# Solar System Objects

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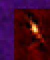
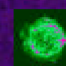
## What kinds of things do we observe with the VLA?

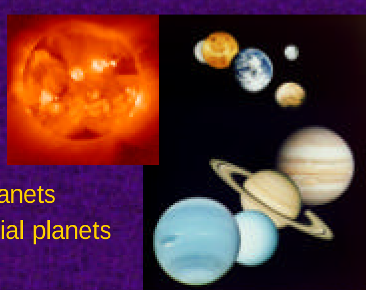

45% - Extragalactic


20% - Galactic


30% - Stellar


5% - Solar system

## Solar System "Bodies"



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

## Planetary Radio Astronomy

**Observation of radio wavelength radiation which has interacted with a solar system body in any way, and use of the data to deduce information about the body:**

- **spin/orbit state**
- **surface and subsurface properties**
- **atmospheric properties**
- **magnetospheric properties**
- **ring properties**

**Types of radiation:**

- **thermal emission**
- **reflected emission (radar or other)**
- **synchrotron emission**
- **occultations**

## 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"**

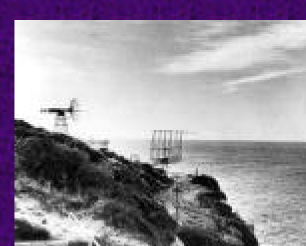
**Galilean Satellites - 1-2"**
**Titan - 1"**
**Ceres - 0.7"**
**Triton - 0.1"**
**Pluto - 0.1"**

**Thetis - .07"**
**Geographos - 0.06"**
**1996 TO66 - 0.025"**
**1999 DZ7 - 0.0036"**

**(interferometry also helps with confusion!)**

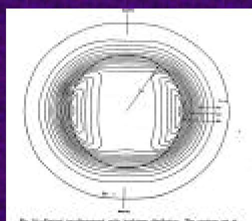
## A Bit of History

The first radio interferometric observations of any celestial body were when the Sun was observed with the "sea cliff interferometer" in Australia (McCready, Pawsey, and Payne-Scott 1947).



## More History

The first sky brightness images were also of the Sun (Christiansen & Warburton 1955):



## What's the Big Deal?

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

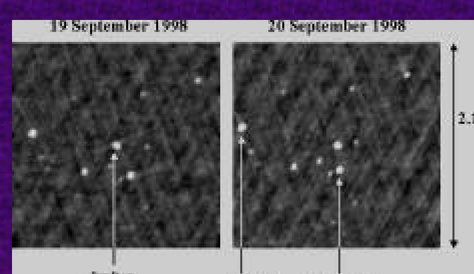
## Object Motion

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 - another example




de Pater & Butler 2002

## Time Variability

Time variability is a significant problem in solar system observations:

- Sun - very fast fluctuations (< 1 sec)
- Others - rotation (hours to days)
- Distance may change appreciably (need "common" distance measurements)

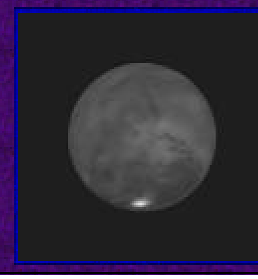
These must be dealt with.

## Time Variability – an example

Mars radar

snapshots made every 10 mins

Butler, Muhleman & Slade 1994



## Implications

- Can't use same calibrators
- Can't 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:

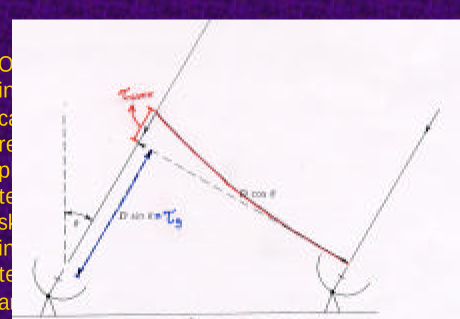
- Sun ~ 6000 K (or brighter)
- Moon ~ 200 K
- Venus, Jupiter ~ 1-100's of K

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, system temperature 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.

## Source Distance - Wave Curvature



## Short Spacing Problem

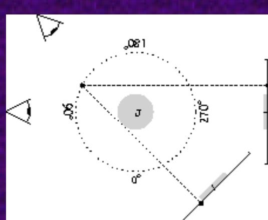
As with other large, bright objects, there is usually a serious short spacing problem when observing the planets. This can produce a large negative “bowl” in images if care is not taken. This can usually be avoided with careful planning, and the use of appropriate models during imaging and deconvolution.

