

The InSight Recovery Campaign Utilizing Novel Detection Techniques

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Abstract

The National Aeronautics and Space Administration's (NASA) Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission operated a set of seismology and geophysics instruments on the surface of Mars from its arrival on 26 November 2018 until its last communication with Earth on 15 December 2022. NASA declared the mission concluded after its power generation system was severely degraded by windblown dust accumulation on its solar panels. A small team of researchers at NASA's Jet Propulsion Laboratory (JPL) was tasked to continue to listen for a signal from the lander in case Martian winds should happen to sufficiently clean the solar panels, restoring some power to the spacecraft. This recovery campaign, lasting roughly two years since the last successful communication with InSight, was conducted daily using Deep Space Network (DSN) telecommunication passes with other NASA and European Space Agency (ESA) landers and orbiters at Mars. During these passes, the DSN's Open Loop Receivers recorded a wide radio frequency band around the nominal carrier frequency of the spacecraft. The recorded data were then routinely analysed for the presence of a potential signal in case the spacecraft had regained sufficient power. In addition to standard power spectral analysis of the radio frequency spectrum, spectral kurtosis is used as a more sensitive way to search for the presence of a putative telecommunication signal in the datasets. Spectral kurtosis, as demonstrated previously in multiple disciplines, provides a powerful metric for detection of non-Gaussianity, and therefore telecommunication signals in noisy datasets. In this paper, we provide an overview of the InSight recovery campaign, the methodology for data collection and rapid analysis, and the latest results from this campaign, including the use of spectral kurtosis to search for weak telecommunication signals from the lander.

Keywords: InSight, Mars, Spectral Kurtosis, Deep Space Network, Open Loop Receiver, Radio Frequency Interference

Acronyms/Abbreviations

dB – decibel

DFT – Discrete Fourier Transform

DSN – Deep Space Network

DSS – Deep Space Station

DTT - Downlink Tracking and Telemetry

EMM – Emirates Mars Mission

ESA – European Space Agency

FFT - Fast-Fourier Transform

FTS - Fixed Time Step

HiRISE - High-Resolution Imaging Science Experiment

Hz - Hertz

I – In-Phase

IF – Intermediate Frequency

InSight - Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

JPL - Jet Propulsion Laboratory

KHz - Kilohertz

M20 -Mars 2020 (Perseverance)

MAVEN - Mars Atmosphere and Volatile Evolution

MEX - Mars Express

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MHz - Megahertz
MOM – Mars Orbiter Mission (Hope)
MRO - Mars Reconnaissance Orbiter
MSL – Mars Science Lander (Curiosity)
MSPA - Multiple Spacecraft Per Aperture
NASA – National Aeronautics and Space Administration
NSYT - InSight
ODY - Mars 2001 Odyssey
OLR – Open Loop Receiver
PLL - Phase-Locked Loop
Q - Quadrature Phase
RF - Radio Frequency
RFI - Radio Frequency Interference
RISE - Rotation and Interior Structure Experiment
SK – Spectral Kurtosis
SNR - Signal-to-Noise Ratio
SPICE - Spacecraft, Planet, Instrument, C-matrix, Events
TGO - Trace Gas Orbiter
UHF - Ultra-High Frequency
UTC – Coordinated Universal Time

1. Introduction

The stationary lander Mars InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) (Figure 1) touched down on Mars on 26 November 2018, with a mission to study the geological history and composition of Mars. Located in the western part of Elysium Planitia at 4.5° north latitude and 135.9° east longitude, some of the mission's major accomplishments were detection and analysis of marsquakes caused by meteoroid impacts, measurement of the size and composition of the Martian core, mapping of the Martian crustal thickness, and measuring the heat flow escaping from the planet's interior. The Rotation and Interior Structure Experiment (RISE) utilized the X-Band telecom system to compute the precession [1] and nutation [2] of the Mars polar axis by measuring the Doppler shift of the radio signal sent to Earth via two medium gain antennas oriented at relatively low angles on the horizon in the eastern and western directions [3]. As the mission progressed, windblown dust gradually accumulated on the lander's solar panels, reducing available power to the vehicle. Time lapse images taken by Mars Reconnaissance Orbiter's High-Resolution Imaging Science Experiment (HiRISE) camera show progressive

