Solar System Objects

Bryan Butler

National Radio Astronomy Observatory

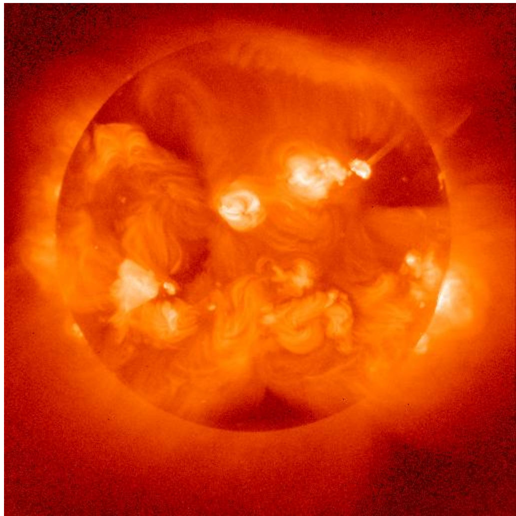
Atacama Large Millimeter/submillimeter Array

Expanded Very Large Array

Robert C. Byrd Green Bank Telescope

Very Long Baseline Array

Solar System Bodies



- Sun
- IPM
- Giant planets
- Terrestrial planets
- Moons
- Small bodies

Why Interferometry?

resolution, resolution, resolution!

maximum angular extent of some bodies:

Sun & Moon - 0.5°
Venus – 60”
Jupiter – 50”
Mars – 25”
Saturn – 20”
Mercury – 12”
Uranus – 4”
Neptune - 2.4”

Galilean Satellites - 1-2”
Titan – 1”
Triton - 0.1”
Pluto - 0.1”
MBA - .05 - .5”
NEA, KBO - 0.005 - 0.05”

(interferometry also helps with confusion!)

Solar System Oddities

Radio interferometric observations of solar system bodies are similar in many ways to other observations, including the data collection, calibration, reduction, etc…

So why am I here talking to you? In fact, there are some differences which are significant (and serve to illustrate some fundamentals of interferometry).

Differences

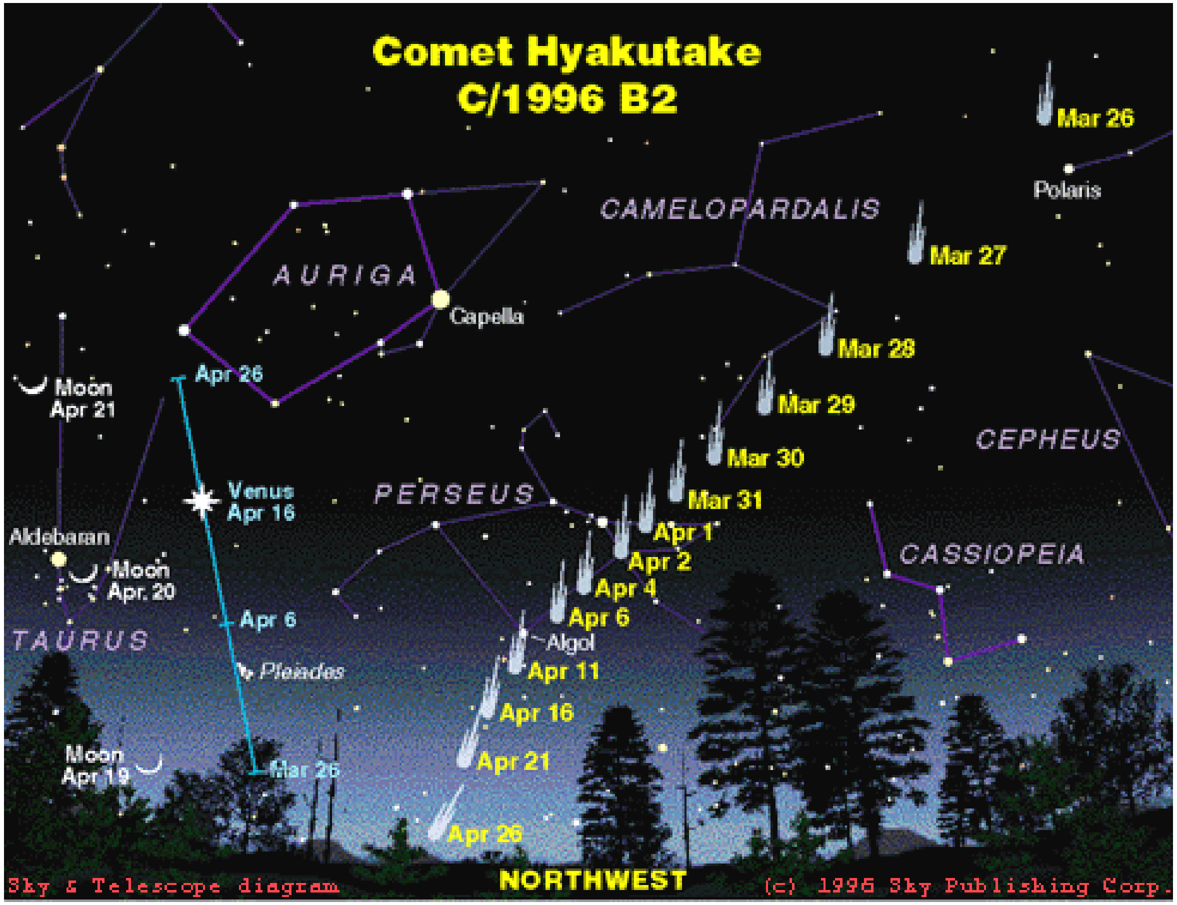
- Object motion
- Time variability
- Confusion
- Scheduling complexities
- Source strength
- Coherence
- Source distance
- Knowledge of source
- Optical depth

Object Motion

All solar system bodies move against the (relatively fixed) background sources on the celestial sphere. This motion has two components:

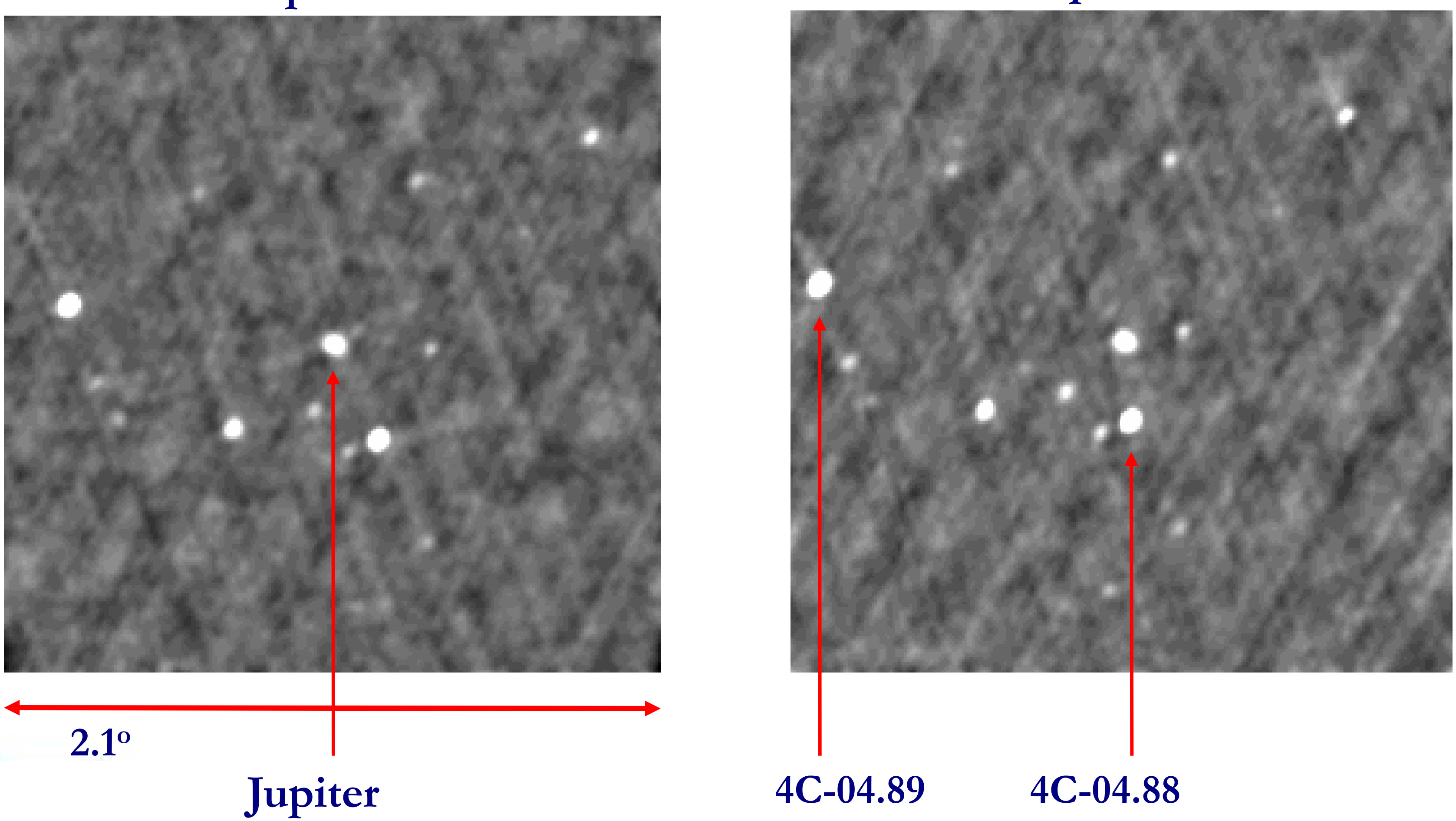
- "Horizontal Parallax" - caused by rotation of the observatory around the Earth.
- "Orbital Motions" - caused by motion of the Earth and the observed body around the Sun.

