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Radio science at low SNR – Radio occultation observations at Mars with the MAVEN low gain antenna

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Abstract

Interplanetary radio science observations are generally conducted using a telemetry-free radio signal and the spacecraft's high gain antenna. However, those requirements can be incompatible with other spacecraft operations. For this reason, the MAVEN Radio Occultation Science Experiment (ROSE) was originally limited to acquiring two pairs of radio occultation observations each week. In order to improve the scientific yield of the investigation and to increase the number of radio occultation observations acquired, the MAVEN ROSE team has also conducted two-way X-band radio occultation observations using the spacecraft low gain antenna with telemetry on the radio signal. Here we report the performance achieved by these opportunistic low gain antenna observations and compare it to the performance of dedicated high gain antenna observations. The results support planning for radio science investigations on future missions that are limited to low SNR.

Keywords: Mars; MAVEN; radio occultation

1. Introduction

Radio occultations are a common method for making remote sensing measurements of vertical profiles of ionospheric electron density and neutral atmospheric density at solar system objects [1-5]. In such observations, a radio signal is sent from a transmitter to a receiver at a time when the ray path between transmitter and receiver passes through the ionosphere and atmosphere of a target object. The transmitter is often on a spacecraft, and the receiver is often an antenna of the NASA Deep Space Network (DSN) on Earth. The value of the received radio frequency is affected by refraction in the ionosphere and atmosphere of the target object. The "frequency residual" is defined as the difference between observed and predicted values of the received frequency, where the predicted frequency includes all effects except refraction at the target object. The time series of the frequency residual can be analyzed to determine the vertical distribution of ionospheric plasma and neutral species at the target object [2,6]. Observations of the vertical profile of the electron density in the ionosphere of Mars are scientifically useful for investigating the behavior of this region at the interface between the planet and the surrounding space environment.

Normally, radio occultation observations are conducted using a carrier-only radio signal and the spacecraft's high gain antenna (HGA), which imposes significant operational requirements. The HGA must be pointed at Earth, which may prevent the spacecraft from acquiring certain other scientific observations. Moreover, although these observations are conducted during a period when a large aperture antenna on Earth is devoted to supporting this spacecraft, it is not possible for the spacecraft to receive uplinked commands or to transmit downlinked telemetry to Earth during such observations.

These restrictions were keenly felt by the MAVEN Radio Occultation Science Experiment (ROSE) [7]. MAVEN is a NASA spacecraft that entered orbit around Mars in 2014, and MAVEN ROSE is a two-way, single-frequency (X-band) radio occultation investigation that uses the DSN to measure vertical profiles of ionospheric electron density at Mars. MAVEN ROSE requires a two-way coherent radio link to measure Mars's ionosphere as MAVEN does not have an ultrastable oscillator (USO) on board. When MAVEN's orbital geometry is favorable, one pair of ingress and egress occultations occur every orbital period (about 4.5 hours). Yet, as MAVEN has biweekly dedicated communications periods that are not much longer than the orbital period, the normal radio occultation scenario outlined above only permitted ROSE to observe two pairs of occultations each week. Additional observing opportunities would be scientifically beneficial.

Here we describe how MAVEN ROSE has overcome these limitations by successfully developing and implementing an alternative observing scenario that imposes fewer operational requirements.

2. Opportunistic observations with MAVEN's low gain antenna

Outside the biweekly dedicated communications periods that use the HGA, MAVEN also communicates with Earth at other times using its low gain antenna (LGA), which has a much broader beam-width and does not require precise pointing towards Earth. At those times, the DSN usually operates in "Multiple Spacecraft Per Aperture" (MSPA) mode, in which multiple spacecraft at Mars communicate with a single DSN antenna. More specifically, multiple spacecraft can downlink to the DSN antenna, but only one can maintain a two-way coherent link with an uplink signal received from the DSN antenna. When the uplink is assigned to MAVEN, then a two-way coherent radio link suitable for occultation observations can be established. Such occultation observations use the LGA with telemetry included on the radio signal. They can only be conducted for ingress observations as the activities of the spacecraft communication systems on egress are incompatible with occultation observations.

The only operational impacts of opportunistic LGA observations occur at the DSN, where specialized receivers are used for the portion of the communications period in which an occultation is observed. The spacecraft is not impacted at all. Indeed, the MAVEN ROSE team can work with the DSN to acquire a radio occultation observation without needing to involve or inform the spacecraft operations team.

