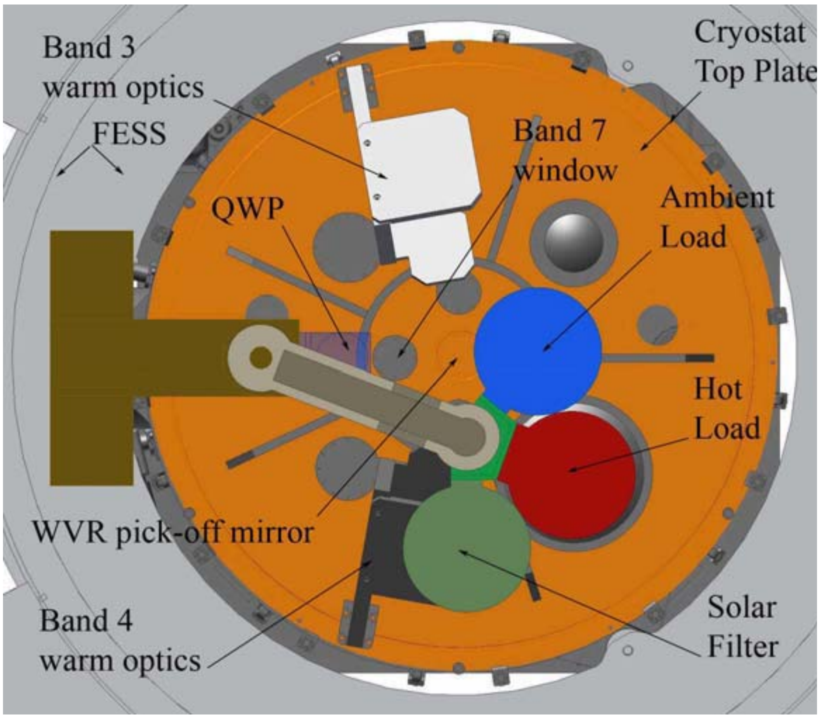
Status of the Calibration “Loads” for ALMA

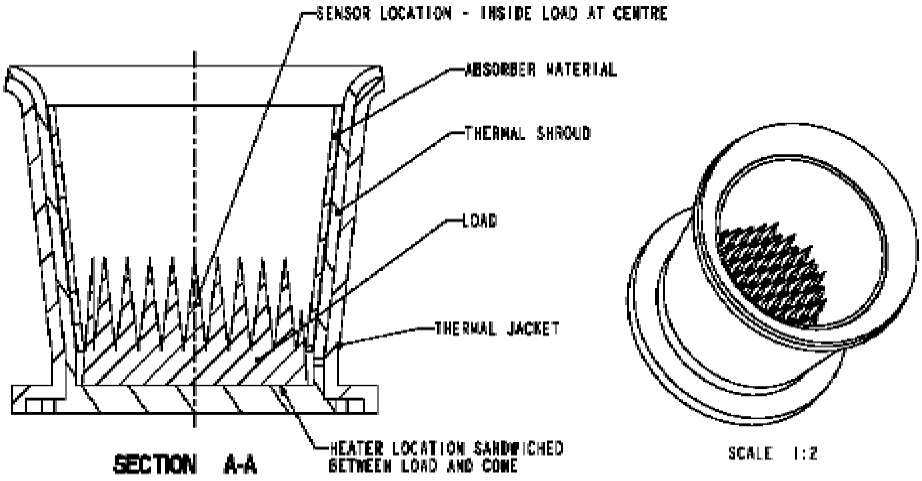
1 Background

It was decide some time ago that the reference sources that will be used for the amplitude calibration of ALMA would consist of two “loads” at temperatures of ~20 and ~70°C (although up to 100 °C should be possible) with emission approximating black-body radiation as closely as is practical. The design of the calibration unit is described in FEND-40.06.00.00-012-A-REP by Carter and Hidalgo. Here is a picture of the concept from that report[1]:



The development of the robot that puts the calibration loads at the right place in the beam is well advanced: the first units should be delivered early in 2008.

The form of the hot load adopted was a set of pyramids which are made of metal for good conductivity but coated with a millimetre-wave absorber. These are placed in a “pot”:



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[1] This diagram is somewhat out of date, in that the final version (see additional Figure at end) has actually got places for more devices on a “calibration wheel”.

Again the development of these loads has been going on for some time and it is expected that two will be available by early 2008 so that they can be installed on the first calibration units in time to be used for system tests in Chile.