Object Motion - an example



Object Motion - a practical example

1998 September 19 **1998 September 20**



de Pater & Butler 2003

Time Variability

Time variability is a significant problem in solar system observations:

- Sun - very fast fluctuations (< 1 sec)
- Jupiter, Venus (others?) – lightning (< 1 sec)
- Others - rotation (hours to days), plus other intrinsic variability (clouds, seasons, etc.)
- Distance may change appreciably (need "common" distance measurements)

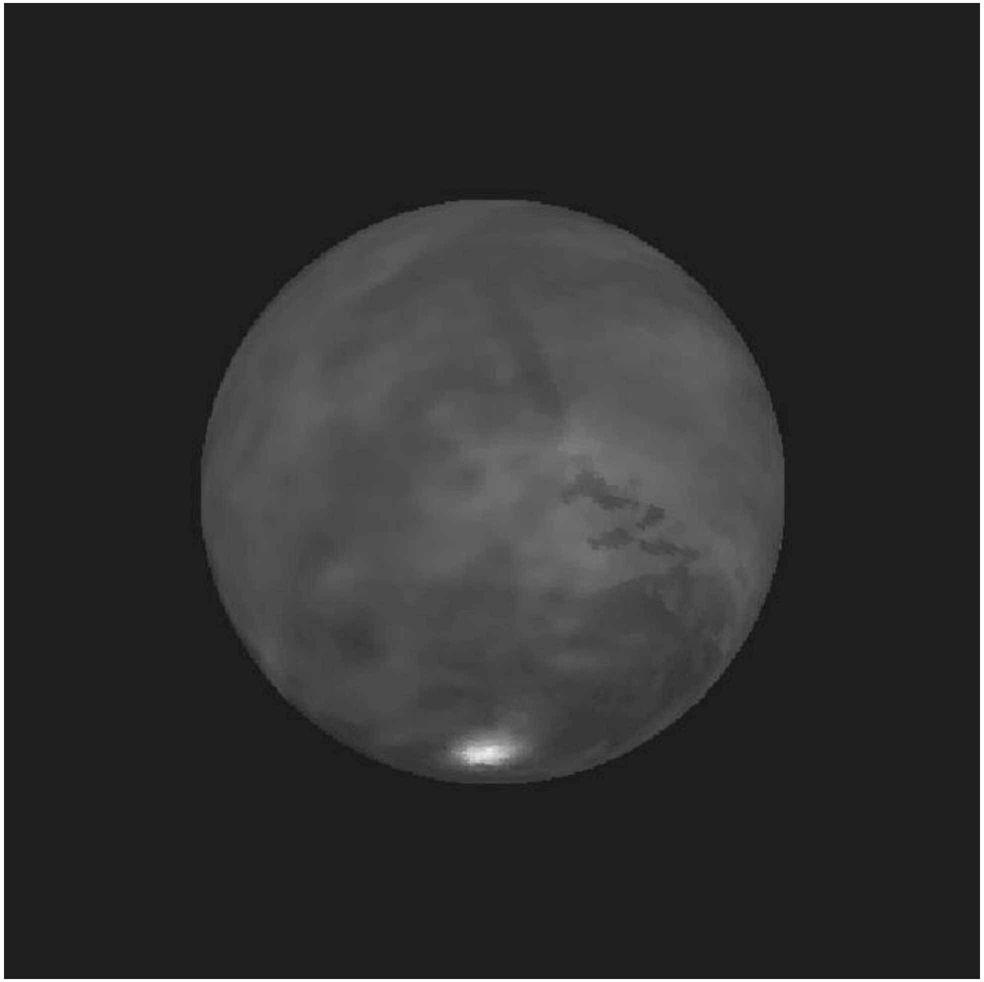
These must be dealt with.

Time Variability - an example

Mars radar

snapshots made every 10 mins

Butler, Muhleman & Slade 1994



Implications

- Often can’t use same calibrators
- Often can’t easily add together data from different days
- Solar confusion
- Other confusion sources move in the beam
- Antenna and phase center pointing must be tracked (must have accurate ephemeris)
- Scheduling/planning - need a good match of source apparent size and interferometer spacings

Source Strength

Some solar system bodies are very bright. They can be so bright that they raise the antenna temperature:

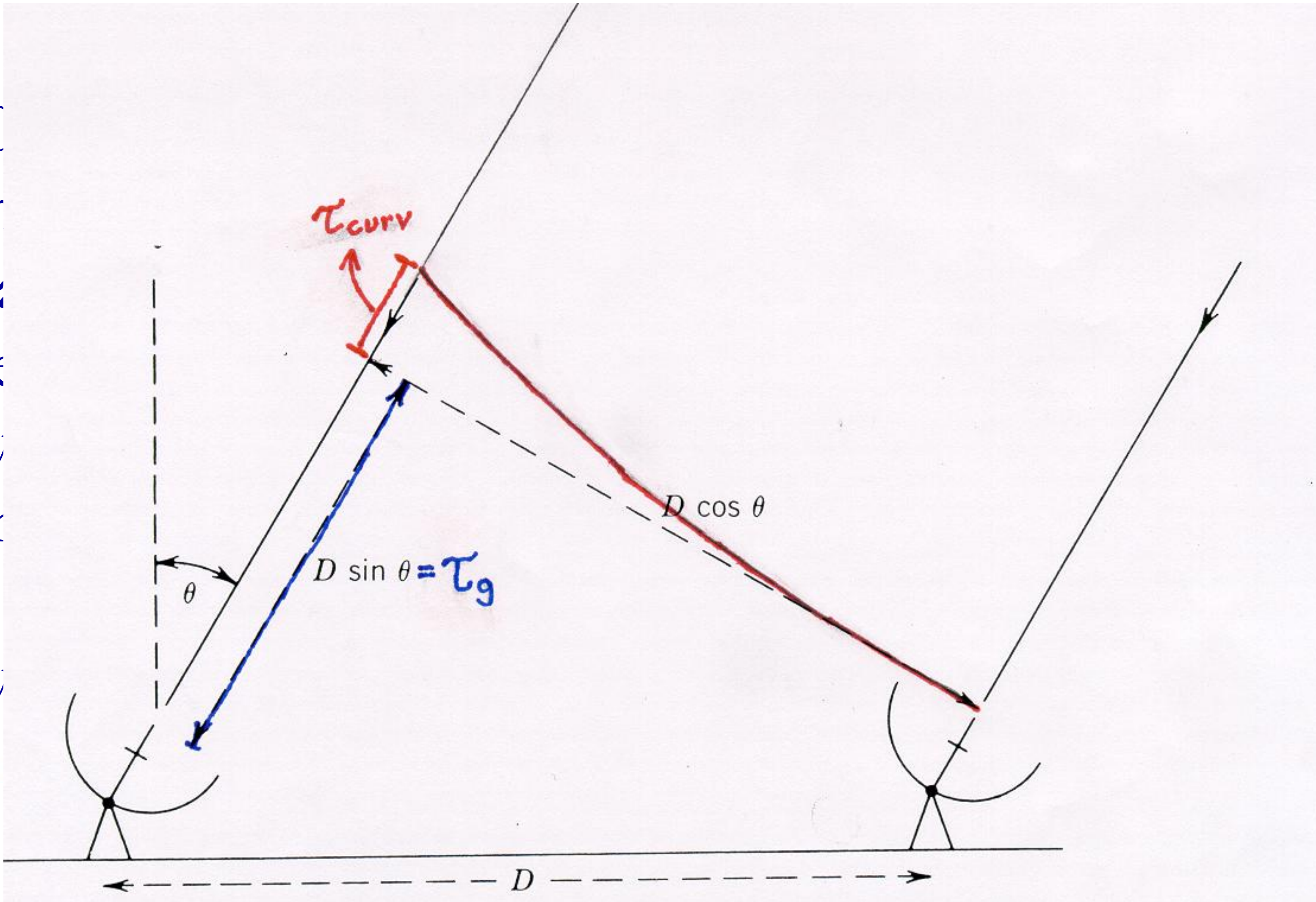
- Sun ~ 6000 K (or brighter)
- Moon ~ 200 K
- Venus, Jupiter ~ 1-100s of K

