Calibration of ALMA

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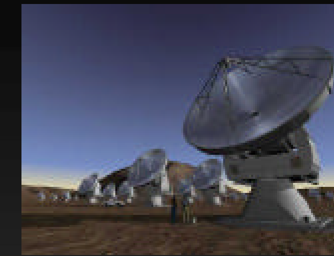
NRAO

What is ALMA?

ALMA is an international collaboration between the U.S. (NRAO/AUI/NSF - with Canadian and Mexican involvement) and European partners (ESO/CNRS/MPG/NFRA/NOVA/PPARC/…) with Japan entering the project as a 3rd partner in the near future (Japan has funding, the "tri-lateral" binding agreement has just not been finalized at this point).

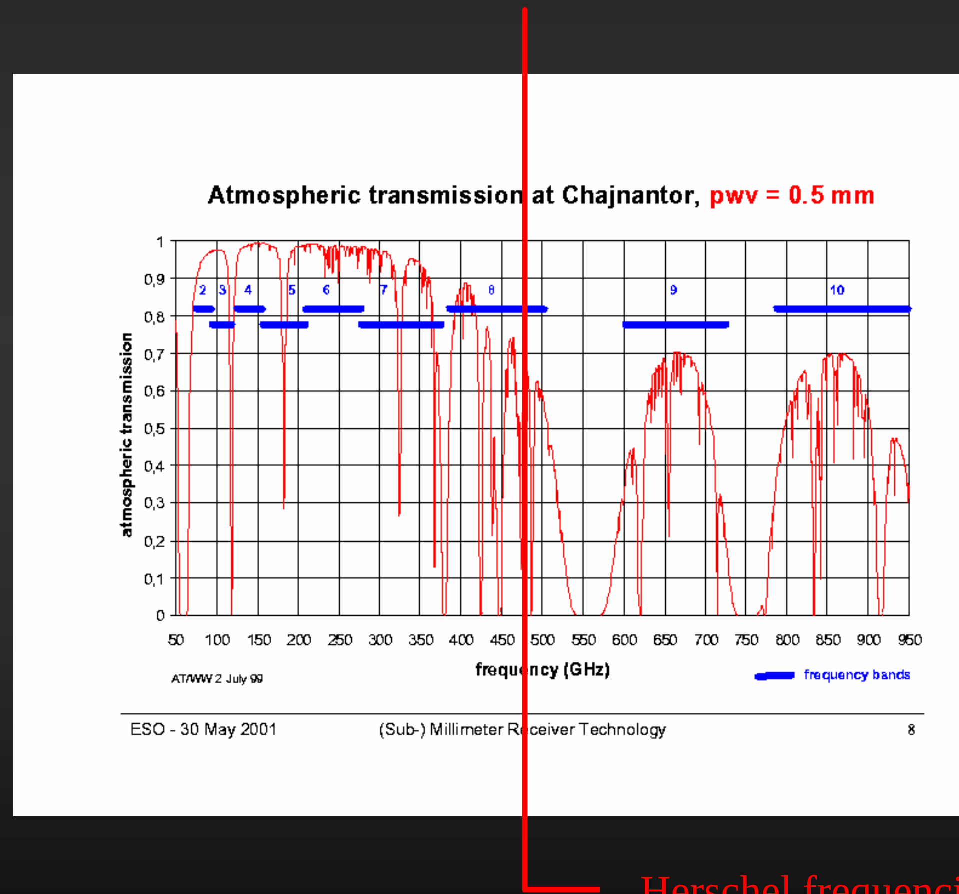
What is ALMA?



- 64 12-m antennas, with extremely accurate surfaces (20 μm) and pointing (0.6”);
- wavelengths from 6mm to 350μm, with incredibly sensitive receivers ($3h\nu/k$);
- antenna separations from 15m to 18km;
- powerful and flexible correlator;
- on an extremely high and dry site in the Chilean Andes.

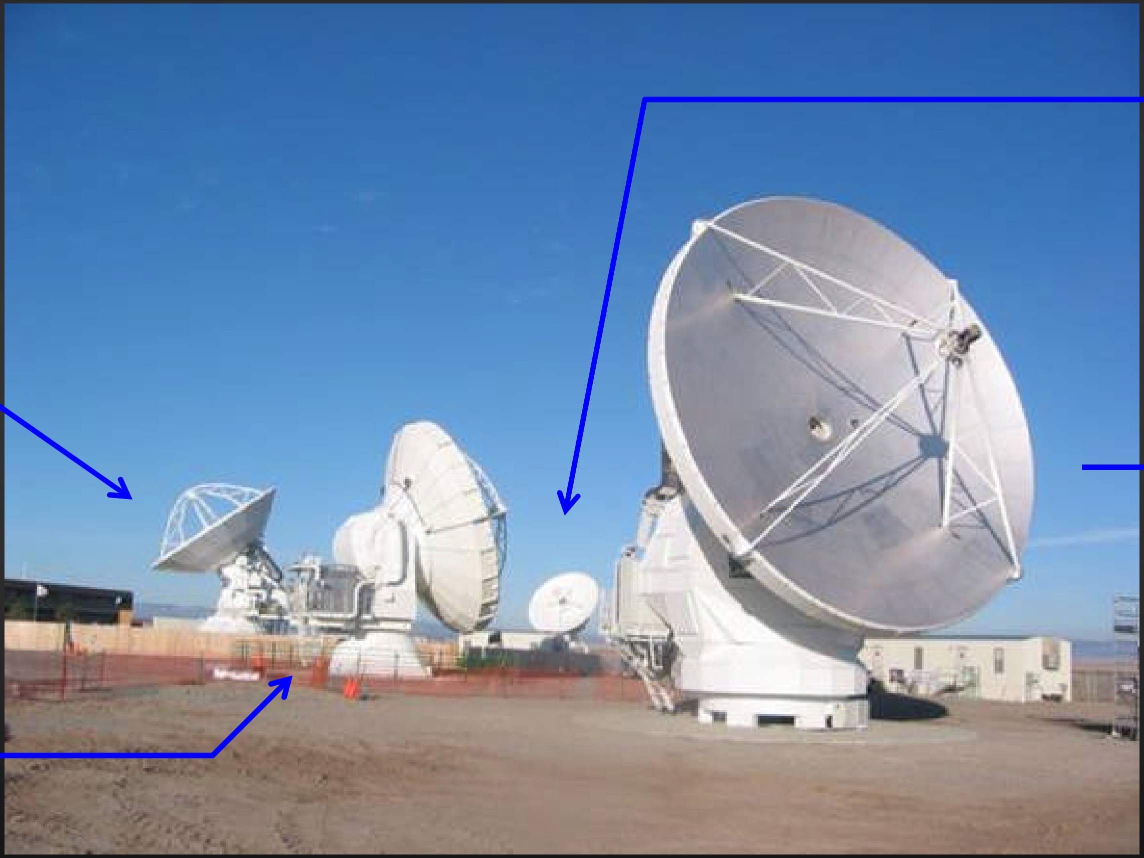
ALMA Receivers

The intent is to cover all of the atmospheric "windows" from 30 to 1000 GHz:



Herschel frequencies

ALMA Antennas



VLA antenna

European (Alcatel/ACE)

Japanese (Mitsubishi)

U.S. (Vertex-RSI)

ALMA Site

Desirable site characteristics:

- dry (high altitude), stable atmosphere;
- largely ‘flat’;
- low latitude;
- good accessibility;
- pre-existing infrastructure.

