Synchronized Multiple Radio Telescope Microwave SETI

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Introduction

Background: August 2019 system and observation report [Ref. 1]

Radio Frequency Interference (RFI) is a confounding problem in radio SETI, as false positives are introduced into receiver signals. Various methods exist to attempt to excise suspected RFI, with a possibility that true positives are rejected, and that un-excised RFI remain as false positives. Uncertain far side-lobe antenna patterns add to the uncertainty. To ameliorate the RFI problem, a system having geographically-spaced simultaneous and synchronized pulse reception has been implemented. A radio telescope at the Green Bank Observatory in Green Bank, West Virginia has been combined with a radio telescope of the Deep Space Exploration Society, near Haswell, Colorado to implement a spatial filter having a thrice-Moon-distance transmitter rejection.

Approximately 135 hours of simultaneous synchronized pulse observations have been captured from November 2017 through February 2019. 45 additional hours were captured in April 2019. These observations are described in a paper presented August 4, 2019 at the annual conference of the Society of Amateur Radio Astronomers at the Green Bank Observatory. [Ref 1] The August 2019 paper describes anomalous simultaneous pulses observed in the pointing direction near HIP 24472, near 5.2 hours RA and -7.6° declination.

This paper describes further observations, conducted in December 2019, using three telescopes, and single telescope observations in February and March 2020.

Paper organization

This paper comprises excerpts of the paper presented in Green Bank in August 2019 [Ref. 1], to give background observations of simultaneous and associated pulses, particularly focusing on observations in the direction of 5.2 hours RA and -7.6° declination. Post-August 2019 observations are included in this paper. The slides in this paper are presented in chronological order of date of observation. Figure numbers retain the numbers used previously, and are therefore not consecutive in this paper.

Geographically-spaced Synchronized Signal Detection System

Transit scan observations at -7.6° declination using overlapping antenna beams

Time and frequency are synchronized using GPS.
Receivers: ≈ 1395-1455 MHz; 3.7 Hz Δf channels

New Hampshire 26 foot

*Telescope systems do **not** communicate with each other.*

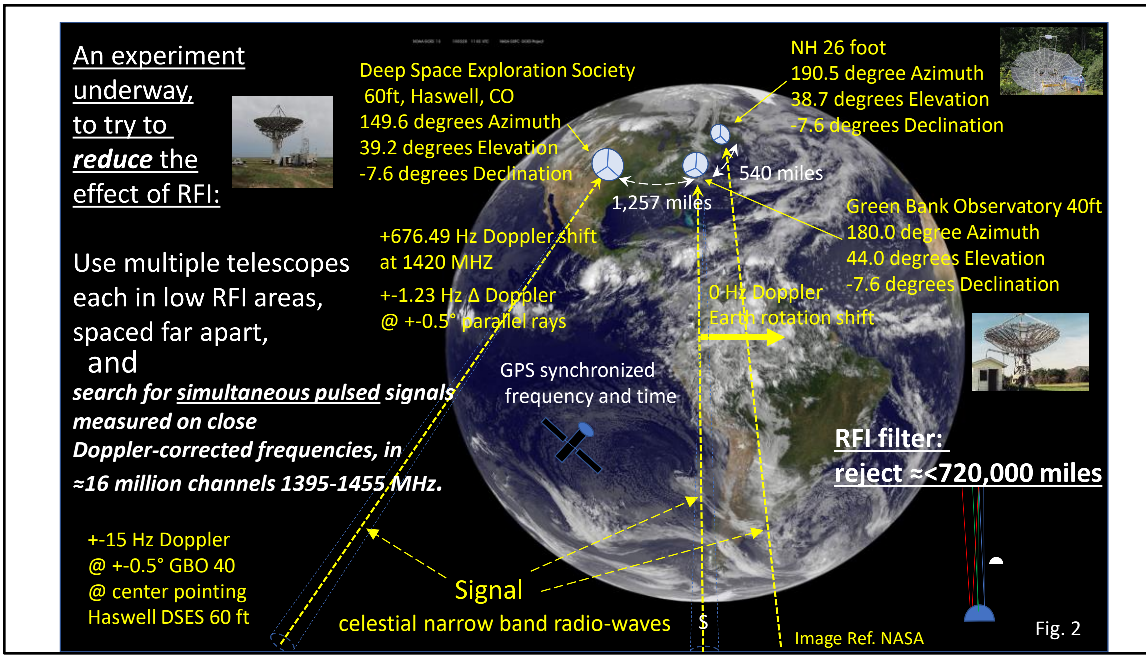
Haswell, Colorado 60 foot

Green Bank, West Virginia 40 foot

Fig. 1

Geographically-spaced Synchronized Signal Detection System (Fig. 1)
The synchronized telescope system currently comprises three telescopes. The New Hampshire telescope has orthogonal circular polarization receivers, Haswell has one circular polarization receiver, Green Bank has one linear polarized receiver. The telescopes operate independently during observations, i.e. are not networked and are not communicating with one another. Similar hardware and software operates at each telescope site. The GPS satellite constellation synchronizes frequency and time using locked ovenized crystal oscillators. Narrow bandwidth pulse measurement files are captured during observations, and post processed after observation runs are complete. Details of signal processing and RFI excision are included in the August 2019 SARA Green Bank paper [Ref. 1 Fig 2 text and Fig 17 text] All multi-telescope observations since late 2017 have been conducted when pointing to -7.6° declination, and transit scanning. The -7.6° declination was chosen primarily due to anomalies observed using two radio telescopes in New Hampshire, during several years of transit scans prior to 2017.

Automatic RFI excision has been added in December 2019 signal post-processing. 1 kHz bandwidth spectrum segments having an anomalously large number of bin hits are suspected to be RFI, and are excluded from post processing. Spectrum segments that contain the number of bin hits expected in noise are included in a post-processing search for simultaneous pulses. Other RFI excision methods are described in the August 2019 Green Bank paper. [Ref. 1 Figs 17,18 text].



Idea to help solve the RFI problem (Fig. 2)

Receiver spatial filtering may be assumed by the transmitting entity, leading to a method to make a transmitter known to a receiver, by intermittently transmitting spatial-**simultaneous** and time-**simultaneous** narrow bandwidth pulses, within an otherwise efficient and high capacity information stream. Additional characteristics of received signals, correlated to these simultaneous pulses, should ideally make the overall event likelihood low in noise, RFI, and natural object models, and support an ETI or distant RFI transmitter hypothesis.

