Comparing Radio Occultation Results from MarCO with Mars Reconnaissance Orbiter and MAVEN: Achievable Radio Science with a CubeSat

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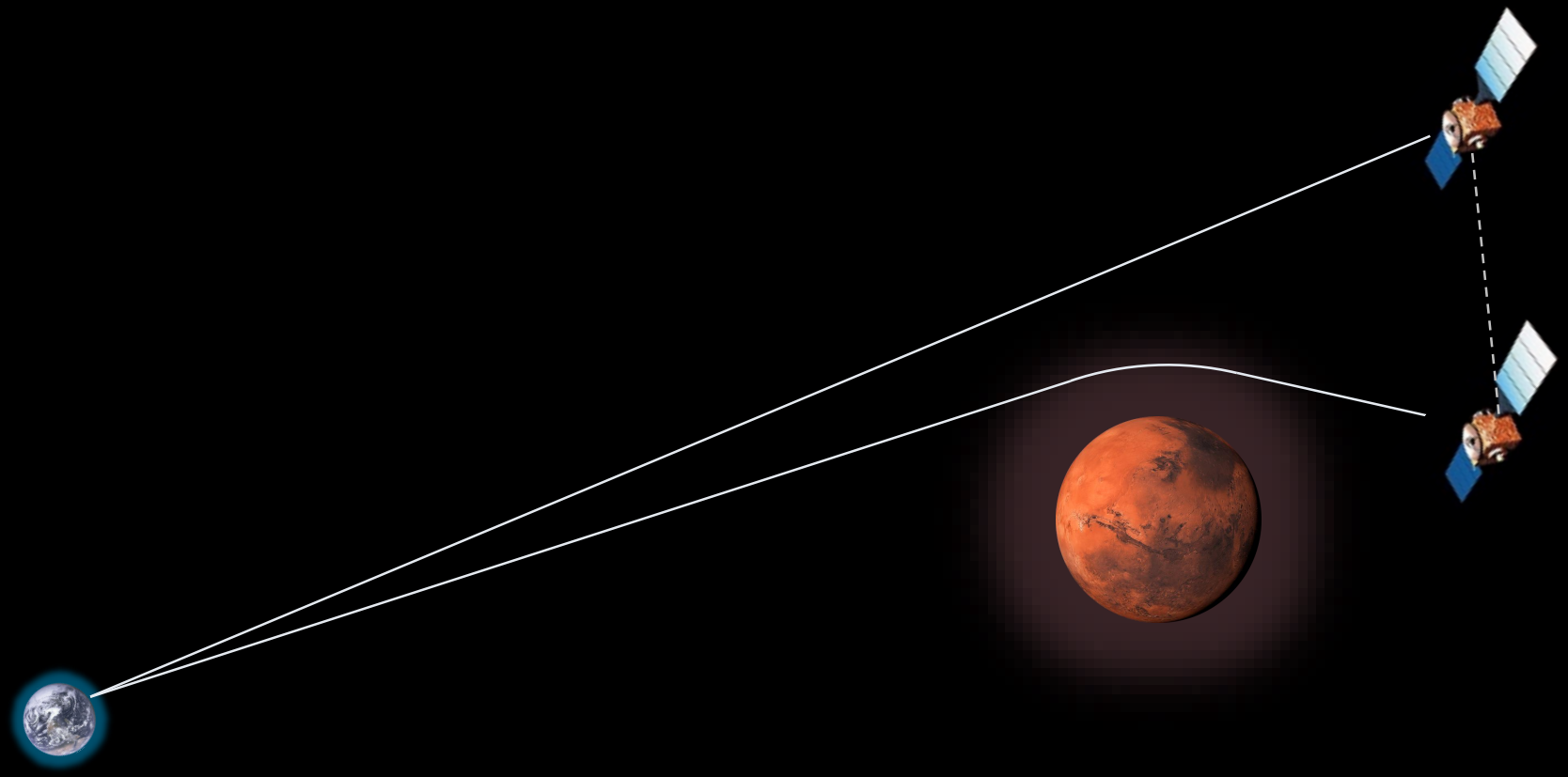
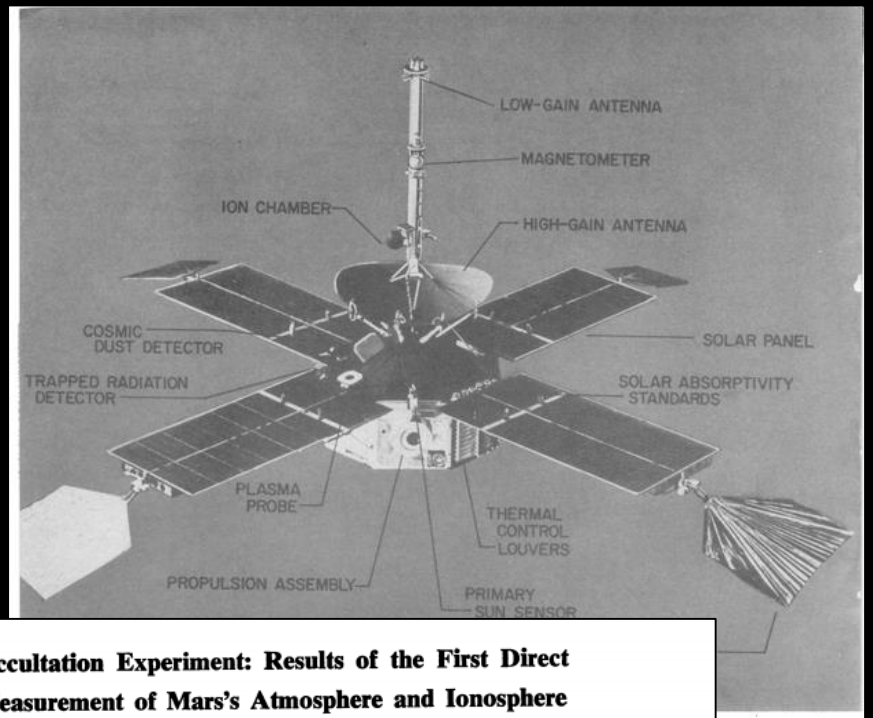
Outline

