

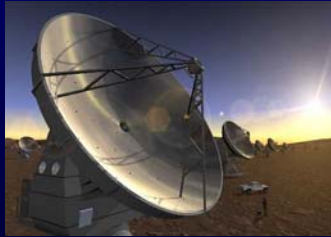


ALMA Calibration

Bryan Butler

NRAO

**ALMA Calibration Group Leader
(until October 1)**



Calibration Documents

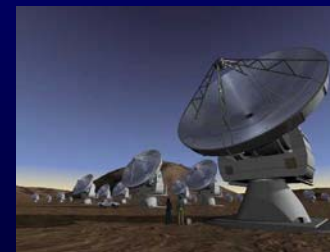


Updated Project Book Chapter 3 is complete, and ready to be submitted to the DAR process (document is titled “Calibration of ALMA” – authors: Butler, Guilloteau, Wootten, van Dishoeck).

Next document is the “Calibration Plan Document” – original target date 2003-Sep-30, but change request in to delay that by one month to 2003-Oct-31. Will use the “Calibration of ALMA” document as basis (memo 372 as well), but contain more details on duration, frequency, and interactions of different calibrations (with examples), and some software/operations issues.



Amplitude Calibration Requirements

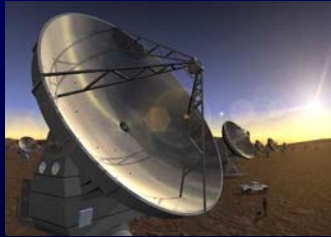


The specification for ALMA amplitude calibration is:

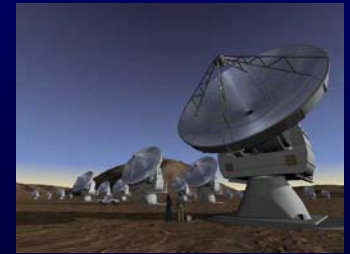
- ☛ 1% accuracy at millimeter wavelengths ($\nu < 300$ GHz);
- ☛ 3% accuracy at submillimeter wavelengths ($\nu > 300$ GHz).

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

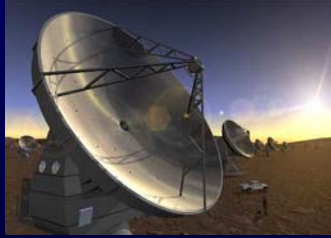


In addition, the specification on imaging fidelity is:

- ☛ 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:

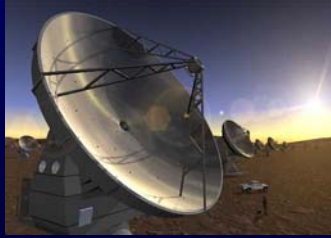
- ☛ set the overall flux density scale to 1 or 3%.
- ☛ track the fluctuations to a roughly similar level.



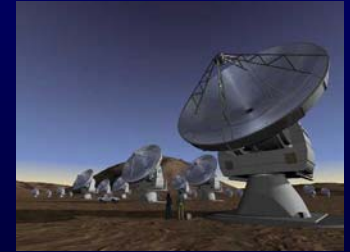
Amplitude Calibration Requirements



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 $\sim 6''$]). 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



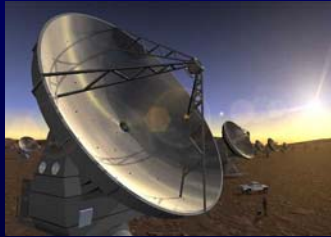
Two possibilities for amplitude calibration:

 *ab initio*

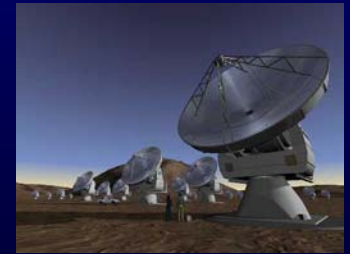
if all telescope properties are known and/or measured accurately enough, then measured correlation coefficients can be turned directly into calibrated (in amplitude) visibilities.