Receiver antennas (Fig. 2) may be distantly spaced to search for simultaneous pulses of hypothetical celestial origin. In the current system, a 1,257 mile receive antenna spacing provides a 720,000 mile spatial filter, to counter local and near-space RFI. The spatial filtering distance is considerably farther than the distance to the two antennas' -3 dB beam overlap point, because Doppler shift within the antennas' beam-width gives space-based-RFI signals a frequency difference potentially greater than an FFT bin size. For example, there is a calculated +-15 Hz difference in Doppler-induced frequency shift for signals arriving across the Green Bank Forty Foot Telescope's -3 dB beam-width, e.g. when the two electromagnetic signal rays and antenna spacing baseline form a triangle, and therefore indicate signals from close-in space transmitters.

A -7.6° declination was chosen for three reasons:
1. declinations close to the celestial equator produce the highest number of unique antenna pointing directions when transit scanning, and increase volumetric search space,
2. the declination is below the Clarke Belt of satellites at North American latitudes, using narrow beam-width antennas, and
3. anomalous pulses were apparent at the -7.6° declination during a few years of transit scanning observation, using two co-located radio telescopes in New Hampshire.

Receiver bandwidth selection
The choice of a 3.73 Hz FFT bin bandwidth and the approximate 1400 to 1450 MHz range results from the processing tradeoffs of on-the-fly narrowband pulse signal detection and data storage using an SNR threshold. A celestial transmitter may transmit with different occupied bandwidths and pulse durations, to increase channel capacity. Signals that are guessed to be intended for ease of detectability likely have various pulse durations, to avoid a receiver-transmitter un-matched filter scenario. The 3.73 Hz bin bandwidth may be considered to be a matched filter to one set of potentially transmitted identification pulses, within a stream of communication signals.

The 1400 to 1450 MHz spectrum is chosen because it is a somewhat well-RFI-protected wide band of spectrum. Contiguous frequency coverage is prioritized in signal processing, over contiguous time, due to the need to identify CW and narrow bandwidth, potentially drifting RFI sources, within the chosen band. The pulse detection system initially operated at one-quarter duty cycle, at four second synchronously triggered intervals. Duty cycle was improved in April 2019 and again in March 2020, described below.

In observations starting in April 2019, we have used improved receiver systems, providing a range of approximately 1395 MHz to 1456 MHz and a one-third duty cycle. The following paragraphs describe the pre-April 2019 and the April 2019 processing systems.

Signal Processing

Signal processing was changed in the observations of April 2019. The following paragraph describes the pre-April 2019, with April 2019 and afterwards described in the next paragraph.

Four 0.27 s duration contiguous time uniform windows are each 2^25 point FFT-filtered and applied to a per-bin SNR threshold. A dwell time between measurements is required to allow GPS-sync'd time triggering of the two telescopes' intermediate frequency analog-to-digital converters. Local oscillator frequency is synchronized using OCXOs at each site, each locked to GPS signals. SNR thresholds are two-fold, at 11.2 dB per FFT bin and 12.0 dB 4x0.27s contiguous time average SNR, to reduce noise-induced false positives. The FFTW3 library is used. Intentionally transmitted signals are expected to often partially straddle adjacent and/or alternate time windows, thus allowing the 12.0 dB threshold to select and store these pulses and partially reject noise-induced pulses. The spectral noise values in SNR is measured in each 256 bin segment of the FFT output, averaged over four time samples. ADC sampling is at 125 MSPS. Sample clock offsets are periodically measured and corrected in post processing. Polarization is circular at Haswell and linear at Green Bank, resulting in a 3 dB maximum polarization match-to-mismatch, given random Poincare-Sphere transmitted polarization and site-differential Faraday rotation. Raw time domain data is not stored. The two telescopes' software systems do not communicate with each other, to avoid near-simultaneous software-event induced corruption of data.

In observations starting in April 2019, modified receiver systems have duty cycle increased from one-fourth to one-third, and dual ADCs' sampling rate reduced to 62.5 MSPS, using IQ down-conversion and a 1425.0 MHz local oscillator, locked through an OCXO to GPS signals. Complex input to complex output FFTs are performed using FFTW3. SNR thresholds were decreased to 11.0 dB per FFT bin and 11.8 dB composite multi-time slot SNR. Cycle time was reduced to three seconds, compared to four seconds in pre-April 2019 observations. Duty cycle was further increased to two-thirds in March 2020. Construction is underway to obtain 100% pulse detection duty cycle, planned to begin in April 2020.