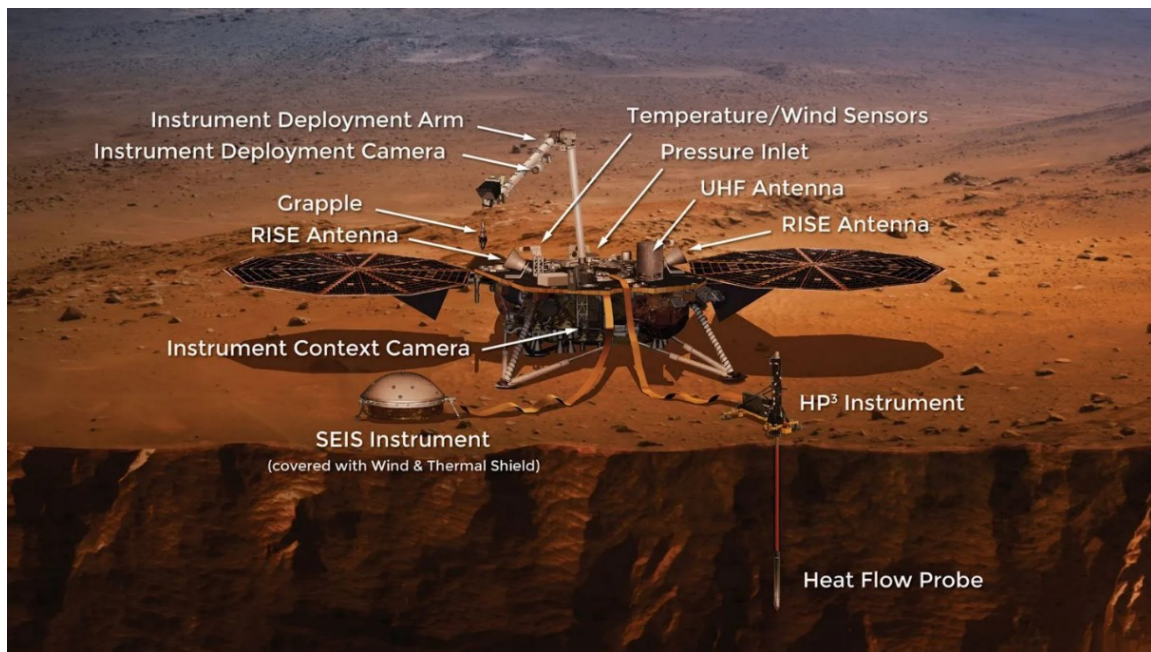


Figure 1. Artist's Concept of InSight Lander on Mars. NASA/JPL-Caltech

accumulation of dust over the course of the mission (Figure 2) [4]. In Figures 2a, 2b, and 2c, up through at least 23 November 2020, sunlight can be seen glinting off the solar panels. By 16 December 2021 (Figure 2d), dust accumulation is evident. In that time frame, various science instruments were powered down in order to save energy, including the RISE instrument, with the last X-Band transmission occurring on 27 May 2022. By 29 November 2022 (Figure 2e), dust accumulation is prevalent, with power to receive any further communications (via relays with Mars orbiters) being completely lost and the official end of mission being declared on 15 December 2022.

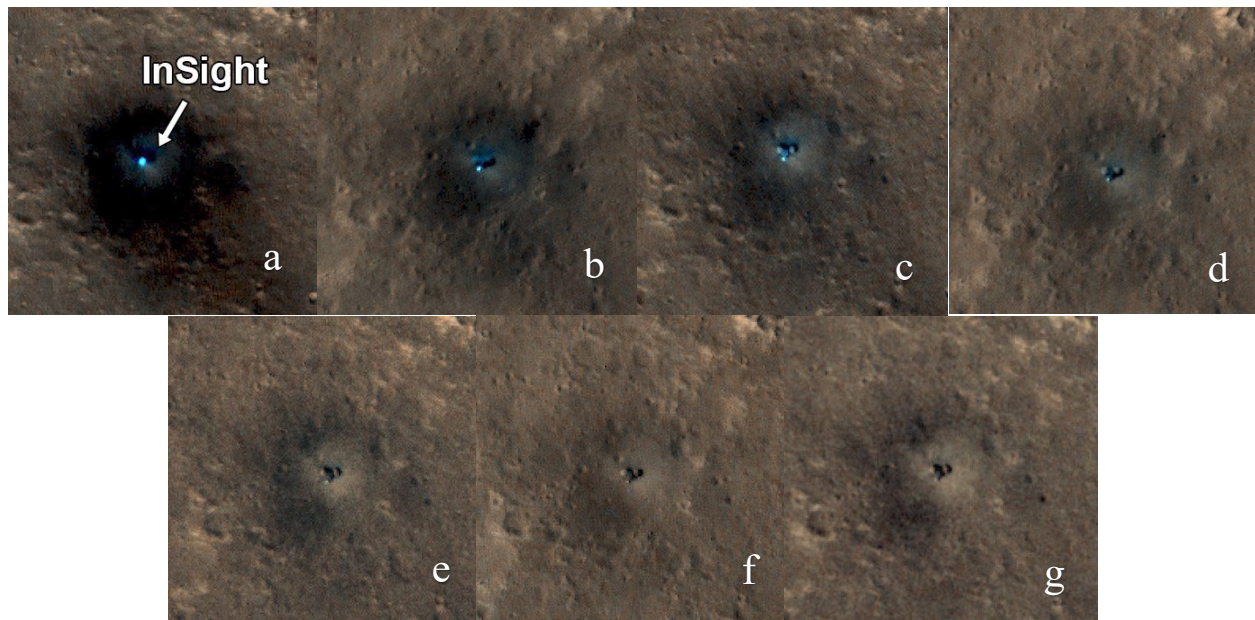


Figure 2. Images taken by Mars Reconnaissance Orbiter’s High-Resolution Imaging Science Experiment (HiRISE) camera on (a) 11 December 2018, (b) 28 November 2019, (c) 23 November 2020, (d) 16 December 2021, (e) 29 November 2022, (f) 3 January 2024, (g) 23 October 2024. [4]

Although all communications had ceased, the lander was expected to enter a “Fixed Time Step (FTS)/Dead Bus” state in which it was still possible, however unlikely, for the lander to awaken should it experience a sufficient solar panel cleaning event. If such an event occurred, the lander would make prearranged radio transmissions which could be received by either Mars orbiters or NASA’s Deep Space Network (DSN). For the next 2+ years, a small team at NASA’s Jet Propulsion Laboratory (JPL) continued to listen for such a signal. This paper reports on the novel technique of passive listening employed when a DSN antenna was pointed at Mars during the tracking of other Mars orbiters and landers. When InSight was visible within the beam of that antenna, the DSN’s Open Loop Receivers (OLRs) were utilized to attempt to detect InSight’s X-band signal. This tracking technique allowed for a robust search campaign without any impact to DSN operations or any of the active Mars missions. (A parallel campaign by other JPL researchers using the orbiters to search for an ultra-high frequency (UHF) relay signal is not discussed herein.)

In this paper, we provide an overview of the process used to collect X-Band data in the 2-year search for InSight after end of mission, including the DSN equipment used (namely the OLRs), the determination of view periods, and the calculation of tuning predicts to anticipate the radio frequency of the signal. Second, we provide a summary of the data collected, including time periods and the methodology for processing this type of data. This analysis also includes detection of radio frequency interference (RFI) from other Mars missions appearing within the dataset and how such detections are ruled out as compared to the sought InSight signal. Third, we demonstrate the method of spectral kurtosis, a useful metric for detection of telecommunication signals in noisy datasets. We conclude with an analysis of the data and report final results for the detection campaign.

2. Data Collection Methodology

Here we provide a brief overview of the data collection methodology used in the InSight X-Band listening campaign. We provide an overview of the Deep Space Network, the Open Loop Receivers (OLRs) used to record the data, the scheduling process, and the OLR recording configuration.

