Demonstration of Mars Crosslink Occultation Measurements for Future Small Spacecraft Constellations

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Abstract—**Future planetary atmospheric profiling via radio occultations (RO) benefits significantly from increased received signal-to-noise ratio as well as geometrical coverage of links between two or more spacecraft in orbit around a target planet. These can be small spacecraft, possibly dedicated to quality radio-metrics with precision clock reference. Motivated by long-term research investigating the optimum SNR for the science performance, the optimum reference clock stability, the number and combination of wavelengths driving the number of transmitters and antennas, the optimum number and orbital spacecraft configuration, and design modifications to existing radio communication systems that would allow these new science objectives on future missions, three crosslink occultation experiments have been acquired between the Mars Odyssey and Mars Reconnaissance Orbiter spacecraft to probe the Martian atmosphere. While crosslink occultations between Earth orbiting satellites have long been used to profile the Earth's atmosphere, this represents the first demonstration of crosslink occultation measurements at another planet. These measurements leverage the proximity link telecommunication payloads on each orbiter, which were designed to provide relay communication and navigation services to Mars landers and rovers. Analysis of the observed Doppler shift on each crosslink measurement reveals a clear signature of the Martian atmosphere, primarily the ionosphere. Inversion of the observed Doppler data yields vertical profiles of the Martian refractivity and electron density. The electron density profiles show the presence of two layers with peak densities and peak heights that are consistent with empirical models.**

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1. INTRODUCTION

From the earliest interplanetary missions, spacecraft communication systems have been exploited to carry out scientific measurements. Radio Science has utilized the radio links between spacecraft and Deep Space Network (DSN) antennas to study the properties of many solar system bodies including their rings, atmospheres and interiors, as well as to advance studies of the solar wind and fundamental gravitational physics. Radio occultations have successfully been applied at numerous solar system targets in the downlink mode using spacecraft-to-Earth communications links (e.g., S-, X, or Ka-bands) in the traditional one-way downlink mode (see decadal paper by Asmar et al, 2009). Monitoring the changes in Doppler profile on the radio links as they pass through an atmosphere provides information on the atmospheric refraction of the signal, leading to vertical profiles of temperature and pressure in the atmosphere. At upper altitudes, the signal variations can track changes in the ionospheric vertical density profile, often using dual frequency measurements to better separate neutral and charged atmospheric components. However, occultations between a planetary orbiter and Earth happen only a few times a day, leading to sparse coverage of atmospheric properties.

Recent advances in spacecraft communication technology are providing exciting additional opportunities for science measurements with these systems. Development thrusts include utilizing software-defined radios, which allow the recording of science data on spacecraft rather than the Earth and enable spacecraft-to-spacecraft links, also known as crosslinks, and ground-to-spacecraft links (one-way uplink occultations), recently demonstrated by New Horizons at Pluto, see Linscott et al, 2011. These links can have the signal-to-noise (SNR) increased by nearly 1000 times relative to the traditional downlink to Earth (there are losses due to increased system noise temperature). Earth science colleagues have started to apply these Radio Science techniques to Earth's atmosphere and have pioneered the use of radio links between Global Positioning Satellites (GPS) and specially-instrumented orbiters to provide much

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higher daily numbers of occultations with much greater global coverage, thus enhancing the study of Earth atmospheric dynamics with unprecedented temporal and spatial sampling of the Earth's atmosphere (Kursinski et al., 1997 and Hajj et al., 2002). Crosslink constellations at Earth have proven to be highly effective atmospheric science tools that uniquely provide very high vertical resolution profiles sufficient to distinguish sharp vertical atmospheric stratification, as exists near the planetary boundary layer and the troposphere/stratosphere boundary. Another feature of these constellations is atmospheric pressure registered at geometric altitudes, used to derive geostrophic atmospheric winds. Finally, cross-link constellations frequently sample the diurnal cycle independently of the seasonal cycle, which is not possible from atmospheric sounders on single platforms.