In the case of the Sun, special hardware may be required. In other cases, special processing may be needed (e.g., Van Vleck correction). In all cases, the system temperature (the noise) is increased.

Coherence

Some types of emission from the Sun are coherent. In addition, reflection from planetary bodies in radar experiments is coherent (over at least part of the image). This complicates greatly the interpretation of images made of these phenomena, and in fact violates one of the fundamental assumptions in radio interferometry.

Source Distance - Wave Curvature



Short Spacing Problem

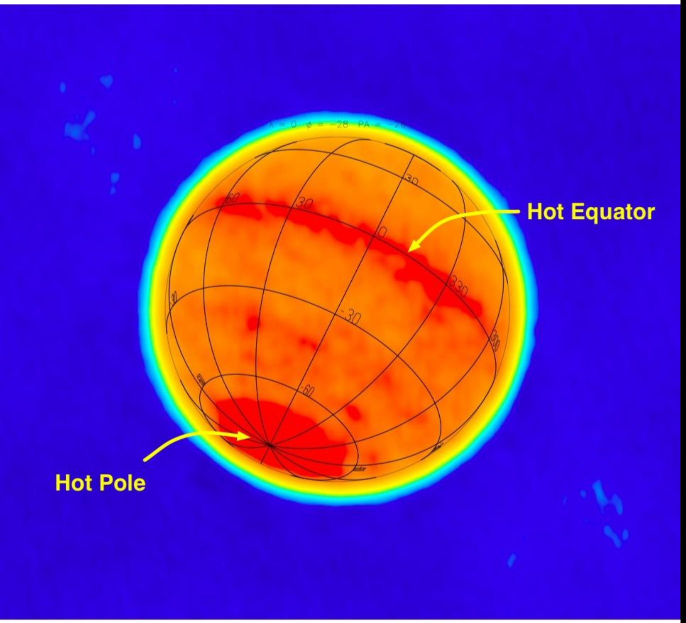
As with other large, bright objects, there is usually a serious short spacing problem when observing the planets. This can produce a large negative "bowl" in images if care is not taken. This can usually be avoided with careful planning, and the use of appropriate models during imaging and deconvolution.

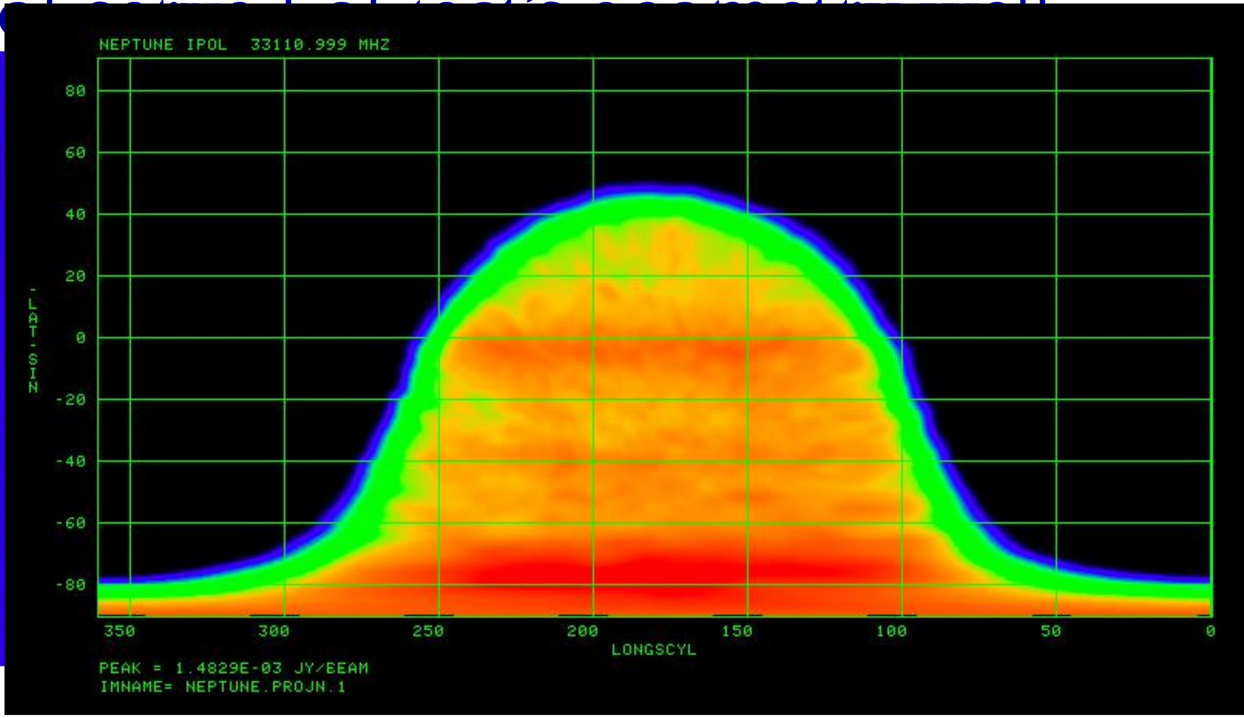
Source Knowledge

There **is** an advantage in most solar system observations - we have a very good idea of what the general source characteristics are, including general expected flux densities and extent of emission. This can be used to great advantage in the imaging, deconvolution, and self-calibration stages of data reduction.