2.1 Deep Space Network

NASA’s Deep Space Network (DSN), a set of large-aperture radio antennas, receives the radio signals from numerous interplanetary missions. Spaced equally in longitude at three complexes (Goldstone, California; Madrid, Spain; and Canberra, Australia), the DSN can provide near-continuous coverage of any radio source as the Earth rotates. Each complex has several antennas which are 34 meters in diameter and one antenna which is 70 meters in diameter. Table 1 lists the antennas in operation at each complex during the InSight OLR listening campaign.

Table 1. Antennas of the Deep Space Network during the 2022-2024 InSight Listening Campaign. Each number is prefixed by “DSS,” or Deep Space Station.

Diameter	Goldstone	Canberra	Madrid
70-meter	DSS-14	DSS-43	DSS-63
34-meter	DSS-24	DSS-34	DSS-53
	DSS-25	DSS-35	DSS-54
	DSS-26	DSS-36	DSS-55
			DSS-56
			DSS-65

The antenna gain is directly proportional to the antenna diameter as $\text{Gain} = 10 \log_{10} E (\pi d/\lambda)^2$, where E is the efficiency of the antenna, d is the diameter, and λ is the wavelength. Thus, the 70-m antennas provide 6 to 7 dB greater sensitivity compared to 34-meter antennas.

Each DSN antenna collects the radio frequency (RF) signal and passes it through a cryogenically cooled low noise amplifier, followed by a down-conversion to a common intermediate frequency (IF, approximately 300 MHz). The IF is digitized by the common platform and is distributed to the various receivers. Thus, even if a DSN antenna is configured for tracking a specific spacecraft, other spacecraft signals within the same beam can also be detected since they are not filtered out at this stage.

2.2 Open Loop Receivers

The microwave signals received by the DSN are converted to lower frequencies and sampled, averaged, and recorded for later analysis. Two receiver types acquire radiometric data: closed loop and open loop. The typical tracking method is closed loop using the Downlink Tracking and Telemetry (DTT) receiver, in which a phase-locked loop (PLL) measures the phase of the carrier signal, using each measurement to anticipate the phase in the next increment. Closed loop data are the primary data type utilized by missions for radiometric Doppler, ranging, and telemetry reception. The open-loop method uses the Open Loop Receiver (OLR) of the DSN to record the full spectrum of the radio signal at a user-defined centre frequency and recording bandwidth. OLRs are typically used in specialized science applications such as very long baseline interferometry, radio science, and radio astronomy. However, they may be used for specialized engineering applications as well. The OLR was uniquely suited for the InSight listening campaign since it could never be assumed that there would be a signal for the DTT receiver to track. Furthermore, the OLR could be operated in a standalone mode, outside the normal DSN scheduling apparatus (see section 2.3).

With the OLR, a file containing predicted downlink frequencies (tuning “predicts”) drives a local oscillator, ensuring that the downlink signal is always within the baseband spectrum of the receiver output [5]. The raw antenna voltages are recorded and converted to In-Phase (I) and Quadrature Phase (Q) digital samples by an analog-to-digital converter. This data type, in combination with the “predicts” file, allows for precise reconstruction of the downlink signal, which provides flexibility in signal processing. The OLR provides superior phase stability, capturing the signal regardless of sudden amplitude or frequency changes when the closed-loop receiver would lose lock; it preserves all information contained in the downlink signal [6]. For these reasons, open-loop data are well suited to search for a signal when the exact frequency of the signal is unknown or the signal is weak.

Each DSN complex houses eight OLRs, each of which can support up to 16 recording channels. Typically, two OLRs are reserved for ad-hoc operations such as used in the InSight listening campaign. Commonly used recording bands range anywhere from 200 Hz to 100 MHz, with sample resolution ranging from 2 to 16 bits, though the aggregate recording rate may not exceed 512 megabits per second [7]. Typical recording bandwidths are in the kilohertz or low megahertz range due to the large file sizes produced (10s of gigabytes).

2.3 Scheduling

Each DSN complex typically tracks Mars daily as the planet comes into view. With few exceptions such as for maintenance, there is usually at least one track due to the large number of missions operating at Mars. During the InSight listening campaign, missions tracked by the DSN included NASA’s orbiters Mars 2001 Odyssey (ODY), Mars

Reconnaissance Orbiter (MRO), and Mars Atmosphere and Volatile Evolution (MAVEN), NASA’s landers Curiosity (MSL) and Perseverance (M20), ESA’s orbiters Mars Express (MEX) and Trace Gas Orbiter (TGO), United Arab Emirates’ Mars Mission (EMM), and India’s Hope mission (MOM). All but MOM transmit to Earth in the X-Band frequency range, approximately 8.4 GHz. With the Multiple Spacecraft Per Aperture (MSPA) technique, up to four of these Mars missions could be tracked at once with the DTT receivers. With DSN tracks no longer designated for InSight, the standalone OLR was set to piggyback on the existing Mars X-Band tracks to look for InSight. During such tracks the station microwave system was already configured to receive X-Band; thus, it was only necessary to configure the correct tuning predicts in the OLR (see section 2.4). The process of timing the recordings was accomplished by using in-house software to compute when Earth was in view of InSight as Mars rotated and cross-referencing that information with the DSN schedule. During all periods when Earth was in view of InSight and there was at least one DSN antenna pointing at Mars, the OLR was set to record (Figure 3). Wherein the antennas are shared amongst all interplanetary missions, the number of separate DSN tracks needed to cover a view period varied depending on the DSN schedule. Although coverage was generally robust, there were occasional gaps within a view period.