ALMA Site

The Atacama desert in northern Chile satisfies these criteria:

- altitude = 5050 m (16,500 ft.);
- median PWV ~ 1 mm;
- excellent phase stability;
- large flat regions;
- latitude = -23 S;
- accessible from the Jama Highway (main route from NChile to Argentina);
- good Chilean infrastructure (ESO).

ALMA Site

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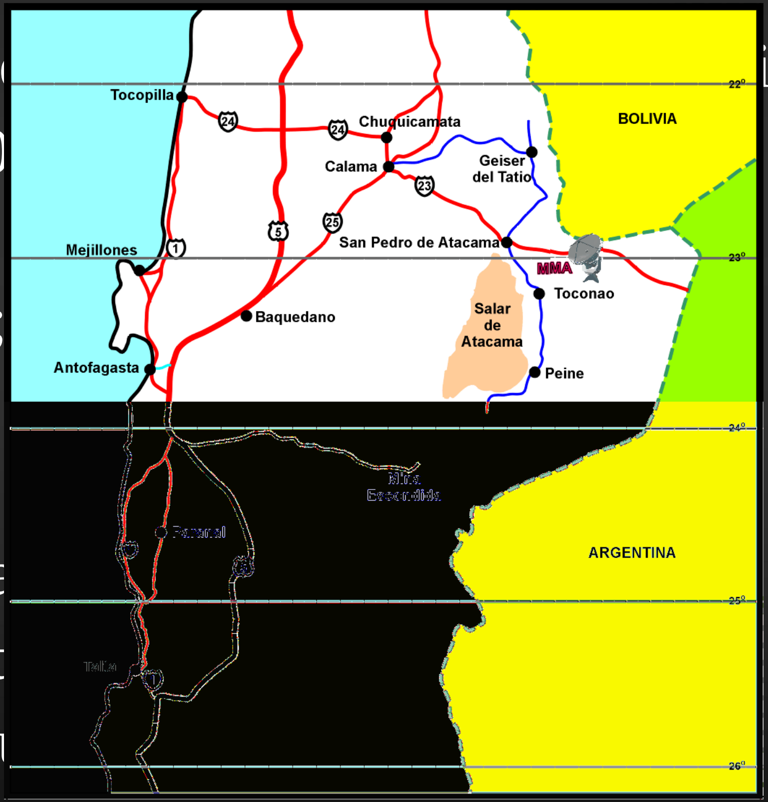


ALMA Site

Picture: Seiichi Sakamoto

ALMA Site

ALMA Camp – General View

Inner Court

Typical Office

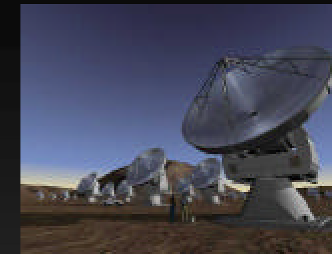
ALMA Configurations

The antennas will be moved into different configurations, to trade off the resolution vs. the brightness sensitivity (for large-scale structure):

- transform smoothly (move a few antennas every few days) from smallest to largest of the so-called “intermediate” configurations (150m to 4km or so);
- jump to largest configuration (“Y+”) - 18 km max baseline, 14 km “effective” max baseline.

The final staging/cycling/amount of time spent in the various configurations is still to be determined (as part of the formal operations plan for ALMA).

ALMA Timeline



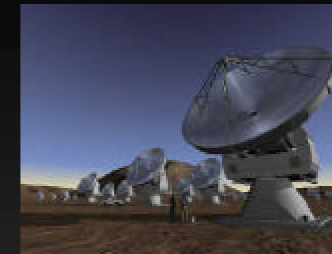
- 2002 January – Construction Project Start
- 2003 August – Test Interferometer
- 2004 January – Site Civil Works in Chile
- 2005 January – Prototype Antenna Decision
- 2005 January – Release Electronics for Production
- 2005 April – Contract for Production Antennas
- 2006 April – First Antenna in Chile
- 2007 July – Interim Operations (8 antennas)
- 2011 July – Construction Complete
- 2011 September – Fully Operational

ALMA Calibration

There are many things to “calibrate” for ALMA, including:

- flux density scale;
- time variable amplitude;
- time variable phase on all baselines;
- antenna locations;
- antenna delays;
- time variable bandpass;
- time variable focus;
- time variable polarization;
- pointing (global, reference, and dynamic);
- optics (main dish, subreflector location, feed pointing, etc…);
- others…

ALMA Amplitude Calibration Spec



I'm assuming what we are interested in here is the amplitude calibration, both the overall scale, and the time variable part.

The specification for ALMA amplitude calibration is:

- 3% accuracy at millimeter wavelengths (ν < 600 GHz);
- 5% accuracy at submillimeter wavelengths (ν > 600 GHz).

THIS IS PRETTY TOUGH!!! Consider:

- current mm interferometers only good to 10% at best;
- little experience in submm interferometry;
- even in radio, where things easier (relatively), only good to about 5% or so (slightly better from 1-15 GHz).

Amplitude Calibration Requirements

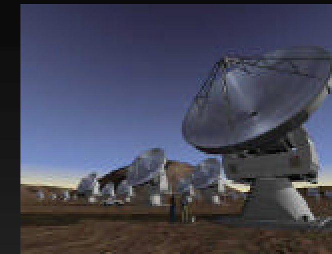
In addition, the specification on imaging fidelity is:

- all pixels > 0.1% of the peak brightness in the image must be noise limited (alternatively, image “fidelity” must be > 100 in all such locations).

So we cannot have gain fluctuations which introduce imaging errors – i.e., we must do both of:

- set the overall flux density scale to 3 or 5%.
- track the fluctuations to a roughly similar level.

