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THE BROAD BAND RECEIVER (BBR) INSTRUMENT ON THE DEMONSTRATIONS AND SCIENCE EXPERIMENTS (DSX) SPACECRAFT

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Final Report

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14. ABSTRACT
This final report summarizes events, analysis, and conclusions regarding the Stanford University Broad Band Receiver (BBR) flown aboard the Demonstrations and Science Experiments (DSX) Satellite, including pre-flight, flight, and post-flight activities, during period of performance covering 04-Apr-2018 to 31-Aug-2022.
BBR—along with the companion instrument TNT—performed well, especially as regards "Boomerang" propagation mode, whereby pulses transmitted by TNT return as echoes then received by BBR, allowing to measure absolute wave intensity and infer injection efficiency, and supporting new wave/particle studies to assess impact to radiation-belt electron populations.
The primary dataset comprises over 2,200 TPK 5channel full-bandwidth Burst mode data files. Several types of expected and unexpected observations and results are presented, many suggestive of new physics yet to be explored.

15. SUBJECT TERMS
DSX satellite, broadband receiver, VLF, magnetosphere

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1. SUMMARY

This final report summarizes events, analysis, and conclusions regarding the Stanford University Broad Band Receiver (BBR) flown aboard the Demonstrations and Science Experiments (DSX) Satellite, including pre-flight, flight, and post-flight activities, during period of performance covering 04-Apr-2018 to 31-Aug-2022.

2. INTRODUCTION

The Stanford University Broad Band Receiver (BBR) is a 5-component (Bx, By, Bz, Ey, Ez) electromagnetic wave receiver designed to measure VLF/ELF (300 Hz – 30 kHz) waves in the Earth's magnetosphere using 2 electric dipoles and 3 magnetic search coils (see next section).

BBR was designed at Stanford with flight unit provided to AFRL by Lockheed-Martin Advanced Technology Center (LMATC). A Tri-Axial Search Coil (TASC) assembly was provided by Goddard Space Flight Center (GSFC). The complete BBR package includes Software Receiver (SRx) algorithms to run in the on-board DSX Experiment Computer System (ECS) to generate reduced data products, as well as corresponding Ground Software to create Quicklook displays.

BBR acquired data Aug 8, 2019 to May 31, 2021 aboard AFRL's Demonstration and Science eXperiments (DSX) Satellite, along with co-manifest Transmitter, Narrowband Rx, Tuner (TNT) and Loss-Cone Imager/High-Sensitivity Telescope (LCI/HST). These three instruments together comprise the Wave-Induced Precipitation of Electron Radiation (WIPER) experiment package to assess the efficiency of in-situ VLF wave injection and, by extension, the effect that these waves—as well as other background waves—have on Earth's energetic electron radiation belts.

BBR performed flawlessly, especially regarding so-called VLF "Boomerang" propagation mode, whereby pulses transmitted by TNT return as echoes then received by BBR, allowing to measure absolute wave intensity and thus infer injection efficiency, and supporting follow-on wave/particle calculations to assess impact to radiation-belt electron populations.

The remainder of this Section 2 describes the BBR hardware and available SRx data products. Section 3 highlights notable events and discoveries during the ~22-month science mission life. Section 4 briefly discusses radiated wave normal angles, wave intensity vs transmit pulse-length, and apparent new form of self-sustained wave/particle emission unique to in-situ wave injection. Section 5 concludes the report.

2.1. Antennas

BBR measures 5 components (Bx, By, Bz, Ey, Ez) of the general 6-component VLF wave-field via 2 electric dipoles formed by DSX boom-pairs and a Tri-axial Search-Coil (TASC) assembly mounted atop the +Z boom (Fig. 1).

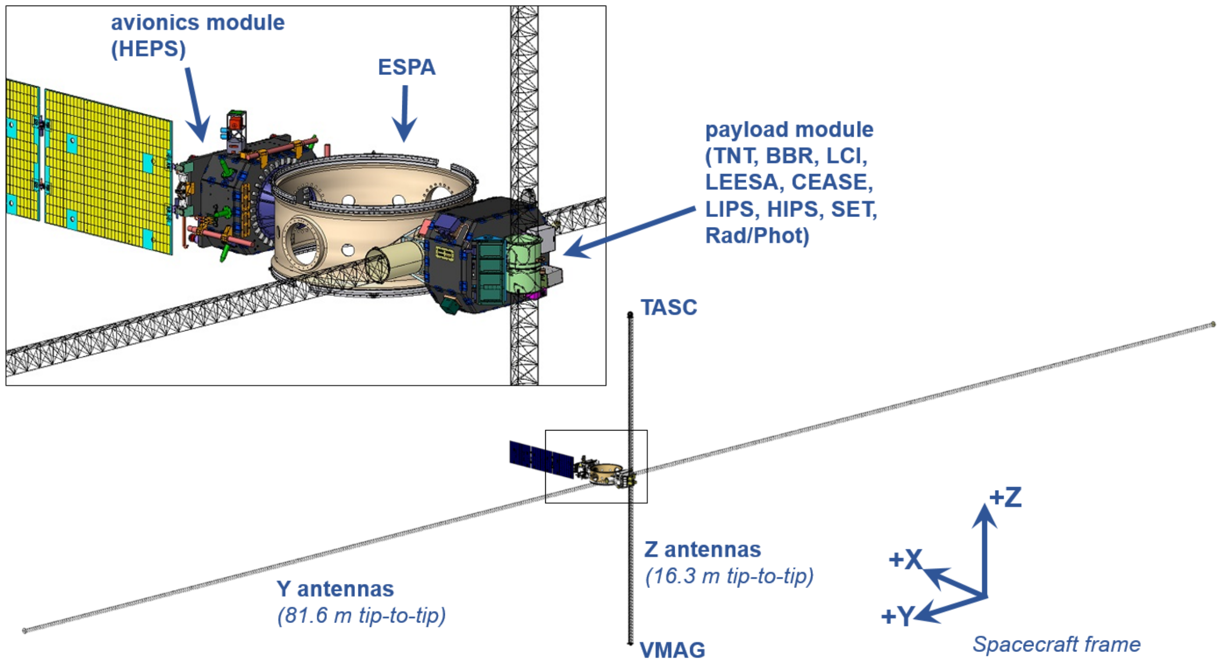

Fig. 1: DSX/BBR Ey (~80m) and Ez (~16m) dipoles; TASC (Bx,y,z) on +Z boom (courtesy AFRL)

<u>Ey Dipole:</u> The Ey component is measured via ~80m electric dipole formed by two opposed ~40m +/-Y booms. Since these booms also serve as the transmit antenna, the Ey terminals are necessarily located within the TNT Transmit and Tuner Units (TATUs), wherein are contained Tx/Rx switching relays and L-C tuning elements.[1] In receive mode, the tuner is disconnected and the Ey signal is first preamplified within the TATUs and then split and sent to both BBR and the TNT Narrowband Receiver (NBR). The shared and distributed aspect of these Ey electronics permits cross-calibration between BBR and NBR.

<u>Ez Dipole:</u> The Ez component is measured by the ~16m electric dipole formed by two opposed ~8m +/-Z booms. Here, Ez preamps are located entirely within BBR, simplifying Ez calibration.

<u>Search-Coils:</u> The Bx, By, and Bz components are measured via Tri-Axial Search-Coil (TASC) at deployed distance ~8m from the Payload Module (PM) on the +Z boom. The TASC assembly comprises front-end preamps, self-calibration excitation loop, and survival heater within a 30 cm thermal sphere/sun shield. TASC sensitivity curves (V/nT vs frequency) are established both via commercial heritage Helmholtz coil (GSFC) and via purpose-built Helmholtz coil (LMATC).

[1] L-C tuning elements alter Ey sensitivity when connected

2.2. BBR Hardware

The BBR hardware unit (Fig. 2) comprises 5 receiver cards, 1 preamp card, and 1 control card. Each receiver card has both a Heritage signal path using commercial parts and a Micro-Rx path using Stanford's rad-hard-by-design Preamp/AAF and ADC microchips (Fig. 3). All 10 total channels are sampled continuously at 100 kHz. Firmware in the control card selects any 5 of 10 available channels and forwards these to the ECS for reduction to *Survey* and *Burst* data products by on-board Software Receiver (SRx) algorithms. Fig. 4 shows specified design B, E sensitivity.

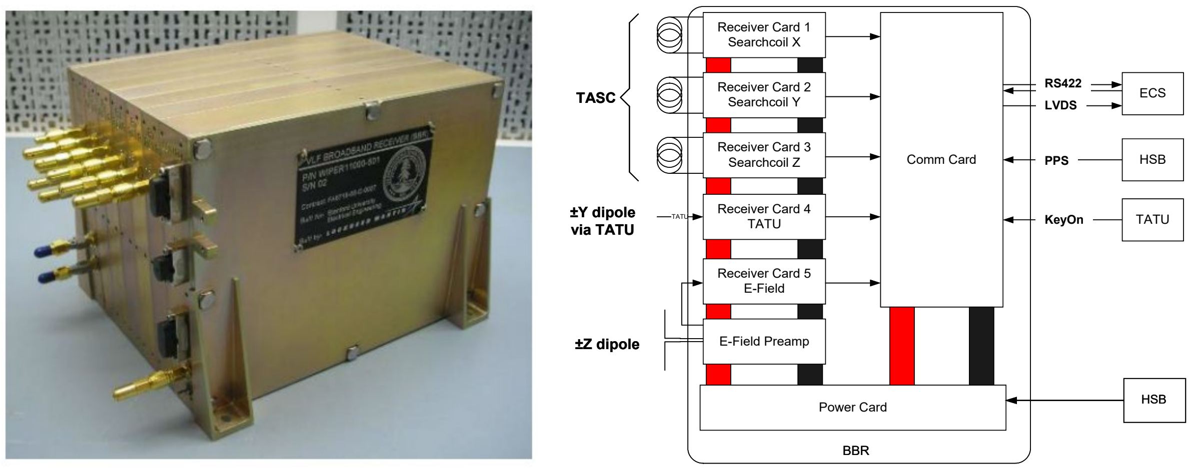

Fig. 2: BBR hardware unit (left) and internal block diagram (right) for 3xB and 2xE components.

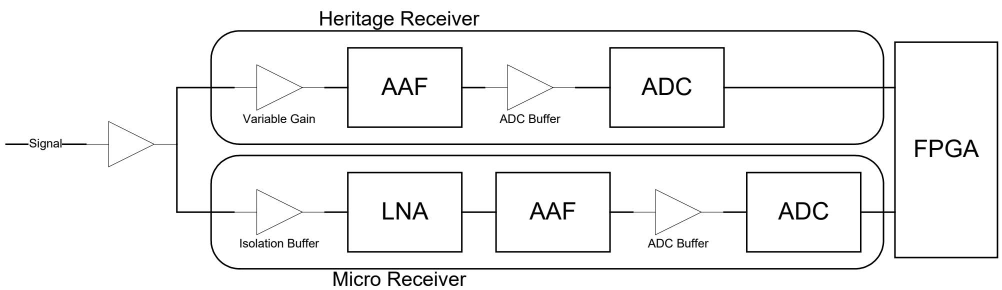

Fig. 3: BBR Receiver Card block diagram showing Heritage and Micro-Rx signal paths.

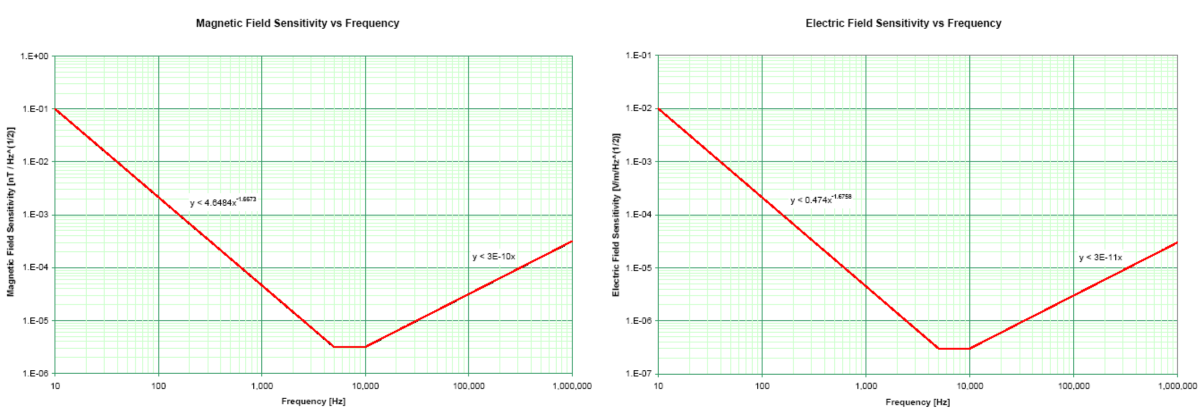

Fig. 4: BBR designed sensitivities when integrated to DSX: (left) magnetic, (right) electric.

2.3. SRx Software

Software Receiver (SRx) algorithms running in the ECS create *Survey*, *Burst*, and *Housekeeping* data products per uploaded schedules (Table 1, Fig. 5). Two *Survey* mode products (SVY, MBA) and two *Housekeeping* products (BBR, SRX) are generated continuously, while any one of three possible *Burst* mode products (TPK, FPK, NBD) may be scheduled for (up to) 30 min duration[2] per weekly Data Collection Events (DCEs) objectives.[3] These reduced data products are stored temporarily in the ECS Solid-State-Recorder (SSR) and downlink at the next ground-contact. Section 3.2 gives examples of the 5 science products. Section 3.3 shows example housekeeping.

Table 1: BBR/SRx Data Products: (2) Survey, (3) Burst, and (2) Housekeeping File Types

Type	***TLA***	***Product Definition***	***Content***	***Nominal Data Characteristics***
Science Survey	SVY	Survey Spectrogram	By, Ey	0-50 kHz each 30s, uniform df =100 Hz
	MBA	Multiband Analyzer	All 5ch	0-50 kHz each 1s, 25 log-spaced bands
Science Burst	TPK	Time-Domain Packed	All 5ch	0-50 kHz full BW, 16-bit @ 100 kHz
	FPK	Freq-Domain Packed	All 5ch	+/-1 kHz BW about selected center fo
	NBD	Narrowband Demod	1..5ch	400 Hz BW about selected VLF Stn fo
House-keeping	BBR	BBR Housekeeping	Digital	Volts, Temps, Gains, 5ch downselect
	SRX	SRX Housekeeping	Digital	Burst post-processing status, File sizes

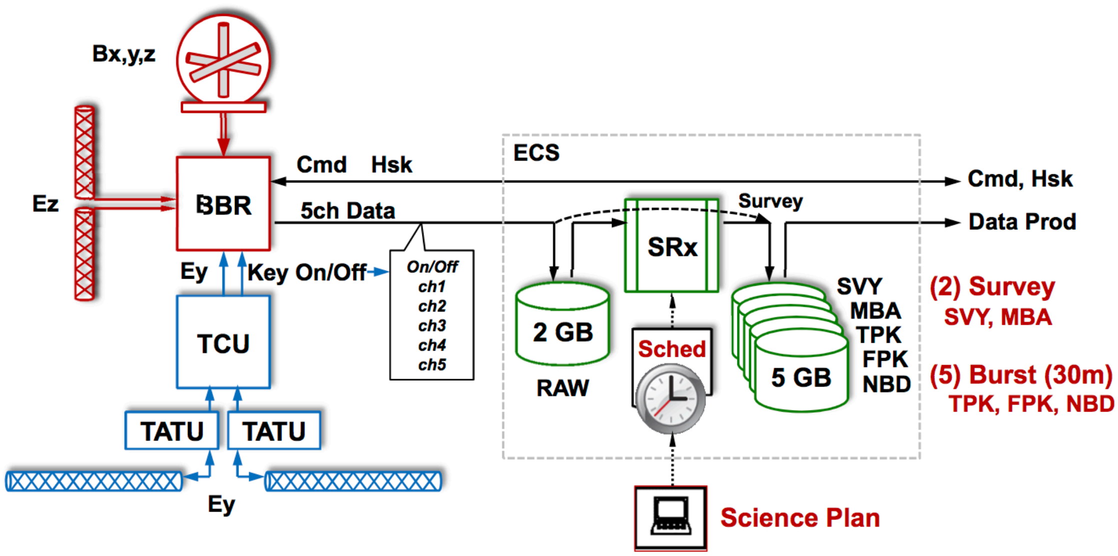

Fig. 5: BBR data flow from antennas to BBR and to on-board SRx data product algorithms.