Our team is in the process of promoting crosslink occultations proven at Earth at Mars and other planetary targets. Towards that goal, we have carried out the demonstrations described below and are currently researching the optimization of future experiments with advanced instrumentation as well as orbital/geometrical considerations.

2. RESEARCH OBJECTIVES

We are investigating the following five parameters relevant to advancing radio occultations on future small spacecraft constellations: (1) the optimum SNR for the science performance, especially important at planetary targets with significant absorption, driving link budgets, (2) the optimum stability driving clock requirements, (3) the number and combination of wavelengths driving the number of transmitters and antennas, (4) the optimum number and orbital configuration of small spacecraft required for specific scientific objectives, and (5) design modifications to existing radio communication systems that would allow these new science objectives for envisioned future missions.

Our previous simulations have demonstrated the rapid reduction in the time span needed to obtain dense global occultation coverage via crosslinks between only two spacecraft, which is two weeks, compared to single spacecraft links to Earth, which is many years as shown in Figure 1, which plots potential crosslink coverage for an Odyssey to MRO crosslinks, as an example. The number of occultations would grow rapidly as the number of orbiting spacecraft increased, although implementation of such crosslinks on two or three orbiters around a single body would still be a significant advance.

The most effective technique for future occultation studies of the atmospheres of other planets and moons would be spacecraft-to-spacecraft radio links, the focus of this research. Such crosslinks would enable higher SNR than links to Earth as well as rapid global geometrical coverage for temperature-pressure and ionospheric density profiling, as demonstrated through our simulations. For obvious cost reasons, crosslinks can be enabled via future constellations of small spacecraft such as cubesats at planetary targets and could fly piggyback on already planned missions with enhanced instrumentation.

The technical approach is based on science-driven questions to assess how adequate constraints on planetary atmospheric structure can be determined for given combinations and families of available and possible signal powers, choices of wavelengths, and temporal and spatial occultation coverage. It is necessary to carry out a detailed investigation of link budgets, transmit/receiver options, and frequency band selection fitting into small spacecraft economics of cost, size, power, mass, longevity, radiation tolerance, etc.

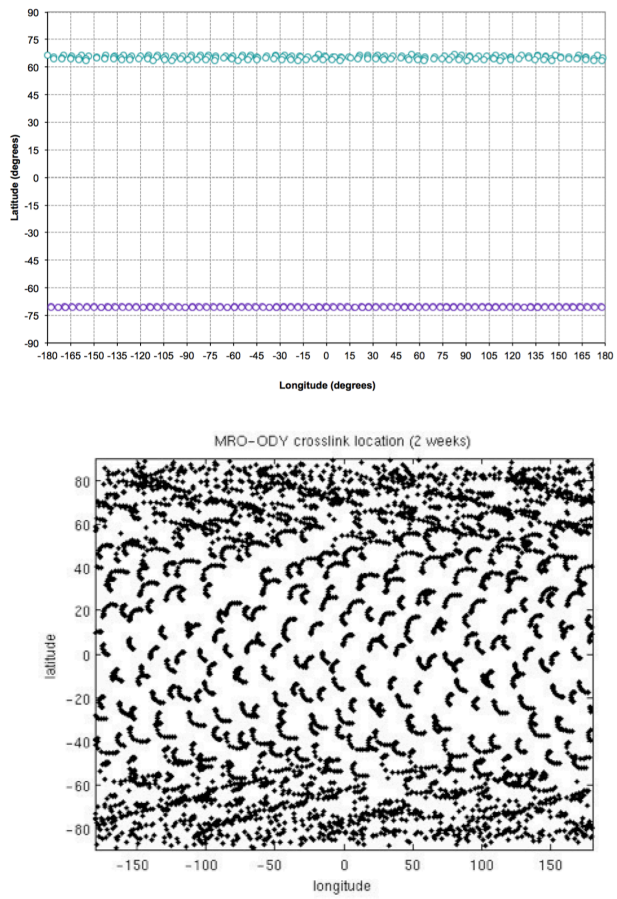

Figure 1: The upper panel shows actual surface distribution of Mars coverage from two weeks of occultation with MRO single spacecraft, traditional downlink to Earth, while the lower panel shows simulated Mars coverage from two weeks of crosslink occultations with two spacecraft.