In the design document, the required accuracy for the temperatures the loads is given as +/–0.3K for the ambient load and +/–0.6K for the hot load. These values can be justified by looking at the sensitivity of the derived values of system temperature to errors in the effective temperatures of the loads and comparing the results to the required ALMA calibration accuracy.

2 The Problem

The effective temperature of the load is affected by a number of things:

1. obviously the actual physical temperature, as determined by thermometers embedded in the structure of the load,
2. temperature gradients between the temperature sensors and the actual emitting surface. These will depend on IR cooling and convection (both that due to the gradients in the air temperature which in turn depend on the orientation, and that due to the forced air circulation produced by the HVAC system).
3. the emissivity of the load, and crucially,
4. the backscatter characteristics of the load.

One way to think about this last item is to consider the load and the receiver as two bodies of different temperatures at opposite ends of a cavity. Because neither body is perfectly black, a standing wave will be set up in the energy that is exchanged between them, resulting in a ripple on the signal that is detected. This will have an amplitude of order $2\ \Gamma_{\mathrm{load}}\ \Gamma_{\mathrm{rec}}\ (T_{\mathrm{load}} - T_{\mathrm{rec}})$. Here Γ_{load} and Γ_{rec} are the voltage reflection coefficients of the load and the receiver. Since the temperature difference is ~300K we need the product $\Gamma_{\mathrm{load}}\ \Gamma_{\mathrm{rec}}$ to be below 5×10^{-4} just to have the amplitude of the ripple match the requirement of +/–0.3K for the ambient load. Clearly we need to do somewhat better than this to allow for the other sources of error listed above. In terms of dB, this means that we need the sum of the return losses for the load and the receiver be better than (i.e. more negative than) about –66dB. Unfortunately the receiver is not likely to have a good return loss: probably not much better than –10dB in this context[2]. Clearly we should be aiming to make loads with a return loss of at least –56dB in the case of the hot load and –60dB for the ambient load.

We now have the test report FEND-40.06.04.00-005-A-REP by Murk and Duric, which includes a thorough study of the backscatter properties of the ALMA prototype loads as well as some alternative designs. The prototypes show backscatter values in the range from –50dB to –70dB over most of the frequency bands of interest, but unfortunately they perform quite poorly at frequencies below ~120GHz with backscatter of worse than –40dB. The report also includes radiometric tests made with at IRAM with a PdBI receiver that is reasonably similar to the ALMA ones. These test showed a substantial standing wave effect, which was at the level of ~1%, approximately confirming the numbers above.

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[2] This is probably a typical value for a millimeter-wave SIS mixer. There will almost certainly be reflections from other components. When the receiver is looking at the load, what it sees is the sum of the radiation from a large number of contributions from individual points on the load. The radiation from each of these arrives at the receiver as a roughly plane wave, some of which will be accepted but most of it which will not be and some will bounces back towards the load. For example only about half the energy that enters the mouth of a feed-horn actually goes into the waveguide, the rest of it is re-radiated (although not with the normal pattern of the feed). This means that even if all the other components of a receiver are well-matched, and there are no flat surfaces at normal incidence in the system, etc., the effective reflectivity will still be quite high. It could easily be worse than –10dB.

In their current form, without a barrier to cut down on IR emission, the ALMA prototype loads also show substantial temperature gradients (several °C) between the tips of the pyramids and their bases and these gradients vary with orientation.

3 Discussion

Clearly these results are disappointing, but the situation is by no means disastrous. For one thing, the separation between the load and the receiver is ~500mm so the period of the ripples will be about 300MHz. This means that for some purposes, for example where one is averaging over a full digitiser bandwidth of 2GHz, the effects of standing waves will be much reduced. We could not however tolerate the several degrees K of ripple implied by the results in the test report in all cases. For example some atmospheric features – e.g. Ozone lines – are narrower than this and some instrumental effects could be too.

One could also try to argue that the requirements of +/–0.3 and 0.6K on the knowledge of the effective temperature of the loads were too tight. I have looked at the simulations carried out by Balthazar Vila-Vilaro and the derivations in several ALMA memos (e.g. 434 and 461) and it seems to me that they cannot be significantly relaxed if we are to achieve the specified amplitude calibration accuracy.

It is nevertheless clear that the prototype loads will be perfectly adequate for the initial test phases where we are sorting out all the procedures, control systems and data reduction methods.