- Introduction – Radio Occultations
- Introduction – MarCO Mission
- MarCO's Radio Instrumentation
- MarCO Radio Occultation Performance Analysis
- Future Radio Science Missions using CubeSats
- Summary

Radio Occultation Geometry



Occultations & The First Interplanetary Science



Occultation Experiment: Results of the First Direct Measurement of Mars's Atmosphere and Ionosphere

omnidirectional
anes," is 6.9 m.

Abstract. *Changes in the frequency, phase, and amplitude of the Mariner IV radio signal, caused by passage through the atmosphere and ionosphere of Mars, were observed immediately before and after occultation by the planet. Preliminary analysis of these effects has yielded estimates of the refractivity and density of the atmosphere near the surface, the scale height in the atmosphere, and the electron density profile of the Martian ionosphere. The atmospheric density, temperature, and scale height are lower than previously predicted, as are the maximum density, temperature, scale height, and altitude of the ionosphere.*

lts

Approximately 1 hour after its closest approach to Mars on 15 July 1965, the Mariner IV spacecraft disappeared beyond the limb of the planet, as seen from Earth, and remained in occulta-

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sure, as well as of th

turned to Earth continuously since that time, except during commanded operations such as the midcourse cor-

of the magnetic field and the var
particle fluxes near Mars during the
proximately 24 hours preceding pic

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structure of the Martian
sphere, with some models
expected peak electron den
2×10^7 electrons per cub
(3).

10 SEPTEMBER 1965

Signal Frequency or Phase (ϕ)

$$(\nabla\phi)^2 = n^2 f^2/c^2$$

Refractivity (n)

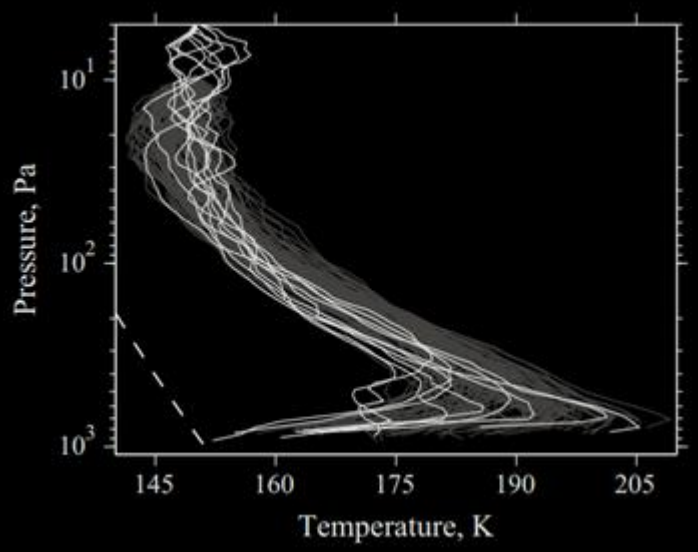
$$T = \frac{n_b T_b}{n} + \frac{m}{nk}\int n(r)g(r)dr$$

Temperature/Pressure (T/P) Profile

Radio Science at Mars: Classic Results

Mars Reconnaissance Orbiter

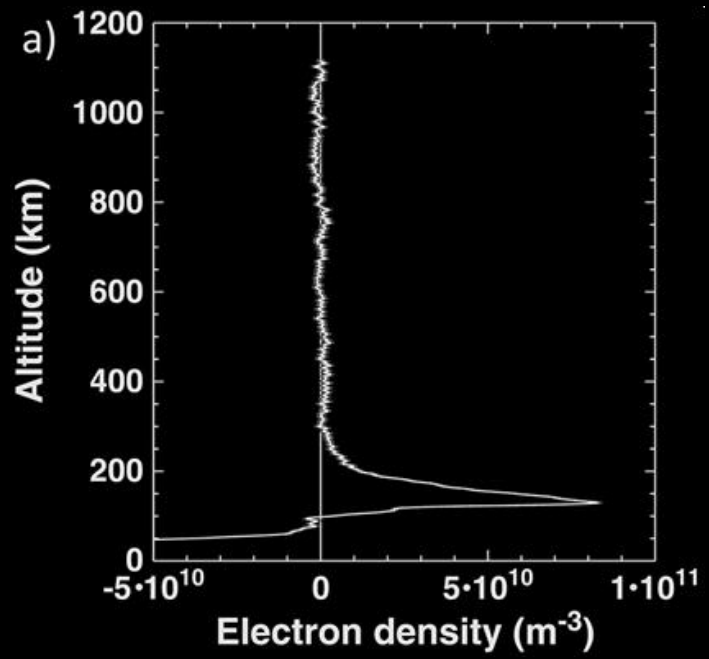
- Over 5000 radio occultations from 2008-2019
- Atmosphere detectability up to ~90 km



Hinson et al, *Initial results from radio occultation measurements with the Mars Reconnaissance Orbiter*, Icarus, 2014.

