ALMA Memo 352 - Design and Development of 183GHz Water Vapour Radiometers

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Summary

This memo describes the plans for the development of the prototype 183 GHz radiometers for ALMA. It is planned that such radiometers will be used to correct for the phase errors introduced by water vapour in the atmosphere. One radiometer will be mounted on each of the antennas and will provide real-time measurements of the brightness temperature of the atmosphere at frequencies near the 183 GHz emission line of water. These measurements will be used to estimate the path fluctuations that are caused by the variations in the amount of water vapour along the line of sight from each antenna. Even on a good site corrections for these fluctuations will be needed for much of the time, especially at ALMA higher frequency bands and on long baselines. A substantial amount of work on the design of the radiometers has already been carried out, so this document contains a description of the instruments to be built, at the level of a conceptual design. Two radiometers of somewhat different designs, but with most components in common, will be built and tested. The intention is to develop a cost-effective and reliable final design suitable for production in quantity. It is expected that the prototype radiometers constructed here will subsequently be used for tests in the field, both to sort out compatibility issues with the rest of the ALMA system and to develop the phase-correction techniques further. The project is being carried out as a collaboration between Chalmers and MRAO.

Introduction

In ALMA memo 303 the requirements for phase correction were set out and possible technical solutions were reviewed. That paper was discussed by the ALMA Science Advisory Committee (ASAC), who agreed that work in this area was a priority for the project and made certain recommendations regarding the specifications and approach to be taken. Those recommendations have been taken into account in these plans.

There are in fact several aspects to the phase correction problem that need to be pursued in parallel. These include:

1. The design and testing of a prototype instrument, suitable for series production (~64 off), matching ALMA's interfacing requirements, and with long life and low maintenance;
2. Further experimental testing of 183 GHz radiometers in the phase-correcting role and gathering more information about the nature of the phase fluctuations on the site; and
3. Modeling of atmospheric profiles to investigate effects of temperature, pressure, scale size, etc.

Although we expect to have some involvement in all three of these activities, this memo is mainly concerned with the first one. That is, it is focused on finding the optimum hardware configuration for the ALMA system and building prototypes to test these designs. (Two prototypes will be built because it is clear that tests on an interferometer will be essential for proving the final design.) It is however important that work on the other aspects proceeds in parallel, and indeed some information from those studies is needed to guide the design of the instrument. There are, therefore, some sections on those topics at the end of this document.

Specification

The essential requirement is that the radiometer must be able to provide sufficient information to give a reliable estimate of the phase delay suffered by the astronomical signal arriving at the antenna. As discussed in ALMA memo 303, we adopt a figure of $10(1 + w_v)$ microns of path, rms, (where w_v is the water vapour along the line of sight in millimetres) for this basic requirement. This should be achieved with a time resolution of 1 second and be maintained over time periods of up to 5 minutes and for changes in zenith angle of up to 1 degree. (These latter numbers are related to the need to make observations of reference sources from time to time. Note that it is actually the change in air mass that is likely to be important rather than just the change in zenith angle, so this last number should be refined after further consideration.)

A second possibility is to use the radiometer to correct the "tip-tilt" errors introduced by the atmosphere at the individual antennas by measuring the gradient of the water vapour content across the aperture. The accuracy needed here corresponds to pointing errors of about $0.3(1 + w_v)$ arc seconds, rms, with the same conditions as for the path. Following the discussion by the ASAC, we are not adopting this as a requirement at this stage of the project, but treating it as something that might be incorporated later. This means that we will try to avoid designing out the possibility of doing single-dish pointing corrections but we will not allow it to become a driver in the design.

A third possible application that has been suggested is to use the radiometers to correct for the broad-band *emission* from water in the atmosphere that will appear as a spurious fluctuating signal when the antennas are being used for total power observations, e.g. in a rapid scanning mode. The assumption here is that the mostly rapidly changing source of total power fluctuation is the emission from the water molecules in the line of sight. This water will be detected by the 183 GHz radiometer and in principle a correction can be made to the signals received by the astronomical receiver. This has not yet been analyzed in detail but will clearly require good sensitivity and stability. At this stage we propose simply to note this as an additional reason for trying to achieve as good a performance as possible from the radiometers without incurring substantial additional costs.

Other requirements are that the radiometer must be compatible with the optical, cryogenic and mechanical arrangements in the receiver cabin, use the same control interfaces, and cause a minimum of interference with other systems. A special problem is leakage of the local oscillator (LO) and its harmonics into other receiver systems. Schottky mixers require a relatively high level of LO and it would be hard to avoid this leaking into the SIS mixers if the radiometer is in the same Dewar as the astronomical receivers. If they are separated there will still be coupling by signals coming out of the feed and being reflected off the subreflector. (In this case a bandpass filter at radiometer input can be used to reduce the harmonics of the LO to more acceptable levels.) The LO's should therefore be locked to the main receiver system's frequency standard so that any interference is at an accurately defined frequency. The design will use the fixed reference frequencies already provided at each antenna. At present we have allowed for the requirement that the LO can be shifted by a small amount so that any interference can be moved away from a critical line, but this could be dropped if it proves unnecessary. It is also true that in principle interference from other parts of the ALMA system could cause problems for the operation of the radiometer. In practice this is not likely to cause a problem since the radiometers are less sensitive than the astronomical systems, so a reasonably well-shielded design should be adequate. Emission in the band 175 to 191 GHz by other ALMA systems should be avoided.

Technical Description

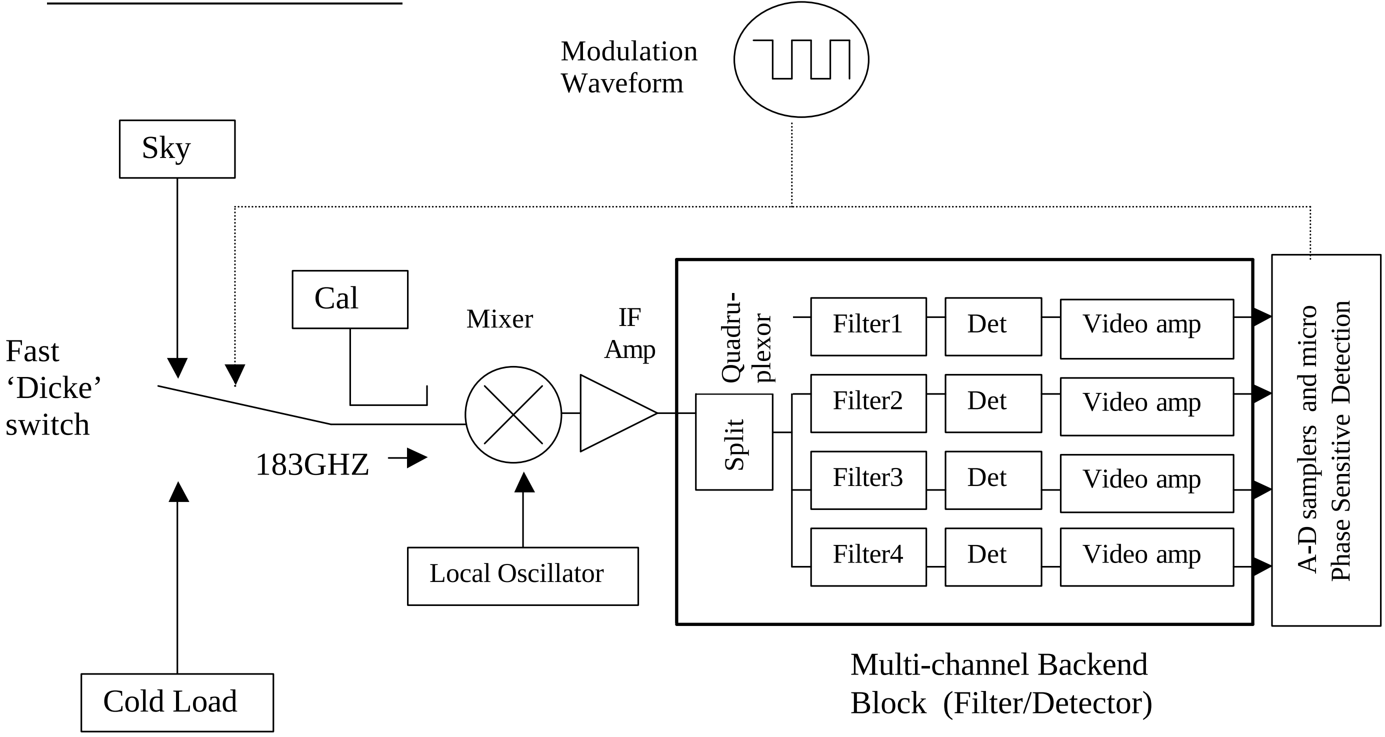
A wide range of options for such things as the type of mixer, the form of switching and the type of backend were considered in ALMA memo 303. We have studied these issues intensively over the past few months and investigated factors like the availability and performance of components, system complexity, costs and manufacturability. In general we have been able to select solutions that are relatively conservative technically, so that a large number of reliable systems can be produced without requiring exceptionally skilled staff. In particular we plan to use Schottky mixers (subharmonically pumped at an LO frequency of 91.65 GHz), to employ commercially available IF amplifiers (covering at least 1 to 8 GHz) and to use filters in the backend. We have also considered carefully the question of whether the radiometers should be cooled or should operate at near to ambient temperature. We have concluded that the cost and effort involved in building cooled systems is not justified, since it appears that well-designed uncooled receivers should meet the sensitivity and stability requirements with an adequate margin. These points are discussed in more detail below.

In one important area, the form of switching to be employed, we have concluded that it is not practical to reach a firm conclusion at this stage and we are therefore proposing to keep this choice open until we are in a position to perform definitive practical tests. We have, however, narrowed the options to just two: quasi-optical Dicke-switching and cross-correlation. The design we have adopted enables us to test both of these with a common set of building blocks.

Radiometer Configuration

The following discussion of the two proposed configurations will also serve to introduce the various components that go together to make up the radiometer.

Dicke-switched Radiometer



Here the 183GHz signal reaching the mixer is switched rapidly (at say 40Hz) between the "Sky" (the signal we want to measure) and a "Load" (a black body radiating at a well-determined temperature). If at all possible, this load will be cold, i.e. at ~ 100K. A calibration signal is introduced ahead of the mixer but after the switch. (This assumes that we can rely on any losses in the switch being stable – see below.) The "Cal" signal needs to be quite large – probably equivalent to 30-50K – and it will also be modulated, but at a different frequency to the Dicke switch (almost certainly at a multiple or a sub-harmonic of the Dicke-switching frequency). The broad-band IF signal is amplified and split into a number of channels which pass through filters to diode detectors. The filters define the bands to be measured. Since the mixer operates in a double-sideband mode, with the LO frequency equal to that of the line, the frequencies of these filters set the offsets from the line centre, which will range from ~1 to ~8 GHz. Four bands are shown here, as this seems the most likely number, but more study of this is needed, as discussed below. After detection and 'video' amplification, the signals are sampled and digitized. Phase-sensitive detection and calibration is performed in the microprocessor to convert the signals to brightness tempeartures.

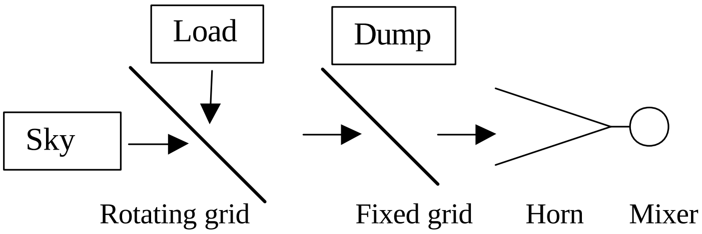
Notes:

1. Because of the large bandwidths employed (up to 4 GHz), rapid switching is required. The radiometers currently in use for ALMA site-testing have a 2 Hz switch rate but this has proved to be too slow to achieve the theoretical sensitivity because of gain fluctuations. The current system achieves ~2 parts in 10^4 over ~1 second. If we assume (pessimistically) that the gain fluctuations scale as 1/root(f), then a 40 Hz switch rate will ensure that their effects are reduced to below 10% of the total noise even with a 4 GHz IF bandwidth. This switching rate of 40 Hz can be achieved easily with electronic switching but will be difficult with mechanical devices, so investigations will be undertaken to find what short-term stability can be achieved I practice. This will allow the optimum switching rate to be determined.
2. Switching rates of greater than a few Hz are too fast for the "flip-mirror" design used on the existing radiometers. A spinning chopper wheel could be used, but it is hard to obtain a good duty cycle: diffraction effects when the edge of the chopper is partly across the beam would produce spurious results. Electronic choppers, such as ferrite devices, can go fast but are very lossy at these wavelengths. Mismatch and the associated standing waves are also likely to be problems with many types of switch. We have therefore selected a polarization switching scheme, described below, as the most promising.
3. The mixer will be a Schottky-diode device driven at half the line frequency e.g. 91.65 GHz. Such sub-harmonically pumped mixers are available from several sources and should provide DSB noise temperatures of well under 2000 K uncooled and probably more like 1400 K. Sub-harmonic pumping makes it easier to achieve the large IF bandwidths required and makes an LO coupler unnecessary. In general these devices can be cooled and the performance at around 80 K would then improve by at least a factor of two or, more probably, three. Devices characterized for cold operation are however substantially more expensive.
4. The LO will be a Gunn oscillator. This requires only modest power (~ +14dBm) and no significant tuning range. It is not practical to cool Gunn oscillators, so for a cooled system the LO has to be brought in on waveguide or a quasi-optical arrangement, which would raise concerns about stability and complexity.

5. The IF amplifier will be broad-band, covering at least 1 to 8 GHz. There is no problem with obtaining these commercially. A noise figure of 1.4dB (max) is the current state of the art, with a power dissipation of ~3W. A low-noise first stage that can be cooled and produces less heat (~ 1W) is available from at least one manufacturer, although again the cost increase is substantial. The cable between the mixer and the IF amplifier must be very short. If at all possible the total gain and power-handling capacity of the IF amplifier chain should be large enough to drive the detectors following the filters without having additional gain stages in the separate channels. The total IF gain required is about 70 dB, so it should be possible to provide this with two packaged amplifiers in series.
6. The frequency-multiplexing and filtering should be compact and designed for good stability. If possible the band-passes of the radiometers on different antennas will be matched to sufficiently high precision that they have the same response to a given amount of water. How good this matching needs to be will be a subject of detailed study. If sufficiently good matching of the filters cannot be achieved, then a calibration method which can determine the responses easily will need to be worked out.
7. We propose to use relatively rapid digital sampling, with modest precision – e.g. 12 bits at 5 kHz – and then do the demodulation digitally. This is more flexible than the traditional method, which would have been to employ analogue phase sensitive detection and integration followed by slower digital sampling. Digital demodulation is also more sensitive with the sinusoidal modulation that will result from polarization switching.
8. Since the system is essentially fixed-tuned, with a total RF band-width of ~16GHz at 183GHz, i.e. under 10%, we can use a relatively simple feed-horn which will be easy to manufacture. A Pickett/Potter design, which has low return loss and essentially the same sidelobe performance as a corrugated horn over such a bandwidth, appears suitable.

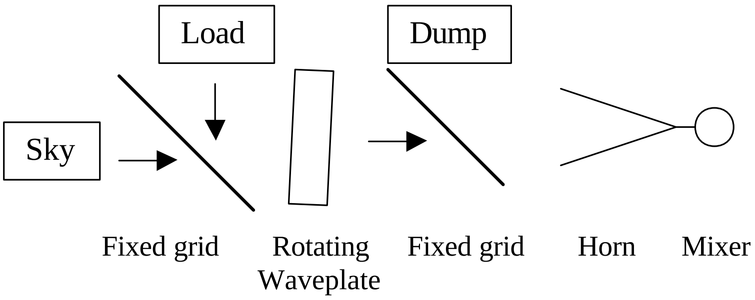
<u>Polarization switching</u>:

One form of Dicke switch which is compact and gives a clean separation of the two inputs is the "polarization switch". The simplest way of doing this is to use a rotating grid:



The grid rotates around an axis perpendicular to its plane so that the mixer, which detects only a single polarization, observes a linear combination of signals from the sky and the load. The ratio varies as the grid rotates producing an (almost) sinusoidal modulation at twice the rate of rotation, i.e. 1200 rpm is need for 40 Hz. Suitable bearings to hold the grid are available with very long life and low run-out. The second, fixed, grid makes sure that any cross-polar components in the response of the horn are terminated on the Dump, which is held at a fixed temperature.

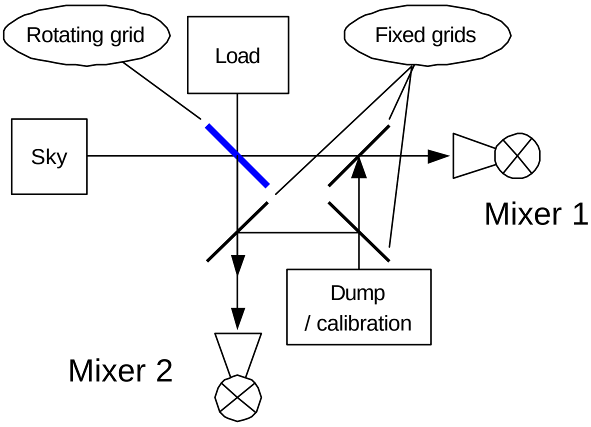
A variation of this scheme is to use a fixed grid to combine the signal from the sky and the load and then a rotating waveplate before the second grid and the mixer.



The rotating waveplate needs to have the property that the optical thicknesses for the two orthogonal linear polarizations differ by half a wavelength. The result is that the plane of polarization of the transmitted beam rotates with respect to the input at twice the rate of rotation of the waveplate, i.e. rotation at 600 rpm would give 40 Hz modulation. If the waveplate is solid it can be mounted on a shaft rather than enclosed in a bearing. The most obvious material to use is crystalline quartz, which would be coated with PTFE and probably tilted slightly to reduce reflections. The question of reflections and what spurious modulation they cause will need detailed investigation in the next phase. A quartz plate would however need to be quite thick (~17mm), so alternatives, such as grooved dielectrics, are likely to be more attractive and will be investigated.

Either of these schemes should provide a switch with low and very stable losses and with low reflections of spurious signals and of the LO leaking from the mixers.

A complete second channel (mixer, filters, etc.) can be added to take the reflected signal from this grid. We can use a single LO source to feed both mixers via a power divider. This improves the sensitivity by root(2) and gives full redundancy. We plan to do this in the prototype version so that any problems associated with this approach are fully explored. A possible RF arrangement for a dual-polarization system with Dicke-switching rotating grid would be:



A drawback with both rotating grids or waveplates as methods of switching is that the modulation has only a sinusoidal form. This leads to a factor of root-2 reduction in sensitivity compared to schemes in which the modulation is a square-wave. Alternative modulation schemes which produce a closer approximation to square-wave chopping will therefore be investigated. A conventional rotating reflective chopper is the fall-back solution.

Correlating radiometer

The alternative to Dicke-switching is to use a continuous-differencing scheme, which is in effect a cross-correlation receiver. In this case the 183GHz signals from the Sky and the Load are each split into two equal parts in the input hybrid and fed to two Schottky mixers. The hybrid can take either a waveguide or a quasi-optical form, but in either case it is effectively a 180-degree hybrid, which means that the Load signal entering one mixer is inverted relative to that entering the other whereas the Sky signals are in phase. The two mixers down-convert these signals and they are then amplified in the two IF amplifier chains. The signals are then split again and recombined using wide-band hybrids.

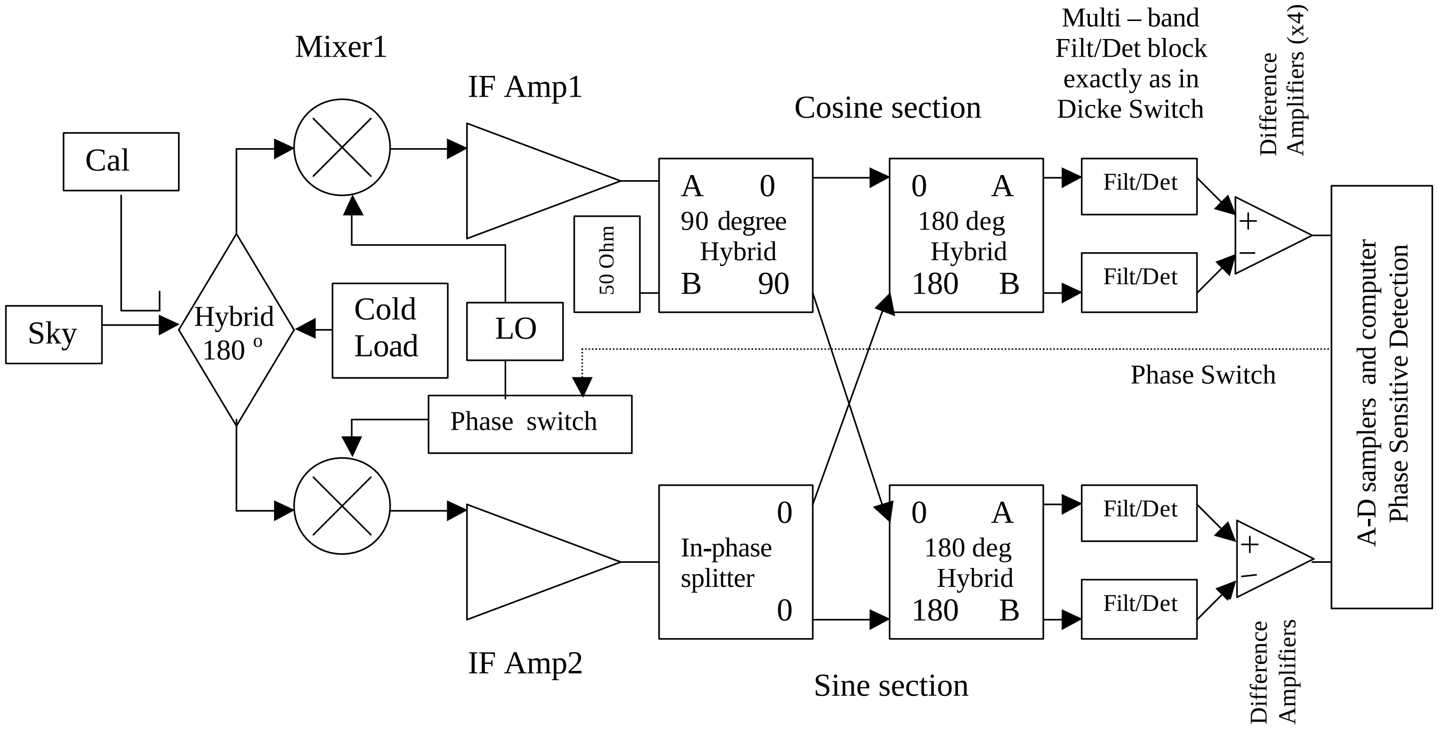
For an ideal realization of this scheme, the final outputs of the Cosine and Sine channels are proportional to:

$$C = G_1 * G_2 * (T_S - T_L) * \cos(\text{Ø})$$

$$S = G_1 * G_2 * (T_S - T_L) * \sin(\text{Ø})$$

where G_1 and G_2 are the (complex) voltage gains of the two channels and T_S and T_L are the brightness temperatures of the Sky and the Load. The phase Ø contains several terms including the relative phase of the LO injected into the two mixers, which has the opposite sign for the upper and lower sidebands. This means that with a suitable pattern of phase switching and demodulation it is possible to separate the upper and lower sidebands, which will help to eliminate contaminating signals and perhaps to separate out any emission from water or ice droplets.