Amplitude Calibration Requirements



In addition, we have a specification that we must measure and record total power on the antennas properly (because we expect to be imaging very large sources, and the submm beams are very small anyway [FWHM at 950 GHz is ~ 5"]). This means that, unfortunately, we cannot always rely on the correlation to bypass the atmospheric emission, nor can we rely on normal phase switching techniques to reject the unwanted sideband in DSB receiving systems, and hence have to calibrate the sideband gain ratio. And finally, we have a problem with receiver saturation.

Amplitude Calibration Options

Two possibilities for amplitude calibration:

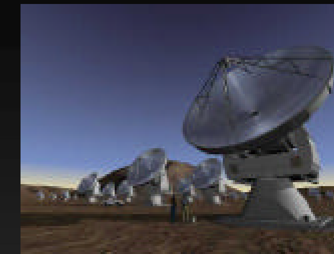
- *ab initio*

  if all telescope and atmosphere properties are known and/or measured accurately enough, then measured correlation coefficients can be turned directly into calibrated (in amplitude) visibilities.

- *a posteriori*

  observe astronomical sources of “known” flux density and use those observations to calibrate the amplitudes.

Ab Initio Calibration



The fundamental measured quantity of an interferometer is the *correlation coefficient*. This is turned into a calibrated *visibility* via:

$$\mathbf{V_{ij}} = r_{\mathbf{ij}} \mathbf{e}^{\frac{1}{2}(t_i + t_j)} \sqrt{\mathbf{G_i T_{sys_i} G_j T_{sys_j}}}$$

where $\mathbf{G_i} = \mathbf{2k} / \mathbf{A_i} h_{\mathbf{a_i}}$

So, if the system temperature, aperture efficiency, and opacities are known accurately enough, there is no need to use astronomical sources for *a posteriori* calibration.

Ab Initio Calibration

Problems with *a priori* calibration include:

- need to accurately measure system temperature, aperture efficiency (actually, full 2-D antenna voltage pattern), and atmospheric opacity (at each antenna);
- must accurately set focus, delay, and pointing;
- decorrelation effects must be accounted for.

Benefits are:

- no need for extra observations (scheduling is easier);
- no need to assume you know the flux density of astronomical sources.

A Posteriori Calibration

If you cannot know or measure the telescope properties well enough, then you can turn the correlation coefficient into a calibrated (in amplitude) visibility by observing a source of known flux density, and directly determining the conversion factor. The flux density can be known via:

- calculation from first principles;
- observation with an accurately calibrated telescope;
- combination of the above two.

A Posteriori Calibration

Problems with *a posteriori* calibration include:

- difficulty in knowing absolute flux density of sources;
- decorrelation effects must be accounted for;
- must still measure T_{sys} and voltage pattern (relative).

Benefits are:

- T_{sys} and voltage pattern measurements can be relative;
- not necessary to know absolute gain or opacity (unless a correction for different elevation is required).

A Posteriori Calibration

Generally, there are very few sources which are true absolute calibration standards (*primary* calibration sources). Since there are so few of them, in order to make it possible to find calibrators at more times/elevations, a number of other sources are observed along with the primary sources, and their flux density is bootstrapped from the primary (*secondary* calibration sources). We would like to have some 10's of these sources, distributed regularly in right ascension. They must be regularly monitored, along with the true primary calibration sources, as they can vary on even short timescales.

A Posteriori Calibration

Types of sources which could be (and have been) primary or secondary calibrators:

- extragalactic (QSOs) – e.g., Cygnus A, 3C286;
- HII (or UCHII or HCHII) regions – e.g., W3(OH), DR21;
- stars, at all ages – e.g., Cas A, NGC 7027, MWC 349;
- solar system – e.g., Mars, Jupiter.

ALMA Sensitivity

How strong do the amplitude calibration sources need to be? We need to have the accuracy of a (relatively short – a few minutes at most) observation have uncertainty dominated by the uncertainty in the flux density of the source itself, not by the uncertainty from the thermal rms. So, the source flux density should be ≥ the thermal rms on a single baseline (or so). In fact, we relax this because we know we will use self-calibration, so the appropriate thermal rms is not for a single baseline, but for the entire array. So, use a criteria that the source flux density is ≥ 33 X the thermal rms of the entire array (for 3% accuracy).

ALMA Sensitivity

frequency (GHz)	1-σ in 1 min (mJy)	required flux density (mJy)
35	0.02	0.66
90	0.03	1.0
230	0.07	2.3
350	0.20	6.6
675	0.70	23.0
850	1.10	36.0

ALMA Resolution

How large can the amplitude calibration sources be? We generally want the source to be significantly smaller than the resolution of the telescope or interferometer, to avoid problems in either having to know the 2-D voltage pattern of the antennas, or extrapolating to the zero spacing flux density.

ALMA Resolution

frequency (GHz)	antenna resolution (asec)	compact config resolution (asec)	14-km config resolution (masec)
35	150	8.8	130
90	60	3.4	50
230	24	1.3	20
350	15	0.9	13
675	8	0.5	7
850	6	0.4	5

Calibration Sources: QSOs

At radio wavelengths, the primary flux density calibrators are mostly external radio galaxies, e.g., at the VLA, the standard is 3C295, which is used to monitor 3C286, 3C48, etc… every 16 months. 3C286 and 3C48 are secondary flux density calibrators (but are effectively used as if they are primaries). Their variations are small and slow, on physical grounds – the emission is dominated by the radio lobes. By the time you get to the mm/submm, the emission is generally weaker, and dominated by the core (lobes go like $\lambda^{0.7}$ while core is closer to flat spectrum), which is variable. So, while they might be good secondaries, these sources are probably not useful as primaries.

Calibration Sources: Stars

Main sequence stars are small in angular size, so are good in that respect, but are too weak (the brightest are of order a few mJy at 650 GHz) to be considered as viable primary or secondary calibrators.

Giant and supergiant stars, however, although cooler, are much larger and hence brighter. The brighter ones have flux density on the order of 10's of mJy at 650 GHz (and scale mostly like λ^{-2}). Their sizes are typically a few masec. They therefore might be reasonable candidates for secondary calibrators (but are weak). They are generally too variable to be considered as primary calibrators.

