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Radio Frequency Interference Impacting the Martian X-Band Radio Environment

Daniel S. Kahan,* Dustin R. Buccino,* Walid A. Majid,* Robert Navarro,† Jeff B. Berner,† and Bradford W. Arnold †

ABSTRACT. — Most spacecraft currently at Mars utilize the X-band (8,400–8,450 MHz) deep space spectrum to communicate with the ground receiving systems such as the Deep Space Network (DSN). Although efforts are made to allocate dedicated bands in the spectrum to individual orbiters and landers, the ever-increasing number of Martian probes and their need to communicate with ground networks has raised the potential for interfering signals that pose serious challenges to robust acquisition of data from these space-borne assets. This work examines data from the DSN's open-loop receivers to diagnose interference tones in the Martian X-band radio environment. By comparing the Doppler shifts on the radio links between the various assets at Mars, the individual asset can be identified, provided there is a priori knowledge of the spacecraft's telecommunication band allocation and a reliable spacecraft ephemeris is available. Radio frequency interference (RFI) has been observed in open-loop techniques as far back as 2004 between Mars Express and Mars Global Surveyor. Most recently, RFI has been observed between the European Space Agency's (ESA) Trace Gas Orbiter and China's Tianwen-1 spacecraft, and between the Mars 2020 Perseverance rover and the MAVEN (Mars Atmosphere and Volatile EvolutioN) orbiter. It will be critical in the future to continually monitor the Martian environment so radiometric tracking and telemetry downlinks to the DSN can continue nominally.

I. Introduction

Mars has been a primary target of deep space exploration of the planets since the early days of spaceflight because of its potential past habitability. Recent discoveries, technology advancements, and reduced cost for building and launching spacecraft have accelerated the exploration of the planet. Since the arrival of four new spacecraft in spring 2021, a total of 13 spacecraft are currently active in the Martian environment: NASA's Mars Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatile EvolutioN (MAVEN), InSight lander, Curiosity rover, and Mars 2020 Perseverance rover and Ingenuity helicopter; the European Space Agency's (ESA) Mars Express and Trace Gas Orbiter (TGO);

* Communications Architectures and Research Section.

† Deep Space Network (DSN) Project Section.

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the United Arab Emirates Mars Mission (Hope); the Indian Space Research Organisation's Mars Orbiter Mission; and China's Tianwen-1 orbiter and Zhurong rover.

Out of these robotic missions, 11 transmit at the deep space X-band spectrum to Earth for telemetry and tracking (Table 1). The deep space X-band spectrum is allocated by the International Telecommunication Union (ITU) for spacecraft beyond 2 million kilometers from Earth. The frequency assignment range is 8,400–8,450 MHz downlink and 7,145–7,190 MHz uplink [1]. With many missions transmitting in this 50-MHz downlink range and more missions planned for the future, the X-band radio spectrum is becoming busy. Although efforts are made to mitigate radio frequency interference (RFI) among the transmitting spacecraft, RFI is frequently observed and sometimes causes unintentional data loss to missions.

NASA's Deep Space Network (DSN) is a set of large-aperture radio antennas spaced equally in longitude at three complexes around the planet (Goldstone, California; Madrid, Spain; and Canberra, Australia) to provide near-continuous coverage for deep space spacecraft. The DSN provides two primary tracking methods: closed-loop and open-loop. The typical tracking method is closed-loop using the Downlink Tracking and Telemetry (DTT) receiver, where a phase-locked loop acquires a downlink signal at a predicted frequency and tracks that signal to record radiometric Doppler and ranging data, and decode telemetry. Up to four spacecraft within the beam of a single antenna can be tracked with closed-loop receivers at the same time using the Multiple Spacecraft Per Aperture technique. 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 center frequency and recording bandwidth. OLRs are typically used in specialized science applications such as Very Long Baseline Interferometry, radio science, and radio astronomy. However, the OLR has specialized engineering applications as well.

This work utilizes the OLR to monitor the Martian X-band radio spectrum, detect spacecraft from their Doppler shift and power spectrum, and diagnose RFI. First, the open-

Table 1. Known or assumed Mars spacecraft X-band transmit (downlink) frequencies as of March 2022.

Spacecraft	Type	Transmit Frequency (MHz)	Max Telemetry Bandwidth* (MHz)	Start Date at Mars
Zhurong	Rover	8400.06	< 1	May 2021
Mars Science Laboratory (Curiosity)	Rover	8401.41	< 1	August 2012
Emirates Mars Mission (Hope)	Orbiter	8402.78	4.0	February 2021
InSight	Lander	8404.05	< 1	May 2018
Mars Odyssey	Orbiter	8406.84	2.7	October 2001
TGO	Orbiter	8410.66	6.0	October 2016
Mars 2020 (Perseverance)	Rover	8414.99	< 1	February 2021
Mars Express	Orbiter	8420.43	3.5	December 2003
Tianwen-1	Orbiter	8431.02	4.0	February 2021
MRO	Orbiter	8439.55	6.0	March 2006
MAVEN	Orbiter	8445.77	2.4	September 2014

*Based on maximum possible symbol rate. Ranging tones, delta-differential one-way ranging tones, and other harmonics may exceed these limits.

loop architecture enabling these observations is presented. Second, the wide-view picture of the Martian radio environment at X-band is discussed. Third, examples of RFI are presented. Finally, the identification of spacecraft and RFI from Doppler shift is discussed.

