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Low Cost Ride-Along Small Spacecraft for Enhanced Science with Radio Links

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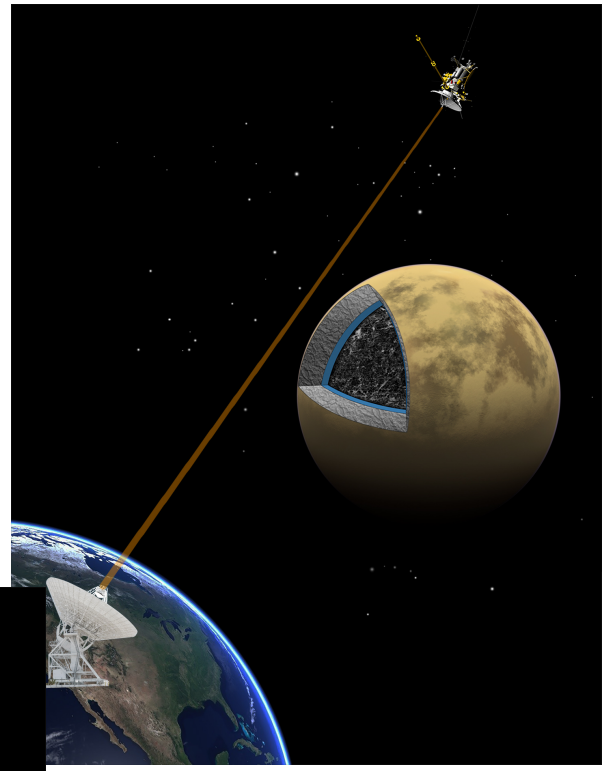
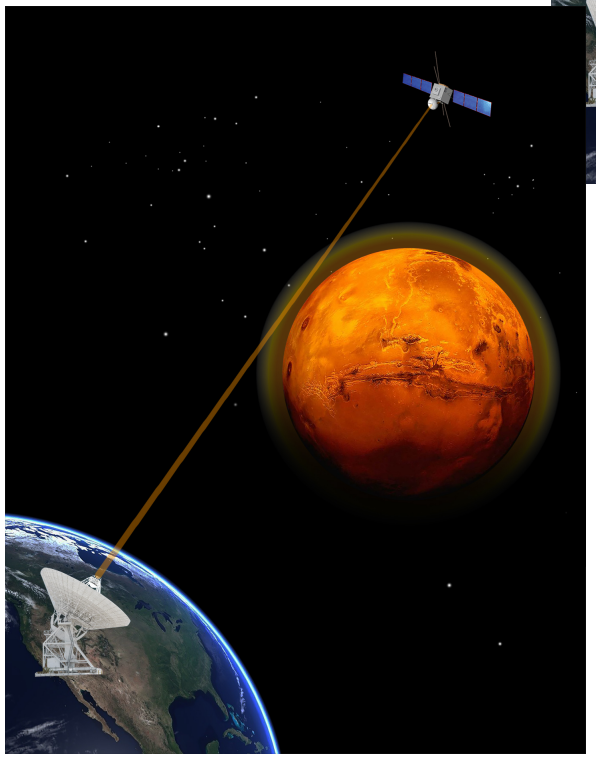
03-05 June 2019
Toulouse, France

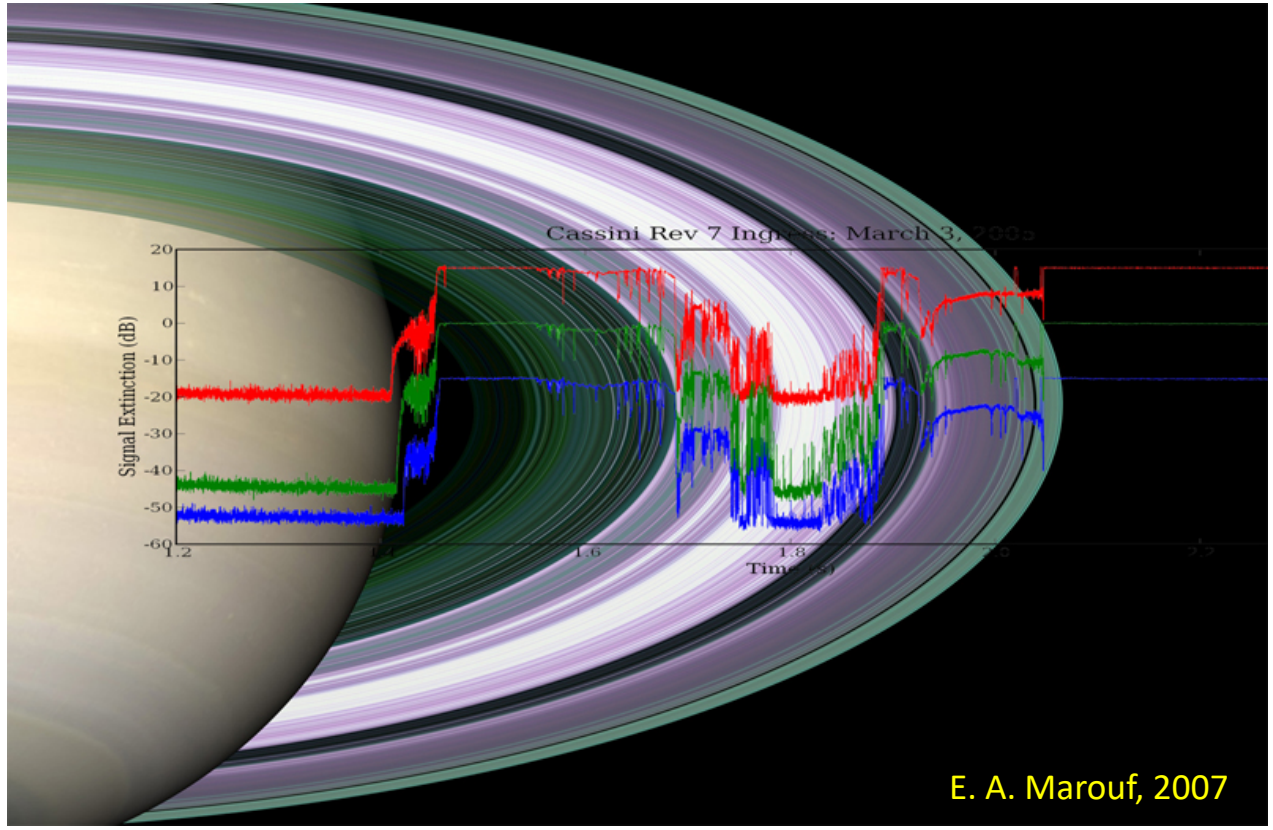
Radio Science: A Key Tool of Solar System Exploration Producing Many Important Discoveries



- **Atmospheres affect the propagation of communication links**
  - ***Study solar system atmospheric properties***
- **Gravitational fields alter Doppler shifts due to spacecraft motion**
  - ***Study interior structures***
- **Atmospheric motions affect Doppler shifts of situ probes**
  - ***Study wind dynamics and turbulence***
- **Small ice and rock particles affect radio phase and amplitude**
  - ***Study planetary rings***
- **Surfaces of solar system bodies scatter radio signals**
  - ***Study surface material/roughness and near subsurface***
- **Sun's extended atmosphere alters signal propagation**
  - ***Study solar corona and wind***
- **Sun's gravitational field affects Doppler and range data**
  - ***Study fundamental physics***