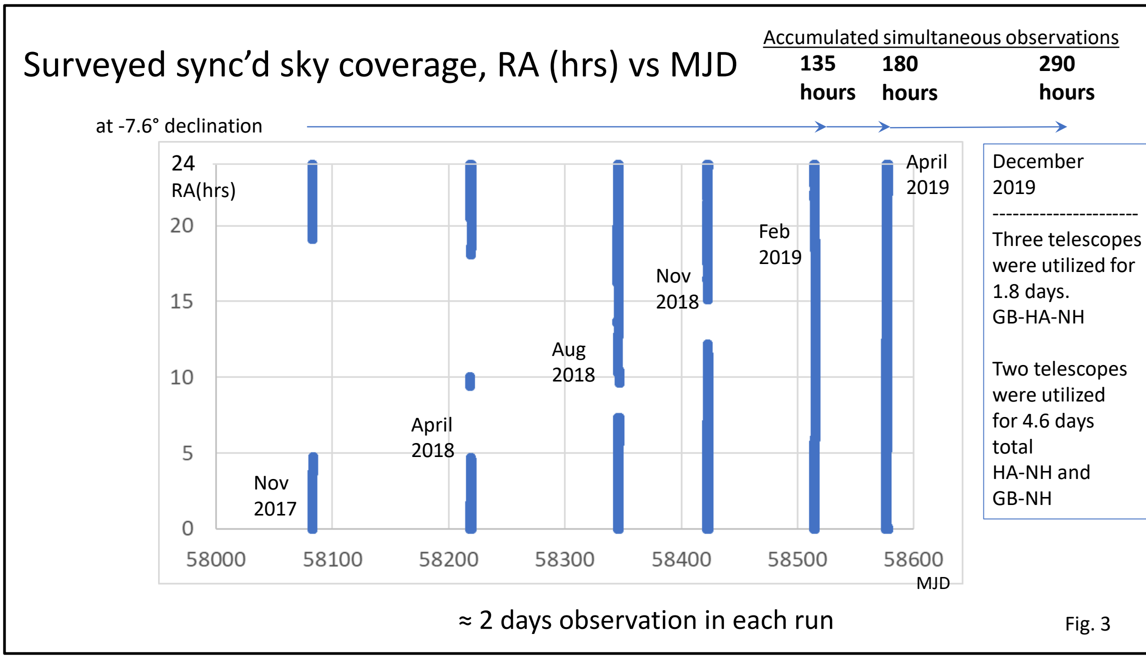


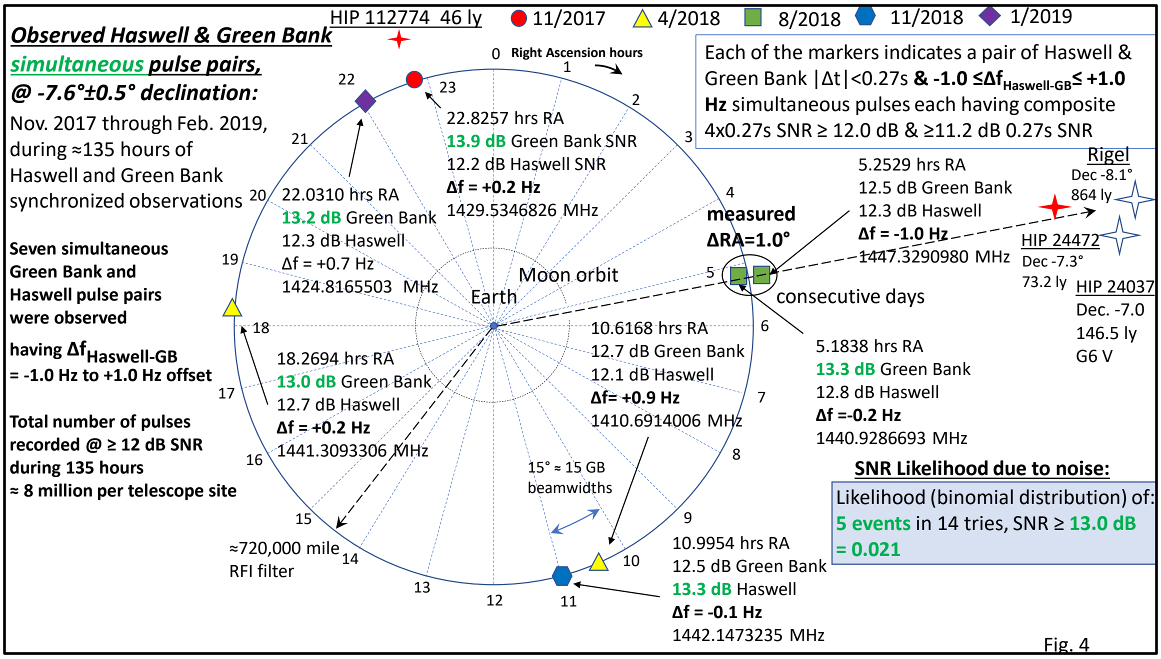
Fig. 3

Sky coverage during simultaneous Green Bank and Haswell observations (Fig. 3)

Fig. 3 is a plot of Right Ascension coverage at -7.6°declination, during simultaneous two-telescope and three-telescope observations.

Descriptions of observations in this paper describe events observed during the initial 135 hours, events observed during an additional 45 hours in April 2019, December 2019 three-telescope events, and single telescope observations in 2020.

November 2017 – February 2019
Green Bank and Haswell observations



Summary of anomalous simultaneous pulses observed during 135 hours (Fig. 4)

The plot in Fig. 4, of an Earth distant view, indicates the occurrences of low site-to-site frequency offset, simultaneous (in overlapping 0.27 s intervals) narrow bandwidth pulses, observed during 135 hours of observation from November 2017 to February 2019. The telescope pointing Right Ascension of pulses are shown that have Haswell to Green Bank offset frequency in the -1.0 to +1.0 Hz range, after Doppler correction, in an FFT bin bandwidth of 3.73 Hz, 1405-1448 MHz, at -7.6° declination. The outer circle represents the approximate expected closest distance to a transmitting source that is subjected to the 1,257 mile antenna-spacing RFI spatial filter.

Two of the seven simultaneous pulses repeated on consecutive days within 1.0 degree of sky pointing angle, near the pointing direction of Rigel, HIP 24472 and HIP 24037.

The signal to noise ratios of five of the fourteen pulses (≥ 13.0 dB) appear to be anomalous, (binomial noise Pr. 0.021), considering a Rayleigh amplitude, exponential power, noise-caused hypothesis, after suspected RFI excision.

Five simultaneous pulses are expected in 135 hours, on average due to noise, in a ±1 Hz offset range, based on an analysis of a large Doppler offset range, derived while assuming that almost all simultaneous pulses in a larger Doppler offset range are due to noise. Therefore, it is thought at least some of the seven simultaneous pulses observed are likely due to noise.

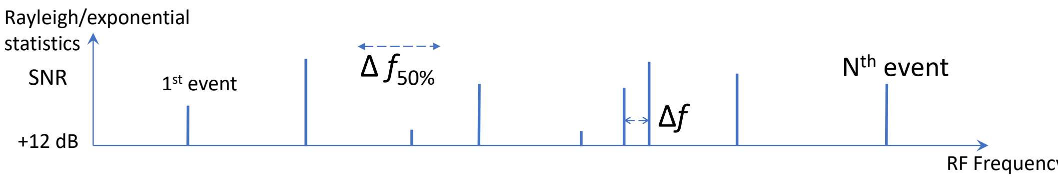
The repetition of a transmitting signal, observed at a single celestial pointing direction, is unexpected from a near-space transmitter, as the transmitter is affected by the Sun-Earth-Moon gravity wells and needs thrust to retain close to the same celestial pointing direction during the period of a day. Such a celestial-station-keeping thrusting system would not naturally be expected in a human-built transmitter. RFI modeling is underway to quantify this idea.

The anomalous 13.9 dB SNR, 0.2 Hz offset, simultaneous pulse at RA 22.8257 hours corresponds to a pointing direction estimated towards HIP 112774 on 11/25/2017. Numerous simultaneous, associated and other pulse events observed in this pointing direction, during five days of transits, are described in a presentation given at the SARA 2018 Annual Conference in Green Bank.

After the August 2018 observation of the close-RA anomaly at 5.25 hours RA, post processing work has primarily focused on comparing observations of this pointing direction with others.

