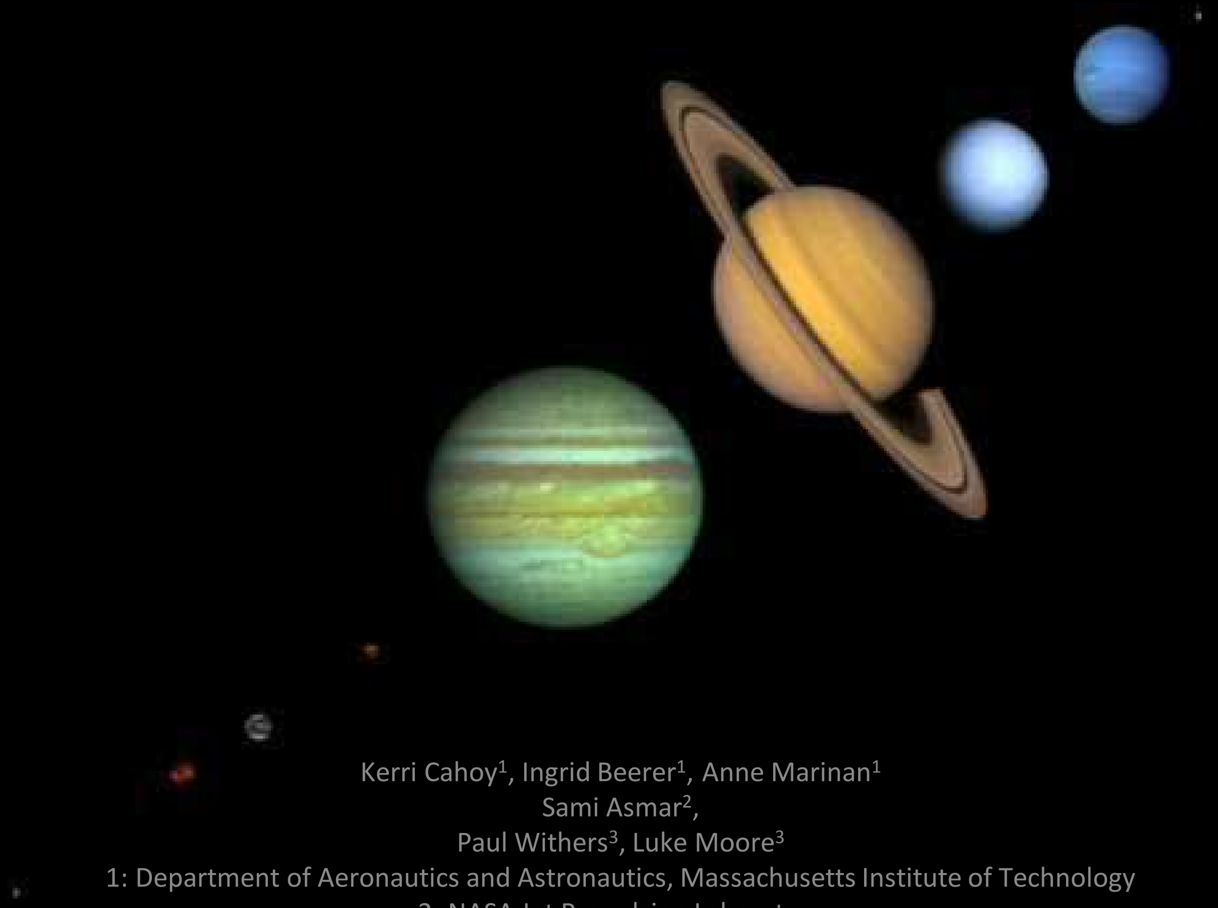
iROCC:
Interplanetary Radio Occultation CubeSat Constellation