4. UHF DEMONSTRATION AT MARS

On September 10, 21, and 26 of 2007, we conducted a three-pass technical demonstration of crosslinks at UHF between two Mars Odyssey and MRO as illustrated in Figure 2, using Electra on MRO as the receiving instrument (Ao et al, 2015). In that period, Odyssey operated in a ~400 km sun-synchronous near-polar orbit. It is equipped with Cincinnati Electronics-505 UHF transceivers for relay

communications, transmitting 12 W at 437.1 MHz on the forward link derived from an external oscillator with a pre-launch characterization of few parts in 10^{-12} Allan deviation for 1 to 1000 second sampling times. A quadrifilar helix antenna mounted on the nadir deck provides a broad radiation pattern, with an on-boresight gain of 4.8 dBic and a 3 dB half-beamwidth of ~52 deg.

MRO operated in a 255 x 320 km sun-synchronous orbit, with an ascending node at 3 PM LMST and utilizes Electra UHF transceivers for proximity link services, and capable of operating over the full 390-450 MHz band. Electra derives its frequency reference from an Ultra-Stable Oscillator (USO) with a pre-launch characterization of of ~$4x10^{-13}$, ~$9x10^{-13}$, and ~$2x10^{-12}$ Allan deviation at 1, 100, and 1000 second sampling times, respectively. MRO transmits a 7 W signal utilizing a nadir deck-mounted quadrifilar helix low-gain antenna, similar in design to Odyssey's antenna.

Key to the success of radio occultations for a software-defined radio is the ability to acquire a high-fidelity open-loop recording of a received signal, which Electra has. During the demonstration passes, the received UHF signal was down-converted to baseband, filtered, and Nyquist sampled at rates of up to 150 kHz, then the in-phase and quadrature components of the baseband signal with 8-bit resolution were subsequently downlinked to Earth for post-processing.

The demonstrations took place, as illustrated in Figure 2, when communication sessions between Odyssey and a Mars Exploration Rover occurred while MRO is on the other side of the planet but in view of Odyssey and the rover. Since no technical or sequence changes were proposed, the timing was opportunistic. During the sessions, Odyssey transmitted a UHF signal towards the rover but in view of MRO, which received the signal via the Electra payload. The Local True Solar Time (LTST) is ~ 15:00 at the start of the three events.

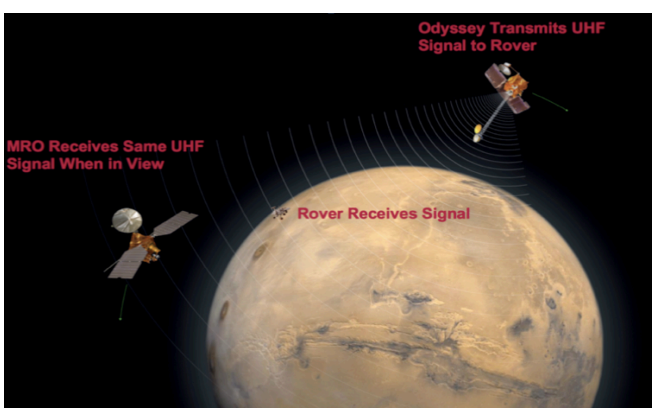

Figure 2: Illustration of Odyssey to MRO UHF demonstration

A link budget is detailed in Ao et al, 2015 with the result that an estimated carrier loop power SNR of 52.3 dB-Hz for a 1-sec integration time, at the UHF frequency of 437.1 MHz, making the thermal noise contribution negligible.