[2] A post-processing lockout period follows each use of Burst mode
[3] Most often in conjunction with TNT high-power transmit mode

2.4. Ground Software

Unpacking Software: Each SRx data product (SVY, MBA, TPK, FPK, NBD) has corresponding ground-software (svyUnpack.cpp, mbaUnpack.cpp, tpkUnpack.cpp, fpkUnpack.cpp, nbdUnpack.cpp) to unpack and inspect the data for errors and to re-save in HDF format. An additional step at AFRL adds time-tags and renames the processed files according to AFRL/DSX convention. These processed files are then bundled by AFRL as virtual DVDs for further offline analysis.

Quicklook Display Software: Corresponding "Quicklook" Matlab m-files (svyQuicklook.m, mbaQuicklook.m, tpkQuicklook.m, tpkQuickFFT.m, fpkQuicklook.m, nbdQuicklook.m) creates relevant displays for each data product. Example Quicklooks are presented throughout Section 3.

Mission Planning Software: Specialized software—notably Stanford's heritage VLF Raytracer, and several custom Matlab DSX-specific scripts (dsx_boomerang.m, dsx_arase_conjunction.m, dsx_firebird_conjunction.m)—were run as needed at Stanford during the mission planning cycle to help select the best transmit frequency for likely reception of Boomerang echoes (by DSX) and/or detection of direct waves by remote satellites (e.g., by ARASE, VPM) and/or their effects on energetic electrons (e.g., by FIREBIRD). These scripts are also useful when interpreting data.

As an example, Fig. 6 shows the 2019-Sep-04 DSX-ARASE conjunction. Here, the left panel "bullseye" plot confirms best field-line conjunction at time 05:57:15, while the right panel shows the two orbit tracks in meridional projection. Plots of this type help interpret whether strongest reception by ARASE occurs at time of best field-line conjunction, or time of closest approach.

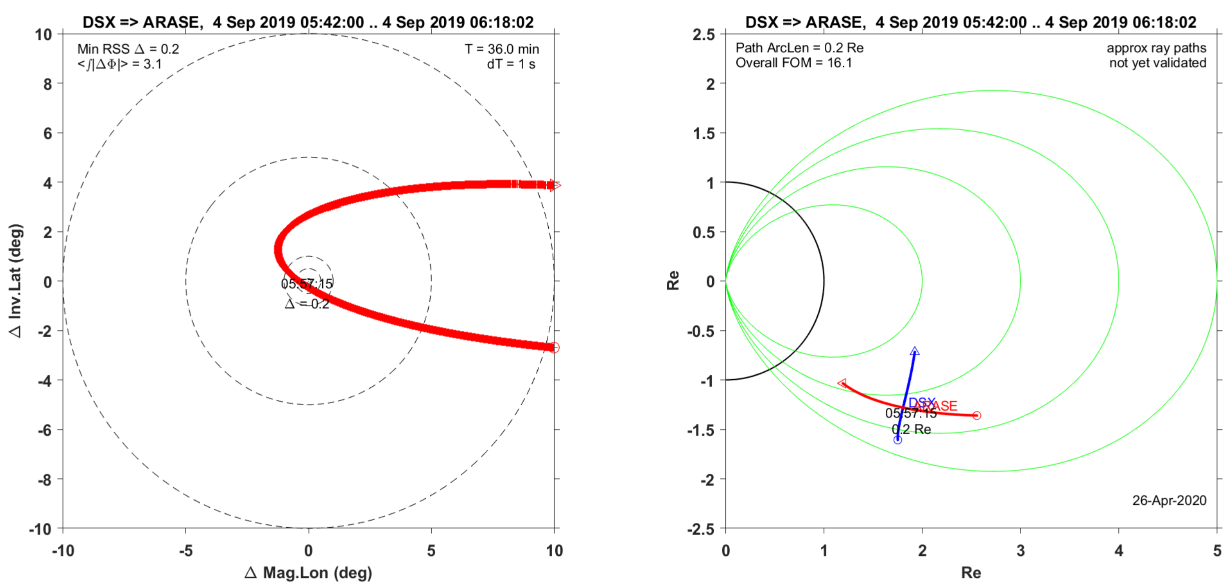

Fig. 6: DSX-ARASE Conjunction: (left) Field-Line "bullseye"; (right) Meridional Projection.

2.5. Transmitter Pulse Patterns

A variety of transmitter pulse patterns were devised and refined throughout the mission for DSX, beginning with simple single frequency repeating pulses and progressing to more complicated multi-frequency staircase patterns. Patterns were designed having ascending and descending ramps with a range of frequency steps and range of pulse lengths.

Patterns are defined in terms of pulse length and frequency offset from target center frequency which is selected by the science operations team per DCE objectives and set at run time in TNT. Table 2 summarizes 9 named patterns as referred to in the DCE logs, of which only 8 are unique (since B1, B1N are identical). These 8 unique patterns are diagramed in Fig. 7 (next page).

Some notes:

1. A group of one or more pulses is transmitted nominally every 3s (every 2s for some B3 cases). Multi-pulse groups have intra-group frequency steps of 25, 50, or 100Hz with pulse lengths from 20ms (BTriggerB) to as long as 1000ms (BGrowthA). Successive pulse groups generally exhibit alternate up/down slope. Sets of 5 groups generally repeat every 15s (every 12s for BFreqLock).

2. Setup intervals of ~1s generally precede each Tx-group in order to configure the Tuner during which time the Ey signal is altered dramatically due to extra L-C load on the antenna terminals. The 3s group spacing allows ~1.5s to ~2s clean listen time after each Tx before each next setup.[4]

3. These patterns are templates and do not show where necessary TNT tuning sweeps will occur (i.e., at startup and periodically) nor where occasional TNT plasmagrams are inserted (typically every ~3-5min). These extra TNT actions introduce shifts to the otherwise regular 15s cycle.[5]

Table 2: Transmit Pulse Patterns for Boomerang Return

Short Name	Long Name	Pulse Pattern	Freq Step	Objective	Remarks
B1	1-step	1x50ms	-	Basic boomerang echo return	Single repeating frequency
B1N	1-step-NBR	1x50ms	-	Basic boomerang echo return	As B1, with NBR listening
B3	3-step	3x50ms	100Hz	Echo vs frequency dependence	NBR on center frequency
BDiag	Diagnostic	5x30ms	50Hz	Echo vs frequency dependence	Like B3, now with 5-steps
BFreqLock	Freq.Lock	50-500ms	100Hz	Echo vs frequency, pulse length	Maybe growth vs pulse len
BGrowthA	Growth	50ms-1s	100Hz	Wider freq. range, longer pulses	Inspired by BFreqLock
BGrowthB	New-Growth	50-500ms	50Hz	Finer freq. step vs BGrowthA	500ms CW is long enough
BTriggerA	Trigger	30-50ms	50Hz	Assess rising emission vs freq.	Used at high mag. Latitudes
BTriggerB	New-Trigger	20-30ms	25Hz	Shorter pulses, fine freq spacing	Trigger sensitivity to freq

[4] Towards end of mission this ~1s setup time was shortened and sometimes eliminated altogether.
[5] Tuning sweeps and plasmagrams are apparent in BBR data and definitive in TNT housekeeping.

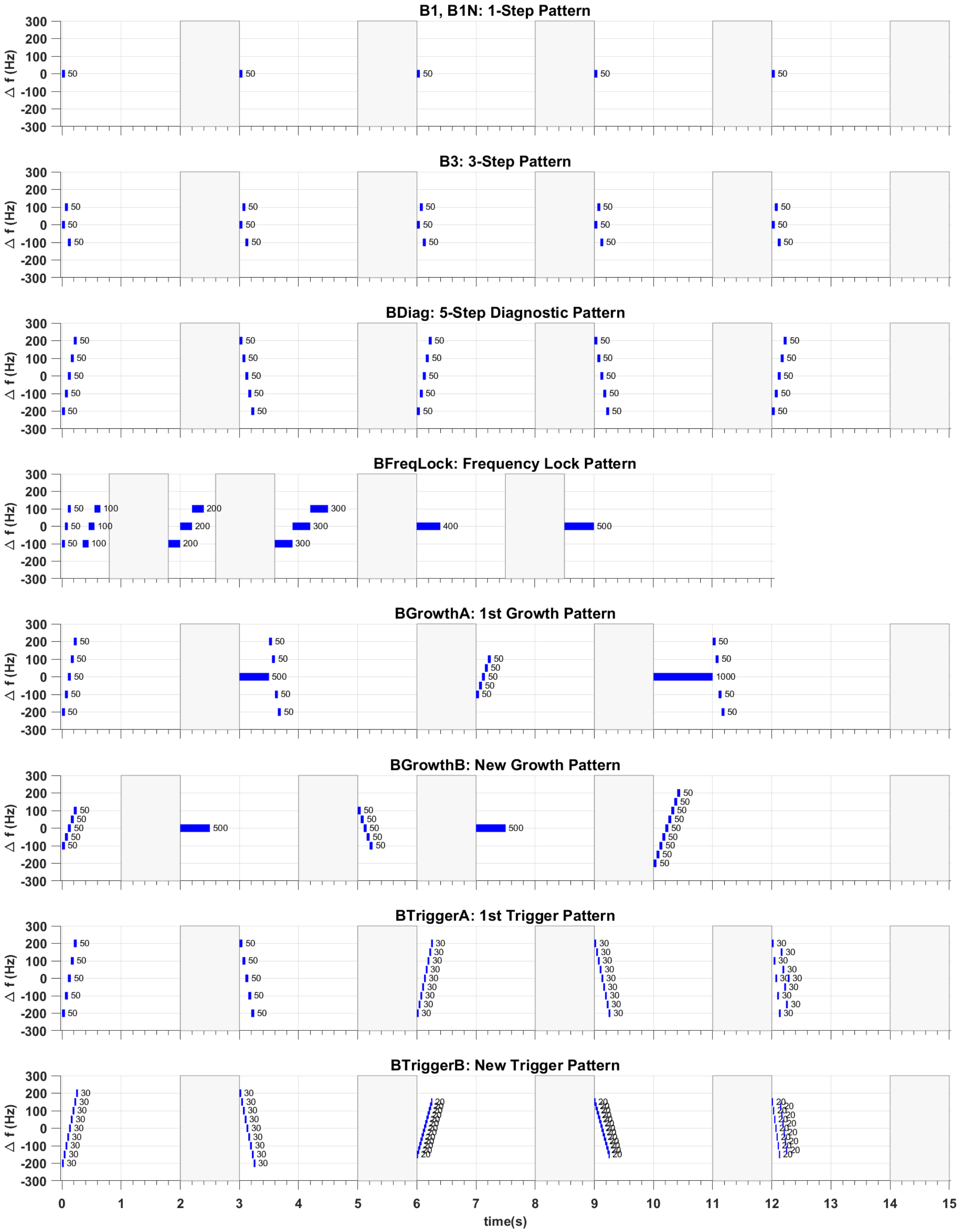

Fig. 7: Boomerang patterns vs time and offset from center frequency. Labeled pulse lengths in ms.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

DSX was launched June 25, 2019 (YYDOY 19176) to nominal 6000 x 12000km, 42 degree orbit. BBR was first powered ON briefly June 27, 2019 (19178) for ~5min "aliveness" check, and then commissioned ~40 days later August 7, 2019 (19219) per Payload Checkout (PLC) procedure.

BBR thereafter acquired science data from August 8, 2019 (19220) to May 31, 2021 (21151) along with co-manifest Transmitter, Narrowband Rx, Tuner (TNT) and Loss-Cone Imager/High-Sensitivity Telescope (LCI/HST). BBR performed flawlessly throughout the ~22-month mission, collecting over 2,200 TPK full-BW files comprising a mix of natural waves and TNT echoes.

The two *Survey* products, SVY (Survey Spectrograms) and MBA (Multiband Analyzer), were run essentially continuously 24/7 except for occasional interruptions for spacecraft operations. The TPK (Time-Domain Packed) full-bandwidth *Burst* product (up to 30min a a time) was run most frequently and provides the majority dataset. The FPK (Frequency-Domain Packed) *Burst* product, which downselects a selected subset of FFT bins, was run only a handful of times, while the NBD (Narrowband Demodulator) *Burst* product, which provides baseband I/Q samples for a limited set of center frequencies, was essentially never run, as these last two types were designed mostly as fallbacks in the event the downlink could not accommodate full-bandwidth TPK data.

Notable events are presented in the form of a mission narrative starting with first-light data and concluding with *Bear-Claw* boomerangs during "Hail Mary" DCEs with TNT at max RF power.

3.1. Commissioning

<u>BBR Thermal:</u> During the first days on orbit prior to the aliveness check, the BBR baseplate temperature was observed warmer than predicted by the DSX thermal model (owing to initial spacecraft attitude). Specifically, the BBR baseplate temperature measured by the provisioned survival heater showed values near ~37C, well above the (default) initial 30C warning threshold, and close to the 40C alarm threshold (beyond which power would be automatically cut if ON). These values were significant as BBR typically rises ~5C after turn-on, thereby exceeding 40C.

Upon review of the BBR thermal model and data from the thermal-chamber test, the decision was made to raise the warning and alarm values to 40C and 50C, respectively,[6] and to continue operations. The subsequent BBR aliveness test concluded without incident and with baseplate temperature holding < 40C. These BBR warning and alarm thresholds were later raised by another 5C to 45C and 55C, respectively, to allow for brief peaks during attitude maneuvers. Thereafter BBR generally remained between 20C and 40C for nominal operations (c.f. Sec. 3.3).

<u>TASC Thermal:</u> TASC (end of +Z boom) was observed to run somewhat colder than expected, with baseplate temperature frequently as low as 0C—activating the survival heater—and often dipping < -30C (despite heater). TASC internal temperatures (viz BBR housekeeping) showed Bx search coil as coldest of the 3, essentially tracking the baseplate temperature most of the time. On at least one occasion, Bx touched -50C (fortunately without harm). These extreme swings appear associated with attitude maneuvers, in particular during seasons of lengthy solar eclipse.

[6] At 50C baseplate, BBR internal junction temperatures maintains Tj <= 85C, well below max limit Tj < 105C.

BBR Checkout: Formal BBR Payload Checkout Procedure (PLC) of Aug. 7 (19219) included several minutes' data collection with BBR's self-generated comb-signal injected first internally to all channel inputs,[7] and then externally the TASC search-coils via inductive excitation loop contained within the TASC thermal sphere. This procedure was run on-ground and in-flight as functional check and to monitor gain drift.[8] The PLC also included several seconds' collection with comb-signal OFF to measure background, comprising BBR *first-light* data shown in Fig. 8.

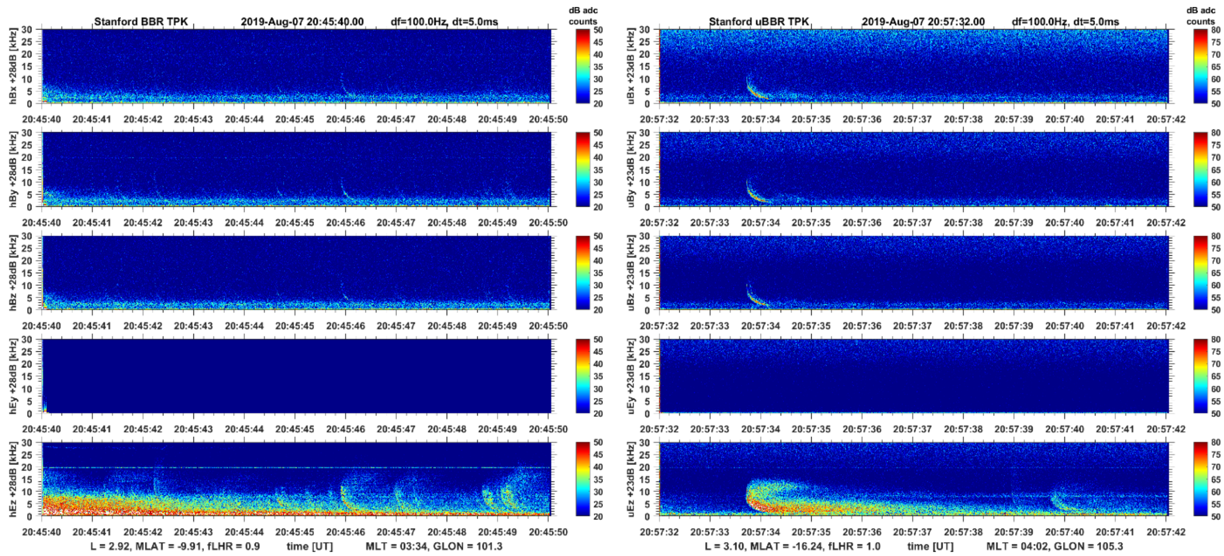

Fig. 8: BBR *First-Light* Data (all but Ey turned ON): (left) Heritage-Rx, (right) Micro-Rx.