Fortunately there are a number of alternative concepts that should be able to provide the performance we need. In particular cones – probably made mainly of metal to provide good thermal conductivity but lined on the inside with a suitable absorber – seem very promising. These are discussed in the test report previously referred to. In addition I will send with this note a very useful “primer” on calibration loads by Axel Murk. The main difficulty is the limited height available in the axial direction, while the cones need to be long in order to have low return loss. This may mean that it is necessary to have a smaller aperture for the main loads which could then only be used for bands 3 and above. A larger load, operating at ambient temperature, would then occupy one of the “spare” locations on the calibration wheel and would be used for bands 1 and 2. The atmospheric transmission is sufficiently high at these frequencies that a single-load calibration technique is almost certainly good enough.

A further alternative is to use condensing optics in front of a smaller cone. This has the advantage that IR blocking could be incorporated more easily, but this scheme is becoming quite complex for what ought to be a rather simple element of the entire ALMA system.

4 Recommendation

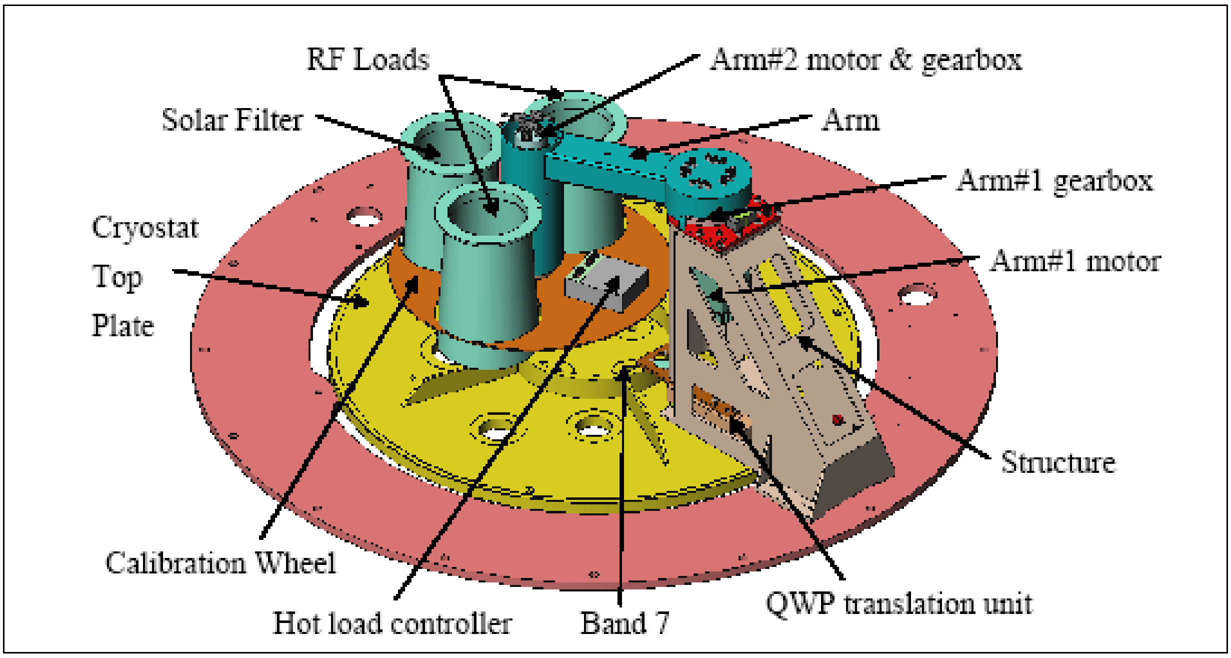
Clearly this all needs to be discussed by the Calibration group and more widely, but I suggest that we should:

1) Continue the procurement of two sets of loads to get us through the initial test phases.

2) Confirm the figures in the calibration design document as being the requirements for the knowledge of the effective black-body temperatures of the loads when used with the ALMA receivers at all frequencies of interest. (As a slight softening here, we could set the specifications at +/-0.5K for the ambient load and +/-1K for the hot load, while maintaining the values of +/-0.3K and +/-0.6K as goals).

3) Start immediately on a program to develop an alternative design of load that does meet these requirements. I am myself convinced that the cone design is sufficiently promising to make this worthwhile, but clearly we should not start on such a study without a clear understanding of what is to be done and on what timescale.

Here is another illustration of the concept of the calibration device.



Note on this sketch: the loads and the solar filter shown here are just placeholders and do not represent the actual design. More devices (calibration loads) could be placed on the calibration wheel but weight and dimensions must conform to the design limits. If more loads are placed there could be potential blockage of beams in one of the parking positions. This is not a major problem but it should be noted that in this case the calibration wheel would need to be moved to the second parking position to free the blocked beam.

Richard Hills (with input from Axel Murk and Ferdinand Patt) 10th Aug 2007