II. OLR Architecture

Open-loop reception takes place without the tracking feedback loop of the closed-loop receiver. Rather, a file containing predicted downlink frequencies (tuning "predicts") drives the local oscillator in the OLR, ensuring that the downlink signal is always within the baseband spectrum of the receiver output [2]. 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 [3]. For these reasons, open-loop data are well suited for investigation of RFI in the Martian environment, wherein the signals from disparate sources may be present within the same recording band.

Each DSN complex houses eight OLRs, each of which can support up to 16 recording channels. Typical 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 Mbps [4]. Typical recording bandwidths are in the kilohertz or low megahertz range due to the large file sizes produced (10s of gigabytes). However, monitor data from the OLR graphic user interface provides snapshots of the observed frequency spectrum that may be preserved for later viewing. Although these snapshots are limited to the bin size and averaging used at the time of monitoring and cannot be reprocessed, with careful planning they can be useful for visualizing a broad spectrum. Each OLR channel can be set to its own tuning predicts; thus, any part of the X-band spectrum may be investigated regardless of which asset is actually being tracked so long as the spacecraft is within the antenna beam (as are all the spacecraft at Mars).

Because of the additional operational complexity and large files created, the OLRs are not used for every DSN tracking pass. Rather, they are typically reserved for specialized scientific investigations as mentioned above. For prearranged activities, the OLR is added to the DSN station's Network Monitor and Control (NMC) link, which allows for direct oversight by the station controller, automatic scheduling management, and automatic delivery of frequency tuning predicts. Adding the OLR to the NMC link requires either an additional manual step by the station operator or keywords in the projects' DSN keyword files, which trigger the station's Automatic Link Build (ALB), the latter being the more common method. Six of each complex's OLRs are available at all times for use by the station operator or ALB—they are colloquially referenced as "green," meaning they are operational and available for use. Operation of the green OLRs requires coordination with either the DSN Network Operations Project Engineer, the Jet Propulsion Laboratory (JPL) Ops Chief, or the project's mission planning team.

The remaining two OLRs are considered “blue,” meaning they are available for ad hoc use, primarily by the JPL Planetary Radar and Radio Sciences Group (PRRSG). For these OLRs, there is no immediate oversight by the DSN in case of problems occurring during a track, scheduling is managed internally by the PRRSG, and frequency tuning must be supplied by the user. However, they may be operated on a noninterference basis, imposing no extra labor on either the project, the DSN engineers, or the station link controller. The blue OLR was used in several of the investigations described in the following sections. No additional DSN scheduling was required, as the OLRs were set to observe the item of interest during preestablished tracking of the various Mars missions.

III. Martian Radio Environment

Currently, a total of 11 spacecraft transmit from Mars within the X-band spectrum. For some spacecraft, the onboard radio continuously transmits a signal back to Earth, whereas some only transmit during their specified communication windows. This is particularly true for orbiters, which in general have more power availability than landers or rovers. Table 1 shows the assumed transmit frequencies and maximum telemetry bandwidth of each spacecraft. The telemetry bandwidths of NASA spacecraft are known precisely for tracking with the DSN, but non-NASA missions may not be as precise and come from either filing with the ITU or the Space Frequency Coordination Group.

During any given transmission from a spacecraft, the carrier signal is modulated to provide additional downlink information to operators and scientists on Earth. Telemetry (data) encoding can either be directly modulated onto the carrier or encoded onto a subcarrier. Telemetry encoding has the effect of broadening the carrier spectrum by a frequency spread proportional to the symbol rate of the encoding. The carrier can either be suppressed within the data or, more frequently, a residual carrier is left to allow for precision Doppler tracking and ease of locking onto the signal. Additionally, spacecraft may transmit ranging tones or differential one-way ranging (DOR) tones for their particular navigation needs.

The spacecraft carrier, and encoding effect of these tones, is easily observed within the OLR when configured appropriately. Figure 1 shows a snapshot (1-s integration time) of the 8,400–8,460 MHz spectrum on May 17, 2021, when Deep Space Station 14 (DSS-14) was pointed at Mars.

Simply by comparing the peak frequency, one can identify specific spacecraft. For example, Mars Express is observed near its assumed downlink frequency (Table 1) with both a carrier and subcarrier telemetry encoding. MRO, on the other hand, is observed transmitting near its assumed downlink frequency with a direct carrier modulation. Additional ranging tones are seen symmetric about the carrier outside the telemetry encoding spectrum. None of the landers or rovers were transmitting during this window, nor could the Hope spacecraft be seen.