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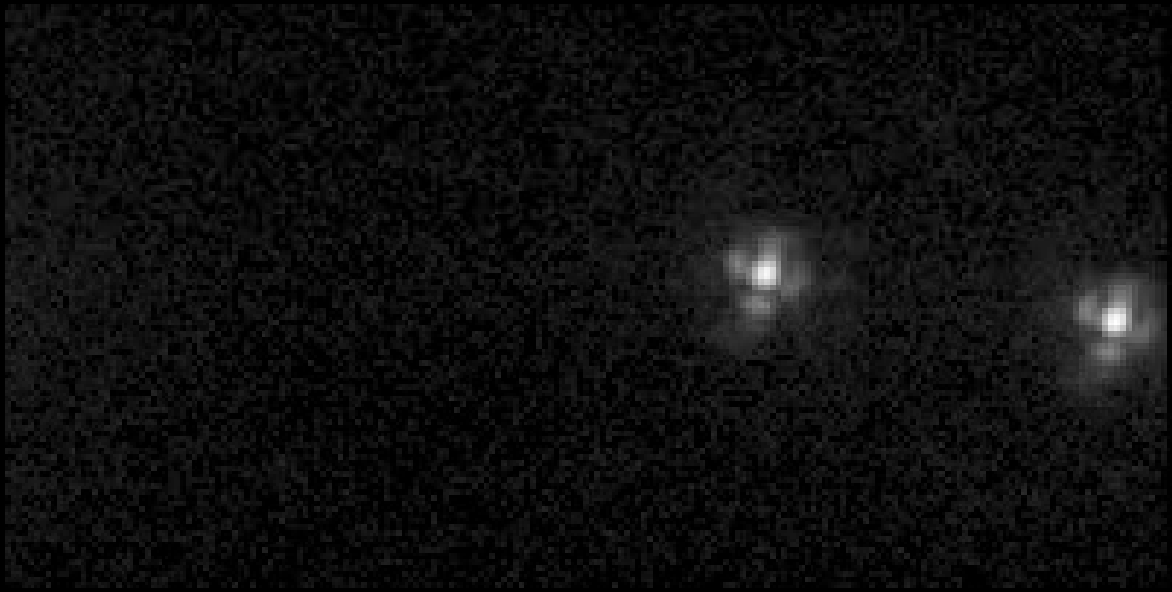
Overview

1. What is Radio Occultation?
2. Which planets/moons “best” for iROCC?
3. What are the CubeSat technologies that we need?
    - Getting there: Cruise and/or orbit insertion “carrier”
        - Controlled and accurate deployment
        - Propulsion to maintain constellation
    - Taking measurements: RO Instrument
        - Stable oscillator/clock, differencing
        - Open loop or smartly “steered” receiver
    - Getting data back:
        - Relay and/or Ground support