## 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.

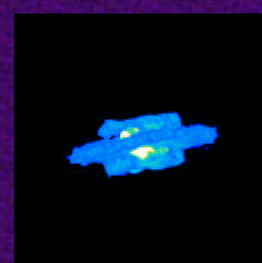
## 3-D Reconstructions

If we have perfect knowledge of the geometry of the source, and if the emission mechanism is optically thin (this is only the case for the synchrotron emission from Jupiter), then we can make a full 3-D reconstruction of the emission:




## 3-D Reconstructions, more...

Developed by Bob Sault (ATNF) - see Sault *et al.* 1997; Leblanc *et al.* 1997; de Pater & Sault 1998



## 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.

## Optical Depth

With the exception of comets, the upper parts of atmospheres, and Jupiter’s synchrotron emission, all solar system bodies are optically thick. For solid surfaces, the “e-folding” depth is ~ 10 ?. For atmospheres, a rough rule of thumb is that cm wavelengths probe down to depths of a few bars, and mm wavelengths probe down to a few to a few hundred mbar. The desired science drives the choice of wavelength.

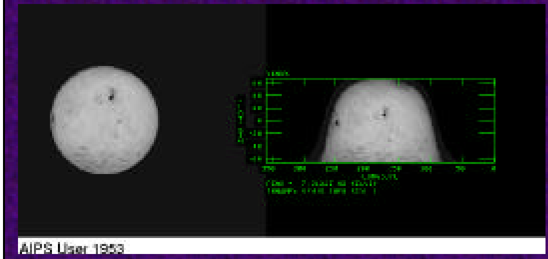
## Conversion to TB

The meaningful unit of measurement for solar system observations is Kelvin. Since we usually roughly know distances and sizes, we can turn measured Janskys (or Janskys/beam) into brightness temperature:

unresolved: $T_B^d = V_o \frac{\lambda^2}{2\,k_B} \frac{D^2}{\pi\,R_b^2} + T_{cmb}$

resolved: $T_B^b(l,m) = F(l,m) \frac{\lambda^2}{2\,k_B} \frac{4\ \ln 2}{\pi\,B^2} + T_{cmb}$

## Conversion of coordinates




## Real Data - what to expect

They're all round!

## 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:

$$V(q) = 2\pi \int \mathcal{A}(r)\ I(r)\ J_o(2\pi r q)\ r\ dr$$

For a "uniform disk", this reduces to:

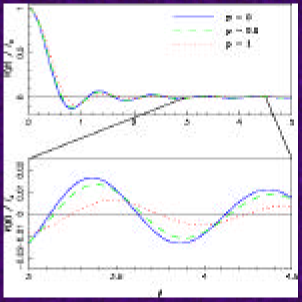
$$V(\beta) = I_o \pi R^2 \frac{J_1(2\pi\beta)}{\pi\,\beta}$$

and for a "limb-darkened disk", this reduces to:

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

## 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):

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

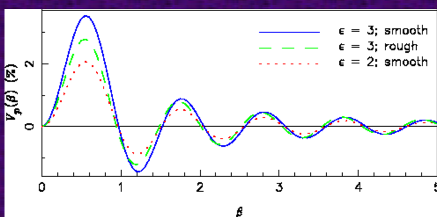
this cannot be solved analytically. Note that roughness of the surface is also a confusion (it modifies the effective Fresnel reflectivities).

For circular measured polarization, this visibility is formed via:

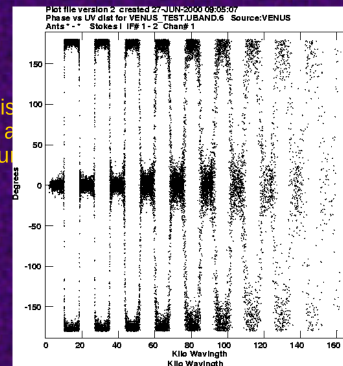
$$V_p = \frac{\Re\{V_{RL} + V_{LR}\}\cos 2\psi + \Im\{V_{RL} - V_{LR}\}\sin 2\psi}{V_o}$$

## Real Data - polarization

Examples of expected polarization response:

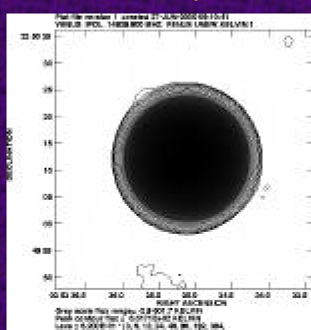



True vis... ving
Venus a...
configu...




## Real Data - an example

The resultant image:



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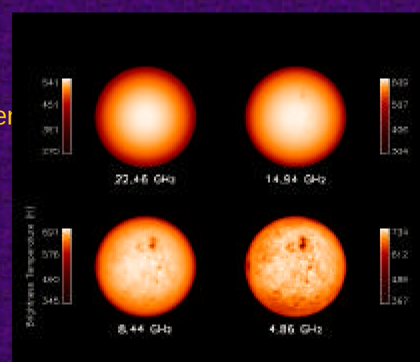


Venus ... ds: