidate is the impulse at t = ~23 sec. Upper-right hand figure is a ~0.1 sec excerpt containing a dust impact EMP candidate, again in REX units. The lower-right hand side plots the in-phase and quadrature (i.e. real and imaginary) components of the signal.

The REX RF power P_n, is computed from each sample V_n, by squaring and adding the I and Q components:

$$P_n = {v_{real}}^2 + {v_{imag}}^2$$

An example sequence of RF power, P_n, computed this way is shown in Figure 1. Both I and Q components, $\{v_{real}, v_{imag}\}$ are 16-bit, signed integers. Accordingly, the power values, P_n, are unsigned, positive integers, represented by at least 32 bits.

3.0 Threshold Testing for the Narrowband Data

A simple threshold test applied to each sample P_n, is proposed:

a. Compare P_n with a threshold[(1)] P_{Th}: $\Delta P_n = P_n - P_{Th}$
b. Ignore if ΔP_n is less than or equal to zero
c. If ΔP_n is greater than zero,
   c.1 Log the values n, P_n and ΔP_n
   c.2 Save the *I* and *Q* pair samples $\{v_{real}, v_{imag}\}n$, for the range *n-M* to *n+M*,
   [(2)]Extend into the previous *frame* if $M > n$, and
   [(3)]Extend into the next *frame* if $n + M > 1250$ (the samples in a *frame*)
   c.3 Skip to the next *frame*.

Notes:
(1) Both the threshold P_{Th}, and the range M, should be 'loadable', i.e. uploaded to the spacecraft. The X-band receiver has been very stable over the course of the Mission, thus the threshold P_{Th} should vary slowly and not require frequent reloading.
(2) If this is logistically difficult, then limit n-M to *unity*, i.e. the first sample in the *frame*.
(3) Again, if difficult to implement, then limit n+M to the last sample in the *frame*.

4.0 REX RF Power Computation for the Broadband Data

The REX processor computes the total RF power in the X-band receiver's Radiometrics channel and accumulates (i.e. adds together the 10 Msamples/sec) RF power in an internal register. The register's value output in the high speed data interleaved into the REX narrowband data ten times in each REX '*frame*'. The REX *frame's* format is listed in Section 5.3.1.5 in Table 1. The samples of accumulated RF power are called the REX broadband power. Let the broadband RF power samples be designated as $P_{bb}(k)$, where $k = 1$ to 10, is the sample index or number in the *frame*.

5.0 Threshold Testing for the Broadband Data

An additional threshold test is proposed for the REX broadband power samples:

a. Compare $P_{bb\,k}$ with a threshold $P_{bb\,Th}$: $\Delta P_{bb\,k} = P_{bb\,k} - P_{bb\,Th}$
b. Ignore if $\Delta P_{bb\,k}$ is less than or equal to zero
c. If $\Delta P_{bb\,k}$ is greater than zero,
   c.1 Log the values k, $P_{bb\,k}$ and $\Delta P_{bb\,k}$
   c.2 Save the broadband power samples for the entire *frame*.
   c.3 Skip to the next *frame*.

Note: The threshold P_{bbTh}, should be 'loadable', as well, i.e. uploaded to the spacecraft. The X-band receiver has been very stable over the course of the Mission, thus the threshold $P_{bb\,Th}$ should change but slowly and not require frequent reloading.

6.0 REX Data Format

The REX processor interleaves the broadband and narrowband sequences of samples in the 5056 byte REX *frame* it delivers to each of the SSR's. The format of these sequences is illustrated in Section 3.3.1.5 of *The New Horizons RF Telecommunications Subsystem to REX ICD*, by C.C. Deboy and L. Funk, 2004, and excerpted here for Table 1.

