Radio occultation mission to Mars using cubesats

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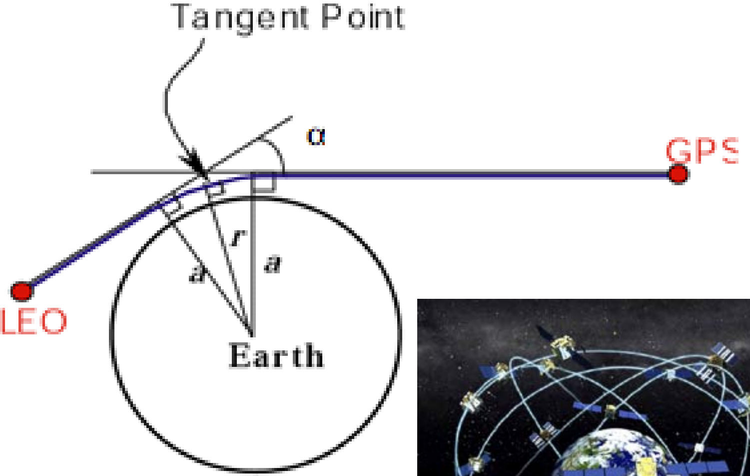
Radio Occultation Overview

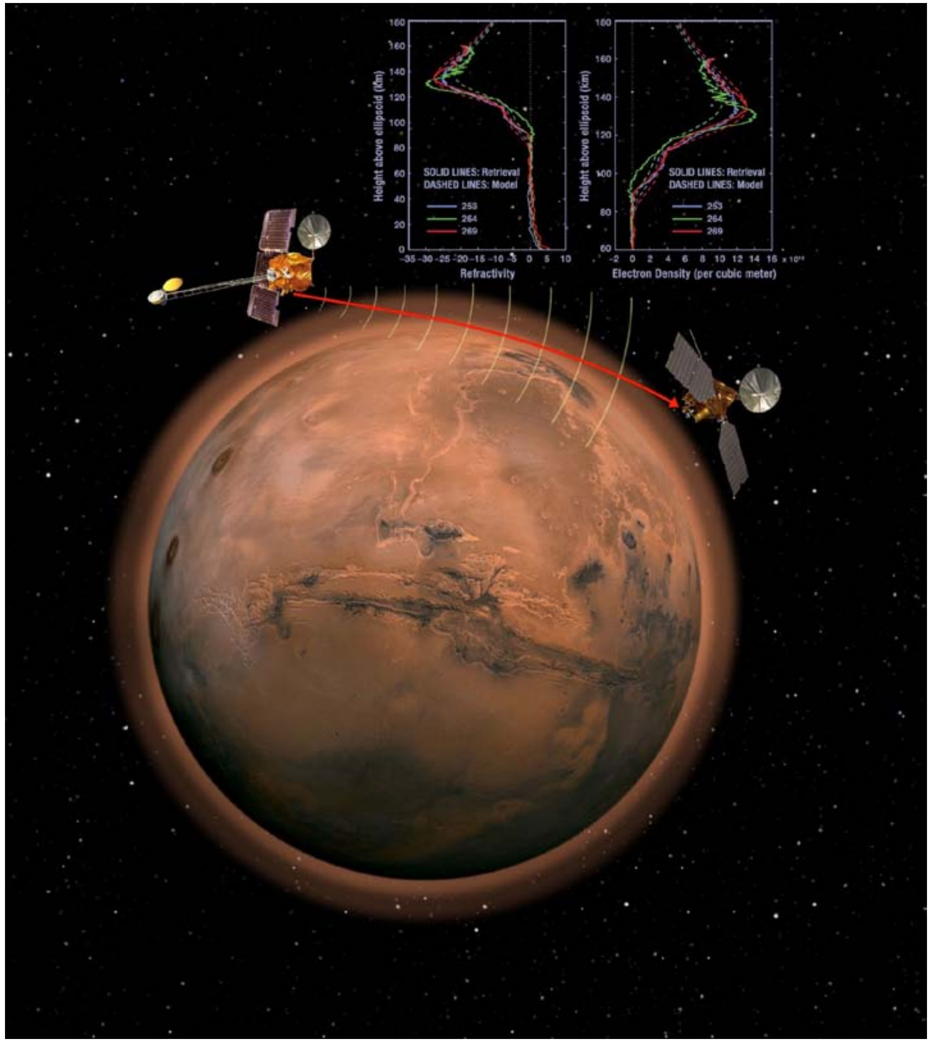
Radio occultations refers to the process of measuring the Doppler shift due to atmospheric bending in a transmitted signal from one satellite as measured from anther satellite.

This Doppler shift due to the atmosphere is used to derive the temperature and pressure of the atmosphere as a function of altitude.

Monitoring from space enables global coverage but the number of profiles generated depends on the orbit location and number of satellites.