Conversion of Coordinates

If we know the



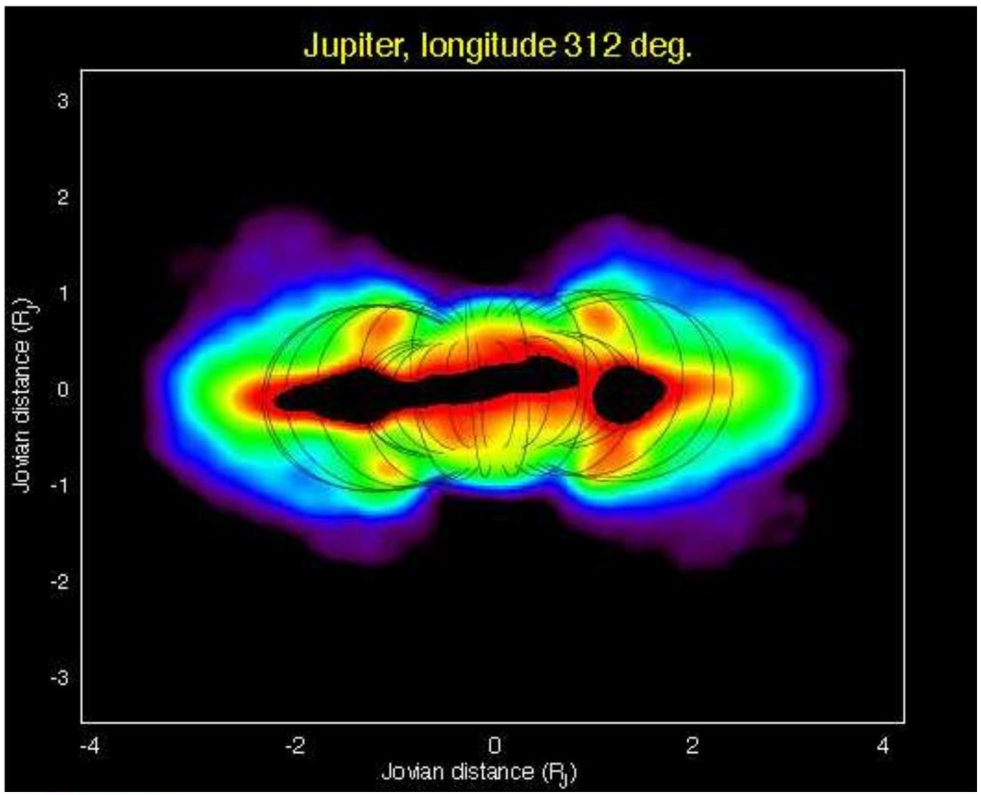


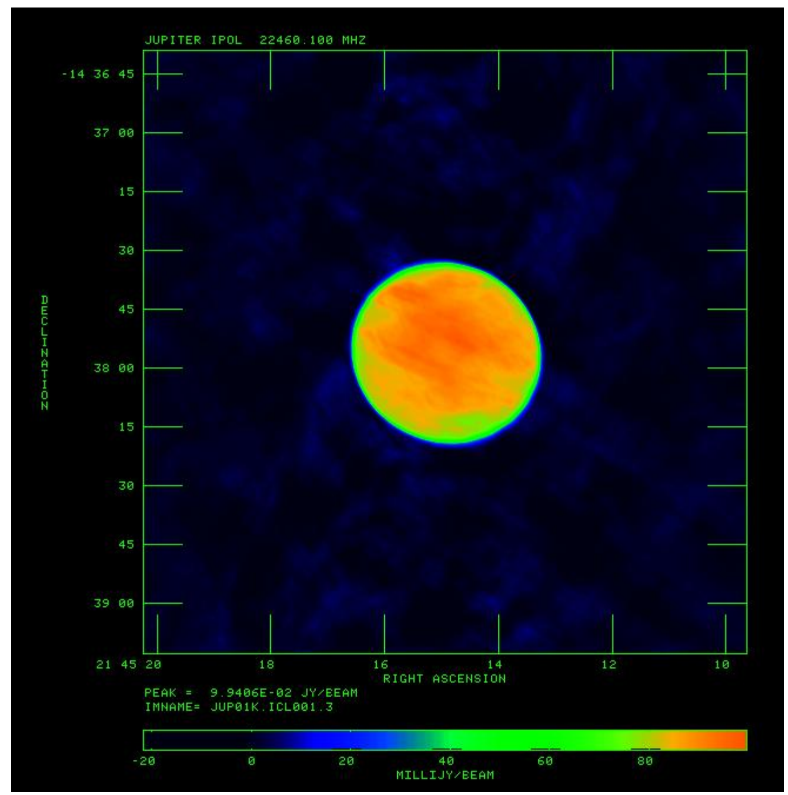
Correcting for Rotation

If a planet rotates rapidly, we can either just live with the "smearing" in the final image (but note also that this violates our assumption about sources not varying), or try to make snapshots and use them separately (difficult in most cases because SNR is low). There are now two techniques to try to solve this problem; one for optically thin targets like Jupiter synchrotron radiation (Sault et al. 1997; Leblanc et al. 1997; de Pater & Sault 1998), one for optically thick targets (described in Sault et al. 2004). This is possible because we know the viewing geometry and planetary cartographic systems precisely.

Correcting for Rotation - Jupiter

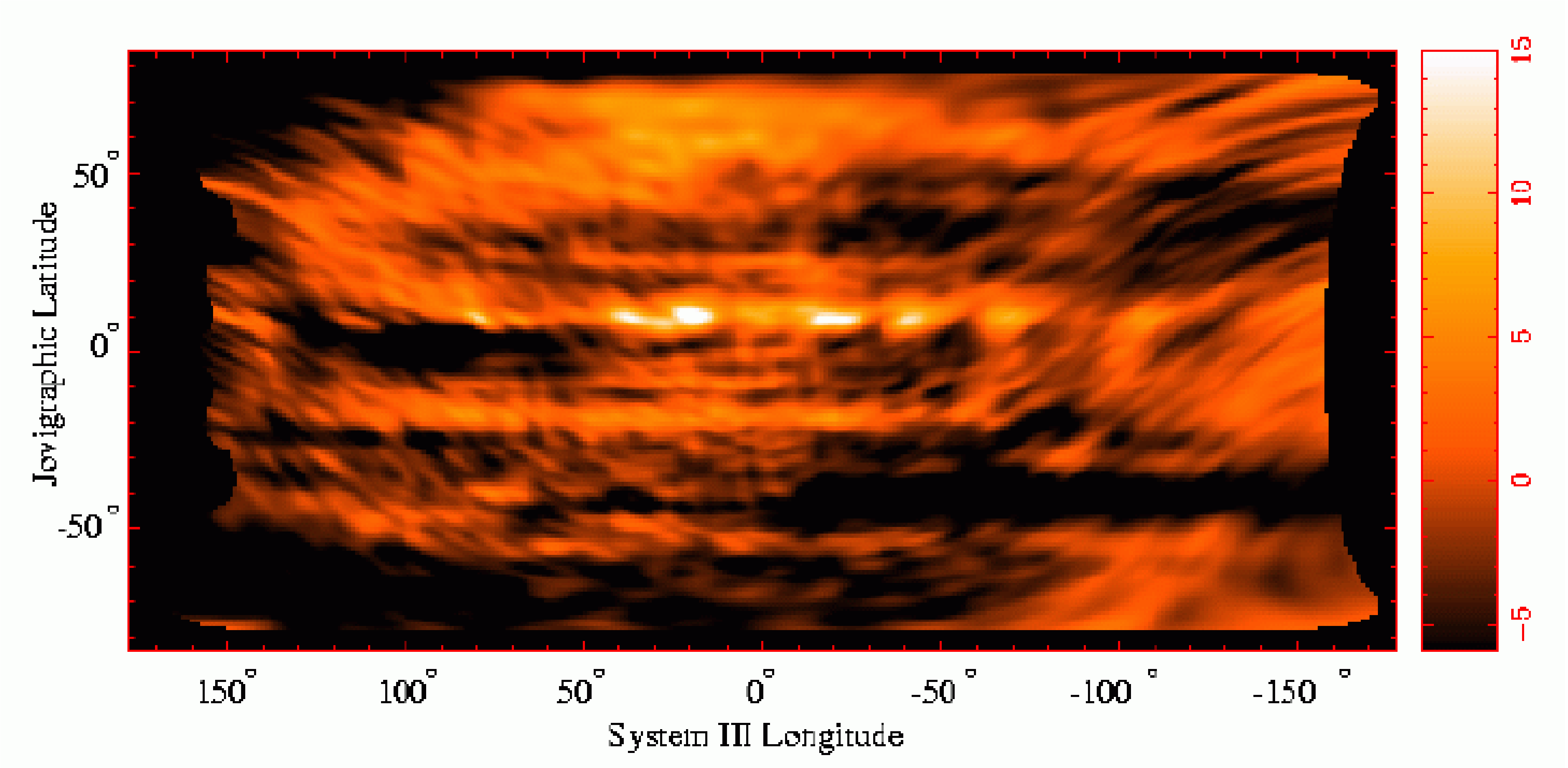
Jupiter at 20 cm (de Pater et al. 1997) and 1.3 cm (Butler et al. 2009) averaged over full track (period is ~10h):