The format of the REX data output sequence in each *frame* was highly constrained by stringent FPGA space limitations, has always been viewed with trepidation by those attempting sample reconstruction. It may well be the most challenging of the FSW upgrade. Although Table 1, appears complex, the structure is orderly and organized into five byte packets. The regularity of this structure is amenable to an algorithmic reformatting and the reconstruction of the radiometer's five-byte samples and the narrowband filter's 2-byte, I and Q sample pairs. Alternativly if flight code space is not a premium, a 5056-element map can be constructed and used for a table look-up to construct the radiometer and narrowband filter samples.

To illustrate a possible algorithmic reformatting of the REX *frame*, we begin with the first byte in the *frame*, and look for a *null* followed by the two-byte REX-*frame*-ID = 0xB7. Accordingly,

- ➔ The next two bytes are the most significant byte (MSB), and least significant byte (LSB) of I(1), the first narrowband filter's in-phase sample.
- ➔ The next five bytes are a null, then the most significant 7-bits of R(1), the radiometer's first sample followed by the two bytes of Q(1), the narrowband filter's quadrature's first sample.
- ➔ The previous step repeats, getting the next two bytes of R(1), and the two bytes of I(2)
- ➔ The previous step repeats, getting the next two bytes of R(1), and the two bytes of Q(2)
- ➔ The previous step repeats, getting the next two bytes of R(1), and the two bytes of R(3)
- ➔ The previous step repeats, getting the last byte of R(1), and the two bytes of Q(3)

What follows next is a sequence of four packets for the Time_Tag and I(4), Q(4), and I(5) and Q(5). The next packet contains the Status code in the place of the last Time_Tag byte, and the two bytes of I(6).

What follows next is a process that repeats nine times, for *n = 0 to 8*[1].

- ➔ For even packets starting with packet 12: Two nulls followed by two bytes for Q(6) …
- ➔ For odd packets starting with packet 13: Two nulls followed by two bytes for I(7) …
- ➔ Up to packet 12 + 250.
- ➔ Next, for packet 12 + 250, there is one null, and the most significant two byes of the next radiometer sample, and two bytes for Q(next).
- ➔ The following four packets have the remaining radiometer sample and the I's and Q's.
- ➔ This process completes for *n = 8.*
- ➔ Finally packets 2258 to 2500, have the remaining I's
- ➔ And Packets 2259 to 2499, have the remaining Q's.

(1) Apologies for using *n* as the repeat index to be consistent with Table 1, when earlier *n* was used for the sample index.

REX High-Speed Telemetry Data Format MAP

7399-9202REX_ICD_RevA_040904 MSWX.docx **Rev A** 02/12/2004

5.3.1.2 FRAME

The Frame signal delimits frame observations. As pertains to REX, an observation is simply a series of frames, with each frame immediately following the previous one. All observations will start with the Frame signal high for five clock cycles, transition low on or before the first bit of a frame, and stay low until the frame is finished. No data is accepted while the Frame signal is high. In fact, the Gate signal, described below, is required to be high whenever the Frame signal is high. This ensures that no valid data bits are being transmitted while the frame signal is high. The interval between frames is exactly 1.024 seconds, so no latency exists between frames.

5.3.1.3 GATE

The Gate signal will be used to mark and ignore null words. All observations will start with the Gate signal high, transition low on the first valid bit of a frame, and stay low for all valid words. All null words will be marked by raising the Gate level to high. This will allow for the interleaving of the several different data streams.

5.3.1.4 CLOCK

The Clock signal will be used to transition the other three high-speed lines on its rising edge. The Clock frequency will be set at 78.125 KHz to allow for all of the data to be interleaved. This signal will have a 50% duty cycle and be synchronous with the USO.

