Introduction to GPS/GNSS in Atmospheric Sensing

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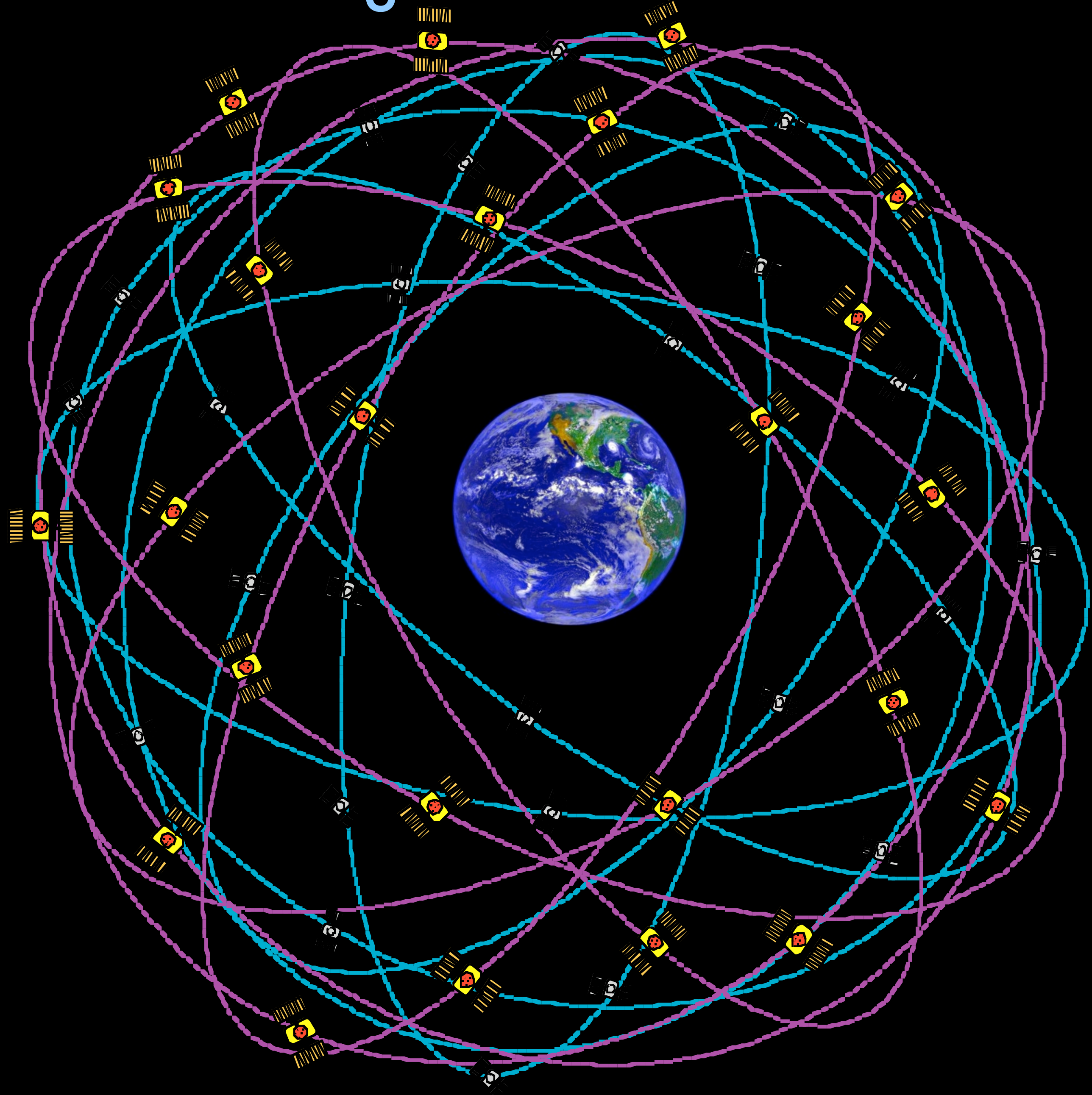
California Institute of Technology

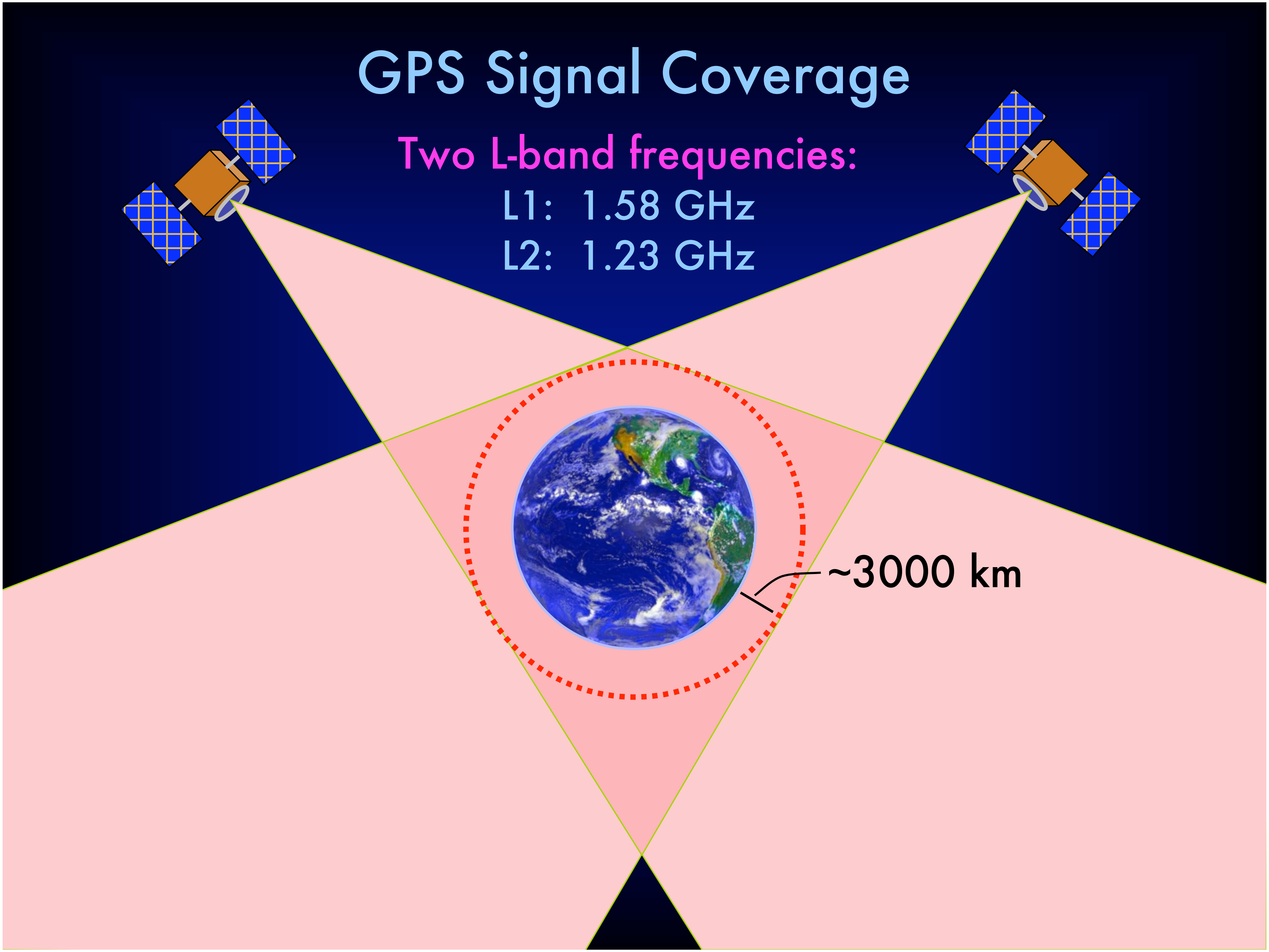
COSMIC Science Summer Camp
Central Weather Bureau
Taipei, Taiwan
30 May 2005

Signals Abundant



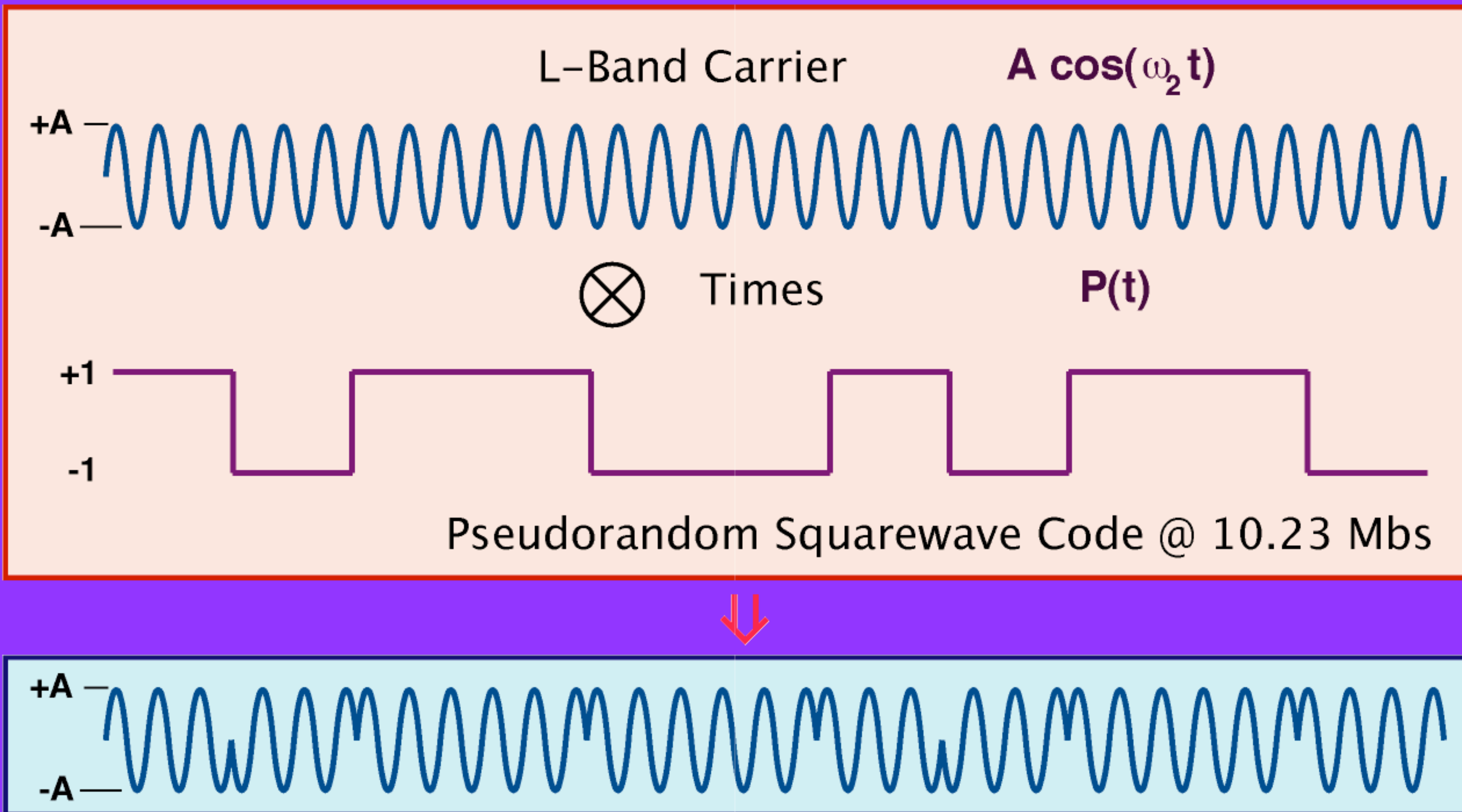
GPS
Glonass
Galileo

60–90
sources
in space



GPS Signal Coverage
Two L-band frequencies:
L1: 1.58 GHz
L2: 1.23 GHz
~3000 km

GPS Signal Structure

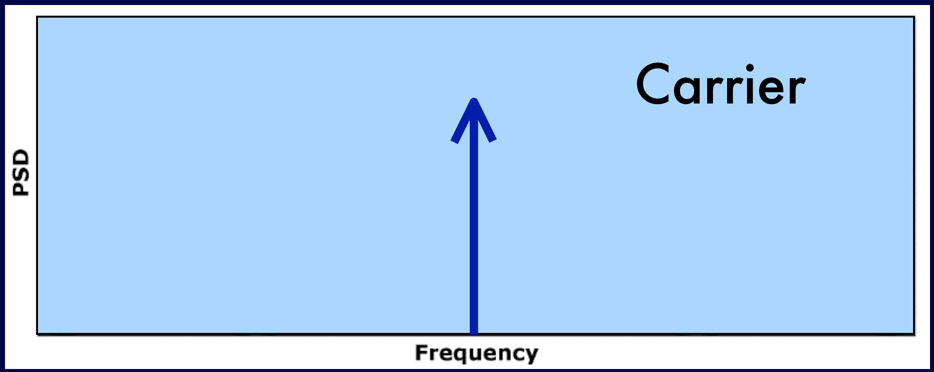


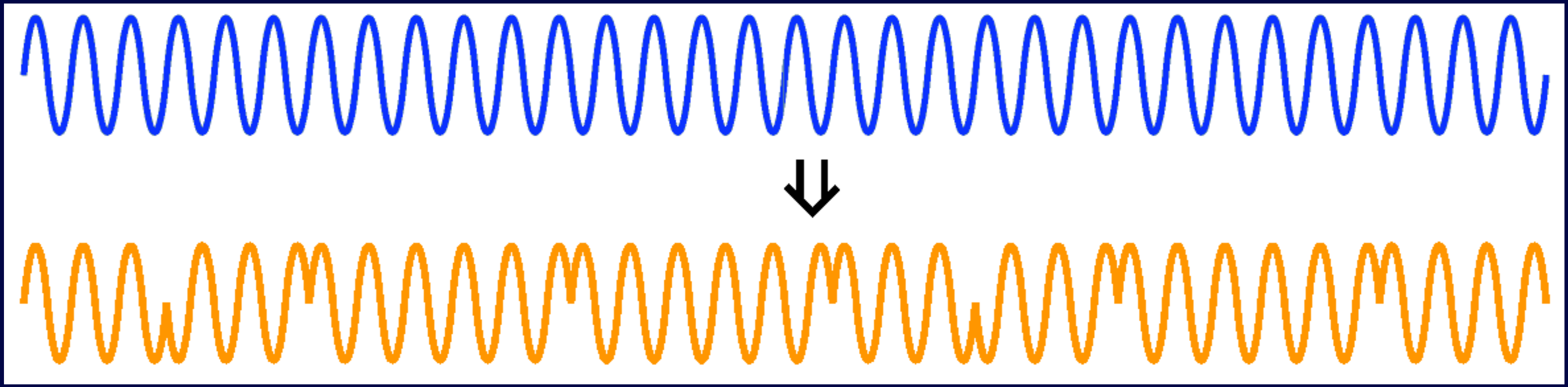
$L2(t) = P(t)\ A \cos(\omega_2 t)$

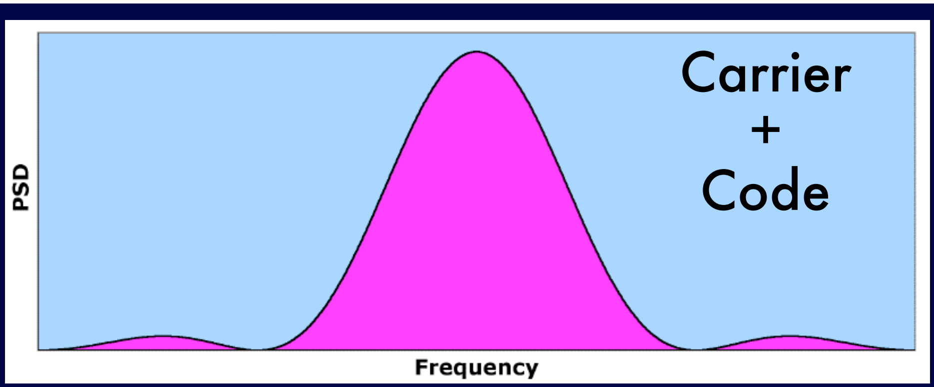
$L1(t) = P(t)\ B \cos(\omega_1 t) + C(t)\ B' \sin(\omega_1 t)$ (L1 Carrier = 1.57542 GHz)

(Pseudorandom Squarewave Code @ 1.023 Mbs)