6. Overview of Results

After Ao et al (2015), Figure 3 shows the spectrograms of the recorded signal with Electra's running time along the vertical axis and frequency on the horizontal axis. Since tuning predictions were not applied and the recorder was tuned to a constant frequency, the signal is Doppler shifted and appears as the vertical, curved lines; the centermost line is the carrier, while the lines parallel to it are harmonics of the subcarrier frequency. The positive Doppler shift is due to the orbiters moving towards each other at the beginning then negative shift as they move away from each other, spanning ~14 kHz; the straight lines are treated as internal electromagnetic interference.

The key scientific observable is frequency versus time. The Fast Fourier Transform software finds the frequency with the highest signal-to-noise ratio within the bandwidth and fits the curve to a sinc function in order to fine-tune the result and acquire greater precision. Special techniques were applied to avoid the interference lines.

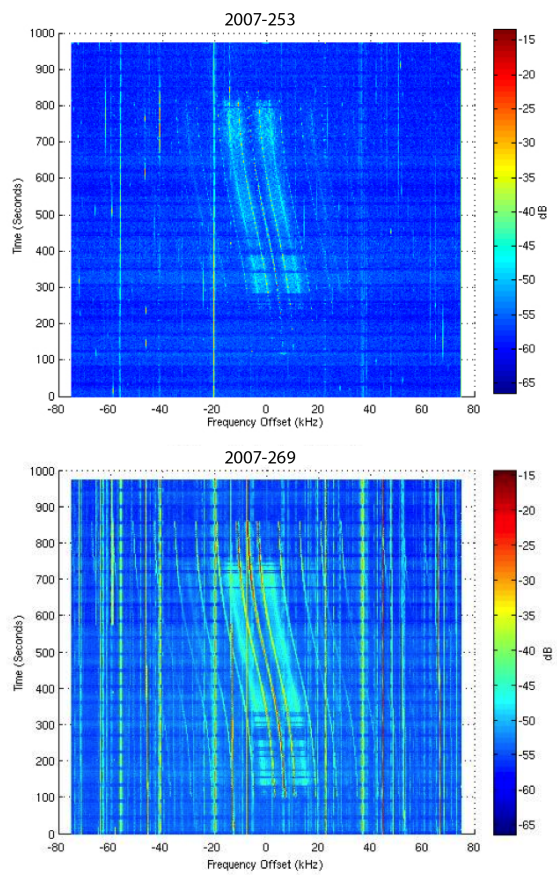

Figure 1: Spectrograms of the UHD (437.1) signal transmitted by Odysse and received in an open-loop mode by MRO's Electra payload for 2007 Day 253 on top and Day 269 on the bottom.

A model of the Doppler shift based on the reconstructed relative motion of the two orbiters is then applied to produce frequency residuals, which are then attributed to the effects of the Martian atmosphere. A ~2 mm/s error in line-of-sight velocity yields ~3 mHz error in the residual Doppler. However, the residual Doppler from the atmosphere and ionosphere has a maximum of about 0.3 Hz, this corresponds to a relative error of ~ 1%.

Figure 4 shows the residual Doppler, the profile after subtracting known orbital motion, and identifies the clear signature of both ionosphere and atmosphere from one of the demonstrations (DOY 269). Figure 5 shows a representative ionospheric density profile from one of the demonstrations.

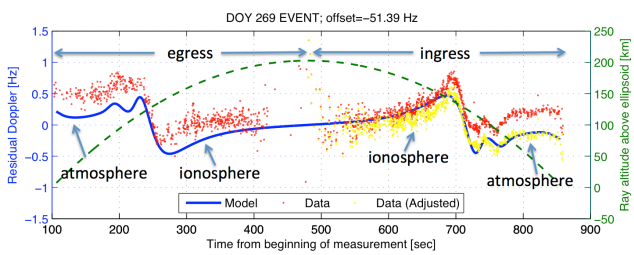

Figure 4: the scientific parameters of interest, the signatures of the Martian neutral atmosphere and ionosphere are clear in the Doppler profile after removing effects due to the relative motion between the two orbiters on the two ends of the crosslink.