5.3.1.5 DATA

There will be 5056 valid bytes out of 10,000 per frame of observation. Each byte will be transmitted in order of MSB to LSB. The frame data are separated into 4-byte packets. The packets are filled in the following order:

- packet 1: null ID(hB7) I[15:8] I[7:0]
- packet 2: null radiometer_data[39:32] Q[15:8] Q[7:0]
- packet 3: null radiometer_data[31:24] I[15:8] I[7:0]
- packet 4: null radiometer_data[23:16] Q[15:8] Q[7:0]
- packet 5: null radiometer_data[15:8] I[15:8] I[7:0]
- packet 6: null radiometer_data[7:0] Q[15:8] Q[7:0]

  Note that radiometer_data is reset at the start of each new frame.
- packet 7: null time_tag[31:24] I[15:8] I[7:0]
- packet 8: null time_tag[23:16] Q[15:8] Q[7:0]
- packet 9: null time_tag[15:8] I[15:8] I[7:0]
- packet 10: null time_tag[7:0] Q[15:8] QI[7:0]
- packet 11: null Status I[15:8] I[7:0]
  - Status[7] = 0
  - Status[6:4] = Input_Select
  - Status[3:0] = 0000

  For n = 0 to 8:
- even pkts 12 + 250*n: null null Q[15:8] Q[7:0]
- odd pkts 13 + 250*n: null null I[15:8] I[7:0]
- packet 252 + 250*n: null radiometer_data[39:32] Q[15:8] Q[7:0]
- packet 253 + 250*n: null radiometer_data[31:24] I[15:8] I[7:0]
- packet 254 + 250*n: null radiometer_data[23:16] Q[15:8] Q[7:0]
- packet 255 + 250*n: null radiometer_data[15:8] I[15:8] I[7:0]
- packet 256 + 250*n: null radiometer_data[7:0] Q[15:8] Q[7:0]
- packet 257 + 250*n: null null I[15:8] I[7:0]
- even pkts 2258-2500: null null Q[15:8] Q[7:0]
- odd pkts 2259-2499: null null I[15:8] I[7:0]

5.3.1.6 OBSERVATION COMMANDS

Observations shall always be generated when REX is in nominal mode. Assertion of the Reset line shall abort generation of the remainder of the current, the next following, and all succeeding telemetry packets until the Reset line is de-asserted and the 1PPS signal activates. The contents and length of the packet being generated when the Reset line is asserted may not comply with the above definitions.

FSCM NO.	SIZE.	DRAWING NO.	REV.
88898	A	7399-9202	1
SCALE : NONE	DO NOT SCALE PRINT	SHEET 28 OF 41	

Table 1. REX Data Output Sequence Map from Section 5, of (Deboy and Funk, 2004).