MAVEN

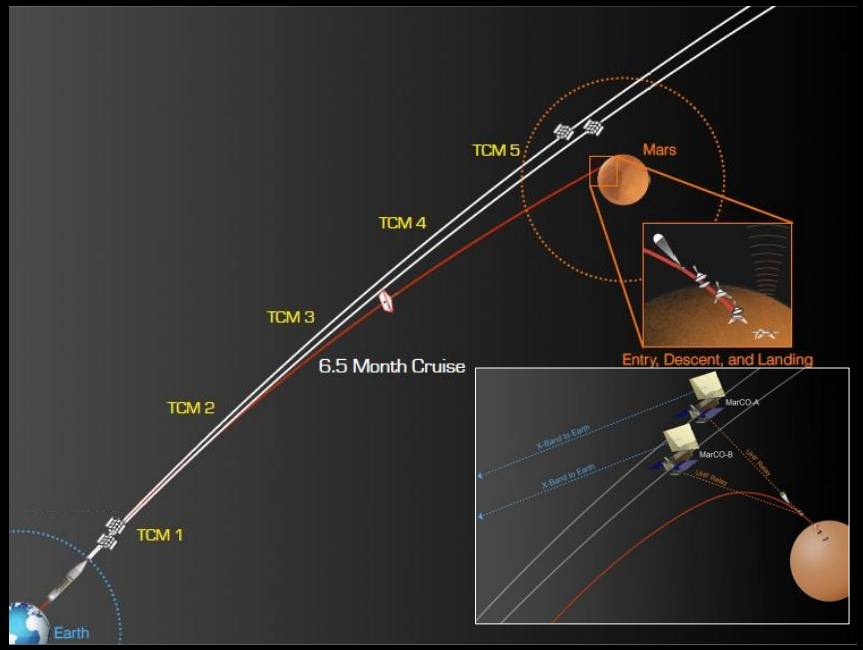
- Ionospheric occultations up to 900 km altitude
- Ionosphere detectability up to ~288 km



Withers et al, *First Ionospheric Results from the MAVEN Radio Occultation Science Experiment*, JGR Space Physics, 2018

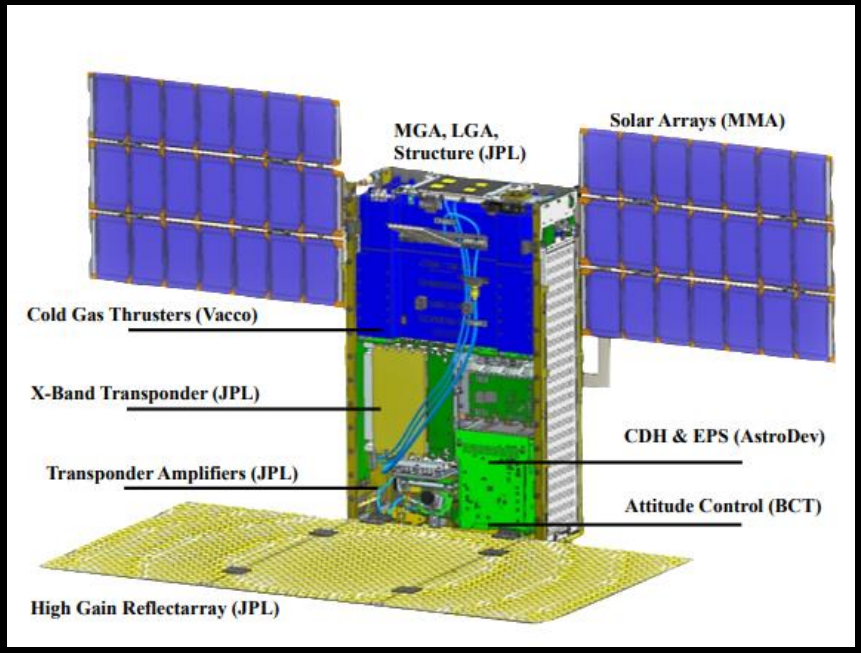
Introduction – MarCO Mission

- Mission Objectives:
  1. Survive the deep space environment
  2. Communicate and navigate with the Deep Space Network
  3. Advance miniaturized telecommunications components
  4. Support InSight during EDL



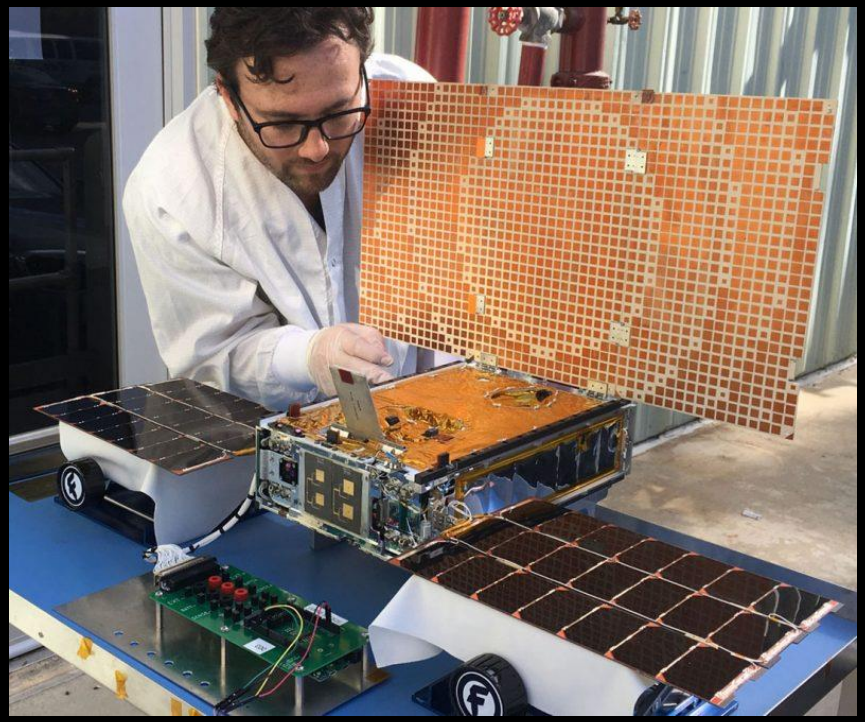
MarCO Radio Communication

- Iris V2 Transponder
  - 1.2 kg, ~0.5 U
- Antennas
  - A low-gain (LGA) patch antenna (for near-Earth communications)
  - A medium gain (MGA) patch array antenna (for communications during safe mode)
  - A high gain (HGA) reflect-array antenna for normal operations and relaying data during InSight's EDL
  - A UHF loop antenna to receive InSight's signal during EDL