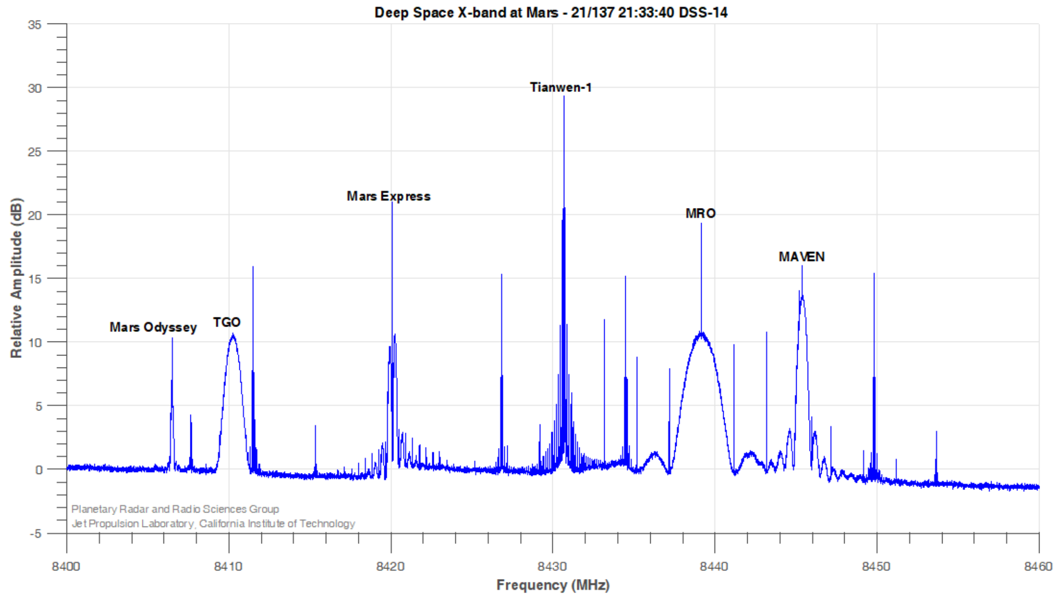

Figure 1. Snapshot of the full spectrum from Mars on May 17, 2021, (DOY 137) at 21:33:40 UTC, captured from DSS-14 using the OLR. Six 16-MHz channels were combined to take the snapshot.

It is quite evident by Figure 1 that the Mars spectrum is busy, and a spacecraft is not necessarily guaranteed a clean spectrum. Telemetry spurs, ranging tones, or DOR tones from one spacecraft can be observed in close proximity to another spacecraft's downlink. Whether that tone causes consequential RFI in a different spacecraft's downlink is subject to many considerations.

IV. Identification of Signals

While one can simply examine the frequency of the signal and compare against a list of known transmit frequencies, in the case of an unknown signal frequency (for example, a new spacecraft or spur), additional analysis is required. By examining the time history of the received frequency, it is possible to deduce the spacecraft transmitting that particular tone. RFI tones frequently occur as a direct offset to the spacecraft's carrier frequency. The spacecraft's carrier frequency, when received on Earth, is primarily affected by the oscillator drift (if noncoherent or one-way transmission) and the Doppler shift of the signal (in any link configuration). The classical Doppler shift relates the received frequency to the relative velocity between the transmitter (in this case, the spacecraft) and receiver (in this case, the DSN antenna). Ignoring relativistic terms, the Doppler shift is

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0, \tag{1}$$

where f is the received frequency, Δv is the relative velocity, c is the speed of light, and f_0 is the transmit frequency. The relative velocity can be computed using the spacecraft

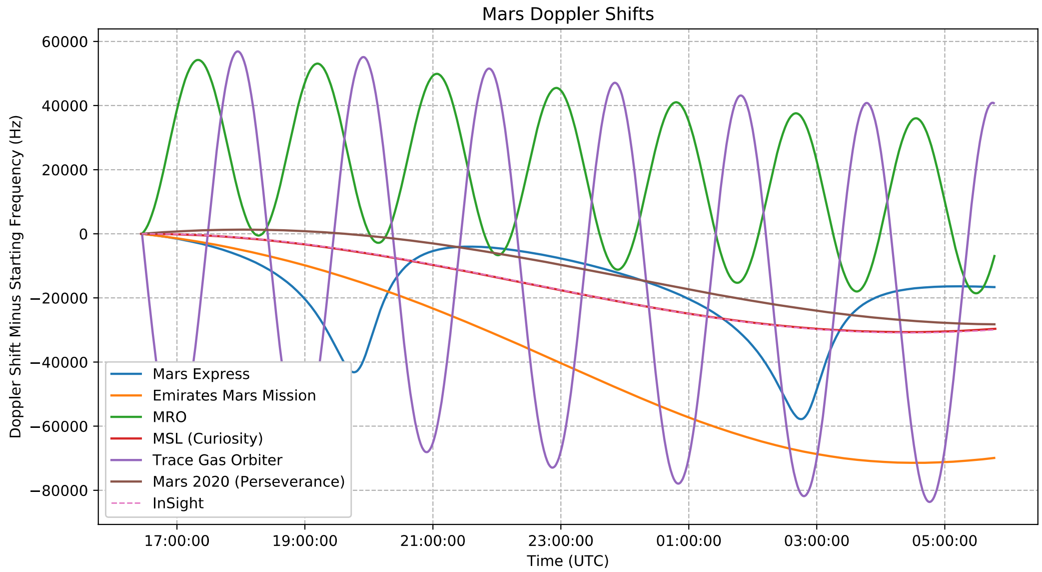

Figure 2. Representative Doppler shifts of seven spacecraft routinely tracked by the DSN over a single tracking pass a little over 8 hours in duration.

trajectory information and planetary ephemeris. Example Doppler shifts of Mars spacecraft are shown in Figure 2 over a single DSN tracking pass.

Important information can be determined by simply examining the Doppler shift. All spacecraft in Figure 2 have a gradual trend caused by the relative motion of Earth and Mars, as well as a 24-h periodicity due to Earth's rotation. Spacecraft in a low Mars orbit (for example, MRO) are clearly identifiable through their orbital period manifested in the Doppler shift. Landed spacecraft, such as Mars Science Laboratory (MSL), have a much larger periodicity due to the rotation of Mars manifested in the Doppler shift. Spacecraft in elliptical orbit, such as Mars Express and Emirates Mars Mission (Hope), have a periodicity larger than those in low Mars orbit but smaller than those of landers. The Doppler shift may be applied to not only the main carrier frequency (e.g., Table 1) but also any spurious tone transmitted from the spacecraft. Thus, to properly compare, one must correlate the Doppler shift of known assets against an unknown signal by applying a constant offset.