7.0 Example Matlab Code to Reformat and Reconstruct the REX Radiometer and Narrowband Samples


```
% REX read for Level-1 FITS files
%     for Commissioning Test on January 5, 2007
%     Side B
%
%   Level-1 FITS data file format
%   5000 bytes of data (1250 samples of I and Q x 2 bytes each)
%         2 bytes for TAG and STATUS
%        50 = 10 * (5 bytes of RADIOMETER data)
%        30 = 10 * (3 bytes for the TIME TAG)
%     82 bytes added
%   5082 bytes total

clear

Packetbytes = 500 + 8 ;    % i.e. (5082 - 2)/10
Fs = 1250/1.024 ;
Ns = 1250 ;
pNoSignal = 1e6 ;          % threshold where signal is present
                           % fbase values     mode     files
                           %      11312       rex001a    36
                           %      xxxxx       rex002a   105
                           %      xxxxx       rex003a   105
                           %      xxxxx       rex004a   695
fBase = 11312 ;
fpath = '/Volumes/G-DRIVE mobile USB/REX backups/USB2/REX/Commissioning/Commissioning↙
January 5, 2007, Side B/level 1/MET 3031 REX 1b to 4b/' ;
fprefix = 'rex_00303' ;    % i.e. 'rex_0077053065_0x7b1_eng_1.fit' ;
fpostfix = '_0x7b3_eng_1.fit' ;

Nfiles = 36 ;
nfadj = 0 ;         % every ~42 files (sec) the file name skips one

clear fest ptots vss
vss = zeros(Nfiles,Ns) + j*zeros(Nfiles,Ns) ;

for nfile = 1:Nfiles,

fintid = sprintf('%4d',fBase + nfile + nfadj - 1) ;
fname = [fpath fprefix fintid fpostfix] ;

fid = fopen(fname,'r') ;
if fid < 0,
    nfadj = nfadj + 1 ;
    fintid = sprintf('%4d',fBase + nfile + nfadj - 1) ;
    fname = [fprefix fintid fpostfix] ;
else
    fclose(fid) ;
end

Finfo = fitsinfo(fname) ;
fdate = Finfo.FileModDate ;
fsize = Finfo.FileSize ;

Fdata = fitsread(fname) ;

Ftag = Fdata(1) ;
Fstatus = Fdata(4) ;
```

```
if mod(nfile,11) == 0,
    fname
end

clear dbytes reald imagd ttag

dbytes(1:2) = Fdata(2:3) ;
dbytes(3:4) = Fdata(5:6) ;
realdo = dbytes(1)*256 + dbytes(2) ;
imagdo = dbytes(3)*256 + dbytes(4) ;
if realdo > 2^15
    realdo = realdo - 2^16 ;
end
if imagdo > 2^15
    imagdo = imagdo - 2^16 ;
end
noff = 6 ;
for n = 1:10,
    na = noff + (n - 1)*Packetbytes + 1 ;
    if n < 10
       nb = noff + n*Packetbytes ;
    else
        nb = noff + n*Packetbytes - 4 ;
    end
    Fds = Fdata(na:nb) ;
    FdsA = Fds(1:24) ;
    FdsB = Fds(25:end) ;
    colA = FdsA(1:3:end) ;
    raddataB(:,n) = colA(1:5) ;
    rsB = (colA(1:5))*2.^[32:-8:0]' ;
    nrs = 10*(nfile - 1) + n ;
    rados(nrs) = rsB ;
    ttagB(:,n) = colA(6:8) ;
    ttB = (colA(6:8))*2.^[16:-8:0]' ;
    timetags(nrs) = ttB ;
    dbytes(1:2:16) = FdsA(2:3:24) ;
    dbytes(2:2:16) = FdsA(3:3:24) ;
    if n < 10
       dbytes(17:500) = FdsB ;
    else
        dbytes(17:500-4) = FdsB ;
    end
    dmsb = dbytes(1:2:end) ;
    dlsb = dbytes(2:2:end) ;
    dword = dmsb*256 + dlsb ;
    dwc = dword >= 2^15 ;
    dword(dwc) = dword(dwc) - 2^16 ;
    dreal = dword(1:2:end) ;
    dimag = dword(2:2:end) ;
    ka = 125*(n -1) + 1 ;
    kb = 125*n ;
    reald(ka:kb) = dreal ;
    imagd(ka:kb) = dimag ;
end

reals = [realdo reald(1:end-1)] ;
imags = [imagdo imagd(1:end-1)] ;
v = reals - j*imags ;
```

```
ptots(nfile) = sum(v.*conj(v)) ;
if ptots(nfile) > pNoSignal,
   fest(nfile) = gweXP(v,Fs) ;
else
    fest(nfile) = 0 ;
end
vss(nfile,:) = v ;
end    % for nfile = 1:Nfiles

if sum(abs(reals)) > 0
   figure(1)
   fs = [-624:625]/1.024 ;
   plot(fs,20*log10(abs(fftshift(fft(reals - i*imags)))))
end
title('Spectrum of last non-zero frame')

figure(2)
ptotc = ptots == 0 ;
ptots(ptotc) = 1 ;
plot(10*log10(ptots),'o')
title('total power in REX channel')

figure(3)
plot(fest,'o')
title('frequency estimate')
```

References

C. C. DeBoy *et al*., "The RF telecommunications system for the New Horizons mission to Pluto," *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720)*, Big Sky, MT, 2004, pp. 1478 Vol.3.

C. C. DeBoy, Funk, L., The New Horizons RF Telecommunications Subsystem to REX ICD, 7399-9202REX_ICD_RevA_040904, APL, 2004.

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