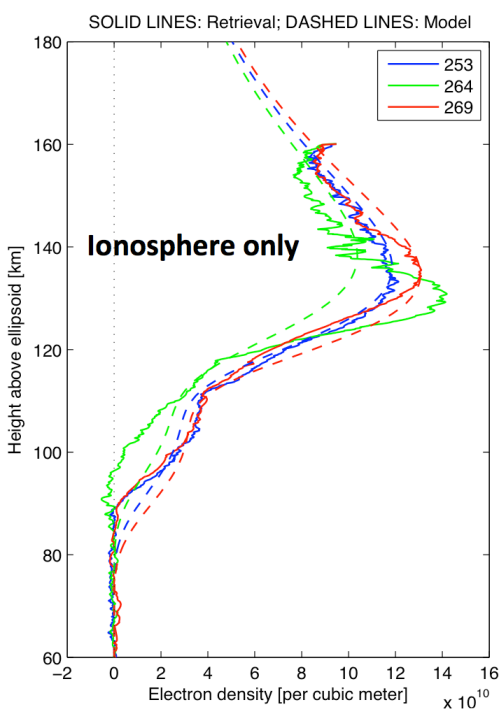

Figure 5: representative ionospheric density profile obtained from a Mars UHF crosslink demonstration.

From Figures 4 and 5, the team has demonstrated the feasibility of such experiments and produced typical atmospheric profiles consistent with our scientific knowledge of the Martian atmosphere. However, due the lack of two USOs in the link, one on each side, the end-to-end quality of the data is not optimum. The ongoing research addresses the optimization of parameters for proposing future experiments, with the addition of USOs being the first priority. Other work currently in progress includes generating a science traceability matrix, and the inventory of choices in available and expected future radio systems, with emphasis on software-defined radios.

The science traceability matrix relates the overall goals of characterizing the atmospheric dynamics globally over time (annual, seasonal, diurnal, etc.) with specific science objectives such as producing temperature-pressure profiles and ionospheric density profiles globally. Furthermore, it describes the observables such as the phase variations during the refractivity and bending period a well as other instrumental and mission-design functional requirements. The instrument requirements include the functionalities of the radio system.

Radio systems examined to date include Electra, which has a long of flight record and whose Radio Science performance had been examined under a previous task called RASSI, and the JPL Iris radio recently developed for communications with planetary cubesat missions. The research also includes future software-defined radio models such as the Universal Space Transponder (UST) and a variation of the COSMIC radio used in Earth radio occultation experiments. If the proposed future crosslink missions are of the small form-factor (such as cubesats), the size, power, and mass resources would become a prime consideration for the choice of radio, amplifier, antennas, and the number of possible simultaneous links.

7. SUMMARY

The demonstrations described here for UHF crosslinks at Mars were opportunistic and did not introduce changes to the normal operations of the Martian orbiters involved. However, they were critically important and successful in demonstrating the first ever planetary (other that at the Earth) radio occultation with potential to study the structure of the planetary atmosphere. With the known and discovered error and noise sources, the resulting recovered signal was not ideal. They helped fine-tune the understanding of the error sources and prepare the team for a design of future experiments with future spacecraft capable of overcoming the known noise sources. In Ao et al (2015) we detail the resulting atmospheric profiles along with complete error analysis.

This three-pass demonstration proved that the team's research to prepare for future crosslink occultations at Mars and other planetary targets. Of the five investigation areas, clock stability was a factor in degrading the quality of the

profile. As expected, SNR was not a significant factor, which is one of the primary drivers for crosslinks, along with fast global coverage. Good insight was obtained into orbital geometries and planetary coverage, supplemented by simulations.

Future constellations of small spacecraft equipped with science-quality software-defined radios, capable of reception and storage of open-loop samples would enable scientists to explore the ionized and neutral layers of planetary atmospheres and characterize their structure.

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