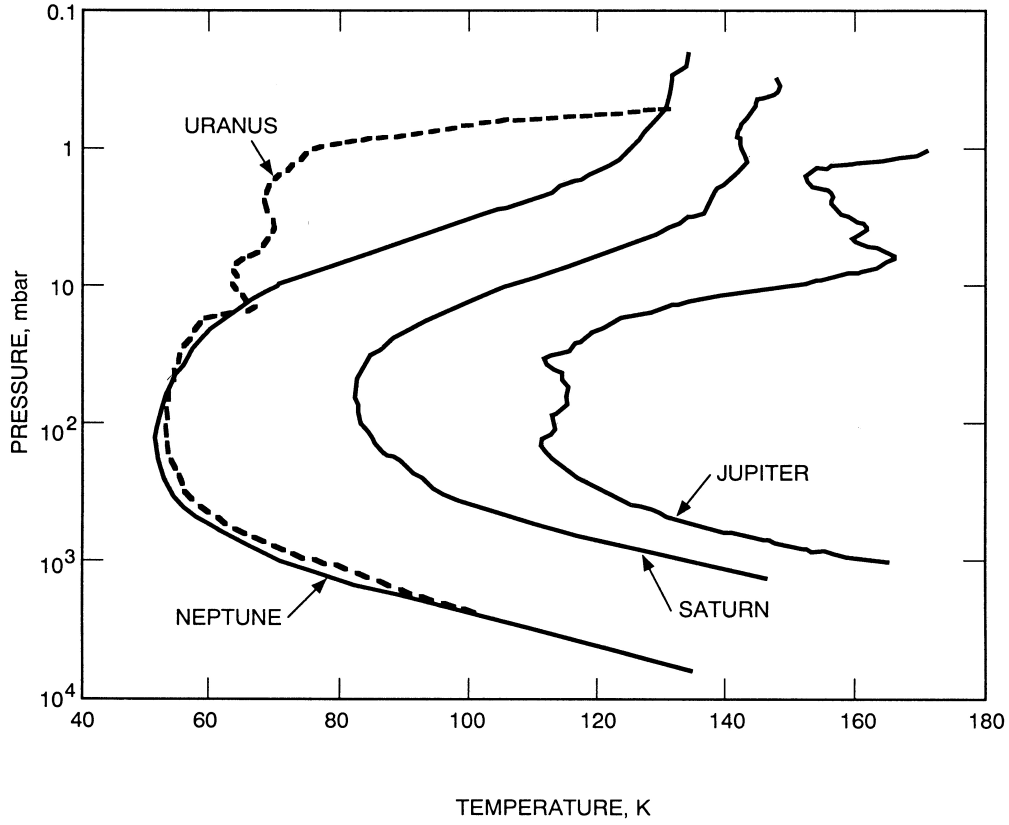


Examples of Results from Radio Occultations



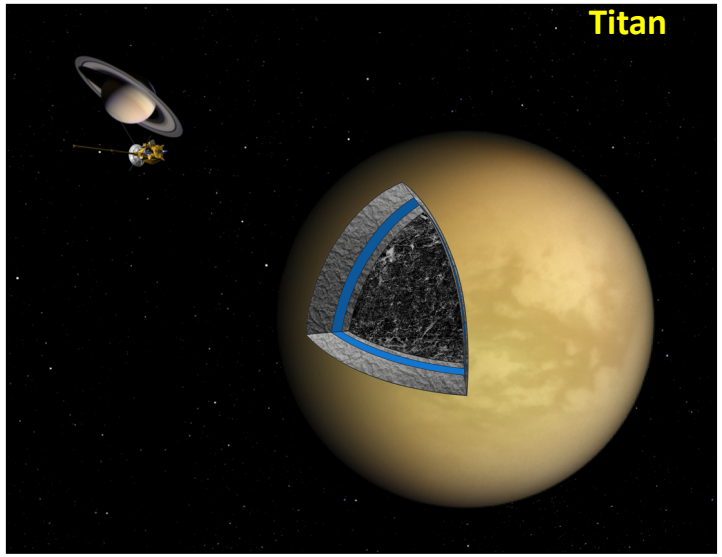
Saturn's Rings In the Cassini Era

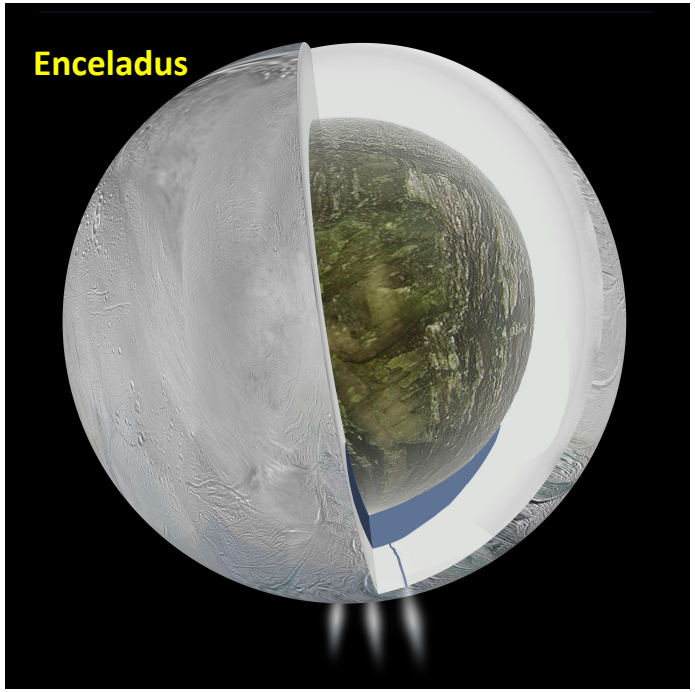
Atmospheres of Giant Planets by Voyager

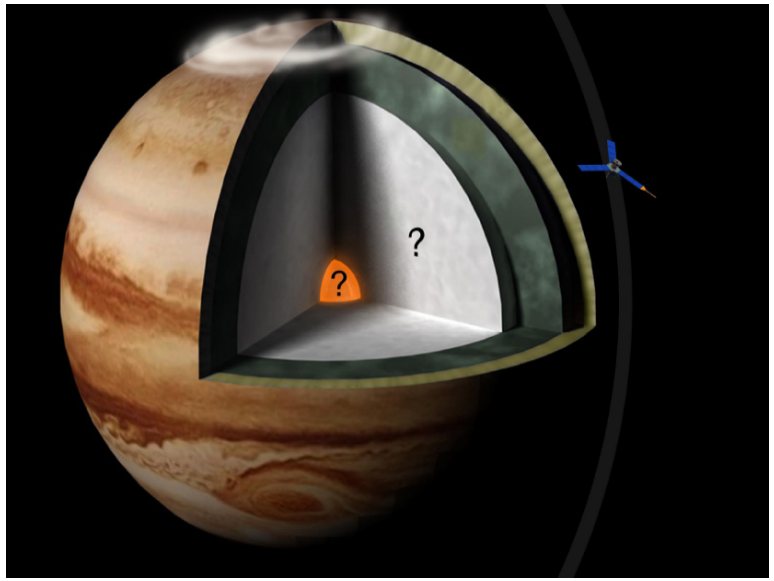


Temperature profiles for the giant planets derived from radio occultation data acquired with the Voyager spacecraft (from Lindal, 1992)

Examples of Results from Gravity Science



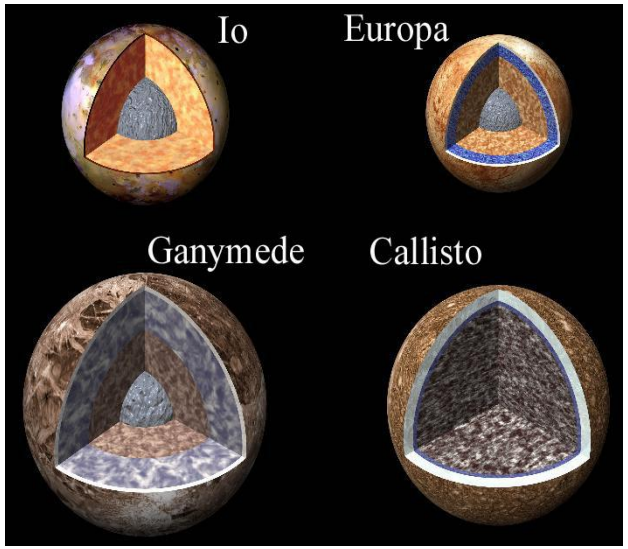




Tidal observations by Cassini gravity team

Titan: Iess et al., 2011 & 2012

Enceladus: Iess et al., 2014



Models of the interiors of the Galilean satellites based on magnetic and gravity measurements