Calibration Sources: HII regions & PN

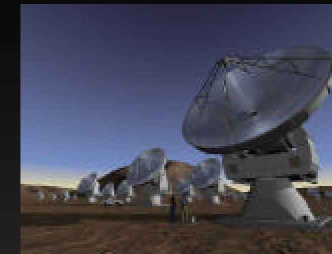
HII (and UCHII) regions and PN have been used as calibrators in the mm/submm for many years. Such sources include DR21, W3(OH), NGC7027, K3-50A, etc…

They are typically a few Jy, and are hence easily strong enough, however, they are typically too large to consider as primary calibrators for ALMA, with sizes on the order of a few to 10's of arcseconds. Small UCHIIs or HCHIIs might be good candidates for secondaries, but this is a research topic. Most of these sources are variable to some degree, so would have to be monitored. There is also some theoretical uncertainty on the far-IR/submm modeling of these sources.

Calibration Sources: Other Evolved Stars

Other stellar sources have also been used for years as mm/submm primary calibration sources. These include one particularly interesting source: MWC 349. This is a star with (apparently) a stellar wind with nearly constant power law density falloff, resulting in a nearly constant spectral index from the IR to radio wavelengths (which goes like $\lambda^{-0.6}$). Its size is reasonable (~ 0.3"), but might be too large for ALMA in some configurations. It is relatively non-variable (except for the H recomb lines). Furthermore, Jack Welch has measured this source absolutely at 30 GHz, and plans to measure it similarly at 90 GHz. It may therefore be a very good primary or secondary flux density calibrator.

Calibration Sources: Other Evolved Stars



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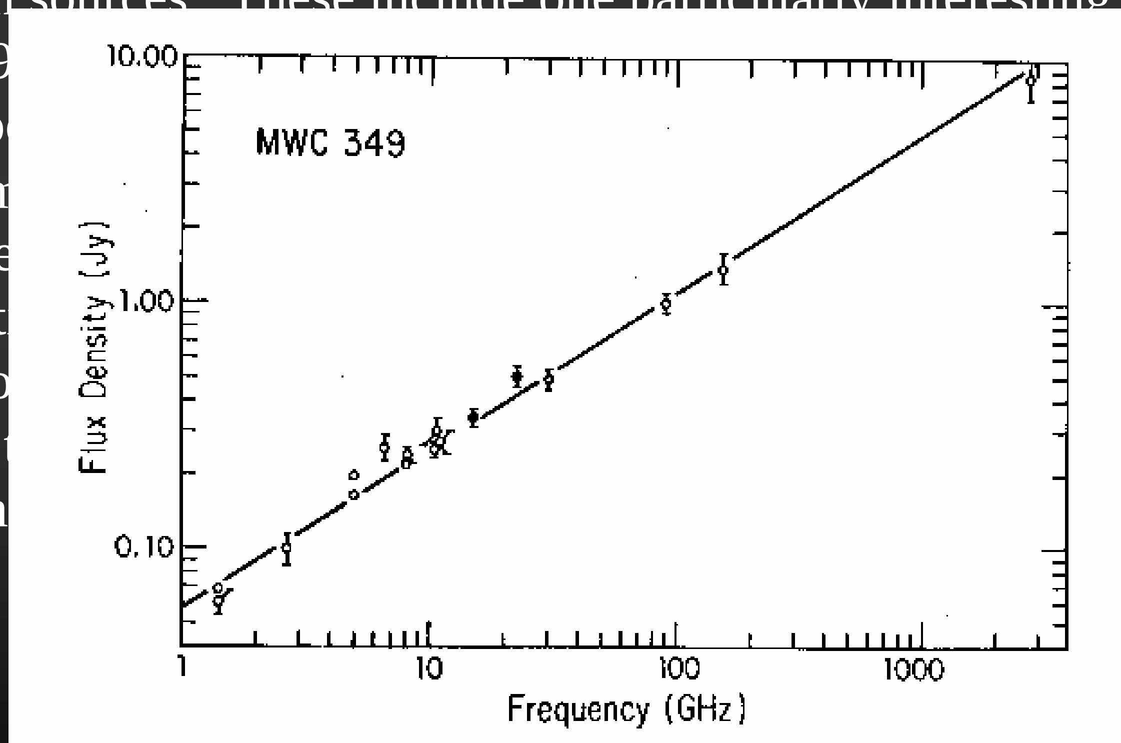
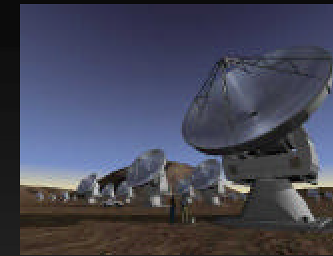
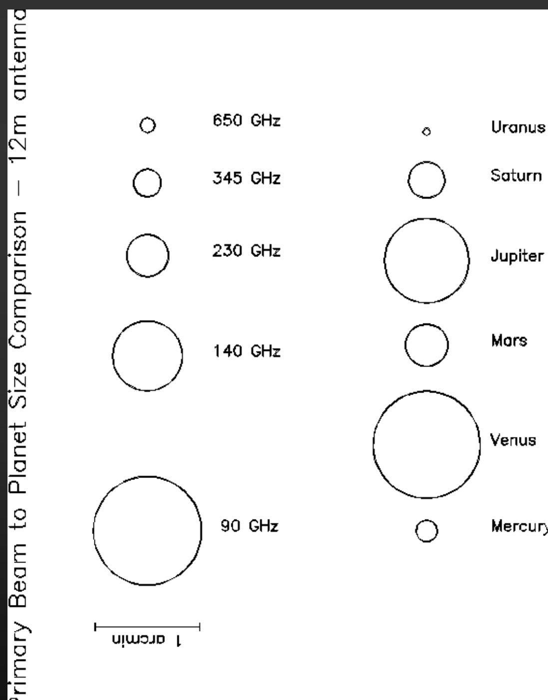


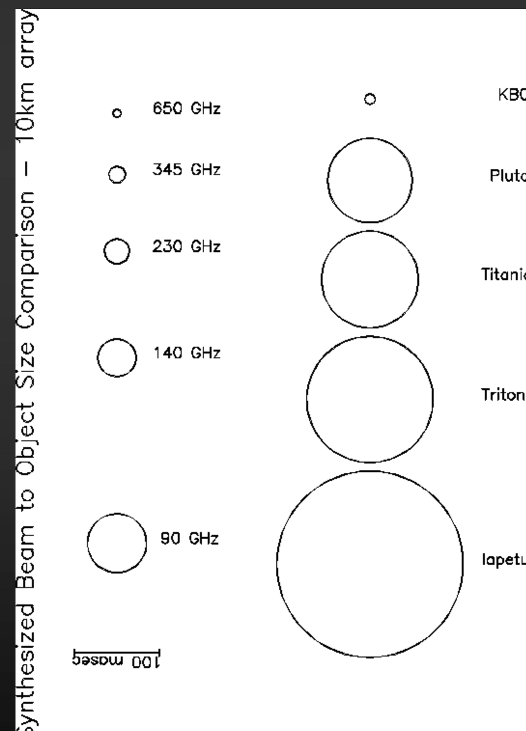
Calibration Sources: Solar System



Many solar system sources have enough flux density. There is a size problem, however:

Primary Beam

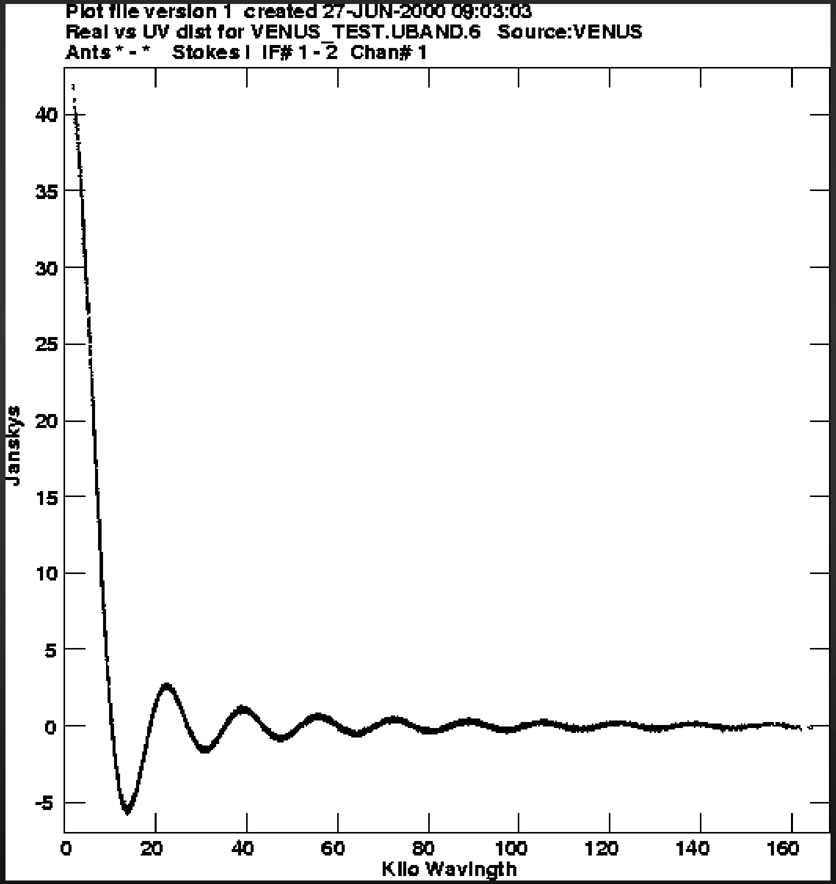




Synthesized Beam

Planets – Visibility Function

We can correct, to some degree, for resolution effects, since we have a good idea of what the expected visibility function is. However, this only works to a certain degree. Must have enough short baselines to make the fitting accurate enough.



Expected Flux Density

You have heard in the last two days about the models of the emission from planetary surfaces and atmospheres.

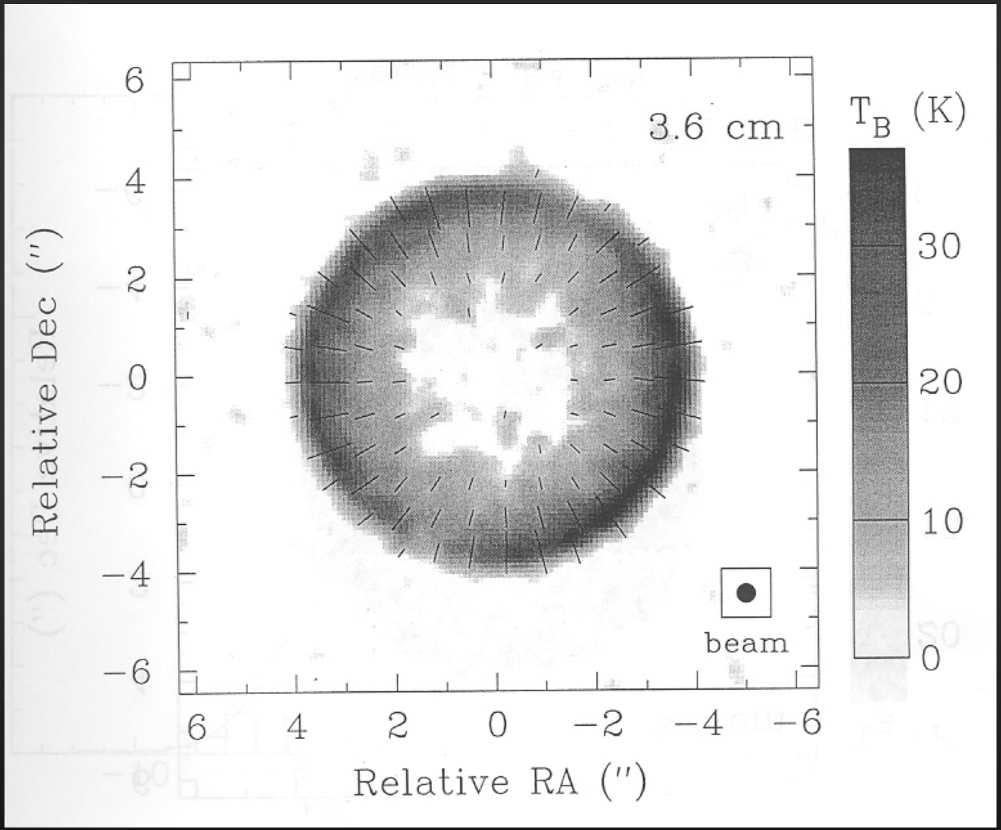
Generally, the models are reasonably good, allowing for decent predictions of the zero-spacing flux density as a function of frequency.

There are, however, a few problems aside from those discussed in the past two days…

Problems: Polarization

For the solid surface bodies, the signal is intrinsically polarized as it passes through the surface-atmosphere interface. This can cause problems if it is not accounted for.