Likelihood of close-spectral tones, due to noise

Transmitted Signal Detectability in noise, during one time interval,
is a function of: frequency spacing, Signal to Noise Ratio



Determine median spacing: $\Delta f_{50\%}$; i.e. 50% of Δf*'s are* $< \Delta f_{50\%}$, due to noise

$$Noise\ Likelihood(\Delta f) = 1 - e^{-\ln(2)\ \Delta f/\Delta f_{50\%}}$$

$$Noise\ Likelihood(\Delta f) \approx \ln(2)\ \Delta f/\Delta f_{50\%} \quad \text{if } \Delta f/\Delta f_{50\%} \ll 1$$

$$Noise\ Likelihood\ within\ N\ events\ \approx N\ \ln(2)\ \Delta f/\Delta f_{50\%} \quad \text{if } N\,\Delta f/\Delta f_{50\%} \ll 1$$

Fig. 6

Likelihood of close-frequency spaced tones due to noise (Fig. 6)
Figure 6 describes a method of calculating the likelihood of close frequency spaced tones in Additive White Gaussian Noise (AGWN), assuming Poisson statistics apply. The measurement of low probability pulse pairs, given a noise cause, or, alternatively, readily identifiable received communication signals, compels the calculation.

Pulses observed at one telescope, temporally, spectrally and/or spatially correlated with a multi-telescope simultaneous pulse, are called associated pulses. The general idea is to look for anomalous events at each telescope that seem to occur, at or close to, the time and frequency of geographically spaced multiple telescope simultaneous events.

Poisson events occur randomly with a Uniform Distribution within a given interval. The number of events expected in the given interval then follows the Poisson Distribution, having a rate parameter. The spacing between events in a Poisson process follows an Exponential Distribution. This property results due to the proportionality between the expected rate of event occurrence and the expected quantity of events. A derivation yields the ln 2 = 0.693 factor in the exponent. At low event spacing, the relationship may be simplified to be minus the exponent. The likelihood of a single close-spaced event observed within a stream of multiple events is estimated to be the product of the individual Poisson event likelihood and the number of event pairs within the stream.

This estimate is useful when calculating the likelihood that a noise model might explain pulses that otherwise might be explained as identification signals in a transmitted signal, an RFI mechanism, equipment faults, natural signals and other models subjected to inference attempts.

A separate calculation determines the noise-caused likelihood of a pulse event given the pulsed signal's SNR, using a Rayleigh-induced exponential distribution of signal power in SNR. The likelihood of the combination of low frequency offset and high SNR may then be considered together, in inferences confirming the accuracy of predictions of certain models in explaining the observed data.

Green Bank *associated* pulses

Within ± 8.25s of time of frequency offset = -1.0 Hz ***simultaneous*** 5.2529 hrs RA-pointing Haswell & Green Bank pulse

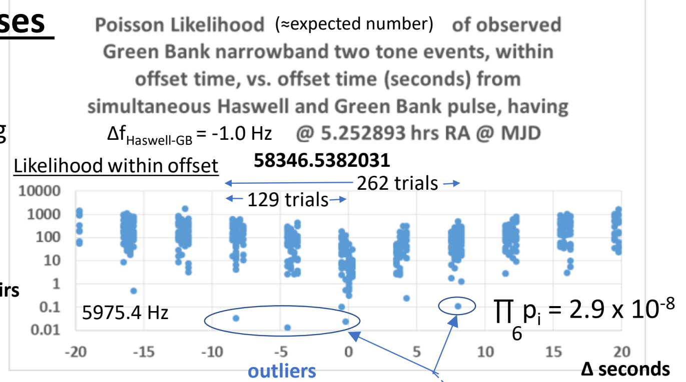
Likelihood Estimate

Tone spacing Rank in file
339 Hz: 15/174,033
607 Hz: 29/174,033
2700.8 Hz: 139/174,033 =0.000799

Δtime /file duration
8s / 10,800s = 0.00074
i.e. **129 trials of tone pairs**
2794.0 Hz: 149/174,033 =0.000856

Binomial distribution
(3 seen,129 trials, pr. 0.000799)
=0.00016

Binomial distribution
(4 seen,262 trials, pr. 0.000856)
= 8.26x 10^{-5}



Offset time	RF Freq.	cSNR	Tone spacing	Event Likelihood	Event Likelihood within offset time
-8.25 s	1427.1206200 MHz	12.739 dB	607.2 Hz	0.000216	**0.0330**
-4.50 s	1429.6278708 MHz	12.596 dB	339.0 Hz	0.000120	**0.0128**
-0.50 s	1429.7780670 MHz	12.681 dB	5971.6 Hz	0.002120	0.1039
-0.25 s	1439.3661335 MHz	12.451 dB	2700.8 Hz	0.000959	**0.0240**
4.25 s	1430.8780819 MHz	12.682 dB	11153.5 Hz	0.003960	0.2416
8.00 s	1447.7421694 MHz	12 dB	2794.0 Hz	0.000992	0.1121

Fig. 7

Anomalous associated pulses are observed (Fig. 7)

A set of four two-tone pairs appear to exhibit the properties one might expect of pulses that are associated with a simultaneous pulse:

1. the observed four two-tone pulses are calculated to be rarely observed (Pr. 8.26x10^{-5}) in random noise,
2. due to a apparent absence of symbol symmetry and/or repetition in the tones, the associated pulses appear to contain a moderate Shannon Entropy, indicating the potential of high information content,
3. the associated pulses occur close in time to the simultaneous pulse, indicating that a noise-caused hypothesis of simultaneous and associated tones may be refuted to a high likelihood,
4. the associated tones described above were not observed in Haswell data,
5. the rank of increasing-value-sorted tone spacing in a four hour duration file was used to estimate close tone likelihoods, after CW and narrowband RFI was excised, implying that un-excised broadband pulsed RFI is unlikely to adequately explain the near-simultaneity of the associated and simultaneous pulses. If multi-tone pulsed RFI is commonly present in the four hour data file, the measured rank of the close-spaced tones would indicate its presence, i.e. as a large number of close-tone outliers. These outliers were not observed.

A relationship between highly anomalous associated pulses and one of the two near-Rigel-pointing simultaneous pulses (described in Fig. 4) appears evident. Simultaneous ±1.0 Hz offset pulses occur randomly due to noise, on average, at approximately twenty-seven hour intervals, while a highly unlikely multi-tone event (Pr. 8.26×10^{-5} in seventeen seconds) occurred at Green Bank, i.e. within ±8.25 s of the simultaneous Haswell-Green Bank pulse. The simultaneous and associated pulse events therefore appear to be time-correlated.