Icy Moons of Large Planets

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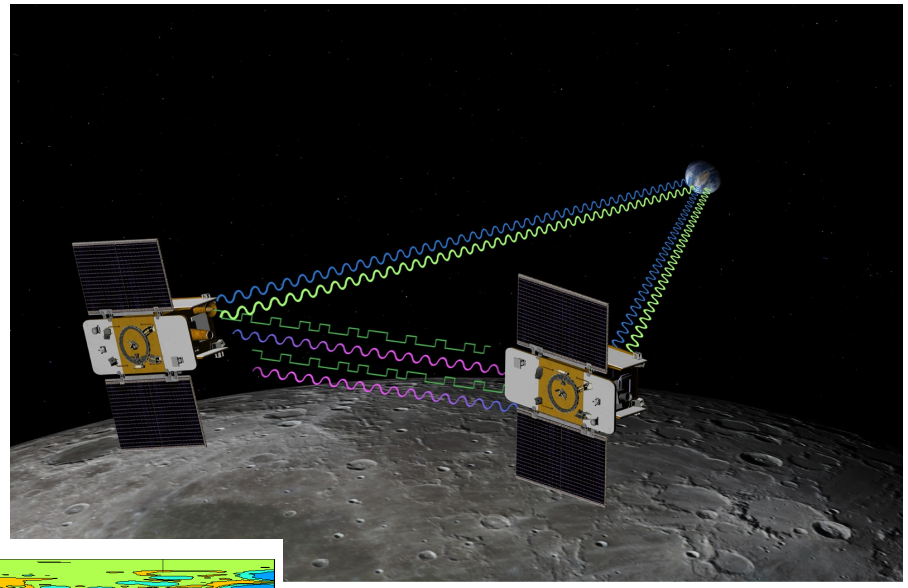
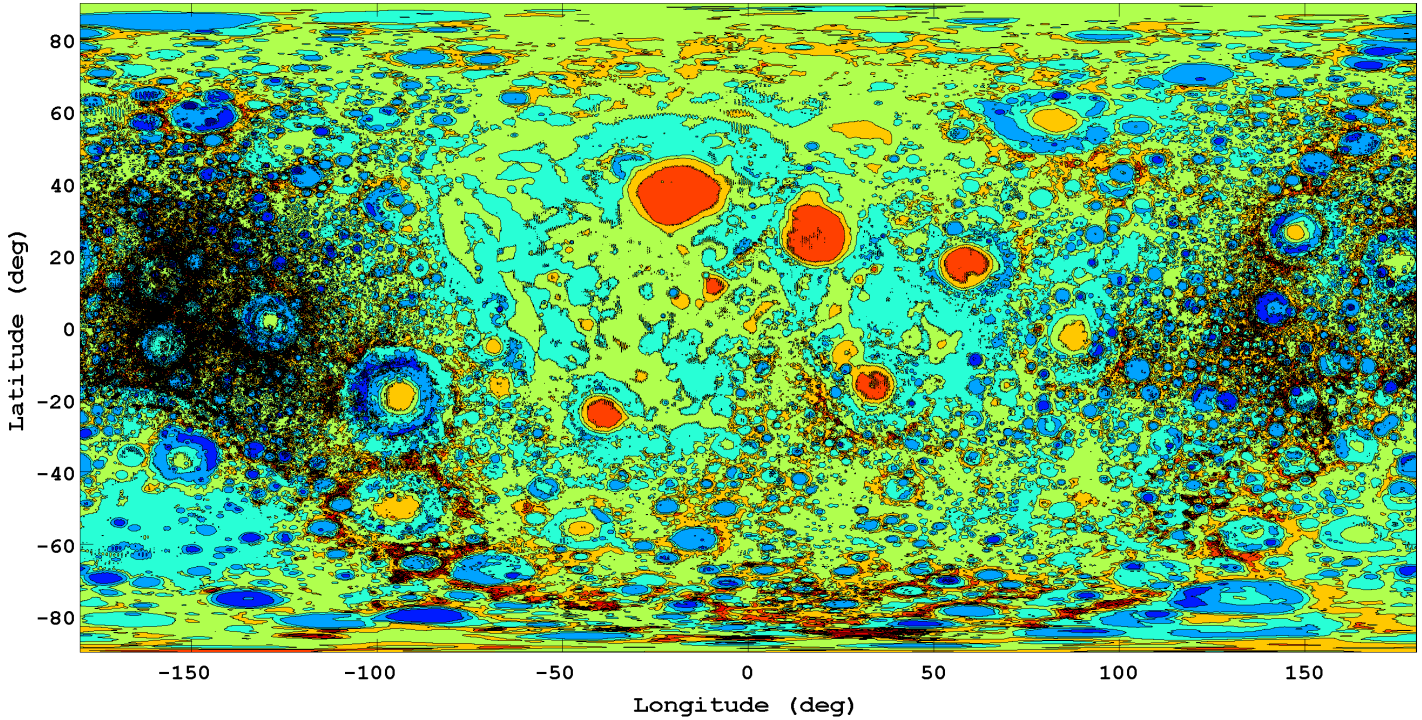
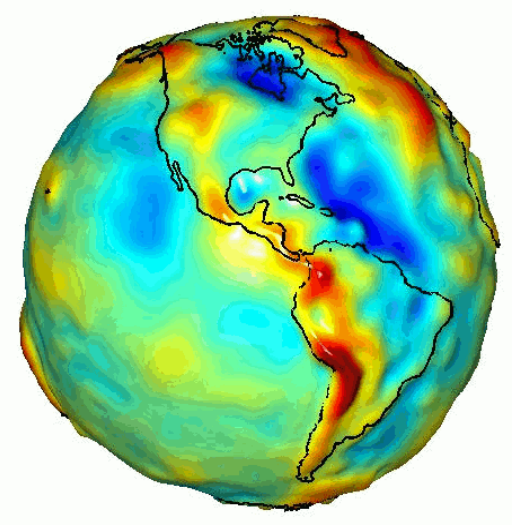
GRAIL Reveals Lunar Interior Structure

Concept of spacecraft-to-spacecraft crosslinks

GRACE Earth mission (large spacecraft)
GRAIL at the Moon (slightly smaller spacecraft)