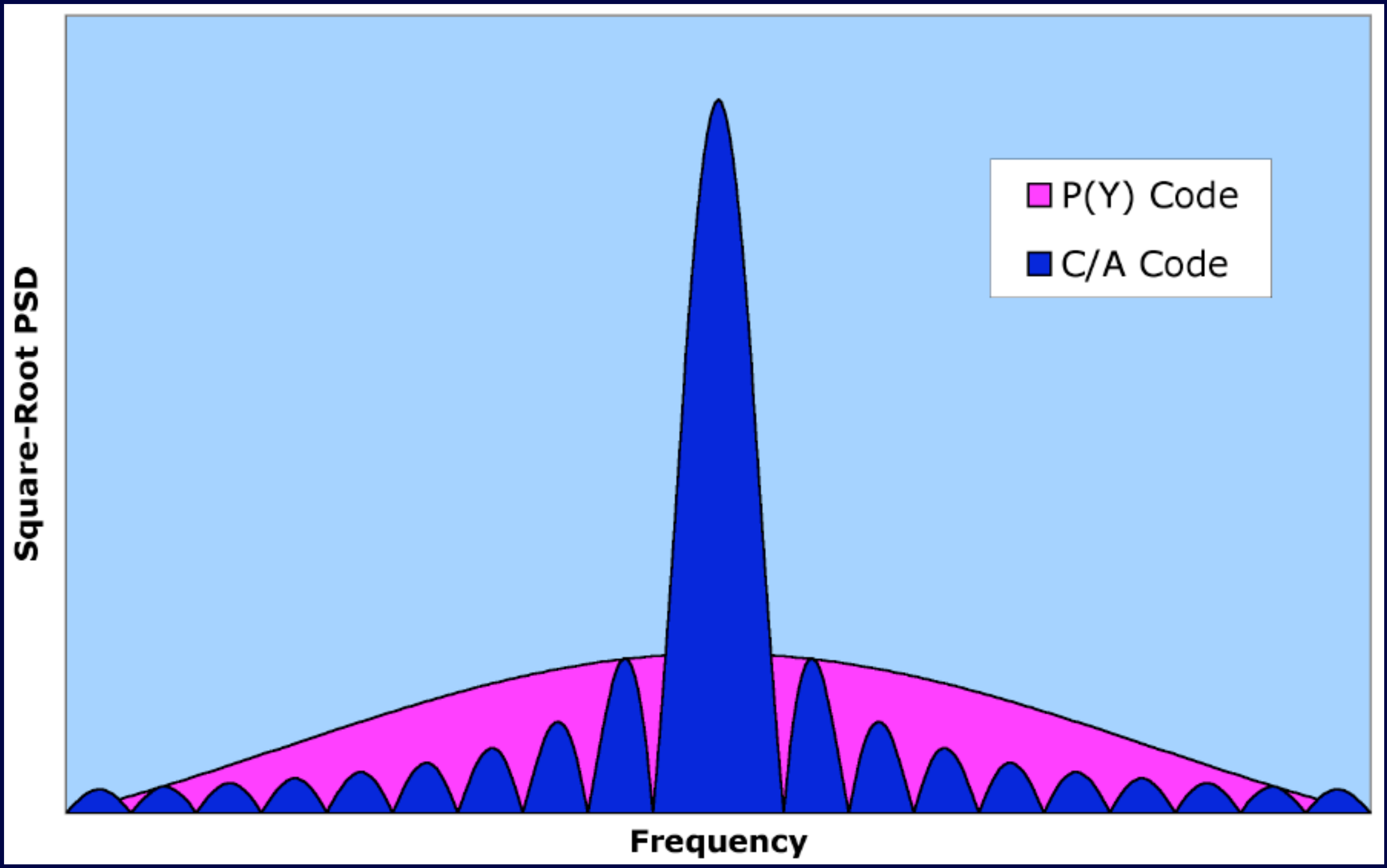
The GPS Signal Spectrum





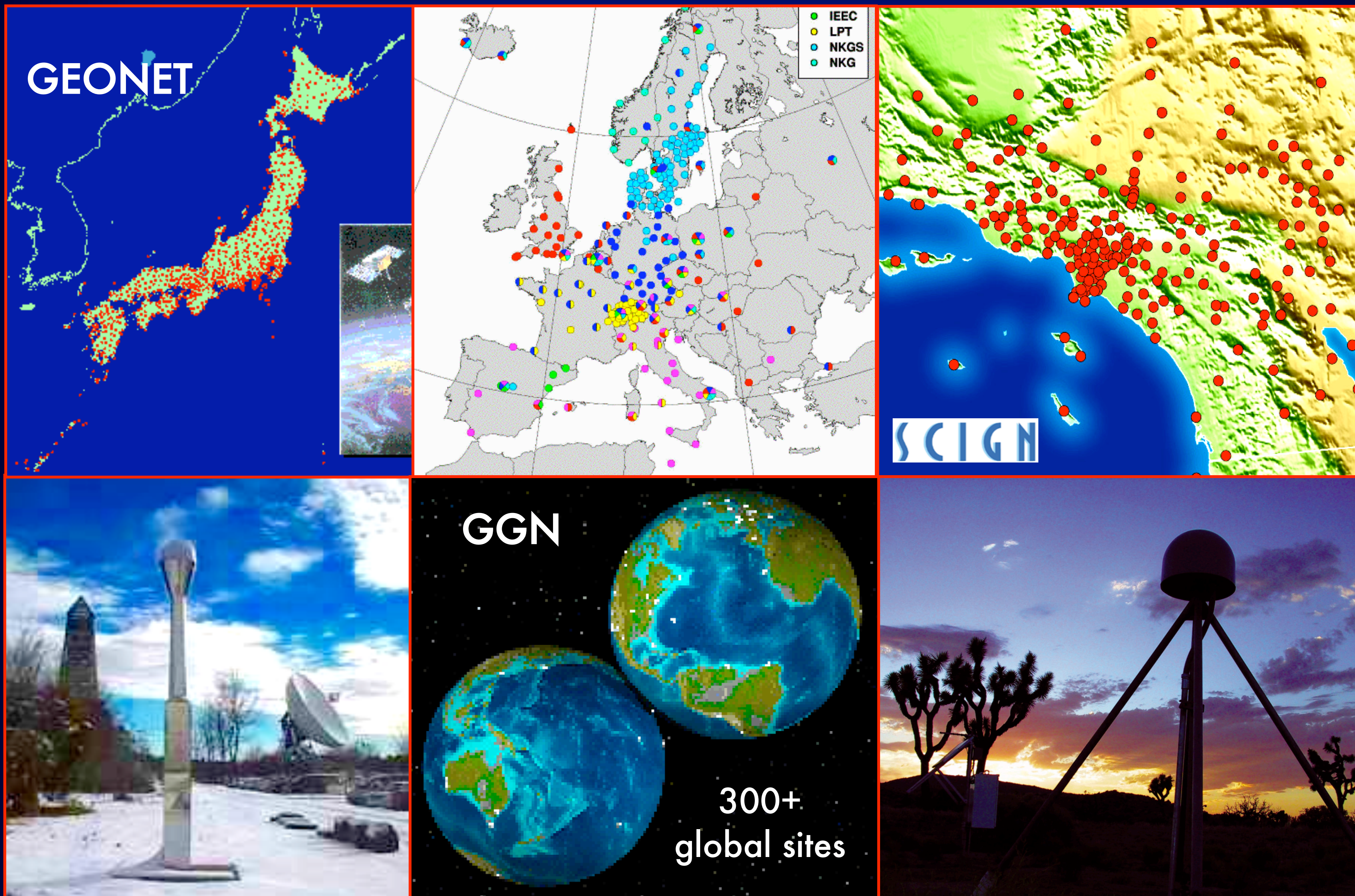


L1 Signal Spectrum

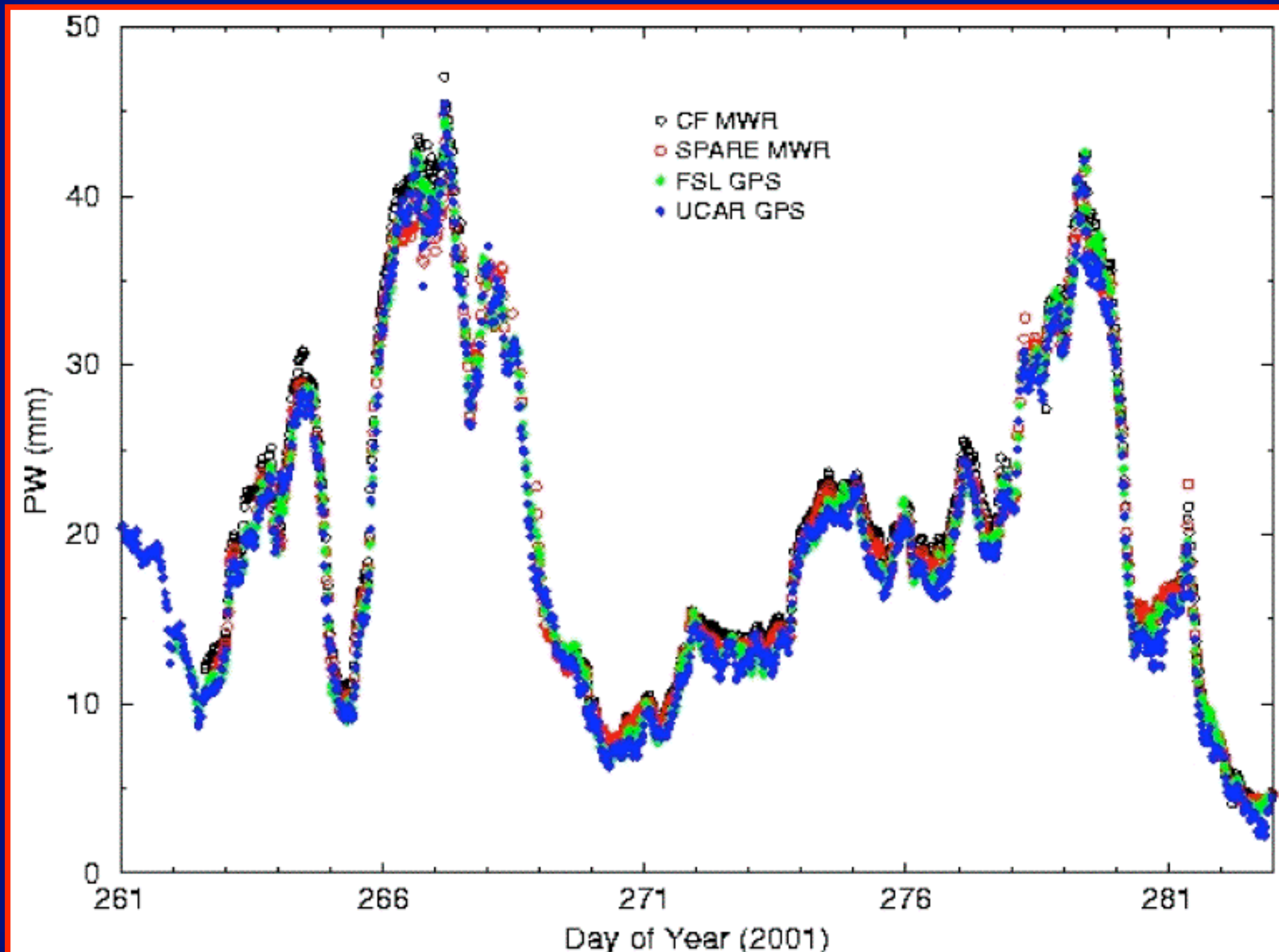


GPS Sounding Began With Geodesy

GPS Ground Arrays

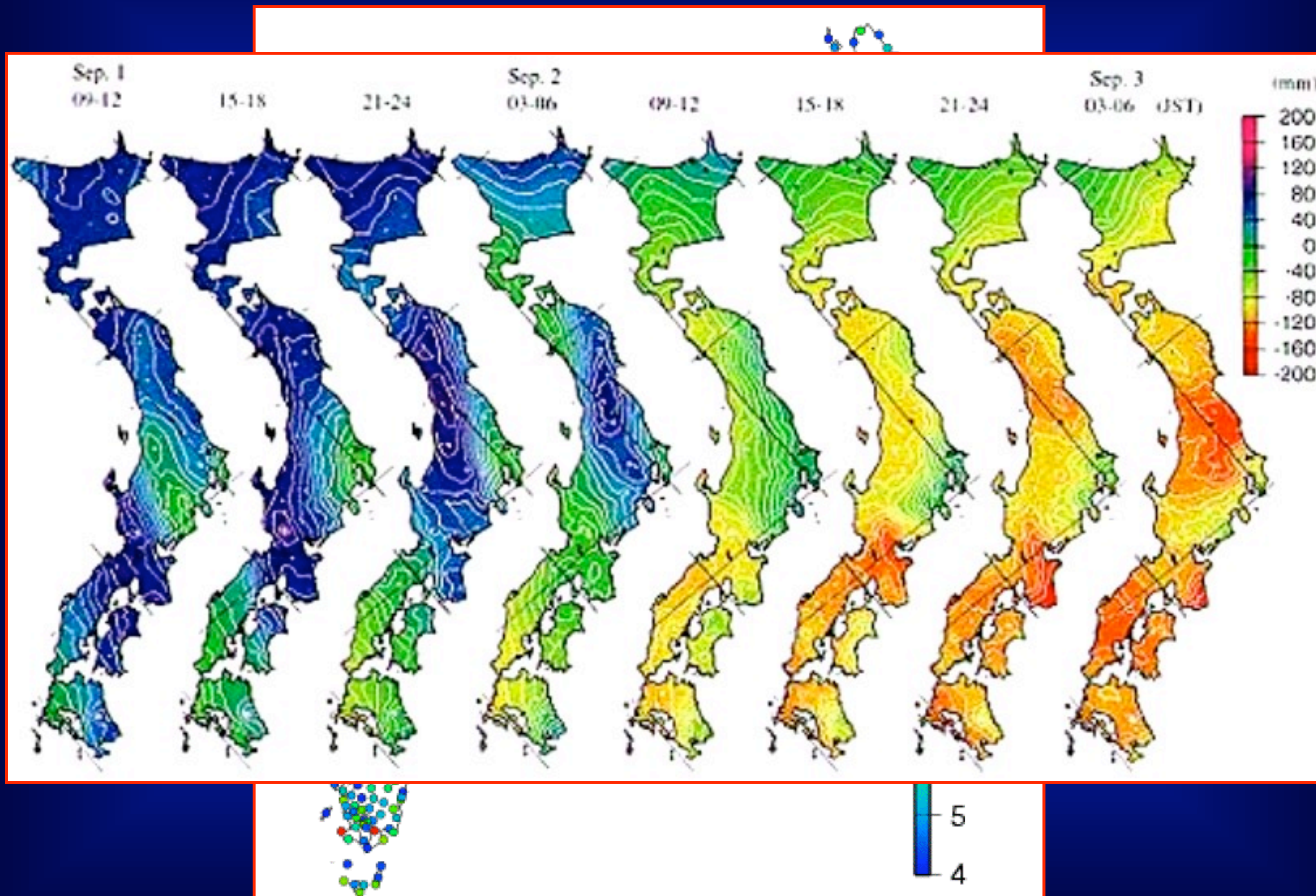


PW: GPS vs Microwave Radiometer



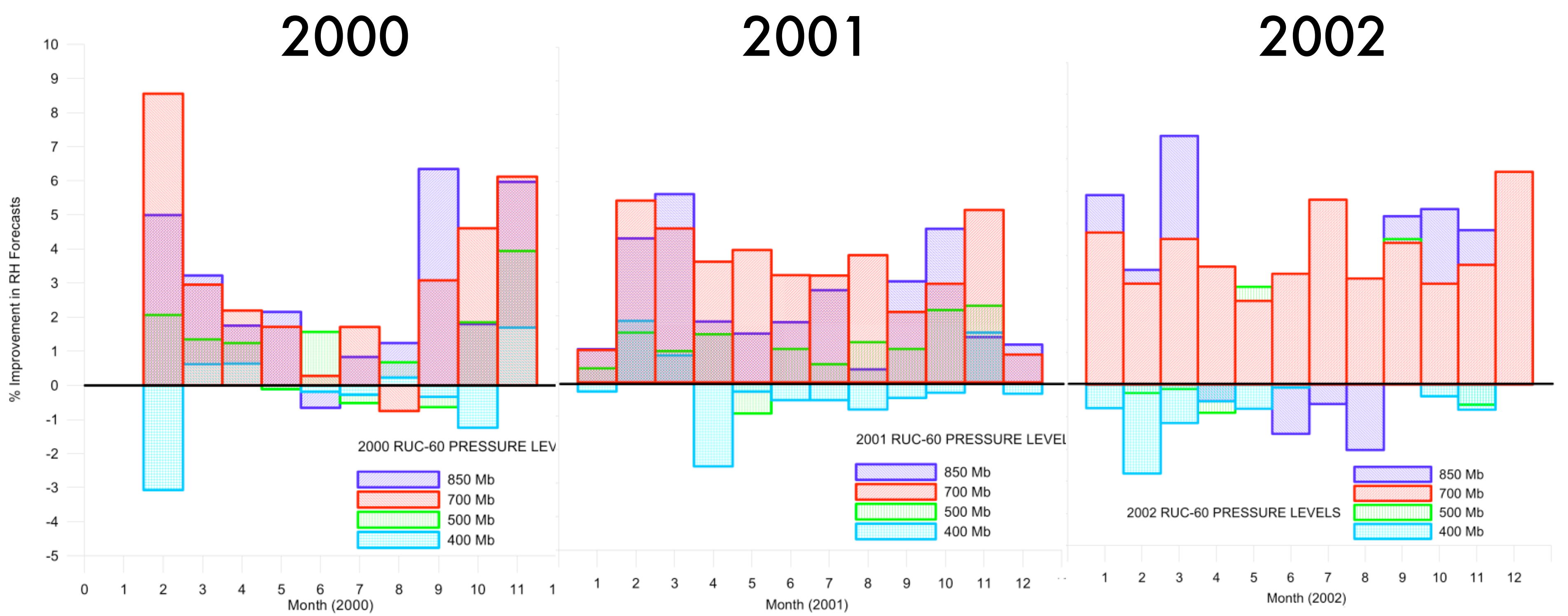
Rocken et al., 2003

Maps of Precipitable Water (PW)



Japanese Meteorological Agency, 2003

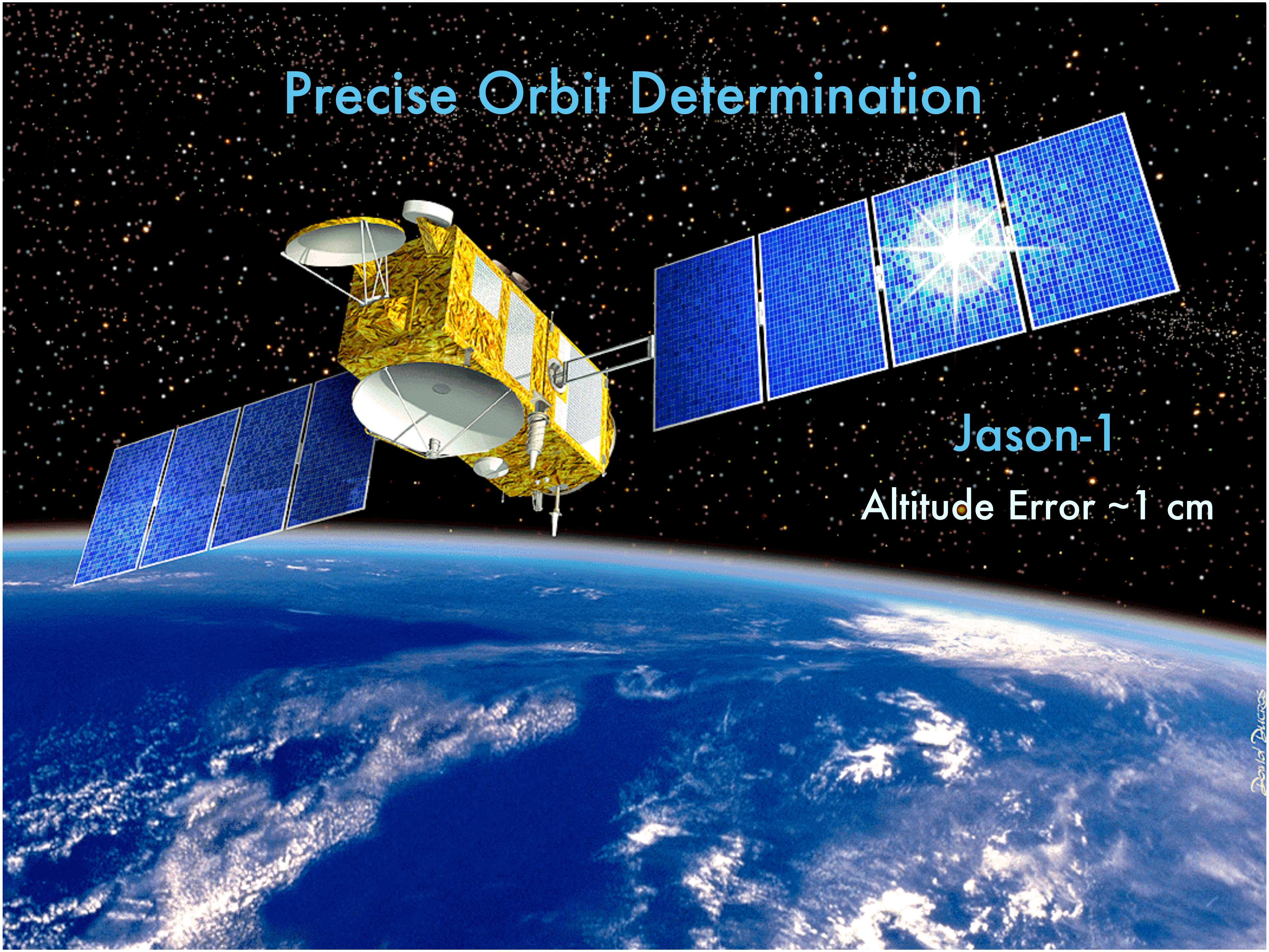
Effect of GPS on Relative Humidity Predictions
NOAA Assimilation Studies 2000-2002



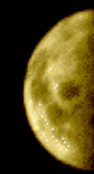
"GPS is one of the most cost effective remote sensing systems tested by FSL."

Gutman et al., NOAA FSL, 2003

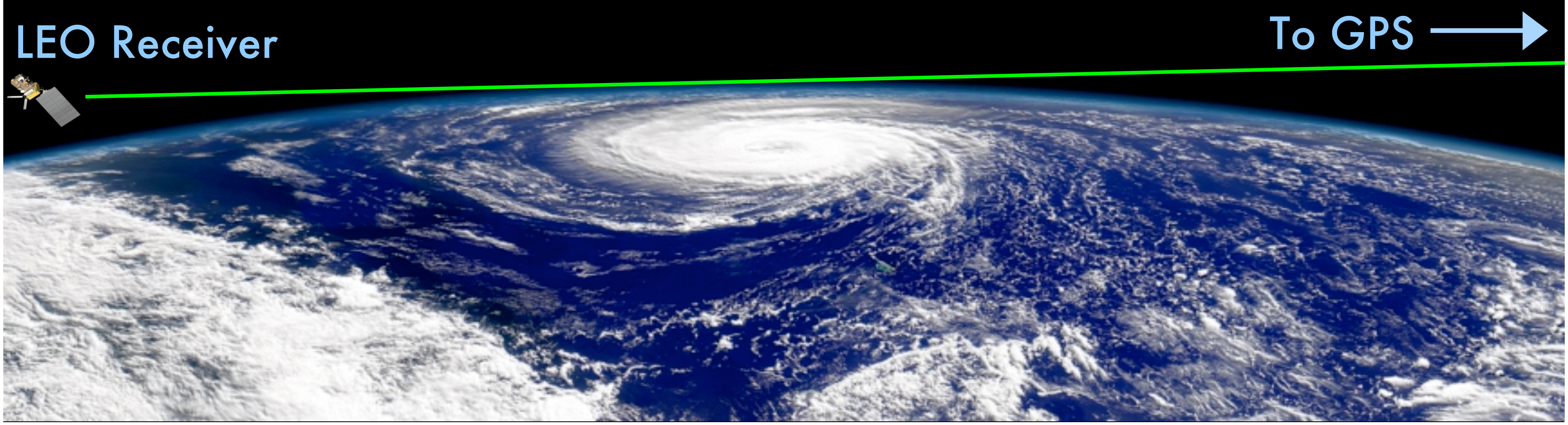
Observing From Space


Precise Orbit Determination
Jason-1
Altitude Error ~1 cm

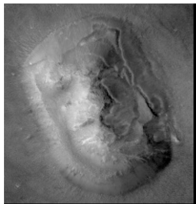
GPS Atmospheric Occultation



- High resolution profiles of:
  - Bending angle
  - Refractivity
  - Density
  - Pressure
  - Temperature / Moisture
  - Geopotential heights
- Temporal and spatial averages, 2D maps
- Global pressure contours, gradients, and geostrophic wind fields

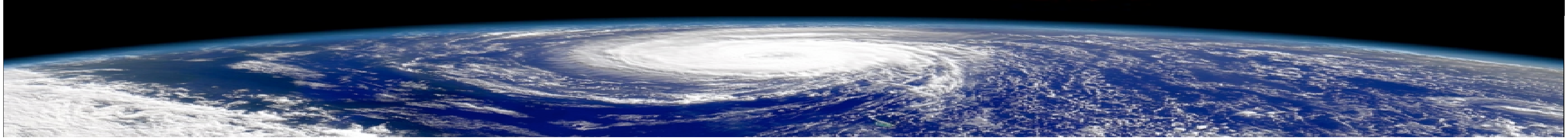


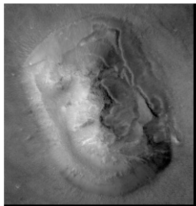
Some Occultation History



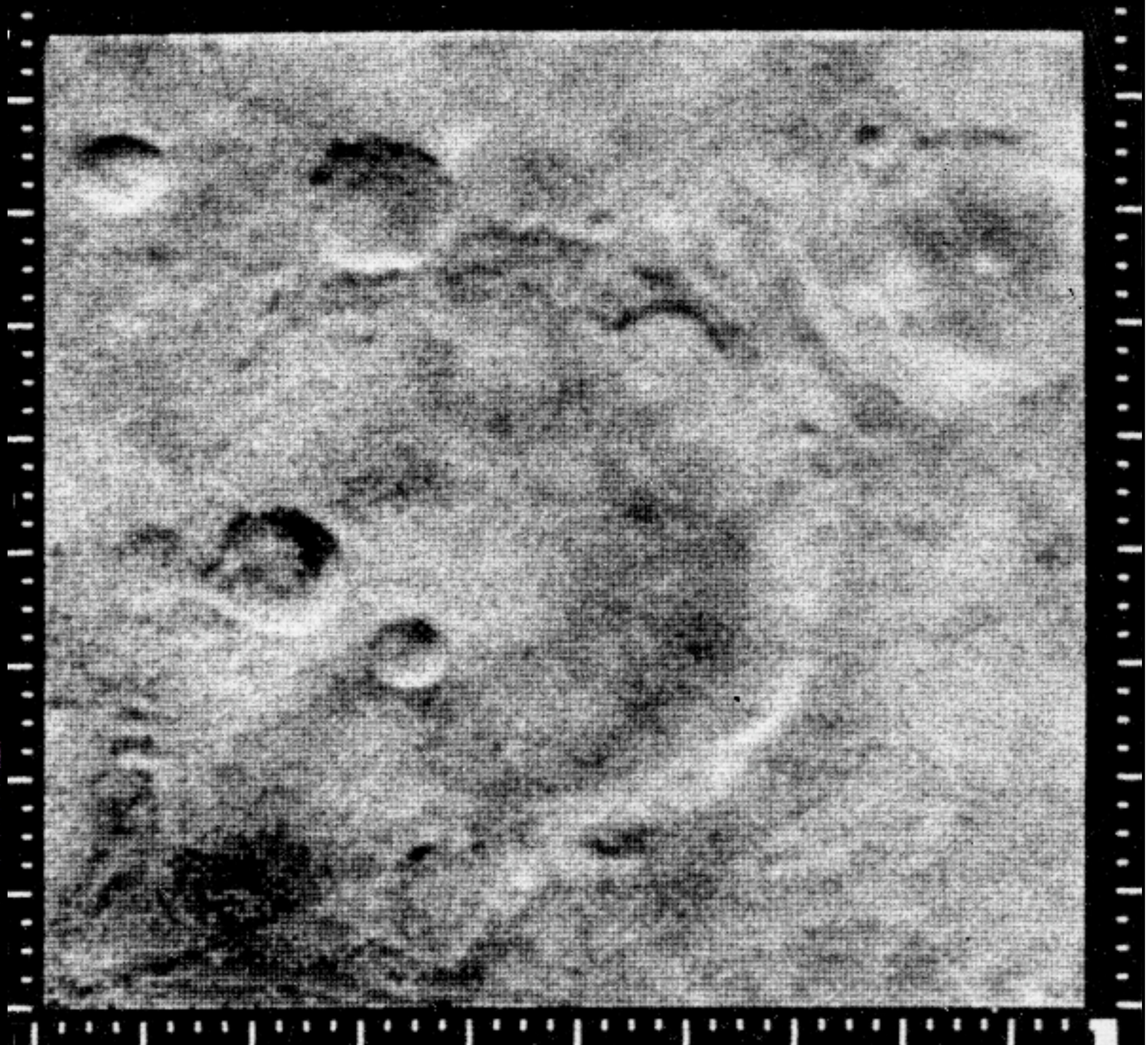
Planetary
Radio Occultation

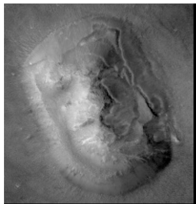
Mariner IV at **Mars**
July 1965





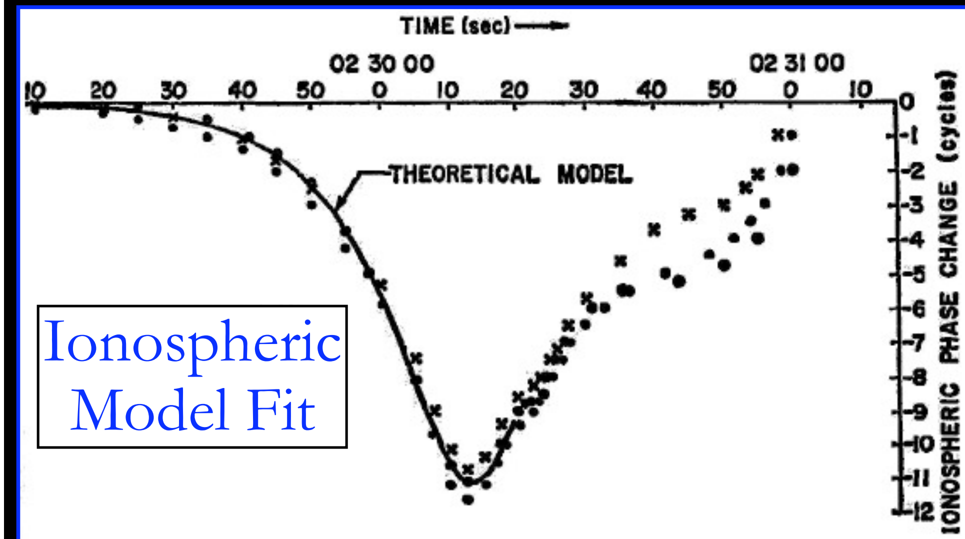
Mariner
IV at
Mars
15 July 1965

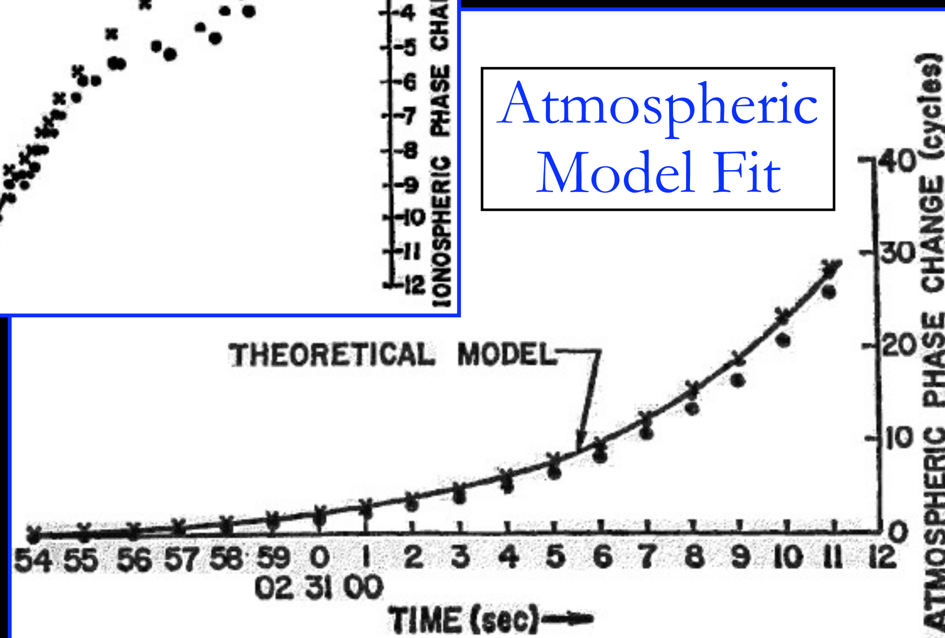


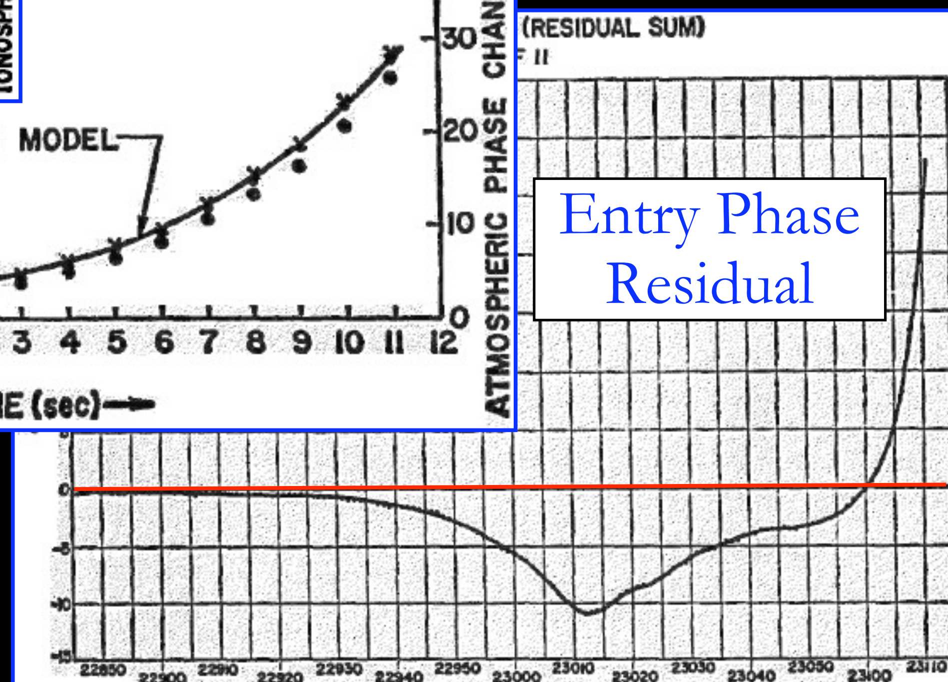


Mariner IV Occultation at Mars:
Earliest Results

Science, 10 Sep 65

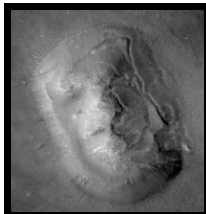


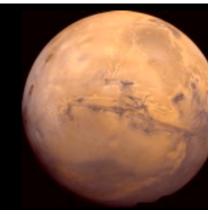


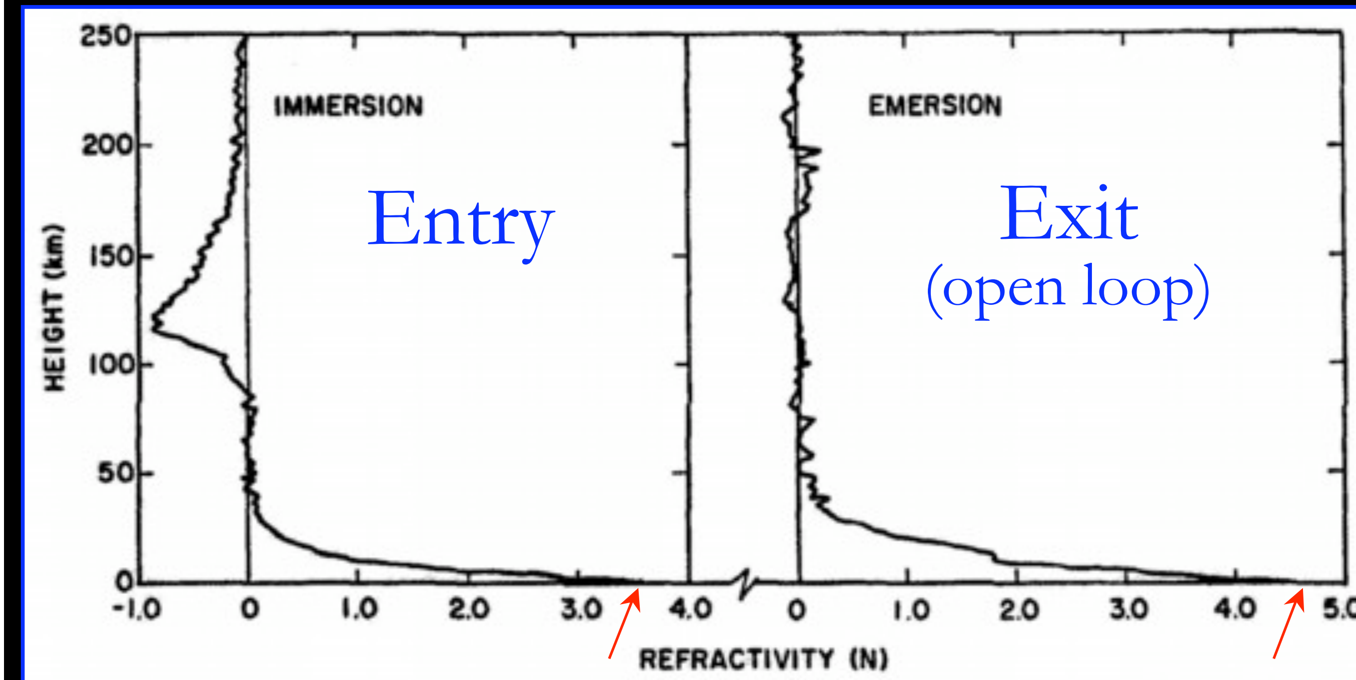


Kliore et al., 1965

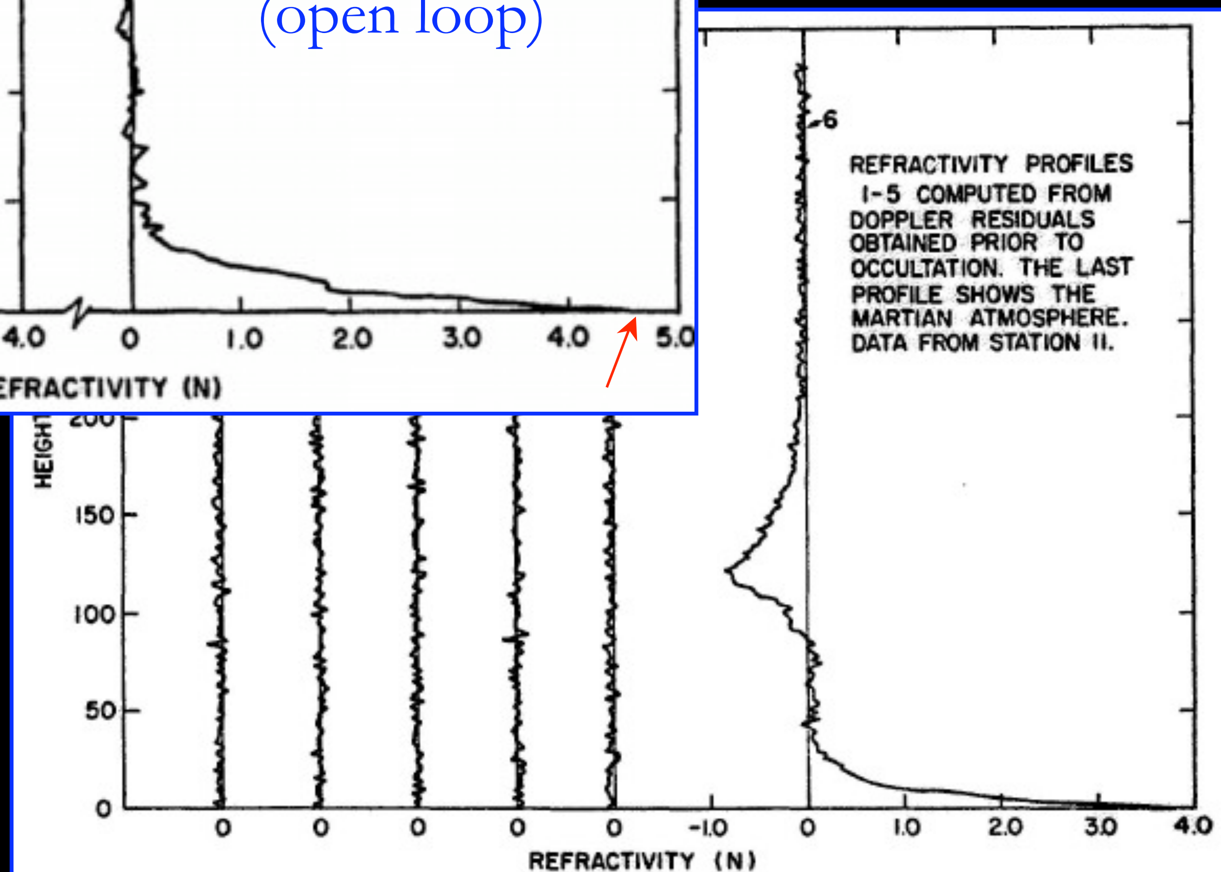
Mariner IV Occultation at Mars:
Refined Results