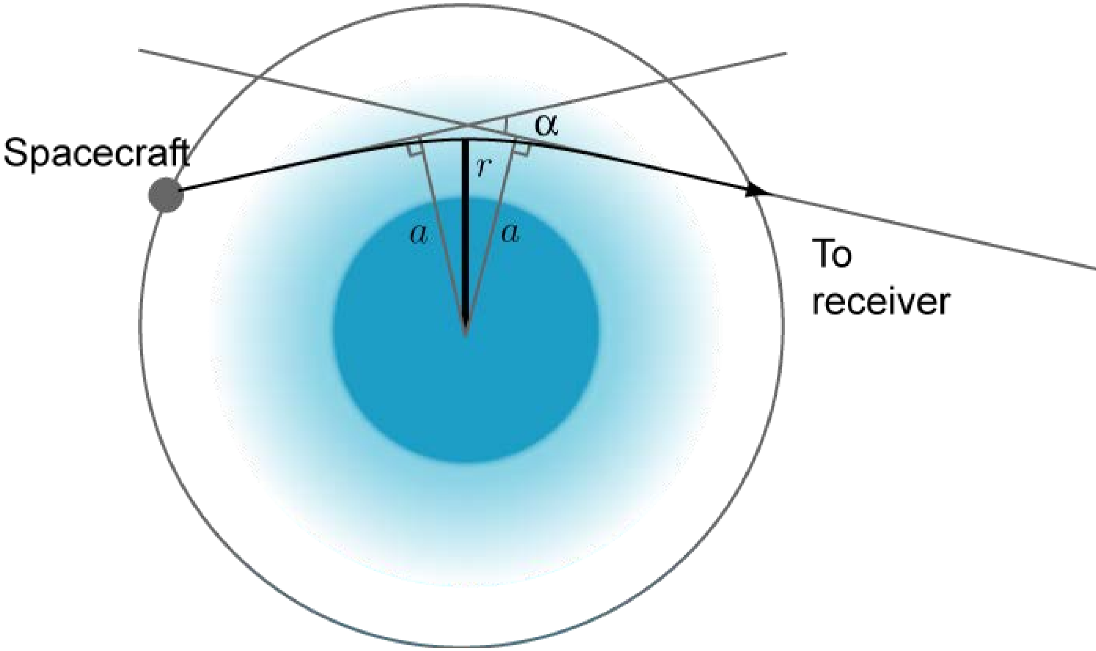
Occultation Concept



- Titan occults a double star
  - Movie courtesy A. Bouchez
- Palomar 241-actuator adaptive optics system on the 5-m Hale telescope
- PHARO near-IR camera, K’ filter (1.95 – 2.30 µm)

What is Radio Occultation?

- Spacecraft transmitter + receiver
- Atmospheric gas + plasma – refractive index
- Refractive index – frequency shifts
- Invert to get thermophysical data
- Ways to do it:
  - Downlink
  - Uplink
  - Intersatellite link
- Design drivers:
  - Frequency stability
  - Signal to Noise
  - Attitude stability
  - Orbit tracking and geolocation



What is Radio Occultation?

- "Bending" α is received as a frequency shift *(Fjeldbo, 1971)*

$$\cos\left[2\pi\left(f(t)+\Delta f(t)+\theta(t)\right)\right]$$

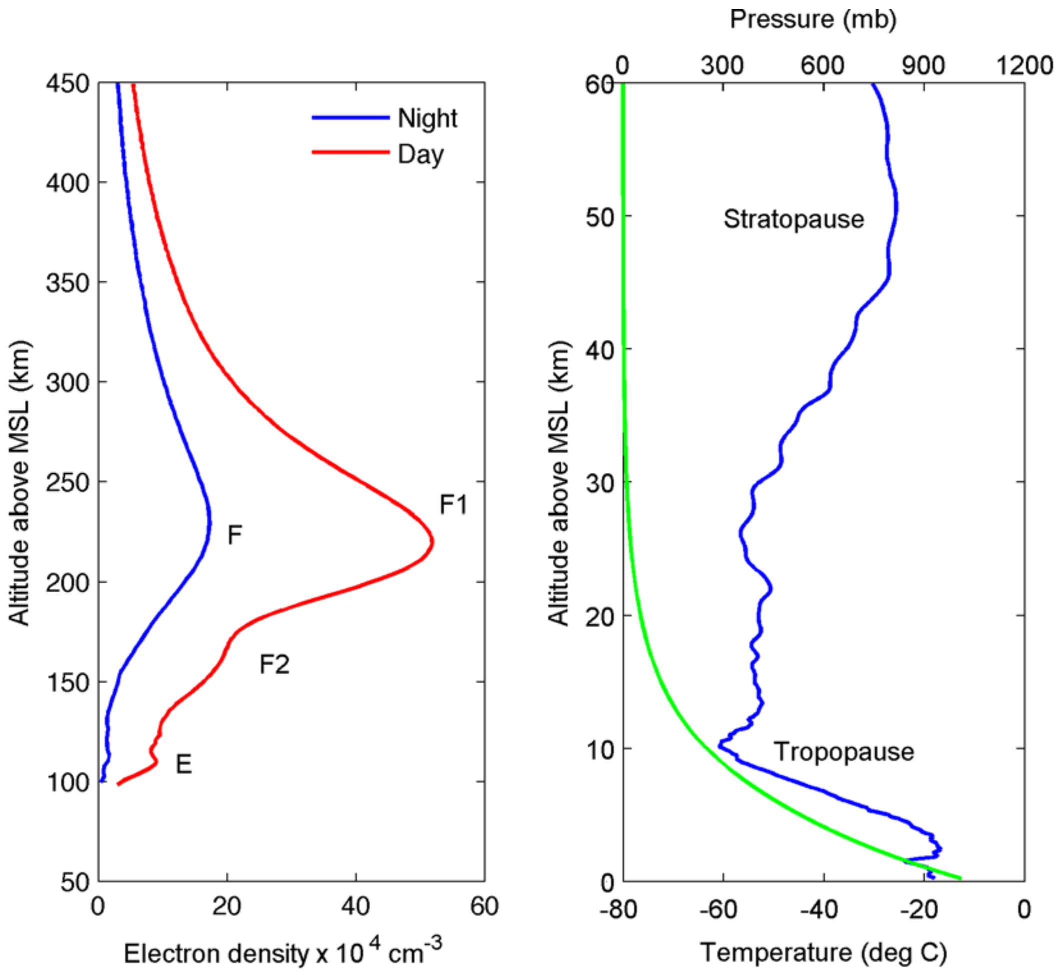
- Abel transform relates the amount of "bending" $\alpha(a)$, to refractivity as a function of altitude, *v(r)*

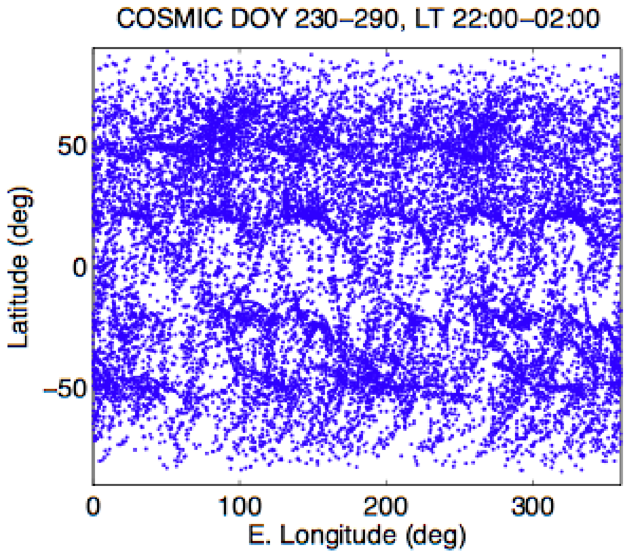
$$v(r_0)=\exp\left[\frac{1}{\pi}\int_{a=a_1}^{a\to\infty}\ln\left(\frac{a}{a_1}+\sqrt{\left(\frac{a}{a_1}\right)^2-1}\right)\frac{d\alpha}{da}da\right]$$

- Yields atmospheric refractivity *profiles*
  - Gas density, plasma density
  - Temperature, Pressure

Niels Henrik Abel, 1802-1829

Example data from GPS—LEO RO on Earth





COSMIC/FORMOSAT-3:
17,544 profiles

- Temperature (blue) and pressure (green) profiles at 03:22:06 UT, 52.5º N latitude and 147.7º E longitude. Daytime electron density profile (red curve) at 19:53:1 UT, 36.8º N latitude and 71.5º W longitude. Nighttime electron density profile (blue curve) at 19:06:01 UT, 35.9º S latitude and 155.7º E longitude.

Which planets/moons are best for iROCC?

- Atmosphere + ionosphere
  - Mercury
  - Venus (CO2, N2)
  - Earth (N2, O2)
    - Moon
  - Mars (CO2, Ar)
  - Jupiter (H2, He, CH4, NH3)
    - Io, Callista, Europa, Ganymede
  - Saturn (H2, He, CH4, NH3)
    - Titan (N2, CH4)
    - Enceladus (H2O geysers)
  - Uranus (H2, He, H2O, CH4, NH3)
    - Titania (CO2?)
  - Neptune (H2, He, CH4)
    - Triton (N2, CH4, CO)
  - Pluto (N2)

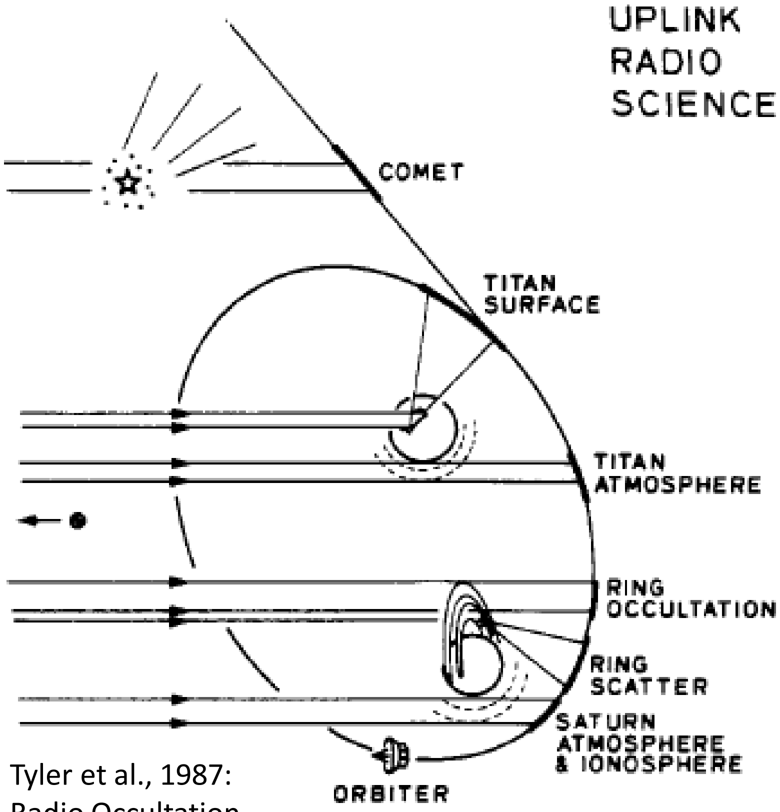
Radio Occultation Planetary Heritage

(input from Withers et al. 2010)

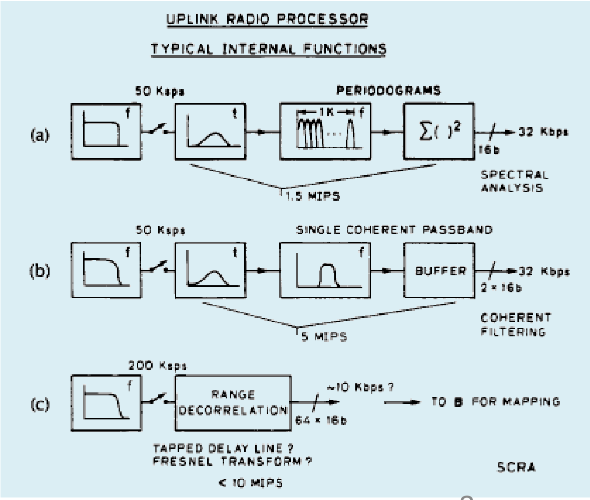
- Mercury
  - Mariner 10 (1973)
- Venus
  - Mariner 5 (1967), 10; Venera 9, 10, 15, 16; Pioneer Venus Orbiter (1978); Magellan (1989); Venus Express (2005)
- Moon
  - Pioneer 7; Luna 19, 22; SMART-1, SELENE
- Mars
  - Mariner 4, 6, 7, 9 (1964, 1969, 1971; Mars 2, 4, 5, 6; Viking 1, 2 (1975); Mars Global Surveyor (1996*); Mars Express (2003); Mars Reconnaissance Orbiter (current)*
- Jupiter, Io, Europa, Ganymede, Callisto
  - Pioneer 10, 11, Voyager 1, 2 (1977); Galileo (1989)
- Saturn, rings, Titan
  - Pioneer 11; Voyager 1, 2 (1977); Cassini (1997)
- Uranus, Neptune, Triton
  - Voyager 2 (1977)
- Pluto
  - New Horizons (2006, en route)
- IP/Halley
  - Vega 1, Vega 2, Giotto