JPL has launched numerous satellites in orbit around Earth using GPS for RO including:
Sac-C
Grace
Cosmic-1
Future missions:
Cosmic-2, Grace FO, Sentinel-6



The proposed experiment would create a constellation of small sats around Mars to generate occultations over a one Martian year period.

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Mars Program Needs Addressed by Radio Occultations

- **MEPAG Goal II: Understand the processes and history of climate on Mars**
  - **Investigation A1.1: Measure the state and variability of the lower atmosphere from turbulent scales to global scales (High Priority). Direct.**
- **MEPAG Goal IV: Prepare for Human Exploration**
  - **Investigation B1.2: Monitor surface pressure and near surface meteorology over various temporal scales (diurnal, seasonal, annual), and if possible in more than one locale (High Priority).**
  - **Investigation B1.3: Make temperature and aerosol profile observations under dusty conditions (including within the core of a global dust storm) from the surface to 20 km (40 km in a great dust storm) with a vertical resolution of <5 km (High Priority).**

Brief Radio Occultation History in Mars Science

- Fjelbo, G, Eshleman V. R. (1968) "**The Atmosphere of Mars analyzed by integral inversion of the Mariner IV Occultation Data**," Planetary Space Science, Vol 16, pp. 1035 to 1059.
  - Used data transmitted back to the Earth to derive occultations of Martian atmospheres
  - A similar method has been used for occultations on other planets (Venus, Jupiter)
- Ao, C. O., C. D. Edwards, D. S. Kahan, X. Pi, S. W. Asmar, and A. J. Mannucci (2015), **"A first demonstration of Mars crosslink occultation measurements,"** Radio Sci., 50(1), 997–1007, doi:10.1002/2015RS005750.
  - First ever cross link radio occultation at Mars between MRO and Odyssey.
- Mannucci, A.J., Chi O. Ao, Sami Asmar, Charles D. Edwards, Daniel S. Kahan, Meegyeong Paik, Xiaoqing Pi and Walton Williamson (2015) **"Crosslink Radio Occultations for the Remote Sensing of Planetary Atmospheres",** Poster P11B-2095, Fall AGU Meeting, 2015, San Francisco, CA, December 14-18.

Mars RO measurements are possible using existing communication satellites.

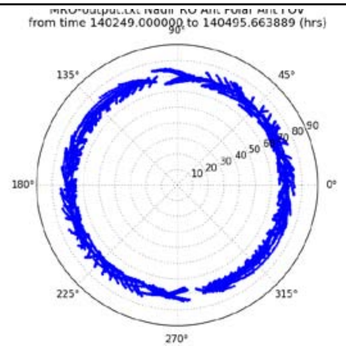
Cross-link occultations were demonstrated between Odyssey and MRO. (C. Ao, et. Al, in 2015)
From this result, a simulation was performed to demonstrate the number of occultations possible using existing assets.

Simulated ten (Earth) days.
Restricted occultations passing through -50 km to +100 km SLTH.

	ODY	MEX	MRO	MAVEN
Periapsis (km)	3761.5	3726.2	3625.1	3546.2
Apoapsis (km)	3928.1	13926.2	3690.1	9396.2
Inclination (deg)	93.2	86.9	92.6	74.07
Period (min)	118	420	112	268.45

Note that MEX and MAVEN are highly elliptical while ODY and MRO are near circular. Best RO provided by ODY-MRO due to minimum distance (and high power ODY TX).

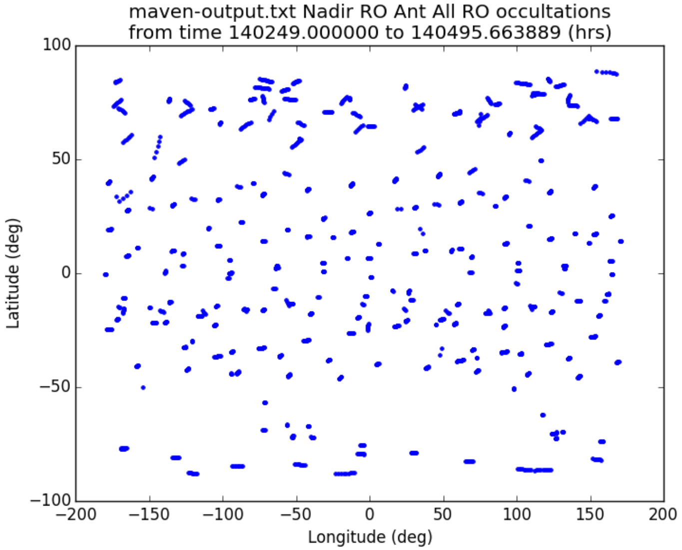
Occultations are measured using the Nadir facing UHF antennas and the Elektra radio



Over this 10 day period, the following number of occultations were generated per pair.

	MRO	MAVEN	MEX	ODY
MRO		189	241	157
MAVEN			129	279
MEX				252
ODY				

The resulting locations (MRO-ODY) provide global measurements.