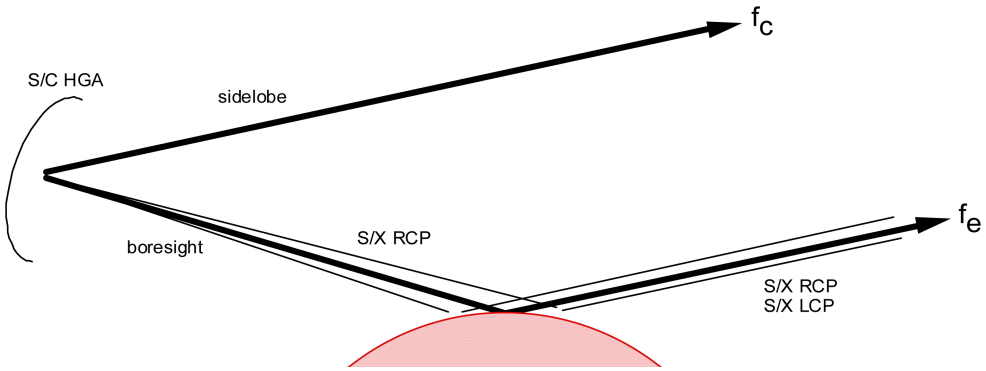


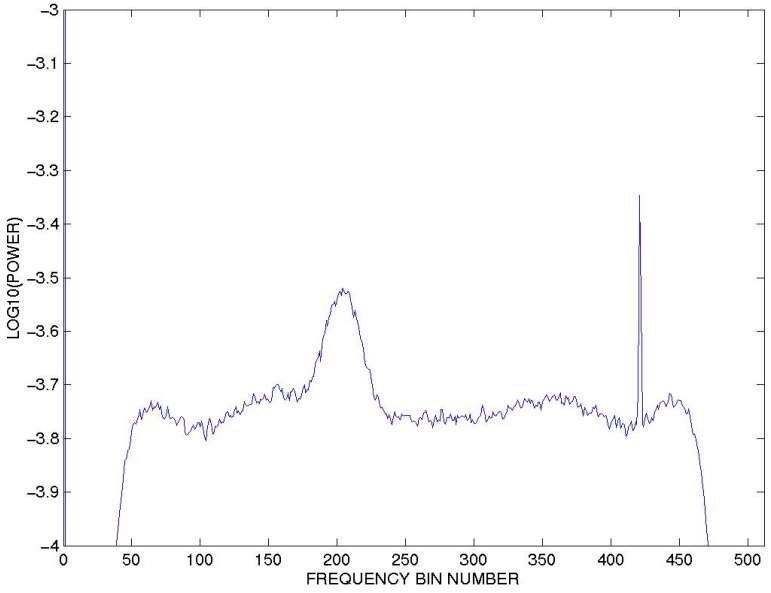




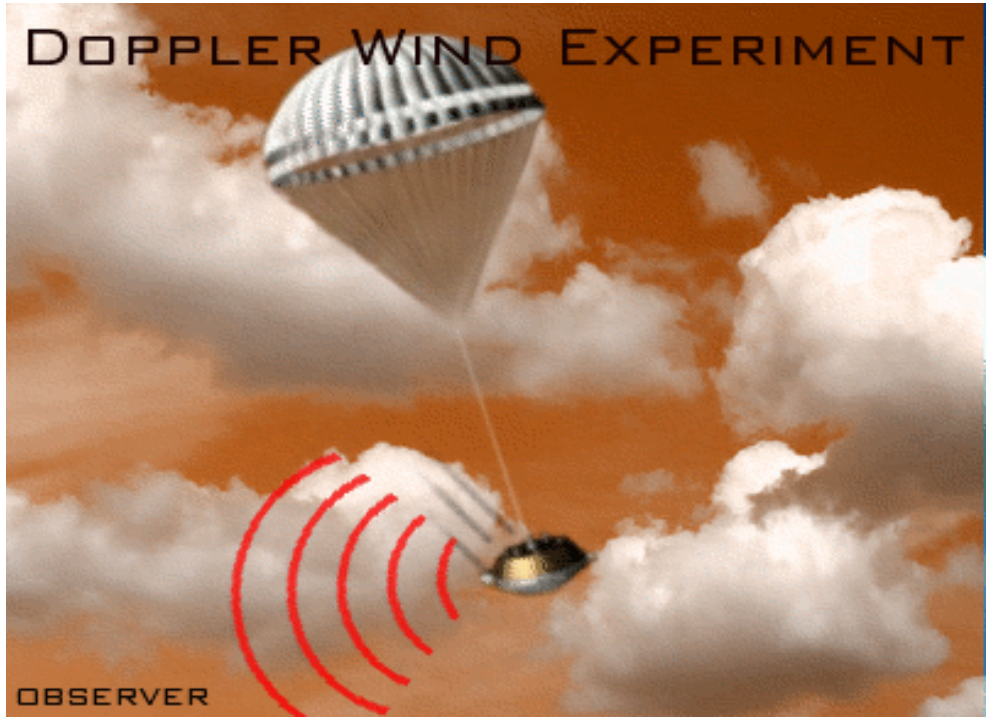
Other Investigation Concepts in Planetary Radio Science

Surface Properties



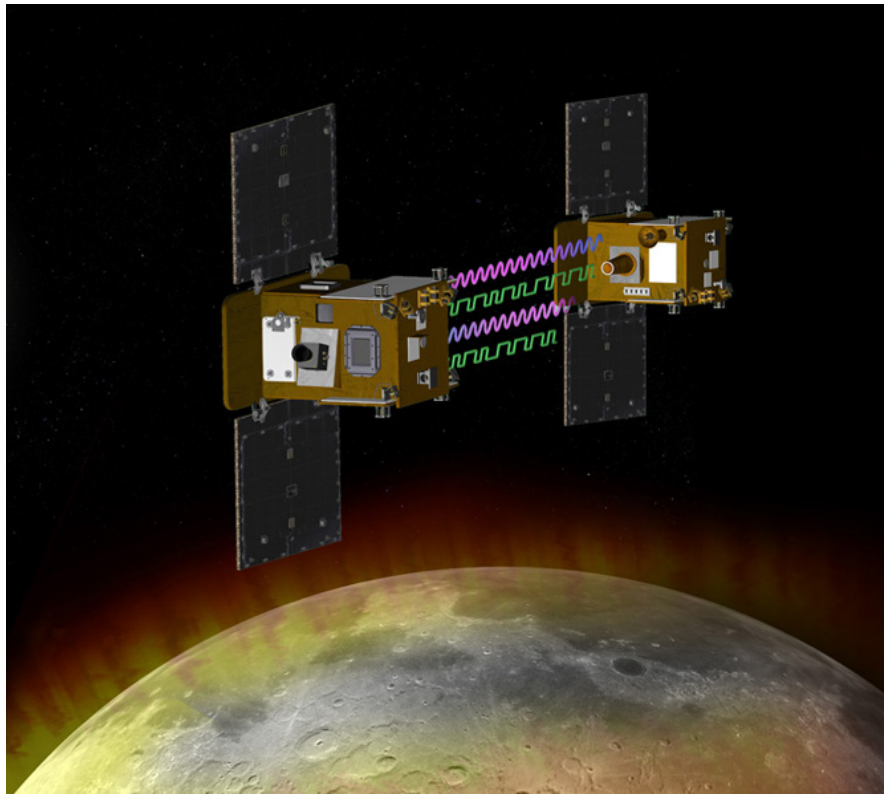


Wind Dynamics



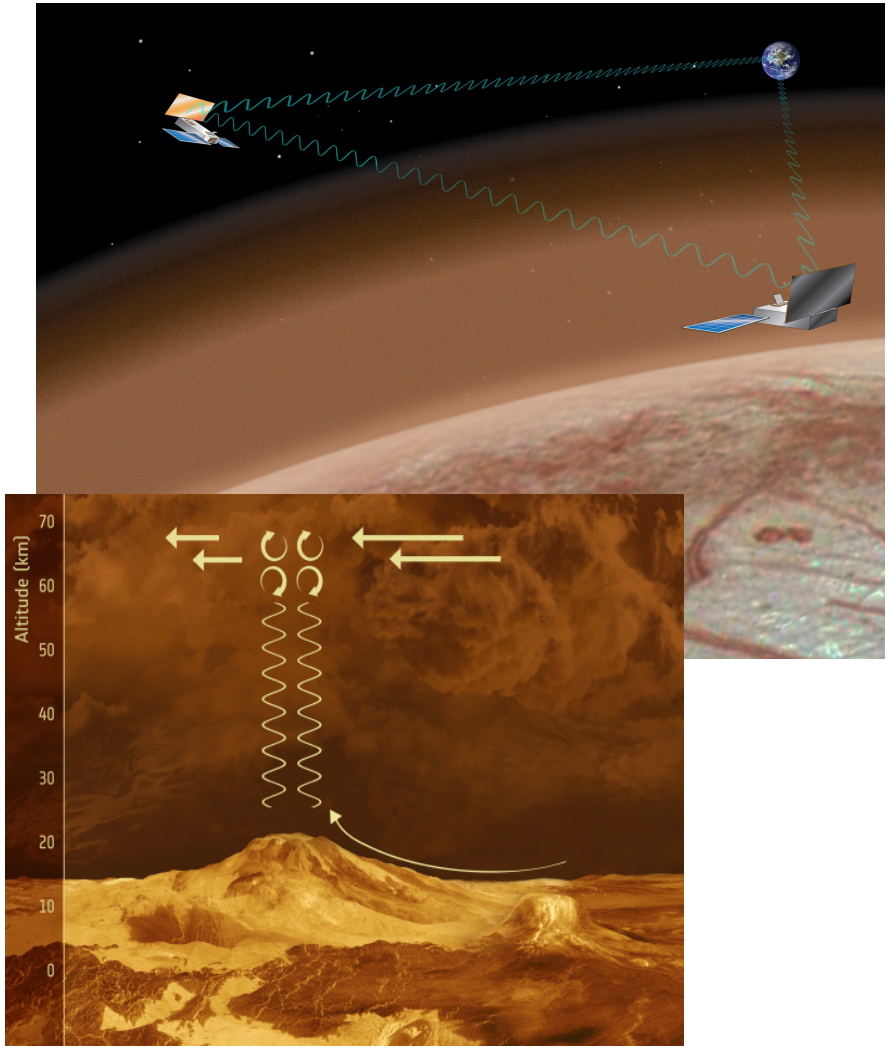
Ride-Along SmallSat Concepts & Scenarios

- **“Small spacecraft,” “SmallSats,” or “CubeSats” defined as 6 to 12 U size**
- Ride-along small spacecraft can be used to explore the atmospheres, surfaces, interiors, rings, and the environment surrounding planets and their moons, as well as asteroids and comets.
- Small spacecraft are well suited as small constellations for crosslink occultations, GRAIL-like gravity and interior science, and multiple entry probes
- **Placed in orbit**
  - Studied extensively for Mars and currently examined for Venus
- **Targeted flybys**
  - Short lifetime probes for key gravity field measurements
    - Benefit by closeness to body and risk reduction
- **Atmospheric entry for in-situ science**
  - Entry probes and balloons



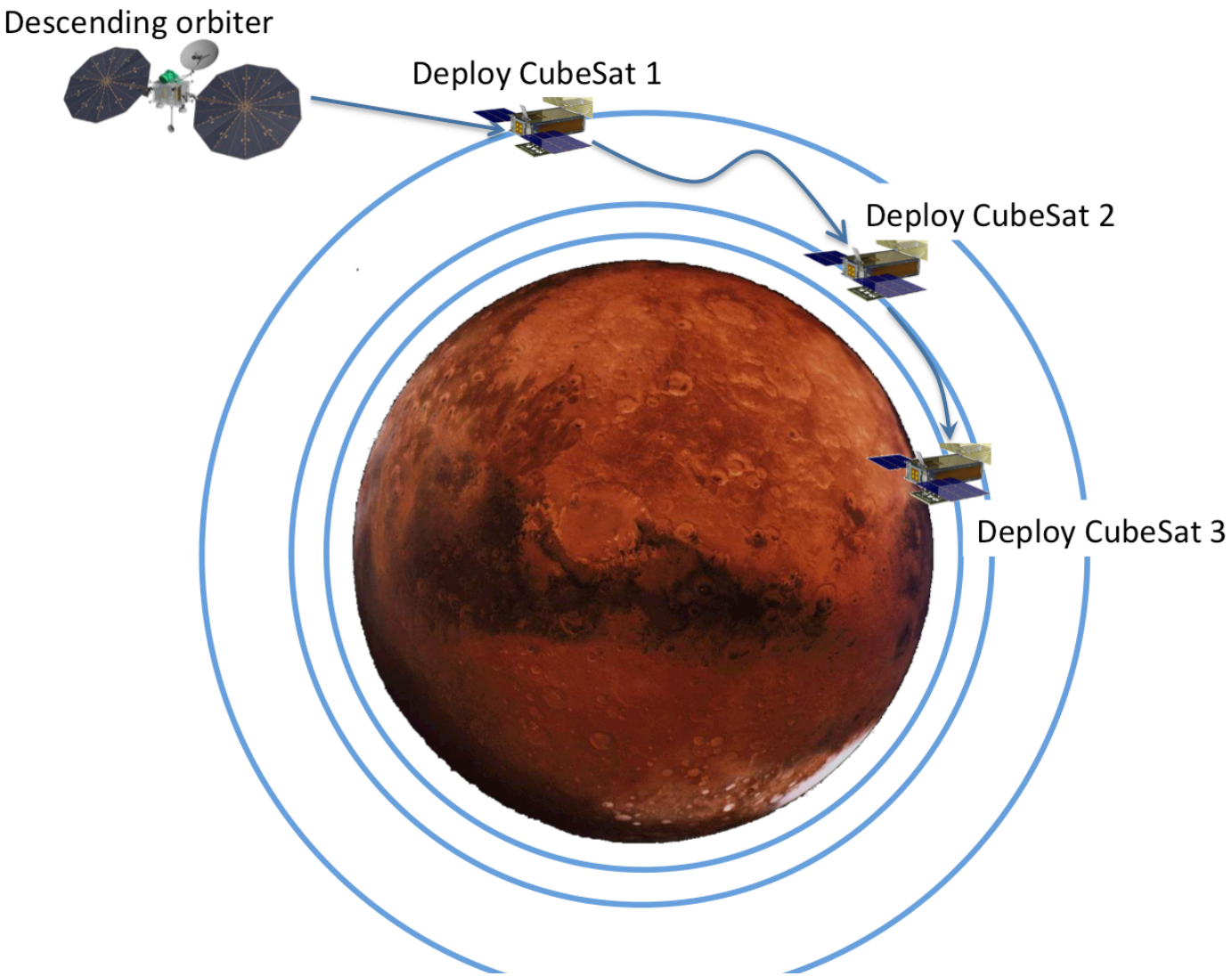
Placed in Orbit

- **Science: Planetary Atmospheric/Ionospheric Structure**
  - High vertical & temporal resolution measurements of atmospheric density, temperature, and ionospheric electron number density (utilizing dual wavelengths) via radio occultations with global coverage
  - **Mission**: 2 or 3 CubeSats in orbits at appropriate altitudes & inclinations to provide frequent line-of-sight for atmospheric occultations
- **Science: Gravitational Fields Interior Structure**
  - High-resolution gravitational field mapping to explore the interior structure and time-varying planetary properties
  - **Mission**: GRAIL with much smaller spacecraft!
- **Science: In-situ Measurements of Planetary Dynamics**
  - Study winds, tides, and waves
  - **Mission**: 2 or 3 entry vehicles/probes
- Science: Surface properties and roughness
  - Signal scattering experiments (bistatic radar) to explore surface and near sub-surface material properties
  - **Mission**: Small body lander or hoppers



High temporal and spatial resolution properties of thermal tides & geophysical-driven waves could be captured by radio occultations, especially if the SmallSats are placed over a dedicated active location

SmallSat Constellation Mission Concept Deployment



Differential precession of CubeSat orbit planes achieves desired variety of orbits at Mars

Venus case: there is no significant J2, no orbital precession.

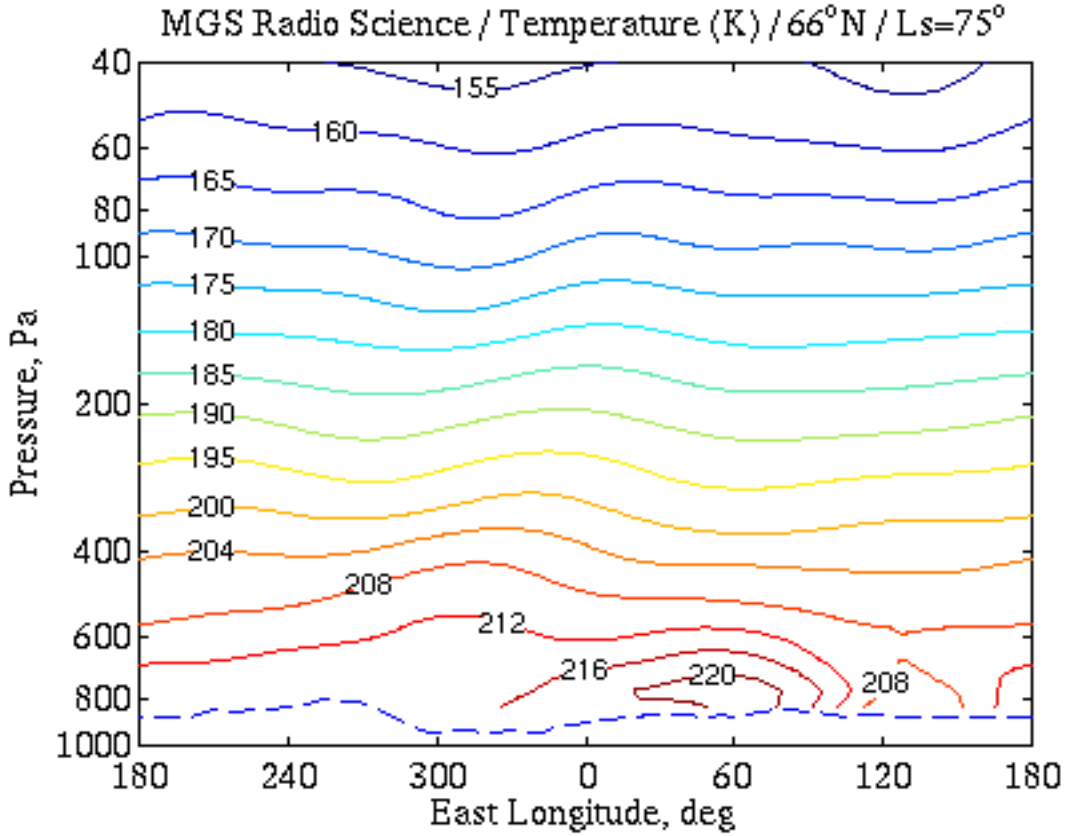
Deploy CubeSats during approach or descent of main orbiter