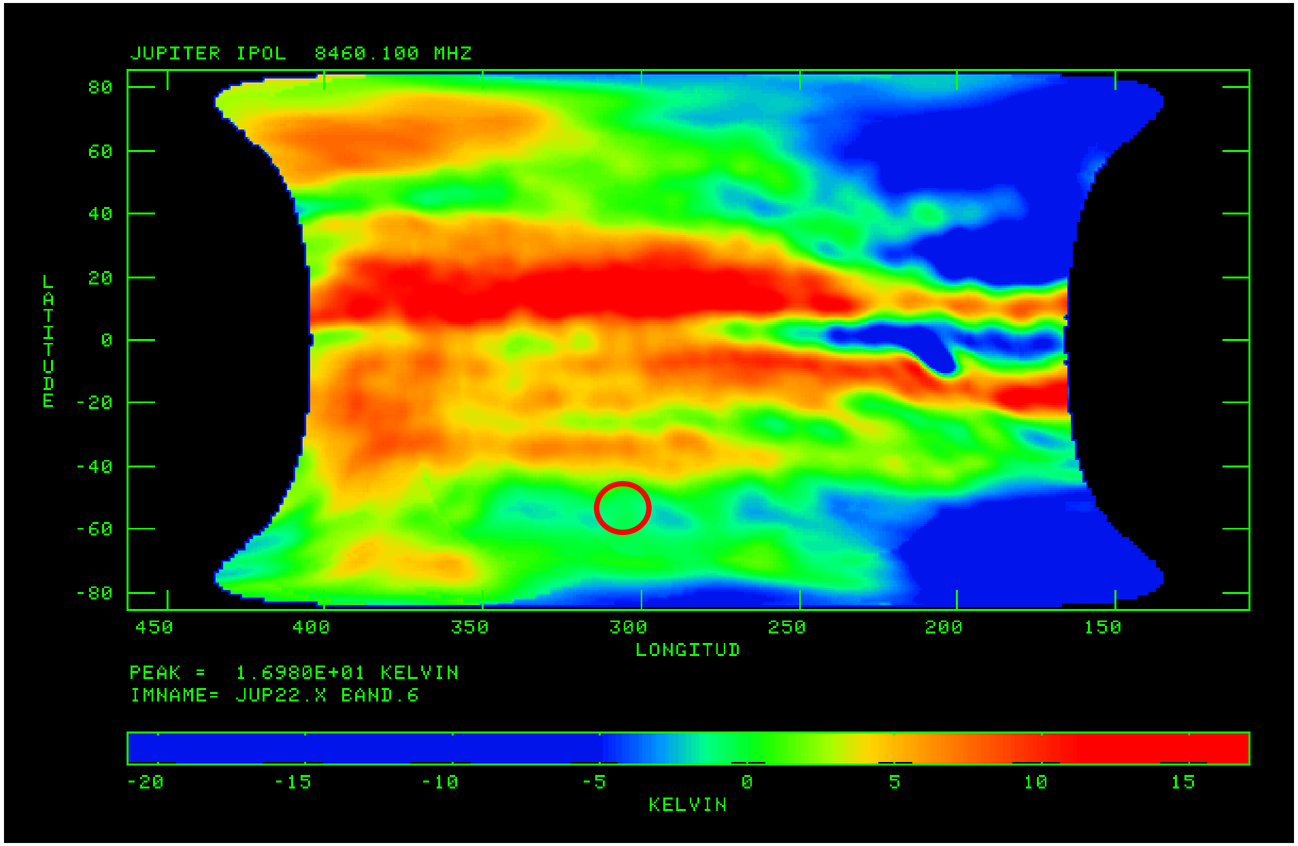
Correcting for Rotation - Jupiter

Jupiter at 2cm from several tracks - Sault et al. 2004:



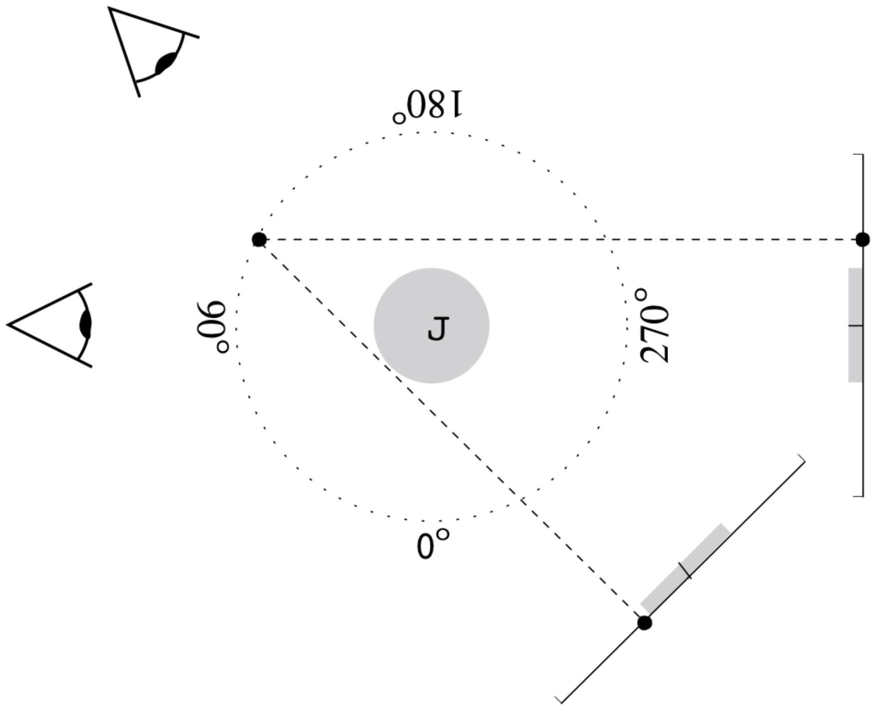
Correcting for Rotation - Jupiter

Jupiter at 3.5cm from four tracks - Butler et al. 2009 (looking for the signature of the impact into Jupiter in summer 2009):

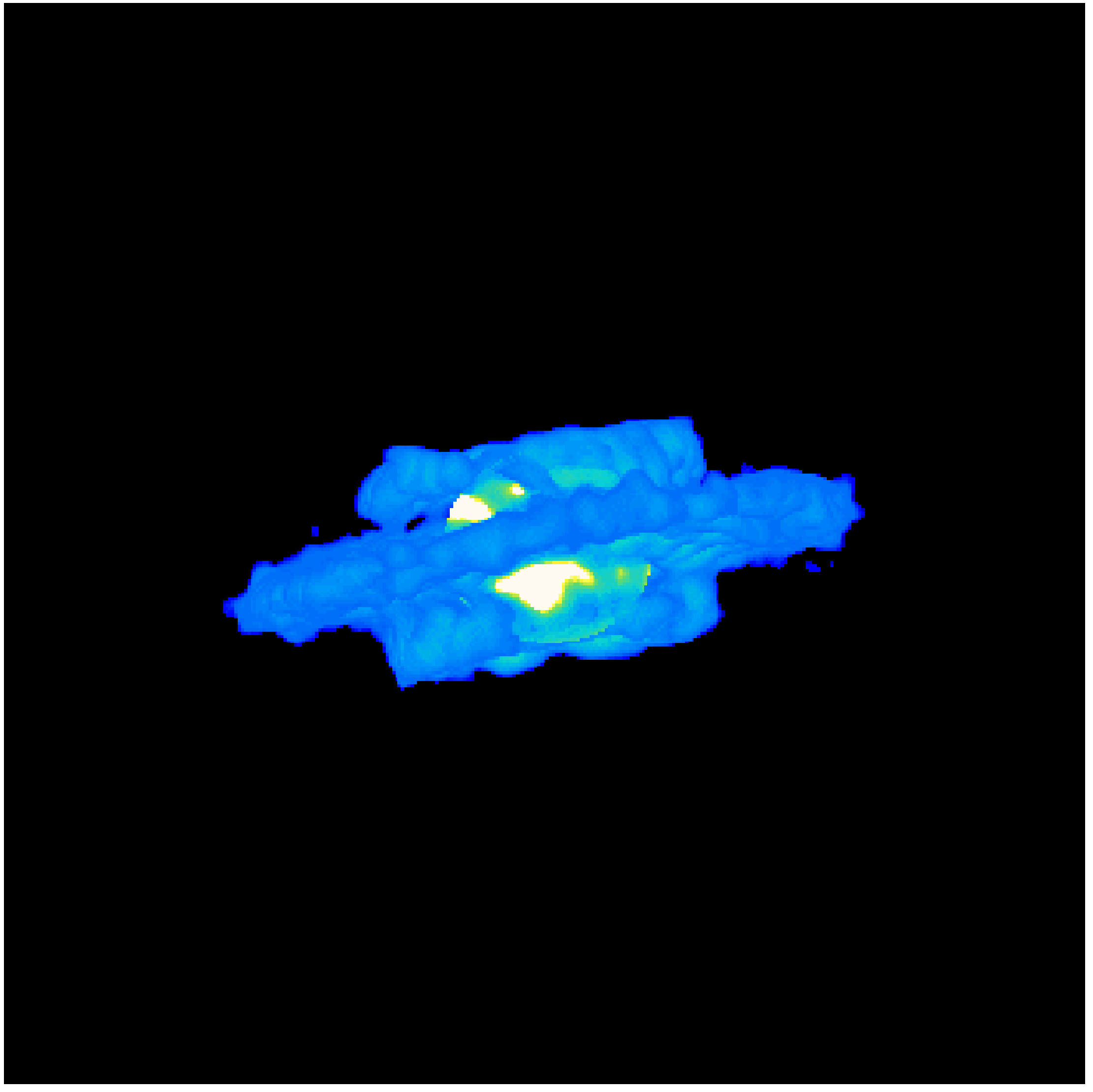


Correcting for Rotation - Jupiter

If the emission mechanism is optically thin (this is only the case for the synchrotron emission), then we can make a full 3-D reconstruction of the emission:



Correcting for Rotation - Jupiter

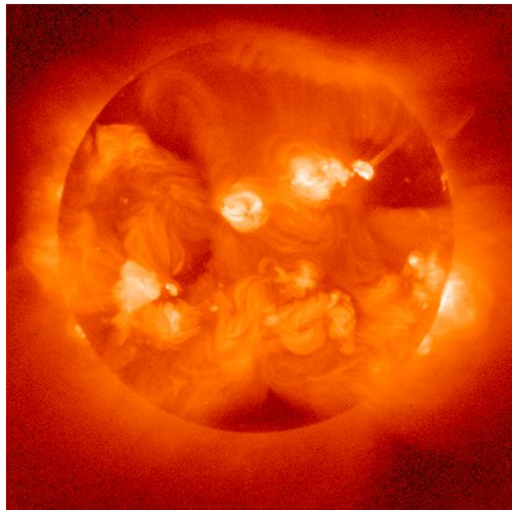


Lack of Source Knowledge

If the true source position is not where the phase center of the instrument was pointed, then a phase error is induced in the visibilities.

If you don't think that you knew the positions beforehand, then the phases can be "fixed". If you think you knew the positions beforehand, then the phases may be used to derive an offset.

Real Data - what to expect



But…

Real Data - what to expect

If the sky brightness is circularly symmetric, then the 2-D Fourier relationship between sky brightness and visibility reduces to a 1-D Hankel transform:

$$V(q) = 2\pi R \int_0^R A(r)I(r)J_0(2\pi rq)r\,dr$$

For a "uniform disk" of total flux density F, this reduces to:

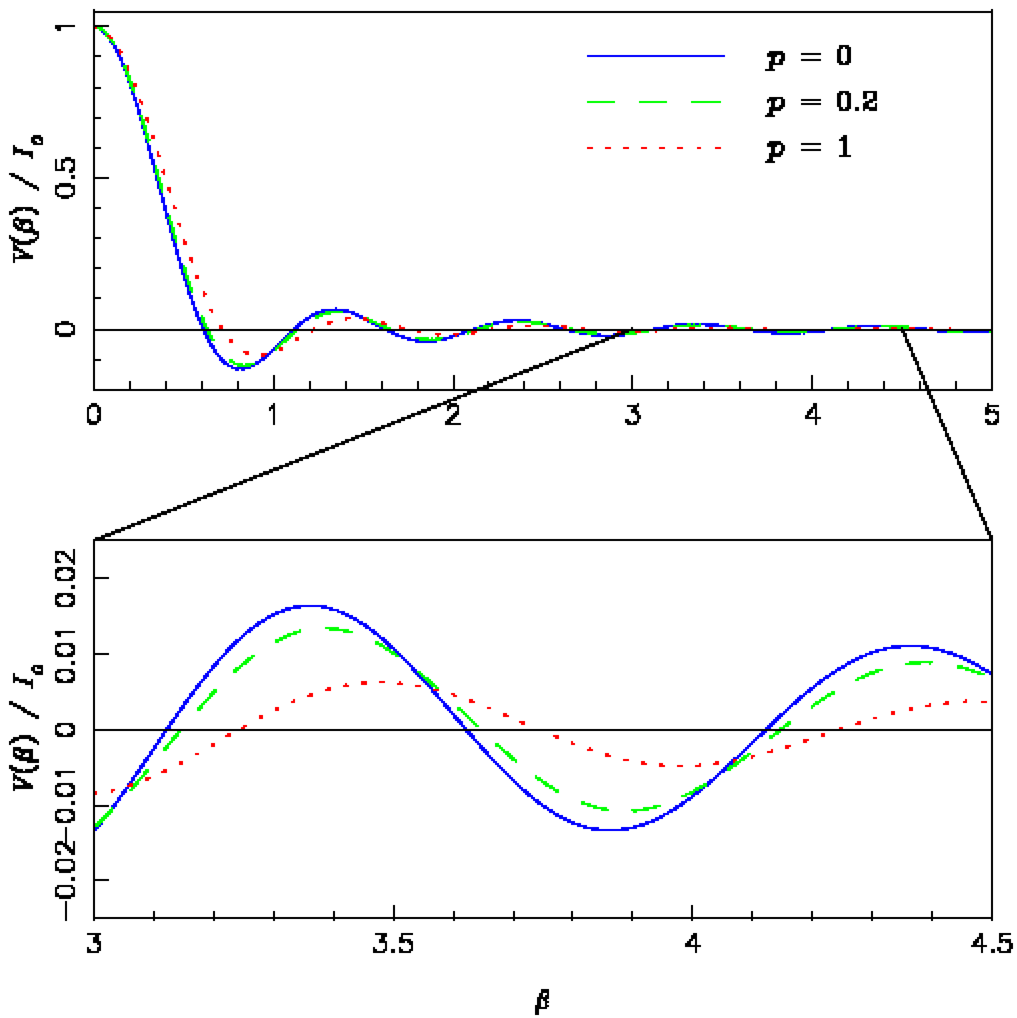
$$V(\beta) = F\pi R^2 \frac{J_1(2\pi\beta)}{\pi\beta}$$

and for a "limb-darkened disk" (of a particular form), this reduces to:

$$V(\beta) = F\pi R^2 \Lambda_q(2\pi\beta)$$

Real Data - what to expect

Theoretical visibility functions for a circularly symmetric "uniform disk" and 2 limb-darkened disks.



Real Data - polarization

For emission from solid surfaces on planetary bodies, the relationship between sky brightness and *polarized* visibility becomes (again assuming circular symmetry) a different Hankel transform (order 2):

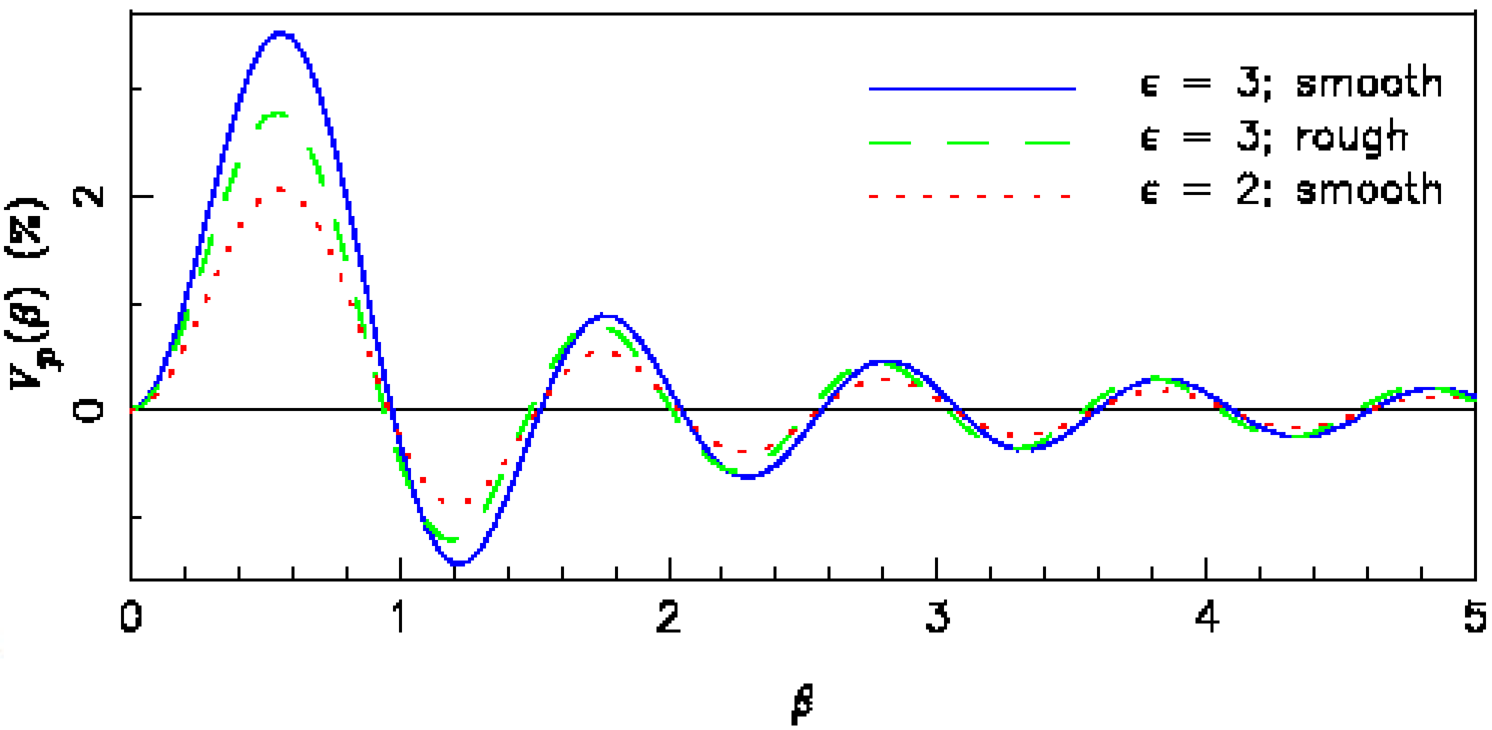
$$V_p(\beta) = \int_0^1 A(\rho)(R_{\parallel} - R_{\perp}) J_2(2\pi\rho\beta)\rho \, d\rho$$