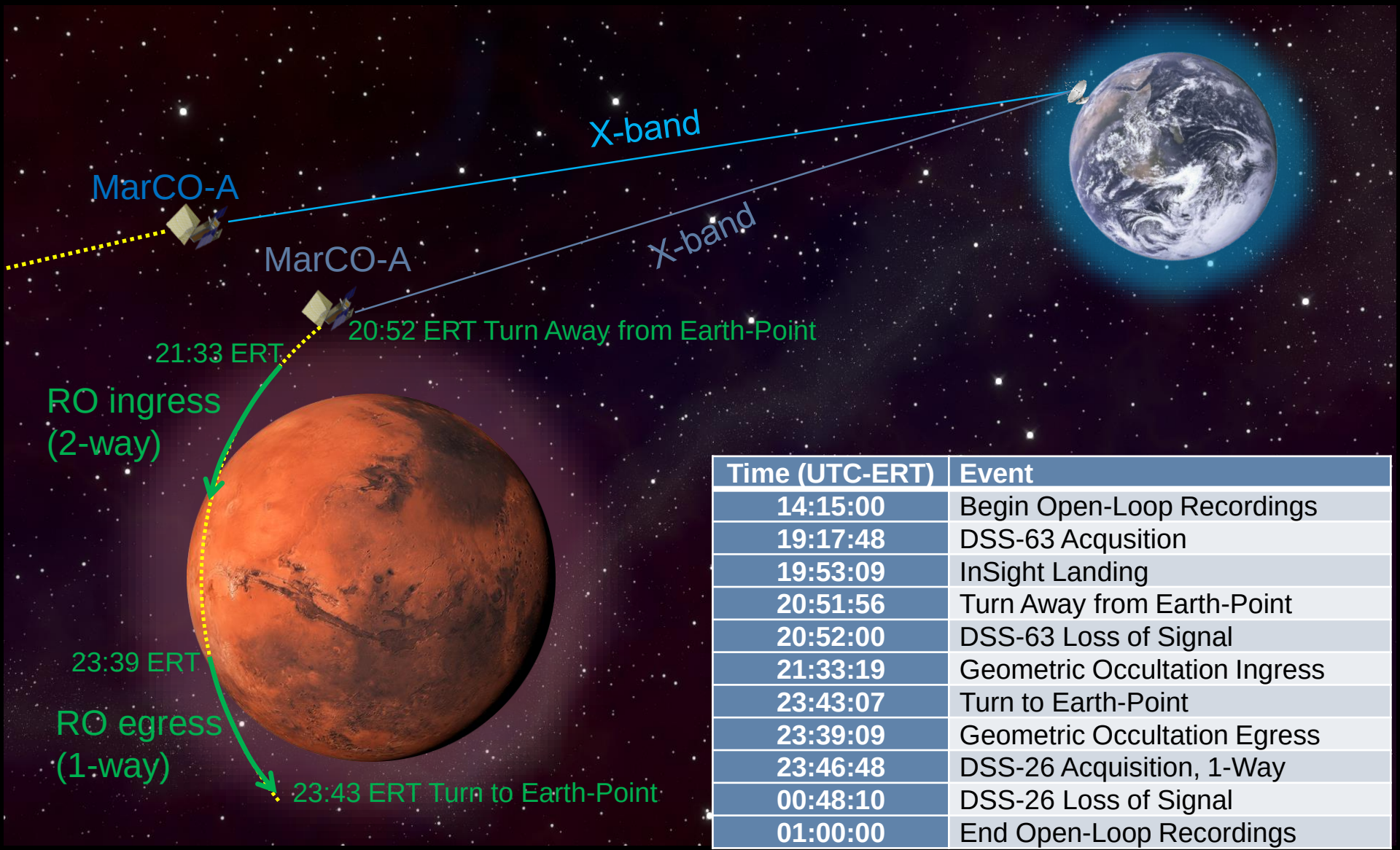


MarCO Foldable Reflectarray

- **Challenge:** bent pipe communication at 1.04AU from Earth – i.e. receive and transmit at the same data rate (8kbps)
- **Main requirements:**
  - Stowage volume: 12.5mm × 210mm × 345mm
  - Gain of at least 28dBic
- **Required aperture:** 335mm × 587mm