 *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*, ρ_{ij} , between antennas i and j . This is turned into a calibrated *visibility* via:

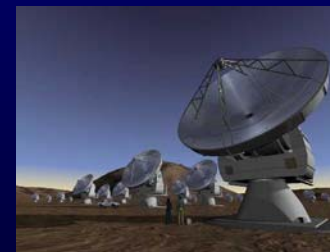
$$V_{ij} = \rho_{ij} e^{\frac{1}{2}(\tau_i + \tau_j)} \sqrt{G_i T_{\text{sys}_i} G_j T_{\text{sys}_j}}$$

where $G_i = \frac{2k}{A_i \eta_{a_i}}$

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

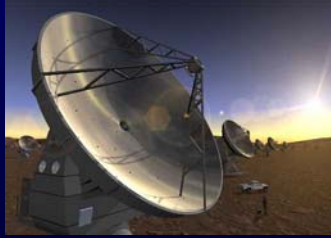


Problems with *ab initio* calibration include:

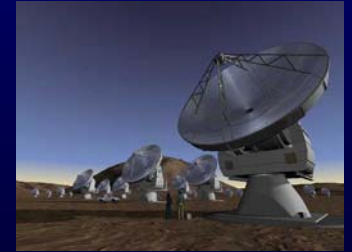
- ❗ need to accurately measure system temperature, aperture efficiency (actually, full 2-D antenna voltage pattern), and atmospheric opacity (at each antenna);
- ❗ must accurately set focus, delay, and pointing;
- ❗ decorrelation effects must be accounted for.

Benefits are:

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

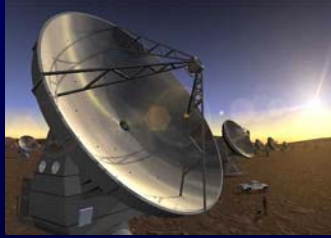


A Posteriori Calibration



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

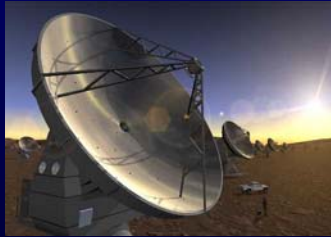


Problems with *a posteriori* calibration include:

- ☛ 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:

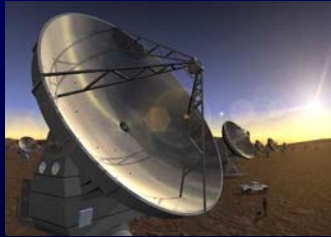
- ☛ T_{sys} and voltage pattern measurements can be relative;
- ☛ not necessary to know absolute gain or opacity (unless a correction for different elevation is required).



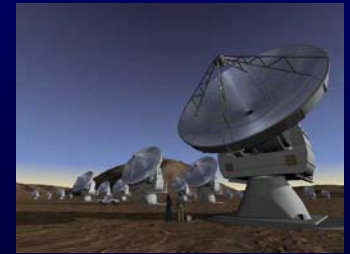
A Posteriori Calibration



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. They must be regularly monitored, along with the true primary calibration sources, as they can vary on even short timescales.



A Posteriori Calibration

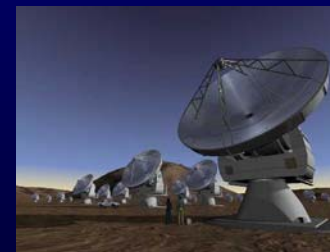


Types of sources which could be (and have been) primary or secondary calibrators:

- ☛ 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.

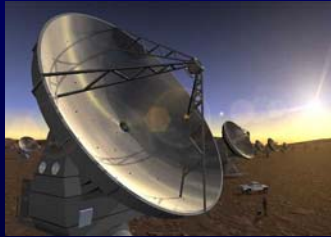


Calibration Devices



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 1% 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 a few months ago, we had been investigating two types of these load devices:

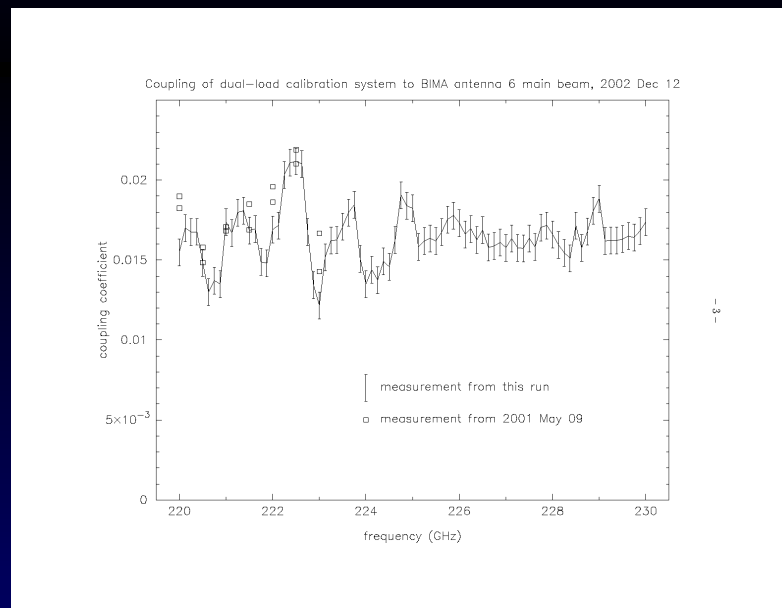
- ☛ dual-load in the subreflector
- ☛ semi-transparent vane