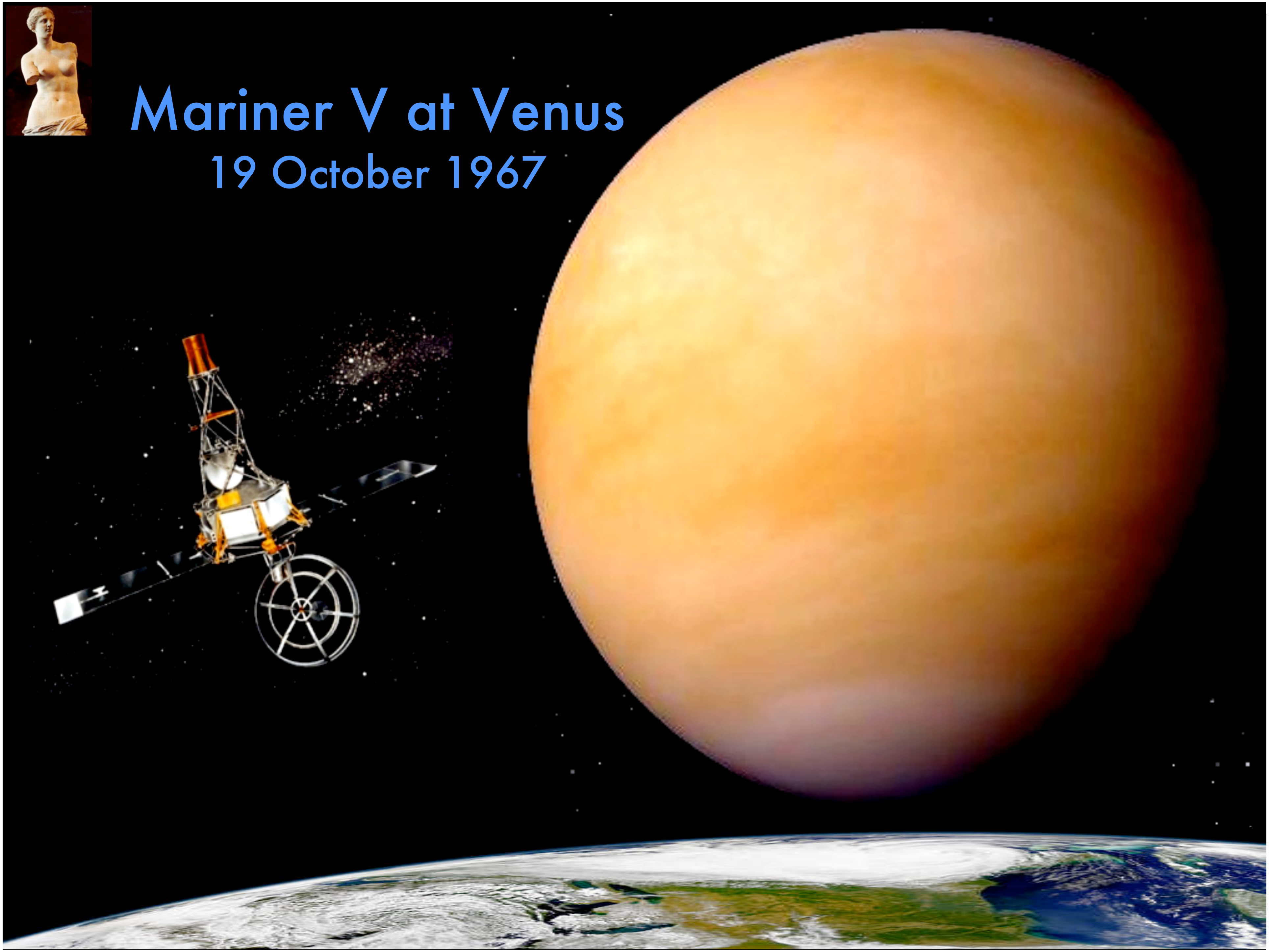


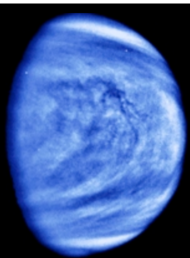




Fjeldbo et al.,
Planet. Space Sci.
1968



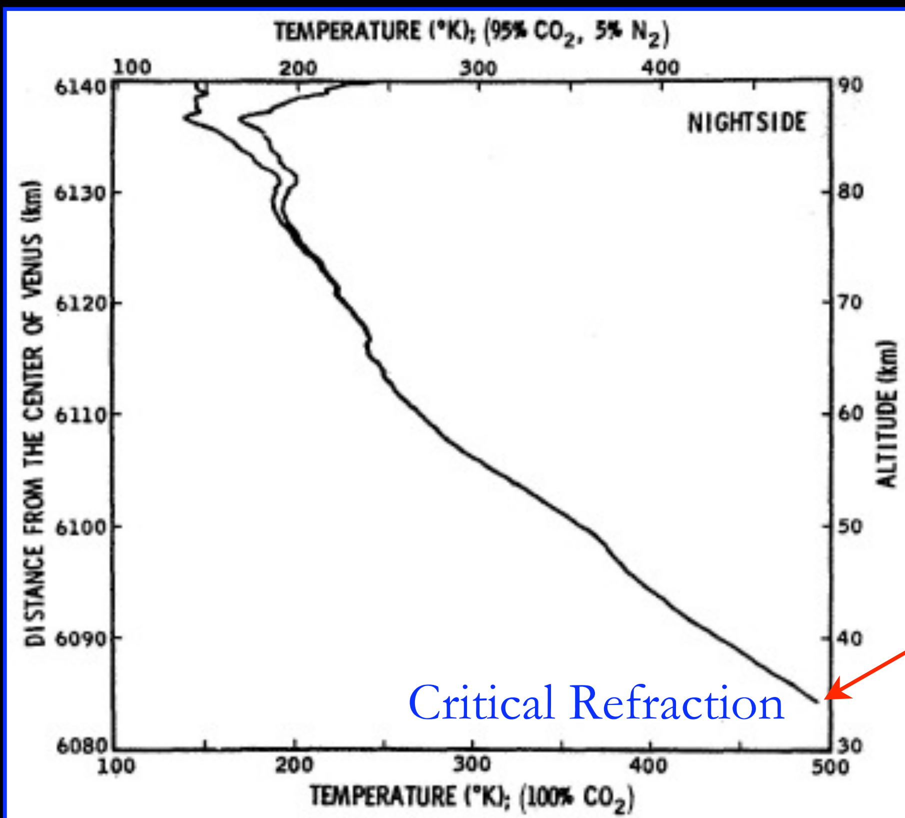

Mariner V at Venus
19 October 1967



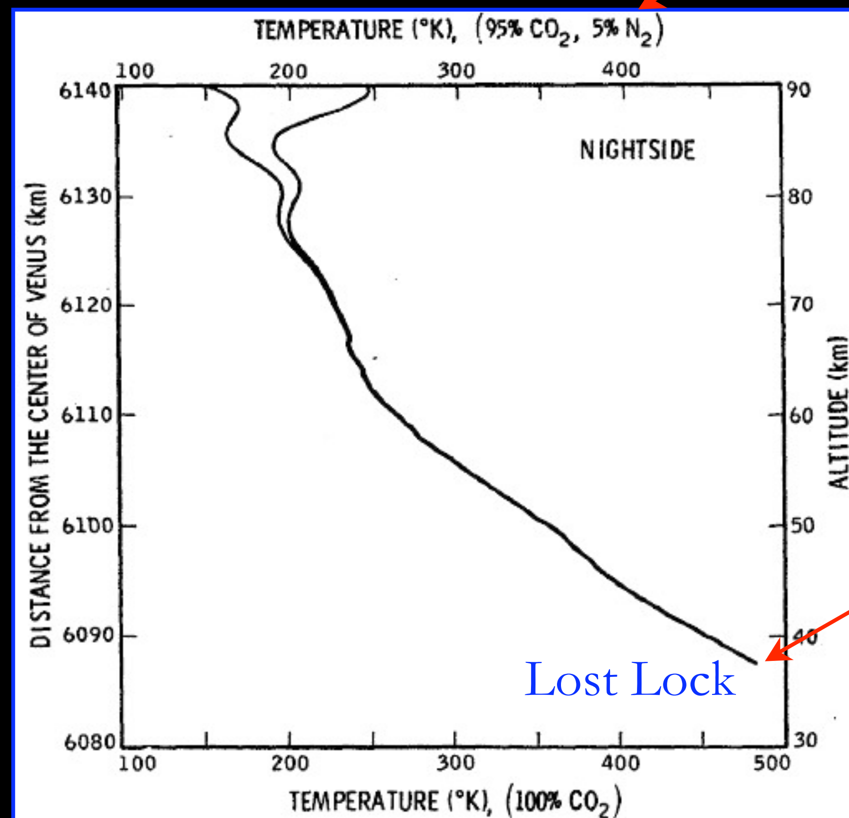
Mariner V Occultation at Venus:

Temperature Profile Comparison

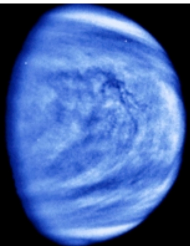
2.3 GHz Phase Retrieval



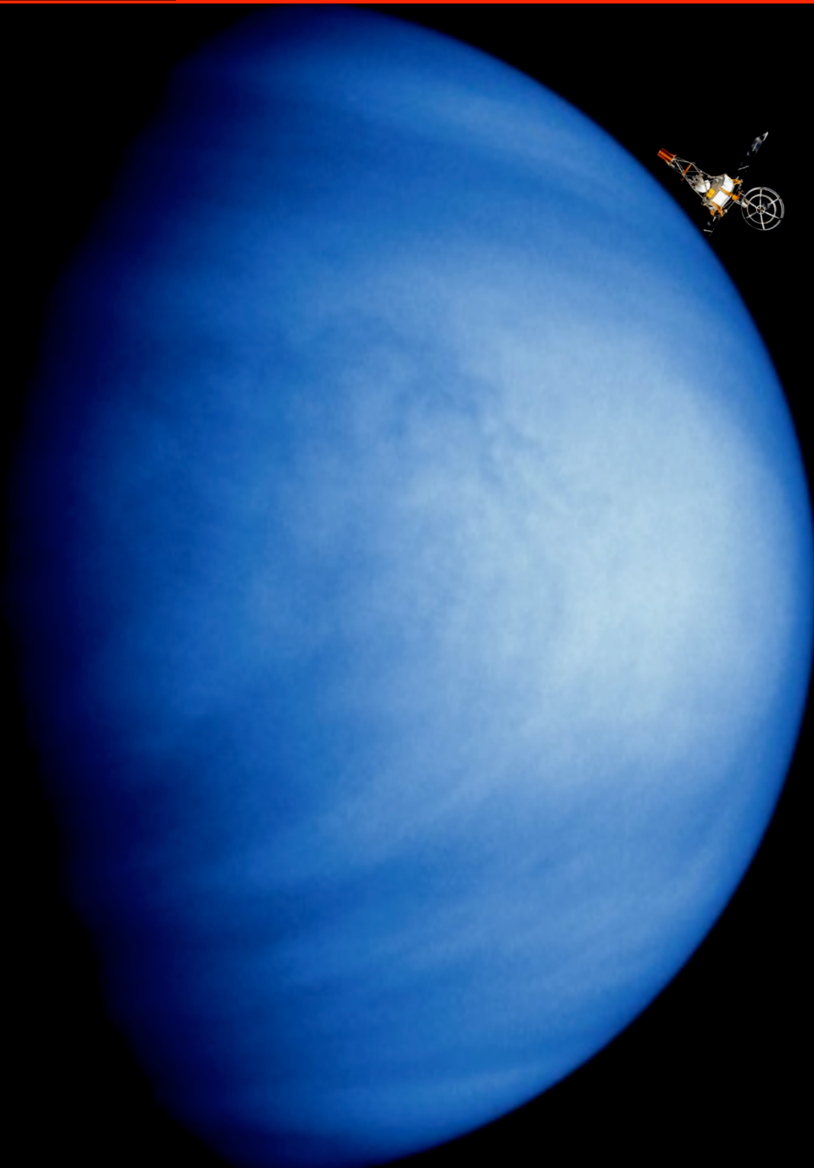
423 MHz Amplitude Retrieval



Fjeldbo et al., 1971

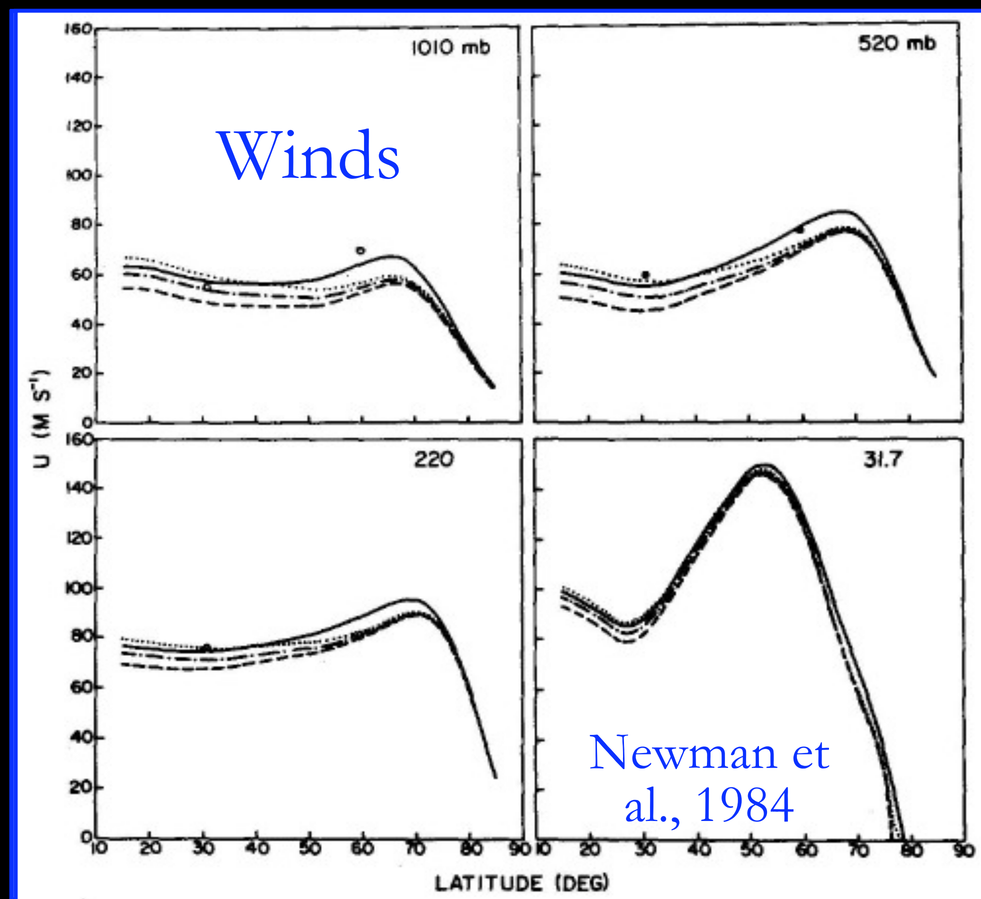


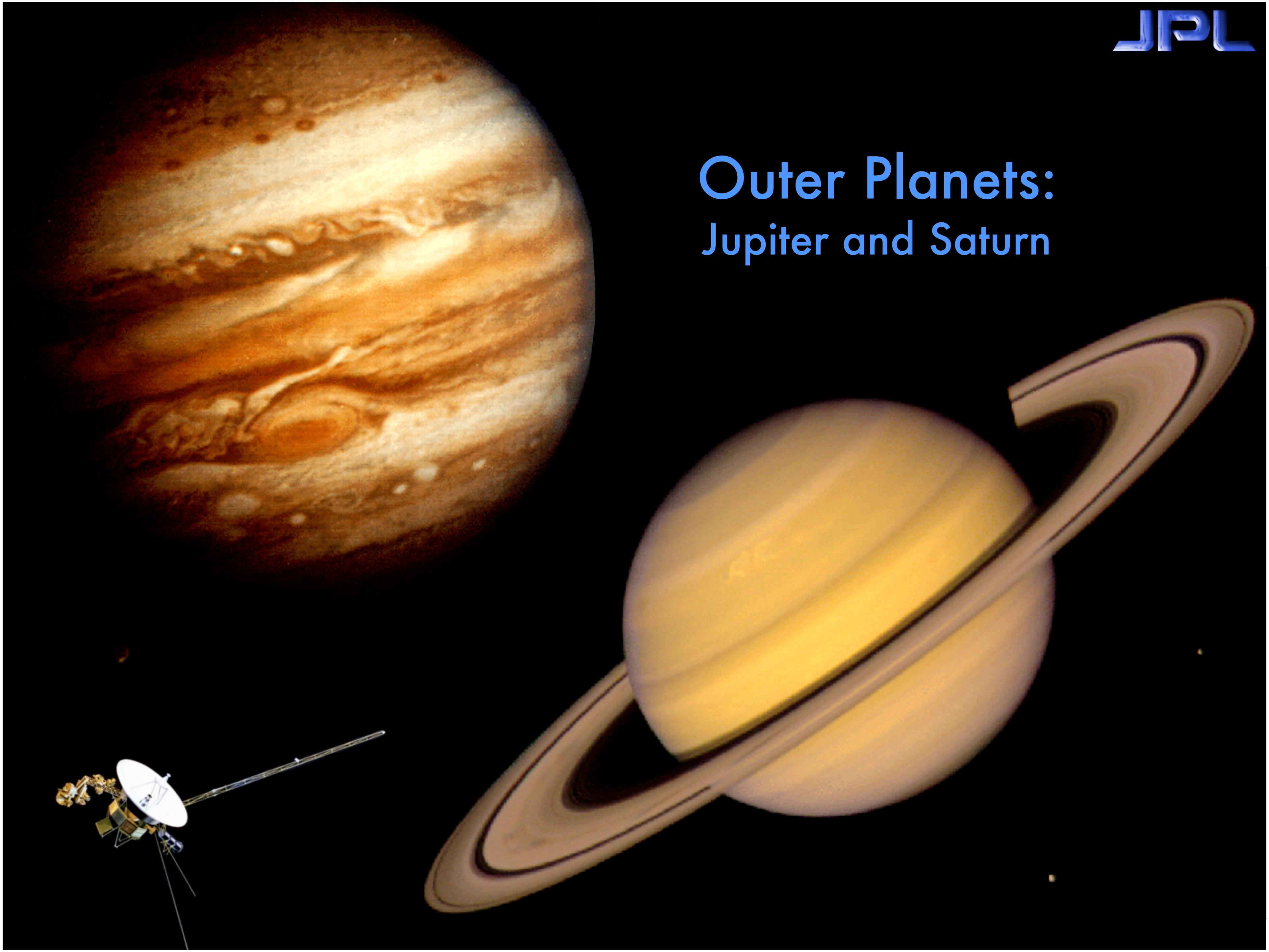
Pioneer Venus Orbiter
1979-1982

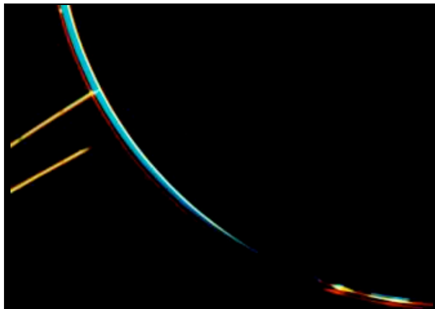
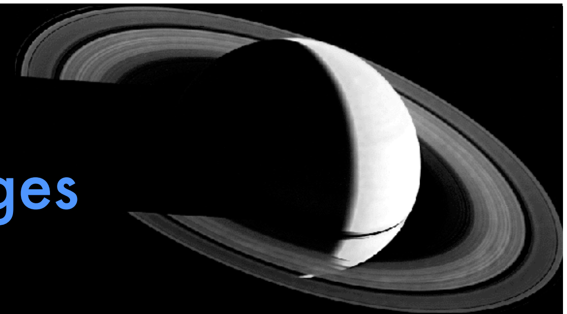


Data taken over multiple seasons

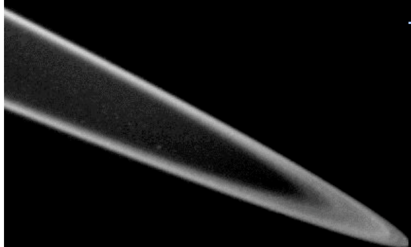
First recovery of zonal winds from pressure




JPL
Outer Planets:
Jupiter and Saturn

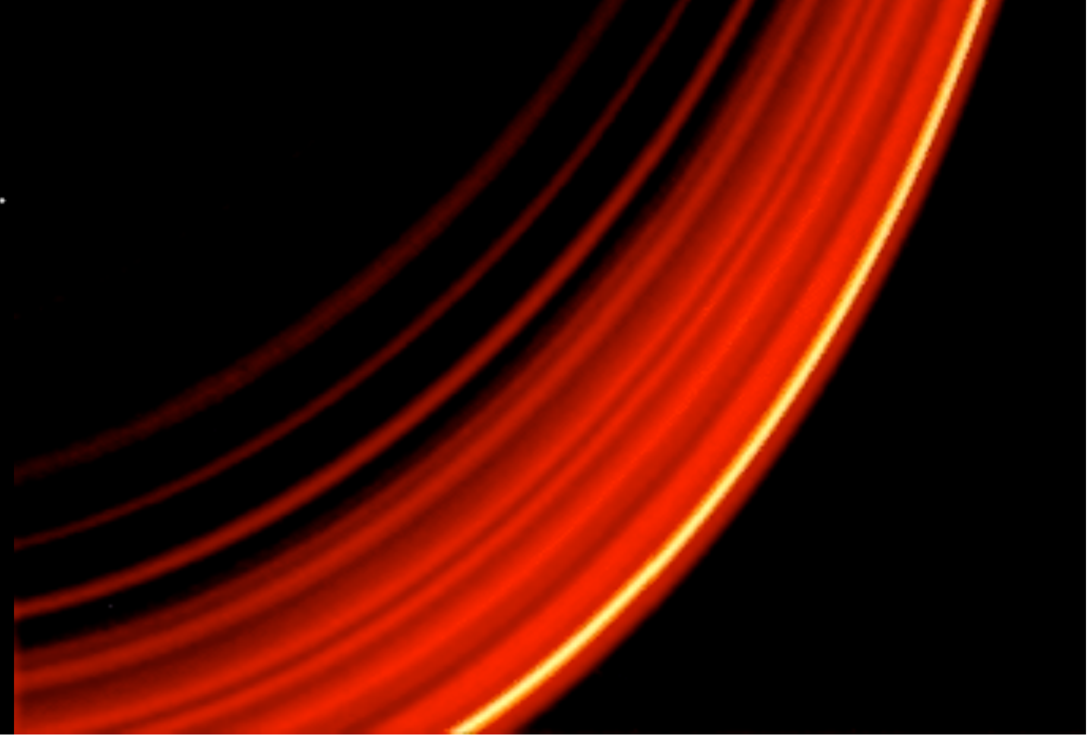
Outer Planets:
Occultation Retrieval Challenges