As an example, when the Chinese Zhurong rover began operations in Summer 2021, a new signal periodically appeared in the deep space spectrum. As shown in Figure 3, the Doppler shift of Zhurong was not characteristic of any known surface asset or orbital asset at Mars, and thus it was deduced that this novel signal appearing in the spectrum must have been the Zhurong rover.

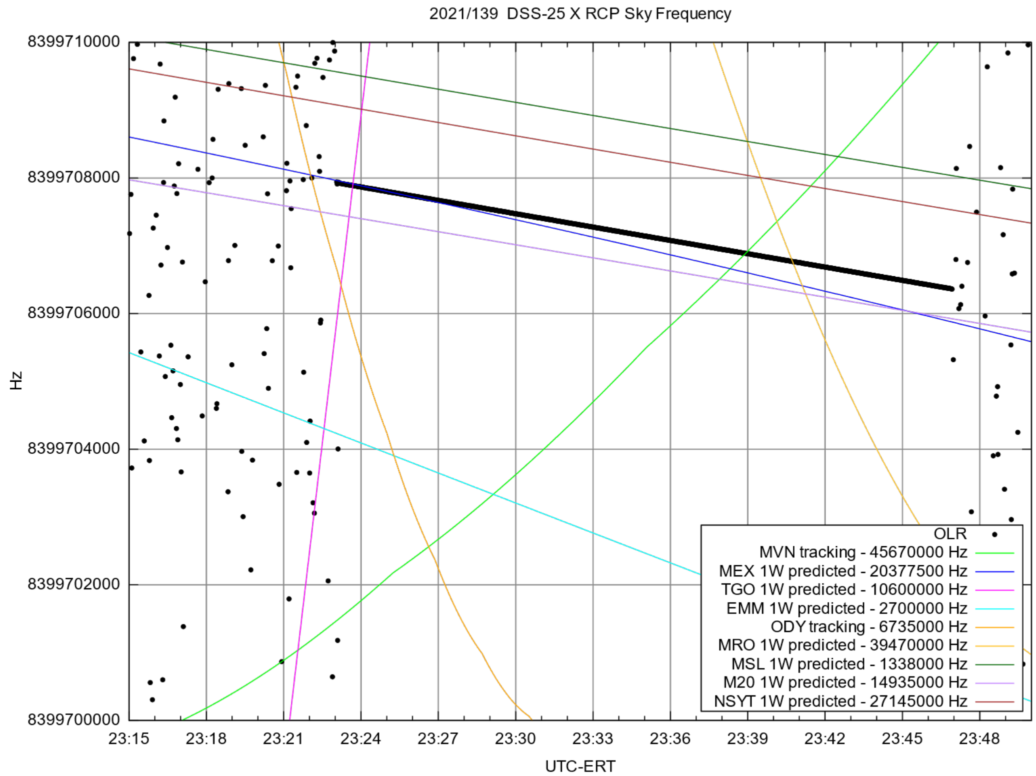

Figure 3. Comparison of a new unknown frequency observed (black dots) in the deep space X-band spectrum at Mars against known assets (colored lines), applying an offset to compensate in the event that this new signal was a spurious tone versus a new spacecraft. It was later determined this signal was coming from the Zhurong rover.

V. Examples of Observed Interference

A. Mars Global Surveyor – Mars Express Interference (2006)

X-Band radio interference from Mars was noticed as early as 2004, when there were only five assets at Mars (Mars Global Surveyor [MGS], Mars Express [MEX], Mars Odyssey, and the Spirit and Opportunity rovers). MEX joined Mars Odyssey and MGS in orbit at Mars on December 25, 2003, and in 2004 it was reported that the uplink from MGS had interfered with the MEX carrier lock onboard the spacecraft.[1] In 2005, DSN discrepancy reports were filed to document radio frequency interference affecting the MGS downlink carrier lock. The "bad" MGS one-way frequency was reported as equal to the MEX carrier frequency plus 2,796,310 Hz.[2] Radio science analysts at Stanford University also had been reporting anomalous signals in MGS radio occultation data recorded on the Radio Science Receiver (RSR)[3]. Upon investigation, the JPL radio science team was able to monitor such a tone in real time and, by monitoring MEX in parallel, witness the extinction of the secondary tone accompanying the MGS carrier as the MEX signal was extinguished by occultation.

[1] S. Kayalar, F. Morgan, M. K. Sue, "Analysis of the Observed MEX RFI Problem" [Interoffice Memorandum], 19 March 2004.

[2] S. Bryant, "MGS 1-way Carrier Frequency Interference" [Interoffice Memorandum], 14 June 2005.

[3] The RSR was the predecessor to the current OLR.

Figure 4 shows the real-time display of the open-loop spectrum on May 27, 2005, with the recording channel centered on the MGS signal and a secondary signal from MEX at right. By the same token, MEX bistatic radar data, typically recorded in a 25-kHz open-loop bandwidth, were found by the MEX radio science team to contain tones from MGS.