TNT Checkout***:*** Given the shared Ey preamp, BBR also collected data during the TNT checkout on the following day Aug. 8 (19220).[9] Fig. 9 shows example 20s *first-light* TPK *Ey* data, while Fig. 10 shows 5.4hr SVY (Survey) data for By and Ey covering ~1.7hr portion of TNT checkout.

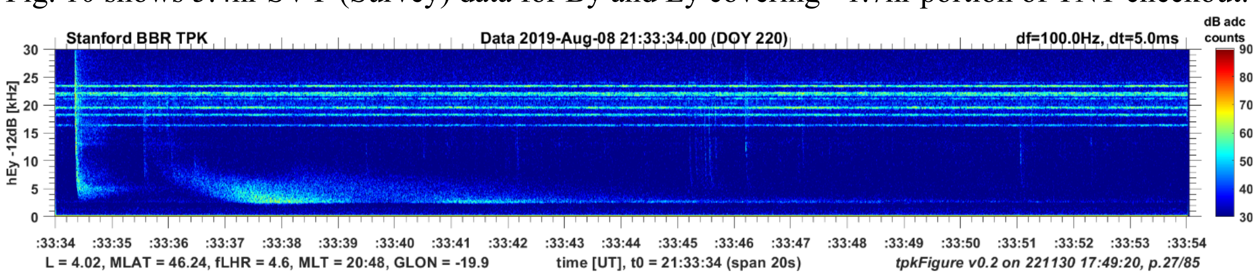

Fig. 9: BBR+TNT *First-Light* Ey Dipole Data. Whistler and many VLF Stations evident.

[7] Internal comb-signal is fed to each channel's adjustable gain input stage *after* (i.e., bypassing) Ey, Ez preamps.
[8] Preliminary review shows no long-term change in BBR gain from pre-launch values during the ~2yr mission.
[9] The prior BBR checkout neglects Ey, as Ey only comes live once the TNT/TATU preamps are powered ON.

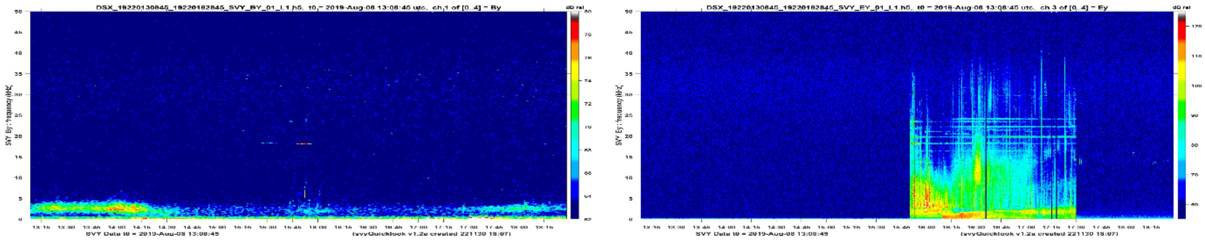

Fig. 10: BBR Survey Spectrograms for (left) By and (right) Ey during TNT checkout.

3.2. BBR/SRx Data Products

SVY (Survey Spectrograms). The SVY continuous 24/7 *Survey* product[10] provides precomputed spectrogram pixel images in PGM[11] format for one magnetic (By) and one electric (Ey) channel with 8-bit dB, 100Hz frequency resolution at 30s cadence. Each SVY file covers approximately one ~5.4hr orbit (4 to 5 per day). This product gives quick impression of overall wave activity and so remains uncalibrated.[12] Fig. 11 shows a particularly clean-sweep pair of SVY images collected at end-of-mission with various sources of spacecraft noise turned OFF. VLF stations, chorus bands, auroral and plasmaspheric hiss are evident. Note Ey is more sensitive than By.

[10] The three letter name SVY for this data product is redundant considering intended *Survey* function.
[11] PGM = Portable Grey Map (here colorized). See, e.g., https://netpbm.sourceforge.net/doc/pgm.html
[12] Calibration of SVY is technically possible but forever limited by precomputed 8-bit dB resolution.

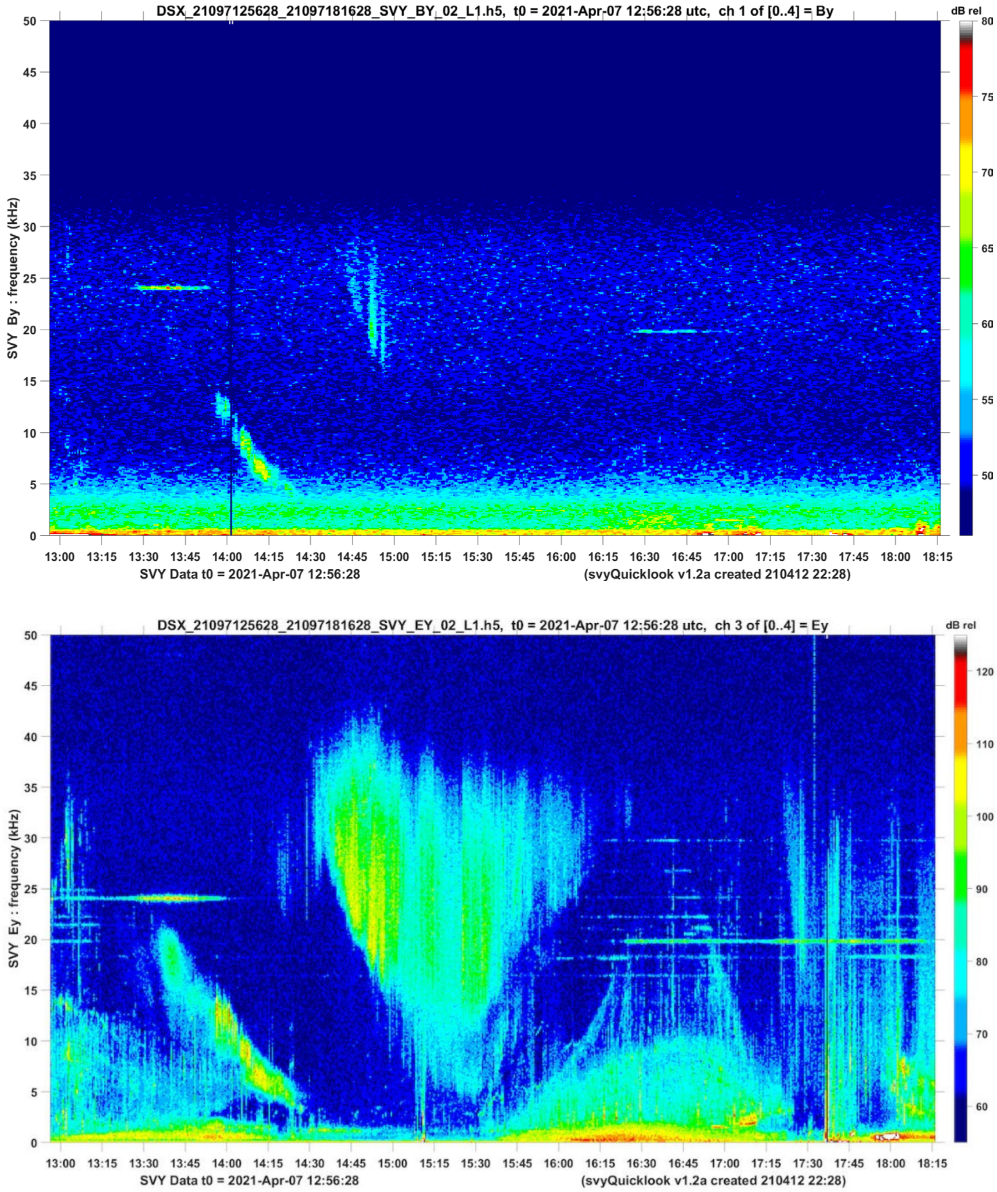

Fig. 11: Example SVY product for (above) By and (below) Ey channels.

MBA (Multiband Analyzer). The MBA continuous 24/7 *Survey* product provides precomputed self-spectra and cross-spectra among all 5 channels at (complex) float32 resolution grouped into 25 log-spaced frequency bands and sampled at 1s cadence. Each MBA file covers approximately one ~5.4hr orbit (4 to 5 per day). The MBA Quicklook display software presents these self- and cross-spectra as an upper-triangular 5x5 mosaic. For convenience the DSX orbit is projected to the magnetic meridional plane and as also to standard ground-track. Fig. 12 shows an example MBA on Aug 8 (19220) from ~13:20 to ~18:50 in which Ey is turned ON during TNT checkout.

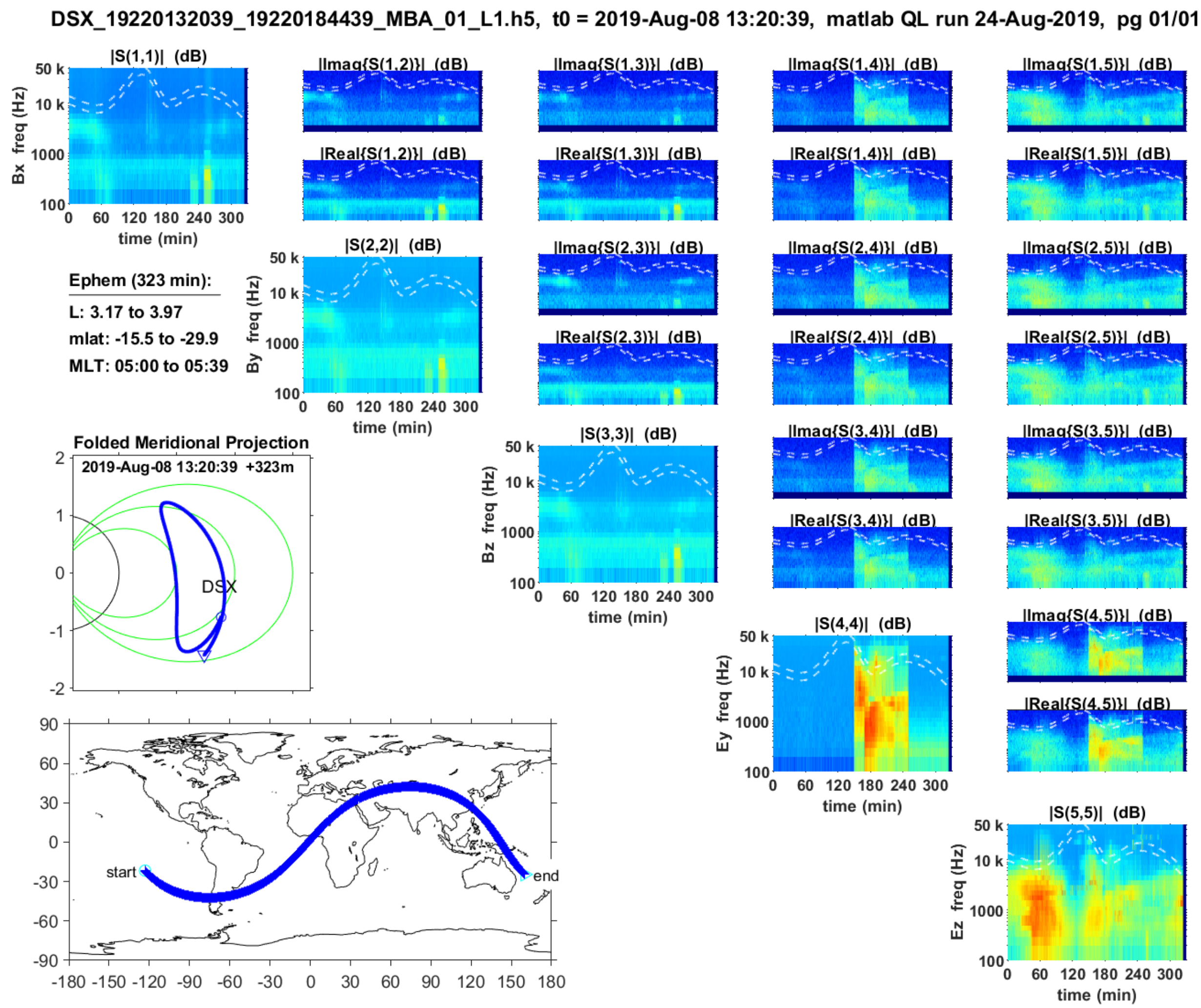

Fig. 12: MBA Quicklook during BBR/TNT checkout. Ey turned ON for ~90min @ t ~150 min.

Like SVY, MBA gives a quick view of overall way activity displayed here in uncalibrated form. Once downlinked, the MBA data are converted to HDF file format[13] (as are the burst products). The float32 resolution allows meaningful post-calibration, subject to averaging over log-spaced frequency bins. In this regard, MBA supports further post-processing to construct 24/7 coverage maps of wave power and wave normal angle vs orbit phase space and vs seasonal variation.[14]

[13] HDF = Hierarchical Data Format, https://www.hdfgroup.org/solutions/hdf5/. MBA .h5 details covered elsewhere.
[14] Algorithms to identify and eliminate a variety of noise artifacts must be developed and applied prior to calibration.

TPK (Time-Domain Packed). The TPK *Burst* product provides 5ch continuous full-bandwidth data at 16-bit resolution[15] and 100 kHz sample rate[16] for up to 30min[17]. The remainder of this subsection highlights notable TPK events and data acquired during the ~22 month mission.

Lightning Whistlers: Many lightning generated whistler events have been captured both during passive receive DCEs and during TNT high-power transmitter DCEs (the later having several seconds listen time between each transmitted pulse). Statistics regarding whistler intensities and wavenormal angles vs orbit location—especially 2<L<3—allow to estimate whistler contribution to energetic-electron loss-rates within the slot region. Moreover, with the advent of ground-based global lightning-detection networks, many BBR-observed whistlers can now be associated with their likely causative discharge (Fig. 13). Such association allows to develop comprehensive models relating discharge characteristics to whistler properties and ultimately to electron scattering and loss. Such models can and should henceforth treat not only the first-pass (0+) coherent descending tone, but also the frequent magneotospherically reflected (MR) echoes and subsequent devolution to short-term sustained plasmasphere hiss (Fig. 14).

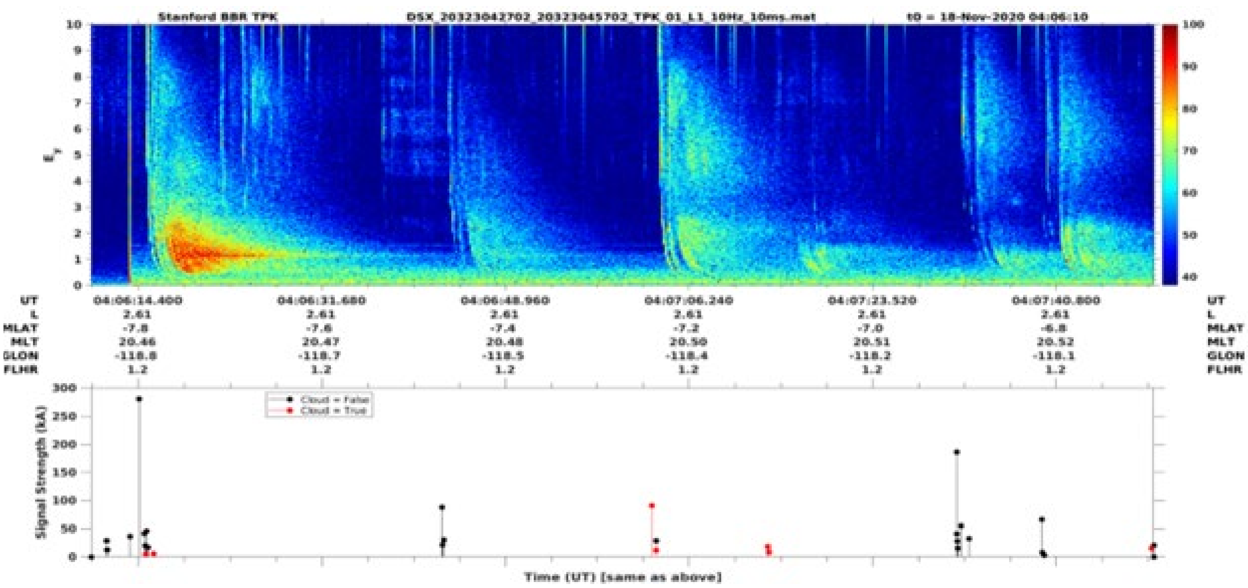

Fig. 13: Whistlers vs causative lightning (beneath). Note MR echoes and devolution to hiss.

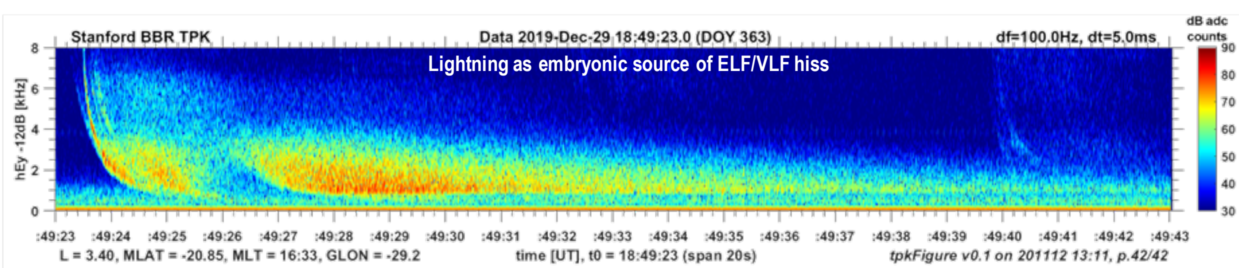

Fig. 14: Lightning whistlers with MR echoes and devolution to enduring hiss lasting > 10s.

[15] BBR Heritage-Rx provides full 16-bit resolution, while Micro-Rx provides 13-bit resolution in 16-bit word size.
[16] BBR internal anti-aliasing filters begin to roll off after 30kHz. See separate report by *Linscott* et al. (link TBD).
[17] Each used of *Burst* requires ~5x recording-time post-processing lockout before another *Burst* can be scheduled.

VLF Ground Stations: A substantial number of DCEs were devoted to VLF ground-stations. Measurement of in-orbit 3xB and 2xE magnetic and electric fields allows not only to estimate the direct impact to local particle populations along the orbit track, but also, in combination with known transmit power, to estimate subionospheric and transionospheric propagation and loss.

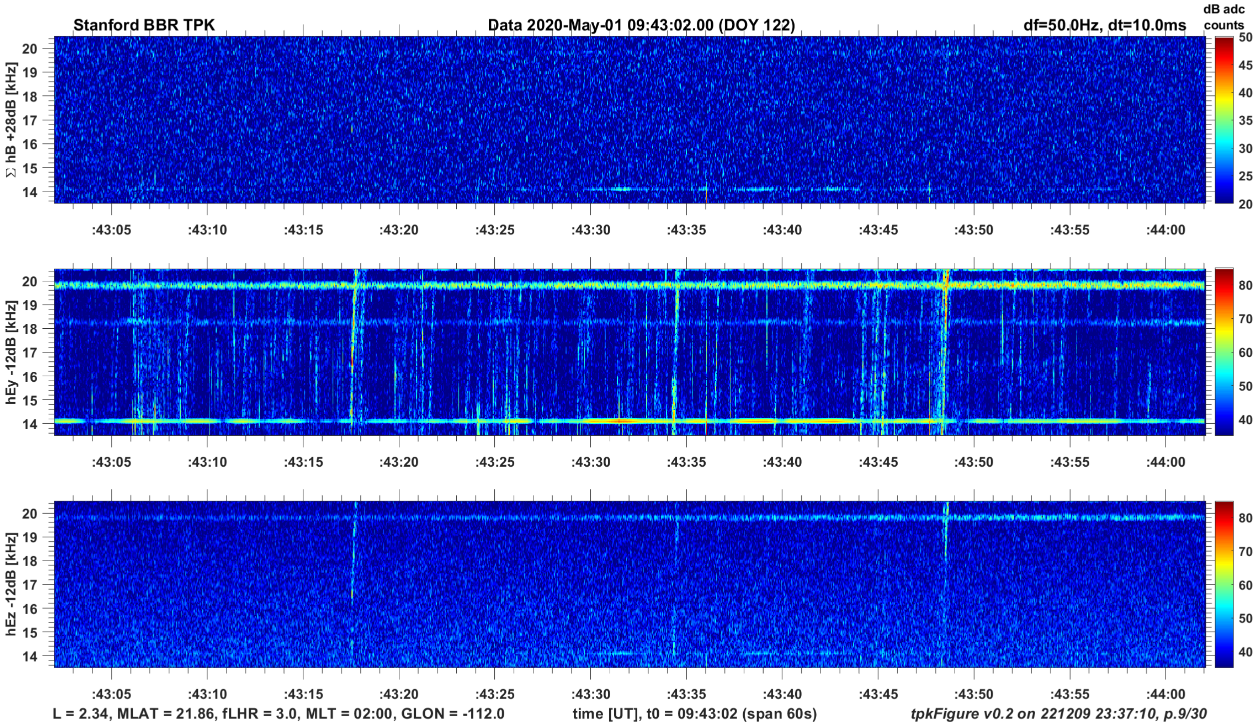

Fig. 15: VLF ground-stations. Strong spectral lines at 19.8 kHz and 14.1 kHz are visible in Ey.

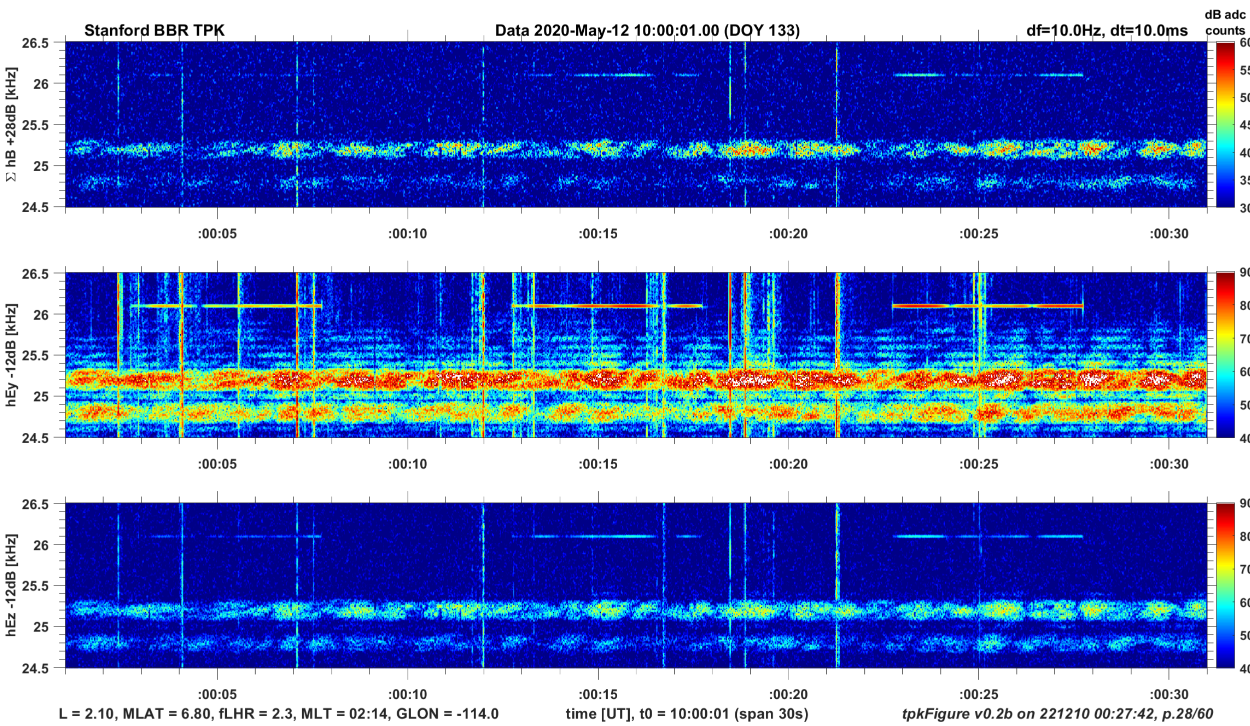

Fig. 16: VLF ground stations. Lines at 24.8 kHz, 25.2 kHz, and 26.2 kHz (pulsed) are visible.

Natural VLF Chorus: On rare occasions, the plasmasphere was sufficiently compressed for DSX to see natural VLF chorus (DSX having ventured close to or beyond the plasmapause). Fig. 17 shows an example with chorus elements seen in all 5 channels, allowing to estimate wave power.

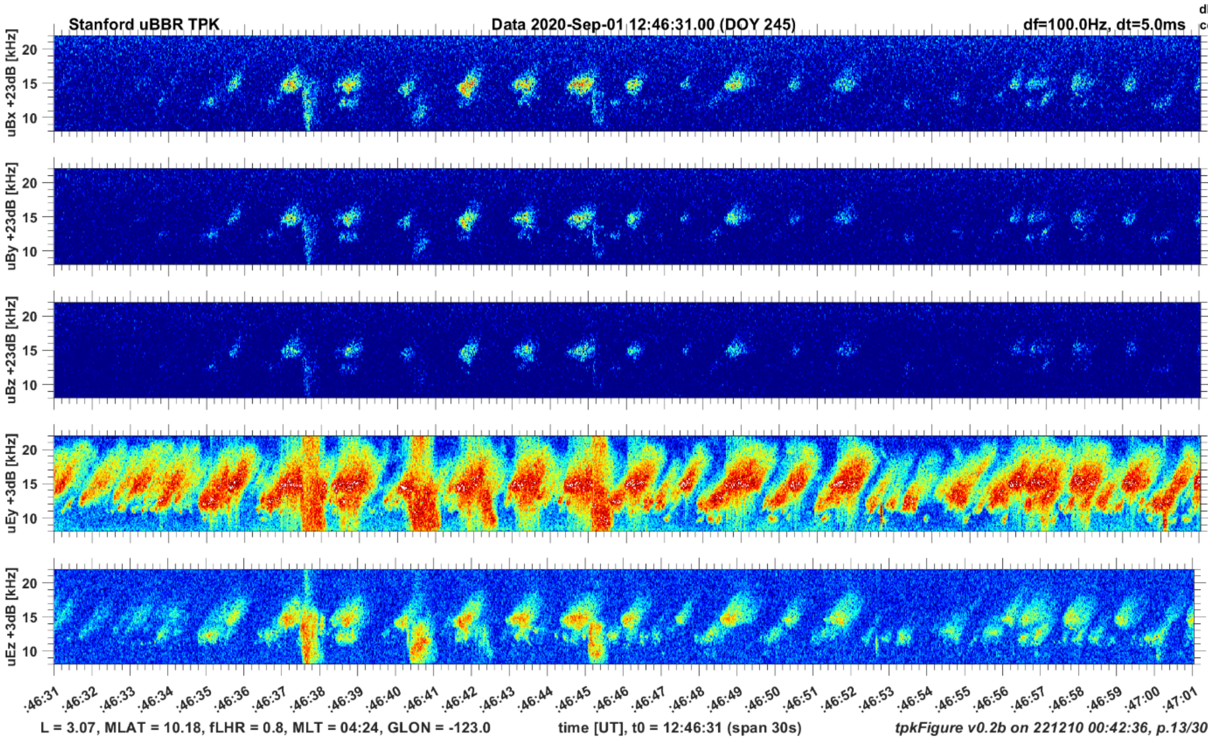

Fig. 17: Natural VLF chorus emissions seen by BBR during compressed plasmasphere event.

Boomerang Echoes: So-called *Boomerang* echoes—whereby TNT pulses are received by BBR after undergoing a form of total internal reflection within the magnetosphere and subsequently return to DSX—comprise the bulk of TPK data. Fig. 18 shows simple 1- and 5-step examples. Typicall, Ey (80m dipole) sees all echoes; Ez (16m) usually does but not always; sum |B| rarely.

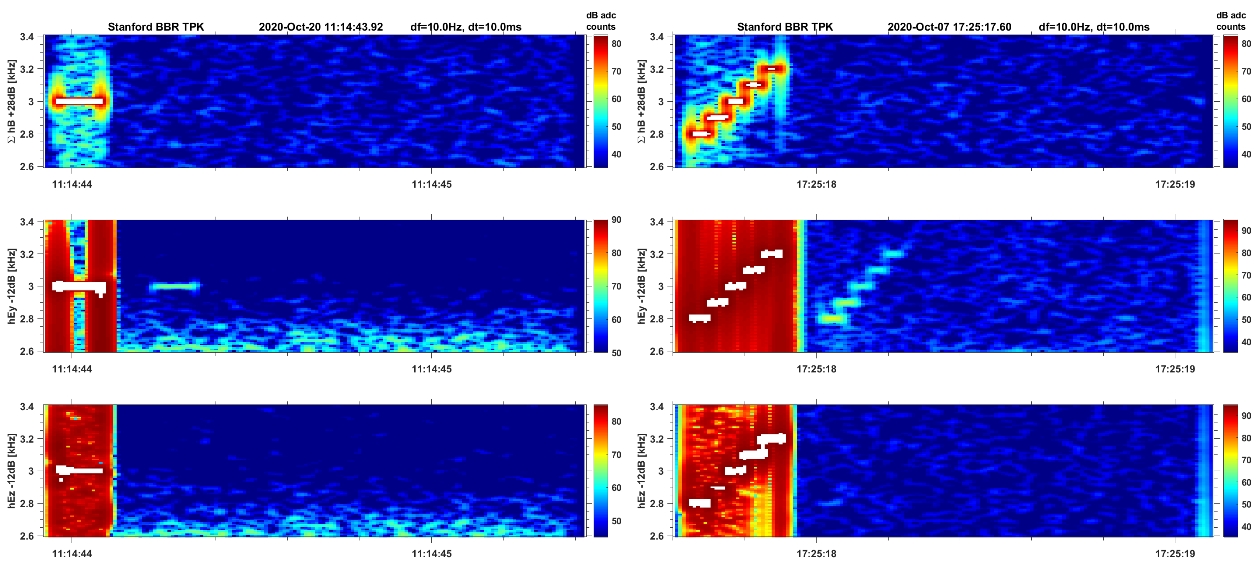

Fig. 18: Boomerang echoes from TNT pulses: (left) single-step pulse, (right) 5-step staircase.

Fig. 19 shows Boomerang echoes from the "BGrowthA" pulse pattern (c.f. Fig. 8, fifth from top) as featured in the Oct 2021 DSX Press Release.[18] Here, the Ey dipole (80m) sees echoes from almost all pulses (i.e., short 50ms, and long 500ms, 1s); Ez (16m) sees the long pulses and only one or two short pulses (at 3 kHz); and Sum |B| sees essentially nothing. The relative intensities among these channels carries information about echo wave normal angles as well as echo power.

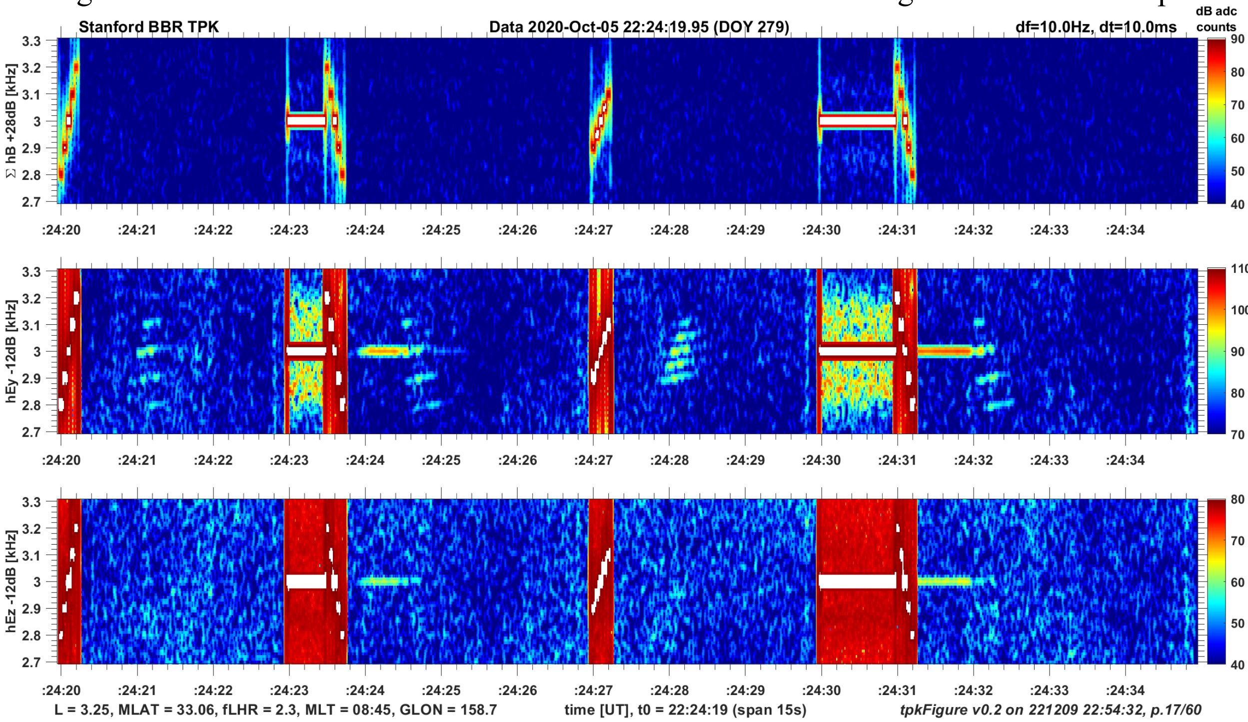

Fig. 19: Boomerang echoes featured in DSX press-release of Oct 2021, showing Ez, Ey, and ∑|B|.

Fig. 20 shows an interesting case of the "B3" (3-step) pattern, where at earlier time (left panels), the 3 kHz shows a strong extended echo, and at later time (right panels), the 2.9 kHz pulse does.

[18] https://www.afrl.af.mil/News/Article/2800402/afrl-presents-results-from-dsx-spacecraft-experiments/

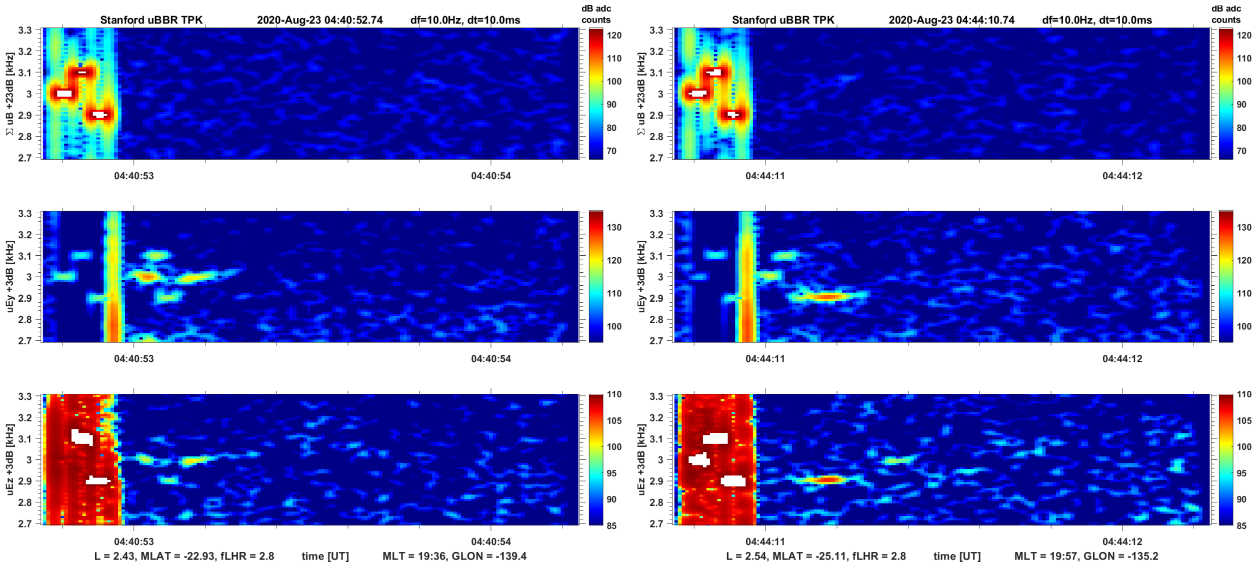

Fig. 20: Example 3-Step Boomerang echoes, where strongest echo moves from 3 kHz to 2.9 kHz.

Boomerang B-Field: Fig. 21 shows two rare cases of detectable magnetic-field in the return echo, allowing to estimate absolute wave power via ExH calculation, and from this, direct calculation of the impact on energetic electron populations. Raytracing study of these two events regarding B-field intensity may yield estimates and bounds for other cases with |B| below detectable limits.

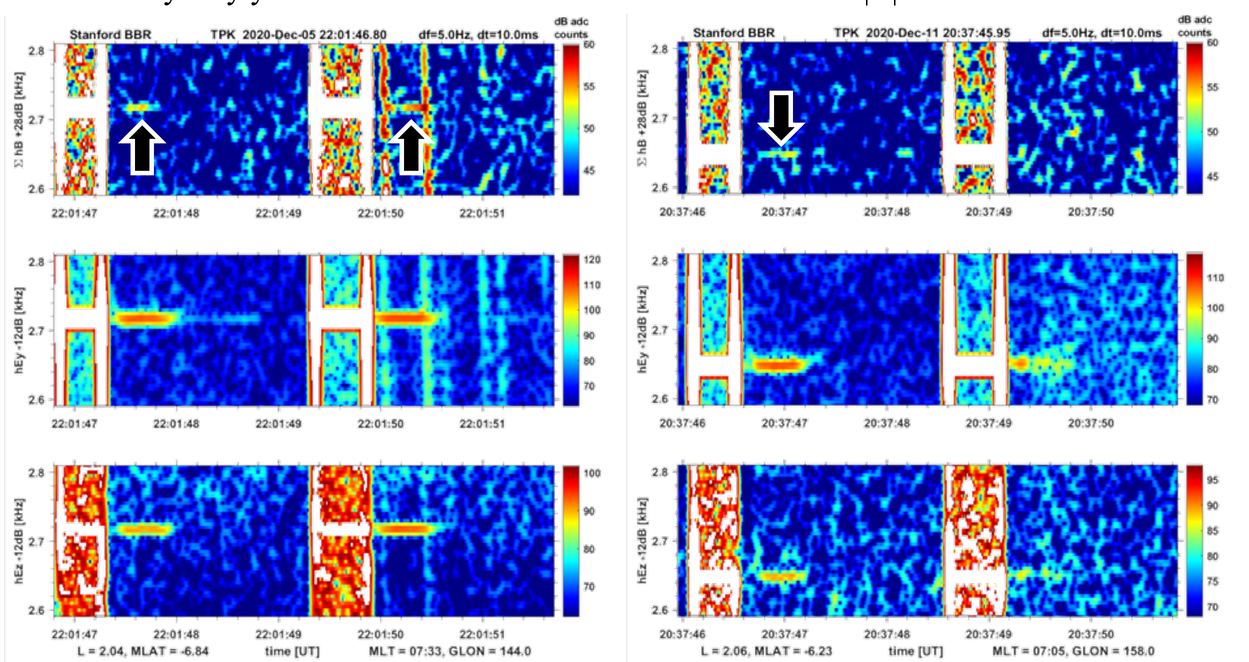

Fig. 21: Two cases (similar location) of Boomerang with detectable magnetic-field (black arrows)

Remote Conjunctions: A limited number of DCEs involved reception of TNT transmitted pulses by remote satellites with BBR listening. The most successful cases involved two DSX-ARASE conjunctions, the first occurring 2019-Sep-04 (19247), the second 2021-Feb-19 (21050). This later case is of particular interest owing to (i) reception by ARASE of both the 2**fo* harmonic as well as the fundamental *fo*, and, (ii) reception by DSX of Boomerang echoes (fundamental *fo*) during the same period (Fig. 22), allowing cross-calibration of self-received Boomerang echo intensities vs far-field direct propagation intensities measured by ARASE.

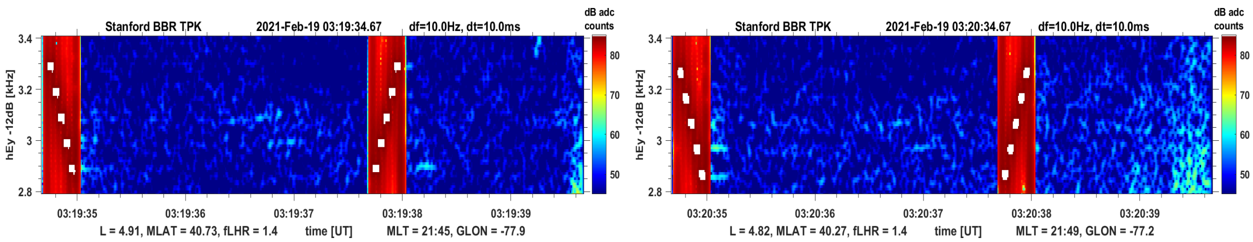

Fig. 22: Boomerang echoes (left) immediately before and (right) after DSX-ARASE conjunction.

Unusual Echo Times. Fig. 23 shows a rare case of unusual Boomerang echo produced by the finely stepped tuning downsweep (*t* > 00:28:48). Similar to the "Bear-Claw" (discussed later), the echo arrival times do not follow the monotonic linear slope of the transmitted pulse times but are folded about the tuned center frequency (~3.2 kHz) into a "V" or arrow shape. Note also, prior 3-step pulse echoes do not preserve 50ms timing; rather, 3.2 kHz arrives more quickly.

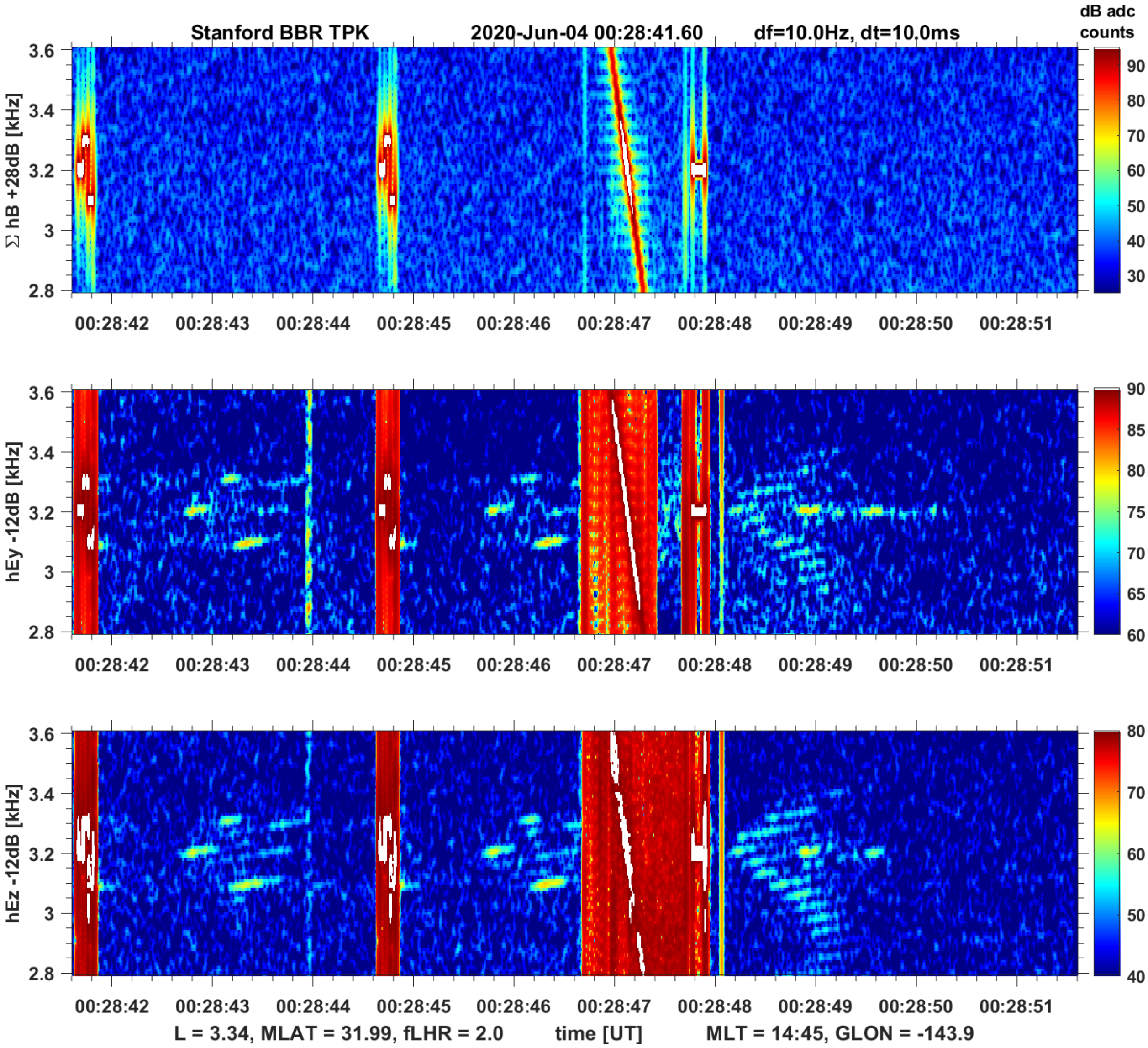

Fig. 23: Unusual Boomerang echo timing: tuned pulse at ~3.2 kHz returns most quickly of all.

Rising Emission Form: As the mission progressed and transmit pulse patterns became more sophisticated and with increased power, many pulses were seen to initiate apparent self-sustained rising emissions whose duration greatly exceeded the transmitted pulse-length.[19] In examining many cases, it appears this emission type often begins with an initial dip to lower frequency, forms a concave "U" shape, and subsequently transitions to an unbroken linearly rising *f-t* slope. Moreover, other transmitted pulses above the emission starting frequency appear to superpose,

[19] That these may be emissions, and not extended passive echoes, is suggested by strong similarity to natural chorus.

creating "bead on string" appearance (intensity enhancements) along the otherwise steady form. Fig. 24 shows 2 examples. Note the duration of the 3 kHz CW pulse does not alter the emission.

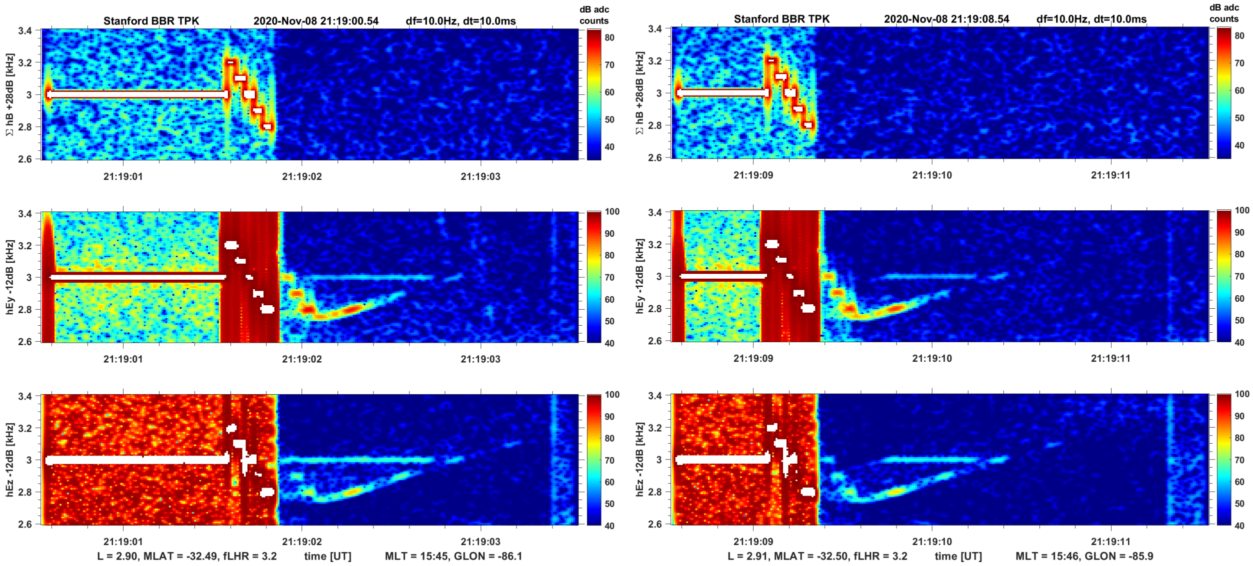

Fig. 24: Example sustained rising emissions showing "bead on string" intensity enhancements.