3. Results and discussion

We illustrate the performance of MAVEN ROSE's opportunistic LGA observations compared to its dedicated HGA observations. We focus on two ingress observations separated by less than 5 hours – an LGA observation at 23:42 on 29 June 2018 and an HGA observation at 04:09 on 30 June 2018.

Figure 1 shows the signal-to-noise ratio (SNR) time series during these two observations. The central portion of each panel, where the SNR is approximately 15 dB-Hz, is when the spacecraft is occulted from the view of Earth by the solid body of Mars. The ingress occultation occurs before this, and the egress occultation occurs after it. During the occultations, the SNR is approximately 33 dB-Hz for the LGA observation and approximately 70 dB-Hz for the HGA observation. On either side of the carrier-only HGA observation (before ingress and after egress), telemetry is switched on and the SNR is smaller, around 40-45 dB-Hz.

Figure 2 shows the time series of the frequency residual during these two observations. Qualitatively, the shape of this time series is characteristic of ingress occultations of Mars [8]. The ionosphere is responsible for the set of positive values around 0.1 Hz and the neutral atmosphere is responsible for the later set of negative values that greatly exceed the range shown here. Quantitatively, the values of the frequency residual around the ionospheric feature reveal the vertical profile of electron density in the ionosphere of Mars. The two sets of frequency residuals look very similar, which indicates that there are no glaring systematic errors in the LGA observation. The root-mean-square of the frequency residual values at early times before the ionospheric feature indicates the experimental noise: 0.012 Hz for the LGA observation and 0.007 Hz for the HGA observation. Although the signal power is reduced by a factor of more than 1000 from the HGA to the LGA observation, the overall noise is merely doubled.

Figure 3 shows vertical profiles of ionospheric electron density from these two observations. Note that the large and negative electron density values at low altitudes are not realistic electron density values. They are a signature of the neutral atmosphere that is present due to a deliberate design decision for the data processing pipeline. They should be neglected [7]. The two electron density profiles look very similar. The differences that do exist are consistent with intrinsic variability in the environment of Mars and do not imply that any glaring systematic errors are present in the LGA observation. The root-mean-square of the electron density values at high altitudes above the ionospheric feature indicates the uncertainty in the derived electron density values: 3.2×10^9 m^{-3} for the LGA observation and 1.6×10^9 m^{-3} for the HGA observation.

We now extend our scope beyond these two sample observations to the full extent of the MAVEN ROSE dataset. Figure 4 shows how electron density uncertainties in LGA and HGA observations have varied between 2016 and 2022. Average uncertainties are 6.0×10^9 m^{-3} (LGA, telemetry on) and 3.7×10^9 m^{-3} (HGA, carrier only). The striking systematic variations in uncertainties with time are influenced by the Earth-Sun-Mars geometry. Uncertainties are greatest when Mars is close to opposition [9].

4. Conclusions

Opportunistic LGA radio occultation observations by MAVEN ROSE with telemetry on have been technically and scientifically successful.

The SNR is typically 30-35 dB-Hz for LGA observations and 65-70 dB-Hz for HGA observations. The corresponding uncertainties in the ultimate scientific data product, vertical profiles of electron density in the ionosphere of Mars, are typically 6.0 x 10^9 m^{-3} for LGA observations and 3.7 x 10^9 m^{-3} for HGA observations.

The acquisition of LGA observations increases the number of ionospheric electron density profiles by a factor of 2-3, with some periods having particularly high cadences of LGA observations. HGA observations occur in ingress/egress pairs two times per week, whereas LGA observations have occurred as frequently as four times per day. This is valuable for investigating time-variable ionospheric phenomena, such as responses to dust storms or solar events. For example, the discovery that energetic protons are responsible for sporadic nightside instances of unusually high densities at unusually low altitudes used 4 HGA and 13 LGA profiles within a two-week period [10].

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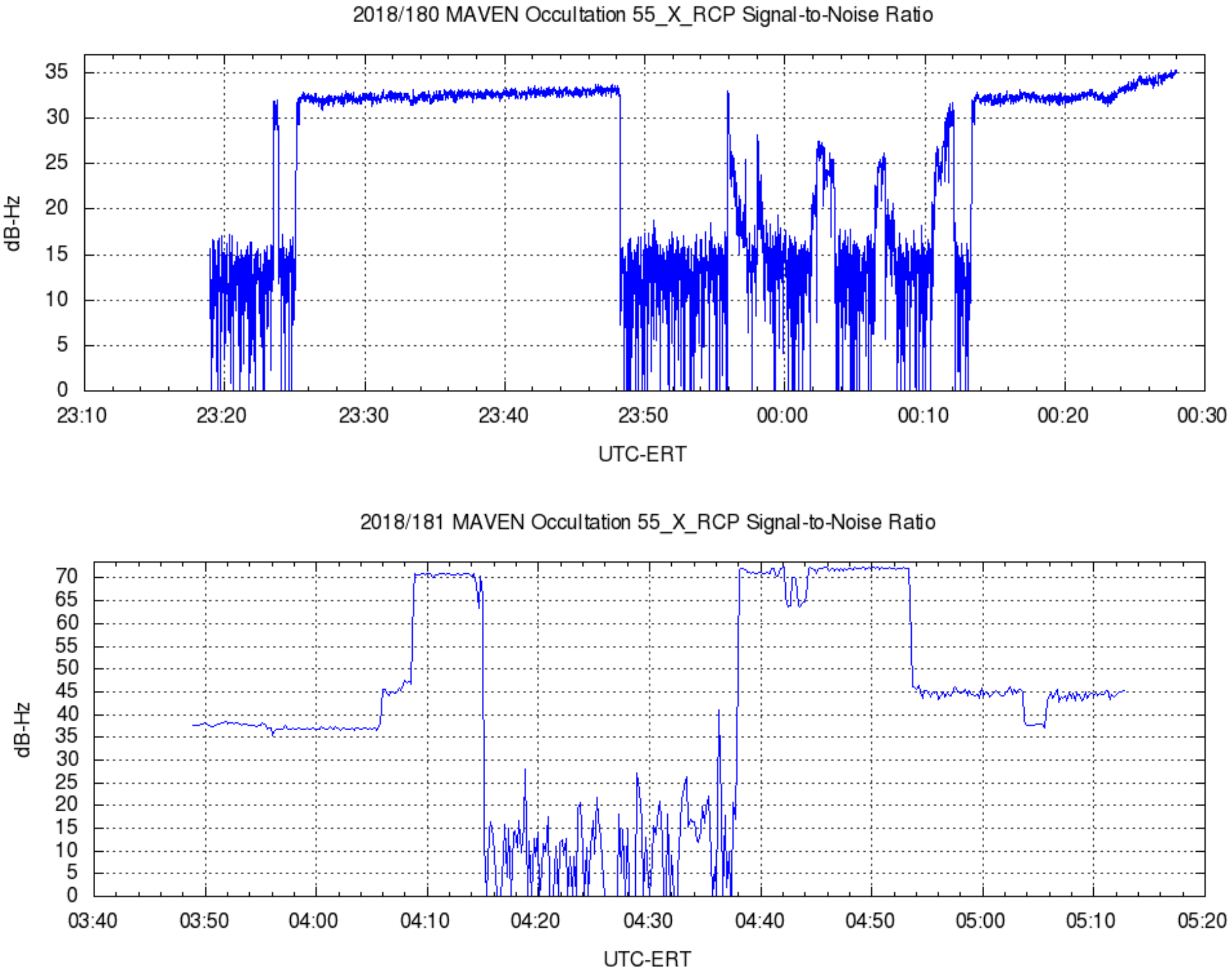

Fig. 1. Time series of SNR for LGA observation at 23:42 on 29 June 2018 (top panel) and for HGA observation at 04:09 on 30 June 2018 (bottom panel).