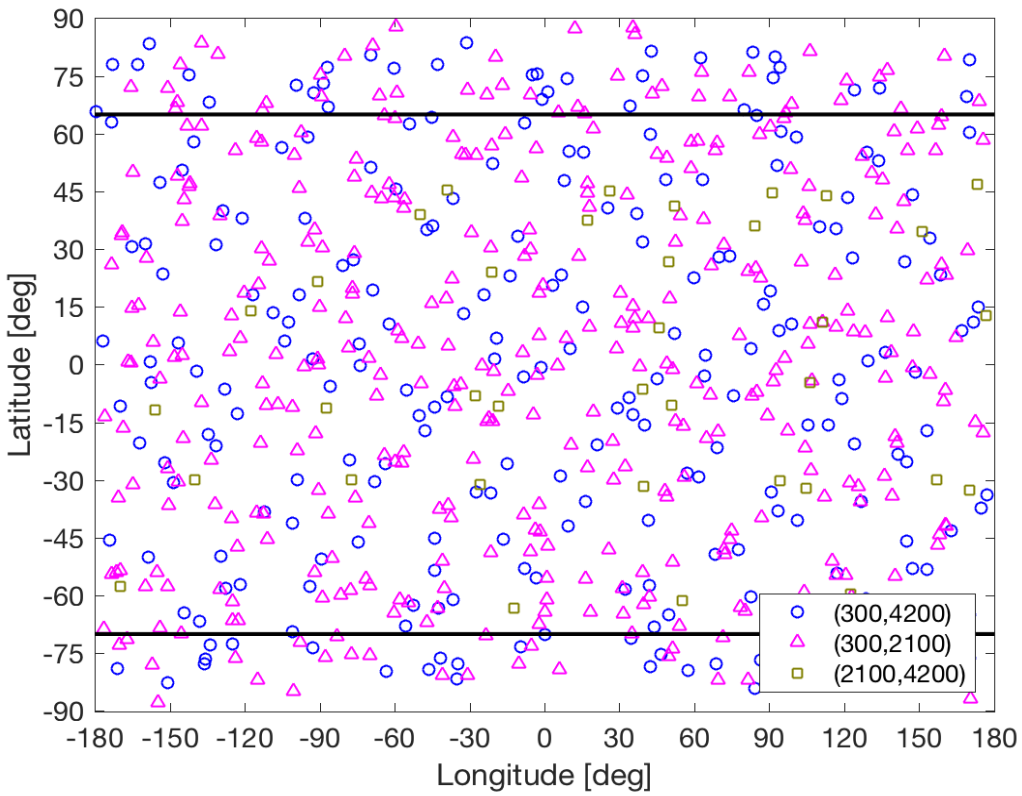
Candidate altitudes:
4200 km
2100 km
300 km

Atmosphere of Mars from
Mars Global Surveyor occultations
Coverage in ten years

vs.

Simulations of global Mars coverage
Three CubeSats at 3 altitudes
Pairwise occultation locations
One week acquisition time





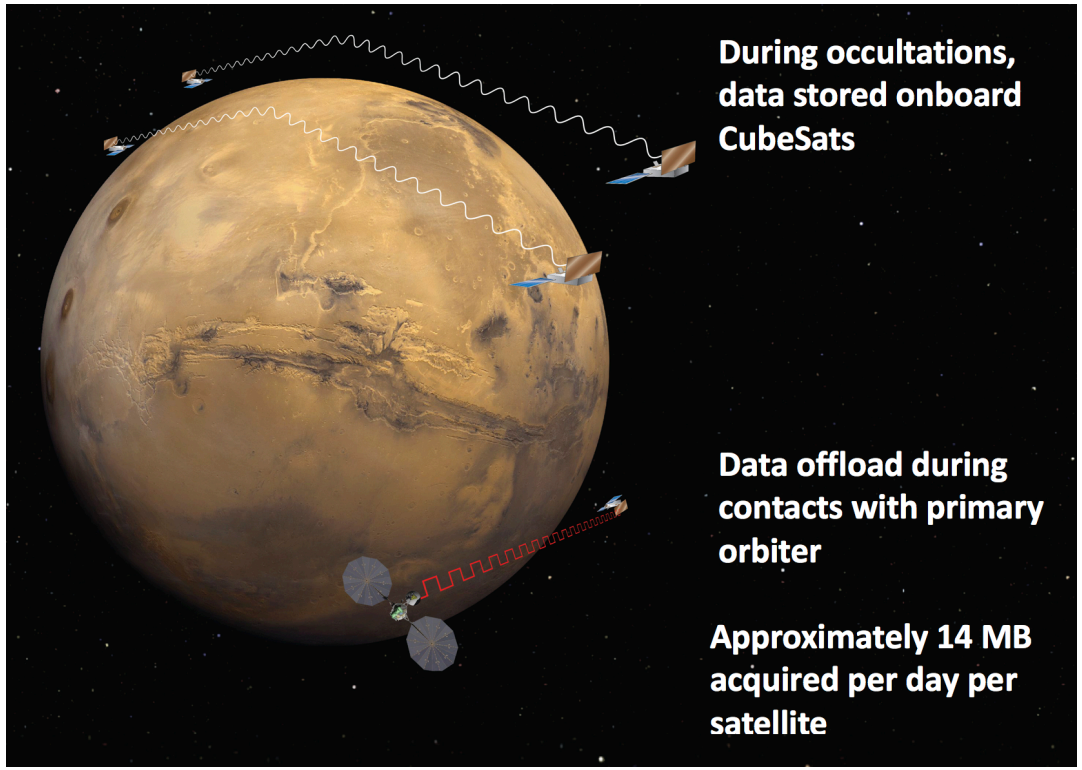
Source: D. Hinson, Stanford Univ.

From *Spacecraft-to-DSN* to *Spacecraft-to-Spacecraft*

- Nearly 6 decades of planetary spacecraft links to Earth
- Earth science community advanced crosslink technique via GPS satellites transmitting to science spacecraft
- Carry *crosslink* concepts to planetary atmospheres for tremendous advantages
- Science motivation & assist human missions (✓)
- Need mission design & navigation (✓)
- Need radio instrumentation (✓)
- Need small spacecraft platform (✓)
- Need a demo of concept (✓)

- Ready for science mission implementation

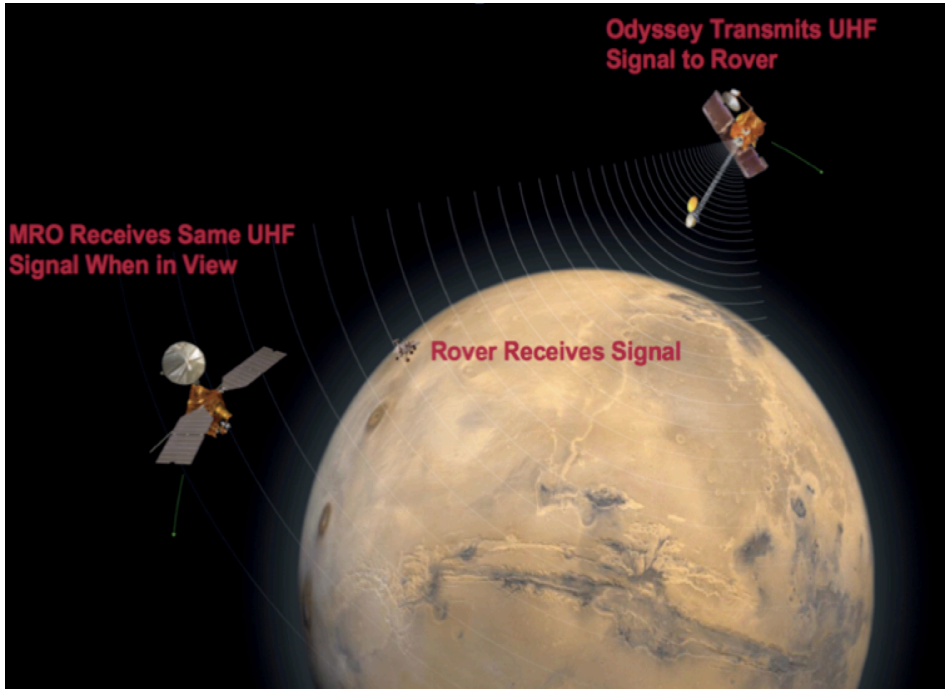
- Approximately 14 MB acquired per day per spacecraft
- Mission lifetime > 1 Martian year

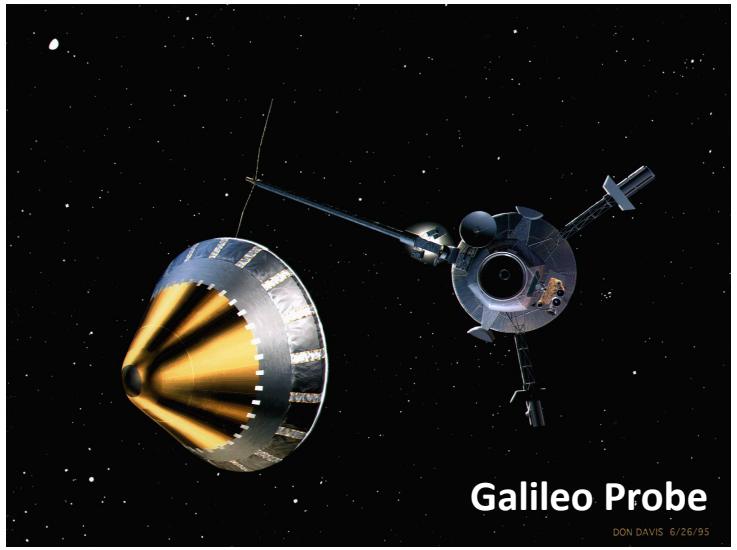


Pre-Decisional Information -- For Planning and Discussion Purposes Only

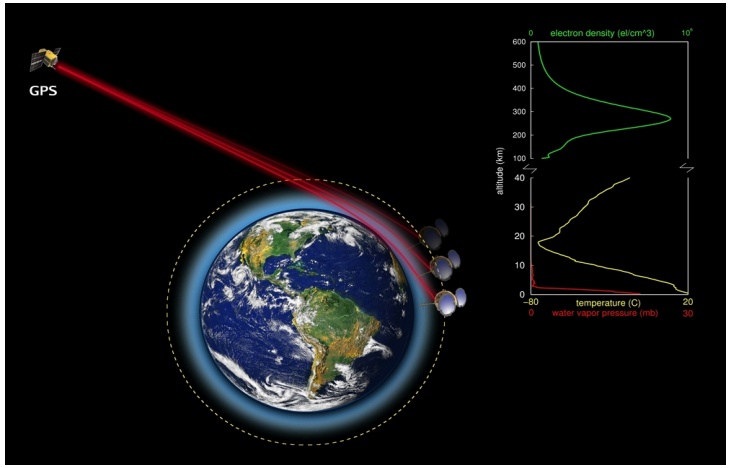
Planetary Crosslinks Already Demonstrated