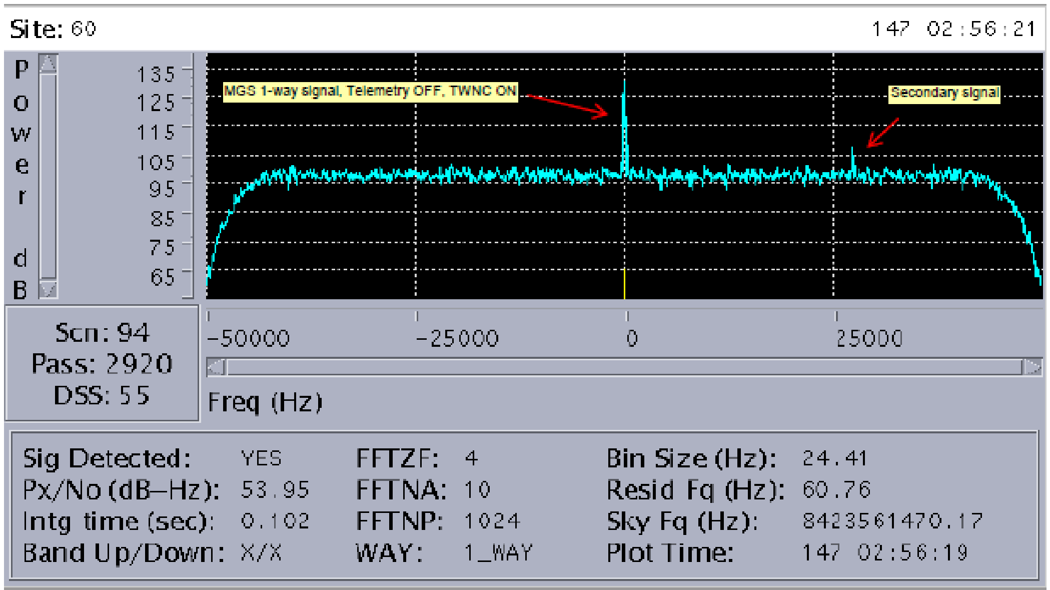

Figure 4. Real-time display of open-loop spectrum of MGS signal in two-way non-coherent mode (center) and a secondary signal from MEX (right) on May 27, 2005.

B. Mars Science Laboratory – Mars Odyssey Interference (2012)

During the first day of MSL's operations on Mars (Sol 1; August 6, 2012), an unexplained tone was detected in the open-loop data a little over 100 kHz from MSL's predicted frequency. Subsequent analysis by JPL's Spectrum Engineering Group confirmed the source to be the 14th harmonic of the Mars Odyssey subcarrier frequency. On November 8, 2013, the JPL Radio Science Group observed "a carrier at the expected MSL carrier frequency in preparation [for an] MSL track" (Figure 5). Similar to the first incident, the source was discovered to be the 23rd harmonic of the Mars Odyssey symbol rate while using direct carrier modulation. After the first incident, an investigation was launched to find a way to mitigate possible future interference. Recommendations were made to avoid future conflicts, including the creation of an interface control document for the avoidance of co-channel usage based on calculated predicts.

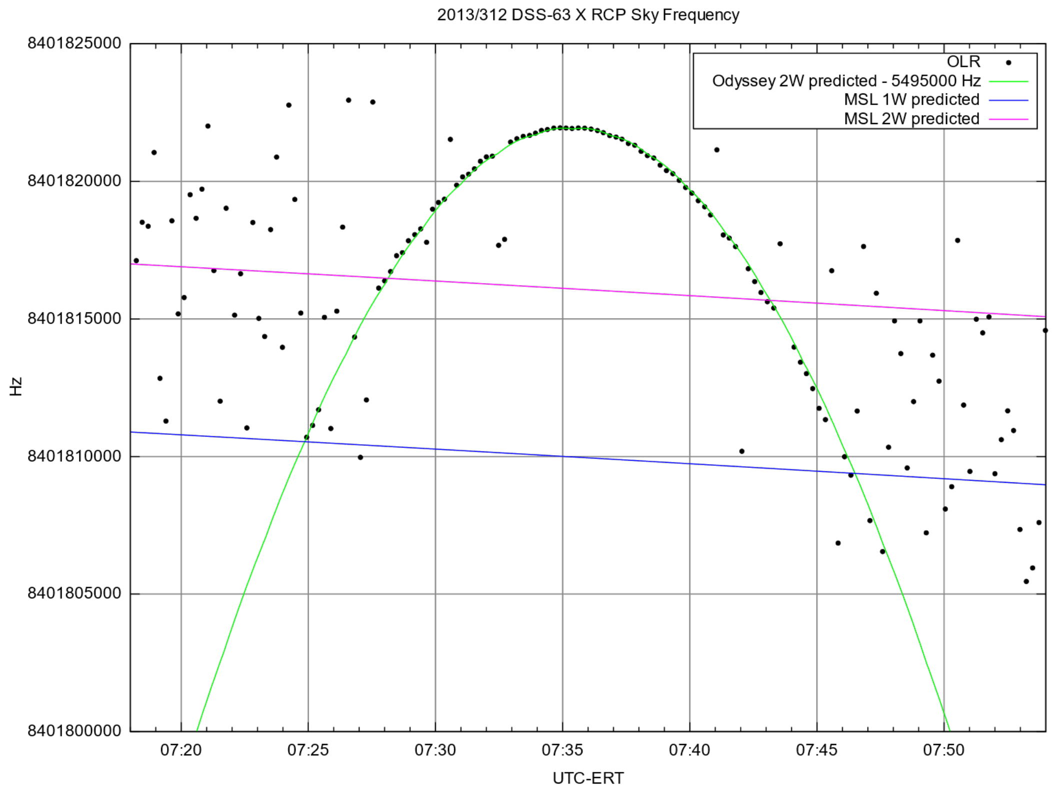

Figure 5. Open-loop analysis of the November 8, 2013, detected spur versus predicted Doppler profiles of MSL and Mars Odyssey.