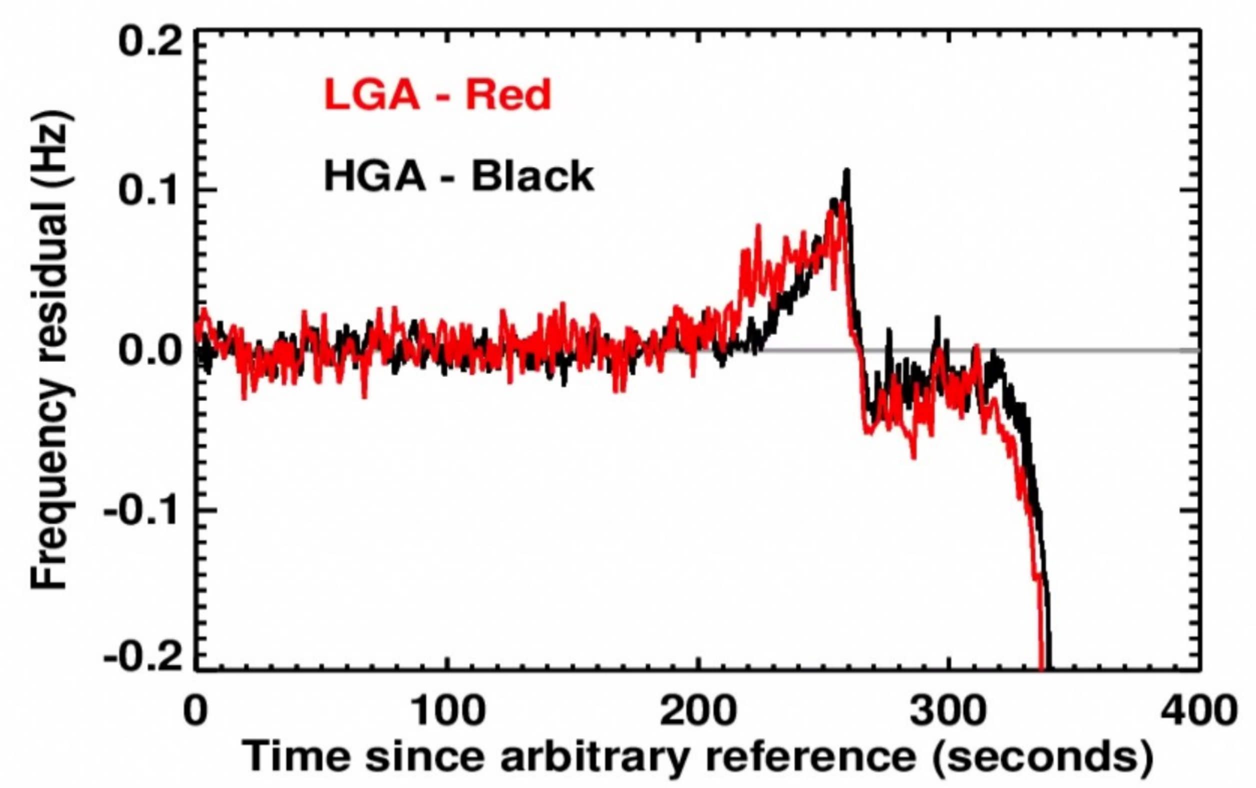

Fig. 2. Time series of frequency residual for LGA observation at 23:42 on 29 June 2018 (red) and for HGA observation at 04:09 on 30 June 2018 (black).

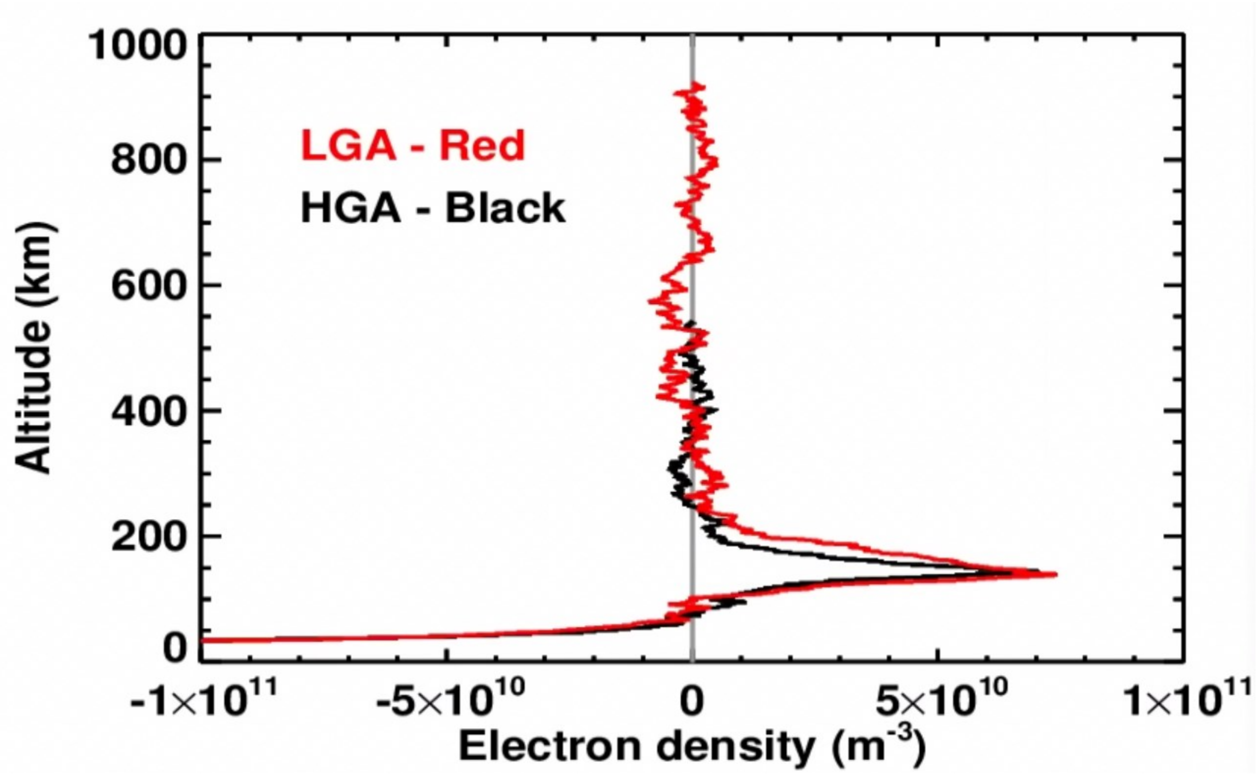

Fig. 3. Electron density profiles for LGA observation at 23:42 on 29 June 2018 (red) and for HGA observation at 04:09 on 30 June 2018 (black).

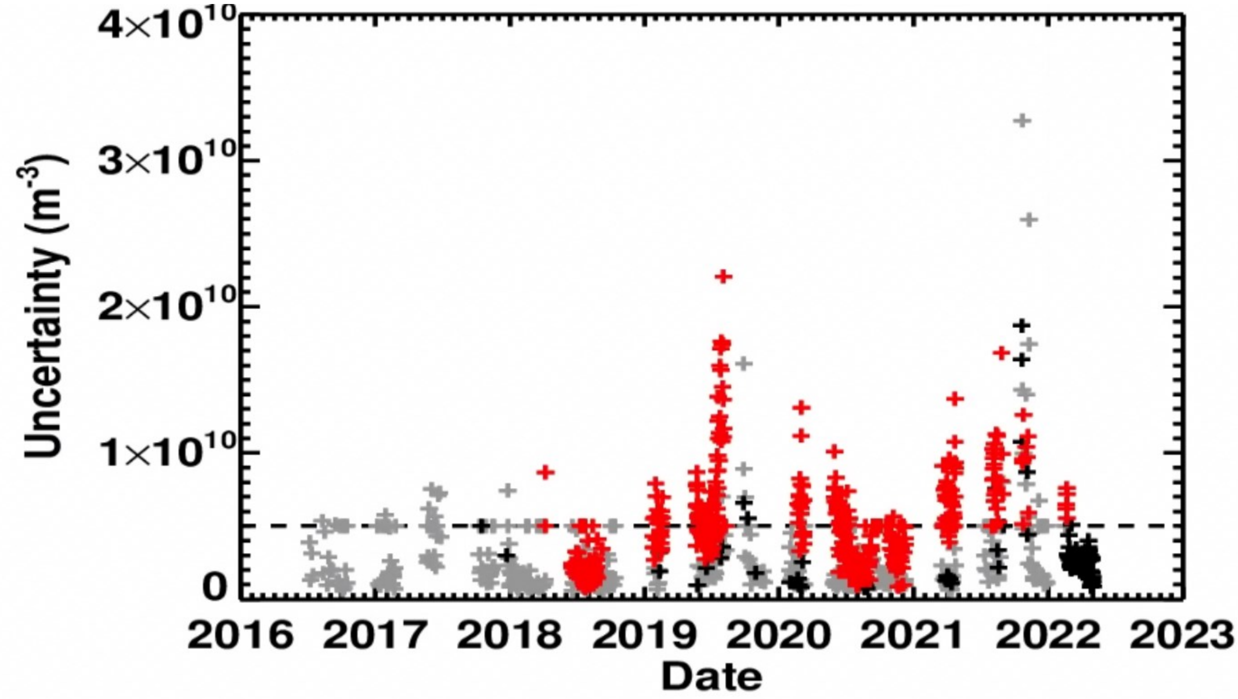

Fig. 4. Electron density uncertainties over the full extent of the MAVEN ROSE dataset. Grey symbols indicate HGA/carrier-only observations, black symbols (rare) indicate HGA/telemetry-on observations, pink symbols (rare) indicate LGA/carrier-only observations, and red symbols indicate LGA/telemetry-on observations. If an electron density profile does not extend to high enough altitudes to yield a direct determination of uncertainty, then the default value of 5 x 10^9 m^{-3} is adopted as the uncertainty.