CubeSat RO configuration

- Uplink
  - DSN can radiate 20,000 to 100,000 W
    - Way better than 10-20 W!
    - Geometry/tracking
  - Onboard processing needed
    - Reduce data downlink
  - Fly-by (like Pluto) or orbiters
- Intersatellite links
  - Constellation design
  - Propulsion
    - Maintain set constellation
    - Or “cat and mouse”
- Downlink
  - Power, geometry, amount of auxiliary data

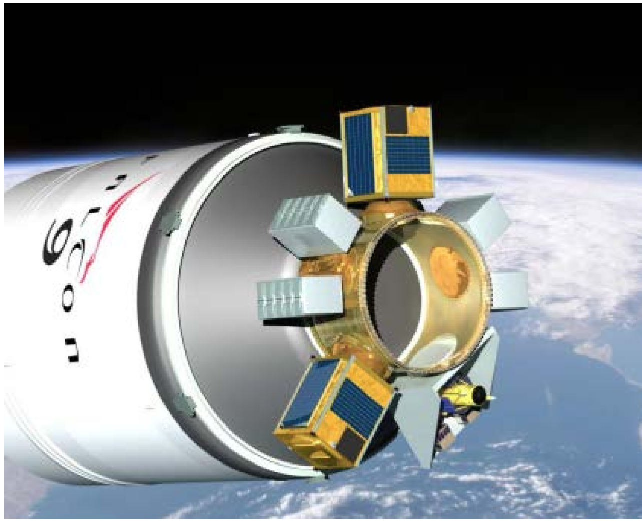


Tyler et al., 1987:
Radio Occultation
Uplink

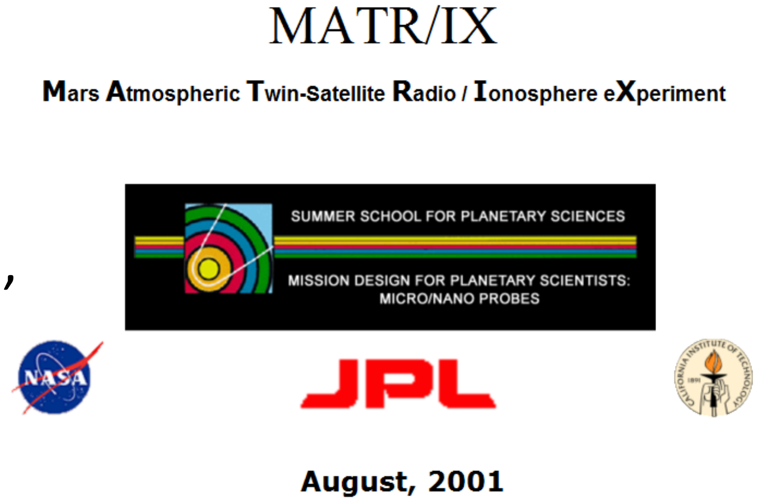


What are the CubeSat technologies that we need?