Given the complexities of “scheduling” these events with committed assets, could we do this with small sats or ***cubesats***?

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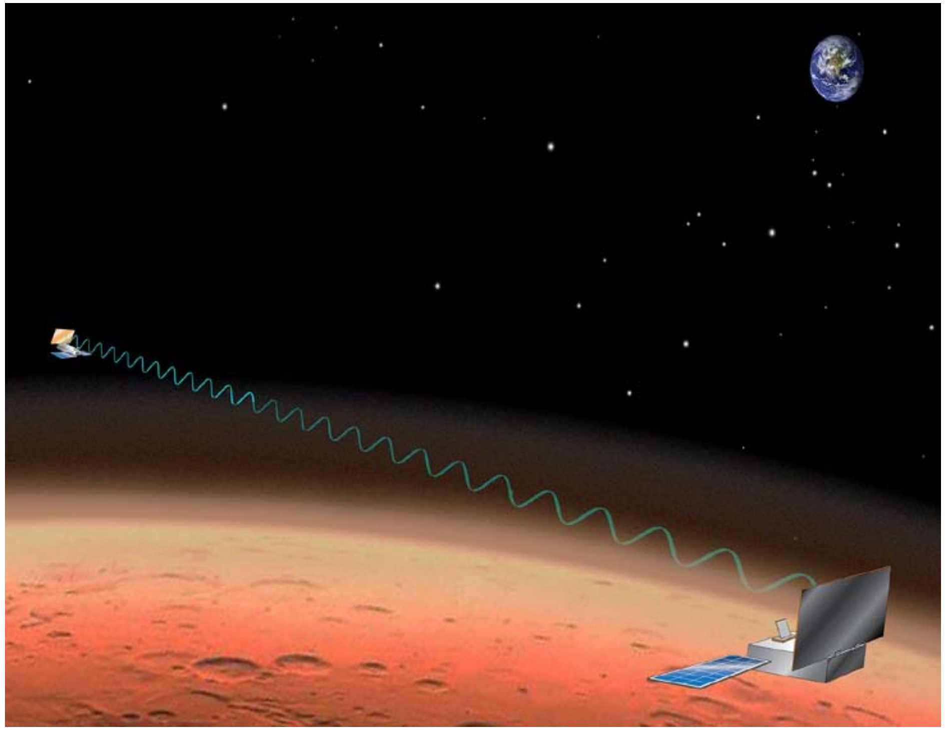
Key Technical Requirements for cross link RO at Mars

- Deliver as many profiles as possible within the lifetime of the mission.
  - Defined in part by the number of satellites in the constellation.
  - Defined also by the orbits available to the constellation.
  - Goal to mazimize the temporal and spatial distribution of the occultations.
  - The lifetime of the satellites will limit the expected duration of the experiment. A goal is one Martian year.
- Occultations will have a bending angle accuracy of 0.2 micro radians (1-sigma) over the altitude range.
  - This value was determined from a requirement of 2 degree C temperature profile accuracy.
  - This value defines the link margin for the cross links communication.
  - It also affects the navigation and attitude control accuracy necessary to point medium to high gain antennas at other satellites for the measurements and telecom.
- Occultations will be in the range of -50 to +100 km straight line tangent height:
  - Used to define total occultation length for each occultation.
  - Limits the amount of data generated and defines scheduling needed.
- Occultations shall have a vertical resolution of at least 2.0 km.
  - Defines sample rate which also leads to data rate.



Small sats or cubesats can be used to meet these technical requirements.