The full version of this scheme would be as follows:



Notes:

1. There are no moving parts, which is a major benefit in this application. Apart from losses in the input hybrid, the sensitivity is a factor of root(2) better than for a single-channel Dicke-switched radiometer. The price paid for this and for eliminating the mechanical hardware is of course that rather more than twice as much electronic hardware is needed per radiometer.
2. The gain multiplies only the temperature differences between the sky and the load. This reduces the sensitivity to gain fluctuations by a large factor, especially when the temperature of the load is close to that of the part of the line which gives the best estimate of the path length being introduced by the water (typically 120-170 K).
3. Phase and amplitude matching in the RF and broadband IF sections are only important *within* the bands of the individual frequency channels and most of the resulting errors will be removed by calibration and switching anyway. Phase errors within the filters do not affect the result because the signals have already been combined at this point.
4. A key problem with this system is leakage of the LO and its harmonics from one mixer to the other. This will require careful investigation: good isolation in the hybrid will be required and we should try to use a switching sequence that cancels any residual offsets.
5. Apart from the hybrids, the main building blocks, i.e. the mixers, LO's, IF's, filters, detectors and digitizers, are essentially identical to those needed for the Dicke-switched system.
6. Somewhat to our surprise, suitable hybrids do appear to be available commercially, both at RF (183 GHz) and at IF even for wide bandwidths (1 – 8 GHz). For the 183 GHz input, it appears that a waveguide ring hybrid offers the best combination of low loss, high isolation and just sufficient bandwidth, although a "magic-T" is also attractive. If the real performance does not match the claims, then a quasi-optical scheme using grids should work very well, although it would be somewhat more complex to build and alignment might be rather critical.
7. We plan to use two separate Gunn oscillators, locked to a common reference, to provide the LO's. This ensures good isolation and means that the phase switching can be inserted digitally in the PLL. Two low-powered Gunns may well be cheaper than one high-powered one anyway.
8. If sideband-separation is *not* required, then the Sine channel is not really needed, although more careful phase matching would then be required. (Even the phase switching is then not strictly necessary, but in practice this is extremely helpful in removing offsets and drifts so we definitely plan to include that.)

It can be seen that the choice between Dicke-switching and cross-correlating schemes involves cost, performance and reliability issues. Making a final decision now would require us to make guesses about some of these factors and this implies some risk. We have concluded that, given the scale of the project, the correct course is to carry the development of both these approaches through to the engineering prototype stage. This will make it possible to reach a conclusion based on firm data rather than hypothesis. Given the high degree of commonality in the two schemes, and the fact that we will in any case need two prototypes to make tests on an interferometer, the development costs are only slightly higher than if the choice were made now. If a major unforeseen problem arises with one scheme then that will of course be dropped.

If, at the end of the test phase, one design has been proved to have substantially better performance than the other, then the poorer one will be converted to the better design before tests are performed on an interferometer. This will be relatively cheap and easy given that many parts will be unchanged and the other parts only need to be copied. If the performance is similar then it will probably be better to proceed to the next phase with the prototypes as they are. Costs and practical considerations would determine the choice of production design in that case.

Cooling

The ASAC commented that, although this is essentially an engineering decision, cooling would be advantageous because it provides additional sensitivity and would also help to ensure that the radiometer is stable. We estimate, however, that even a single-polarization Dicke-switched radiometer with 2000K system temperature (i.e. uncooled), 1 GHz bandwidth and a 1 sec integration time would have a sensitivity of ~0.13K. With 1mm of precipitable water vapour this corresponds to a path length error of about 10 microns, which is already a factor of two below the specification. Our goal, for both the systems described above, is to achieve a further factor of two better sensitivity than this. We also believe that a well-designed receiver with good thermal regulation at say +40C can be made to have just as good a gain stability as a cooled system. The only strong case for cooling the radiometers therefore appears to be that it would provide the additional sensitivity that might be required for single-dish pointing corrections or continuum subtraction.

Cooling the radiometer adds considerably to the costs and effort involved. As noted above, more expensive components are needed, together with more complicated arrangements for bringing in the local oscillator power. Substantial additional work on packaging would be required and new problems such as making very low-loss windows and keeping them free of moisture would have to be addressed. If cooling were to be used, a choice would have to be made between having a stand-alone system and installing the radiometer in the main receiver Dewar. The former is not in fact very expensive: suitable coolers for say 90K are available commercially with several Watts of cooling power at around $7.5k, including the small compressor which consumes about 500W of electrical power. An additional cooler would however be an unwelcome operational complication in the final ALMA system. Installing the radiometer in the receiver Dewar would make the interface with the rest of the system much more complicated and is likely to create interference problems.

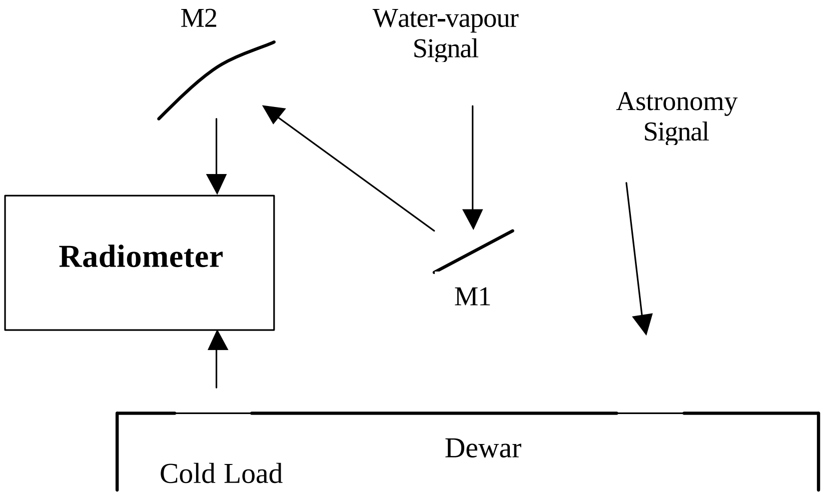
Given that cooling does not appear to be essential and that it would make the project take longer and be more expensive, we plan to develop only uncooled systems. The predicted performance, taking full account of all likely sources of noise and loss, will be reviewed at the PDR. We expect to be able to demonstrate that these can meet the requirements, as they are presently perceived, quite comfortably. If it is decided however that more sensitivity is required, then cooled systems could be developed as a further step, although the cost and effort required would increase. The work on uncooled systems would be by no means wasted since almost all of the concepts and techniques and many of the components would remain unchanged.

As noted above, a cooled reference load is likely to give a substantial advantage, even if the rest of the radiometer is uncooled: it would provide better stability and make the calibration easier. We will therefore develop suitable cooled loads as part of this project.

The cold load may be either a quasi-optical type or a terminated waveguide, depending on other choices in the system configuration. In either case the critical requirements are that it have lowreflectivity and that it maintain a very stable and accurately-known temperature. For the prototype systems these loads could be free-standing and cooled by liquid nitrogen, although other possibilities, such as Peltier cooling, will be explored. If a satisfactory cold reference load with its own simple cooling arrangement can be provided, this is probably the best overall solution for the final system too. If not, then this load would need to be located in the main receiver Dewar, where it should take up a rather small amount of space and add only modestly to the heat load on the first stage of the refrigerator. If a waveguide load is used then this should present a very simple interface to the receiver system. A quasi-optical system makes the problem somewhat more difficult, in that the issues of vacuum windows and optical alignment would need to be addressed. Since this is the worst case, it should for now be assumed that the water vapour radiometer will need access to one port on the main receiver Dewar containing a quasi-optical cold load. For a range of practical reasons, including development, testing and keeping the interfaces simple, it is however clearly better for the water-vapour radiometer to be self-contained. The preferred solution is therefore an internal Peltier-cooled load, so this will be the initial goal.

Optics

The optical arrangement that has now been adopted for the astronomical receivers has them positioned on a series of rings of different radii with the central on-axis position left clear. The pick-off mirror for the water vapour radiometer, M1, will be located in this central position ensuring that the radiometer beam is always reasonably close to the astronomical one. The offsets are around 5 arc minutes for the high-frequency receivers and a little over 10 arc minutes for the low-frequency ones. M1 reflects the signal to a refocusing mirror M2 which produces an image of the secondary mirror inside the radiometer.



It is easy to change this optical arrangement to allow for correction of the single-dish pointing. The mirrors (M1 and M2) would then be approximately twice as large and further apart so that only half the secondary mirror would be illuminated. M1 would be equipped with a beam-steering system so that the radiometer's illumination pattern can be moved rapidly between 4 positions on the secondary, which would allow the gradients in the water content of the path to be measured.

Other Technical Issues

A stable noise source is required to provide calibration. It would be possible to do this with an ambient temperature or warm black-body load connected to the input by e.g. a mirror that is flipped into the beam from time to time. It would however be better to have a continuous calibration added through a coupler (as indicated in the block diagrams) and to modulate this signal electronically so that no moving parts are need. A millimetre-wave noise diode would be ideal for this. We have not found a source of these for frequencies as high as 183 GHz but they are sold for 110 GHz. It is likely that these devices will in fact provide adequate power at the higher frequency in a suitable mount. This option will be the first to be tested.

In the outline design above, the IF system consists of filters and square-law detectors with suitable systems for combining and differencing the signals. An alternative based on an analogue delay correlator has also been considered but looks less attractive at this time, for two reasons:

1. It appears difficult to obtain the large fractional bandwidth (a ratio of ~8 to 1) without having an additional stage of up- or down-conversion, which adds to complexity and expense.
2. The total bandwidth of the present designs is only about 4 GHz, which is not really sufficient for our purposes: two of the currently available units would be needed, together with a down converter.

This issue will however be kept under review. Delay correlators are being built for the 22 GHz water-vapour radiometers on BIMA and wider bandwidth devices are under development.

With the filter solution we can chose the bandwidths to obtain the best performance at each frequency: we use narrower filters close to the line centre, where the emission is strong but changing rapidly with frequency, and wider ones further out to give more sensitivity where the water emission is weaker. As an example, the four filter bands might be 0.8 – 1.3 GHz, 1.5 – 2.3 GHz, 2.6 – 3.8 GHz and 4.2 – 8.0 GHz.

The Phase-Lock for the Gunn oscillator will use an existing design based on digital phase-frequency chips. A variety of schemes to do this using the standard frequencies available from the ALMA reference system appear to be possible. For example we can generate a microwave reference frequency of 11.5GHz (92 times 125MHz) and lock the Gunn to the 8th harmonic of this with an offset that could be –375MHz (3 times 125MHz) +/–15.625MHz (125MHz divided by 8), so the Gunn is at 91.61 or 91.64 GHz. The division by 8 provides the opportunity to introduce digitally-controlled phase shifts, while changing the sign of this term would move any interference spikes in the astronomical signals by ~100 km/s.

As already noted, the issue of leakage of the LO signal and its harmonics from the radiometer into the astronomical receiver is an important one. There are two levels at which such leakage could cause problems:
(i) the spurious signals are at a relatively high level such that, even when they are not in the astronomical band that is being observed (i.e. the part that is being down-converted to IF), they interact by driving the SIS mixers into saturation or by causing spurious intermodulation products.
(ii) at much lower levels, when they are in the down-converted band, they show up as narrow "spikes" on the detected output.