- Superstructure for cruise and orbit insertion
  - Propulsion
  - Timed deployment control
- Or, iCubeSat aerobraking with deployable solar panels
  - Requires an atmosphere…
- Formation flight
  - Thrusters
  - Intersatellite links
- iCubeSat mag-torquers
  - Magnetic fields: Earth, Jupiter, Saturn, Uranus, Neptune



Example: DecaPOD (Spaceflightservices.com)



MATR/IX

Mars **A**tmospheric **T**win-Satellite **R**adio / **I**onosphere e**X**periment

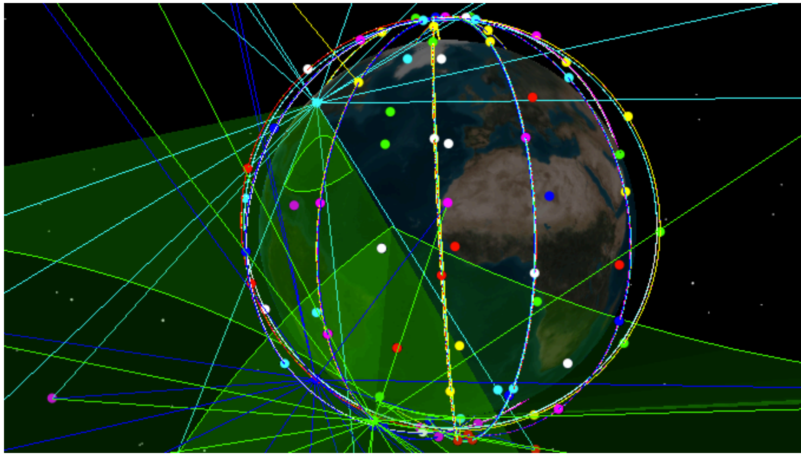
SUMMER SCHOOL FOR PLANETARY SCIENCES

MISSION DESIGN FOR PLANETARY SCIENTISTS: MICRO/NANO PROBES

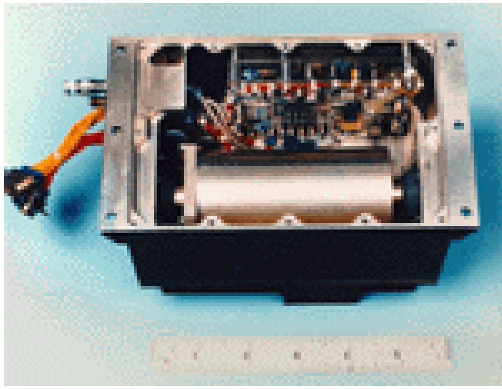
August, 2001

What are the CubeSat technologies that we need?

- Radio science instrument
  - Software defined radio rx/tx
    - Multi-channel
    - Multi-frequency
    - “Open loop”
  - Stable oscillator/clock
  - Onboard processing
  - CubeSat navigation and ranging
- Antennas
  - Larger aperture
    - Beware shadowing solar panels
    - Beamforming?
  - Radiating efficiency
    - Broad band multi-frequency intersatellite
  - Beamwidth



GNSS simulation, I. Beerer

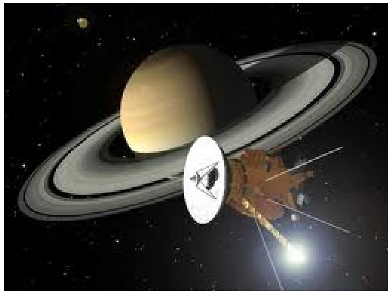


Mars Global Surveyor’s
Ultra-stable Oscillator

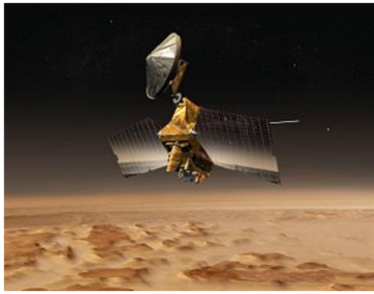
What are the CubeSat technologies that we need?