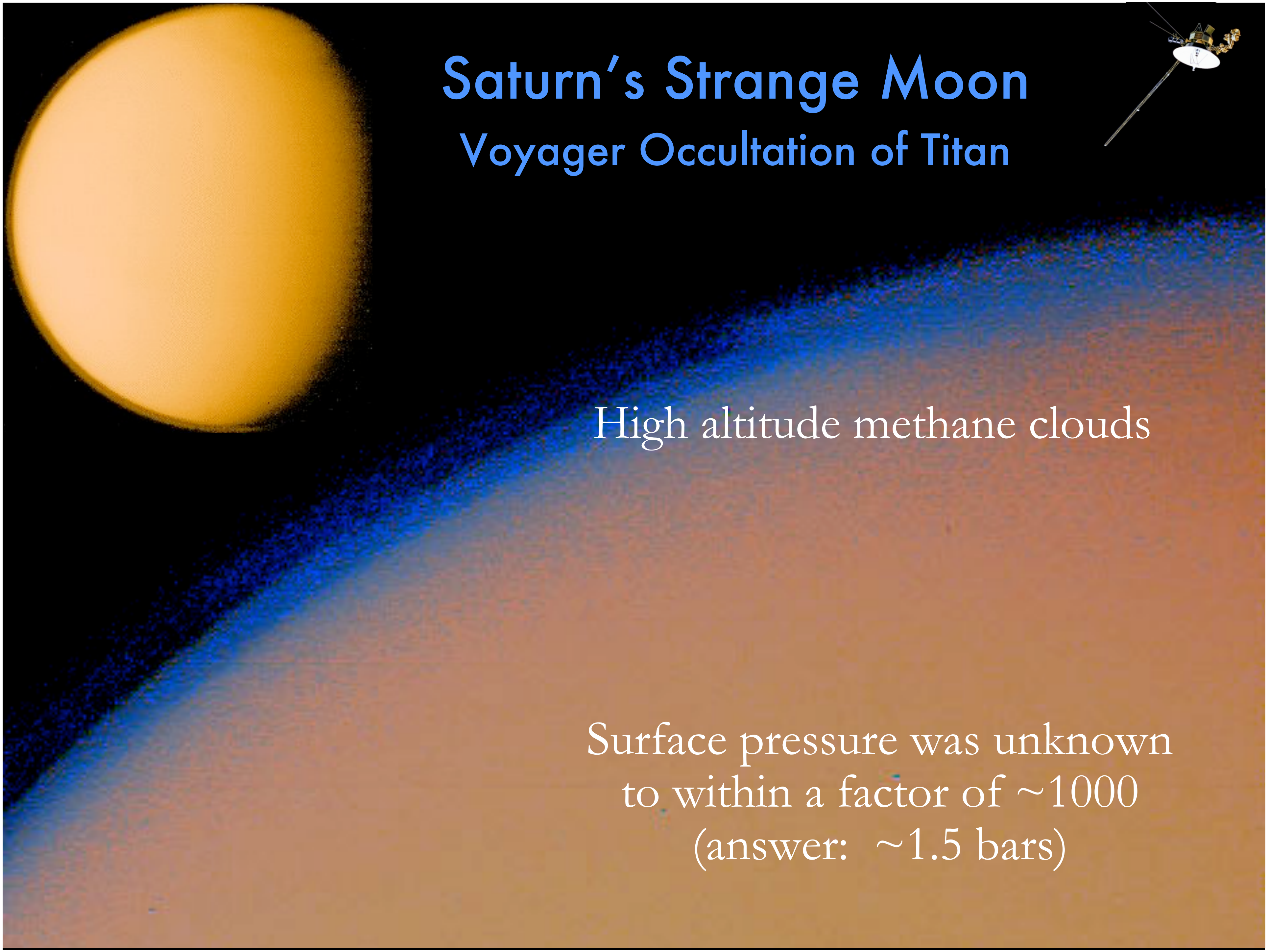


Uncertain composition and mixing

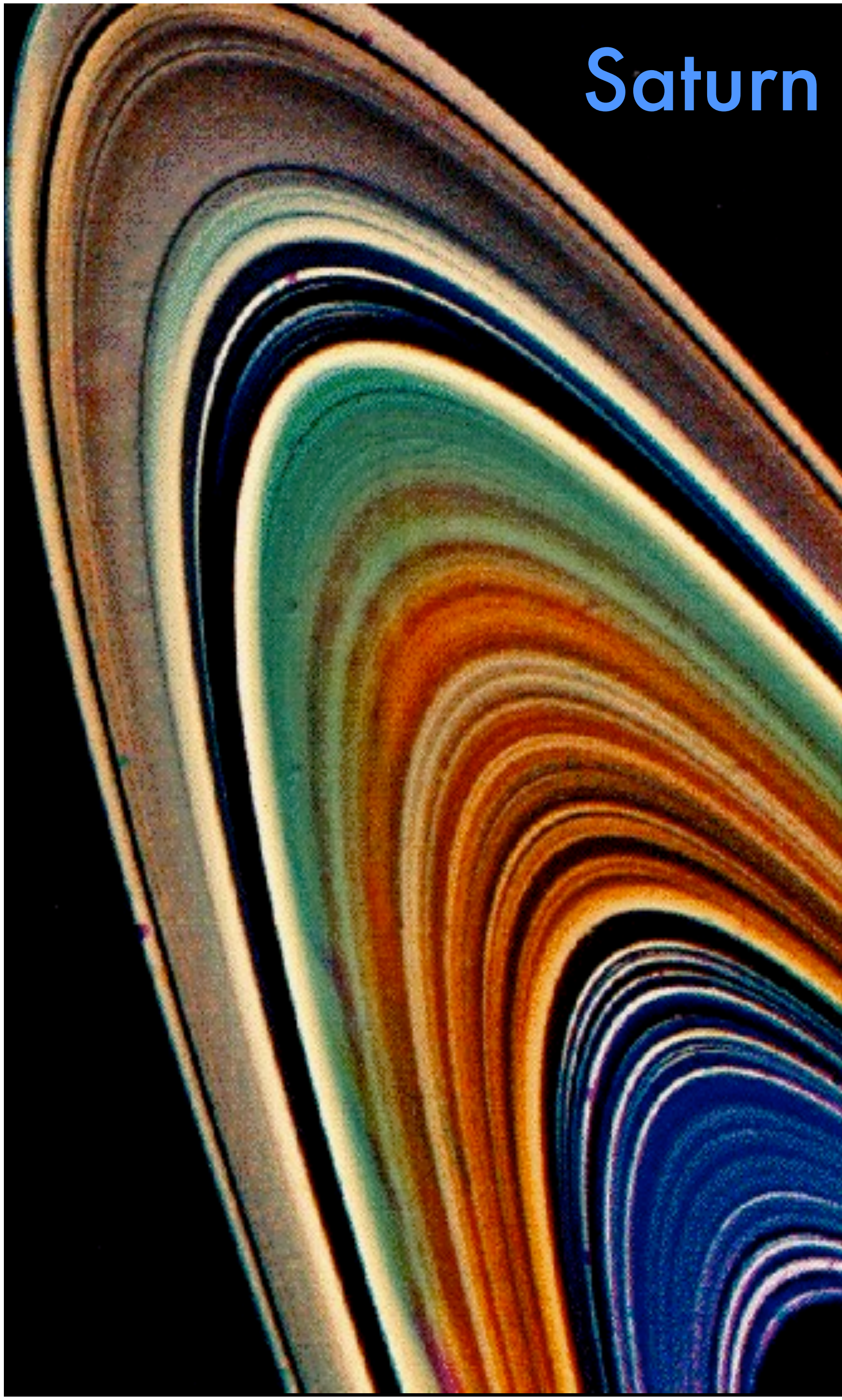
Uncertain rotation rates

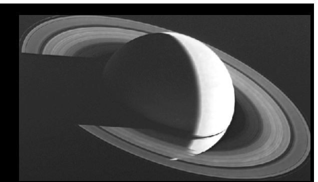
Pronounced oblateness

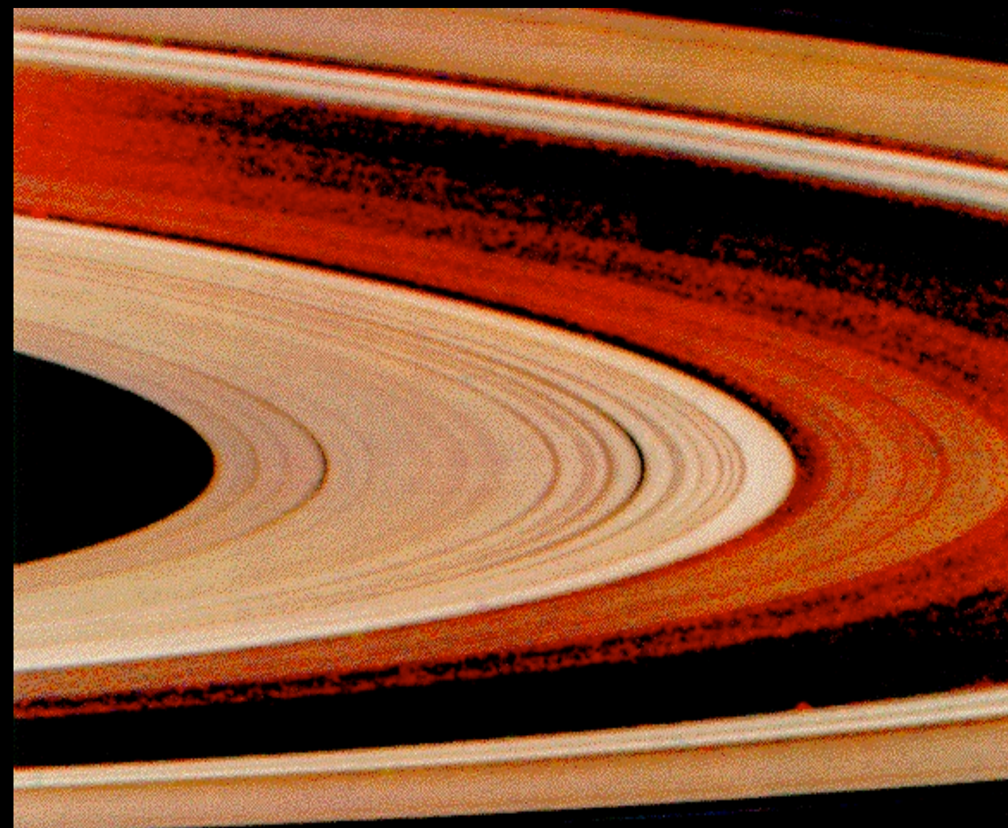

Saturn's Strange Moon
Voyager Occultation of Titan
High altitude methane clouds
Surface pressure was unknown
to within a factor of ~1000
(answer: ~1.5 bars)

Saturn Ring Occultation

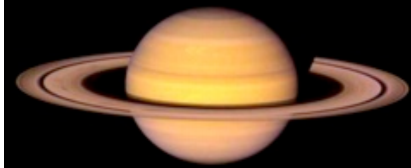




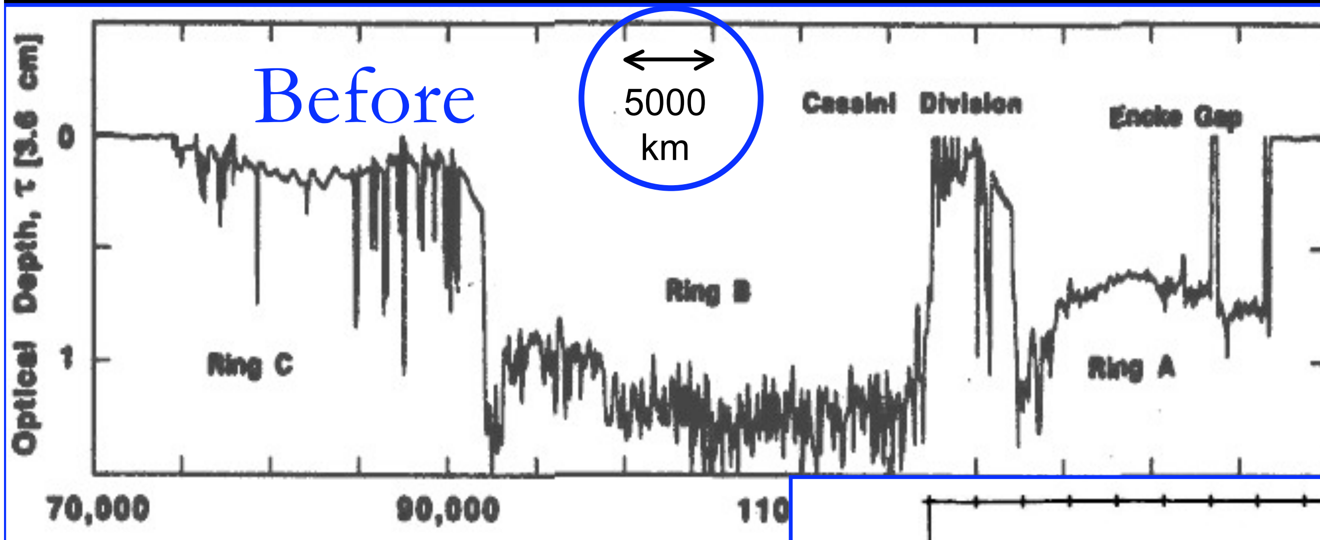
The rings act as a vast, thin, complex diffraction screen.



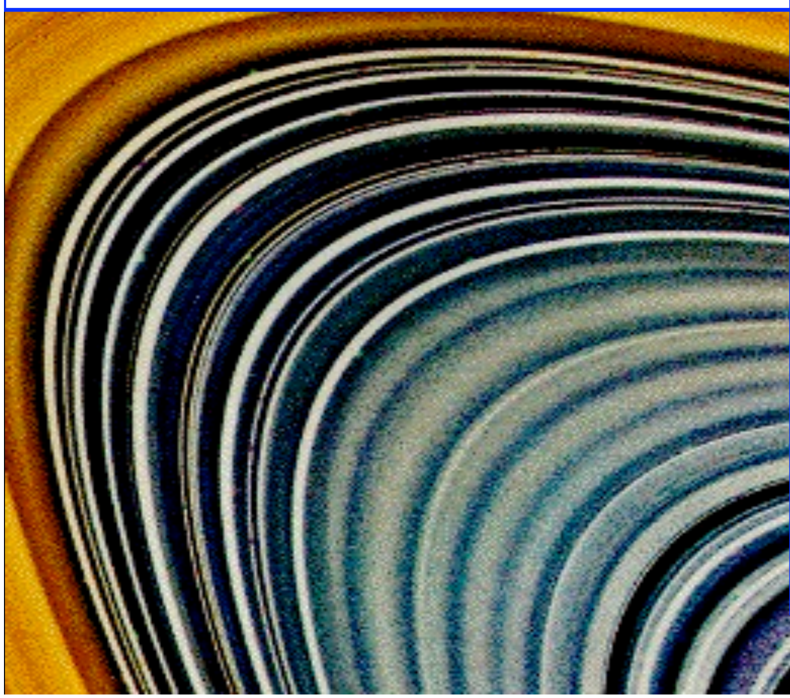
Sampling of the phase-amplitude hologram allows detailed reconstruction of the ring structure

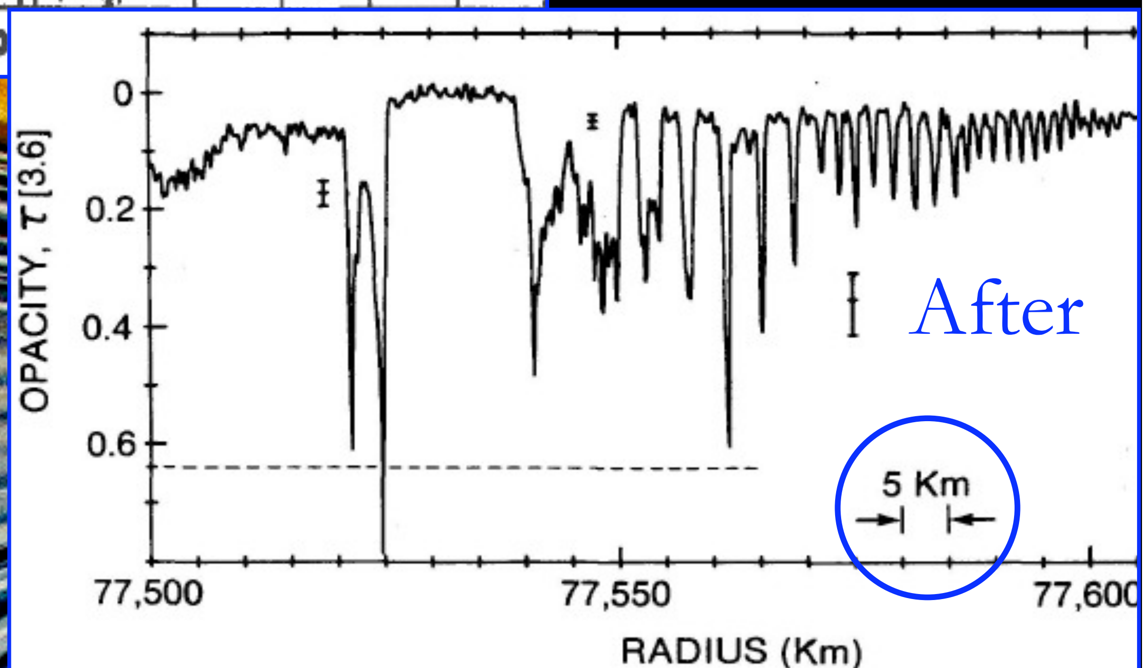


Saturn Ring Occultation



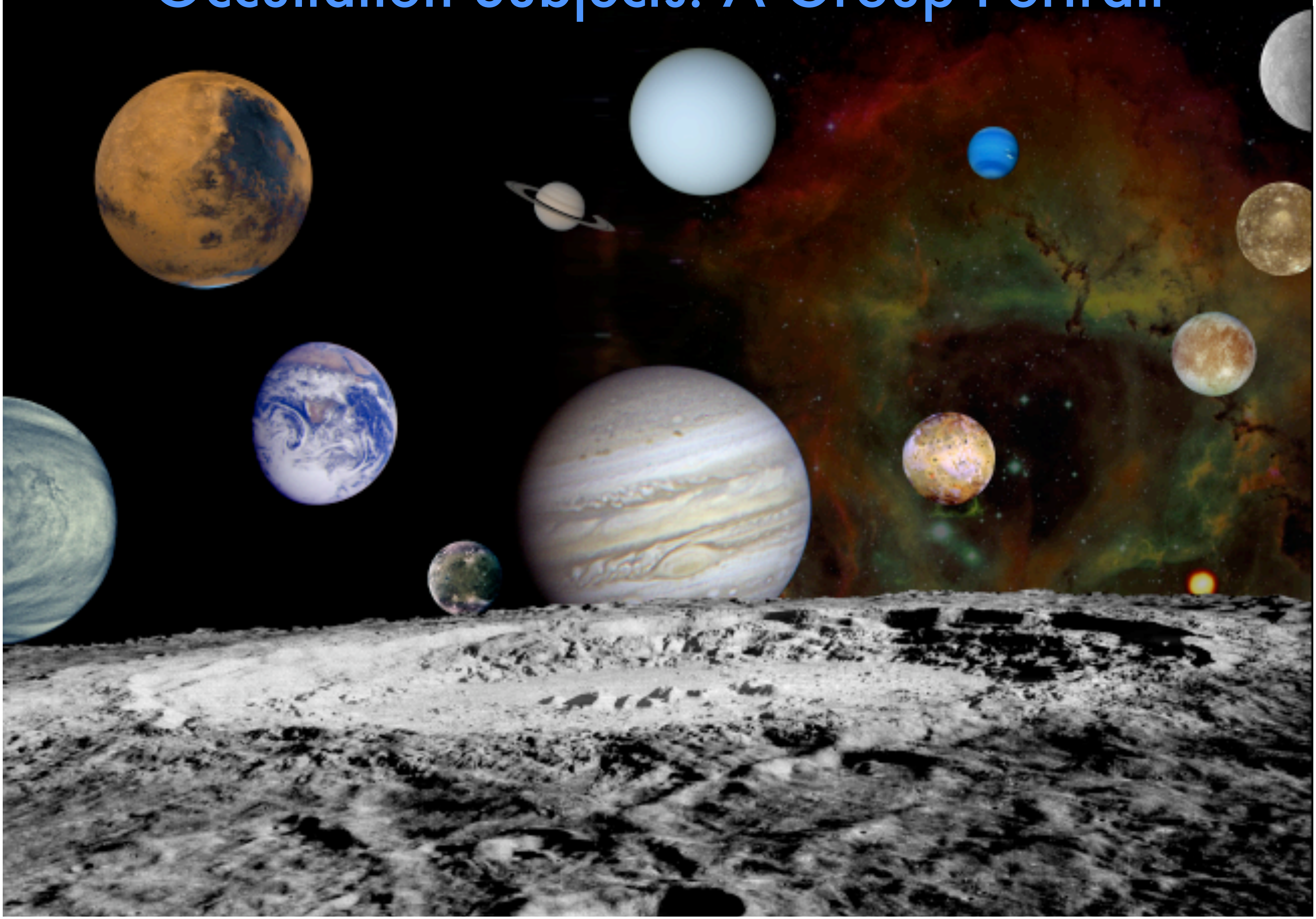
This 'inverse Fresnel filtering' improves resolution by x50-90 over the ~15 km Fresnel limit



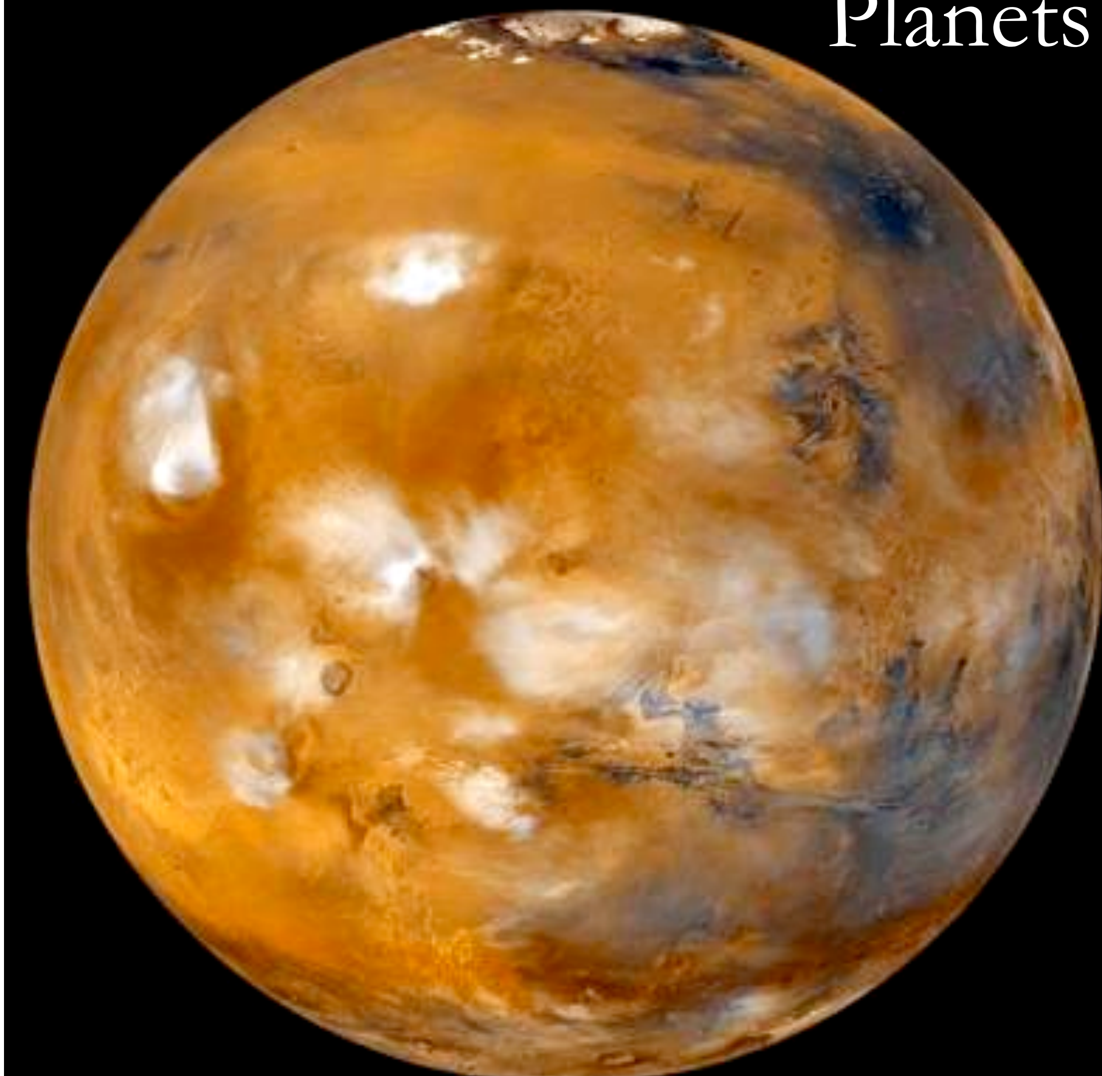


Marouf, Tyler, Rosen, 1986

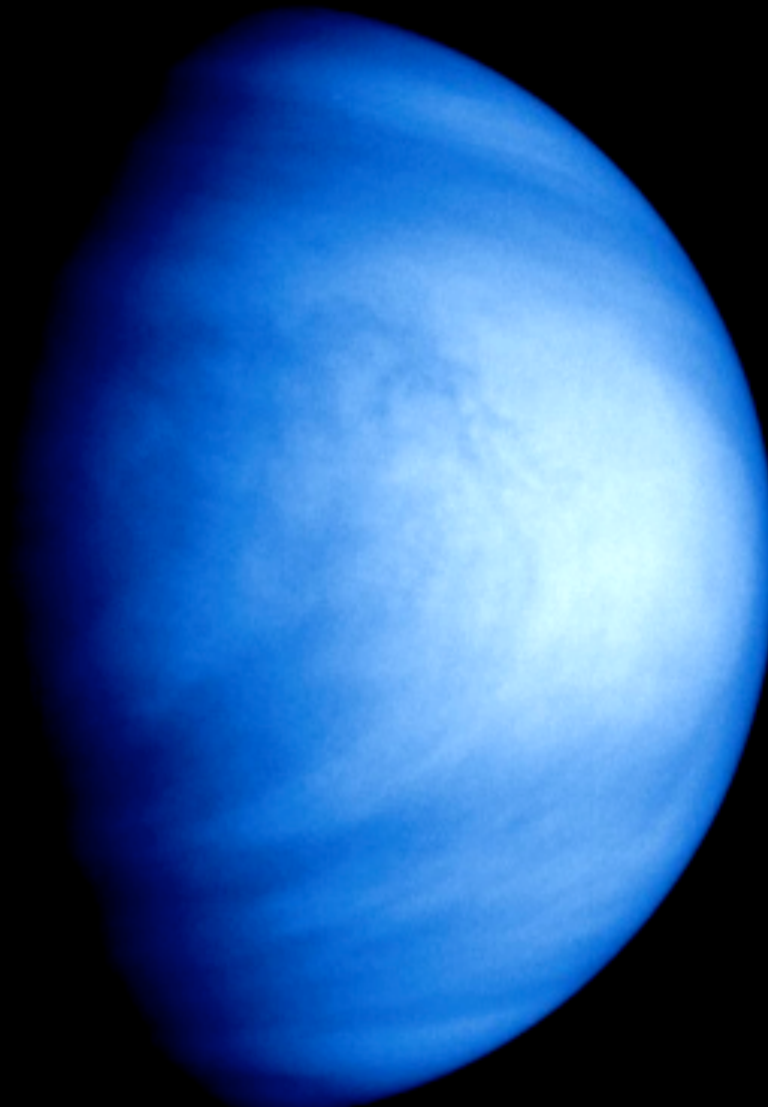
Occultation Subjects: A Group Portrait



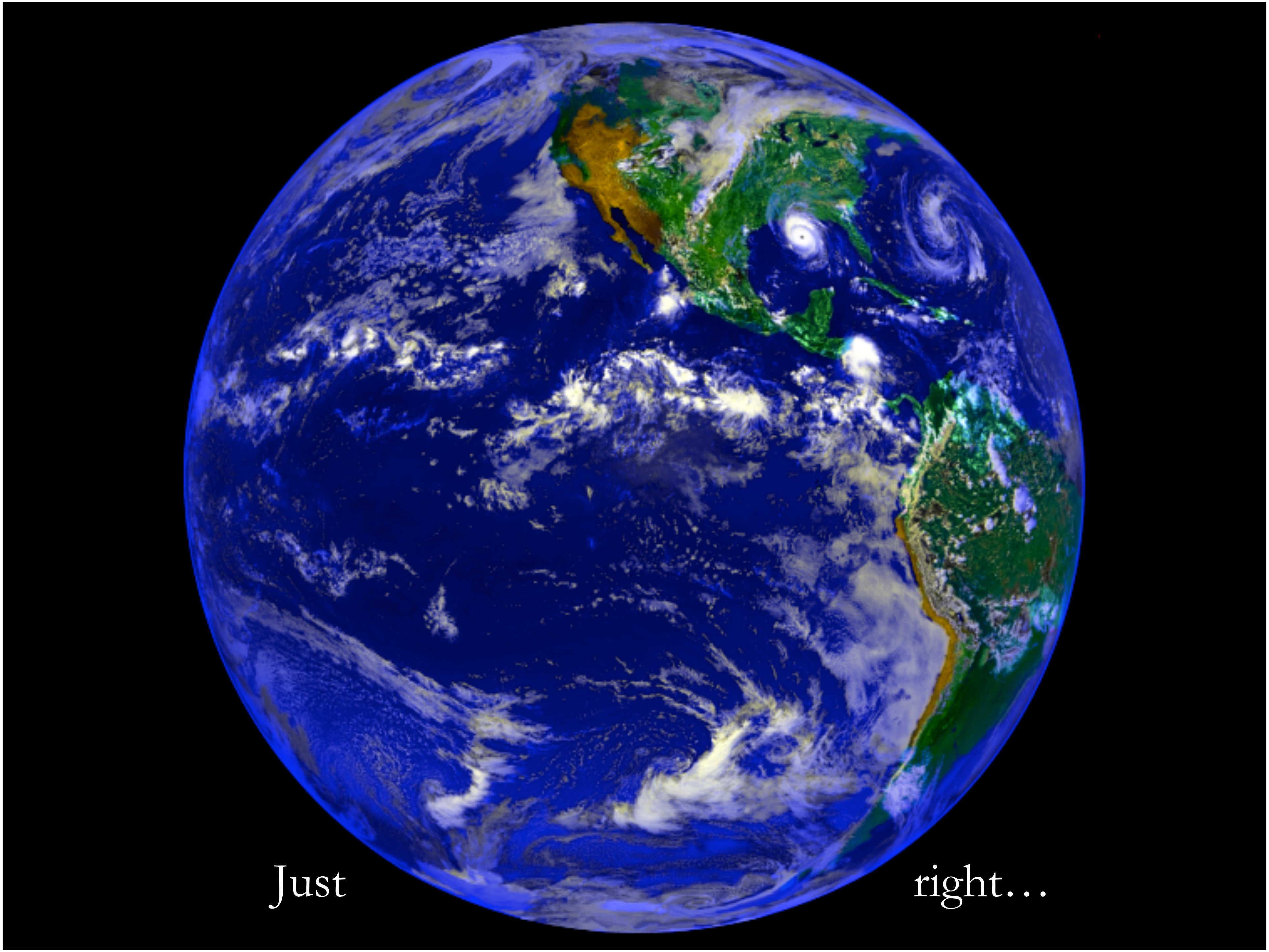
An Observation on the Terrestrial Planets