It appears that the first of these can be avoided quite easily. The maximum level at which we intend to drive the mixers is below +10dBm. This is at 91.65 GHz. This frequency will not propogate in the input waveguide connecting the mixer to the feed-horn and will therefore be very well contained within the receiver. The 183 GHz signals generated in the mixer will be at a level of around 0dBm and only a relatively small fraction of this should be radiated, so the signal coming out of the radiometer should be in the range –5 to –15dBm, depending on how well balanced the mixer diodes are. (Higher harmonics of 91.5 GHz will also be present, but at substantially lower levels. It is planned to remove these with a quasi-optical band-pass filter at the input to the radiometer unit. Such filters can provide attenuations of at least 30 and probably >40 dB without causing excessive losses over the operating band 175 to 191 GHz.)

So long as the optics are carefully designed the strongest coupling path between the radiometer and the astronomical receiver will be reflections from the secondary mirror. The loss over this path at 183 GHz is approximately 55 dB if nothing is done to treat the centre of the secondary mirror, and substantially greater than this if a suitable scattering cone is placed there. The outcome is that even the 183 GHz signal seen by the astronomical receivers is at a power level no greater than that from a 290K black-body entering over the RF band of the receiver. Since the mixers need to be linear up to at least these levels (e.g. for calibration purposes) this should not cause a problem. A direct test of this will however be undertaken as part of the development programme. If absolutely necessary 183 GHz isolators can be installed in the radiometers which will attenuate the LO leakage by a further large factor. These would however produce a significant penalty in sensitivity.

Interference at the second level will be harder to avoid because of the great sensitivity of the ALMA receivers. There are however many more techniques available for preventing these signals from showing up on the final spectra. These include the fact that the phase rotation expected on astronomical sources will not be present and that the frequencies of the spikes can be moved (as described above) so that they can be identified and “cleaned” off. Initial estimates of the residuals suggest that only observations close to the 183 GHz water line itself will be seriously effected. Other methods of phase correction may have to be used when this line is to be observed in sources in certain radial velocity ranges. A means of turning off the LO power remotely will be provided so that there is no possibility of leakage of signals when the radiometers are not being used.

The Control and Data-acquisition will be carried out by a dedicated microprocessor interfaced to CANbus. We already have experience of this on the HARP project for JCMT. It is expected that laboratory testing of the prototypes will be carried out using standard commercial system (e.g. Labview). Selection of the microcontroller modules , etc., for the final systems will be made in discussion with those responsible for control and monitor systems for ALMA.

This completes the technical description of the radiometers. We now discuss briefly the other related activities that are being undertaken.

Atmospheric Modeling

A good deal of work has already been carried out on modeling the atmosphere to gain an understanding of how well we can expect to be able to correct the phase by using radiometers. This needs to be carried further and directed towards the particular requirements of the ALMA project. It is anticipated that this will involve collaboration with the other groups already working on phase-correction, which include BIMA, SMA, NRAO, OVRO, IRAM, Yebes and Nobeyama. We intend to use existing atmospheric codes to carry out this work rather than try to develop new ones, so the effort required should not amount to more than 3 to 4 person-months. The main topics that require attention are:

1. Choice of the optimum number and frequency distribution of IF channels. The number of 4 which has been assumed here seems plausible on the basis of what has been done so far, but estimates need to be made of how accurately the path can be determined over an appropriate range of conditions for the ALMA site. These results should then be compared with designs with either greater or smaller numbers of channels so a cost/benefit trade-off can be made.
2. The advantages of being able to separate the sidebands should be investigated. It is likely that this will help in separating out any emission from particles (e.g. ice in cirrus clouds) and perhaps emission from other species such as ozone.
3. The coupling of the radiometer and of the astronomical signal to the emission and refraction produced by the molecules in the atmosphere needs to be worked out more thoroughly, taking proper account of the near-field effects. When combined with the data being obtained from the ALMA site about the altitude and scale sizes of the turbulent layers, this will enable us to understand the constraints on optical arrangements, time-constants, etc.
4. The other possible applications mentioned in the introduction – correction of single-dish pointing and subtraction of continuum emission from total-power observations – should also be investigated more thoroughly through models.

More generally the work on the water vapour radiometers needs to be connected to that on the calibration of ALMA as a whole. Since the radiometers will measure the total amount of water in the line of sight rather accurately and will give indications of other parameters, such as temperature and pressure, it is likely that they can play a valuable role in the calibration of the astronomical data. We therefore expect that the post-doc to be employed on this project will keep in close contact with the work of the ALMA calibration group. This work is likely to require a further two to three person months of effort over the course of the project.

Test Program

Laboratory testing will be undertaken to establish the sensitivity and stability of the radiometers. This will include measurements of the effects of temperature and orientation as well as investigations of the statistical properties of the data the instruments produce to find noise floors, 1/f “knees”, etc. Direct comparisons of the two designs will be undertaken and any differences in their performance investigated so that the lessons learned can be fed into the final design.

As mentioned above, we need to find out what levels of CW power are acceptable to the ALMA astronomical receivers, especially those which include the 183 GHz frequency within their RF bands. These tests will need to be carried out in coordination with the groups responsible for the development of those instruments. It will then be possible to define the maximum leakage levels that can be allowed from the radiometers and laboratory tests to ensure that these are met will be carried out.

It has been suggested that the goal of this program should be to install radiometers on the two ALMA prototype antennas during the test phase at the VLA site. This will clearly be a critical test from a point of view of the engineering aspects (e.g. the optical, electronic and control interfaces) and it will also provide a check that the LO leakage problem is under control. Unfortunately the 183 GHz band will not be covered by the receivers on the test interferometer, so such tests will be limited to the leakage at 91.65 and 277 GHz.