- Ground station support
  - Tracking
  - High power for uplink RO
  - High gain for downlink RO
  - Multi-frequency (uplink, downlink)
    - Can do more with intersatellite RO
  - Cost
- Relay spacecraft
  - Interplanetary orbiters with HGAs
  - Still require ground station support
  - Outward-looking LEOs or GEOs

Juno



Cassini



Mars Reconnaissance Orbiter

DSN Goldstone 70 m

Conclusions

1. Radio Occultation: great science match for iCubeSats!
2. Titan especially interesting, Saturn, Mars, Venus
3. Identified CubeSat technology development areas
   - Getting there: Cruise and/or orbit insertion "carrier"
     - Controlled and accurate deployment
     - Propulsion to maintain constellation
   - Taking measurements: RO Instrument
     - Stable oscillator/clock, differencing
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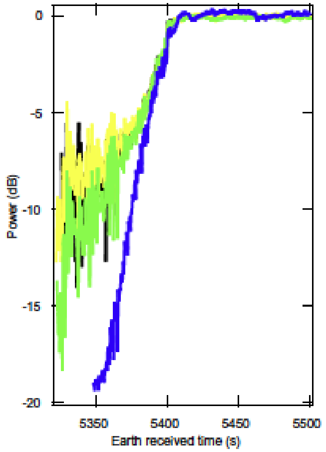

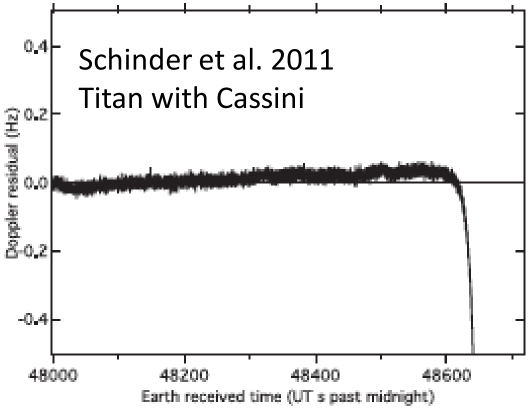

Schinder et al. 2011
Titan with Cassini

Fig. 5. Doppler residual frequencies for DSS-63, X band, 16 kHz data, for the T14 ingress occultation.

iROCC

- A constellation of CubeSats can use small and simple spacecraft radio transmitters and receivers to globally and frequently measure temperature, pressure, and electron density profiles of a planet’s atmosphere and ionosphere with a technique called radio occultation. During a radio occultation experiment, a stable radio signal is transmitted to or from a spacecraft as it drops behind the limb of a planet. The electromagnetic signal interacts with the molecules in the planet’s atmosphere and the charged particles in its ionosphere. The vertical distribution of the molecules and charged particles creates a refractivity gradient. In geometrical optics terms, the electromagnetic ray travels straight through “empty” space but is symmetrically “bent” as it encounters the refractivity gradients of the atmosphere and ionosphere. The received frequency of the signal is thus slightly but detectably shifted from the initial frequency. These measured frequency residuals or amount of “bending” can be inverted to calculate atmospheric neutral densities or ionospheric electron densities of the volume of atmosphere through which the ray passed, from which high vertical resolution profiles can be derived.

- The Interplanetary Radio Occultation CubeSat Constellation (IROCC) concept consists of six 3U CubeSats, each contained by a Poly-Picosatellite Orbital Deployers (P-PODs) as a secondary payload on a larger interplanetary spacecraft. We discuss system design trades and requirements for this constellation, from deployment of the CubeSats after orbit insertion around a planet or satellite to orbital decay of the constellation. Trades analyzed include the timing of P-POD deployments into the desired orbit planes that also minimize any risk to a primary mission, the radio occultation experiment configuration itself (multiple frequencies, intersatellite links, signal to noise ratios, timing, and tracking), the different architectures for transmission of the collected radio occultation data back to Earth, the opportunity to study atmospheric drag as the CubeSat orbits decay, and planetary protection requirements on Cubesats. Additional target-specific parameters are also considered, such as the reduced amount of available solar power for the already-tiny CubeSats at larger distances from the Sun, the radiation environment, the presence or absence of a magnetic field, orbital decay and mission duration, and the selection of radio occultation frequencies to correspond to the spectral features and compositions of the targets.