Mitchell 1993



Problems: Polarization

BUT, this polarized signal can actually be used to determine the effective surface dielectric, which is needed for modeling the thermal emission. Form a polarized visibility of:

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

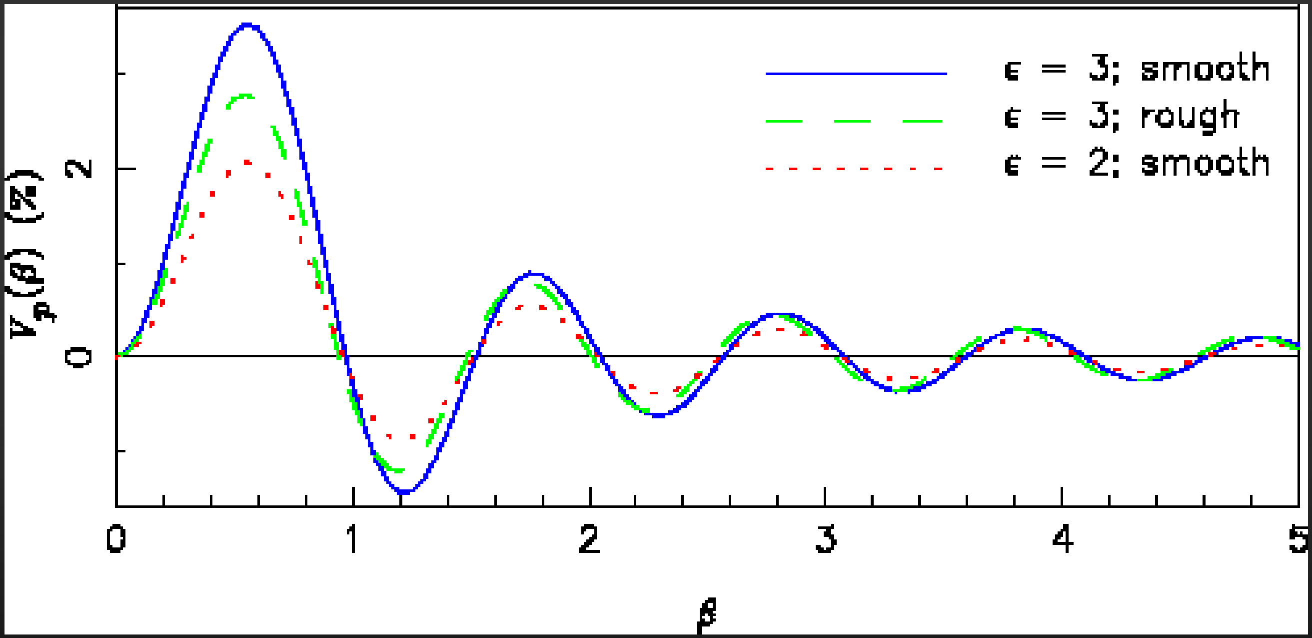
which is, theoretically:

$$V_p(b) = \int_0^1 (R_p - R_s) J_2(2prb)\, r\, dr$$

which can be inverted to find the dielectric.

Problems: Roughness

Surface roughness modifies both the total and polarized emission. For example, the polarized vis. fn. is modified:



It can be measured and modeled, but is another complication.

Mars

Mars is one of the best mm/submm primary flux density calibrators. The best current model is that of Don Rudy (current keepers are B. Butler and M. Gurwell). This model is good, but has several shortcomings:

- based fundamentally on cm scale (Baars et al.), since measurements were done at 2 & 6 cm at VLA;
- no roughness;
- no subsurface scattering;
- no lateral heat transport;
- uncertainties with surface CO_2 ice, extent & properties;
- somewhat outdated surface albedo and emissivity information (based on old Viking information);
- no detailed surface albedo or emissivity information;
- no atmosphere.

In addition, Mars is a bit big (as large as 25").

Mars

The model takes into account the viewing geometry and martian season. Here are the models over one martian day and one martian year.

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

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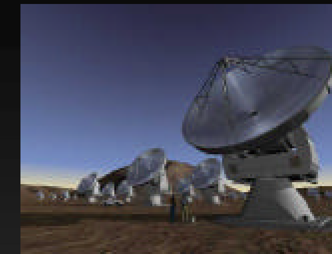
Uranus

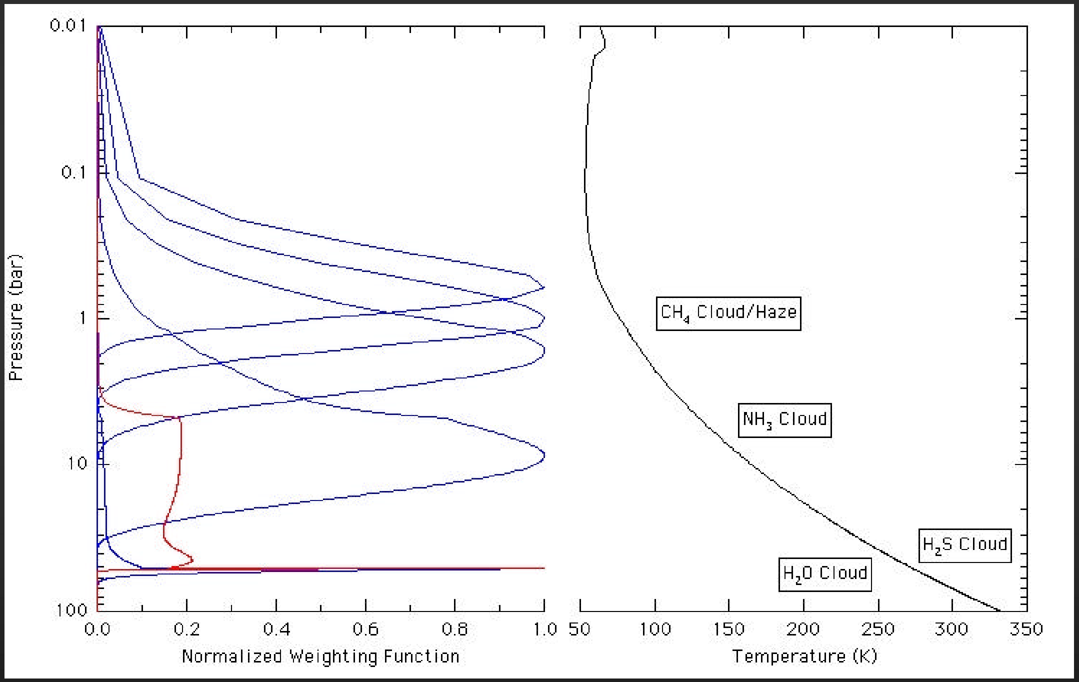


Another very good calibrator, and smaller than Mars, Uranus has been used as a primary calibrator for many years. The best models are those of Griffin and Orton, Moreno, and Hofstadter. It doesn’t suffer from extreme contamination from atmospheric lines, has little or no PH_3, etc… Gene Serabyn has some values for the submm brightness temperature (15%?). There are, however, some problems with the model for it:

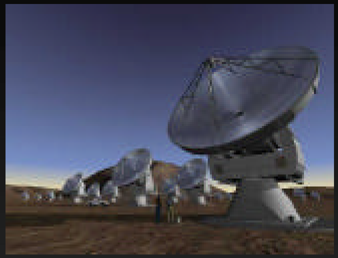
- $T(z)$ might be varying with time;
- cloud/haze layers?;
- constituent opacity uncertainties.