The four close-tone pairs' noise likelihood of 8.26×10^{-5} is calculated using the binomial distribution and a common individual event probability, based on the noise-likelihood of the 2794.0 Hz tone spacing. The expected composite multi-tone likelihood value is significantly lower than the calculated composite likelihood, due to the unlikely presence of the closer tone spacing pairs, at 607.2 and 339.0 Hz, given the same probability as the 2794.0 Hz tone pair. During system validation, a comparison of post-RFI-excision tone spacing likelihood, in sky data, to the calculated probability of noise-induced Poisson close tone spacing, has been examined, with close match of sky noise to theory. Evidence of time-correlated two-tone bursting signals does not appear within the files examined for such anomalies, except for the anomalies described near RA 5.25, and anomalies expected due to a noise model.

Further analysis is required, and potential equipment issues and assumptions need to be questioned, as a multi-tone transmit-receive mechanism using simultaneous and associated pulses appears to be present in the observed data, implying a powerful signal identification and RFI amelioration mechanism might exist.

April 2019
Green Bank and Haswell observations

April 2, 2019 simultaneous pulse $\Delta f_{Haswell\text{-}GB}$ = -5.8 Hz at Green Bank and Haswell (a third simultaneous pulse @ ≈5.25 hrs RA)

130 simultaneous pulse pairs were observed in April 2019 with measured |Δf| < 7500 Hz having a target RA 5.181 to 5.271 hours.

Likelihood of target RA, April 2019, simultaneous pulse measuring |Δf| < 5.8 Hz = 0.101

≈Rigel & HIP 24472 pointing Δf = -5.8 Hz

Green Bank

ϕ.site	MJD	pre-Doppler Freq. (MHz)	SNR_1 (dB)	SNR_2	SNR_3	SNR_4	comp.SNR	**Δfreq(Hz)**	RA (hrs)
1.1	58575.91094040	1395.0271226	11.198	2.136	6.514	-1.616	**12.854**	**-5.8**	5.2706305
1.2	58575.91094040	1395.0278081	11.156	-1.193	2.368	-7.062	11.913	**-5.8**	5.2706305

Haswell

7th highest SNR GB pulse, of 130 GB pulses
Noise Likelihood of SNR and Δf: **0.0108**, GB and Haswell

Are there pulses associated with these simultaneous pulse elements?

Fig. 8

April 2, 2019 Simultaneous Pulse Observations (Fig. 8)

A simultaneous Haswell-Green Bank pulse was observed on April 2, 2019 while pointing approximately at the Right Ascension of Rigel. This third approximate Rigel-pointing simultaneous pulse has an estimated likelihood of occurring, assuming measured sky data adheres to a Gaussian noise model, during an RA sweep through the target pointing direction, in April 2019 observations, of 0.101. The higher than expected SNR of the Green Bank pulse reduces the likelihood of the pulse due to a Gaussian noise model, having Rayleigh amplitude statistics, to 0.0054 for Green Bank pulses and 0.0108 considering both Haswell and Green Bank pulses. The Gaussian noise model is therefore thought to be unlikely to explain this third pulse. The April, 2019 simultaneous pulse is moderately rare in noise, when considered in isolation. Non-isolated considerations, including associated pulses occurring during the same time sample window, are discussed further in this paper.

The Rigel direction was scanned a total of eight times during the full Nov. 2017 through April 2019 observations, twice each in 8/2018, 11/2018, 1/2019 and 4/2019. SNR thresholds were lowered by 0.2 dB in April 2019 observations, resulting in a higher number of April 2019 simultaneous pulses in the data, all else equal.

Estimate of likelihood of simultaneous pulses given RFI and ETI models depends on assumptions about signal transmitter duty cycle.

The difference in Haswell and Green Bank measured RF frequency in the observed pulse is -5.8 Hz, a significantly higher magnitude offset than expected, given residual frequency offset measurement noise, and modeled pointing direction Doppler offsets. Normally, such a result would be rejected from further consideration. However, there are several partial unknowns in the experimental system, as the system compares the Likelihoods of multiple models, each within multiple hypotheses:

1. A variation in received GPS satellite constellations, and/or geometric quality, might induce a rare and momentary shift in short term GPS-locked OCXO frequency, in the range of ±10 Hz.

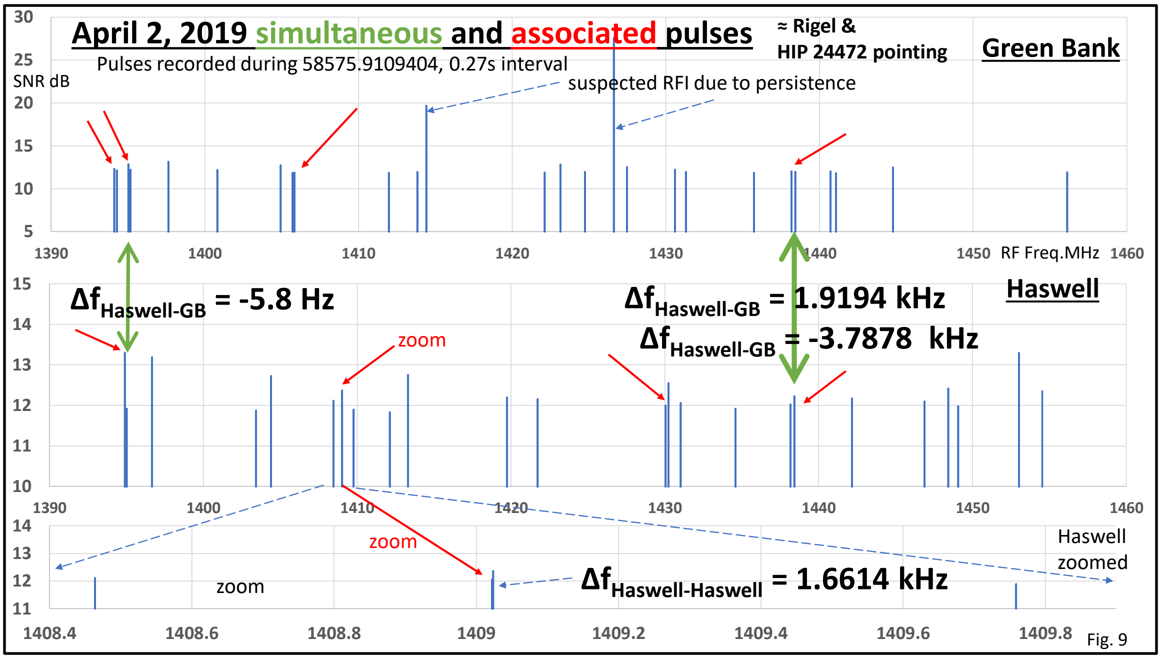
2. Observations, Shannon's Law, and transmitter speculation contributes to the idea that a high channel capacity communication system need not transmit geographically spaced simultaneous pulses on exactly the same frequency. Near zero offset frequency is as readily detectable as zero offset. Geographically spaced received signals are not unreasonable to consider if large phased arrays are speculated to be used in the celestial transmitting system.