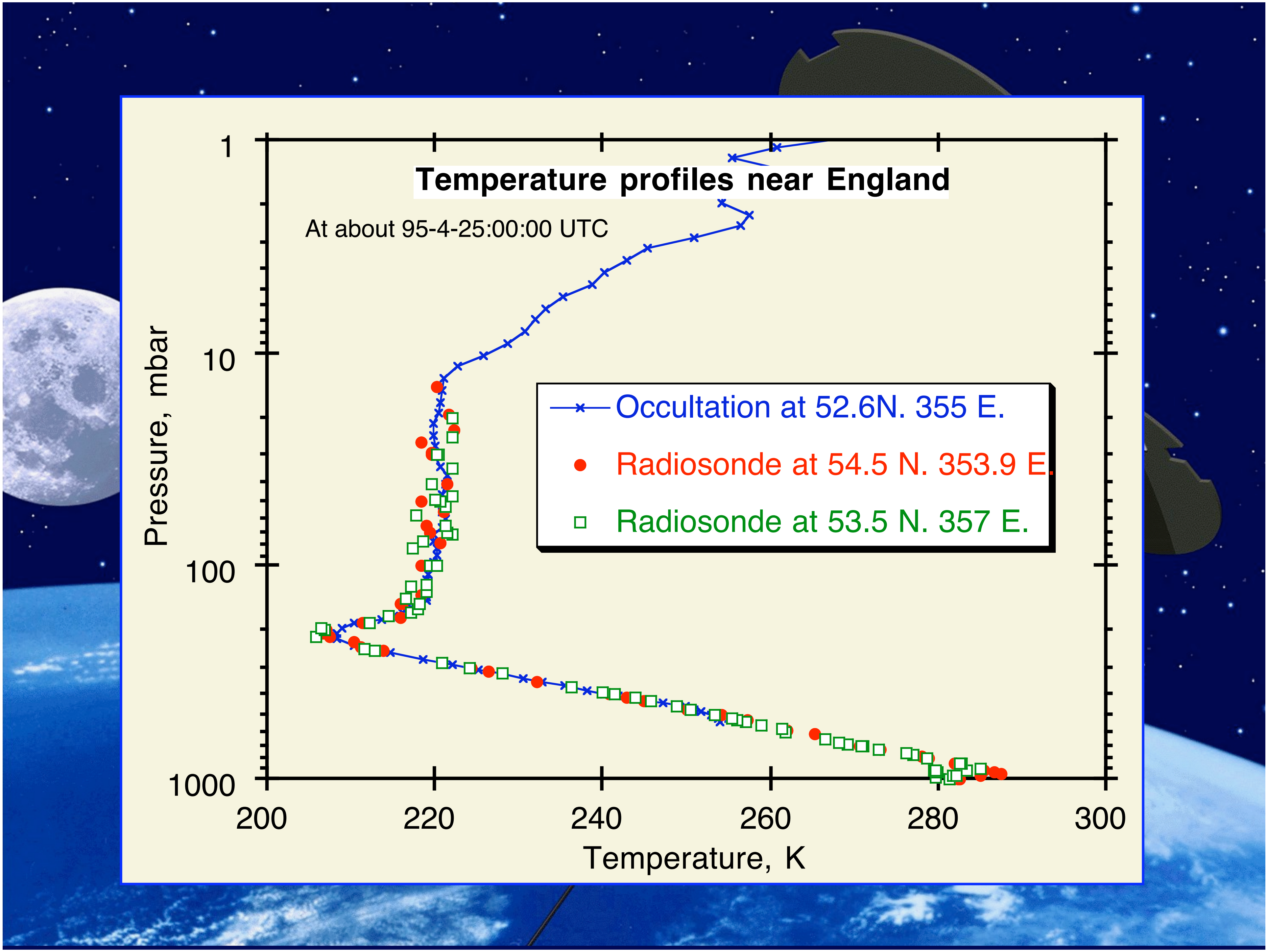
This atmosphere is too thin

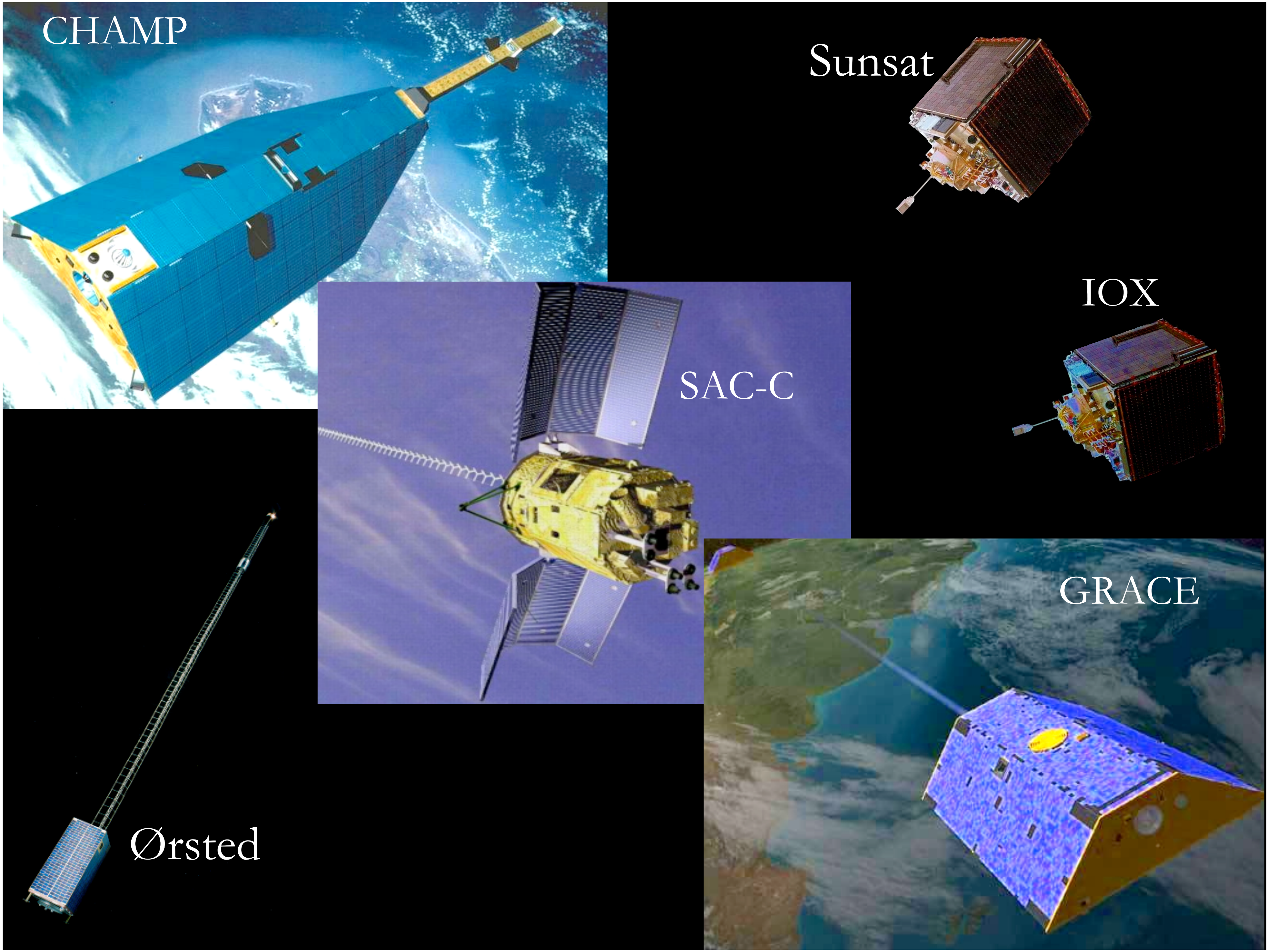


This atmosphere is too thick

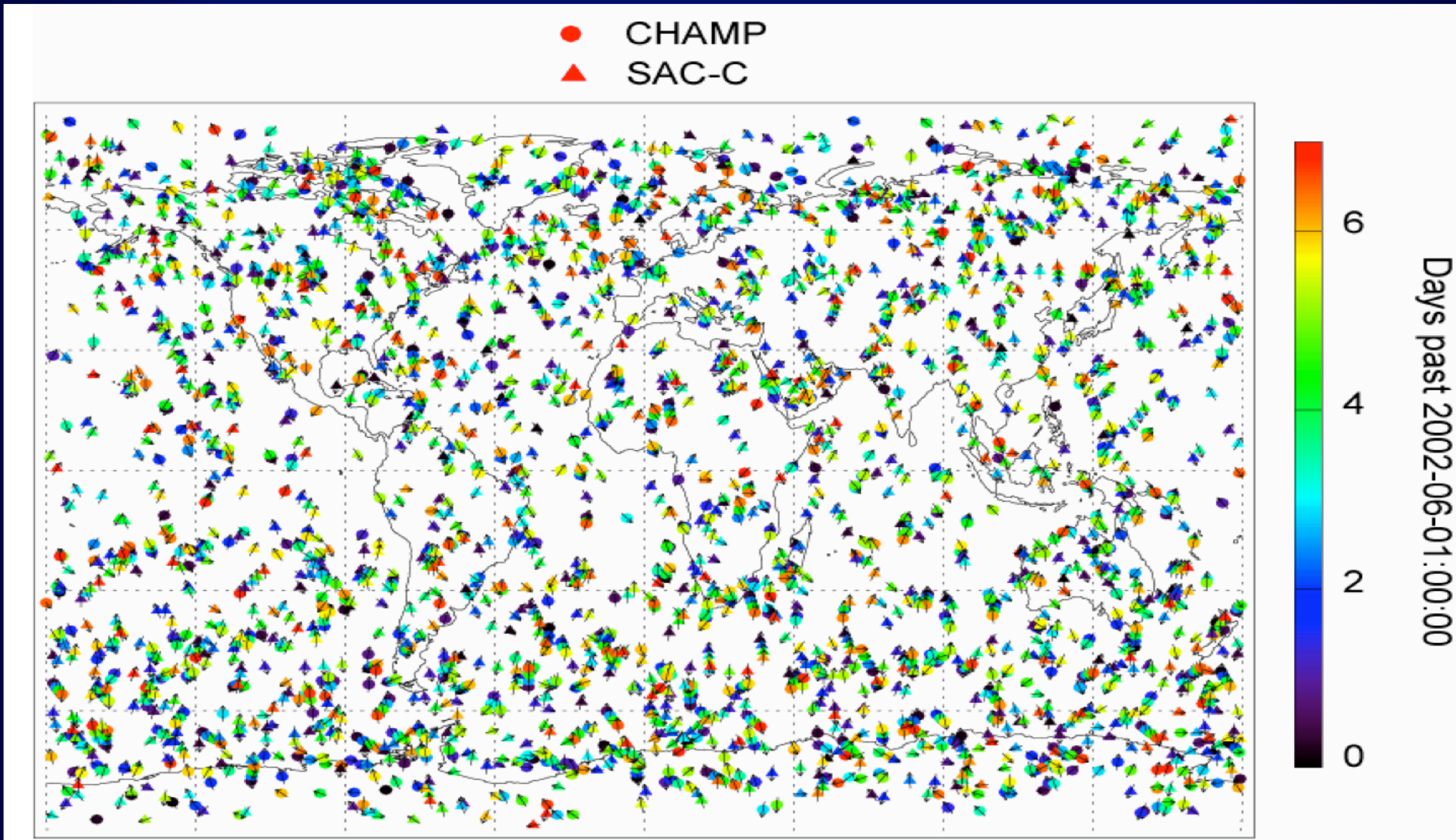

Just
right…

A Sampling of Results


Temperature profiles near England
At about 95-4-25:00:00 UTC
Occultation at 52.6N. 355 E.
Radiosonde at 54.5 N. 353.9 E.
Radiosonde at 53.5 N. 357 E.
Pressure, mbar
1
10
100
1000
200
220
240
260
280
300
Temperature, K

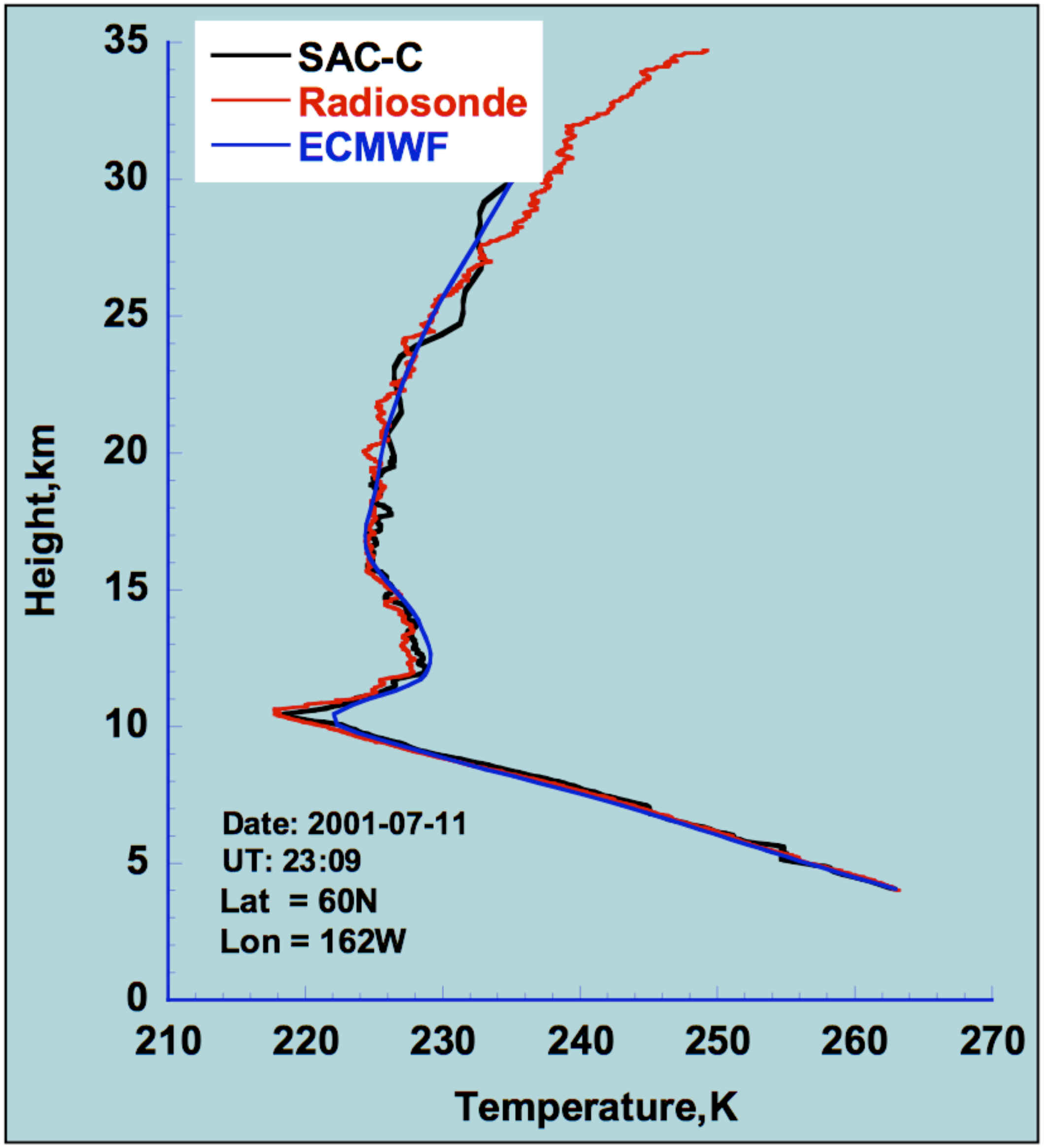

CHAMP
Sunsat
IOX
SAC-C
GRACE
Ørsted

CHAMP-SACC Coverage, 1-7 June 2002



Hajj et al., 2004

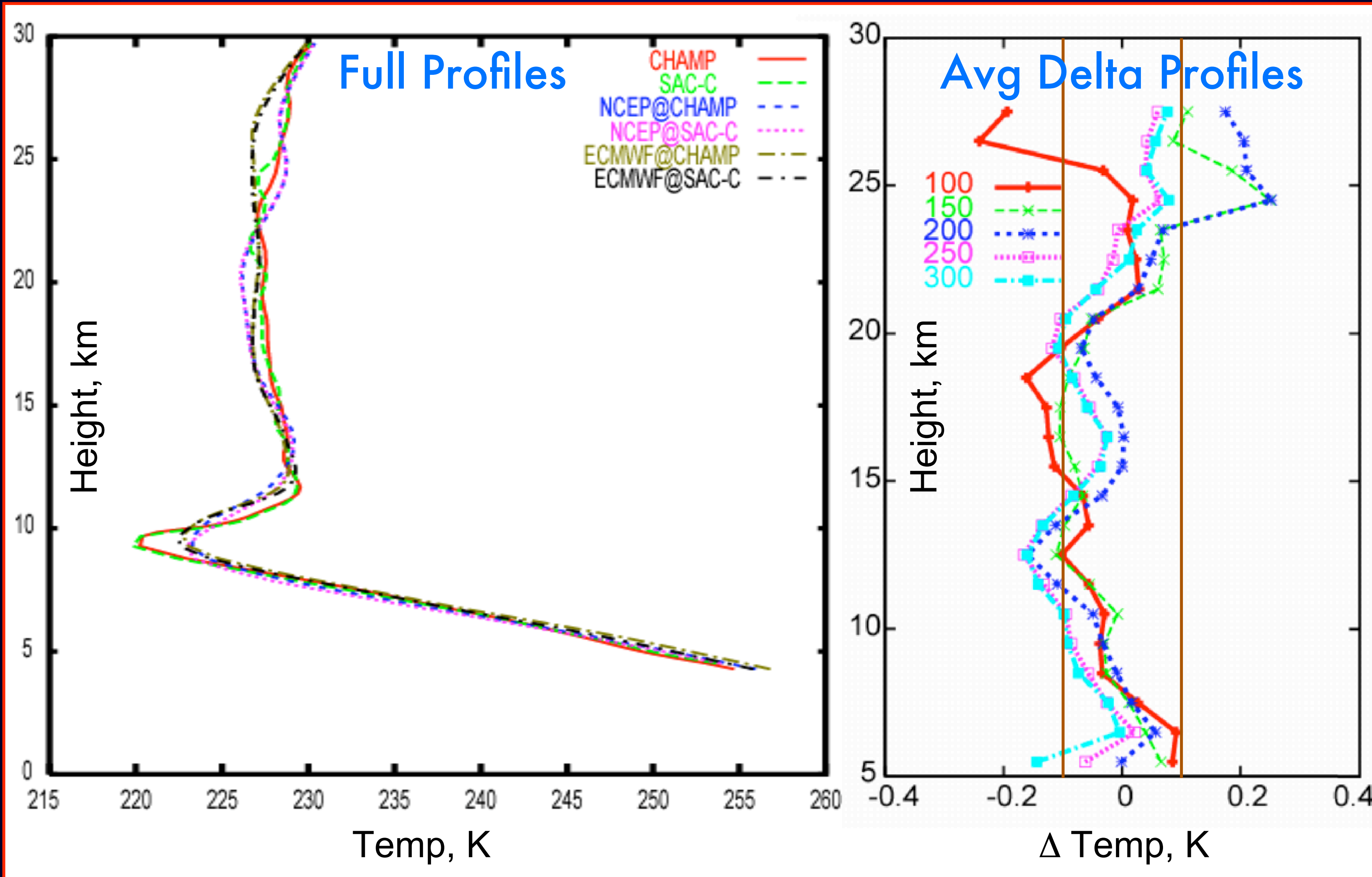
Comparing Three Techniques



High correlation between SAC-C and nearby radiosonde illustrates the accuracy and high resolution of GPS occultation temperatures profiles. The best available weather model (ECMWF) overestimates the tropopause by 2-4K.

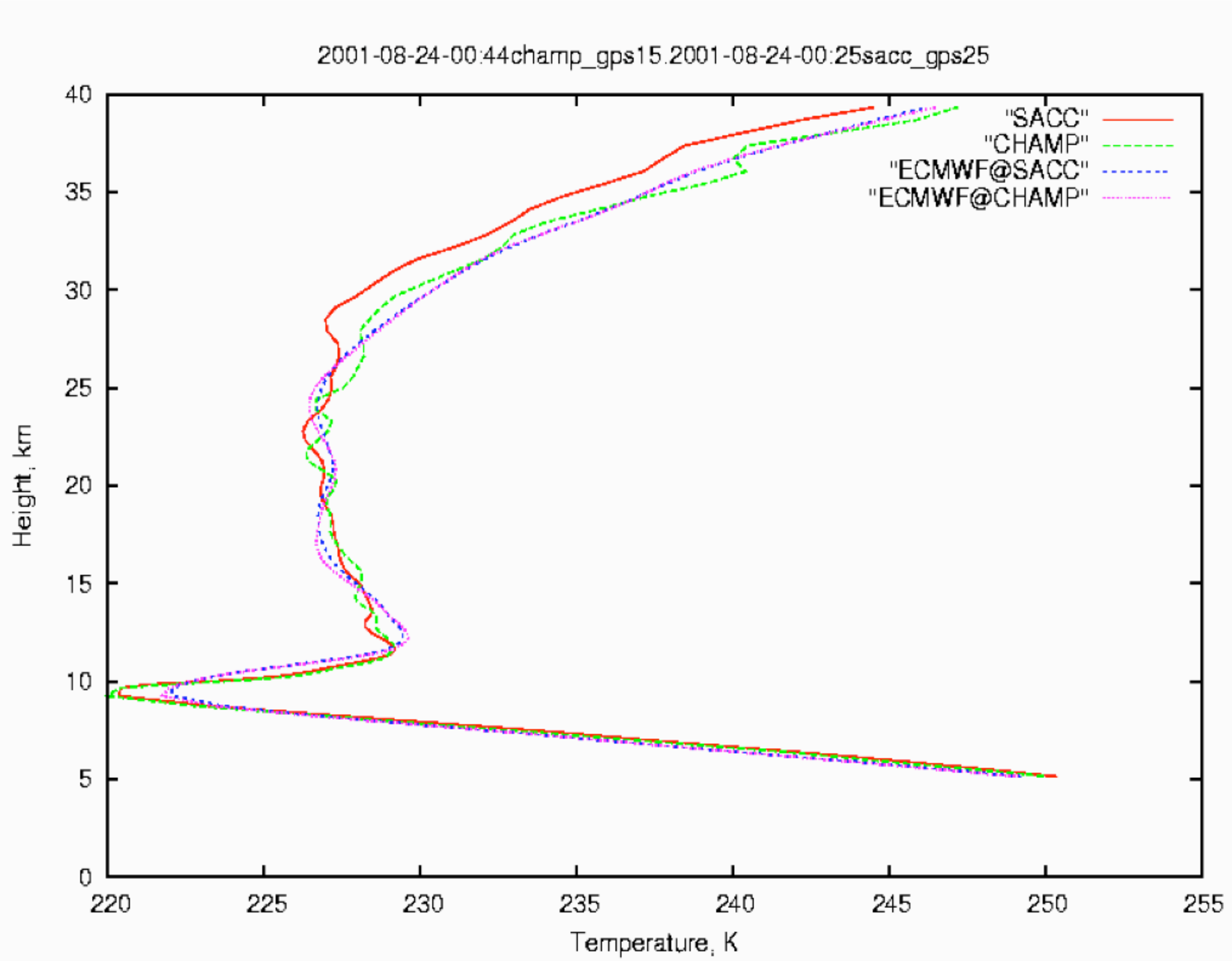
Hajj et al., 2004

CHAMP-SACC Profile Comparison



Hajj et al., 2004

CHAMP-SACC Profile Comparison



Features:

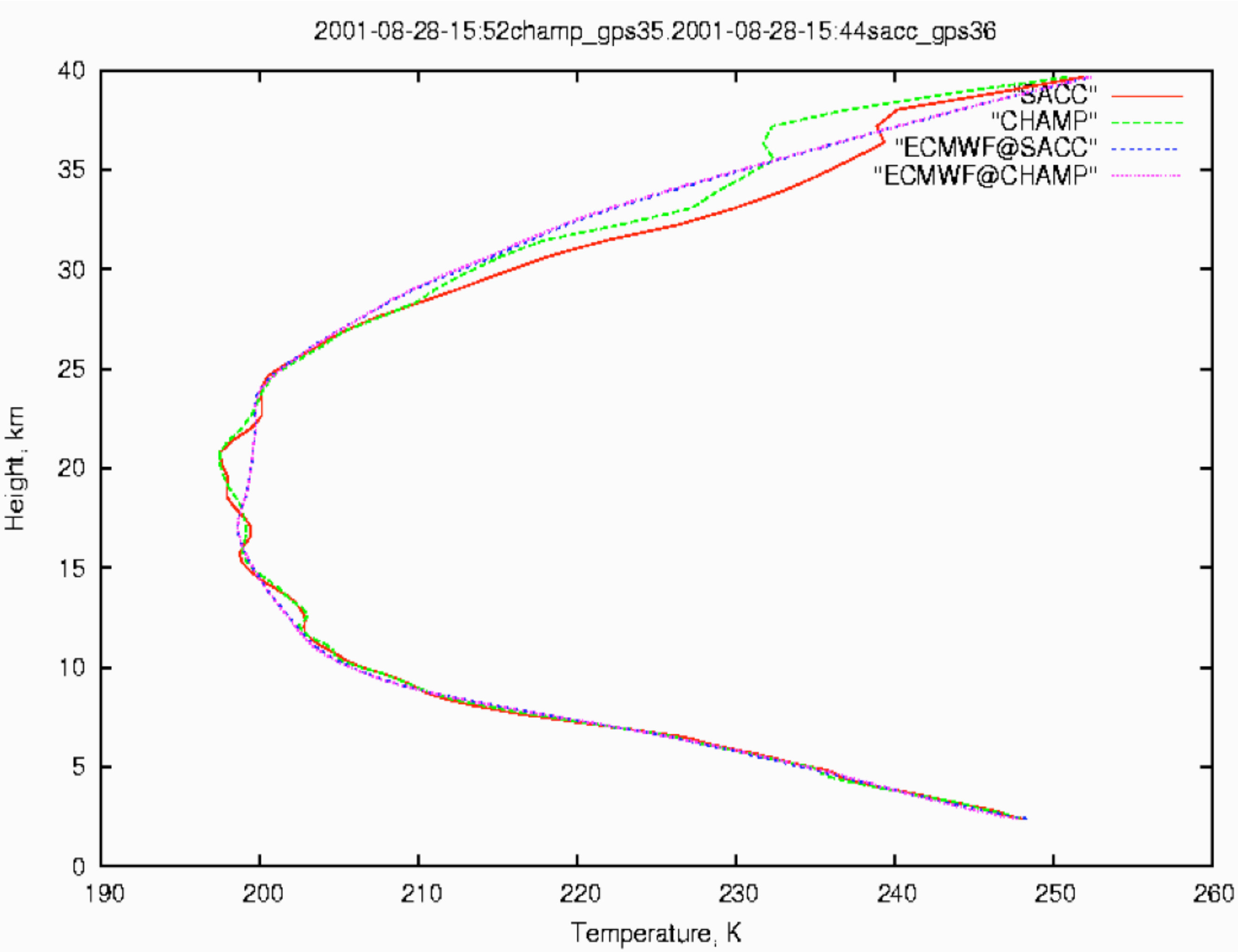
Agreement to <1/2K between CHAMP and SAC/C below 20km.