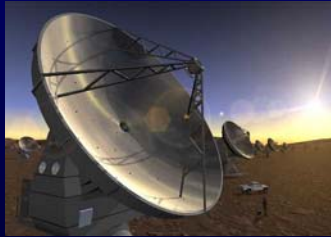
Calibration Devices Subreflector Dual-Load



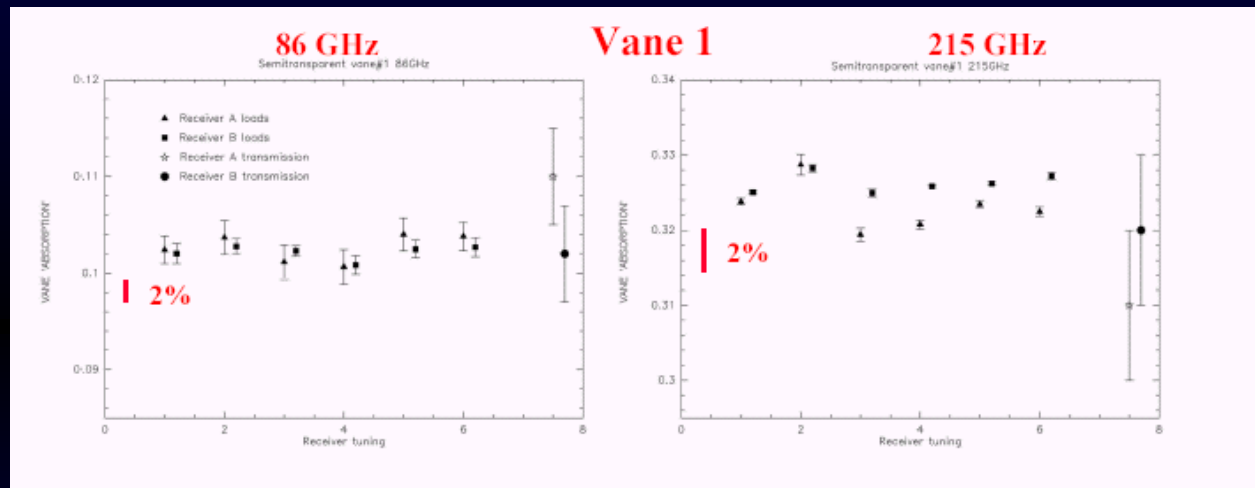
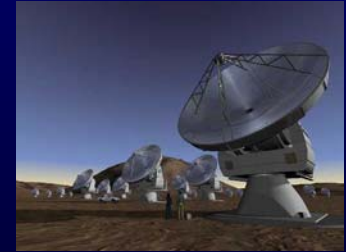
Preliminary tests have not been encouraging – the coupling of the loads to the feed seems to change unpredictably with time/ambient conditions.



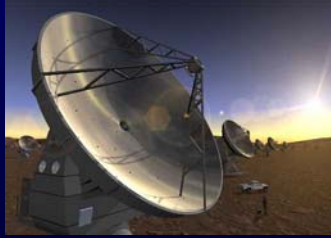
Variation as function of frequency shown at left (Bock, Welch, & Plambeck). Further tests showed differences in this spectrum of order 10% as a function of temperature and focus position (standing wave postulated but not certain).



Calibration Devices Semi-Transparent Vane



Preliminary tests have been more encouraging – see figure above (Martin-Pintado et al.). An accuracy of 3% 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 FE group has stopped all testing on these devices and materials.