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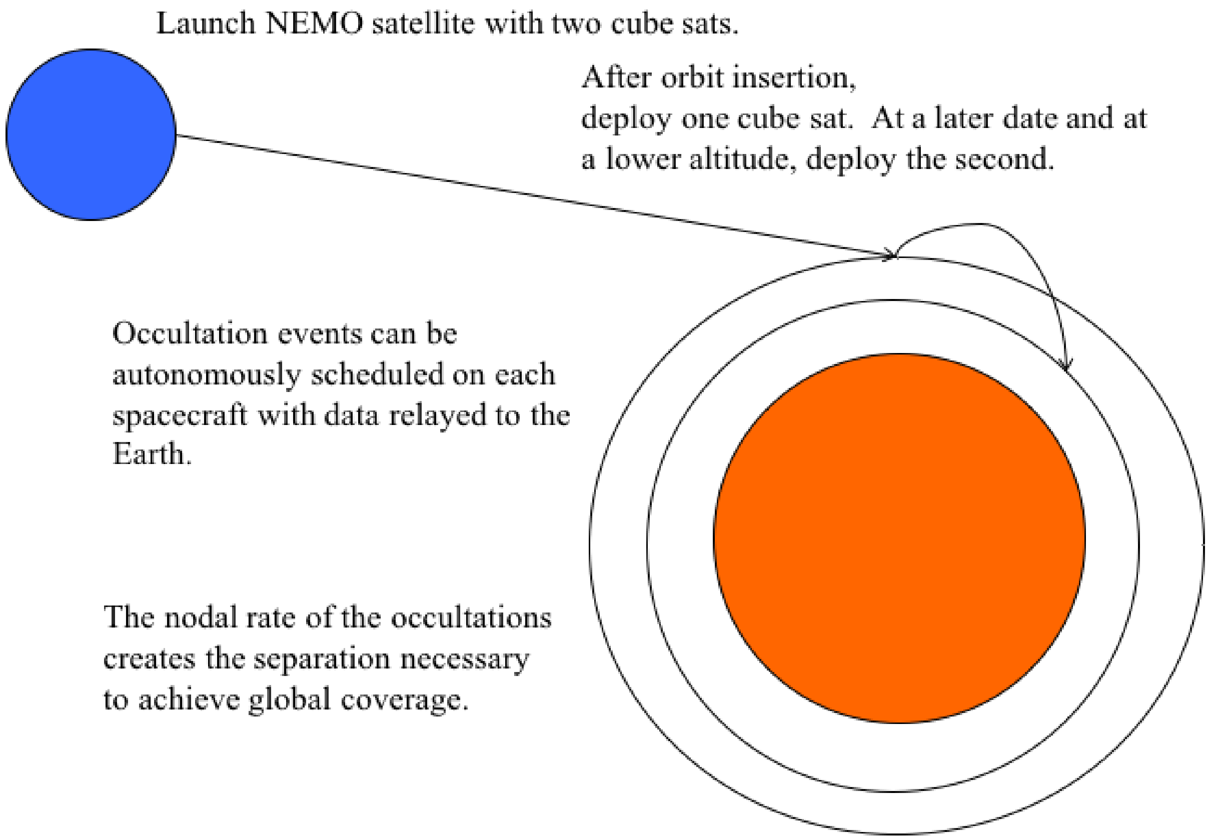
The delivery of the constellation is achieved by hitching a ride on a larger orbiter.

The large orbiter carries the cube sats into orbit around Mars.



As the larger orbiter spirals from high orbit (10,000 km) to low orbit (300 km), it deploys cube sats at different altitudes.

The variation in nodal rate as a function of altitude enables dispersion of the cubesat orbit planes over time. This improves global and temporal coverage.

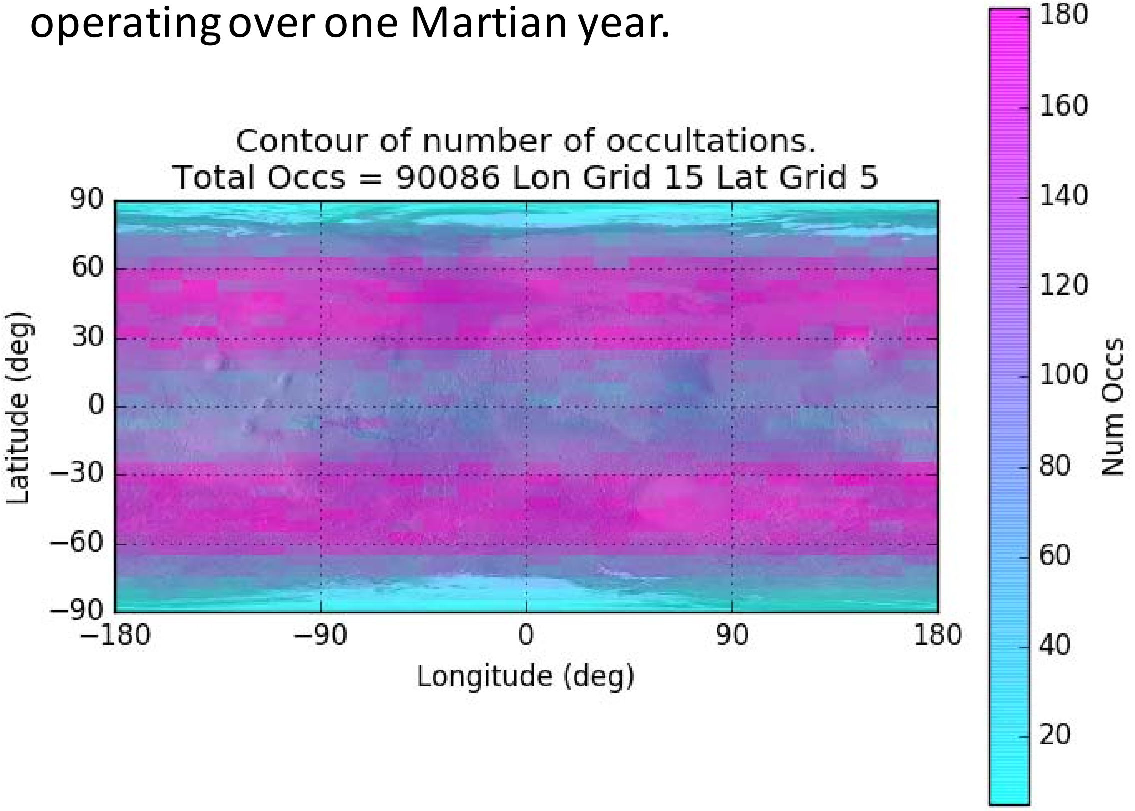
Given the inclination angle of the insertion orbit, the deployment altitudes are selected to maximize the nodal rate separation and increase spatial coverage.