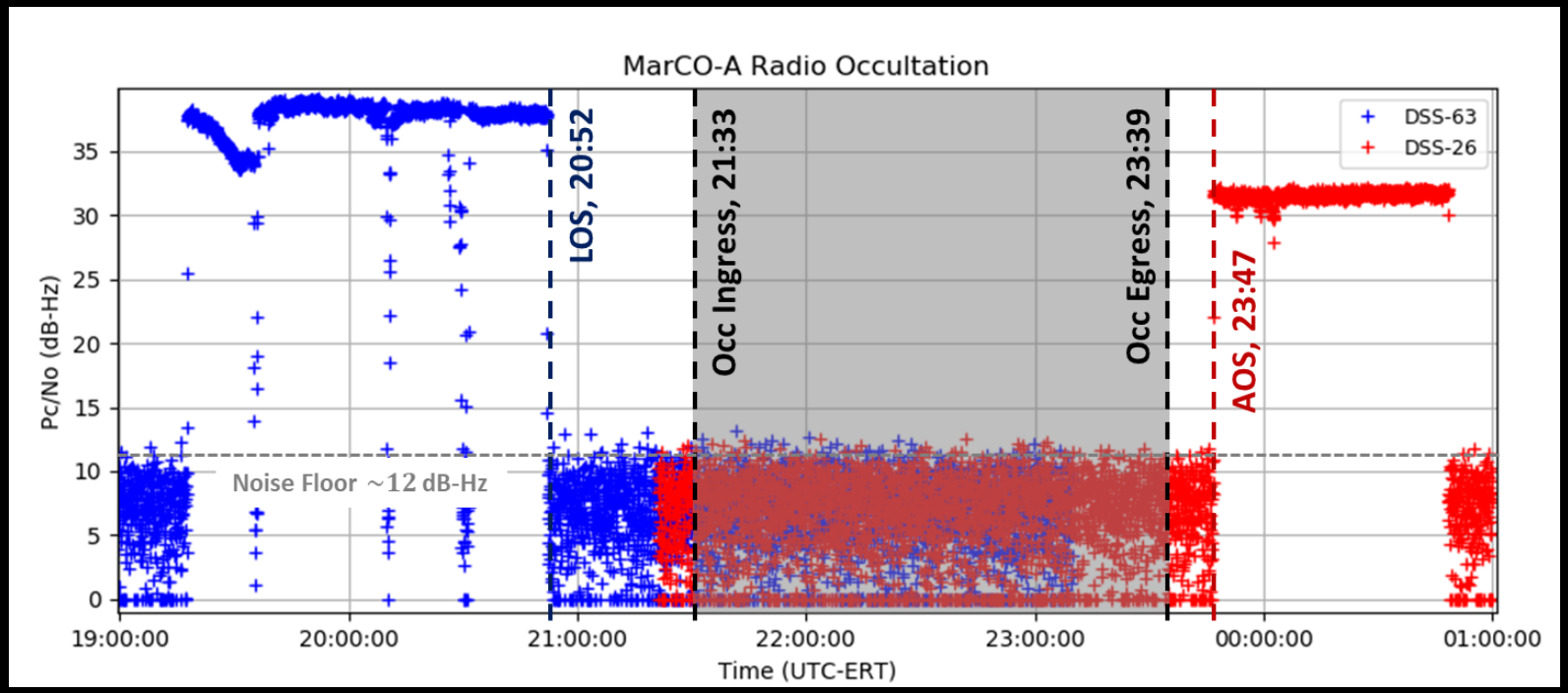


Radio Occultation Experiment

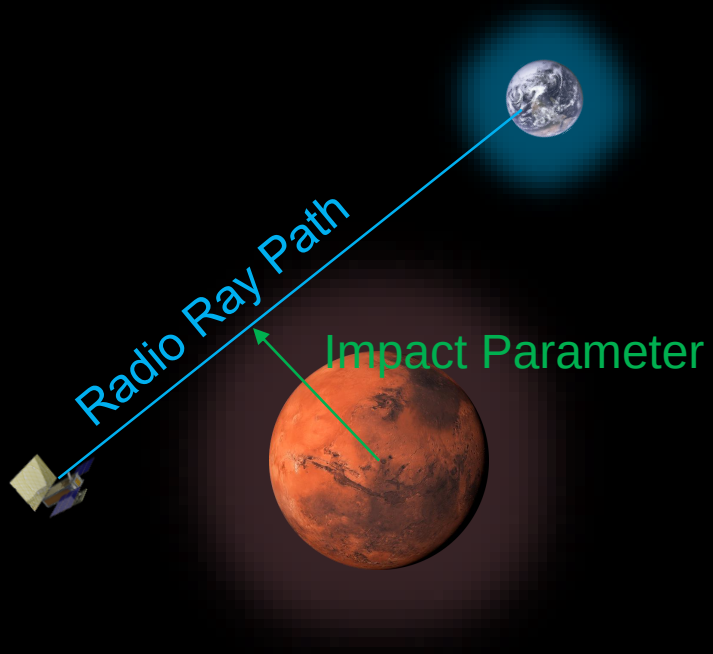


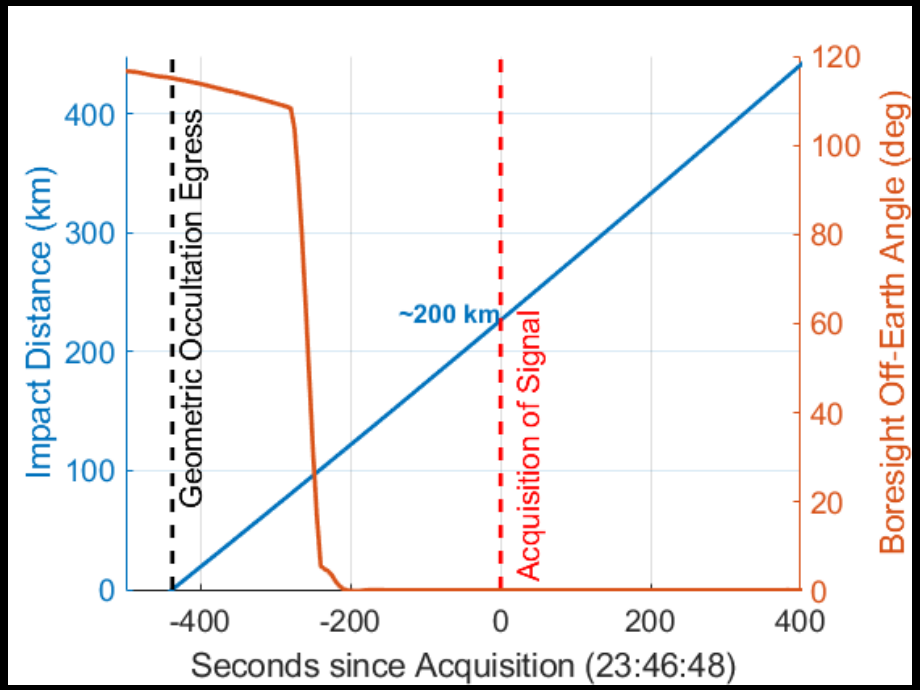
Time (UTC-ERT)	Event
14:15:00	Begin Open-Loop Recordings
19:17:48	DSS-63 Acqusition
19:53:09	InSight Landing
20:51:56	Turn Away from Earth-Point
20:52:00	DSS-63 Loss of Signal
21:33:19	Geometric Occultation Ingress
23:43:07	Turn to Earth-Point
23:39:09	Geometric Occultation Egress
23:46:48	DSS-26 Acquisition, 1-Way
00:48:10	DSS-26 Loss of Signal
01:00:00	End Open-Loop Recordings