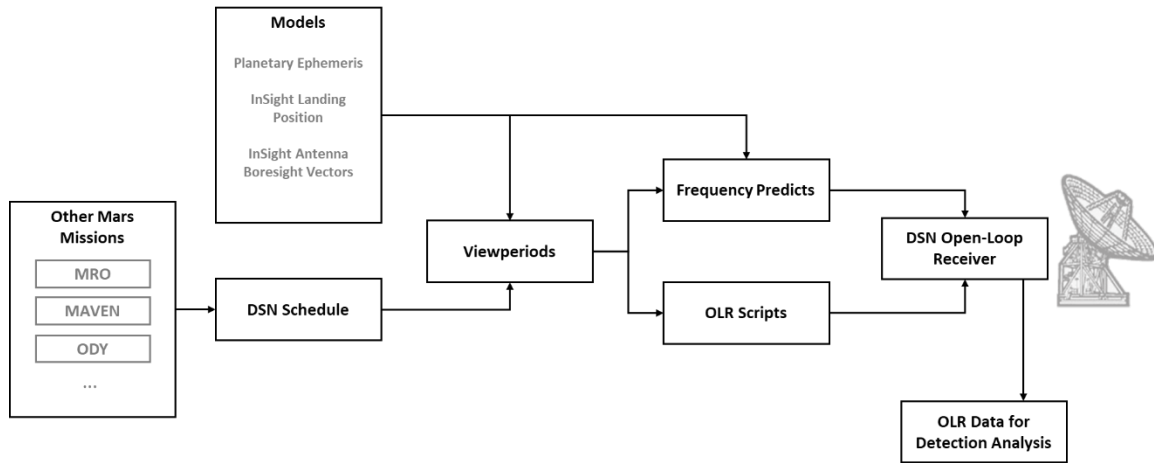


Figure 3. Flowchart of the scheduling software used to operate the OLR when InSight was in view.

In all, the OLR was used on 2,163 separate tracks to search for InSight during the listening campaign from December 2022 through December 2024, a total of 9,250 hours or slightly over 385 days of recorded data. Among those tracks, many overlapped, and no measures were taken to prevent such overlap, as a redundant detection at multiple stations would have been welcome reassurance. However, to minimize excessive use of resources and extra processing with diminishing returns, completely redundant potential tracks were not utilized. However, one exception was made for the 70-m antennas, whose tracks were always used regardless of overlap with their 34-m counterparts, because of the 6-7 dB gain. Accounting for overlapping coverage, the amount of recorded data is reduced to 8,507 hours, slightly more than 354 days. While most recording took place over 34-m stations, the three 70-m stations—DSS-14, DSS-43, and DSS-63—accumulated about 39, 24, and 37 days of data, respectively, for a total of 100 days. See Table 2 for a summary of the dataset.

Table 2. Tracking Statistics for the 2022-2024 InSight Listening Campaign

Duration of Listening Campaign	Total data collected	Average Track Length	Total data collected accounting for overlapping coverage	Data collected at DSS-14	Data collected at DSS-43	Data collected at DSS-63
Dec 2022 – Dec 2024	385 days	4.2 hours	354 days	39 days	24 days	37 days

2.4 OLR Configuration

The OLR recorded during predetermined X-Band tracking of other Mars missions. With no formal process in place to track InSight, frequency tuning for the OLR was managed with in-house software, utilizing the Spacecraft, Planet, Instrument, C-matrix, Events (SPICE) toolkit [8] and the location of InSight on the surface to compensate for the Doppler shift resulting from the relative motion of Earth and Mars and Mars’ rotation. There was no uplink to InSight from the DSN; rather, the transmitted frequency would be dependent on InSight’s on-board oscillator. A best-guess

frequency range, based on average temperatures on the Martian surface and their effect on the oscillator, was provided by the InSight telecom team.

During available view periods, the OLRs were set to record over the entire expected frequency range, even accounting for fluctuations caused by the Martian seasons. That range was approximately 100 KHz. One 100-KHz band on the OLR was dedicated to recording the entire range, while seven other channels, 16 KHz each and offset 12.8 KHz from each other, covered this same range (Table 3). The use of narrower channels was intended to facilitate detection of a potentially weak signal with a lower data rate. The choice of 16-KHz specifically was a balance between greater sensitivity and use of resources, keeping the number of files to a manageable amount and leaving enough OLR resources available for other users.

Table 3. OLR Configuration during the 2022-2024 InSight Listening Campaign

Subchannel	1	2	3	4	5	6	7	8
Bandwidth (KHz)	16	16	16	16	16	16	16	100
Offset from Centre Frequency (KHz)	-38.4	-25.6	-12.8	0	12.8	25.6	38.4	0

3. Data Analysis and Initial Results

In this section, we describe the analysis applied to the OLR data. We describe the processing technique, provide the criteria needed to discern a positive detection, and assess Radio Frequency Interference (RFI) present in the data.

3.1 Open Loop Data Processing

The OLR data from each track were transmitted back to JPL for analysis. For each data file, Fast-Fourier Transform (FFT) software was used to compute the frequency with the highest carrier signal-to-noise ratio (SNR) within the recording band. Figure 4 shows the SNR and residual frequency—the difference between the observed and predicted frequency—for the last nominal X-Band track of InSight on 27 May 2022. When no signal is present, the reported peak frequency (lower panel) appears at random, while a low, non-zero SNR (upper panel) is computed. In the figure, there is no signal until approximately 20:20 UTC when the SNR rises to 22 dB-Hz. The residual frequency after 20:20

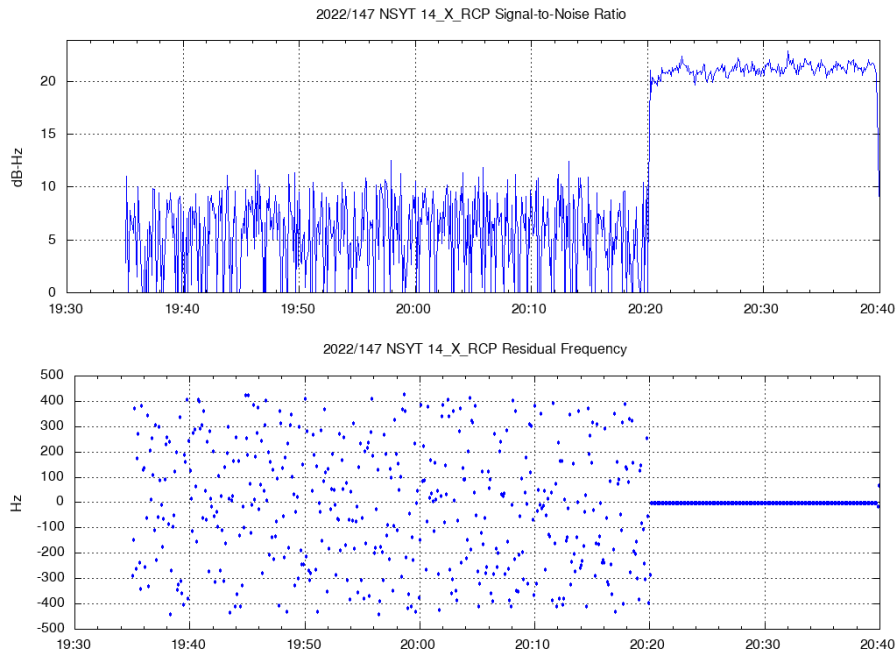


Figure 4. Signal-to-Noise Ratio (top) and Residual Frequency (Bottom) during the last X-Band track in which InSight was detected. Detection occurs from 20:20 UTC until the end.