3. Doppler offset of near-Earth space-based RFI may be present, assuming that the signal's propagation directions fall within the two antennas' approximate beam-widths.

4. The anomalous pulses may be due to noise, compelling further analysis to find a potential false positive.

The pre-Doppler frequency values in the table are data produced by the pulse capture systems before site-differential sample clock offset and Doppler-induced corrections were included in post-processing software.

A non-noise model's statistical significance of this third simultaneous pulse at 5.25 hour RA depends on a presence of associated pulses, analyzed in the next section.



Graphical summary of simultaneous and associated pulses observed during Rigel & HIP 24472 transit of April 2, 2019 (Fig. 9)

Fig. 9 is a graphical representation of the simultaneous and associated pulses observed on April 2, 2019 at Haswell and Green Bank. Details of these pulses are contained in the SARA Green Bank August 2019 paper. [Ref. 1 Figs. 14 and 15 and text]

All of the spectra in Fig. 9 are of signals received in the same 0.27 s FFT window as the simultaneous pulse.

The red pointers indicate anomalous close frequency spaced tone sets, individually observed on each telescope.

Two close-frequency-spaced tone sets occur near in frequency to the frequency of the simultaneous pulse. Another Green Bank tone set is close to a tone set at Haswell.

Threshold-exceeding pulses, in a Gaussian noise model, adhering to Poisson process statistics, are expected to be separated in frequency by approximately 2.3 MHz in

April 2019 files, estimated by examining the 58577.166678 MJD Green Bank sky data file, after excising suspected RFI, based on time persistence on a frequency, while having higher than expected SNR. Examination of the aggregate of pulses in the file do not show a significant tail at low frequency spacings.

Numerous pulses observed in the 0.27 s sample interval, associated with simultaneous Haswell and Green Bank pulses, have frequency spacing significantly less than the 2.3 MHz frequency spacing expected in a white Gaussian noise model.

The presence of multiple pulses at Haswell and Green Bank, having low intra- and inter-telescope frequency offset, appears anomalous.

The observations, contrary to predictions, compel additional observations, analysis and tests of various signal models and potential equipment issues.

December 2019
Green Bank, Haswell and New Hampshire

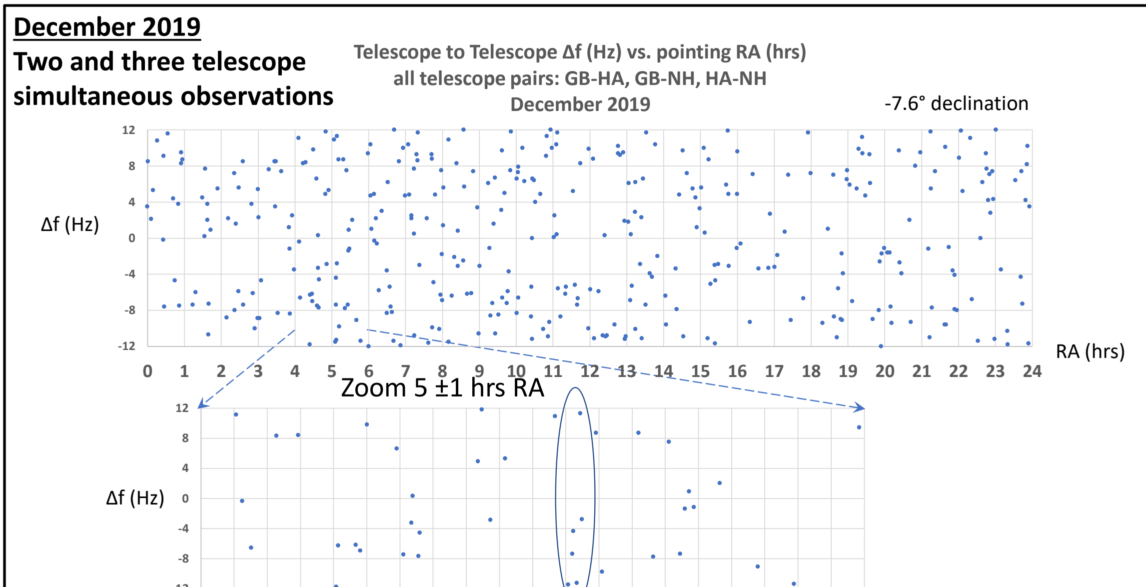


Fig. 10

Anomalous number of simultaneous pulses in the approximate target pointing direction (Fig. 10)

An RA pointing direction of approximately 5.2 hours, at a declination of -7.6° appears, in past work, to be related to anomalous indications of simultaneous pulses at two distant synchronized radio telescopes. Details of three anomalous simultaneous pulses and associated pulses are described in this paper and in more detail in the August, 2019 presentation at the Green Bank SARA 2019 Annual Conference [Ref. 1 Figs. 5-18].

Observations in December 2019 indicate statistically significant anomalous pulses in approximately the same pointing direction, i.e. approximately 5.2 hrs RA and -7.6° declination, pointing.

The plot in Figure 10 captures the simultaneous pulses within ±12 Hz at each telescope pair, after accounting for site-to-site Doppler shift and receiver metrology. ±12 Hz is chosen as a search limit due to estimated metrology residuals and other reasons, explained as follows. In post processing, limiting the simultaneous pulse Δf search range to an overly low value can create a tendency to overlook important experimental aspects and unknowns, e.g. Doppler calculation errors, GPS constellation induced offsets, RFI mechanisms, and transmitted communication signals intentionally offset in frequency, spatially, to increase Shannon channel capacity. The details of the latter process, multibeam phased array MIMO, (Multiple In – Multiple Out) are described in the August 2019 Green Bank paper. [Ref. 1 Fig 22a text describing multiple transmit and receive antennas in modern communication systems].