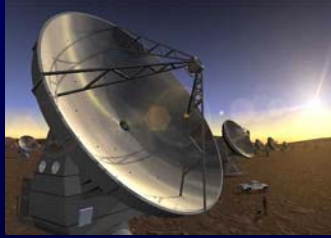
Calibration Devices

What we'd really like



Even having two loads is not enough, however, because of the problem of receiver saturation. The recent memo of Stephane Guilloteau (ALMA memo 461) has shown that what we really need to even hope to meet the current specification (1% or 3%) 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

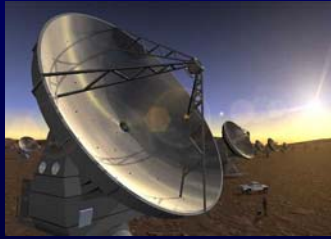
What we'd really like



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 %).

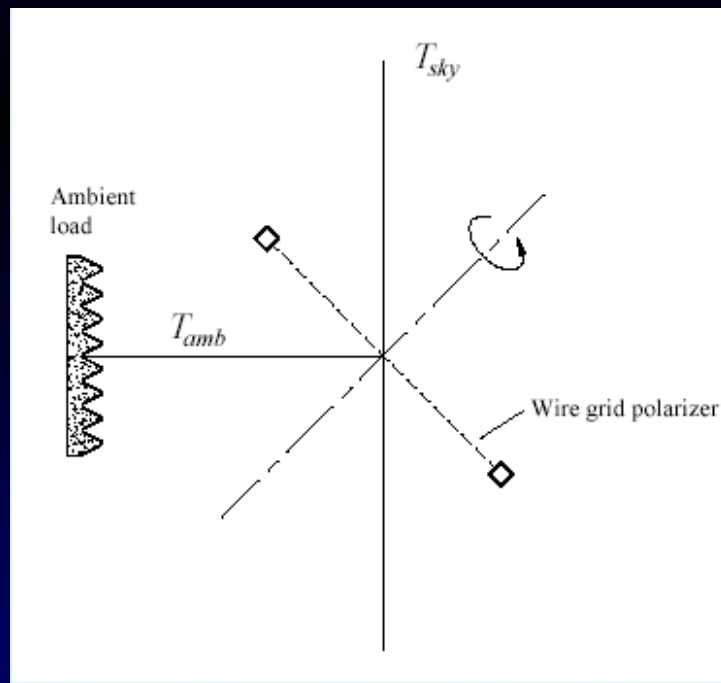
AND NOTE THAT THIS ASSUMES A GAIN STABILITY OF 1 PART IN 10^4 !






Calibration Devices Couplers

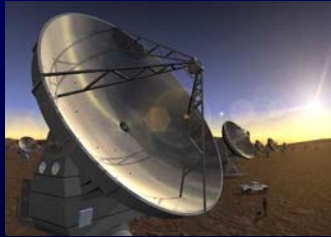


In any of these schemes, there must be some element in the device that couples signals from two loads into the beam:



There are three reasonable current options:

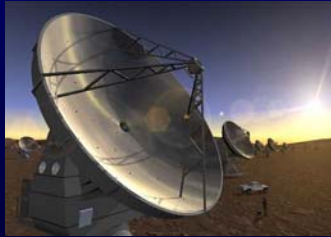
-  semi-transparent vane
-  polarizing grid
-  dielectric film



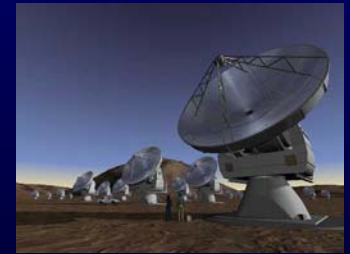
Calibration Devices Couplers - Comparison



	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%	~3% (@ mm)	?	?



Conclusions



- ☛ Make decision on *ab initio* vs. *a posteriori* (this might not happen until experience shows us how well we can do with *ab initio*).
- ☛ Need more studies of coupling elements and overall widget design.
- ☛ Have to pick few true primaries, and probably need some more observations + theory. Good current candidates: MWC 349, Titan, Uranus, Mars. Question: do we make measurements of the primaries ourselves or rely on others to do so for us?
- ☛ Decide on what to use for secondaries (probably QSOs and/or asteroids), and monitoring scheme for them.



Conclusions



- ☛ Will need good models of sky brightness distribution (I + pol'n) for all of them (primaries AND secondaries).
- ☛ 1% (or 3%, even) is highly unlikely. Can we get guidance from ASAC on loosening this req (can the DRSP help in this respect)? In particular:
 - ☛ Can we separate the overall flux density scale and the fluctuating part?
 - ☛ Can we get direction on how often this has to be met?
- ☛ There is a clear manpower problem – how to resolve it?