UTC is very close to 0, as the downlink signal is referenced to the uplink, which was used in the formulation of the downlink frequency predicts.

3.2 Detection Criteria

All OLR subchannels, both 16- and 100-KHz, were processed via FFT to search for a signal during the InSight listening campaign. In theory, a detection should look similar to Figure 4, with the signal appearing sometime during the track. The main difference would be due to the signal being generated by the onboard oscillator instead of being referenced to an uplink from the DSN. The onboard oscillator is not temperature-controlled and thus the oscillator's output frequency changes with temperature. In the recovery state the spacecraft's temperature, and therefore the temperature of the oscillator within the radio, would be transient and the frequency would likely be drifting with respect to the downlink predicts due to temperature changes. Also, it could not be assumed that the SNR would be comparable to that seen during the surface mission since the signal power would vary depending on Earth-Mars distance and Earth's angular distance away from the antenna boresight. Lastly, the InSight project supplied identifying features, inherent to the lander's programming, associated with a recovery from the FTS/Dead Bus state. Namely, a carrier-only signal should be present for ten minutes, and a second carrier signal with adjoining 25-KHz subcarriers should occur 98 minutes later, lasting for another ten minutes. With the amount of available power unknown, it was plausible that either of the two transmissions could be cut short if the battery was depleted in the middle of the sequence.

3.3 Radio Frequency Interference

To declare a detection of InSight, it would first have been necessary to eliminate other potential X-Band radio sources present in the data. Such sources could either be on the ground, within the DSN or OLR systems, or other assets located at Mars. Other X-Band radio sources falling within the beam of the DSN antenna pointing at Mars were extremely unlikely. Doppler analysis of these detections usually provided quick resolution, with the source attributed

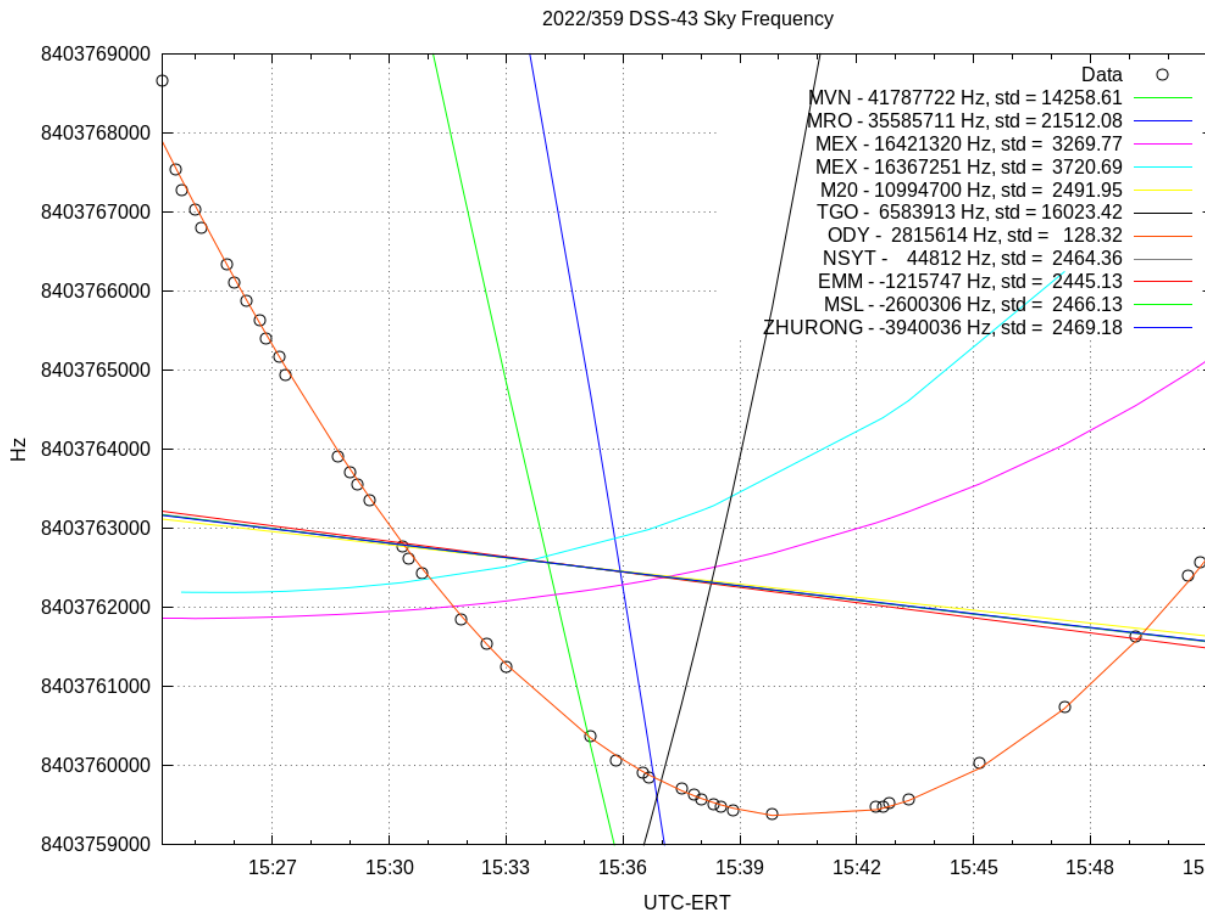


Figure 5. Sky frequency of detected signal (black circles) and predicted frequencies of Mars assets (solid lines).

occasionally to a ground source but usually to a Mars orbiter. Kahan et al [9] document the prevalence of RFI from Mars that can be detected at the DSN during Mars tracking.