Uranus

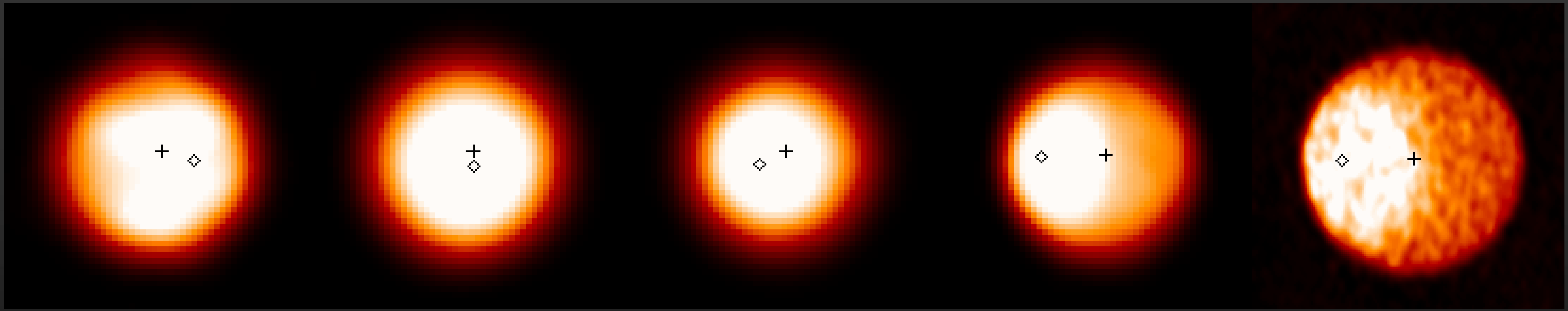
Weighting functions for frequencies of 1410, 675, 350, 90, 15, and 6 GHz. The methane cloud is probed at all frequencies, and the ammonia cloud is probed at 90 GHz.



Uranus



The temperature structure of the deep atmosphere seems to be changing with time (Hofstadter & Butler 2002). Is this occurring higher up in the atmosphere?



1981	1985	1989	1994	1994
6 cm	2 cm	6 cm	6 cm	2 cm

Large Icy Bodies

The large icy bodies might be good choices for primary calibrators. These include: Galilean satellites, Titan, Triton, and smaller moons of Jupiter, Saturn, and Uranus.

Problems are:

- confusion from primary (but interferometry helps!);
- less known physically about the surfaces/subsurfaces;
- mm emissivity problem for Ganymede and potentially Europa (Muhleman & Berge 1991).

Titan gets around some of these problems and might be a very good choice.

Titan

Titan might be a very good primary calibrator, since it does not suffer from contamination from surface emission (in mm/submm, all emission effectively comes from atmosphere – exception is 35 GHz), and the uncertainties that come from it. There are still possible problems however:

- flux density not currently known to better than 10%;
- modeling effects of haze;
- atmospheric lines.

Asteroids

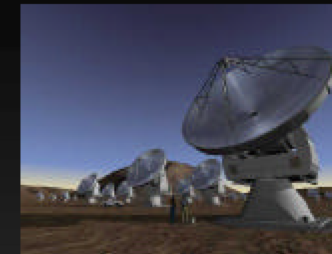
Asteroids are possible flux density calibrators. Larger asteroids (D > 150 km or so) are relatively spherical, and so have only weak light curves (few %), and can be well modelled (work by Lagerros and Müller). There are 34 such MBAs. They are relatively small, relatively strong (~ 100 mJy at 230 GHz, and going up like λ^{-2}), and have modellable light curves. They are not (in my opinion) good for primary flux density calibrators, but should be excellent secondary flux density calibration sources.

Calibration Devices

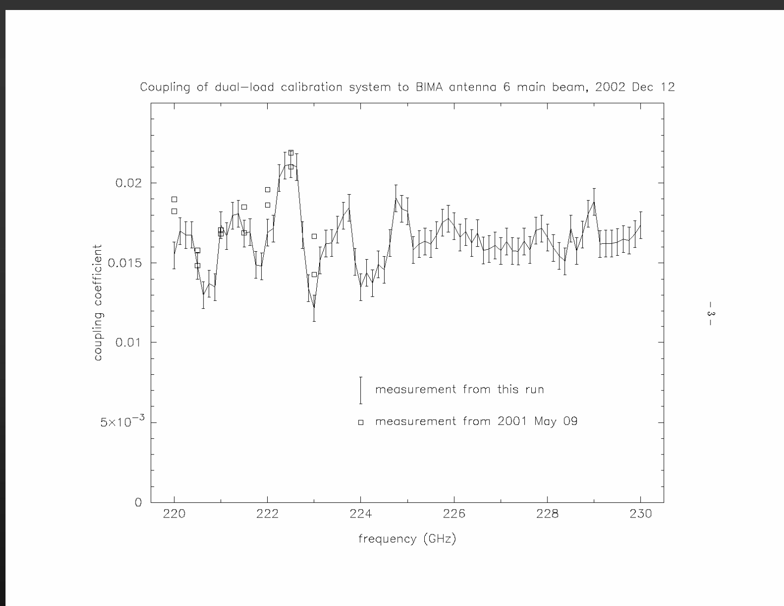
In either case, we must measure the time variation of the atmospheric emission. The traditional way of doing this at millimeter wavelength interferometers is by means of a chopper wheel with an ambient load. This will not meet the 3% amplitude calibration specification. We therefore need a more complicated load/switching device (as an aside, if we did not need the total power, this requirement might go away [except some of the fluctuation can be correlated]). Until about 18 months ago, we had been investigating two types of these load devices:

- dual-load in the subreflector
- semi-transparent vane

Calibration Devices
Subreflector Dual-Load

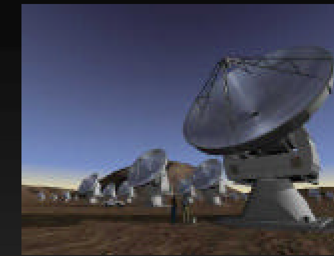


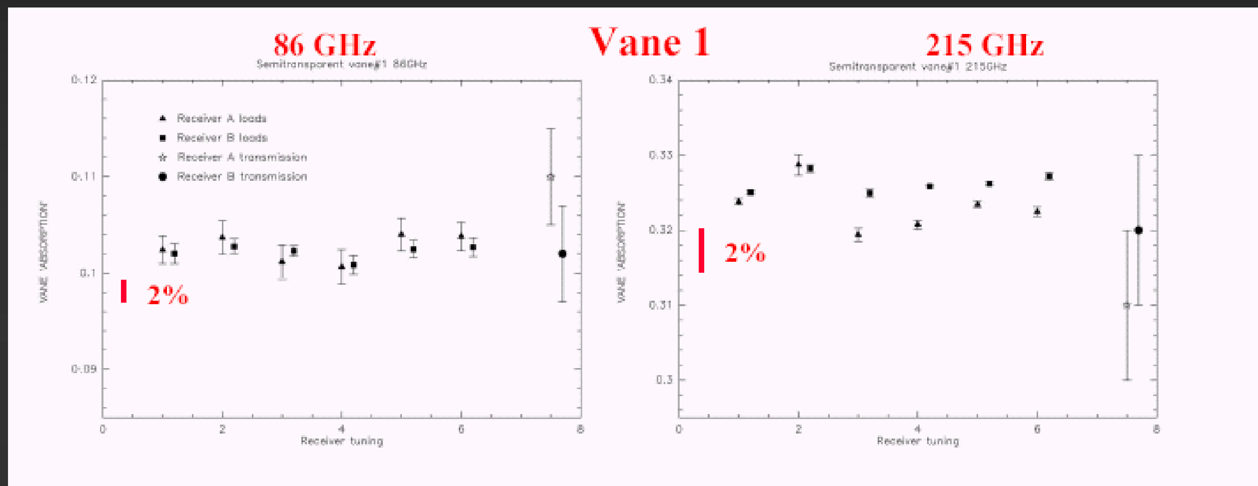
Preliminary tests have not been encouraging – the coupling of the loads to the feed seems to change unpredictably with time/ambient conditions.



Variation as function of frequency shown at left (Bock, Welch, & Plambeck). Further tests showed differences in this spectrum of order 10% as a function of temperature and focus position (standing wave postulated but not certain).

Calibration Devices
Semi-Transparent Vane





Preliminary tests have been more encouraging – see figure above (Martin-Pintado et al.). An accuracy of 5% at mm wavelengths seems achievable. There are still concerns about structure in the materials, reflections, etc…, it is not clear that it will get any better. Note also that the ALMA FE group has stopped all testing on these devices and materials.

Calibration Devices
What we'd really like

Even having two loads is not enough, however, because of the problem of receiver saturation. The memo of Stephane Guilloteau (ALMA memo 461) has shown that what we really need to even hope to meet the specifications is a device that has two loads, of temperatures ~285 C ("ambient") and 385 C ("hot"), and the ability to measure the following combinations of sky, ambient, and hot loads:

- sky
- ambient
- sky + ambient
- hot
- sky + hot

Calibration Devices What we'd really like

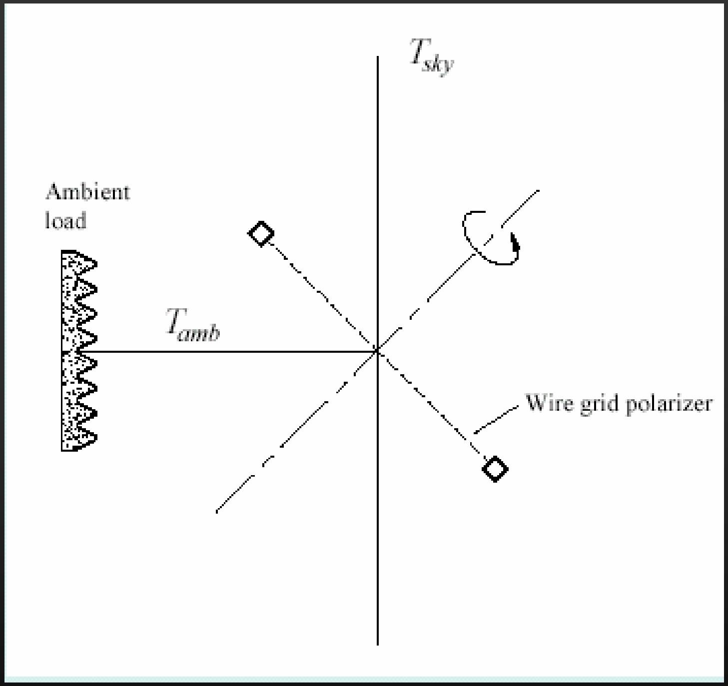
Even with these five combinations, we will still have to measure several quantities quite accurately:

- load coupling fraction (to 1.6%);
- temperature of ambient load (to 0.3 K);
- temperature of hot load (to 0.6 K);
- the emission from the atmosphere (to < a few tenths of %);
- the atmospheric opacity (to < a few tenths of %);
- the antenna aperture efficiency (to < a few tenths of %).

and note that this assumes a gain stability of 1 part in 10^4!

Calibration Devices
Couplers

In any of these schemes, there must be some element in the device that couples signals from two loads into the beam:



There are three reasonable current options:

- semi-transparent vane
- polarizing grid
- dielectric film

Calibration Devices Couplers - Comparison

	dual-load	S/T vane	wire grid	dielectric b/s
cost	moderate	low	high	moderate
freq. depend.	significant	significant	slight	moderate
ruggedness	moderate	good	poor	moderate
simplicity	moderate	good	poor	moderate
predictability	poor	poor	good	moderate
accuracy	~10%	~5% (@ mm)	?	?

Conclusions

- Make decision on *a priori* vs. *a posteriori* (this might not happen until experience shows us how well we can do with *a priori*).
- Have to pick few true primaries, and probably need some more observations + theory. Good current candidates: MWC 349, Titan, Callisto, Uranus, Mars.
- Decide on what to use for secondaries (probably QSOs and/or asteroids), and monitoring scheme for them.
- Will need good models of sky brightness distribution (I + pol'n) for all of them (primaries AND secondaries).
- 3% (or 5%, even) will still be difficult.

ALMA → HSO

How can ALMA help HSO wrt flux density scale calibration?

- High spatial resolution (and sensitivity) maps of objects will help constrain the models (asteroid shapes, e.g.);
- Time monitoring will tell about (potentially unexpected) variability;
- High spectral resolution can help understand the composition/chemistry of objects, helping to understand how lines may contaminate the spectrum of objects;
- Direct overlap in 350-625 μm;
- But - will mostly be post-HSO, so involves "back-calibration".