- **For Atmospheric radio occultations**
  - **Odyssey to MRO (Mars)**
- **For gravity science**
  - **GRACE (Earth) and GRAIL (Moon)**
- **For the in-situ Doppler wind experiments**
  - **Galileo probe to the Galileo orbiter (Jupiter)**
  - *Huygens to Cassini (Titan) Link failure due to operation error*





Experience from Earth Science



Radio occultation science, detection of atmospheric gravity waves has been demonstrated by COSMIC

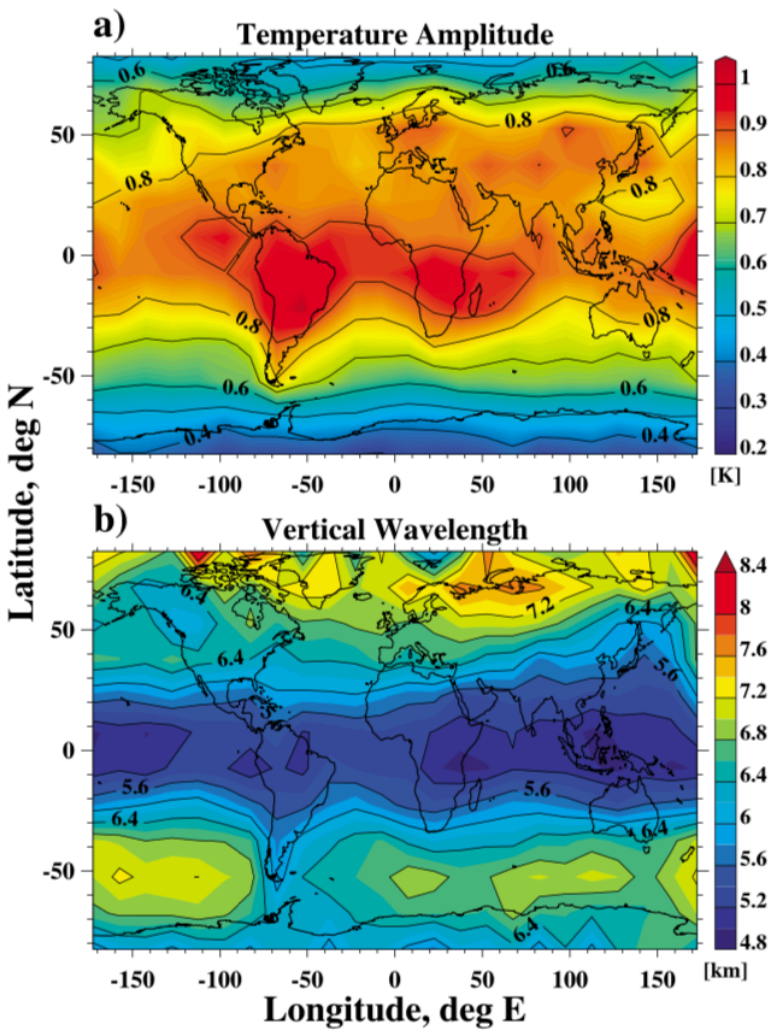
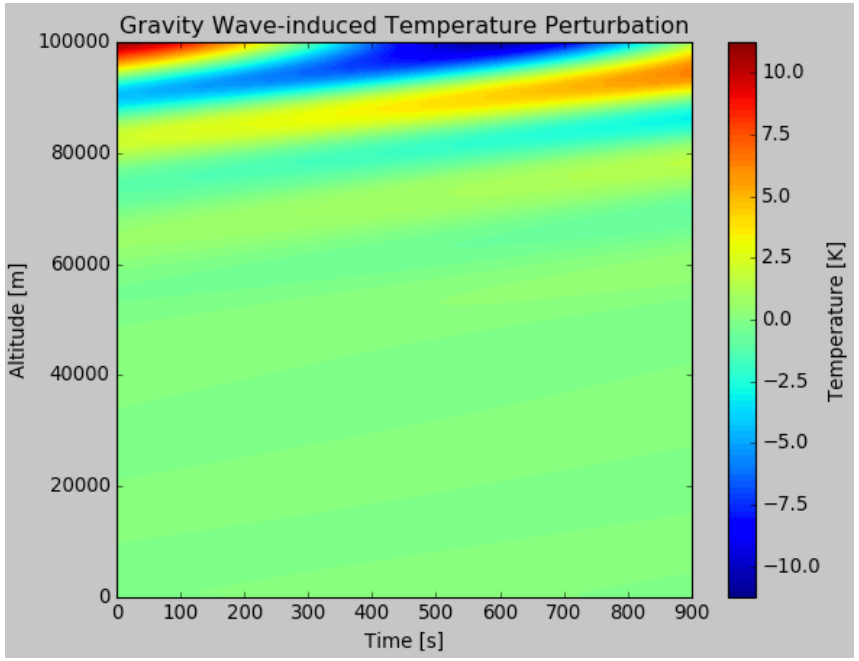


Figure 3. Contoured map of 2006–2007 December-January-February (a) seasonal mean gravity wave dominant temperature amplitude and (b) vertical wavelength averaged in the altitude range of 17.5–22.5 km from the combined COSMIC and CHAMP GPS RO data.

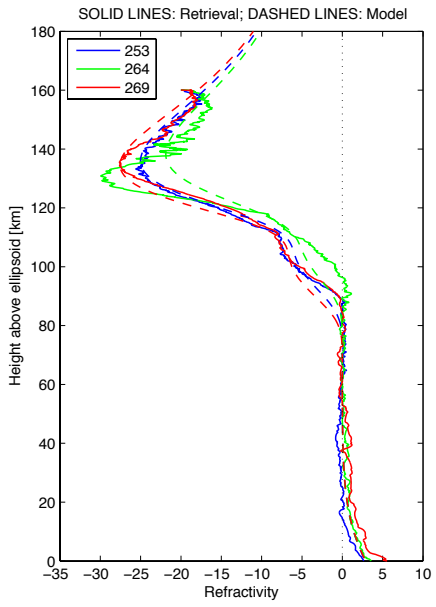
Wang & Alexander, 2010

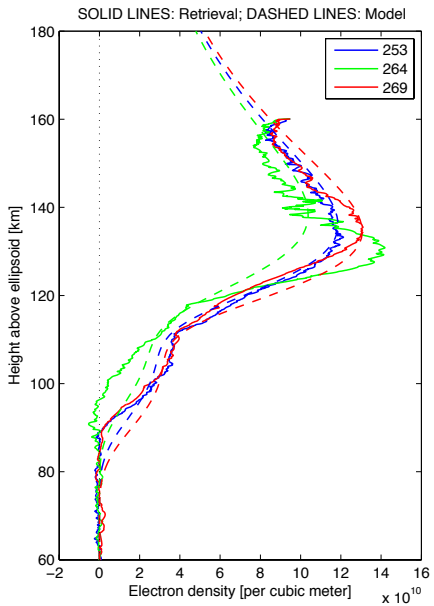


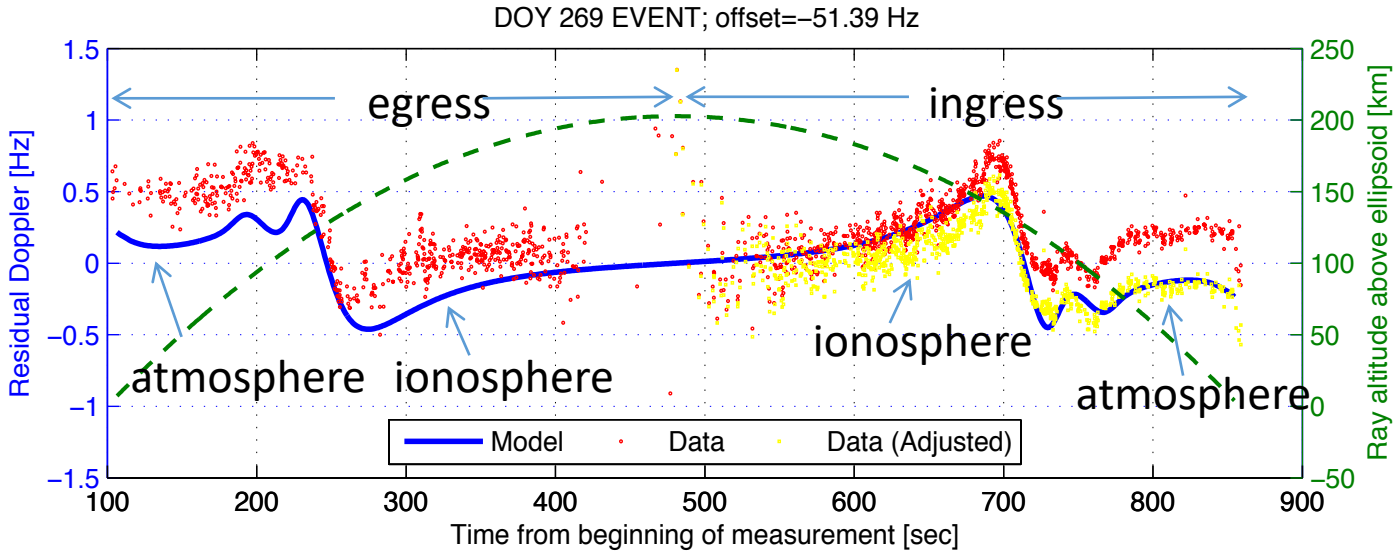
New simulation (by P. Vergados) of temporal evolution of temperature perturbations as a function of altitude (from the surface up to 100 km) caused by vertically propagating gravity waves that were produced by an earthquake that caused 15 cm vertical displacement of the ground.

This is an example what is expected on Venus in case of planar gravity waves during seismic activity.

Demonstration: Ionospheric profile from UHF
Link between Odyssey and MRO



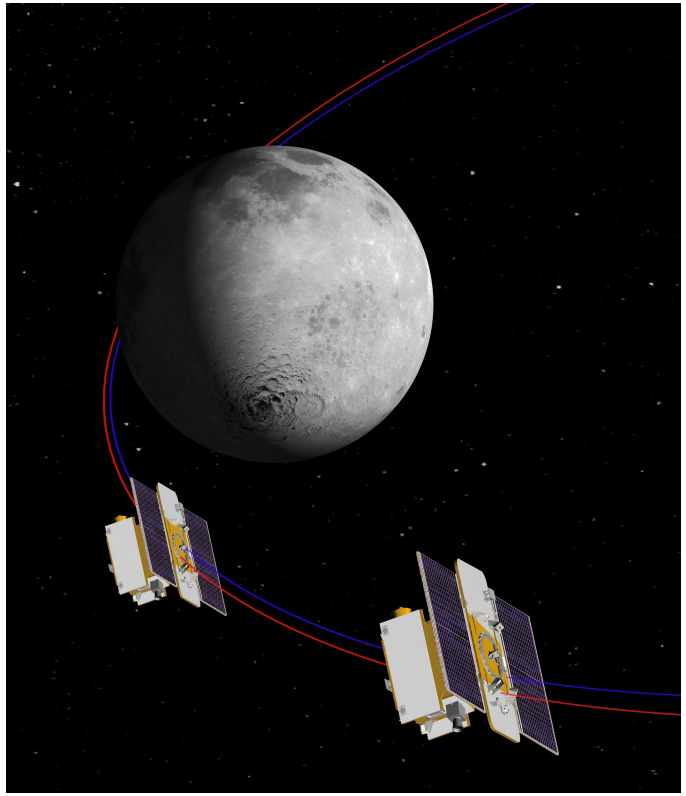




Geometries where orbiters communicating with rover on surface were in line-of-sight for a crosslink (λ ~75 cm); made possible due to flexible design of the Electra software-defined radio.

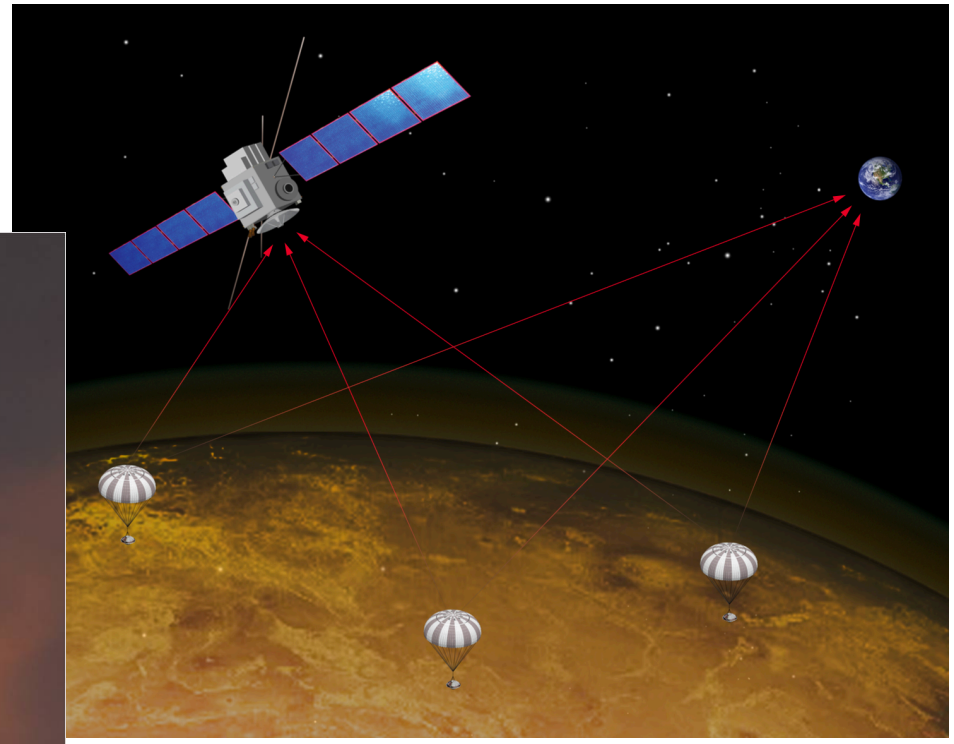
Target Flybys

- Short lifetime probes for key gravity field measurements
- Benefit by closeness to body and risk reduction

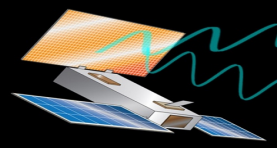


Atmospheric Entry

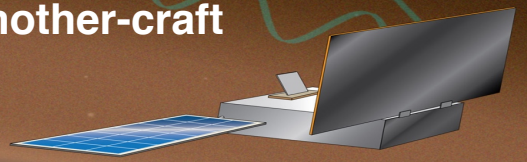
- Determine the atmospheric zonal winds, composition, and structure at high spatial resolution, as well as the temporal evolution of atmospheric dynamics.
  - Highest Priority Science Objective for a Uranus Orbiter and Probe mission (PSDS 2013-2022)



Summary



- Evolution from Spacecraft-to-DSN to Spacecraft-to-Spacecraft links for enhanced science
- To accomplish science goals, completed a JPL Team Xc study on SmallSat design
  - A viable design is possible using a MarCO 6U baseline as a starting point
  - Electrical power sufficient at Mars and Venus but a limiting resource in the outer solar system
  - Orbit insertion propulsion not feasible, so spacecraft carried into orbit by the mother-craft
  - Relay through mother-craft is required
  - Iris radio augmented with simultaneous X-band transmit-receive capability
    - Dual one-way X-band Doppler reduces clock requirements
    - Transmit power ~ 1 W (adequate at Mars)
  - SmallSat trajectories (position and velocity) must be known to high accuracy (requirement: 0.18 mm/s)
    - Flows from temperature (2 K) and vertical resolution (2 km) requirements
  - SmallSats at 400 km & 4000 km altitudes, various relative orientations



- Possible at Venus with exciting new science possibilities

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