Colder and sharper tropopause captured by CHAMP and SAC/C relative to ECMWF.

Significant difference between CHAMP and SAC/C in the upper stratosphere (most likely real), missed by the analysis

Hajj et al., 2004

CHAMP-SACC Profile Comparison



Features:

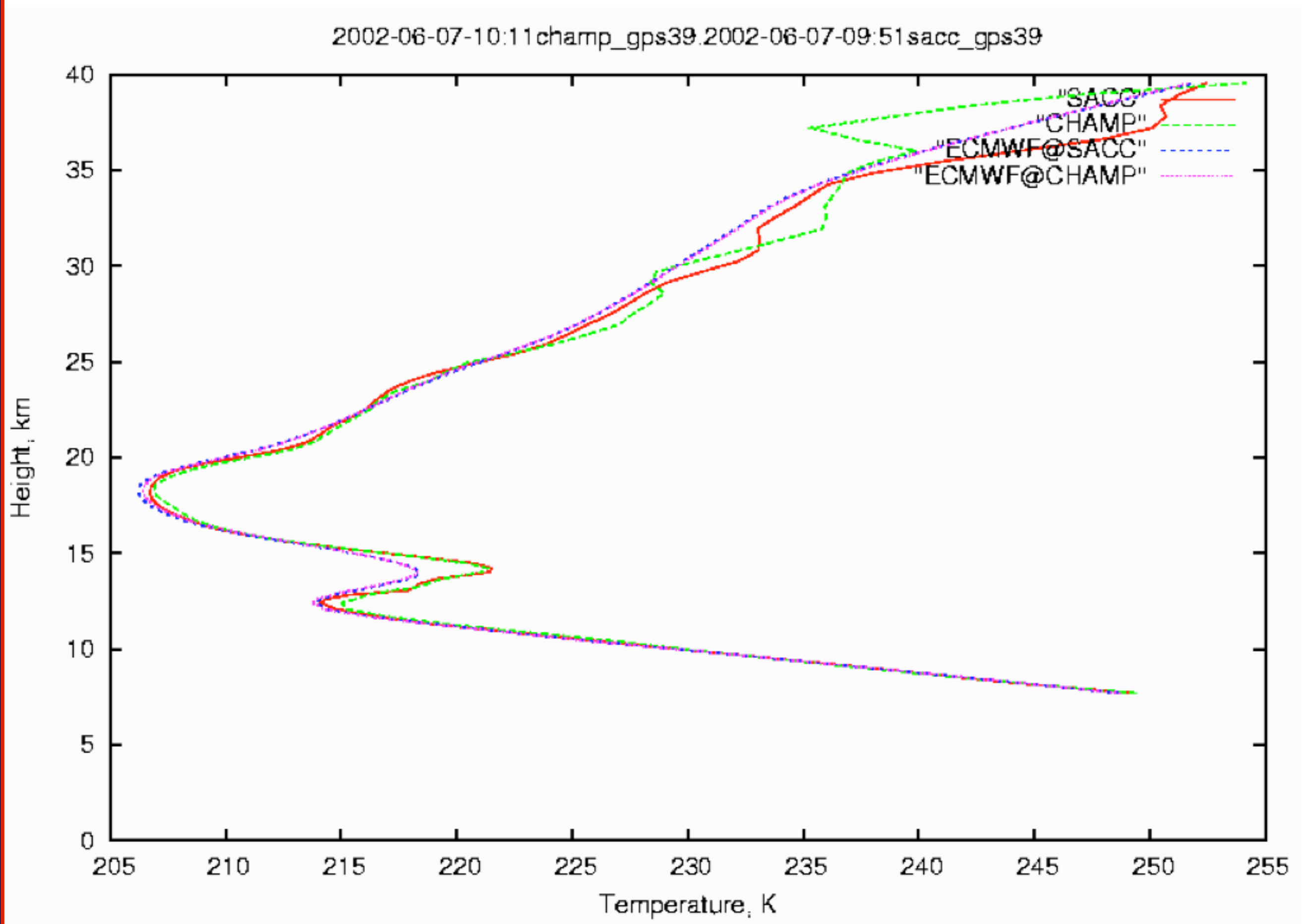
Agreement to <1/2K between CHAMP and SAC/C below 27km.

Nearly identical wavy structure seen by CHAMP and SACC including a strong correlation of temperature structure between 35-40 km .

Significant difference between CHAMP and SAC/C in the upper stratosphere missed by the analysis

Hajj et al., 2004

CHAMP-SACC Profile Comparison



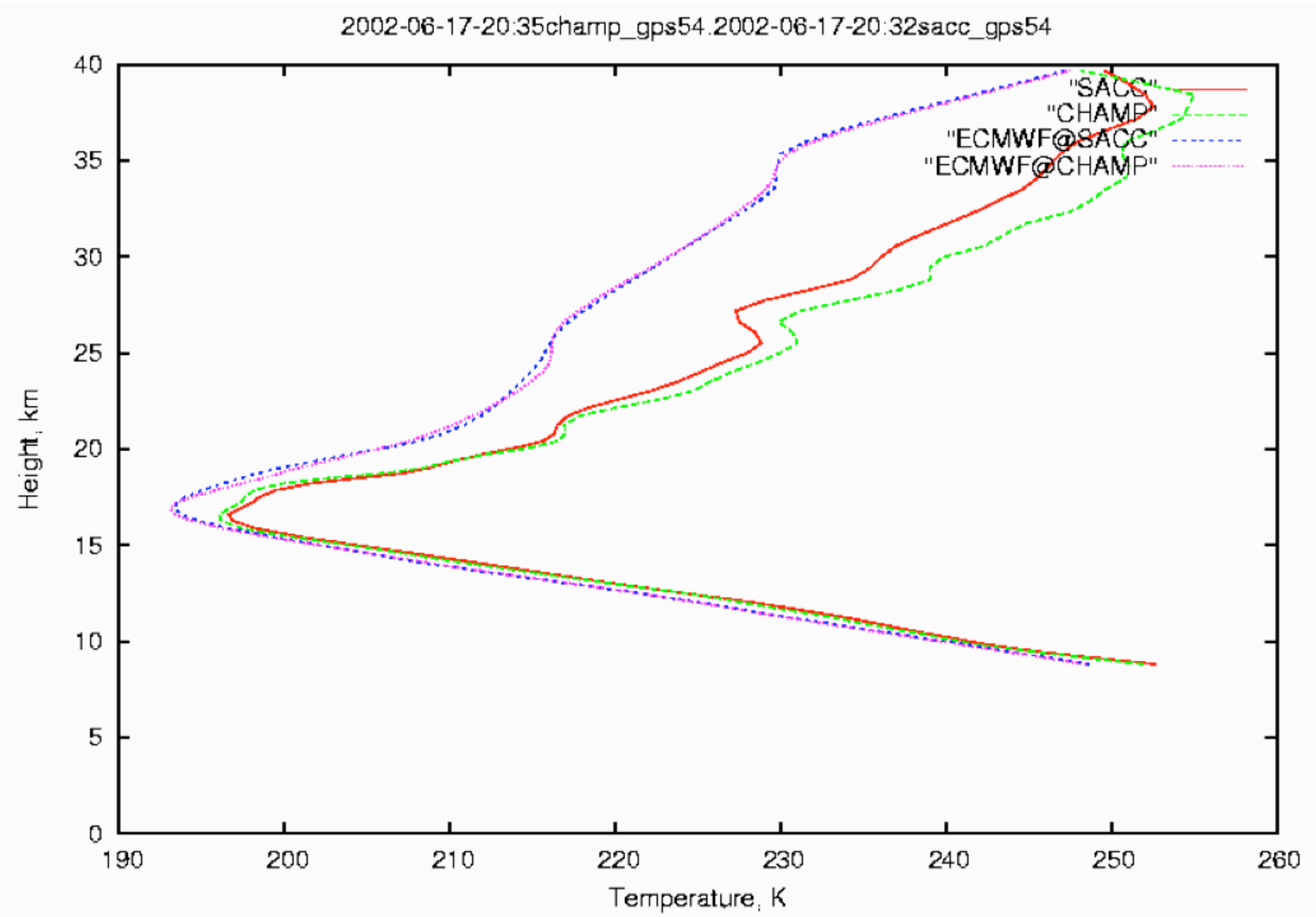
Features:

Very strong correlation between CHAMP and SAC/C below 25km

Warmer temperature captured by CHAMP and SAC/C near 15km

Hajj et al., 2004

CHAMP-SACC Profile Comparison



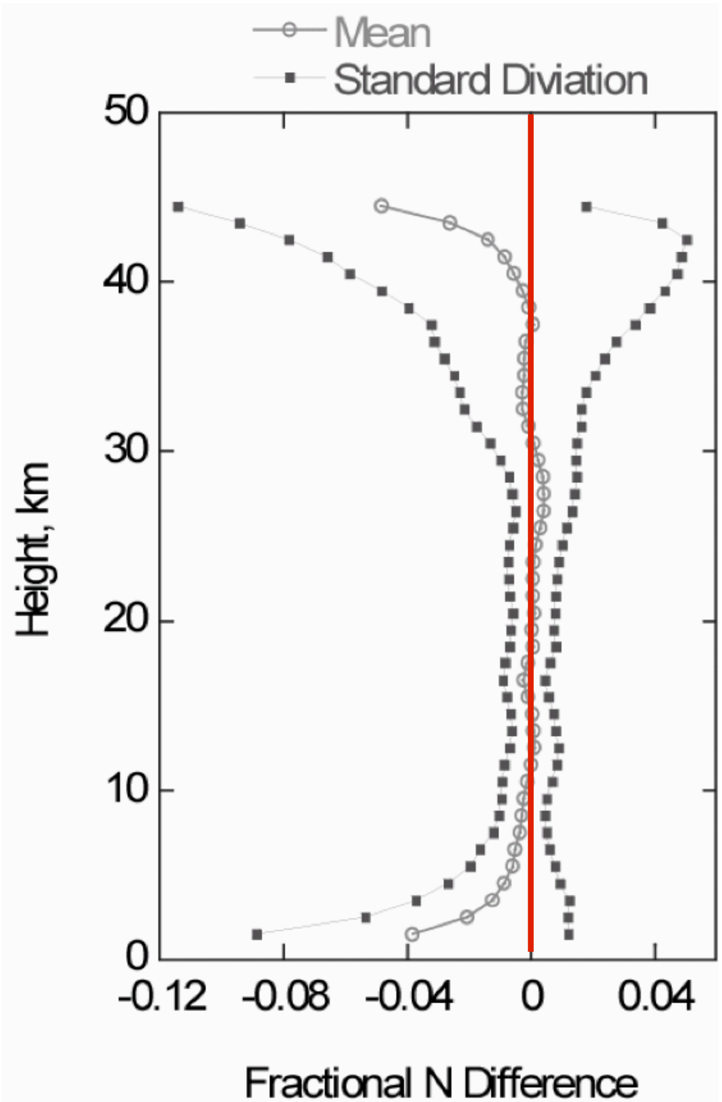
Features:

Strong correlation between CHAMP and SAC/C temperatures

ECMWF systematically underestimates stratospheric temperature by ~10K.

Hajj et al., 2004

Refractivity Statistics



Model independent retrievals of CHAMP refractivity shows no significant bias relative to ECMWF between 7-40 km and a standard deviation of ~1% fractional N difference between 7-30 km. Negative N-biases are seen below 5km and above 40km. Statistics are obtained for the period 1-7 June 2002.

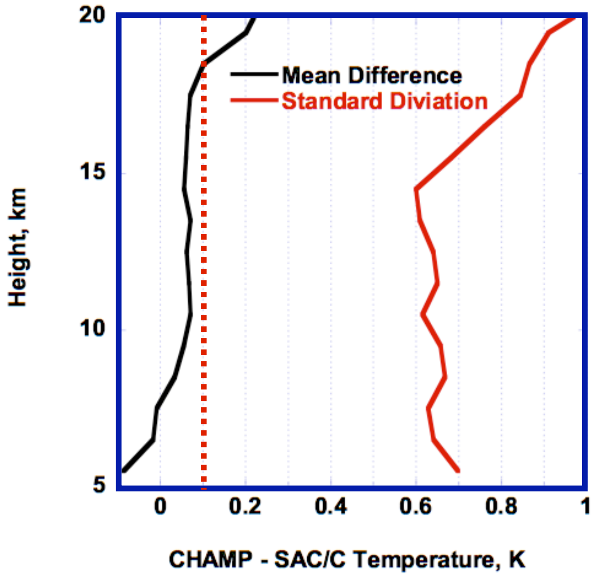
Bias at top is caused by extrapolation of bending above 40km with a constant scale height. A remedy—which still does not rely on a model—is a better parametrization of the upper mesosphere, enhanced signal SNR, enhanced orbits and ionospheric calibration.

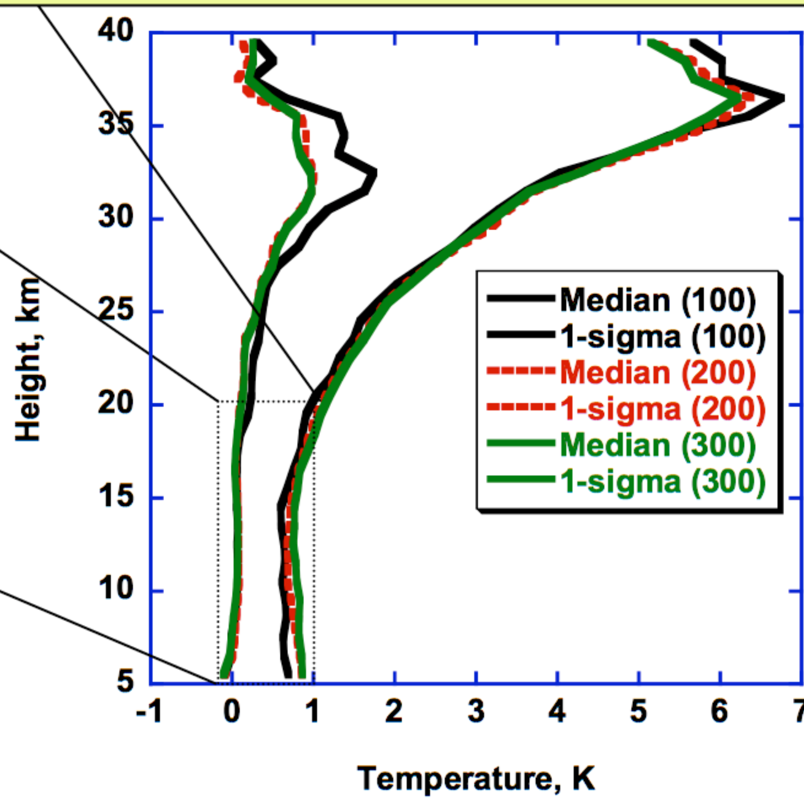
Bias at bottom is due mostly to receiver tracking errors in very humid regions.

Hajj et al., 2004

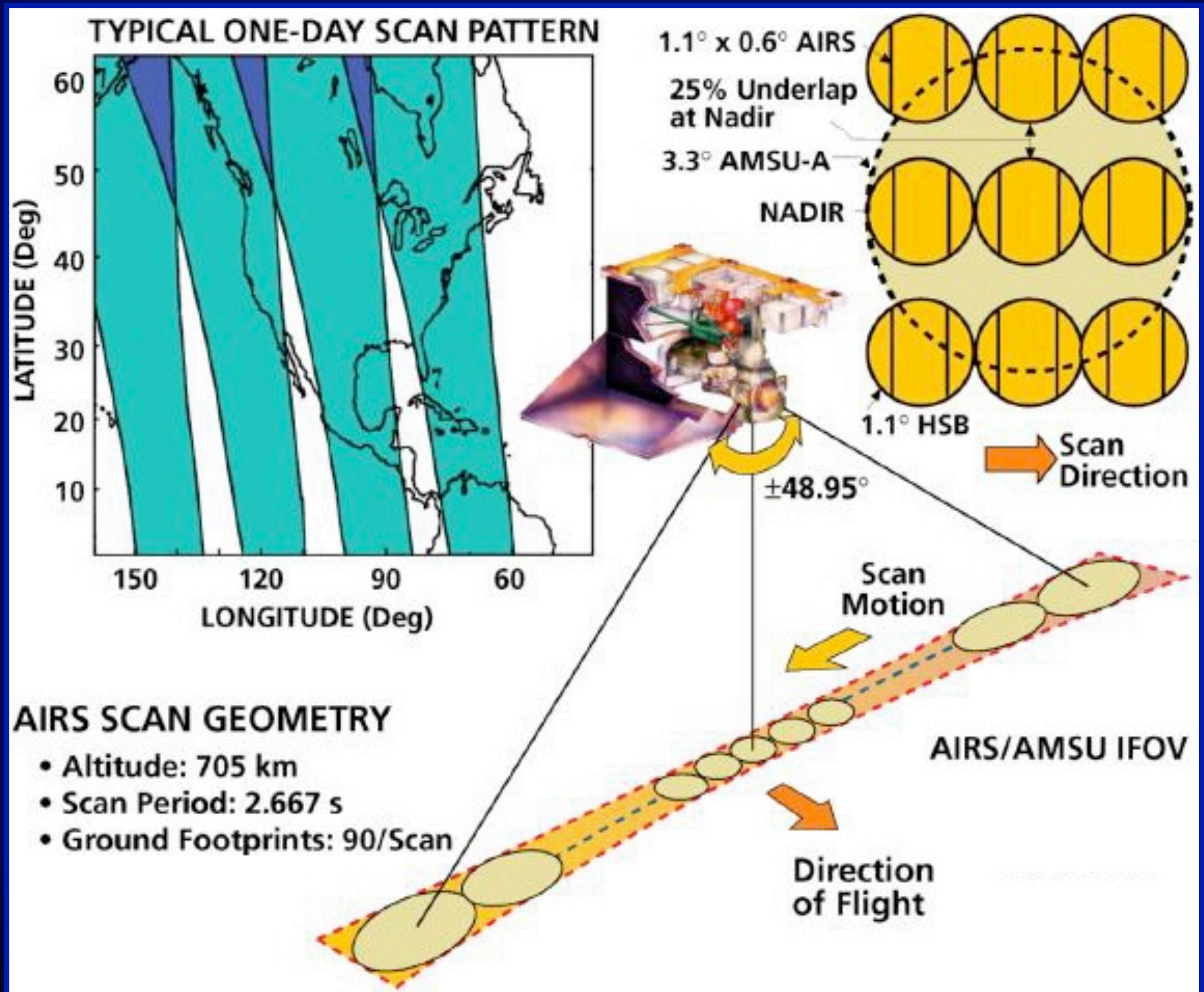
Temperature Statistics

Subtracting off the estimated temperature gradient based on the ECMWF analysis, we compute the median and 1-σ confidence interval of the difference in temperature between coincident occultations that are <100, 200 and 300km apart. The 1-σ is then scaled by 1/sqrt(2) in order to estimate the error due to each occultation, assuming they are independent. The results are shown below indicating a median of <0.1K below 18km and <1K below 30km. The 1-σ confidence interval (equivalent to standard deviation) is ~0.6K below 15km and < 1K below 20km. It grows to ~7K above 35km.