Data Analysis of the MarCO Occultation



MarCO Occultation Geometry

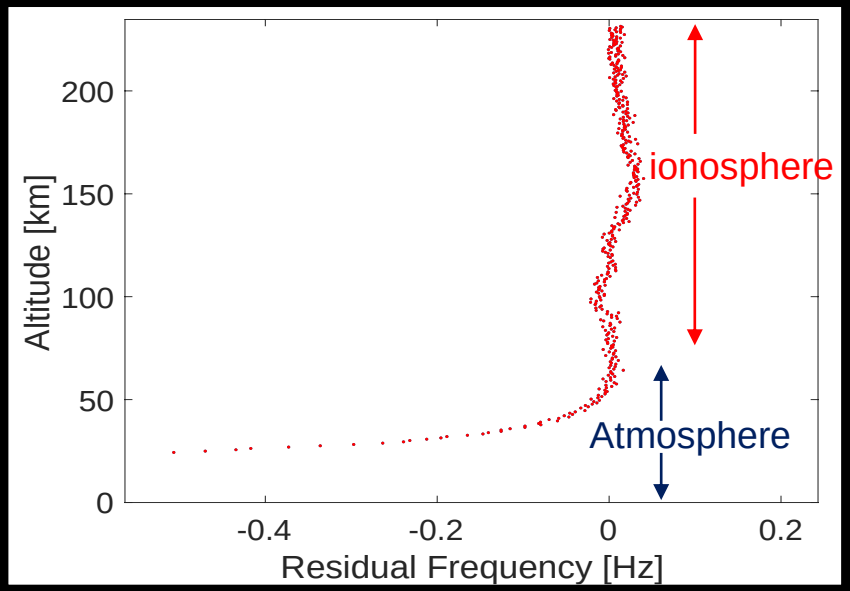




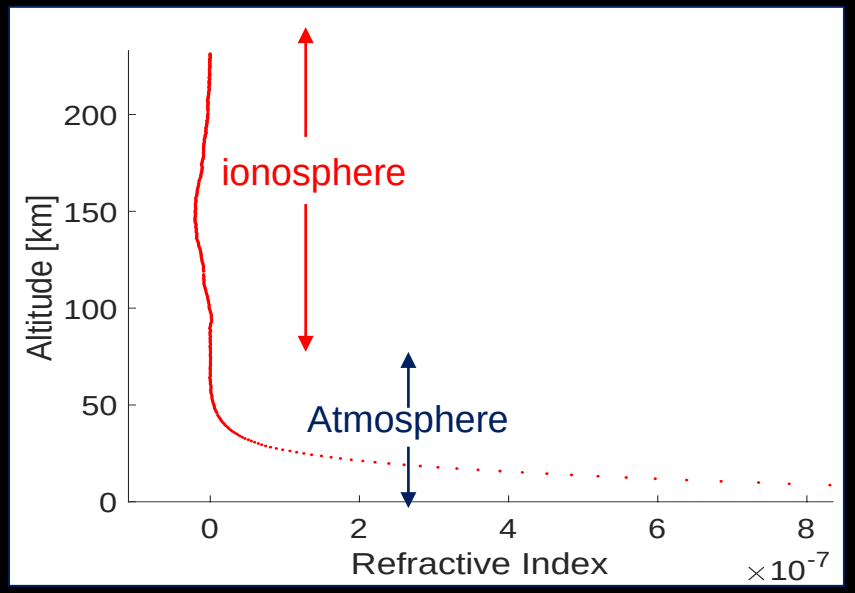
Neutral Atmosphere Detectable to **90 km** (MGS & MRO – *Hinson et al 1999*)
Ionosphere Detectable to **288 km** (MAVEN – *Withers et al 2018*)