The tell-tale sign of a ground source in the data would be a constant sky frequency, the summation of the 8.4-GHz tuning predicts and the residual frequency, since there would be no Doppler shift associated with a ground source. The Doppler profile of another lander would be the most likely to look like InSight. However, limited X-Band transmissions, along with well-known timing, made the elimination of landers straight forward. The Doppler shift of orbiters could vary depending on geometry, and telemetry or ranging tones could in fact be seen many Megahertz from the carrier frequency, thus having the potential to be mistaken for InSight. For Mars orbiters, the Doppler signature could usually be used as an elimination factor, as the residual frequency would appear as an arc and/or a transient signal sweeping through the recording band. Furthermore, usually the detection criteria associated with the FTS/Dead Bus state (e.g., a 10-minute duration) were obviously not met

While most detections could be ruled out quickly, some required in depth checking, as the Doppler arc of an orbiter could be mistaken for the InSight lander over a short time span. Such analysis involved a direct comparison of the detected signal to the tuning predicts of all Mars assets. Figure 6 shows an example of an RFI detection determined to be Mars 2001 Odyssey. In the figure, the black circles represent the OLR data, with outliers removed. For each Mars asset, the key shows the offset in Hz applied relative to the predicted carrier frequency and the standard deviation of the difference between that frequency and the observed frequency. In this example, the standard deviation for the predicted ODY frequency as compared to observation is substantially lower than for all other missions.

While the majority of tracks contained no signal whatsoever, many contained RFI. Figure 5 shows the percentage of tracks with RFI in at least one of the recording channels, not accounting for overlap in the track times. Not accounting for the number of separate interferers, 691 of 2,163 tracks, or 32%, contained some type of RFI. The SNR of the RFI was generally weak, as evidenced by the fact that 57% of 70-m tracks showed RFI as compared to 20% for 34-m tracks. The difference is attributed to the ability of the larger dishes to receiver fainter signals, as mentioned in section 2.3. The presence of RFI is clearly correlated with the proximity of Mars to Earth (Figure 6), as the strength of the signals is inversely proportional to the square of the distance.

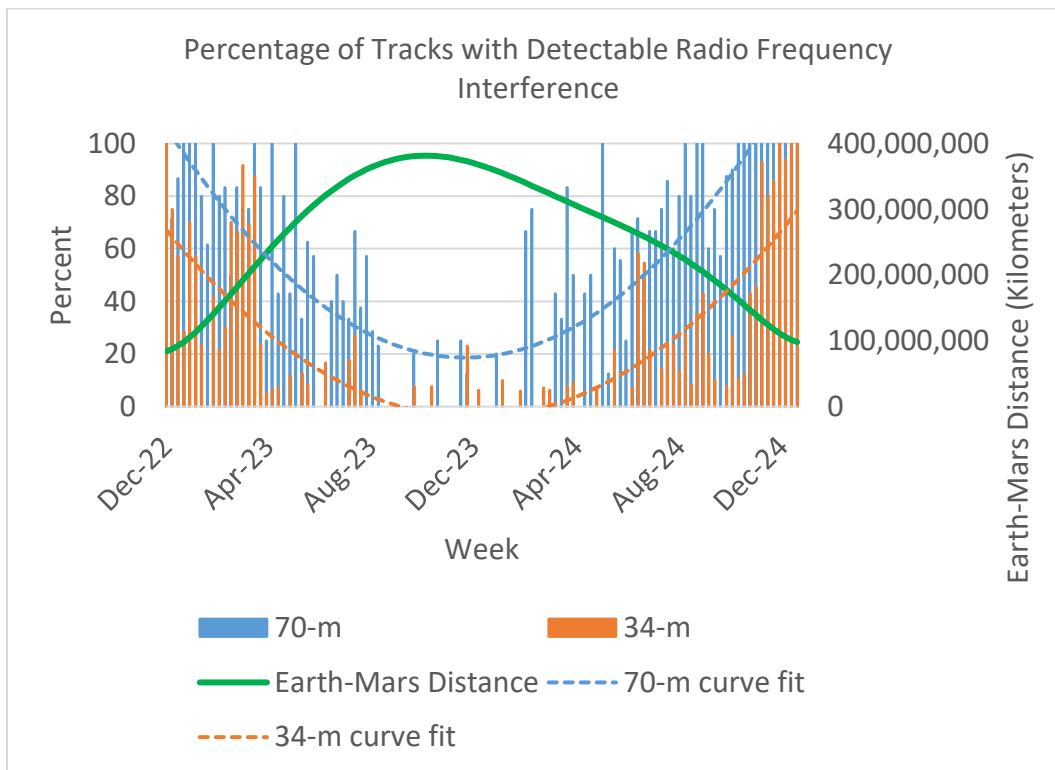


Figure 6. Percentage of DSN tracks with X-Band Radio Frequency Interference. Dashed lines show a polynomial fit to the data

4. Spectral Kurtosis

4.1 Theory

Spectral kurtosis (SK) is a complementary spectral analysis tool intended to be used with the power spectrum, indicating at each frequency bin if the signal contains a nonstationary, stationary harmonic, or harmonic process [10]. Spectral kurtosis, κ , can be estimated with M nonoverlapped blocks, where each X_i is an N -point Discrete Fourier Transform (DFT) of signal, $x(n)$.

$$\hat{\kappa}_x(m) = \frac{M}{M-1} \left[\frac{(M+1) \sum_{i=1}^M |X_i(m)|^4}{(\sum_{i=1}^M |X_i(m)|^2)^2} \right] \quad (1)$$

SK is positive for the time varying, nonstationary spectral components. Pure sine wave tones have a negative SK value, and SK tends to zero for stationary signals, even with frequency resonance. We will see in the next sub-section that even time varying drifting tones can be seen as tones if the DFT frequency resolution is course enough.

4.2 Examples with known weak signal and time varying strong signal

Test data from 2022-05-13 provide an example of a pure tone with progressively weakening signal strength (Figure 7). The power spectrum waterfall does not have the dynamic range in linear grayscale to show the weak signal tone relative to the strong signal near the end, but SK reveals the weak tone shown as negative values in black. If Figure 7a was plotted from 500 to 6000 seconds, the tone would be visible in the grayscale. Each of the power spectrum and SK plots below have an integration time of 10 seconds.