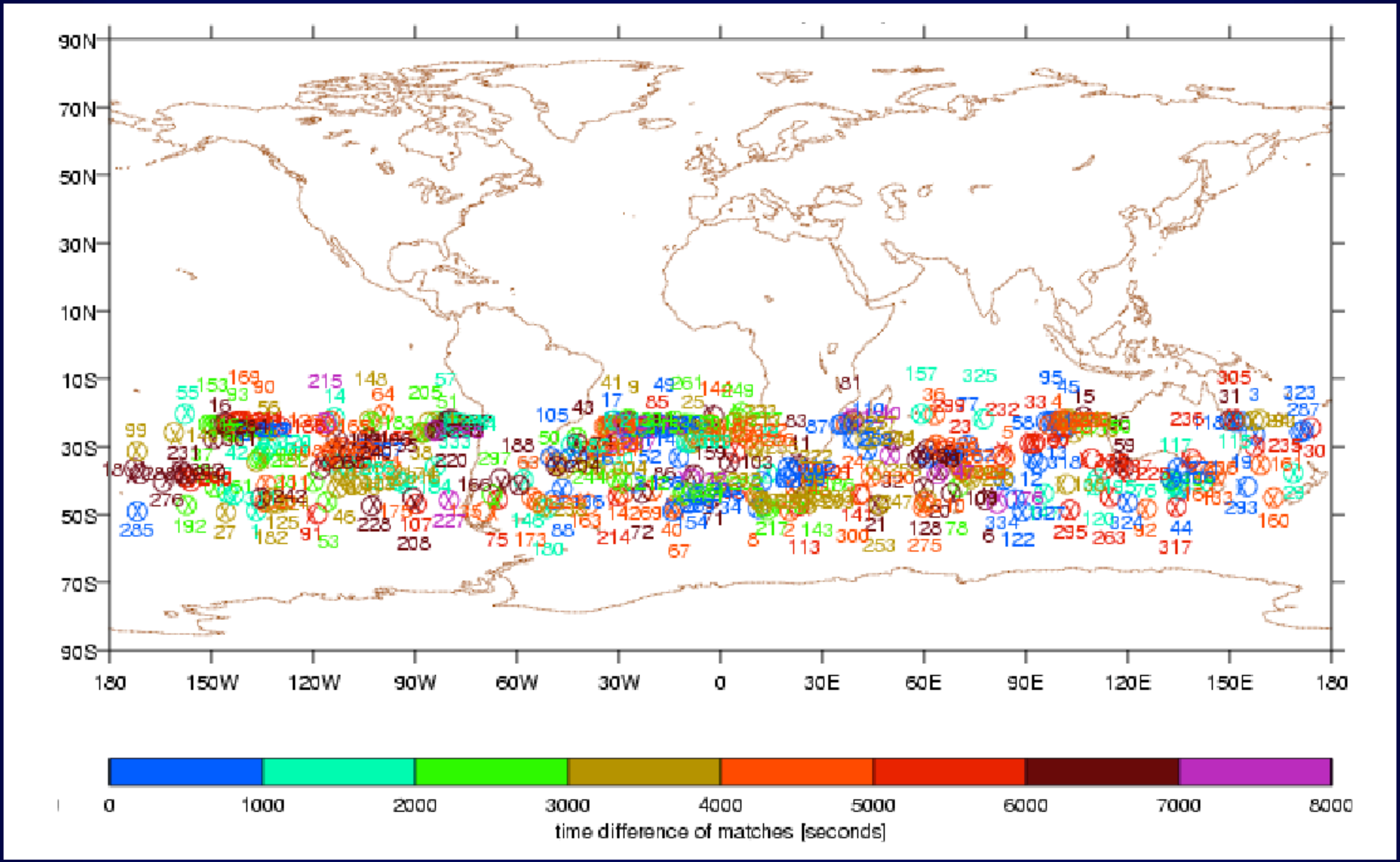




Comparing GPS with AIRS

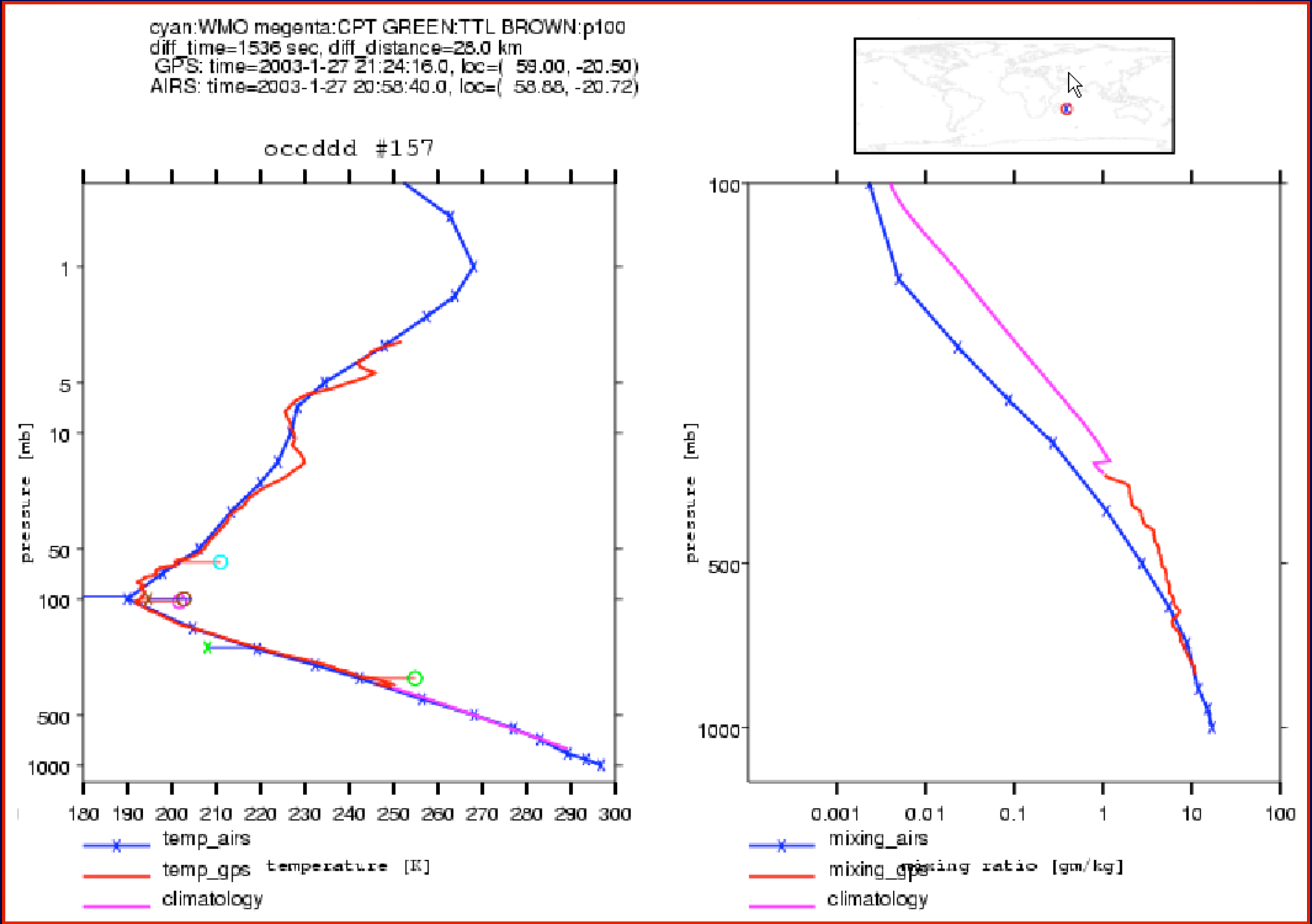


AIRS/GPS Matchups

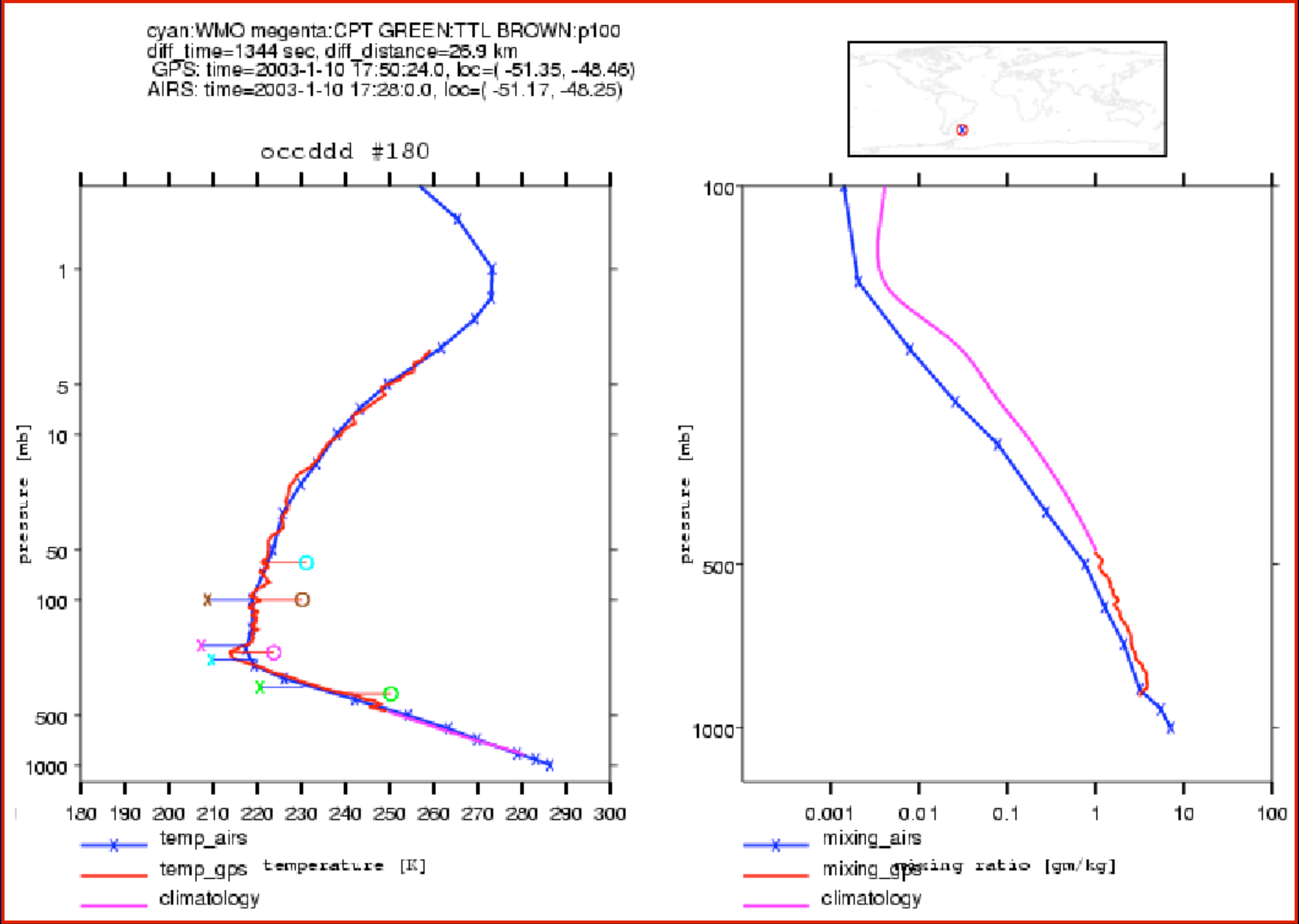


Jan 2003, latitude -50 to -20 deg => 336 matchups
(see http://sciflo:8080/sciflo/Private/SciFloWiki/GpsAirsComparison for more)

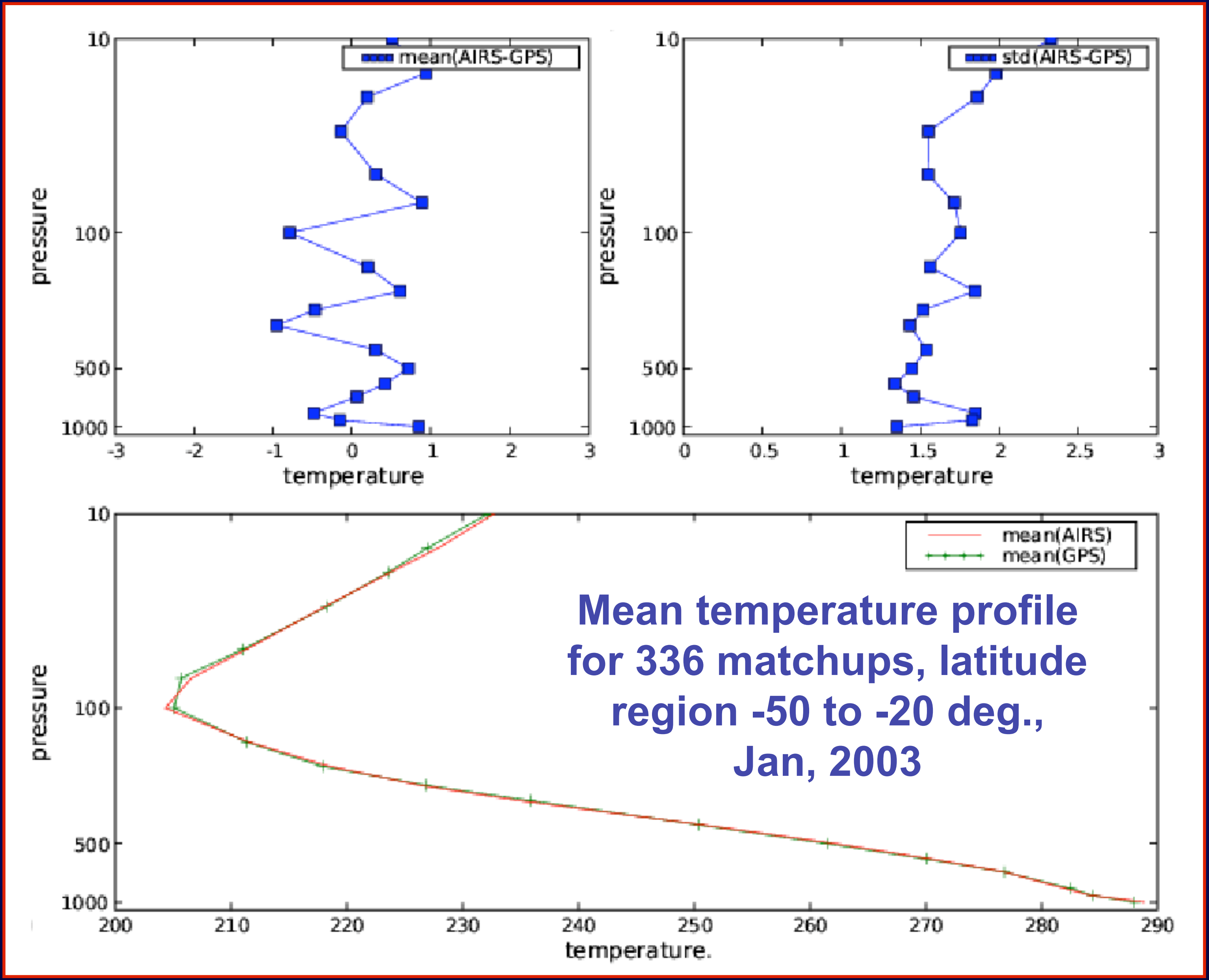
AIRS/GPS Temperature & Water Vapor Comparison Plots



AIRS/GPS Temperature & Water Vapor Comparison Plots



AIRS/GPS Temperature Difference Statistics



Attractions of GPS Radio Occultation

1. High accuracy: Averaged profiles to < 0.1 K

2. Assured long-term stability

3. All-weather operation

4. Global 3D coverage: stratopause to surface

5. Vertical resolution: ~100 m in lower trop

6. Independent height & pressure/temp data

7. Compact, low-power, low-cost sensor

Joint AIRS/GPS Retrievals

Define the Problem

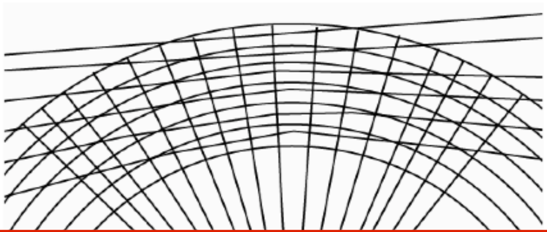
- How to best combine GPS and AIRS data such that information on horizontal structure (AIRS) and high-vertical resolution (GPS) are maintained

Solution

- Use horizontal gradient information from AIRS
- Devise a new retrieval strategy for GPS occultations which does not assume spherical symmetry
- Assuming the horizontal gradient of AIRS, derive a high vertical resolution profile from GPS occultation

Implementation

- Compute atmospheric refractivity as a function of height based on AIRS derived temperature and humidity
- Interpolate AIRS refractivity to the occultation plane
- Divide the occultation plane into pixels with resolution commensurate to those of GPS occultations in the vertical direction and to AIRS in the horizontal direction

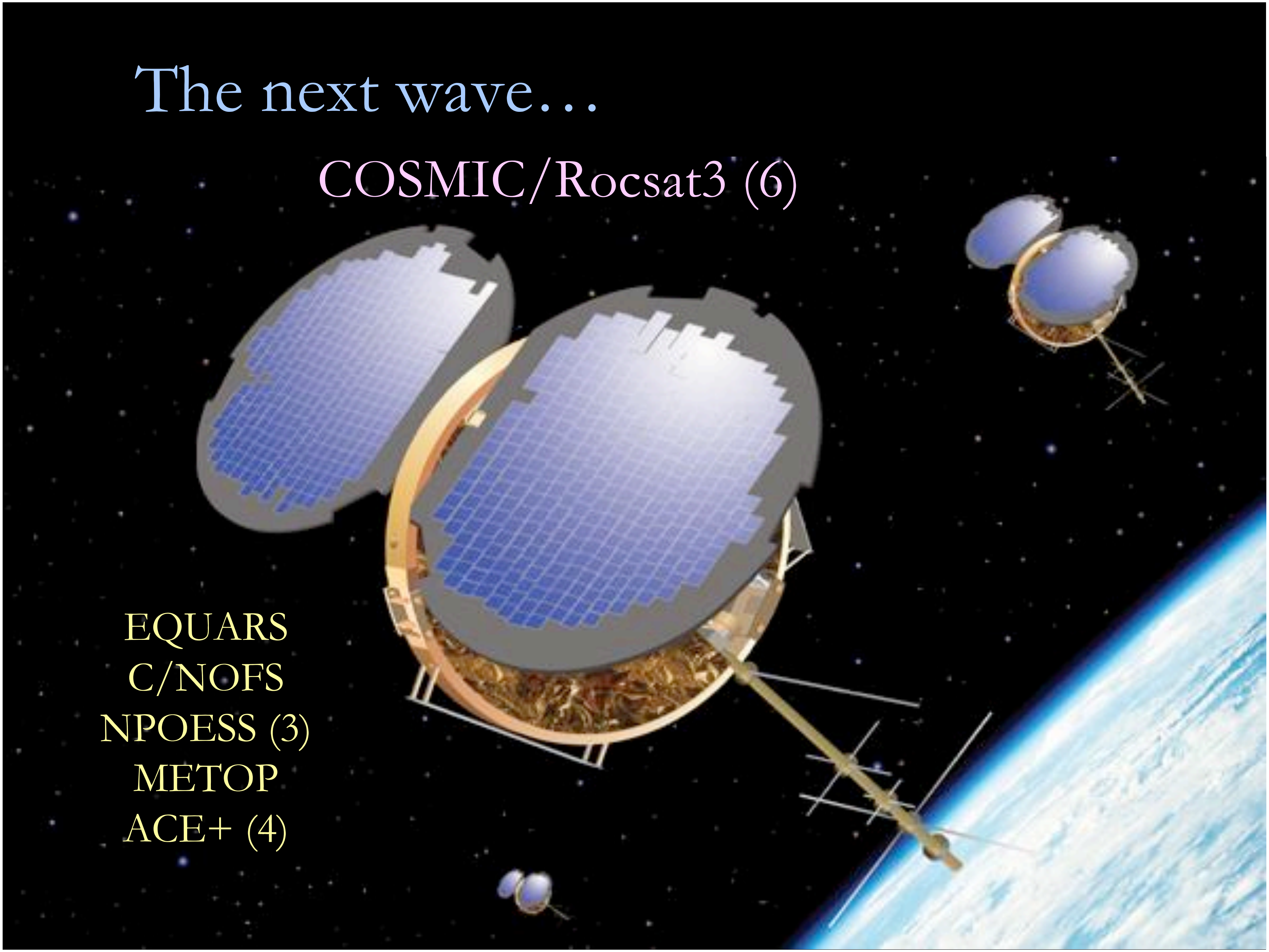


Hajj et al., 2004

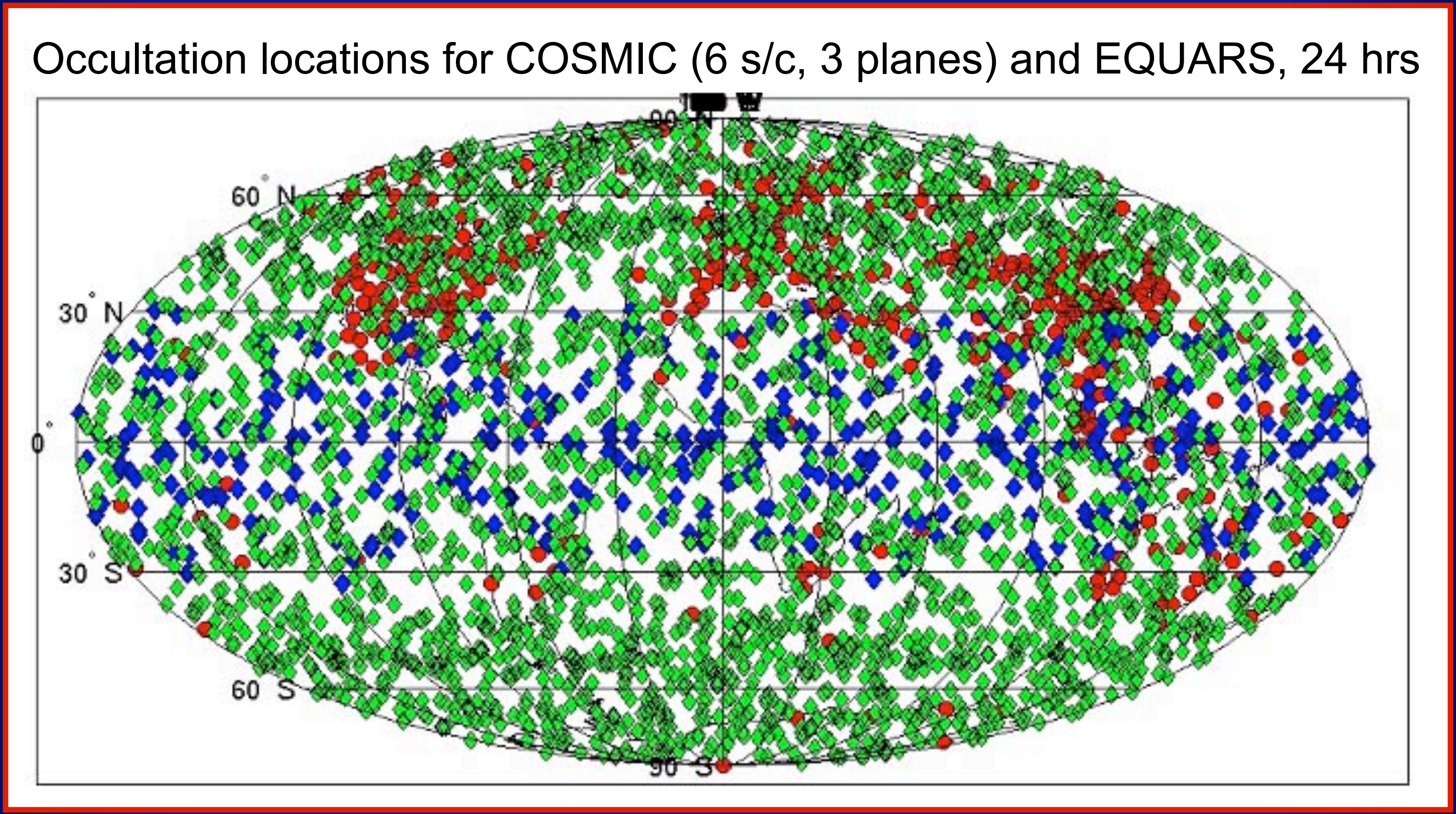
Benefits of combining AIRS and GPS

- AIRS can be calibrated against GPS data for weather and long term climate research
- Obtain high resolution in the vertical (from GPS) and horizontal (from AIRS) directions
- Resolve dry/wet ambiguity in interpretation of refractivity in the lower troposphere
- Gross consistency in GPS and AIRS retrievals can serve as a quality control on both data systems

Hajj et al., 2004

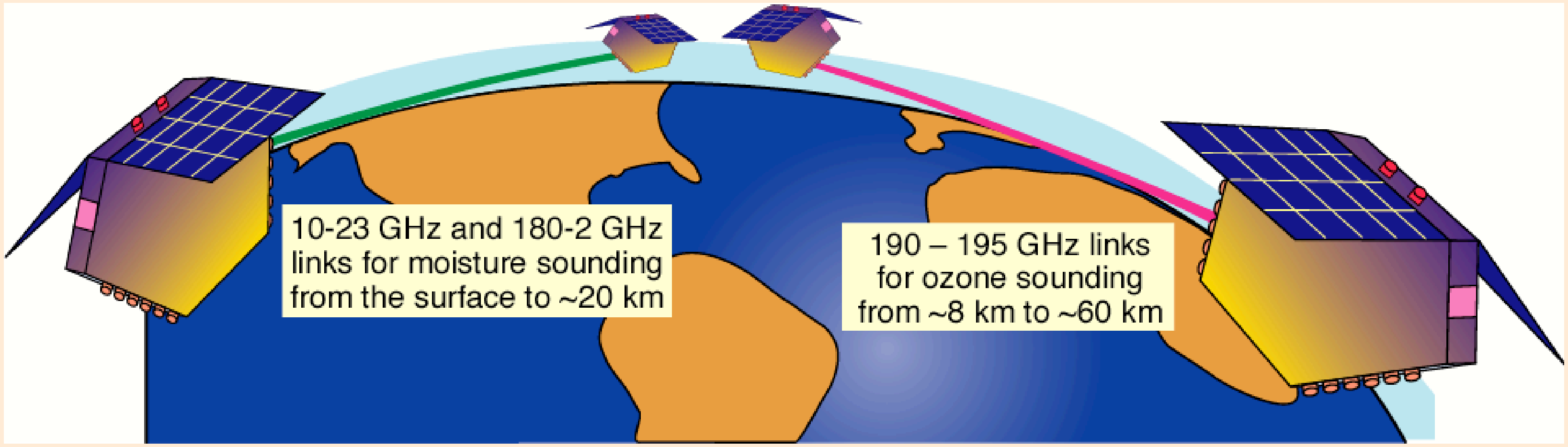

The next wave…
COSMIC/Rocsat3 (6)
EQUARS
C/NOFS
NPOESS (3)
METOP
ACE+ (4)

COSMIC + EQUARS Soundings in 1 Day



Crosslink Occultation: Absorption & Bending

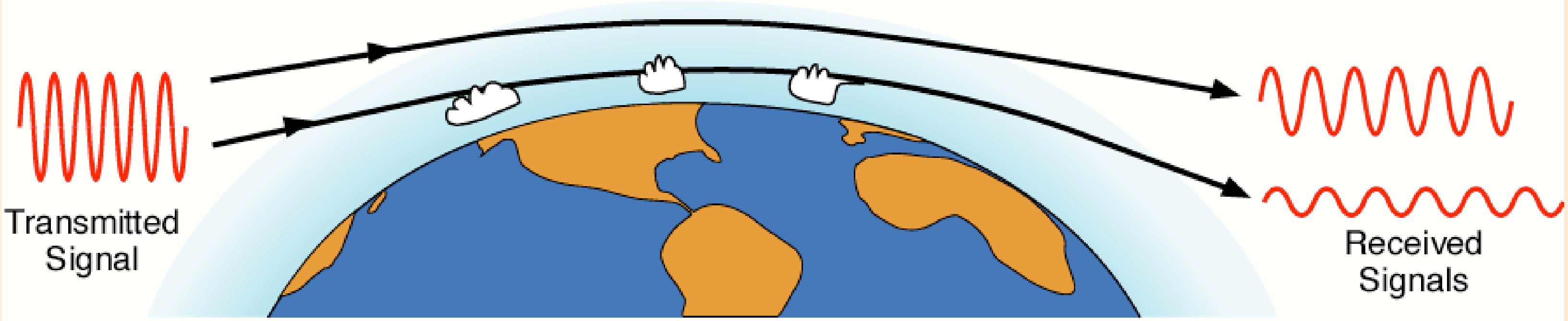
ATOMS: Active Tropospheric Ozone & Moisture Sounder



Exchange of microwave crosslinks between pairs of occulting LEOs.

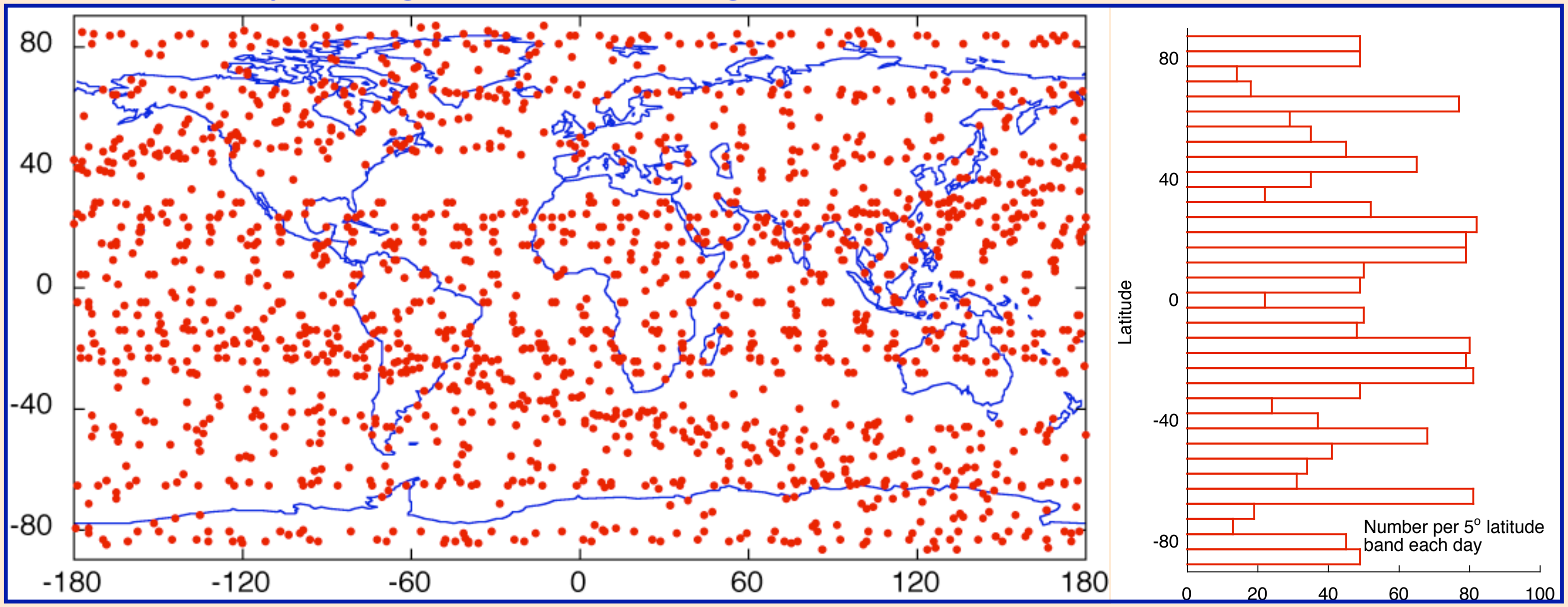
The changing signal amplitude is measured to assess absorption by molecular ozone and moisture.

Crosslink Occultation (cont.)