Fig. 25 shows an even more enigmatic case in which several emissions (two rising, one falling!) appear to branch from the same (or nearly same) start frequency. A strong resonance or possibly local emission occurs at ~2.77 kHz unrelated to TX frequency. Note lower hybrid f_{LHR} ~2.9 kHz.

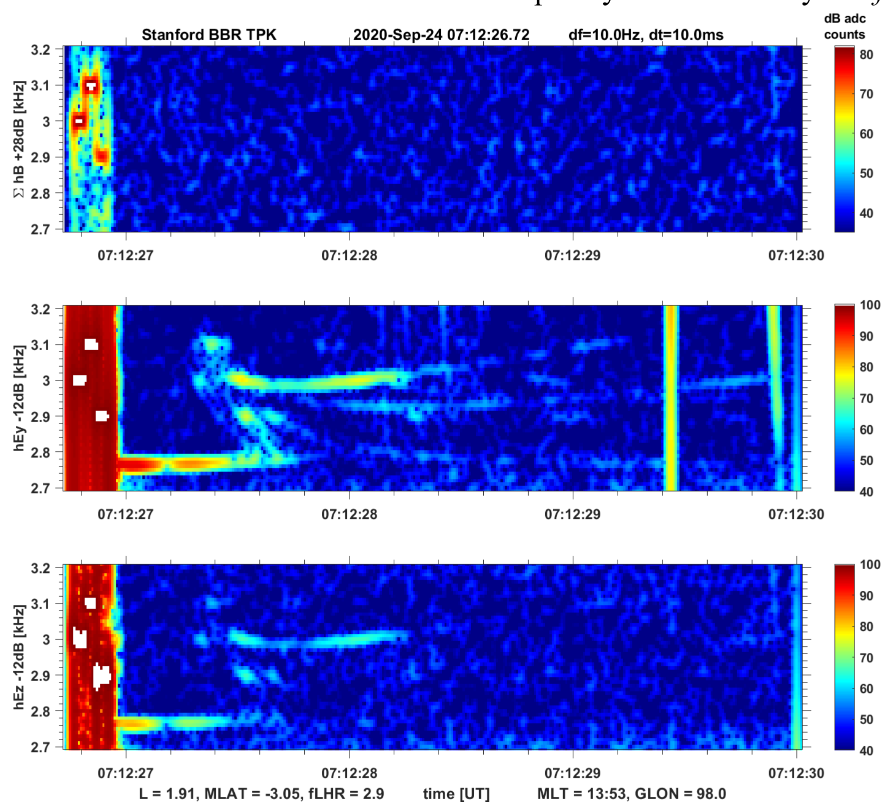

Fig. 25: Unusual emission splits into 3 branches. A 4th form appears at 2.77 kHz.

"Bear-Claw" Boomerang: During the final months, TNT was set for maximum transmit power, which produced, among other results, the so-called "Bear Claw" appearance (Fig. 26) in the Boomerang echoes in response to high-power tuning downsweeps. *The surprise form of these echoes warrants further theoretical and experimental treatment of this unexpected phenomenon.*

Notable observations:

(i) Not all transmitted pulses return (although absence of some return pulses vs frequency is consistent with other Boomerang observations),

(ii) Arrival times of individual Bear "Claws" do not follow the monotonic slope of the transmitter downsweep, even accounting for differential wave speed vs frequency,

(iii) The duration of each Bear "Claw" is many times the individual transmitted pulses, suggesting possible wave-normal dispersion and/or novel wave/particle emission process,

(iv) The frequency of earliest return[20] is also the frequency of peak tuning efficiency,[21] and presumably then, the frequency of maximum transmitted wave power,[22]

(v) The frequency spacing among the Bear "Claws" does not correspond one-for-one to the frequency spacing of the transmitted downsweep pulses.

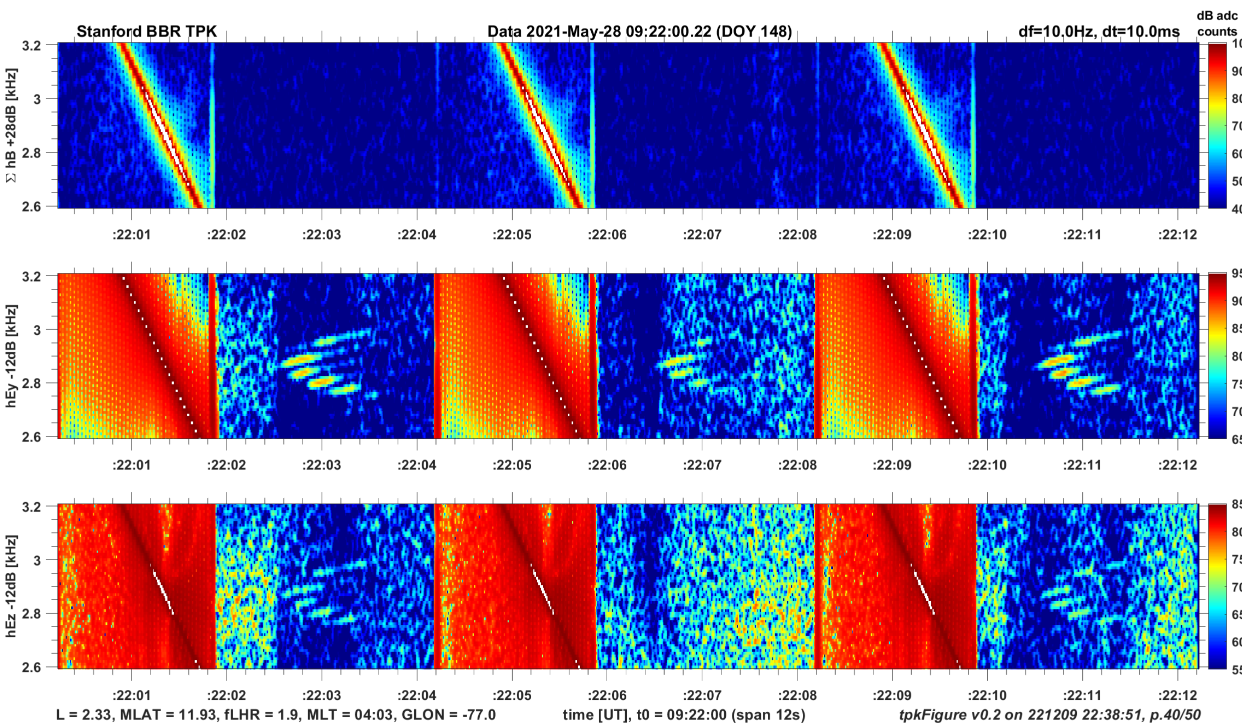

Fig. 26: "Bear-Claw" feature in Boomerang echoes from high-power TNT tuning downsweeps.

As a final comment, comparing Fig. 26 with Fig. 23, is possible that the "Bear-Claw" represents the general canonical response of the magnetosphere to in-situ VLF wave injection, and that the various other forms of Boomerang echoes are partial elements of such general response whose particular occurrence and detectability varies with satellite location and proximity to MR points.

[20] Had the causative wave been a lightning whistler, the leading frequency would be termed the "nose" frequency.
[21] Evidenced by maximal parasitic signal power (white pixels) in B and Ez data, centered on the *f*=~2.9 kHz pulse.
[22] The lead arrival at *f*=2.9 kHz may be a combination of best signal power and early onset of an emission process.

FPK (Frequency-Domain Packed). The FPK *Burst* product was designed to provide 30:1 data reduction to meet a provisional fallback requirement in light of an uncertain downlink allocation. FPK obtains this reduction via run-time selectable +/-1 kHz FFT-domain filters spaced at integer center frequencies, with appropriate BBR/FPK filter co-scheduled vs TNT transmit frequency. Eventual mission allocation essentially always allowed choice of full-bandwidth TPK over FPK.

Nonetheless FPK was tried on two occasions, 2019-Nov-26 (19330) and 2019-Dec-14 (19348), as proof-of-concept (respective centers 24kHz and 25kHz). The expected FPK files were created, but unfortunately during this season the TNT key-filter (which indicates Transmitter = Active) was held anomalously high, thus muting all data to zero (intended behavior when transmitting).

Instead, for reference, Fig. 27 shows example FPK data acquired during pre-launch timing tests. During this test, a pulsed 16 kHz signal under GPS timing control was injected to the TASC search-coils via external loop to monitor BBR sample-clock and IAS/HSB SCLK stability.[23]

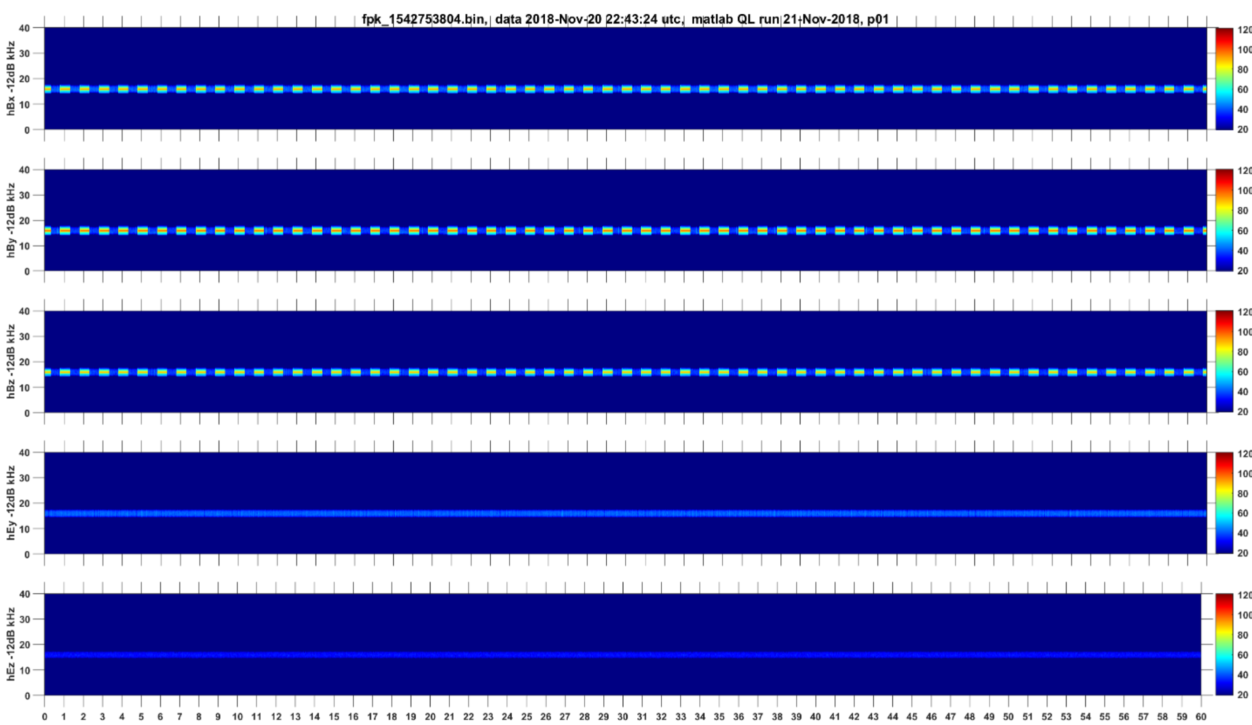

Fig. 27: FPK pre-launch 16kHz On/Off pulse injected to TASC via external loop for timing check.

[23] Analysis of BBR and SLCK stability (i.e., drift) relative to GPS/UTC reference truth is discussed elsewhere.

NBD (Narrowband Demodulator). The NBD *Burst* product provided an ultimate data reduction ratio in the form of baseband I/Q samples at 1 kHz rate and float32 resolution after applying a ~400Hz wide FIR filter centered on specified center frequencies. As mentioned for FPK, actual mission downlink allocation essentially always allowed choice of full-bandwidth TPK vs NBD.

For reference, Fig. 28 shows an example NBD display collected during pre-launch ground tests. The input signal was 16kHz continuous sine-wave injected to TASC via external loop antenna. The NBD product contains I/Q data from 1 magnetic (By) channel and 1 electric (Ey) channel.

The four panels show (top down): By magnitude (relative), By phase (from I/Q), Ey magnitude, and Ey phase. Note the constant roll in By phase due to the imperfect match between signal generator 16kHz vs filter center frequency 16kHz derived from BBR internal 20MHz oscillator. Also note the parasitic coupling to Ey (~40dB down wrt By) with understandably noisier phase.

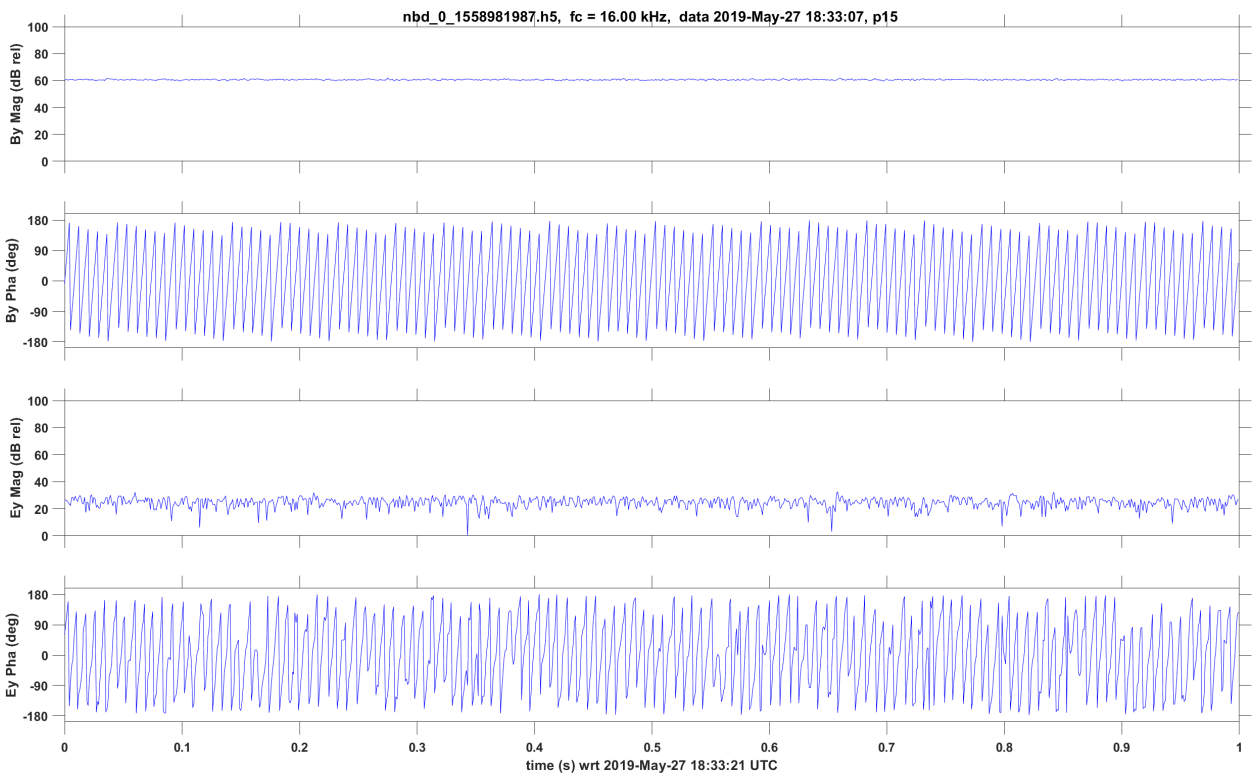

Fig. 28: NBD pre-launch test for 16 kHz continuous since wave injected to TASC via external loop.