OLR data from the InSight search campaign on 7 November 2024 provide an example of a drifting time varying tone with strong signal strength (Figure 8). This data set contains an RFI signal from MAVEN and three unknown RFI signals. Varying the frequency resolution affects SK in whether the signal is seen as a pure tone or time varying signal. In Figure 8b, the RFI signals at 1-Hz resolution remain as time varying signals and remain as barely visible positive SK values. In Figure 8d, the RFI signals at 5-Hz resolution begin to appear as tones and begin to take on negative SK values. In Figure 8f, the RFI signals at 10-Hz resolution appear as strong tones and have strong negative SK values. All the power spectrum figures 8a, 8c and 8e look similar with corresponding fine to coarse resolutions.

4.3 Application of kurtosis to InSight Data

In searching for InSight, we expect the signal to appear closer to a pure tone than a highly time varying signal, since the predicts for InSight are well known due to the static location of InSight on Mars. Figure 9 provides an example of the power spectrum and SK for OLR data collected on 10 June 2023 in the search for InSight. Unfortunately, no signal is detected by either method on this track. As indicated in Table 2, there are many more data to examine with this method. However, the present examination process involves manual inspection by eye and needs to be automated. The automated algorithm will scan the power spectrum for positive peaks, scan the SK for negative peaks, and correlate the two for matching time and frequency components.

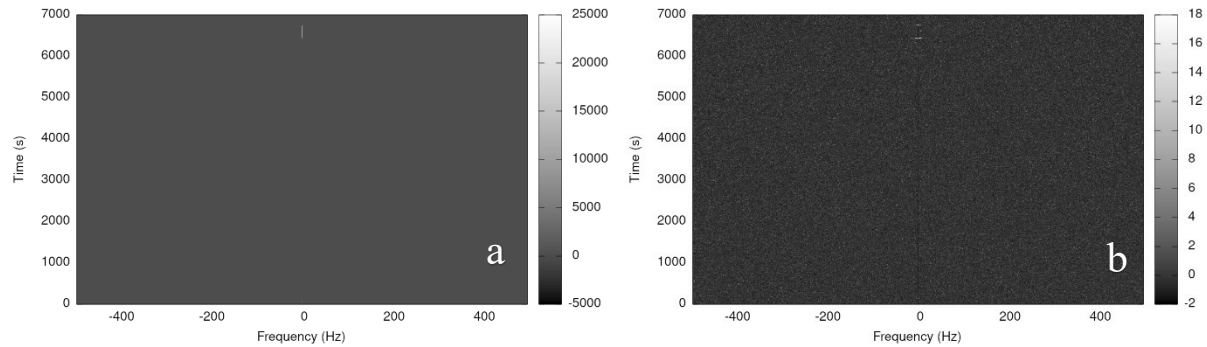


Figure 7. Constant test tone with weak signal strength. (a) Power spectrum at 1-Hz resolution; (b) Spectral Kurtosis at 1-Hz resolution