The conditions on the VLA site are, however, so different from those at the ALMA site that this may not be very helpful for testing the performance of the systems and refining the technique. Proper tests of the technique require a high dry site and access to an interferometer. The most promising options appear to be working on Chajnantor with the existing 11GHz interferometers or working on Mauna Kea with the SMA and/or JCMT and CSO. Going to Chajnantor has the advantage of removing any questions about the relevance of the site, but the fact that one is working with small antennas and at relatively low frequencies means that the beams of the radiometers and the interferometer dishes do not sample the same section of atmosphere very closely, making interpretation difficult. Tests using the millimetre-wave telescopes on Mauna Kea would solve this problem, but they will have to be planned in collaboration with the SMA project and the people involved in linking the SMA to JCMT and CSO. It is probably still too early in those projects for them to make commitments to a test program which would be mostly aimed at support of ALMA.

Given these uncertainties, we have not yet prepared a specific plan for testing the radiometers outside the laboratory. It is nevertheless clear that a test phase should follow straight after the development work described here. Further work with the existing radiometers (built at MRAO and Chalmers) will be going on at both sites and any new information from this will be taken into account in the radiometer design.

Interfaces

The only significant interfaces between the radiometers and other parts of the system are with the receiver optics and the control and monitor system. Close liaison will be maintained with the optical design work at IRAM and RAL. The control system will use CANbus modules and will conform to the protocols and standards adopted for ALMA.

Deliverables

The outcome of the work outlined here will be two prototypes (one using Dicke-switching the other correlation) together with detailed test data from laboratory measurement. The Dicke-switched radiometer will be a dual-polarization system. A plan for testing these devices in the field will also be produced, along with recommendations for any hardware changes needed before those are undertaken (e.g. reconfiguring one radiometer so that it has the same design as the other if that should prove necessary). Recommendations for the design and manufacture of production devices will be provided, together with cost information and interface requirements. This will include design drawings for the prototype radiometers. It is anticipated that some further revisions to these are likely to be required, as a result of the testing, before they can be put into production.

Programme of work

The project will be carried out as a collaboration between MRAO and Chalmers. The division of work is as follows:

Chalmers	Development of Dicke-Switching system (including optics for this version) Noise source for calibration LO injection scheme for the Dicke-switched system Assembly and test of this version including temperature regulation and other infrastructure.
MRAO	Optical design Purchase and check-out of mixers and IF amplifiers LO’s and Phase-locks Microwave units i.e. filter/ detector combinations Correlation RF and IF sections Data acquisition and control Assembly and test of correlation version including infrastructure as above

To minimize risk it is intended to manufacture the prototype radiometers almost entirely from catalogue commercial items. Given the scale of production planned, it is likely that more compact and economical systems can be built using custom designs for some components. An important activity is therefore that of identifying companies who are able to carry out such work and getting them involved. We also need to identify firms who would be able to perform the assembly and testing of the production systems. Some initial work in these areas has already begun and will continue at both MRAO and Chalmers in parallel with the prototype development work.

Timescales

The project is expected to take two and a quarter years in total. Most of the money for equipment will need to be committed rather early in the project, so it is proposed that a detailed Design Review will be held approximately four months after the start of work (i.e. when systems analysis and component selection has been completed). A Status Review will take place at the beginning of systems integration.

Acknowledgement

Many people have contributed to the ideas set out in this memo. In particular Andy Harris made a number of very valuable comments and suggestions. We greatly appreciate all the help we have received.

ID	Task Name	Duration	Start	Finish
1	**CHALMERS**	**98 wks**	**Mon 15/01/01**	**Wed 12/03/0**
2	Project Management (Chalmers)	98 wks	Mon 15/01/0	Wed 12/03/0
3	Development of Dicke Switch Front end	50 wks	Mon 15/01/0	Mon 04/02/0
4	Calibration noise source	20 wks	Tue 05/02/0	Mon 24/06/0
5	Integration & Assy of Dicke Switch Radiometer	12 wks	Tue 25/06/0	Wed 16/10/0
6	Testing Dicke Switch Radiometer	12 wks	Thu 17/10/0	Wed 12/02/0
7	Report	4 wks	Thu 13/02/0	Wed 12/03/0
8				
9	**MRAO**	**98 wks**	**Mon 15/01/01**	**Wed 12/03/0**
10	Project Management (MRAO)	98 wks	Mon 15/01/0	Wed 12/03/0
11	System analysis, design & component specification	26 wks	Mon 15/01/0	Fri 13/07/0
12	***Design review***	0 wks	Fri 13/07/0	Fri 13/07/0
13	Liaison with RF sub component manufacturers	15 wks	Mon 07/05/0	Wed 19/09/0
14	Feedhorn Production	9 wks	Mon 07/05/0	Fri 06/07/0
15	Correlation Radiometer front end	12 wks	Thu 29/11/0	Mon 25/02/0
16	LO/Mixer/IF block	26 wks	Mon 02/04/0	Wed 31/10/0
17	IF Hybrid block	4 wks	Thu 01/11/0	Wed 28/11/0
18	Data Acquisition Unit (Hardware & Software)	26 wks	Thu 15/11/0	Mon 20/05/0
19	Data analysis software	42 wks	Mon 16/07/0	Mon 10/06/0
20	PSU's & support electronics	8 wks	Mon 04/02/0	Fri 29/03/0
21	Support Chalmers on integration	2 wks	Tue 11/06/0	Mon 24/06/0
22	***Readiness Review***	0 wks	Mon 24/06/0	Mon 24/06/0
23	Integration & assembly (Hardware & software)	12 wks	Tue 25/06/0	Wed 16/10/0
24	Testing Correlation Radiomenter	12 wks	Thu 17/10/0	Wed 12/02/0
25	Report production	4 wks	Thu 13/02/0	Wed 12/03/0
26	***'Sign-off' Review***	0 wks	Wed 12/03/0	Wed 12/03/0