3.3. BBR/SRx Housekeeping

Housekeeping files for the BBR instrument and SRx software (considered a virtual instrument) contain measured parameters (volts, temperatures, etc.), command history, and processing state. Each BBR and SRx housekeeping file general spans 24 hours with checkpoints each 00:00 UTC. Ground software creates respective health plots as well as human readable state-history text files.

<u>BBR Housekeeping</u>***:*** Fig. 29 (left) plots BBR voltage and (right) temperature (including TASC) at power-on.[24] The initial slew-in of duration ~5vmin (most obvious in the voltage plots) arises from a long time-constant on the BBR internal voltage reference.[25] Note BBR temperatures rises ~5C from ~26C ambient ~31C steady-state. Fig. 30 shows timing data which relates each SCLK PPS edge to BBR 20MHz FPGA ovenized clock count.[26] Point-by-point inspection of successive *Fpga2* values gives SCLK drift since last update. Fig. 31 (next page) gives example state history.

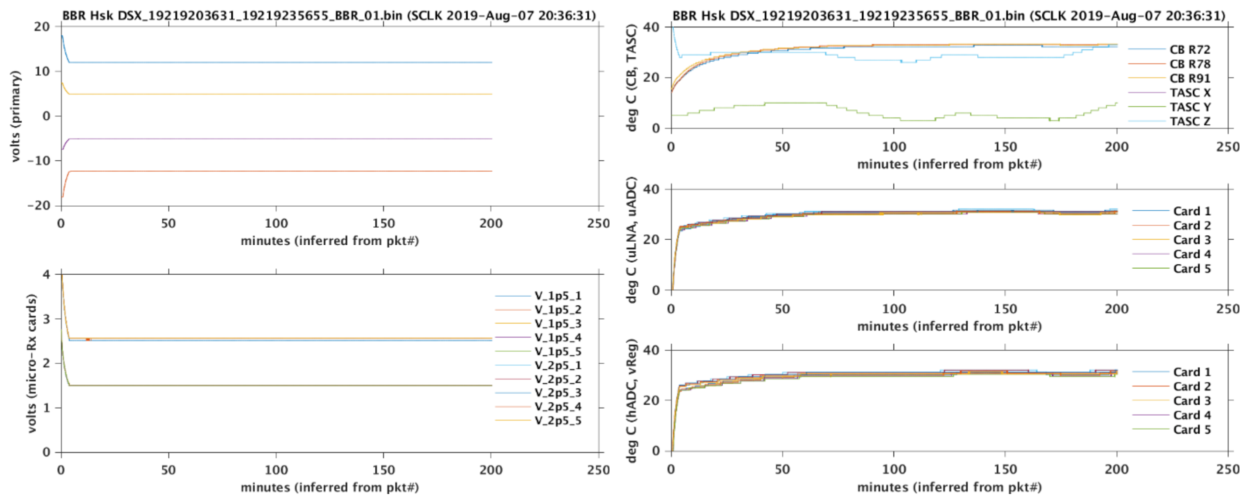

Fig. 29: (left) BBR internal voltages; (right) BBR temperatures. Values valid > ~5min slew-in.

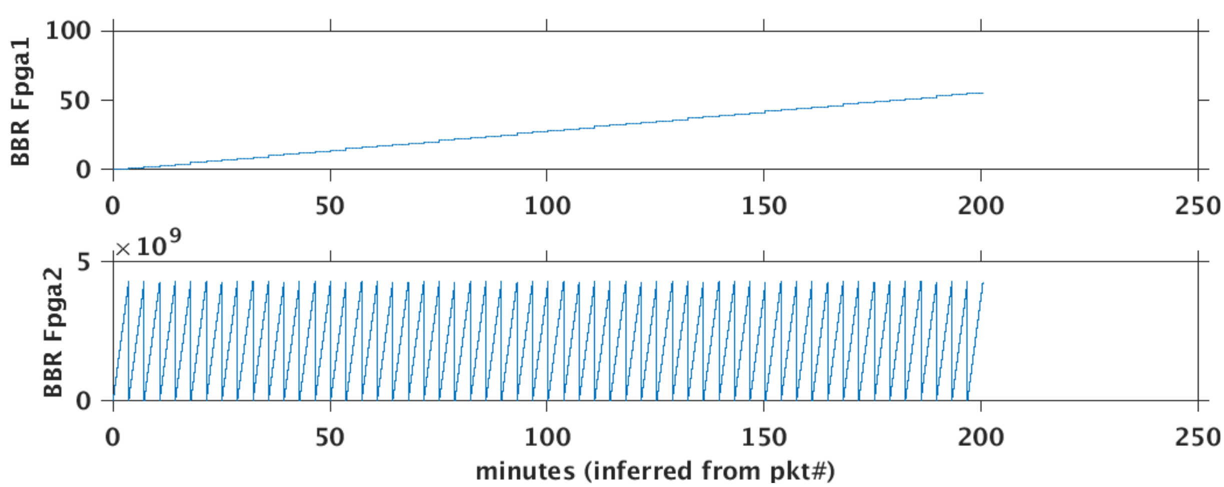

Fig. 30: BBR 20MHz count @ each SCLK PPS, from which SCLK drift maybe inferred.

[24] These first-light data, acquired at first power-on, are representative of all subsequent power-on (reset) events.
[25] Hence voltage and temperature values become meaningful once ~5min have passed following cold power-on..
[26] From which SCLK drift vs time & temperature may be derived for ground-correction of SCLK to true UTC .

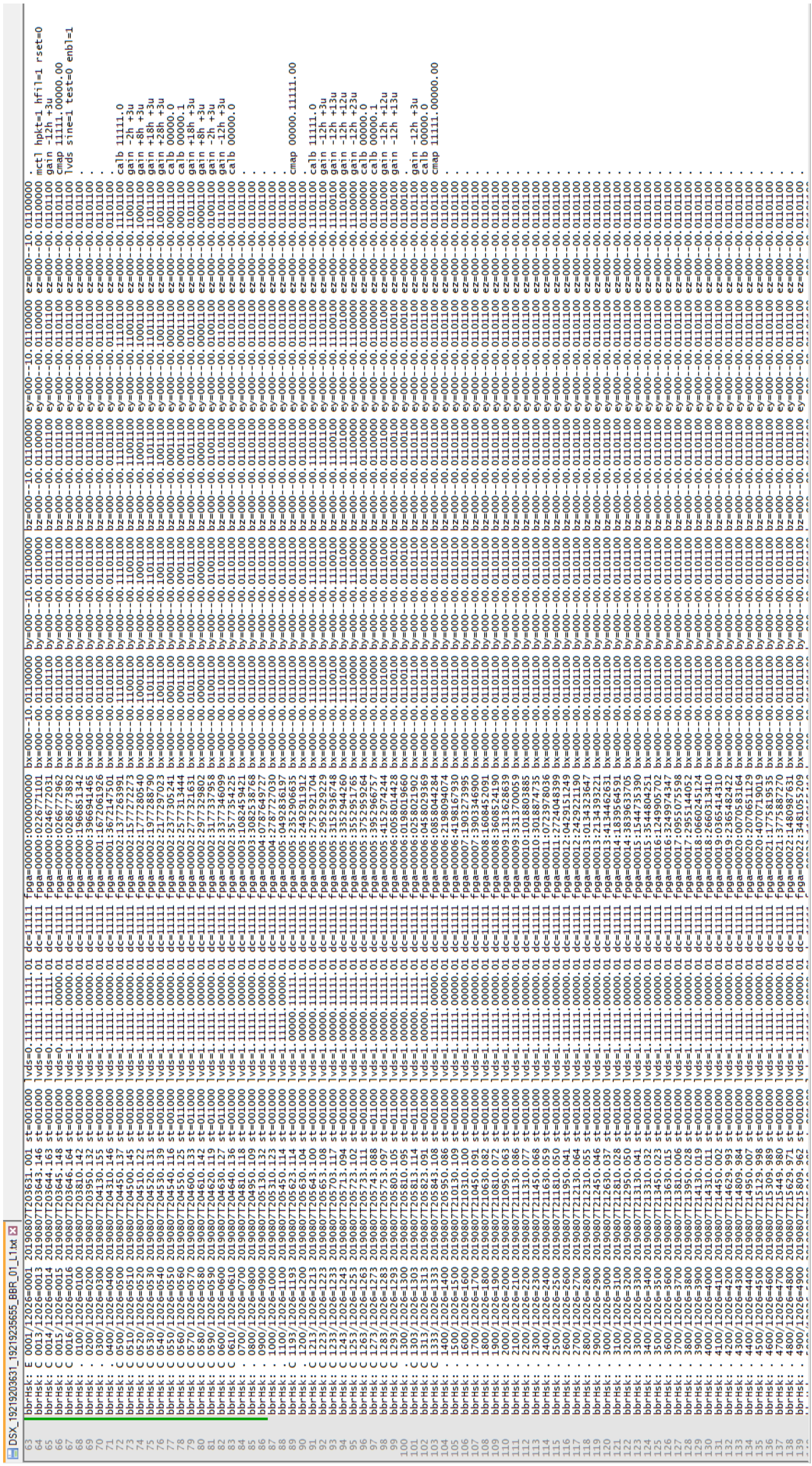

Fig. 31: First on-orbit BBR instrument state and command history.

SRx Housekeeping: Fig. 32 plots SRx file sizes (top 3 panels) and channel-state configuration (bottom panel) for one of the more interesting Data Collection Events which includes several transitions from *Survey* to *Burst* mode and back, as well as switch from 5ch all-Heritage-Rx to 5ch all-Micro-Rx and back, *and* brief mix of 4ch Heritage plus 1ch Micro-Rx (dual Ey case).

Here, the SVY and MBA generally products generally grow at constant rate up to pre-arranged checkpoints every ~5.4hr (approx.. one orbit) regardless of *Survey* or *Burst* mode. In contrast, the *Burst* products first record all BBR data from the actual DCE (bottom panel, green line), then subsequently post-process these data to the selected output product (black). Occasional blank gaps in the configuration-state indicate unusual periods when SRx was idle, which typically for brief periods following a spacecraft IAS or ECS reset.

Fig. 33 (next page) shows partial SRx state history for this DCE in human-readable text format.

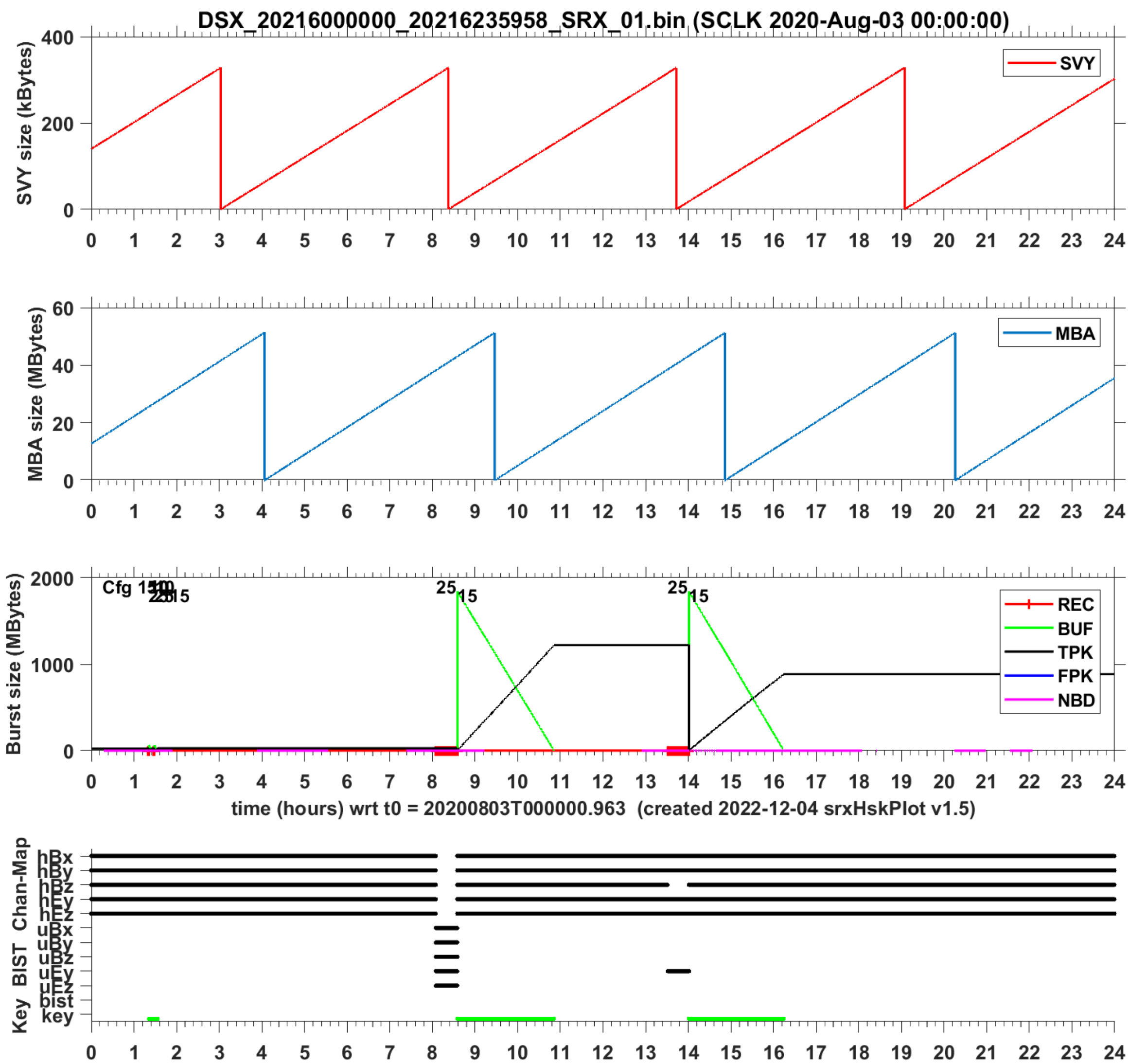

Fig. 32: SRx housekeeping: (top 3 plots) file sizes, (bottom) BBR channel configuration-state.

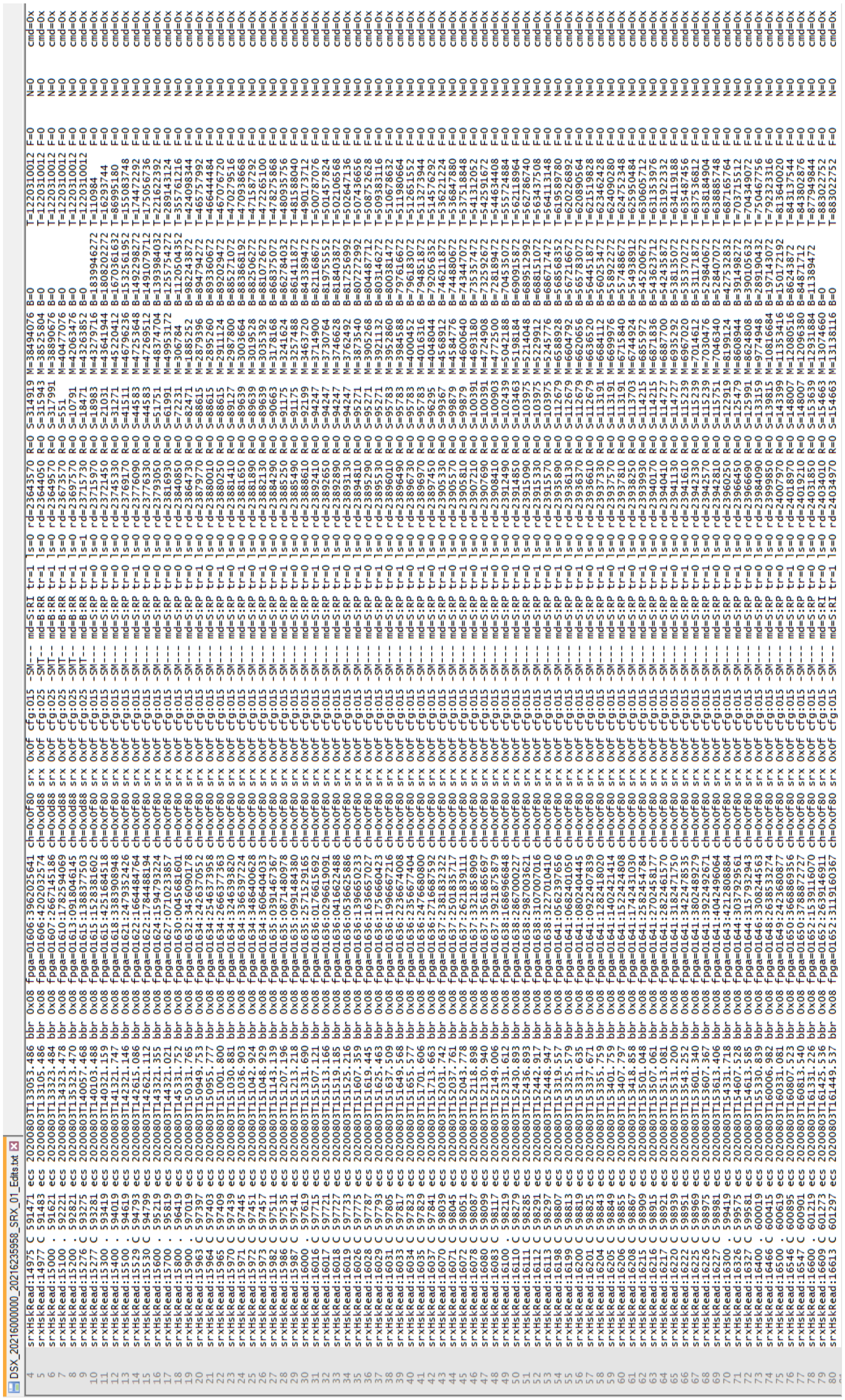

Fig. 33: SRx Housekeeping shows *Burst* recording and post-processing to TPK.