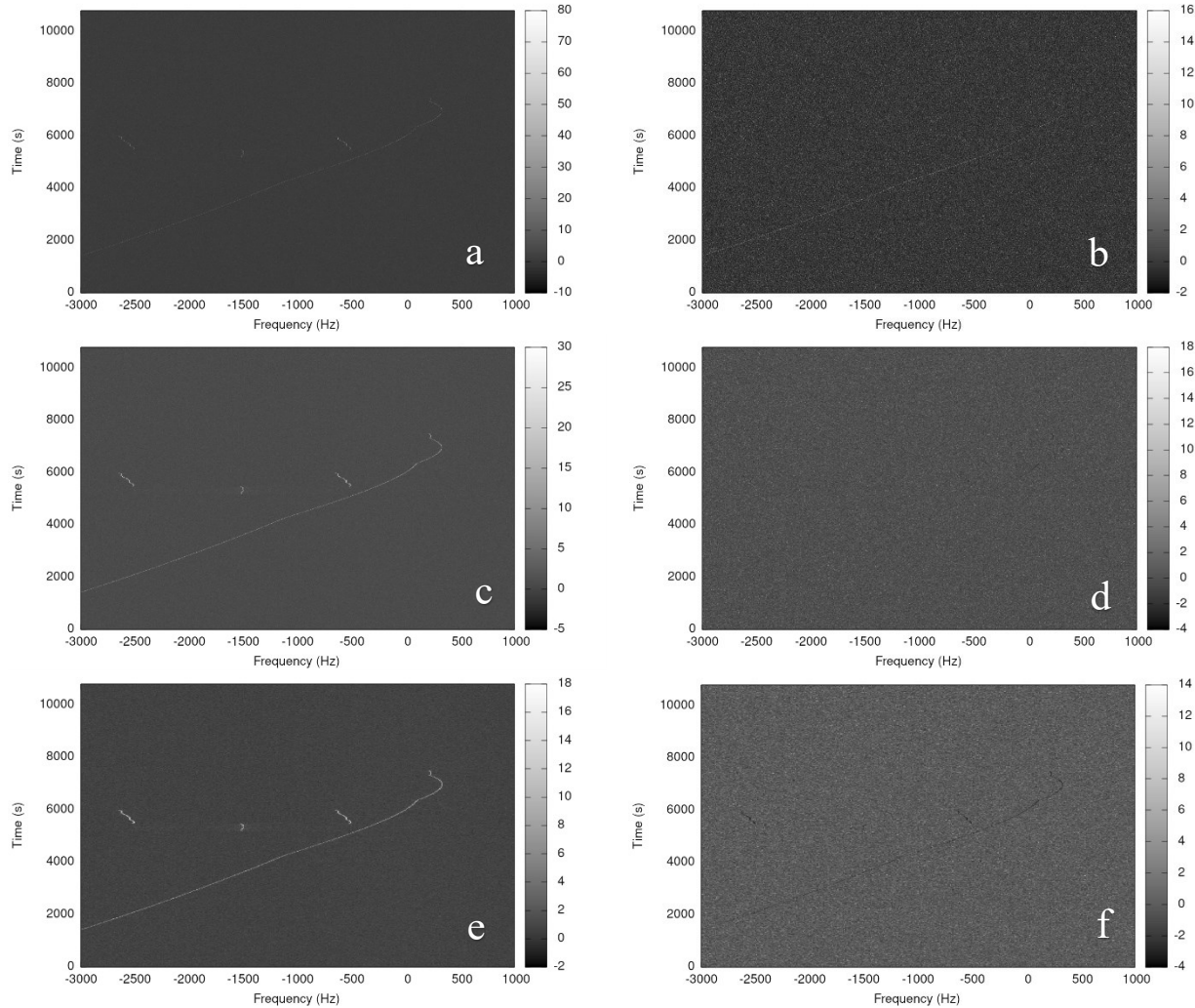


Figure 8. Drifting time varying tone with strong signal strength on 7 November 2024. Power Spectrum at (a) 1-Hz, (c) 5-Hz, (e) 10-Hz Resolution; Spectral Kurtosis at (b) 1-Hz, (d) 5-Hz, (f) 10-Hz resolution

5. Results and Discussion

The listening campaign concluded as of January 2025 with no detections of the InSight lander. Figures 2f and 2g corroborate this lack of detection, with no cleaning of the solar panels evident in HiRISE imaging. With the expected behaviour of the InSight signal, additional analysis is unlikely to lead to a detection of the InSight lander with the current data set. However, the research team at JPL retains a robust OLR data set which can be analysed further with more advanced detection techniques for the purposes of RFI characterization and filtering, for example.

Aside from the unknown transmitted frequency based on the temperature of the oscillator on Mars, radio frequency interference from Mars provides an additional challenge in analysis of the InSight search data. In the event of a future suspected detection of InSight from either this data set or future recordings, extra steps must be taken to sleuth out all other possible sources, such as shown in Figure 5. As shown in Figure 6, RFI is possible at any time, especially when Mars is closest to Earth—the time when the InSight signal would otherwise be most easily detected. Nevertheless, it should be noted that without at least one other mission at Mars, the opportunistic listening technique employed here would not be possible in the first place.

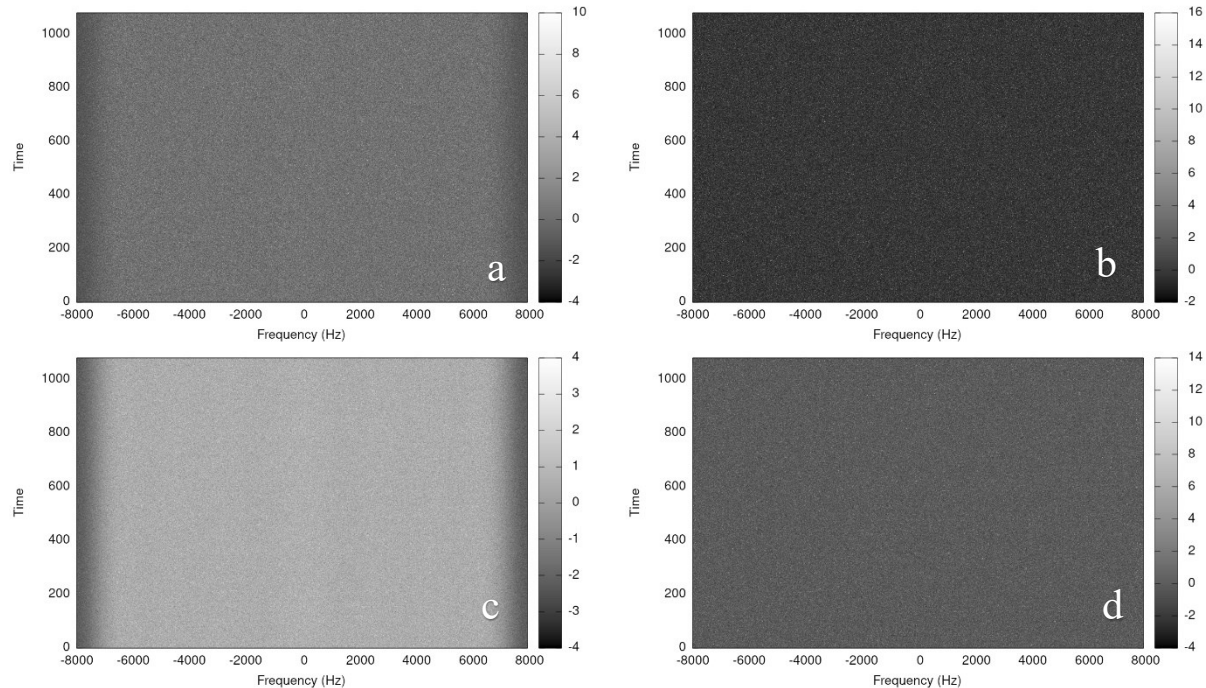


Figure 9. OLR data collected on 10 June 2023 in the search for InSight, Power Spectrum at (a) 1-Hz, (c) 10-Hz resolution; Spectral Kurtosis at (b) 1-Hz, (d) 10-Hz resolution

Spectral kurtosis provides another methodology for the detection of weak signals in the InSight OLR data set. As compared to the power spectrum method utilized to produce Figures 4, 5, and 6, a lack of Doppler compensation in the band might be advantageous for detection via spectral kurtosis. Further analysis of the data set lies in applying spectral kurtosis as demonstrated in Section 4 to the entire data set. The challenge lies in examination of the spectral plots produced. Analysis via the primary method discussed in Section 3 was done by eye and was completed gradually over the course of the listening campaign. The next step in analysis is to review the kurtosis results *en masse*, removing the need for a manual checking process. The development of such an algorithm will also be applicable to the methods employed in Section 3, opening the opportunity for analysis with different processing parameters such as different integration times.

We recommend the continuation of periodic imaging of InSight by MRO's HiRISE instrument or other capable instruments at Mars. Such images may yet reveal a solar panel cleaning event, in which case an X-Band transmission in the FTS/Dead Bus state might still be possible. In such an event, with no impact to the DSN or any of the Mars missions currently in operation, passive listening with the OLRs could be resumed.

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