Modeling of the MarCO Radio Occultation

Simulated MarCO RO Residual Frequency



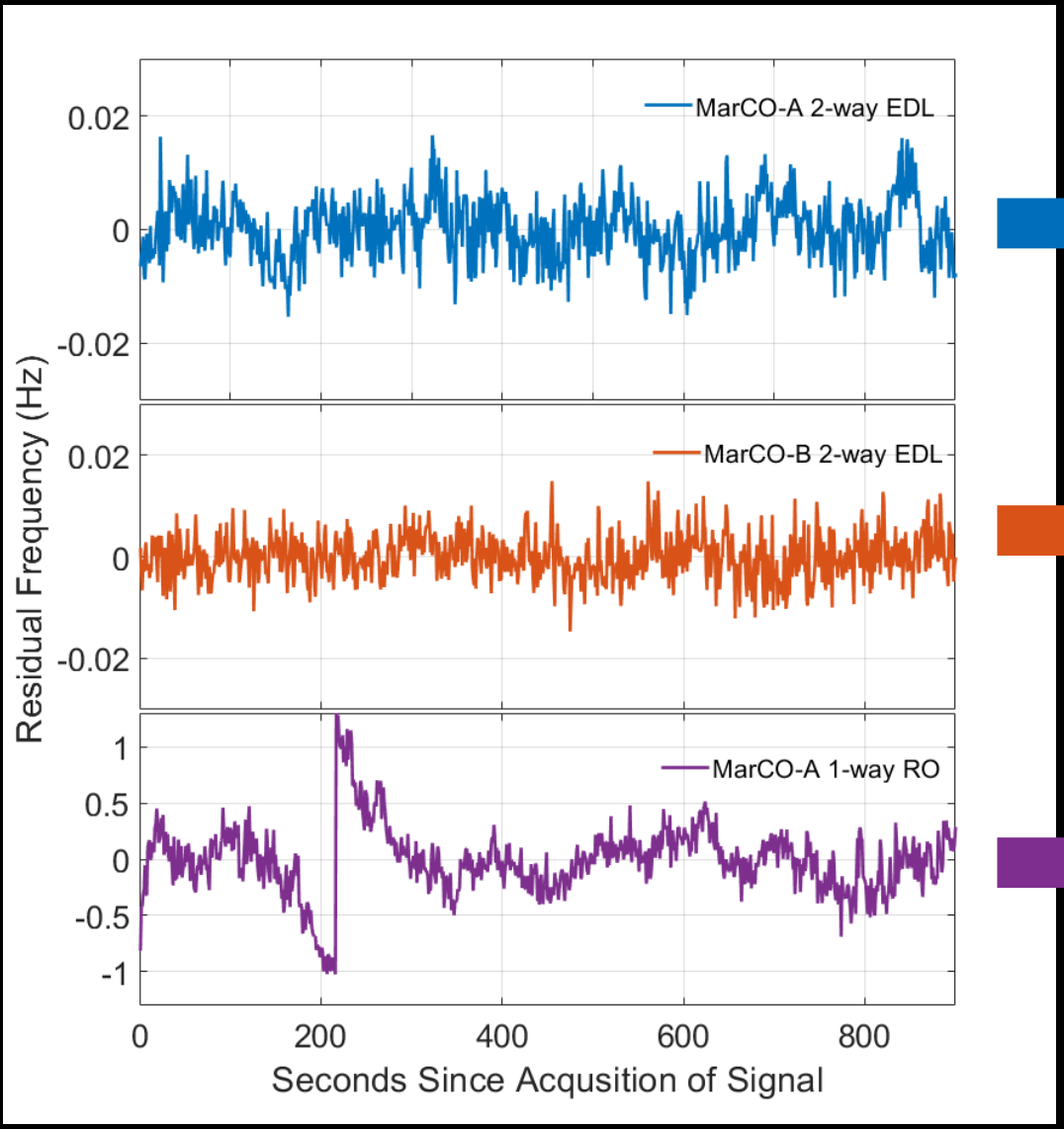
Simulated MarCO RO Refractive Index



These atmospheric and ionospheric profiles are retrieved from the refractive ($N(h)$), which is defined as: $N(h) \approx (n(h) - 1)10^6 = 130.6\frac{P(h)}{T(h)} - (40.3 \cdot 10^6)\frac{n_e(h)}{f^2}$

where n is the unitless refractivity index, h is the altitude in km, n_e is ionospheric electron density, P is the pressure of the atmosphere, and T is the air temperature in Kelvin.

Frequency Performance



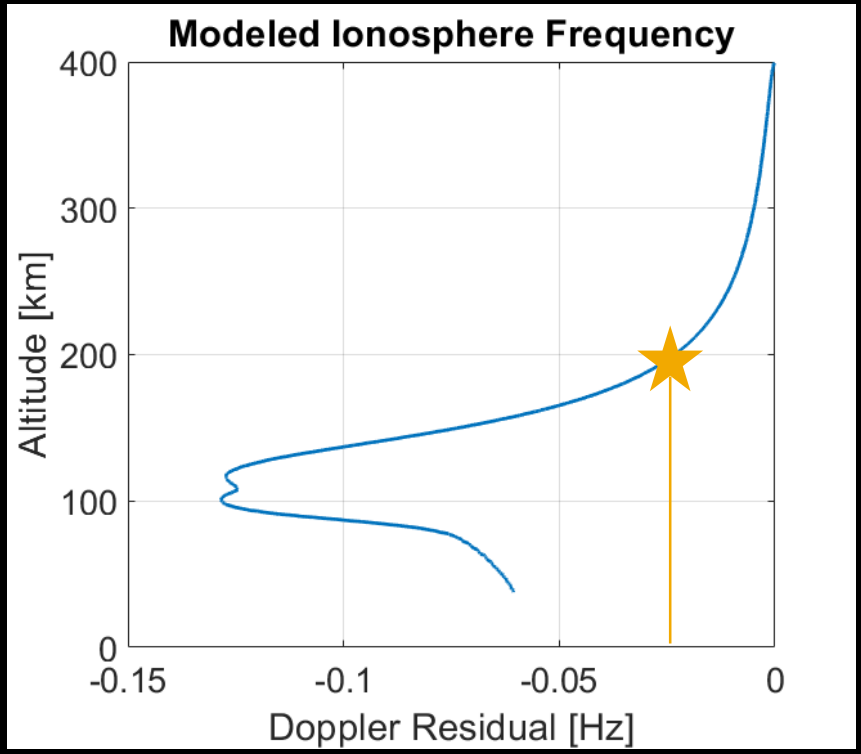
0.004 Hz

0.005 Hz

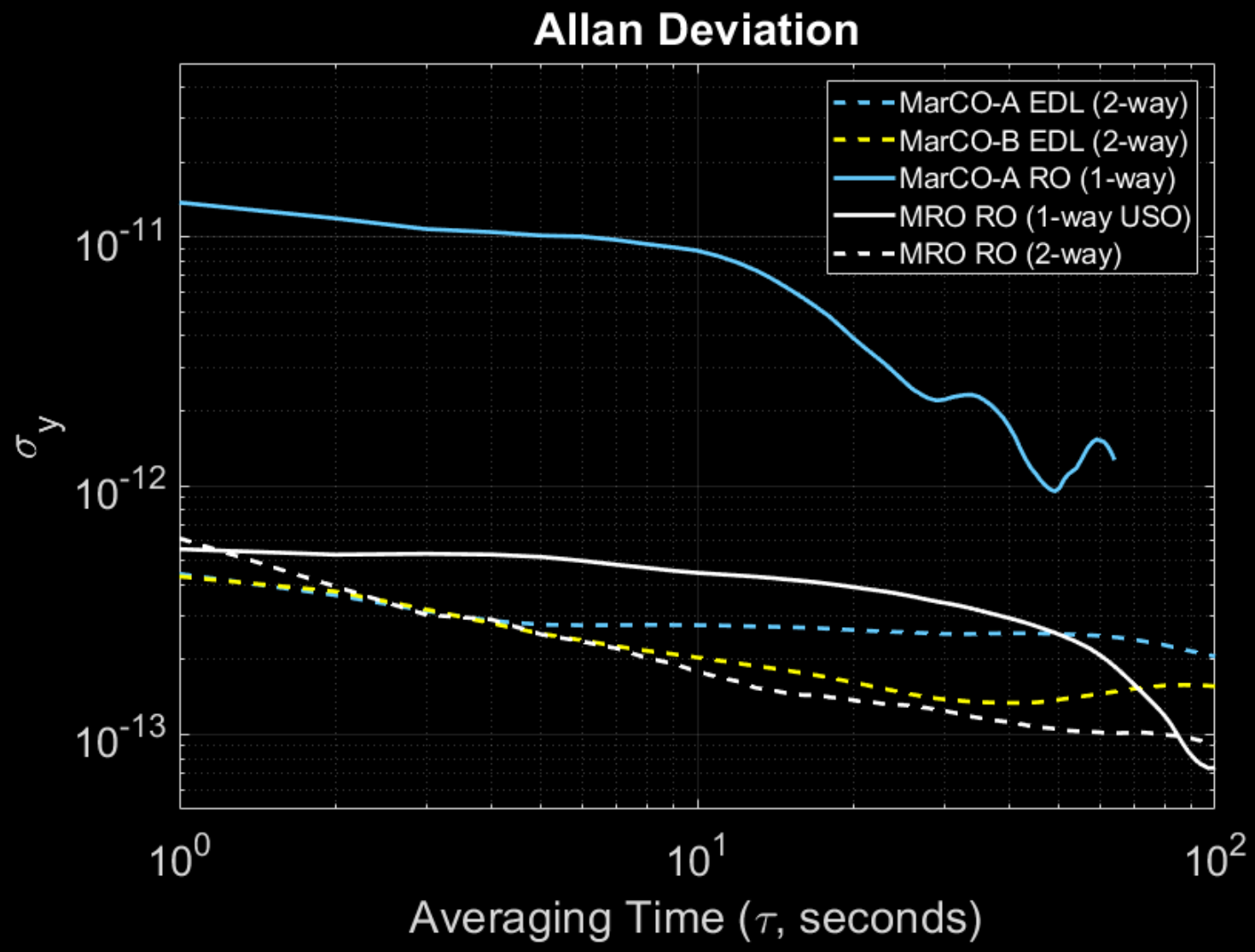
0.42 Hz

Occultation Assessment

- Mars Ionosphere was not detectable during the MarCO radio occultation
- Mars Ionosphere could have been detected in 2-way mode but not in 1-way mode
- Neutral atmosphere **could** have been detected **if** the spacecraft was pointed to Earth at geometric occultation egress <35 km



Frequency Stability & Comparison with MRO



Impact on Future SmallSat Radio Science

- **Frequency Stability –** MarCO's 1-way signal is not sufficient for precision radio science measurements
  - Typically, an Ultra Stable Oscillator (USO) is required for precision radio science measurements
  - USO's are heavy (1-2 kg) and consume power (1-10 W)
  - For missions without a USO, ***2-way occultations are possible*** and have been proven on multiple missions (e.g. MRO, Cassini)

- **Geometry –** MarCO's signal was not acquired until well above the atmosphere and in the ionosphere
  - Ingress occultations are more favorable, particularly in 2-way mode
  - At other planets, atmosphere is denser and limb tracking maneuvers may be required for deep atmospheric occultations

Summary

- MarCO-A Radio Occultation did not detect the Mars atmosphere or ionosphere during the flyby
- An assessment of the MarCO flyby and RO data indicates that the MarCO 2-way data has a stable frequency residual and performance is in the same order of MRO 2-way data.
- Modeling results suggest that the 2-way MarCO radio signal could have been able to have a positive detection of the atmosphere and ionosphere comparable to MRO
- Frequency residual measurements derived from MarCO X-band radio links confirm that the 1-way X-band data could have detected the neutral atmosphere but not the ionosphere

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