C. Mars Cube One (MarCO) CubeSats – Mars Express Interference (2018)

Two CubeSats, MarCO-A and MarCO-B, were sent to Mars with the main InSight lander payload. The CubeSats relayed the lander's telemetry to Earth via X-band during InSight's entry, descent, and landing. During the event, while the DSN was searching for the MarCO-A downlink, a signal was noted by the DSN operator at 8,413.79 MHz, a few kHz of difference from the nominal MarCO-A downlink. A frequency offset was added to the predicts, and the operator was able to lock to the signal; however, there was no telemetry on the signal, indicating it was not MarCO-A. The operator broke lock to continue looking for the MarCO-A downlink. A follow-on analysis of open-loop data by the radio science team determined that the RFI was a signal from MEX, which was tracking in a three-way configuration with uplink from ESA's Cebreros Station (Figure 6). Tones from MRO, though not as strong, were also evident in the band.

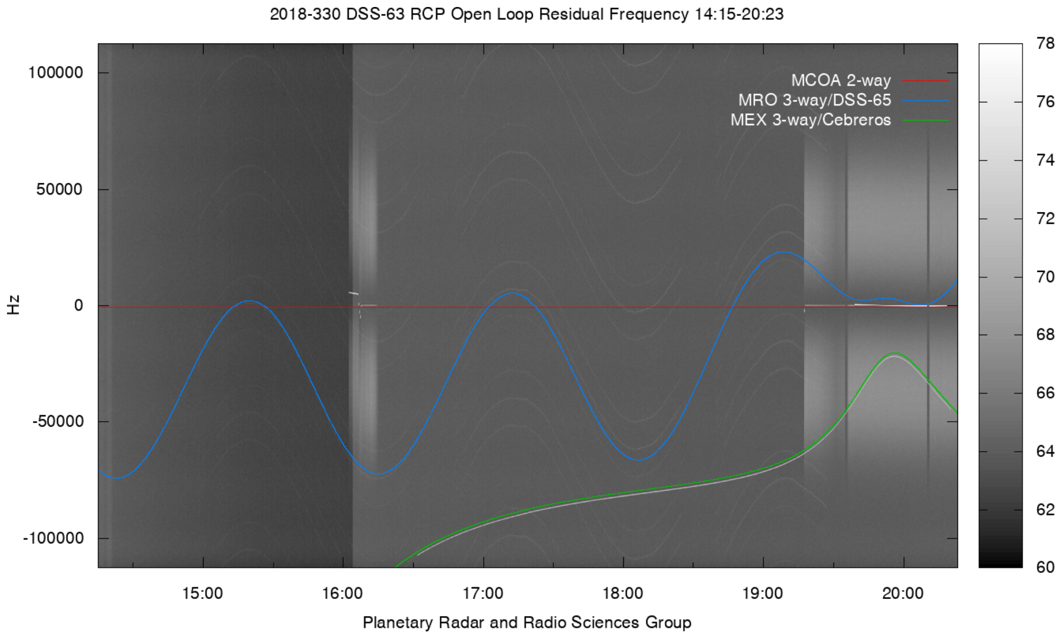

Figure 6. Spectrogram of open-loop data using MarCO-A predicts. Signal intensity is indicated by brightness. The red line denotes the center of the passband on MarCO-A predicts. The blue line denotes MRO predicts, and the green line denotes MEX predicts, each with a constant offset applied.

D. Mars 2020 – MAVEN Interference (2021)

Telemetry spurs interfering with rovers are not just experienced by MSL. On the very first day of operations of the Mars 2020 rover (Sol 1), a spurious signal was detected on the OLR at 21 kHz from Mars 2020's nominal predicts, about an hour after detection of Mars 2020's first X-band "beep" transmission and an hour before its first direct-to-Earth telemetry tracking. The spurious signal persisted throughout the telemetry tracking. Comparing the Doppler shift profiles, the source was proven to be a telemetry spur from MAVEN's Quadrature Phase Shift Keying telemetry encoding. This tone was also present prior to landing on approach to Mars and on numerous other tracks during subsequent surface operations. On the eighth day of surface operations (Sol 8), a different tone was observed. Using the same Doppler shift comparisons, the new tone was determined to be MEX (Figure 7).

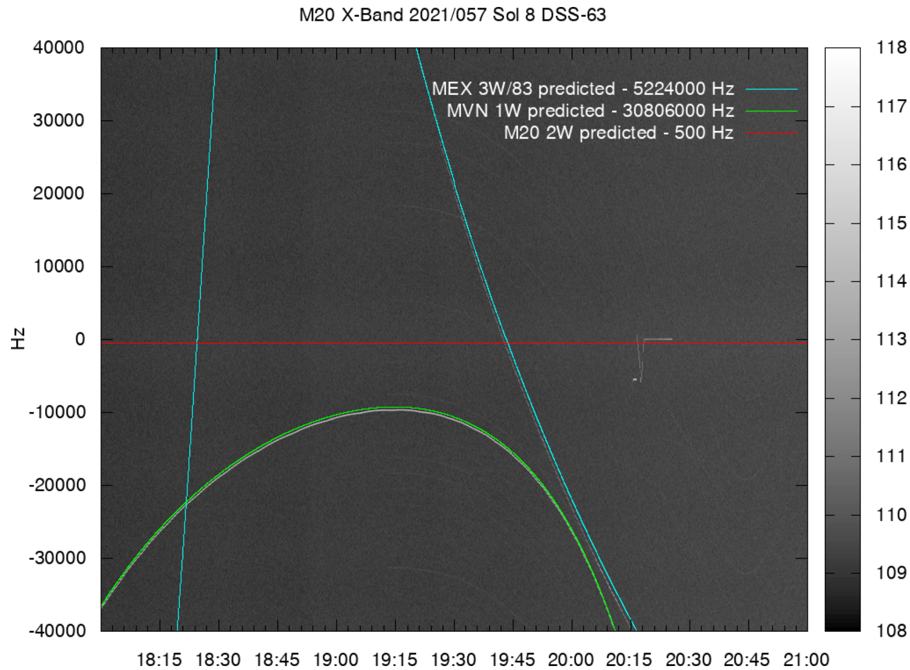

Figure 7. Spectrogram of open-loop data using Mars 2020 predicts. Signal intensity is indicated by brightness. The red line denotes the center of the passband. The green line denotes MAVEN predicts with a constant offset of 30,806,000 Hz. The cyan line denotes Mars Express predicts with a constant offset of 5,224,000 Hz.

E. Trace Gas Orbiter – Tianwen-1 (2021)

Around November 2021, TGO began experiencing unexplained telemetry dropouts over DSN tracks. The timing of the dropouts was sporadic, sometimes occurring numerous times during a tracking pass and sometimes going for hours without any incident. To investigate, the PRRSG began recording open-loop data of TGO's DSN tracking passes using the "blue" OLR, which required no additional effort on the part of either the DSN or the TGO project. Initially, wide bandwidths of several MHz were needed to capture the entire telemetry spectrum. With successive attempts, the parameters for viewing the spectrum were optimized, and thus it was not necessary to record large swathes of data.

Examination of the spectrum often revealed a tone around 1.25 MHz from TGO's carrier frequency. The frequency of this tone did not directly match any of the known carrier frequencies listed in Table 1. Furthermore, tracking over time revealed the tone's presence to be unrelated to the presence of the TGO carrier, which is easily known based on occultation times when the spacecraft flies behind Mars and the signal is blocked from Earth's view.

In order to determine the source of the tone, a 64-MHz OLR bandwidth was used, but by using a technique to capture the OLR's built-in Fourier transforms, the recording did not need to be saved. Figure 8 shows a representative example of the Mars spectrum on November 20, 2021, at 16:34:52 UTC. At this time, the carriers of Mars Odyssey, TGO, MEX, Tianwen-1, MRO, and MAVEN were all visible. Several other strong tones were also evident—a few of which were attributed to MRO and could be identified by their simultaneous appearance and disappearance when MRO was occulted by Mars as viewed from Earth. Figure 8 also labels four tones that appeared and disappeared coincident with the Tianwen-1 carrier. These tones were measured as multiples of a ~3.8 MHz increment in spacing from the Tianwen-1 carrier. The fifth harmonic of these tones was what fell near TGO's downlink.

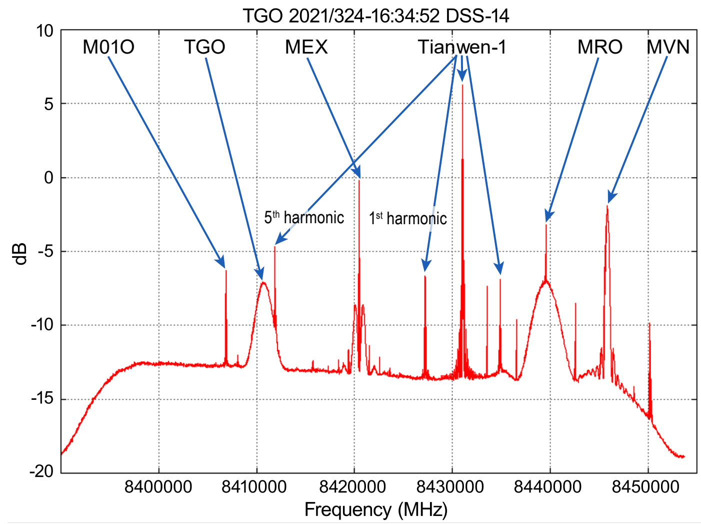

Figure 8. November 20, 2021, DSS-14 64-MHz spectrum.

With TGO transmitting at a 1.25 megasymbols-per-second telemetry rate, the tone fell very close to TGO's second harmonic. By using a narrower 4-MHz open-loop bandwidth as displayed in Figure 9, the Doppler profile of the interfering harmonic appears significantly different from that of TGO, as frequencies in the plot are referenced to TGO's carrier frequency. The difference of the Doppler shift between the tone and TGO's carrier is an integer multiple of the difference between Tianwen-1's carrier frequency and TGO's Doppler shift, indicating this tone is clearly coming from the Tianwen-1 spacecraft. Although not much is known about Tianwen-1's orbit or telemetry rates, it is presumed that either the occultation of Tianwen-1 or changes in telemetry rates are responsible for the changes in Tianwen-1's carrier and harmonics, and are thus the cause of the sporadic dropouts of TGO telemetry.

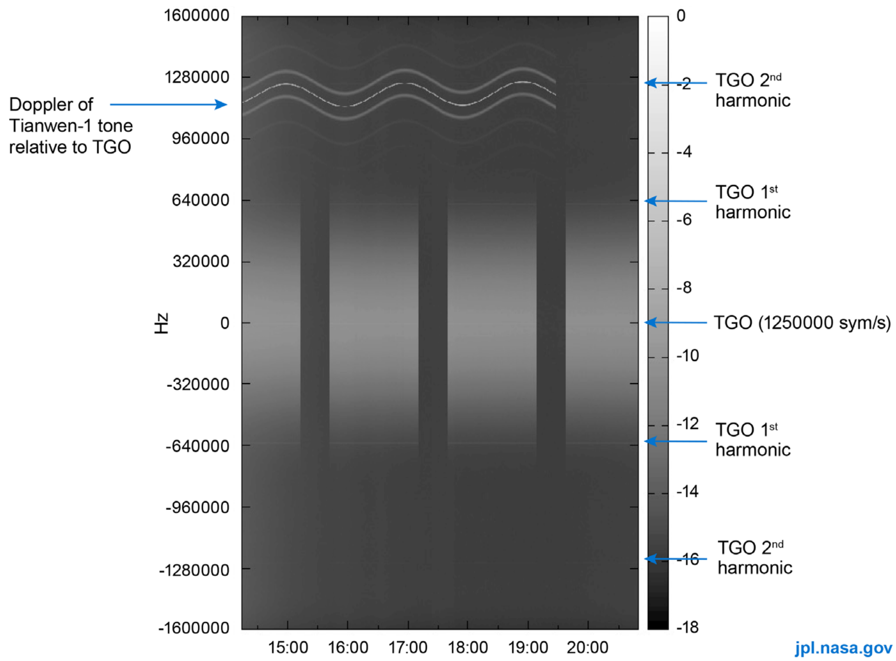

Figure 9. Spectrogram of 4-MHz OLR band centered at the TGO carrier frequency (November 30, 2021, DSS-25). Tianwen-1 tones can be seen crossing the first and especially the second harmonic of TGO.

VI. Conclusions

The Martian radio environment is very busy. Using the OLR of the DSN, the radio environment can be observed and radio frequency interference can be diagnosed. Since 2004, interference has been observed between assets in orbit or landed on the surface of Mars. The source of the interference mostly comes from a harmonic of another spacecraft's subcarrier, telemetry, or ranging tones, as seen with MSL and Mars Odyssey, Mars 2020 and MAVEN, and most recently TGO and Tianwen-1. Direct interference is possible, as seen in 2004 with MGS and MEX, and in 2018 with MarCO-A and MEX. The interference can be nondestructive or destructive. For example, in the case of Mars 2020, open-loop recordings mitigate the interference by allowing for easy separation between the signal of interest and the interfering tone. However, interference can be an issue, as seen with Tianwen-1 harmonics overlaying on TGO's telemetry encoding.

Interference can impede investigations when searching for missions in distress. For example, when the last confirmed signal from MGS was observed during routine operations on November 3, 2006, a spacecraft emergency was declared and the RSR was used to search for a signal from MGS. Although MGS was not detected, open-loop data revealed on numerous attempts the detection of a signal near MGS's predicted frequency. Further analysis revealed that the detected signals were, in fact, the result of MEX receiving the uplink intended for MGS and returning the signal to Earth, as originally reported in 2004. When attempting to detect both the Spirit and Opportunity rovers when they stopped transmitting at the end of their missions, telemetry tones from MRO were often present in RSR/OLR recordings. For Opportunity, while MRO tones were ever-present, MEX and MAVEN tones sporadically appeared on top of the MRO tones, requiring additional analysis to be proven as false positives.

Although the busy spectrum at Mars presents some problems as described above, it could also be leveraged for opportunistic scientific investigation. The introduction of an orbiter with open-loop X-band recording capability would allow for numerous radio occultation measurements done by cross-link configuration. Furthermore, surface scattering (bistatic radar) should provide strong echoes at both polarizations (right- and left-hand circular polarization) whenever the cross-link beam grazes the surface.

There are several additions to the Mars radio environment expected in the near future. The Escape and Plasma Acceleration and Dynamics Explorers (EscaPADE), a SmallSat mission to study the atmosphere of Mars, will be dropped off at Mars by the Psyche mission in 2024 on its way to the asteroid Psyche. Other potential arrivals include a Mars Orbiter Mission 2 by the Indian Space Research Organisation, Mars Sample Return by NASA, and efforts by SpaceX to accomplish the first landings of humans on Mars. With more spacecraft being planned for residency at Mars, the RFI issues mentioned in this paper will certainly persist and likely get worse.

Alternate approaches to mitigate interference will need to be developed, perhaps even with the telecommunications system design. An example of such mitigation at the design level may be a choice to use, instead of X-band, Ka-band links (32 GHz) where the spectrum allocation is much wider. In addition, because most spacecraft transmit at right-hand circular polarization (RCP), transmitting at left-hand polarization would reduce the strength of any tones seen by the RCP-transmitting missions. Careful selection of telemetry modulation could also reduce the impact of higher-order harmonics. Furthermore, improving monitoring techniques of the Martian radio environment will provide situational awareness and interference mitigation to telecommunications engineers and decision makers.

Acknowledgments

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