Δf within ±12 Hz is chosen in this present work to balance experimental and hypothetical source uncertainties with the unavoidable increase in calculated likelihood of events in noise. Further, a wider frequency offset search range is helpful to search for anomalies among differing data populations using statistical methods, e,g, Cohen's d analysis, [Ref 1 Fig. 7].

An RA region in the vicinity of 5.2 hours RA, within the full RA range, is isolated, as a prior, to examine data for anomalous events, due the RA region's apparent significance in prior simultaneous pulse observations., e.g. August 2018 and April 2019. [Ref 1] Statistical significance calculations are simplified if such a prior is used to limit analysis to a closely examined data set. Measurements of this RA range, compared to others, are further detailed below.

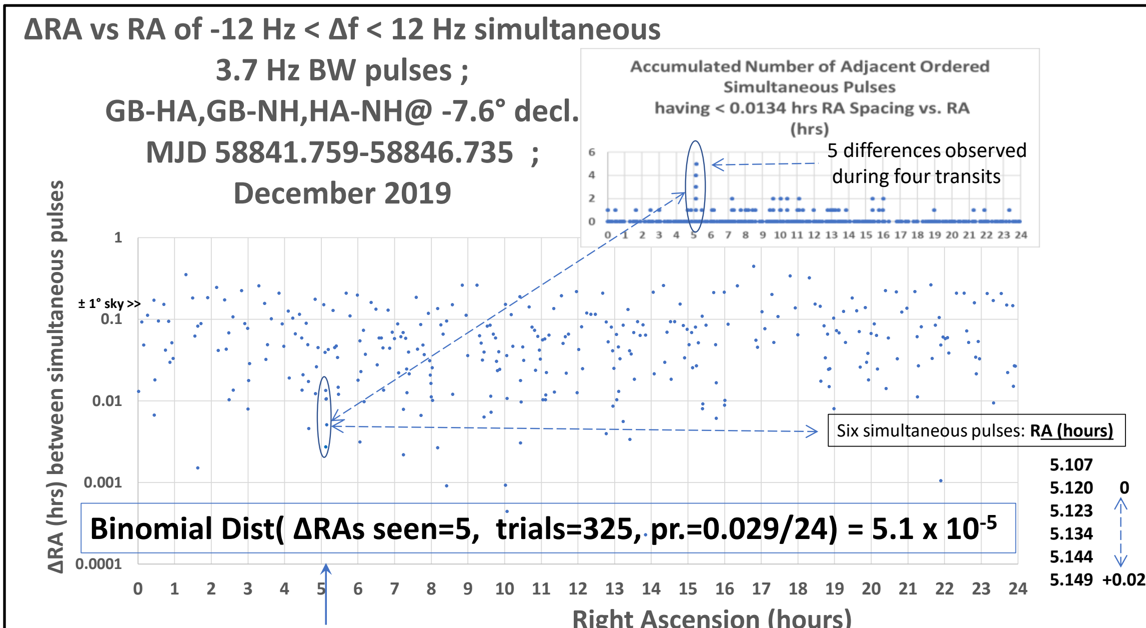


Fig. 11

Simultaneous pulses observed near the 5.2 hours RA pointing direction (Fig. 11)

Six anomalous simultaneous pulses were observed in the approximate prior established pointing direction, among 325 candidate simultaneous pulses observed over all RAs during the December 2019 observation run. These six simultaneous pulses add to the three anomalous Green Bank-Haswell pulses observed in prior observations, two simultaneous pulses in August 2018 and one simultaneous pulse in April 2019. [Ref 1].

An assumption is made that close-time spaced pulses are significant to study. Reasoning implies that intermittent communication, bursted noise, or an RFI source may transmit pulses that have spectral components primarily restricted to a relatively low event time spacing. Given this assumption, the difference in recorded RA of increasingly ordered RA values is plotted against RA. A sub-diagram in Figure 3 bins the number of simultaneous pulse low RA differences captured, on the three pairs of telescopes, within a particular RA range of pointing, versus RA. The RA window for likelihood calculations, i.e. 0.029 hours, is approximately one half beamwidth of the Green Bank and Haswell telescope antennas. The New Hampshire beam-width has been measured to overlap the Green Bank and Haswell patterns, using supernova remnant NRAO5690 as a celestial test source.

An apparently anomalously low RA-spaced set of six simultaneous pulses, having five RA differences, appear to be present in the plotted post-processed data. The number of simultaneous pulses observed per telescope pair is GB-HA(2), GB-NH(3), HA-NH(1). Based on the average occurrence of close RA-spaced simultaneous pulses in other pointing directions, it is estimated that one of the six simultaneous pulses might be due to noise.

The five pulses following the first pulse at 5.107 hrs RA, increasing in value ordered in RA, have a binomial distribution in noise likelihood, of presence in one of 828 RA bins, at 5.1 in 100,000 tries of multi-day assays, each assay having approximately 325 simultaneous pulses, i.e. the number observed in December 2019. The 828 RA bins are established from the observed close RA spacing of the first and last of the five RA-ordered simultaneous pulses at RA values above the 5.107 hrs RA pulse, i.e. 0.029 hours, with RA bin = 24 hrs/828. The chosen bin near 5.2 hrs is a statistically significant prior due to previous observations in the approximate pointing direction of 5.2 hours. Uncertainty in the significant pointing direction by a factor of 3, i.e. 3 of 828 bins, increases the noise likelihood of the five pulse event to 1.5 in 10,000 experiment assays.

Are simultaneous pulses observable using <u>one</u> telescope?

Post-process New Hampshire radio telescope **orthogonal circularly-polarized pulses**, looking for close frequency offsets between polarized signals.

Transits were observed
during Feb 20, 2020 to March 11, 2020

Rationale

It is expected that linear and elliptical polarized signals will produce simultaneous pulse indications on orthogonal circular polarized signal receivers. Such a response should be observed at close to zero frequency offset between the receivers.

If an offset frequency significantly different than zero Hz is measured between circular polarizations, it is possible that a transmitted signal contains distinct signal components on the two polarizations. This type of transmitter-receiver polarized signal system may be used to increase the communication channel capacity, given a Shannon-limited energy-per-bit per spectral noise power channel, all else equal. It therefore seems reasonable to consider the existence of polarization frequency offsets, in simultaneous pulses, and search for them.

The post processing software that searches for multiple telescope simultaneous pulses may be utilized to search for simultaneous orthogonal polarization frequency offset pulses.