this cannot be solved analytically. Note that roughness of the surface is a confusion (it modifies the effective Fresnel reflectivities). For circular measured polarization, this visibility is formed via:

$$V_p = \frac{\Re\{V_{RL} + V_{LR}\}\cos 2\psi + \Im\{V_{RL} - V_{LR}\}\sin 2\psi}{V_0}$$

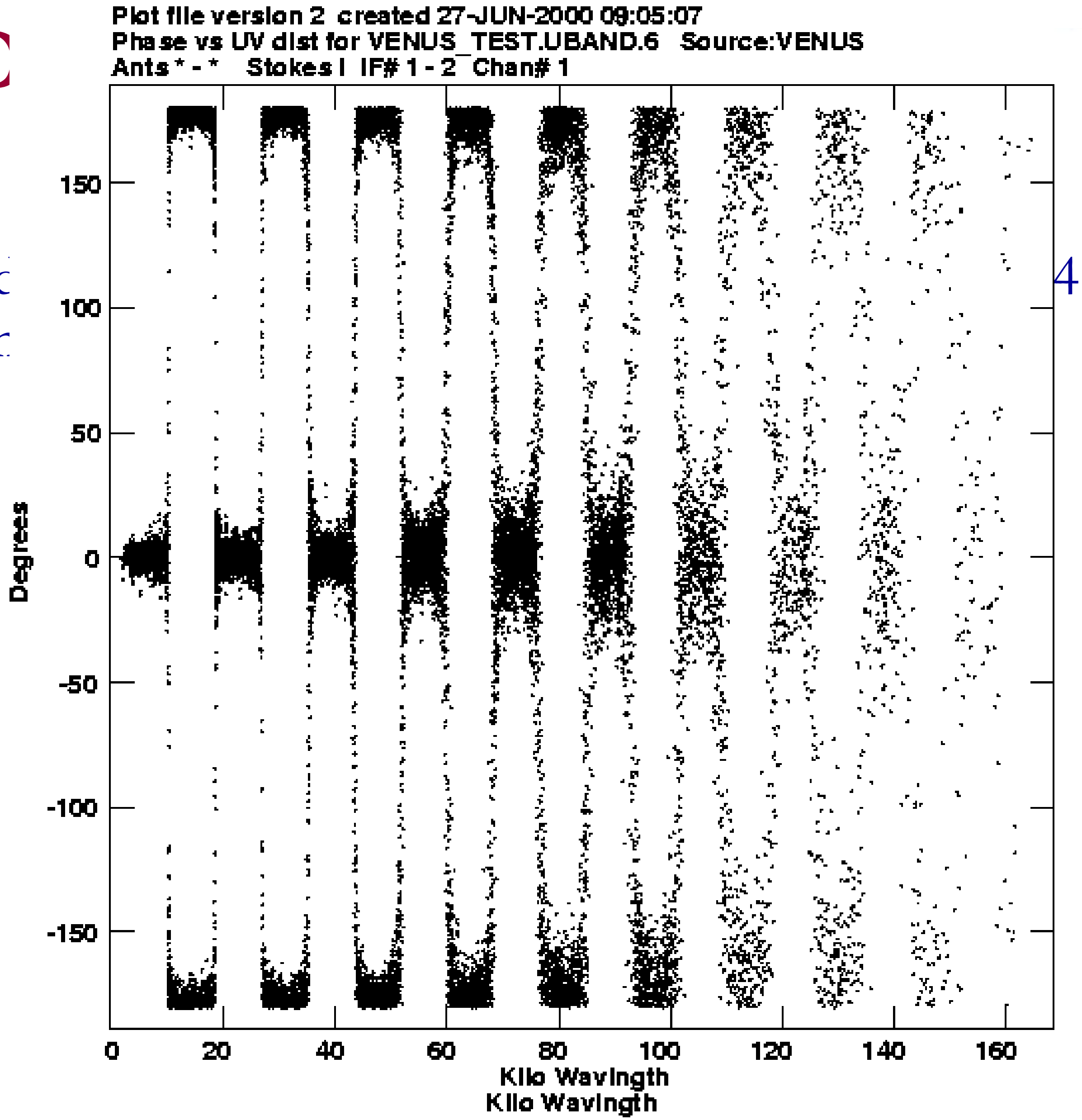
Real Data - polarization

Examples of expected polarization response:



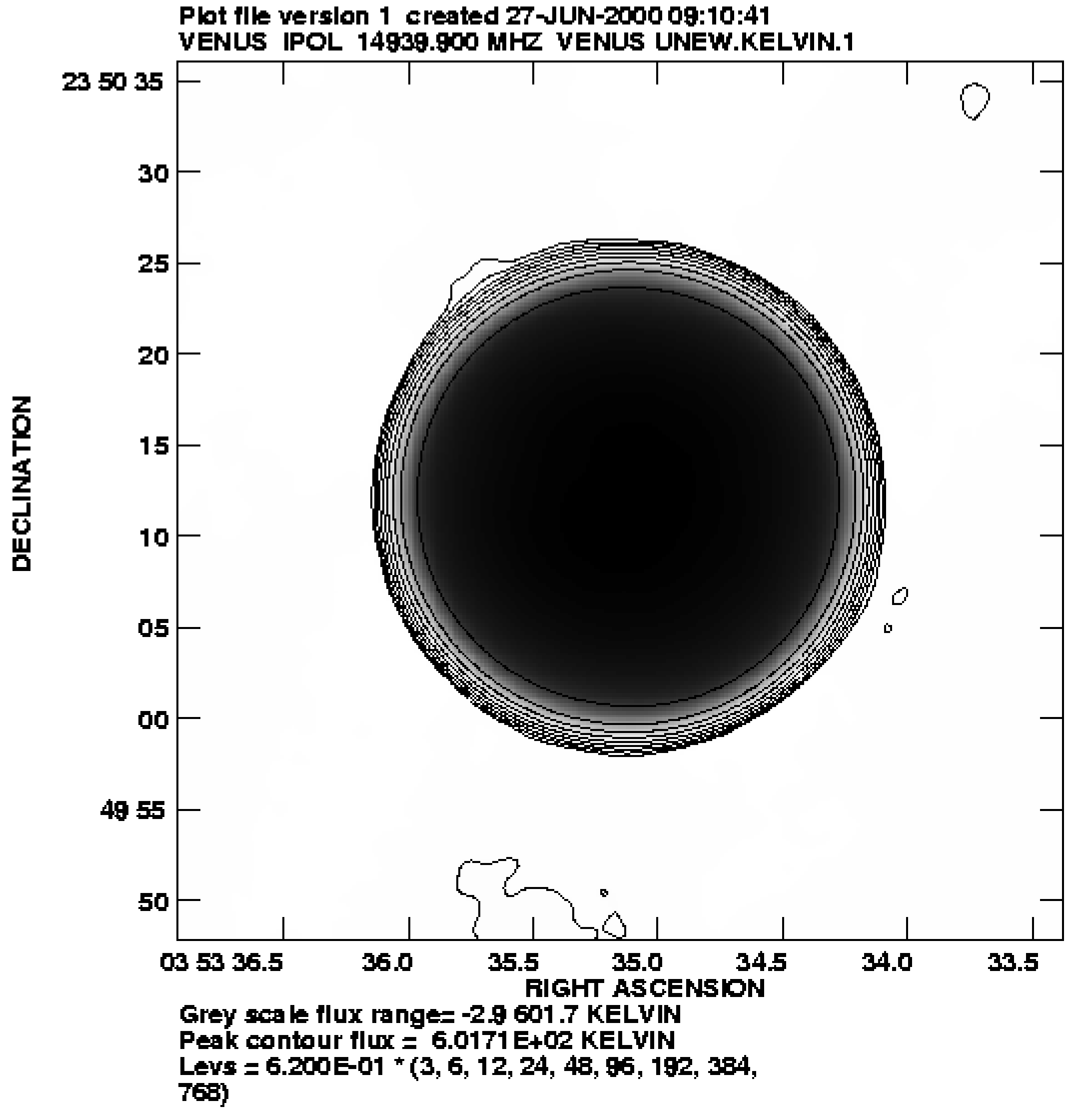
Real D

Visibility c... 4 AU
distance ir...