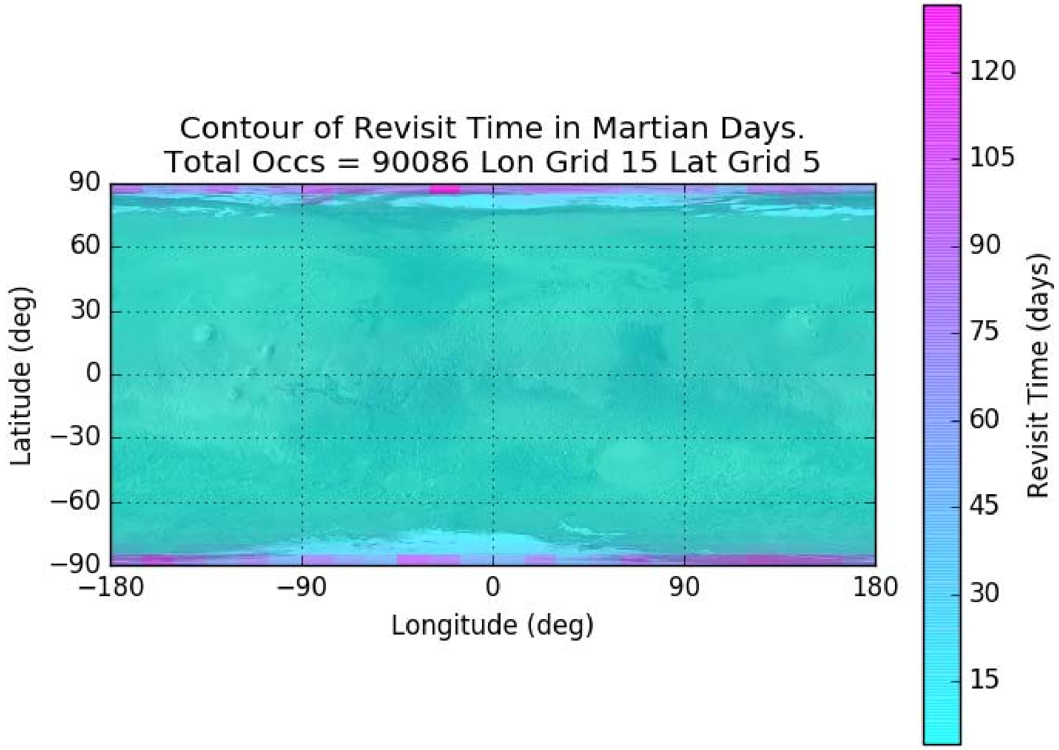
With four cubesats at these altitudes, the number of occultations per day averaged between 16-40 per pair.

Since there are 6 pairs with four satellites, there are 96-240 occultations per day providing global coverage!

Simulation results of a four satellite constellation at Mars

The following maps show the number of occultations and revisit times (days) for four satellites deployed and then operating over one Martian year.



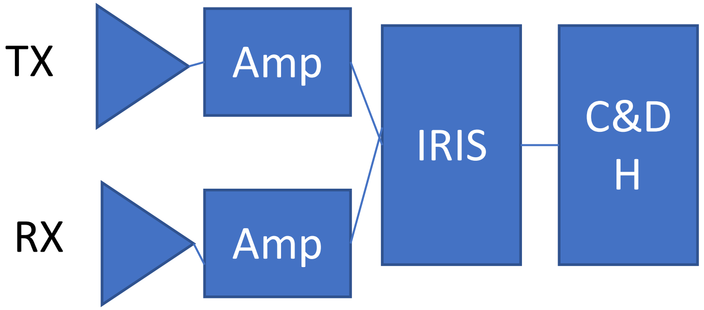


Simulation results of a four satellite constellation at 92 degrees of inclination at altitudes **330, 706, 1350, 3098 km show global coverage** for a grid of 15 degrees in Longitude and 5 degrees in Latitude

Revisit times over the period show that the constellation provides excellent temporal coverage over most of the Latitudes.

Mission designs performed assuming heritage hardware (MARCO and IRIS).

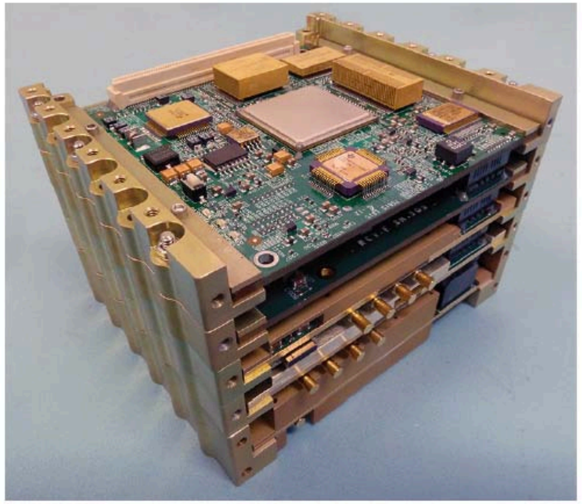
Instrument Architecture



The RO instrument consists of a standard TX/RX radio with specialized RO software/FW.

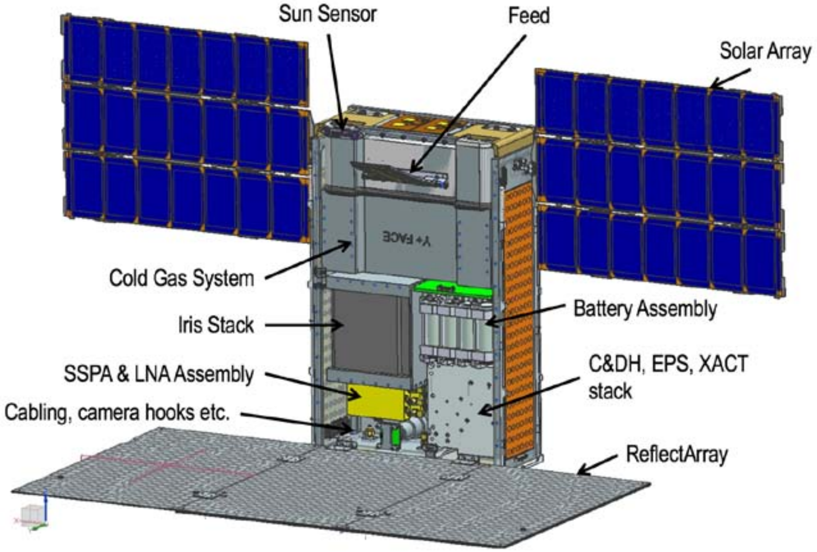
Key Architecture Parameters:

- TX Power: ~5 Watts.
- TX Antenna Gain: 9-12 dBi
- RX Antenna Gain: 9-12 dBi
- Operational Power: 35 Watts
- Signal Frequencies: X-Band
- Phase tracking output rate: 0.1 Hz.



The instrument can be built around the standard IRIS radio. The radio provides transmit and receive capability, operates at UHF, S, X, and Ka bands, and includes data processing capability.

Modified IRIS required to perform dual one-way Doppler measurements.

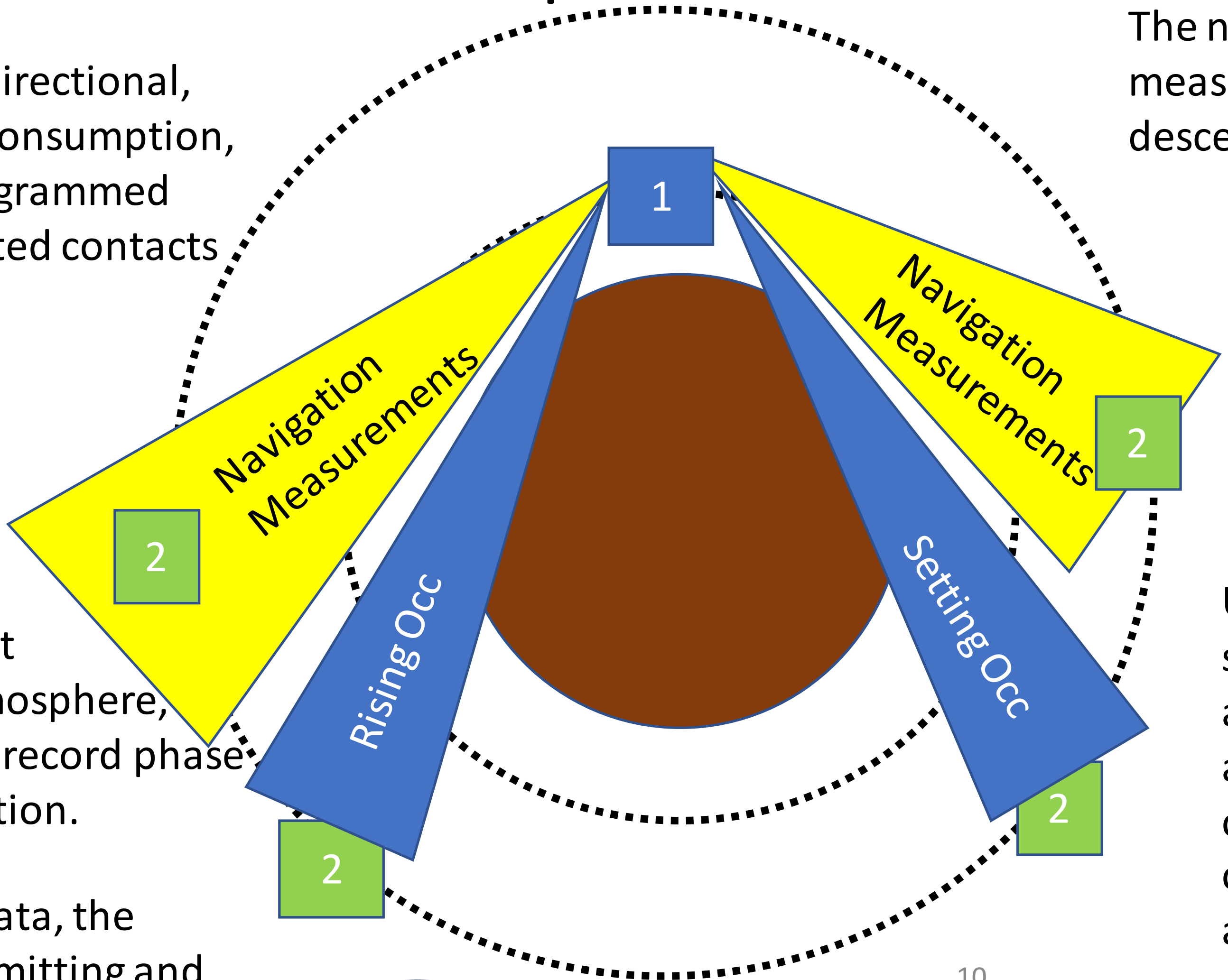


The IRIS fits within 6U cubesat designs such as the JPL developed MarCO cubesat. This cubesat provides power, attitude control, and deployable antenna features. The IRIS radio is used to retrieve data from Insight and transmit to Earth in X-Band and UHF frequencies.

Requires tailoring for the radio occultation mission including larger solar panels, and a more directional antenna.

Navigation measurements are generated as part of the occultation process.

Because the antenna is directional, and to minimize power consumption, the cubesat must be programmed (weekly) with the predicted contacts with the other satellites.



As the satellite rises so that the signal is above the atmosphere, both satellites continue to record phase data to be used for navigation.

Based on the predicted data, the two satellites begin transmitting and recording at a specified time.

The navigation and occultation measurements are repeated on the descent.

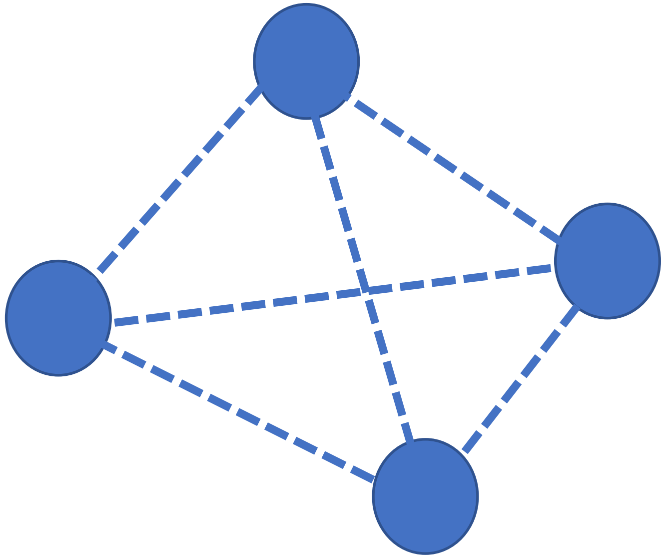
Clock errors are removed using the concept of ***dual-one-way range measurements***. Both satellites transmit tones simultaneously at offset frequencies.

Using the constellation of four satellites plus contacts for data and navigation enables navigation accuracy that pushes the effect of navigation error to an order of magnitude below the bending angle requirement.

Data Link Requirements

Since both satellites must transmit and receive, both satellites record data from each contact. This data must be transmitted back to the Earth for ground processing via a "mother ship" communication or via a direct DSN link (similar to Marco).

A constellation of four satellites will have up to six total occultation pairs. Each pair has 20-40 occultation opportunities per day.



Each occultation lasts < 250 seconds and requires ~10 Hz observables.

Occultations Neutral Atm Data Rate	
Occultations Per Day	40
Average Occultation Duration (sec)	250
Frequencies Tracked	1
Observable Rate (Hz)	10

Each pair generates 2 Mbytes/day at each satellite.

Summary Average Data Rate over 24 hours	bits/s
Neutral Atm Occ Data Rate (40/day)	39.7
Additional Ranging Data for Nav and Iono	135
Logs and Health	12.8
Total bits/s	187.5
Total Data Volume per 24 hours (MBytes)	2.025

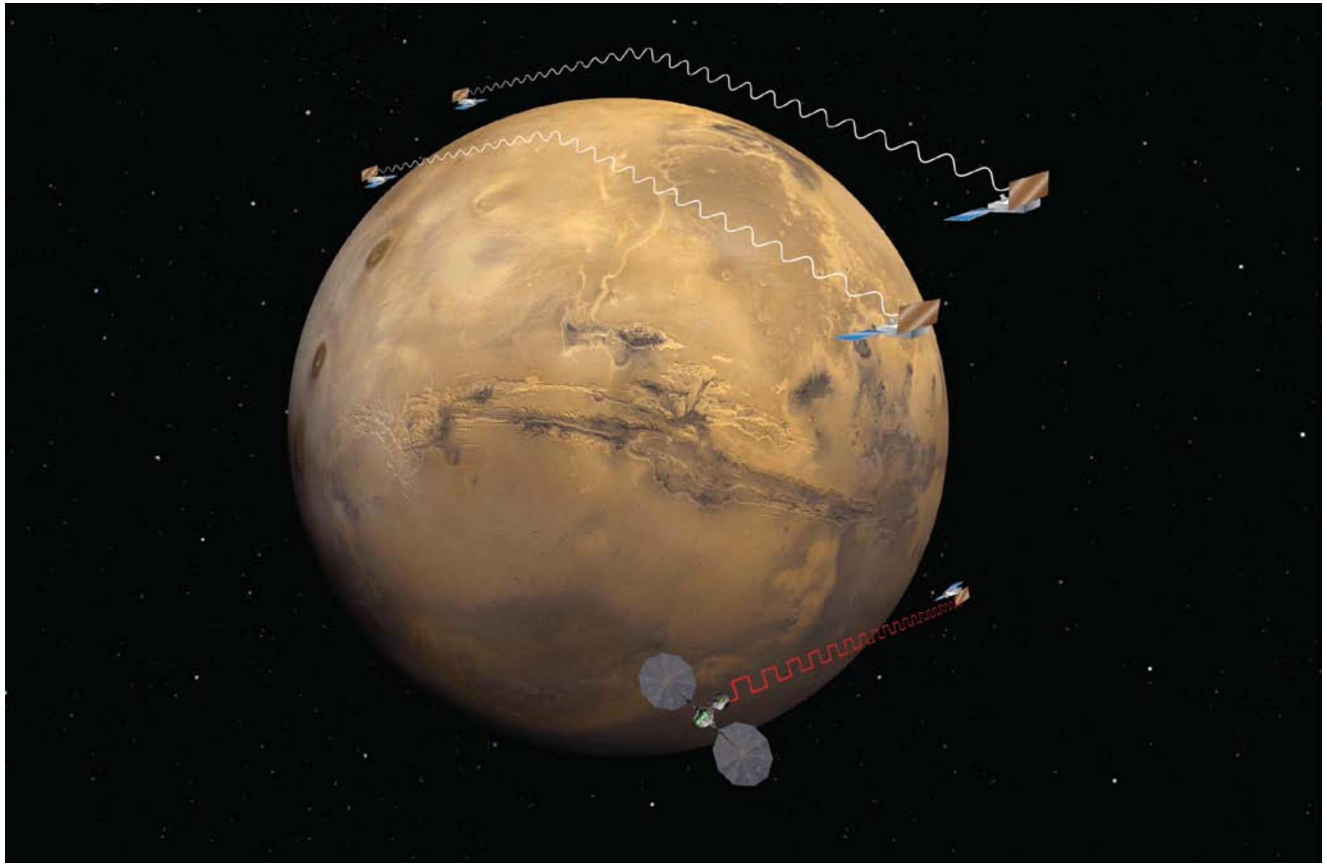
Each satellite will generate ~6.1 Mbytes/Day

Number of satellites	4
Total Data per satellite (Mbytes)	6.1

Data from each satellite will be transmitted to a larger communication satellite for transfer to the Earth. Uplinks will be performed weekly to each satellite to provide the list of scheduled occultation events.

Summary

- Using a constellation of small satellites, it is possible to achieve global coverage of the Radio Occultation profiles in the Martian atmosphere using cross link radio occultations.
  - Cross links use existing radios to provide additional science data.
  - The IRIS radio with appropriate antennas can provide adequate performance to meet science requirements for occultations.
  - Would provide orders of magnitude more data than presently available for the study of the Martian atmosphere and transport phenomena.
- The mission can be executed on a smaller budget due to the low cost of the satellites and the ability to make use of the telecom system so that no new instruments are required.
  - Satellites similar to MarCO provide the necessary baseline capability.
  - Deployment opportunities from larger missions provide the means to get to Mars.



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