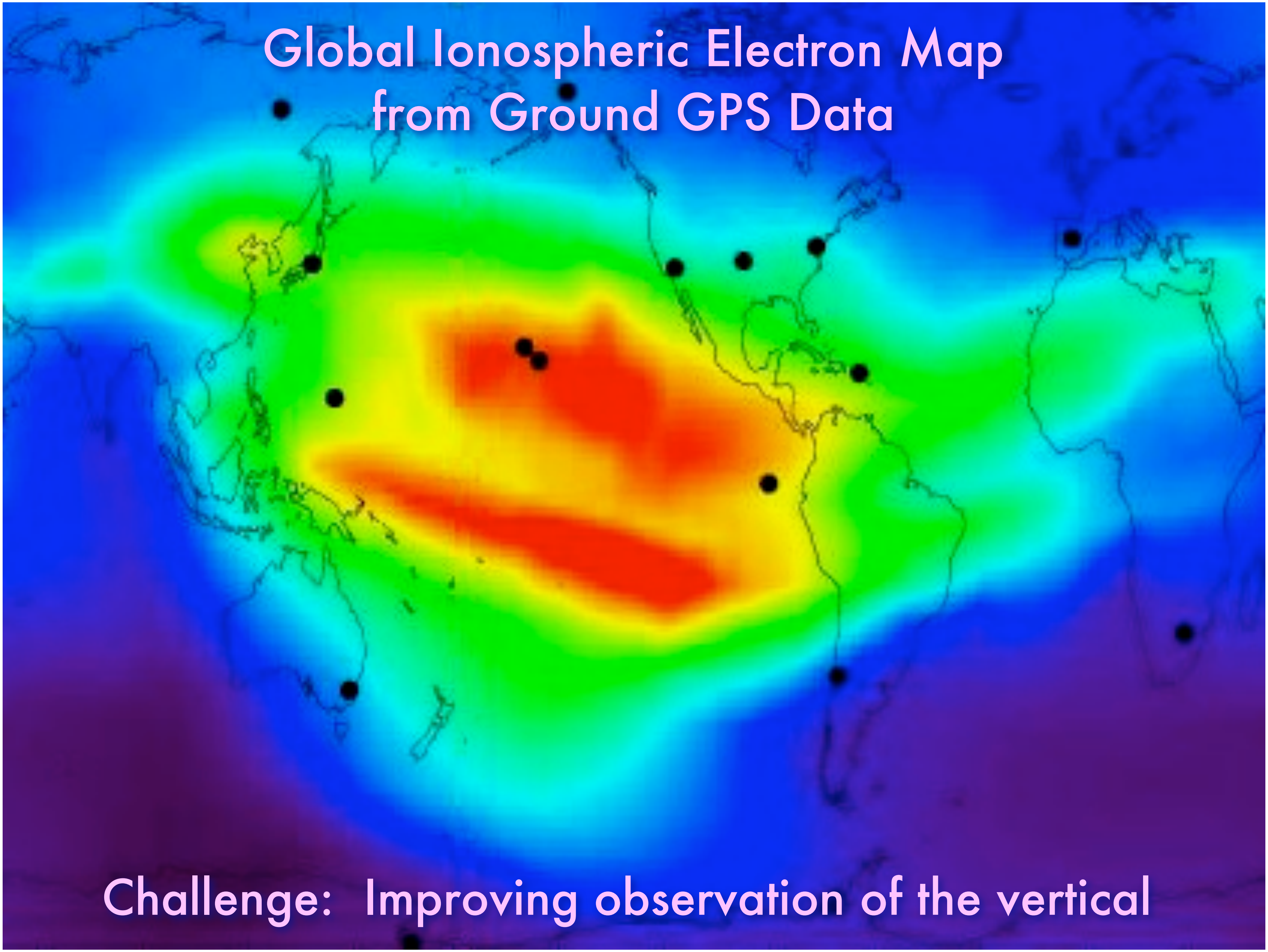


ATOMS exploits signal attenuation from molecular absorption of RF frequencies from 10-200 GHz to make precise profiles of ozone and mosture concentrations

Daily Geographic Coverage with a 12-Satellite Constellation

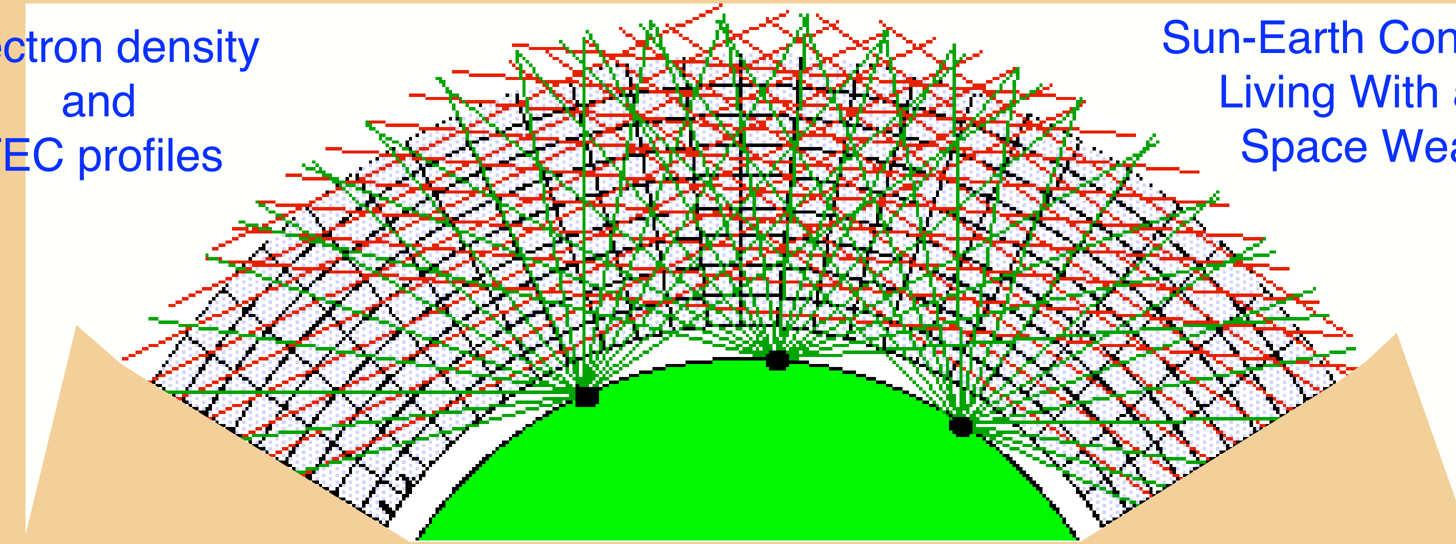


Bonus:
The Global Ionosphere


Global Ionospheric Electron Map
from Ground GPS Data
Challenge: Improving observation of the vertical

Snapshot 3D Ionospheric Imaging

Electron density
and
TEC profiles

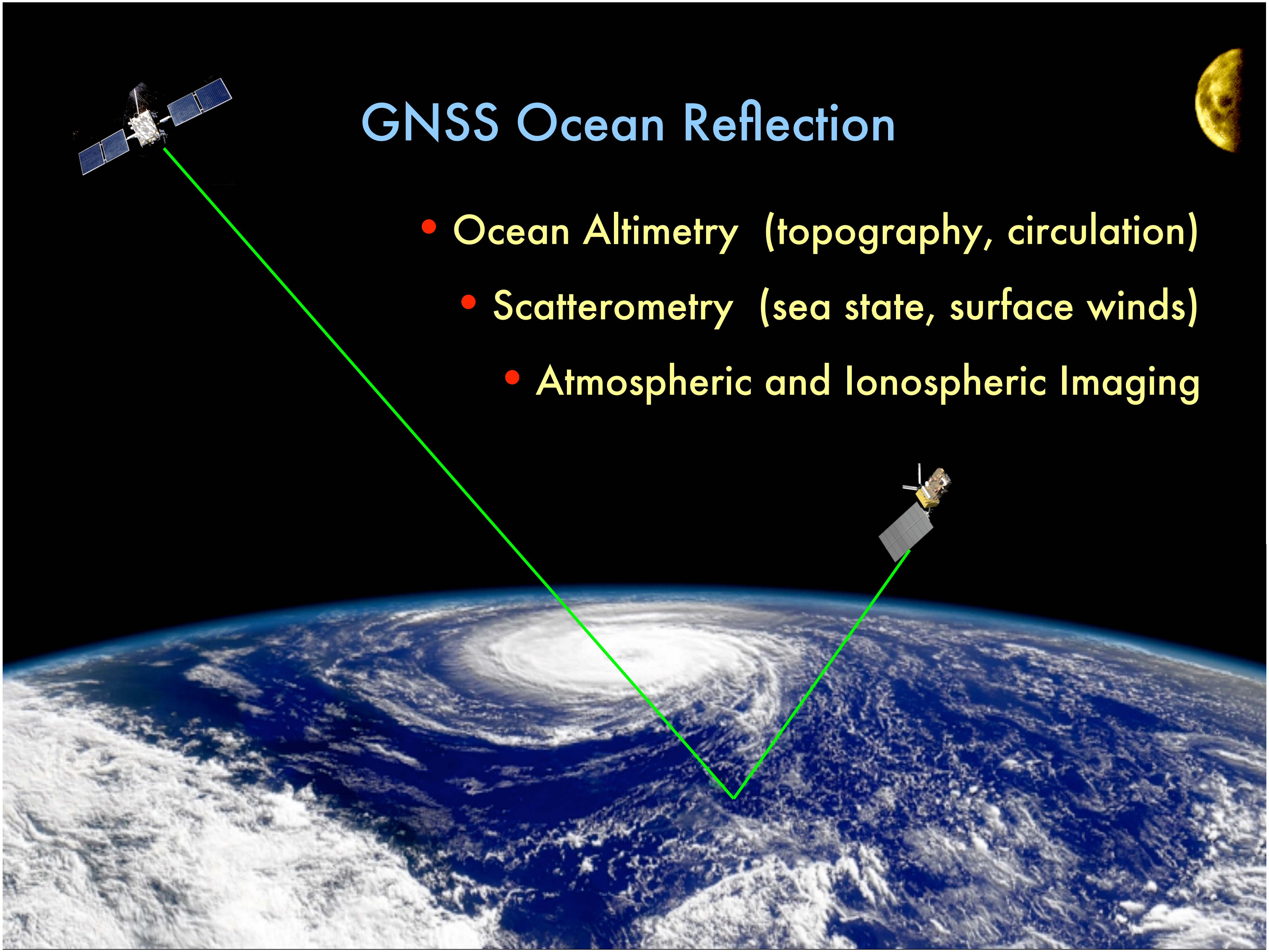


Sun-Earth Connections
Living With a Star
Space Weather

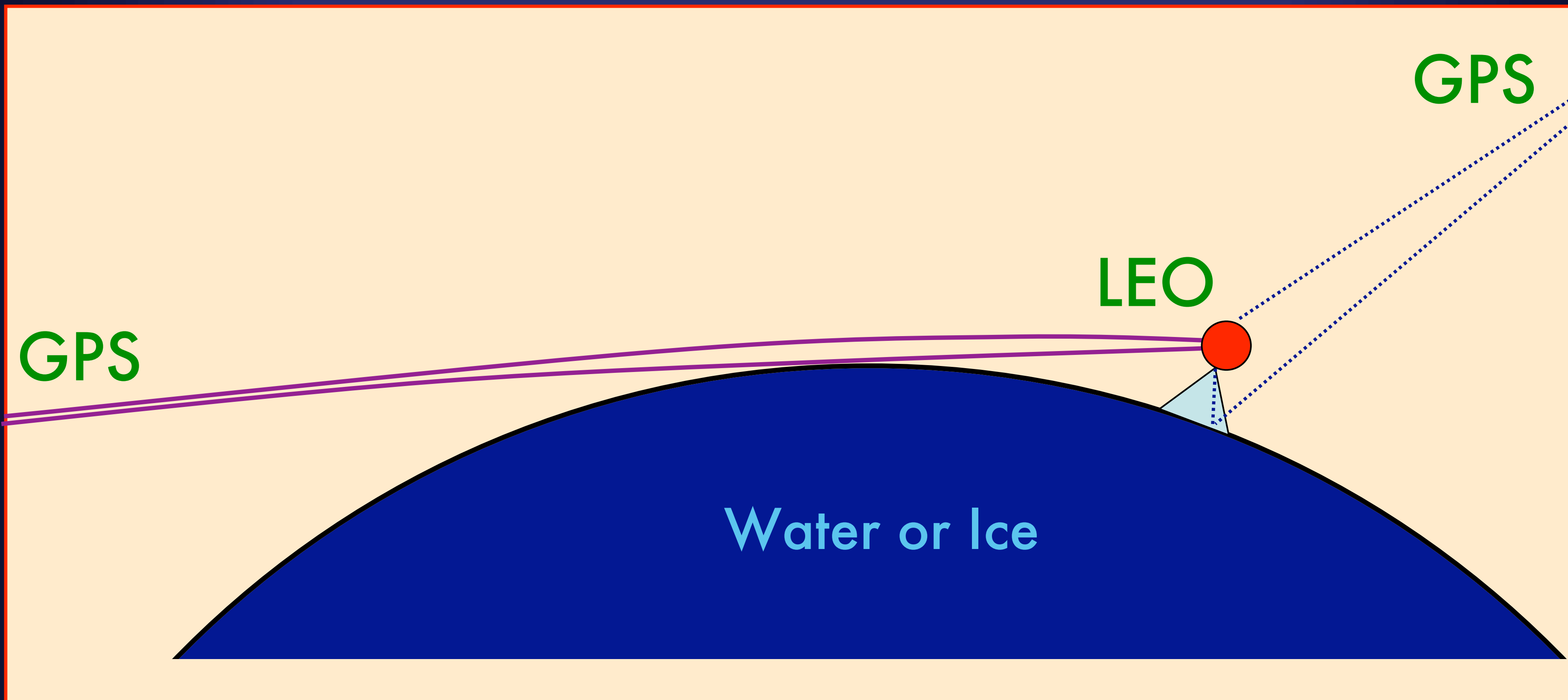
Applications

- Observe ionospheric dynamics and refine models
- Chart the course and evolution of space storms
- Provide near term prediction of space weather
- Study TIDs and global energy transport
- Probe iono-thermo-atmosphere interactions

Ocean Reflections Too!

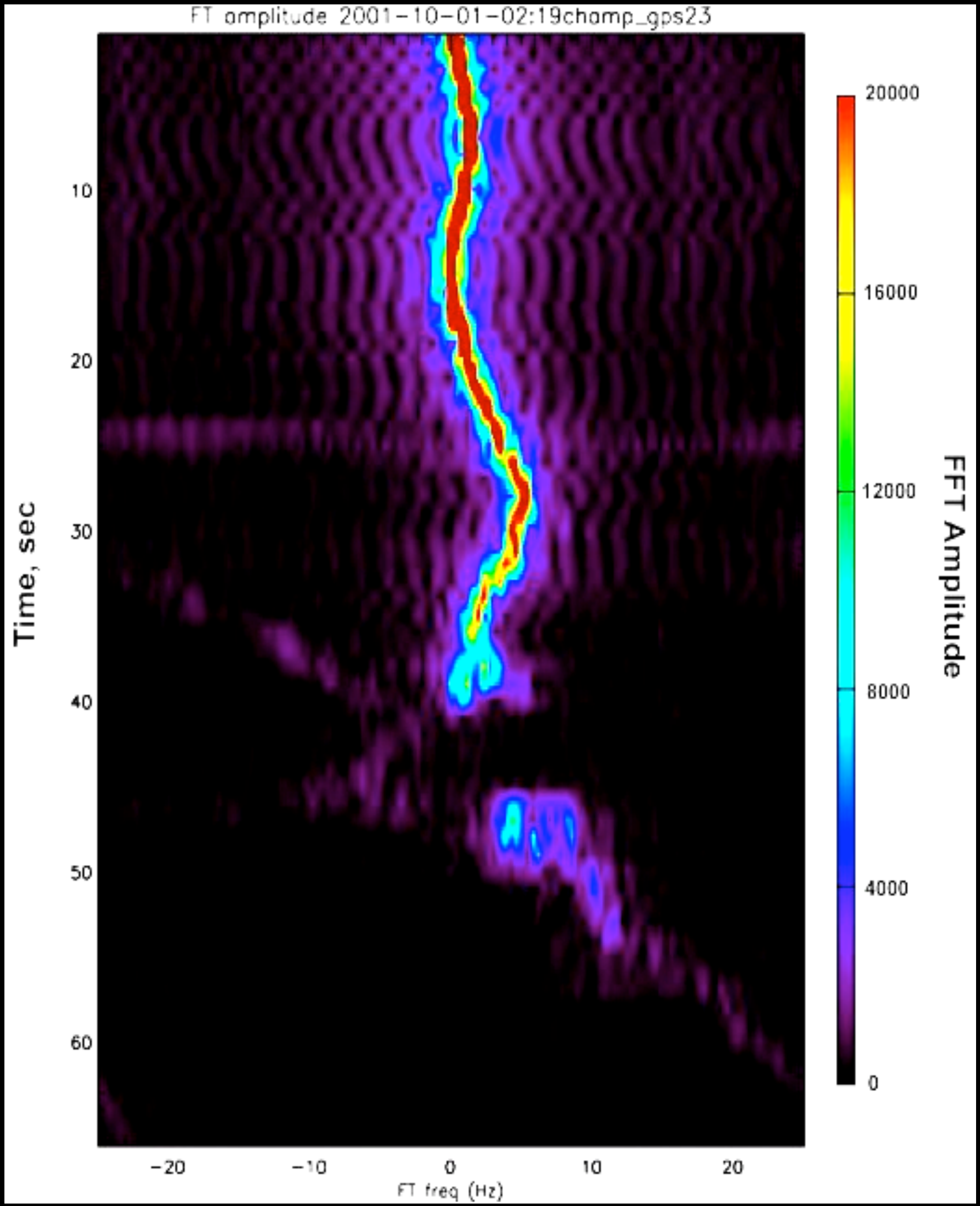

GNSS Ocean Reflection
• Ocean Altimetry (topography, circulation)
• Scatterometry (sea state, surface winds)
• Atmospheric and Ionospheric Imaging

Reflections from All Directions



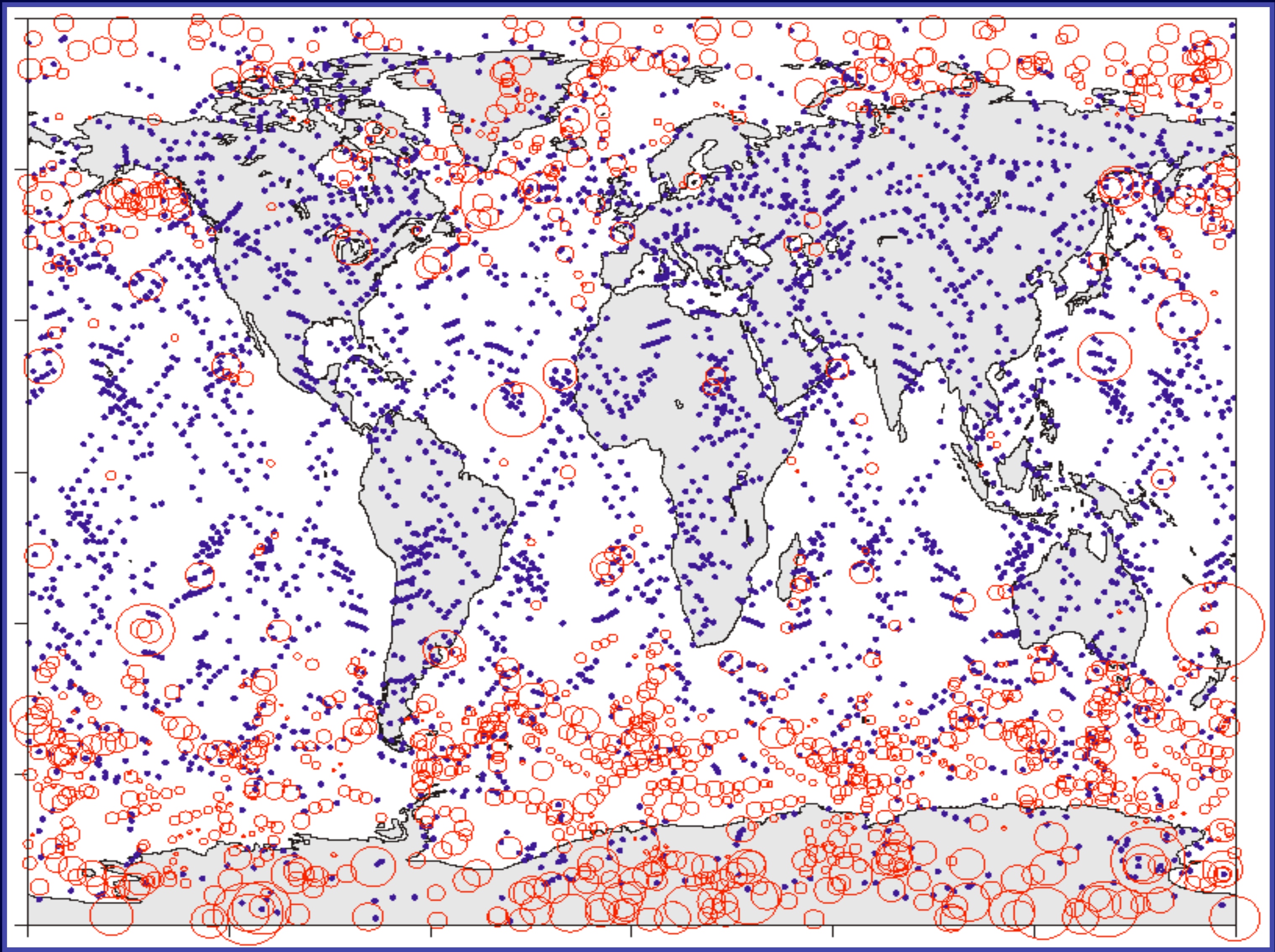
Reflections at nadir are difficult
Reflections at horizon are easy

Anatomy of a CHAMP Occultation



Hajj et al., 2004

Reflections at Horizon Viewed with CHAMP Occultation Antenna

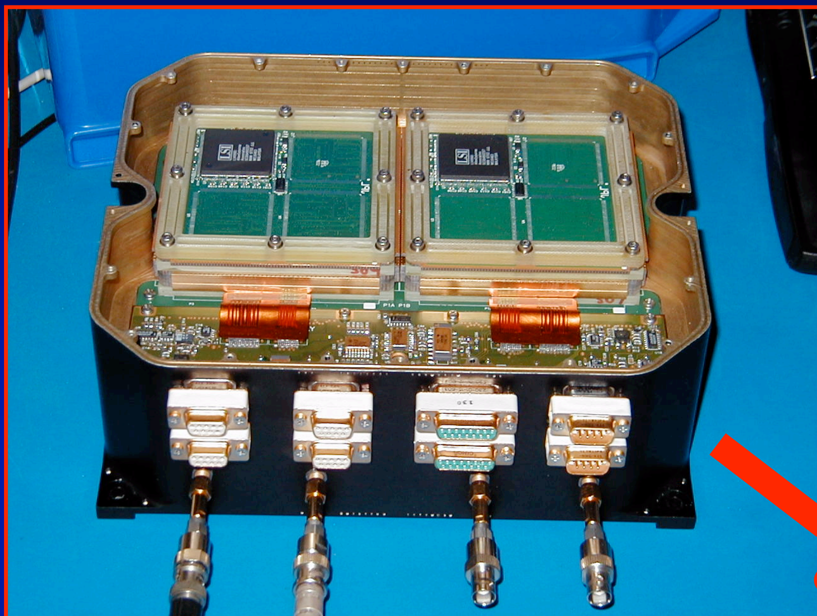


From Beyerle et al. (2002)

○ Indicates observed reflection

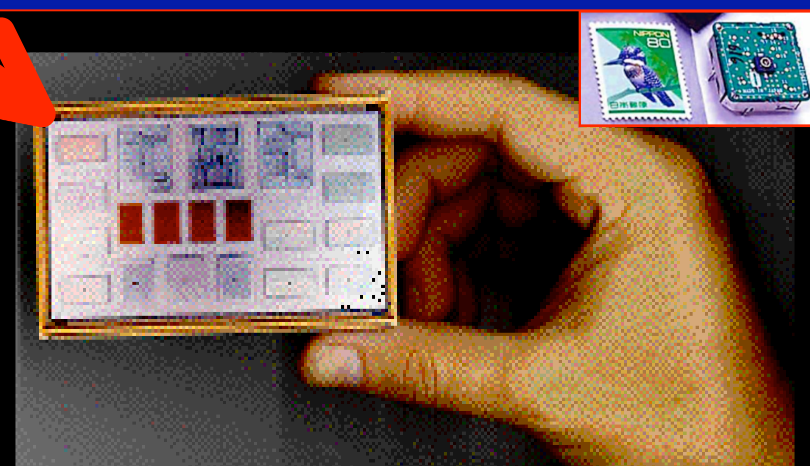
Looking Ahead

NASA's BlackJack Flight Receivers



Dual stack, 4-antenna layout for Champ and SAC-C

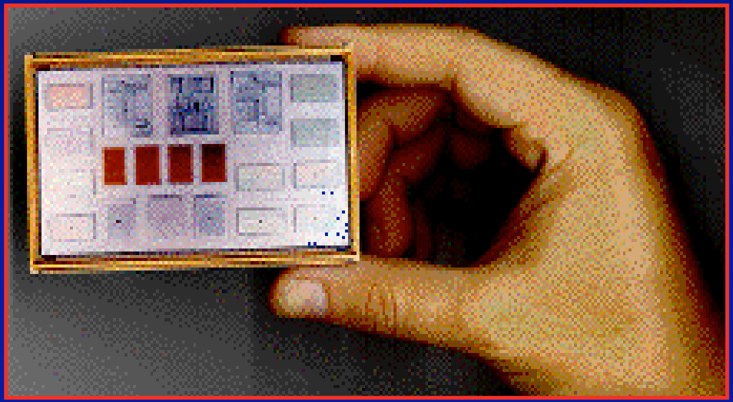
Single stack, single antenna receiver for Jason, ICESat, VCL, and FedSat



The Next Generation?

Extended Functions

- Real-time position, velocity, attitude, and time
- Uplink reception
- Embedded transmitter
- On-board mass storage



Future receiver concept

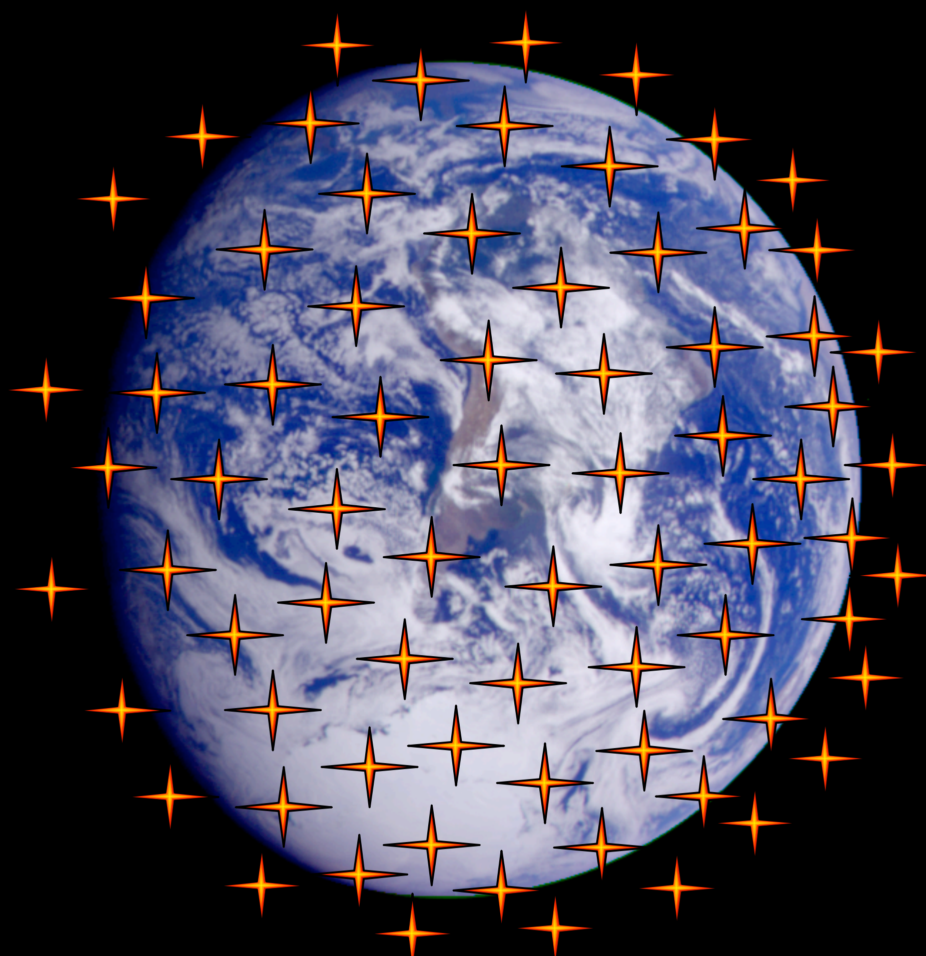
- On-board spacecraft computing and control
- Science: atmosphere, ionosphere, oceans, ...

International Space Station


INTERNATIONAL SPACE STATION
"Houston, can it play
Region 5 Russian discs?"
SONY

Cellular Interferometer for Continuous Earth Remote Observation

CICERO



END

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