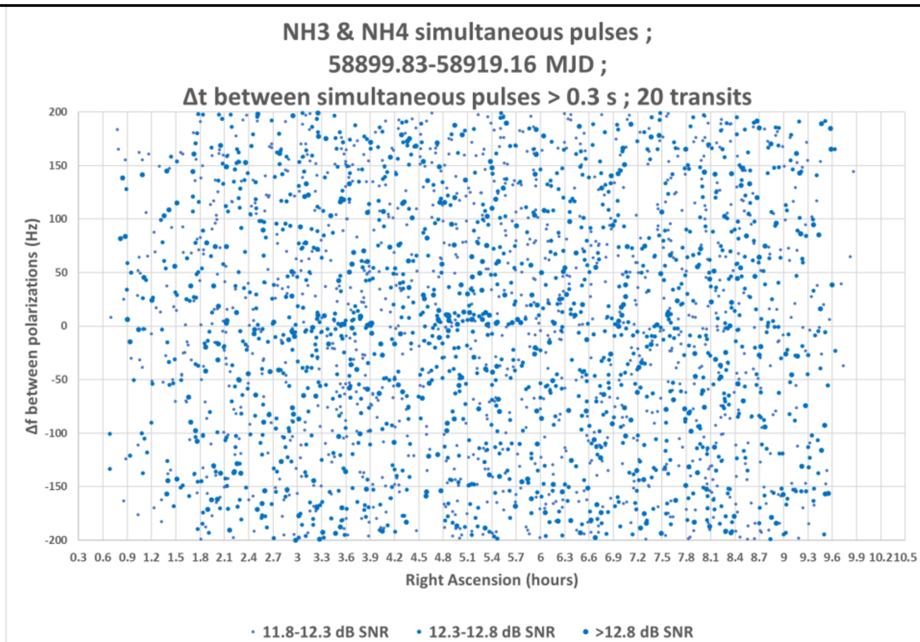


Fig. 15

Simultaneous pulses after twenty transits of the New Hampshire telescope at -7.6° declination

An experiment was performed to see if anomalies exist when looking for simultaneous pulses on orthogonal circular polarizations. The New Hampshire telescope was utilized, continuously running 0 to 24 hours RA transit scans at -7.6° declination. The plot in Fig. 15 records the frequency spacing between orthogonal circular polarizations of pulses exceeding various SNR thresholds, over the ± 4 hour range around the prior significant RA, i.e. 5.25 hours. Larger points indicate higher SNRs.

An apparently anomalous set of pulses appear to be present in the 0 to +15 Hz frequency offset range, in the RA window of 5.1 to 5.4 hours, corresponding to the approximate -3 dB beam-width of the antenna. The 4.8 to 5.1 hour RA window also appears to indicate significant anomalies. Observations and analysis are underway to determine the significance and repeatability of these events.

An RFI filter was added in post processing to reject simultaneous pulses that occur in adjacent time intervals, 0.27 seconds apart, i.e. the FFT capture time, the inverse of the matched filter bandwidth of 3.7 Hz. Some RFI tends to be persistent in time, and can be filtered in this way. This RFI filter was utilized in the plot of Fig. 15.

The use of various filters complicates the calculation of statistical significance, as filters can reject false positives incompletely, leaving apparent positives. The resulting decreased probability of data validity and model validity confounds attempts to use Bayesian Inference to establish that the observed data is explained by one model to a higher Likelihood than another model. Various RFI filter methods are being envisaged and tried, given this consideration.

Conclusions:
Observed anomalies compel further observations, and multiple hypothesis development and testing.

Noise hypothesis appears unlikely to explain data.

Plans:
Fourth and fifth low-RFI telescopes,
≈28 foot diameter,
dual polarization, are under construction.

Plan three synchronized telescopes operating 24/7 in 2020.

Produce RFI models
Try to refute RFI-cause hypothesis.
Seek satellite experts' gleanings.

Encourage others* *to try simultaneous multi-telescope radio SETI experiments.

Fig. 16

Conclusion
The observed anomalies compel further observations. A known noise hypothesis, e.g. Additive White Gaussian Noise (AWGN), explaining the 5.25 hour RA -7.6° declination anomalies, appears unlikely to explain the observations. In Bayesian Inference, [Ref. 1, Fig 21], assuming high probability that experimental data is valid, and assuming high probability that the AWGN noise and Poisson process models are valid in the experiment, the AWGN noise model's calculated probability as an explanation, i.e. a Bayesian likelihood given December 2019, earlier observations and noise model validity, tends to refute the AWGN noise model's explanation as a cause of the observed anomalous simultaneous and associated pulses. Further work is required to refine the conclusion regarding the AWGN hypothesis. Further work is required to study likelihoods of each explanatory model grouped within various hypotheses.

Improvements underway (Fig. 16)
Improvements are underway to enhance the statistical significance of observations that provide detail to the models needed in Bayesian Inference hypothesis selection.

Further work
Additional observations are underway to seek and refute various hypotheses, e.g. RFI,

noise, natural object, ETI, equipment, using Bayesian Inference calculations. Two additional approximate 28 foot diameter antennas are under construction, planned to be operated continuously, and synchronized with the New Hampshire 26 foot antenna. One of the two antennas under construction is being designed to be transported and operated almost continuously. Another is planned to be located at, or relatively near, the New Hampshire telescope site, and operated almost continuously, together with the current New Hampshire telescope. In mid-March 2020 the duty cycle of FFT captures was increased from 33% to 66%. Plans are underway to increase duty cycle to 100% at New Hampshire. Telescopes at Green Bank and Haswell will be utilized to produce up to a five simultaneous synchronized antenna system, when observation time on the Haswell and Green Bank telescopes is available. Metrology, the use of different telescopes by other groups, improved system hardware and software, and seeking independent post processing of raw telescope data are additional tasks underway.

References:

1. Details of the synchronized telescope SETI project and observations are in a paper presented in August 2019, in Green Bank, West Virginia:
http://dses.science/wp-content/uploads/2019/08/SARA_2019_GreenBank_Crilly_73_f.pdf

2. Close frequency tones observed and described in Fig. 9 of the August 2019 paper are played in the following WAV file:
http://dses.science/wp-content/uploads/2019/02/Fig_7_tones.wav

3. The Deep Space Exploration Society Publications page is:
http://dses.science/deep-space-exploration-society/dses-publications

Thank you!

Thank you

Steve Plock

Deep Space Exploration Society team

Green Bank Observatory team

family and friends

Questions?