4. RESULTS AND DISCUSSION

This section presents brief observations of several cases as starting points for future analysis.

4.1. Radiated Wavenormals

Fig. 34 shows preliminary raytracing analysis which replicates the simplest form of Boomerang. Here, all permissible Earthward traveling rays (upper-right panel, red rays) are launched initially from the DSX location at all permissible wavesnormals supported by the (cold) magnetoplasma. By the multi-ion MR process,[27] the Earthward traveling waves undergo a form of total internal reflection and travel back toward DSX (upper-right panel, blue rays), and are received by BBR.

With slight tuning of the cold plasma density model, the echo features (return and dwell-time) are well matched (left panels) by a *subset* of rays whose initial launch wavenormals are known. These responsible launch wavenormals (lower-right panel) are thus established as having been radiated by the DSX transmit antenna at angles approaching and along the resonance cone, *confirming essential aspects of theoretical models for VLF wave radiation by an electric dipole immersed in a magnetoplasma.*[28]

Further analysis can also reveal the radiated wave numbers (in *k*-*ω* space) and wavelengths (λ).

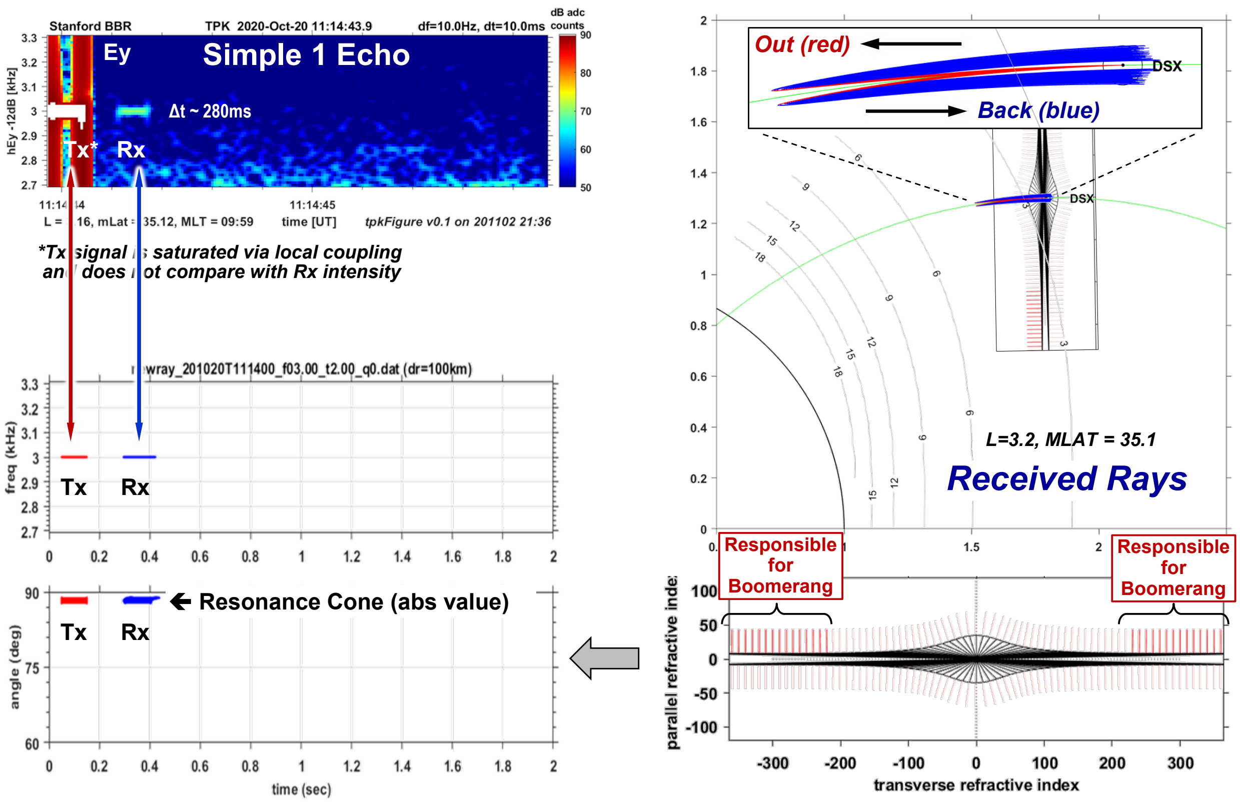

Fig. 34: Raytracing analysis of simple Boomerang echo from nearby MR point.

[27] Edgar, B.C., 1972, "The structure of the magnetosphere as deduced from magnetospherically reflected whistlers."
[28] Ginet, G.P. 2020), "VLF far-field radiation from a linear dipole immersed in a plasma: Baseline model for DSX," MIT Lincoln Laboratory Report 95–002, DTIC #AD1103378, https://apps.dtic.mil/sti/pdfs/AD1103378.pdf

4.2. Growth vs Pulse Duration

Fig. 35 shows a case where Boomerang echo strength increases with transmitted pulse duration. Durations 50ms, 500ms, and 1s were transmitted (not in that order) at tuned frequency 3 kHz.[29]

The upper panel shows relative signal strength in dB[30] for a 100Hz FFT bin at 3 kHz. Here, the moderate length 500ms (1/2s) pulse @ *t*~10s produced an echo strength ~5dB greater than the short 50ms pulse @ *t*~7s, while the longer 1s pulse @ *t*~2s produced an echo ~10dB greater.

While this increase in echo strength vs pulse-length may involve the superposition of sustained reflected waves, there is reason to believe it may also involve wave amplification by some form of wave/particle interaction (i.e., energy exchange) process leading to wave-growth.

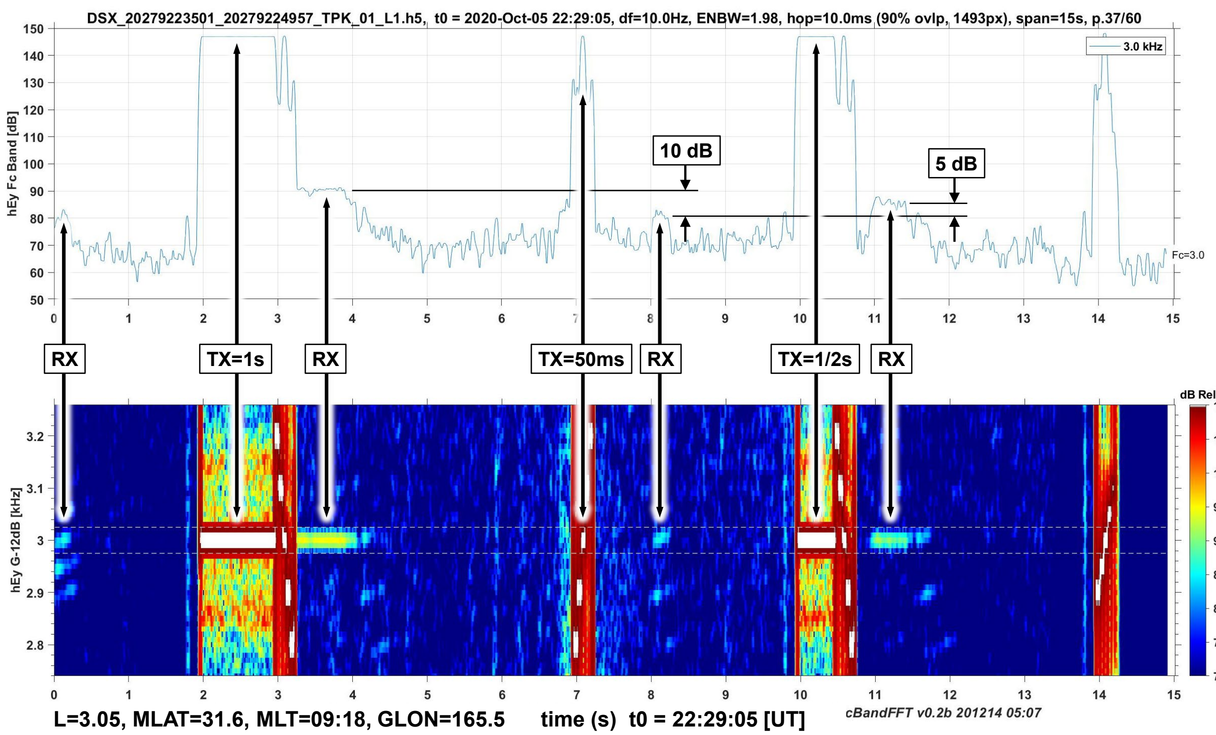

Fig. 35: Boomerang echo strength shown increasing vs increasing transmitted pulse duration.

Similar analyses applied to controlled VLF ground station pulses received by BBR (not shown) suggests wave-growth can occur even at these low L-shells (2<L<3), as for *Siple* (L>4) cases.[31]

[29] Tuned *fo*=3kHz is both the CW pulse transmitted prior to and mid-frequency of each transmitted staircase pattern.
[30] Apparent transmitted pulse intensities (those > 145 dB) are parasitic and *NOT* meaningful to compare to echo dB.
[31] R.A. Helliwell (1988), VLF wave-injection experiments from Siple Station, Antarctica, *Adv. Space Res,* 8(1):279.

4.3. Sustained Rising Emissions

Fig. 36 shows an unexpected type of Boomerang return—a sustained rising emission—often occurring but under conditions not yet elucidated. In this example, the observed data (upper-left) shows a normal simple echo ("1st MR") followed by a sustained, unbroken linearly rising (*f-t*) form starting below 3 kHz and rising to 3.2kHz after ~1.2s (strongly resembling natural chorus).

Also appearing is a short-lived resonance at the local lower-hybrid frequency ~2.7 kHz (est.), seemingly unrelated to any of the transmitted pulse frequencies (all of which are $f \geq 2.8$ kHz).

But perhaps most remarkable are the "bead on string" enhancements occurring along the rising emission at the same discrete frequencies as transmitted in the initial downward staircase pattern.

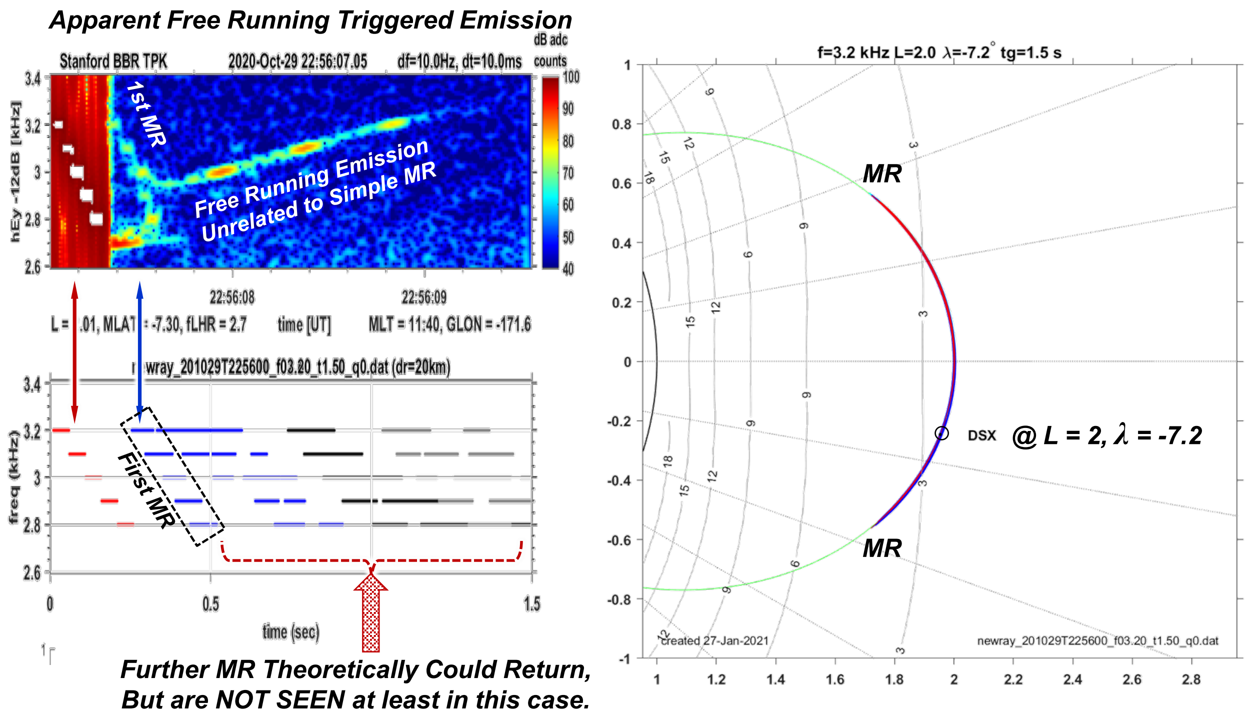

Fig. 36: Sustained rising emission triggered by DSX occurring after initial simple MR echo .

Raytracing analysis (right panel) readily replicates the simple echo from the downward staircase (lower-left panel, "First MR"), but in no way accounts for the unbroken rising feature. At best, allowing for multiple MR passes *may* partially explain the "bead on string" enhancements as due to subsequent MR echoes being superposed atop the free-running emission, as the echo timing is reasonably plausible.

In any case, this rising feature—and its many examples—could be a new form of wave/particle emission which occurs *only* for in-situ transmitted waves. If so, fresh attention must be given to the novel underlying physics, including the relation between transmitted waves, reflected waves, the wave/particle interaction/amplification process, and the ultimate effect on energetic particles.

5. CONCLUSIONS

This report has reviewed the essential elements of the Stanford BroadBand VLF Receiver (BBR) and associated software-receiver (SRx) flown on the DSX satellite from June 2019 to May 2021.

The 5 primary science data products and two housekeeping data products have been described, with many representative and intriguing examples of natural and DSX initiated events presented.

The most important dataset comprises over 2,200 TPK 5ch full-bandwidth *Burst* mode data files. All together nearly 3800 *Survey, Burst*, and *Housekeeping* files totaling ~ 700 GB were collected. Several types of expected and unexpected results have been presented, many suggestive of new physics yet to be explored.

BBR—in conjunction with TNT—has provided the necessary data for DSX to declare success regarding the primary objective to characterize in-situ VLF transmitter wave injection efficiency and calculable impact to energetic particle populations in the Earth's radiation belts.

The science data returned by BBR has validated the DSX mission and in addition demonstrated the value, significance, and utility of companion VLF Micro-receiver using rad-hard-by-design custom signal processing microchips. The observed new phenomena confer compelling incentive for continued exploration of VLF in-situ wave injection behavior and wave/particle interactions in the Earth's magnetosphere and radiation belts.

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