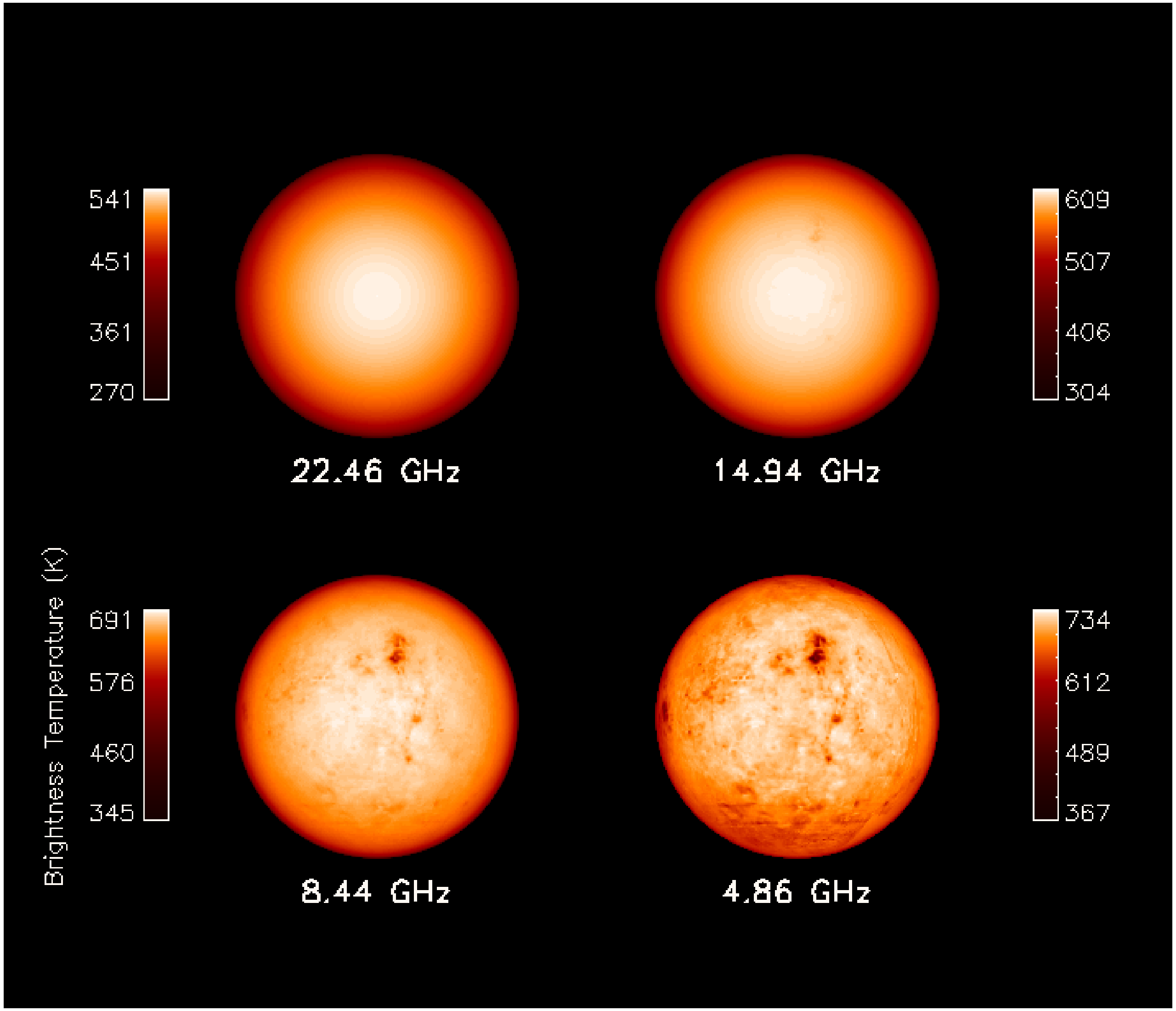
Real Data - an example

The resultant image:



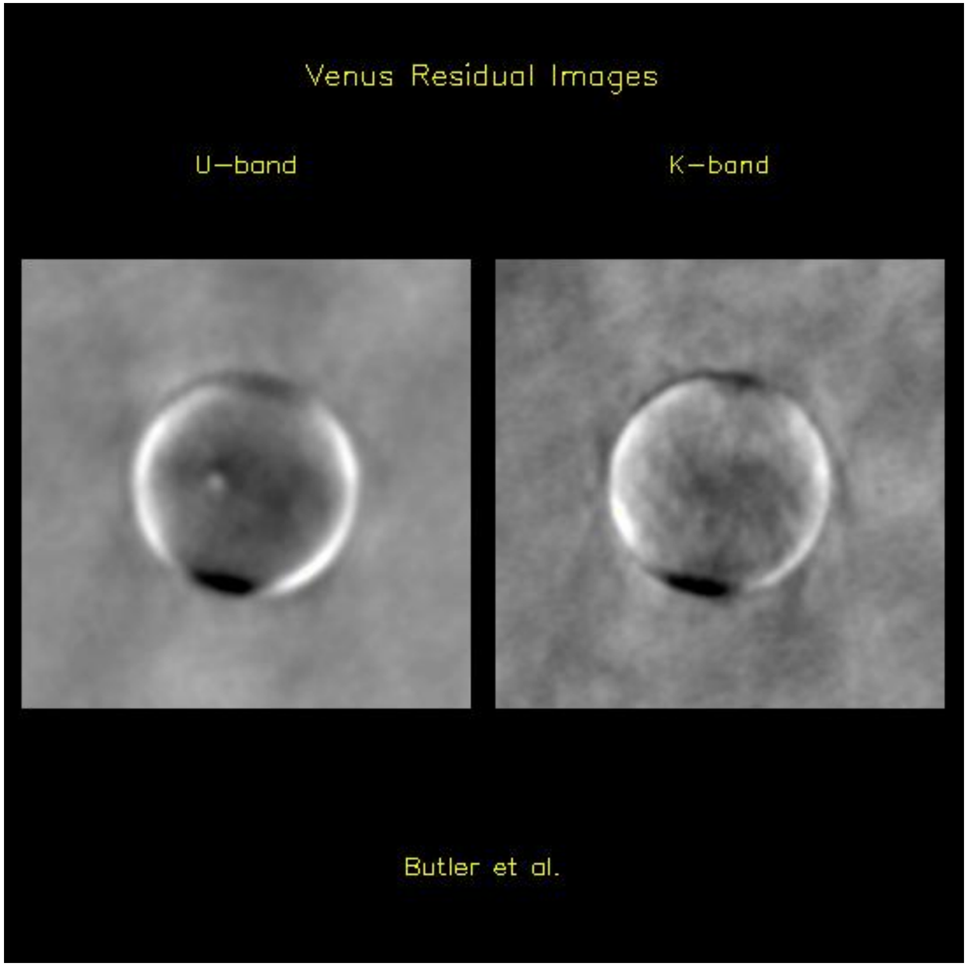
Real Data - an example

Venus models at C, X, Ku, and K-bands:



Real Data - an example

Venus residual images at U- and K-bands:



Real Data - a polarization example

Mitchell & de Pater (1994) observations of Mercury showing the polarization pattern on the sky: