Report of the ALMA Scientific Advisory Committee: March 2000 Meeting

ALMA Scientific Advisory Committee

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1. Introduction

The ALMA Scientific Advisory Committee (hereafter ASAC) was formed in late 1999, as requested by the ALMA Coordinating Committee (hereafter ACC). The role of the ASAC is to provide scientific advice to the ACC, the ALMA Executive Committee (hereafter AEC) and the project, via the project scientists. As requested, the ASAC developed its own charter, which we supply as Appendix A. The ASAC decided to hold monthly telecons and regular meetings. For the near future, we will meet before each meeting of the ACC, in order to deliver a report in time for the ACC meeting. The telecons will supply rapid responses to queries from the project management and project scientists, and the minutes will be posted on the web. The meetings will allow exploration in more depth of particular issues and will result in a written report, such as this one. To ensure good communications, the ASAC will designate members to act as liaison to each of the working groups in the project; these are listed in Appendix B. The ASAC members also committed themselves to helping to educate the larger community about ALMA.

This document reports on the first meeting of the ASAC, held in Leiden, The Netherlands, on March 10-11, 2000. The topics covered at the meeting emerged from our telecons or from queries from the working groups. Some issues require further study and some topics were deferred to future meetings. These are listed in section 8. We summarize the overall recommendations in section 9.

2. ALMA Liaison Group Issues

The possibility of a contribution of Japan to the ALMA project has received strong and positive support from the ASAC. Such a contribution will make ALMA the largest international collaboration in astronomy and enhance the project in a number of important ways. It will increase the sensitivity of the array and add new technical capabilities. If this collaboration is achieved, Japan will have an equal partnership in the ALMA project with America and Europe and share the infrastructure and running costs.

At this point, it seems that the basic contribution of Japan to the ALMA project will be to add 12-meter antennas to the 64 x 12-meter antennas agreed to by the current collaboration. This greater collecting area will result in a better sensitivity (or observing speed), close to the original goal of a $10,000\,\mathrm{m}^2$ array. This improved sensitivity will compensate the need to share the observing time with a greater number of users.

Further contributions of Japan to an enhanced ALMA project are related to specific technical developments, including the participation in the future correlator, construction of the highest frequency receivers, or the photonic LO system. It is too early for the ASAC to prioritize the importance of these possible contributions; further discussion is needed.

It is clear that the contribution of Japan to the ALMA project could also open new perspectives for the project. In particular, the possibility to add to the project a compact array of smaller, high accuracy dishes would be a most interesting addition. It would improve the image quality for extended sources and the performance at the highest frequencies. This possibility should therefore be discussed again when the Japanese participation is confirmed.

3. Receivers

Along with the telescopes, the receiver packages largely determine the capabilities of ALMA. The Joint Receiver Development Group (JRDG) has raised a number of questions and requested clarification from the ASAC. These may be broken down into questions concerning the frequency bands and their priority, the total power stability, the Water Vapor Radiometer (WVR) specifications (dealt with in a separate section), polarization requirements, calibration accuracy, and receiver configurations (principally single sideband versus double sideband operation). Recommendations for each of these areas are outlined below.

Frequency Bands. The ASAC concurs that the four bands to be initially installed on the array should be (in order of increasing frequency) Band 3 (86-116 GHz), Band 6 (211-275 GHz), Band 7 (275-370 GHz), and Band 9 (602-720 GHz). The ASAC reiterates that the frequency coverage should be as complete as possible, but we respond to the request for prioritization of the bands as follows.

- First Priority: Bands 3, 6, 7, and 9
- Second Priority: Bands 1, 4, and 2 (see below)
- Third Priority: Bands 5, 8, and 10

We strongly urge that the JRDG study the possibility of extending the lower frequency range of Band 3 to include the SiO maser transition near 86 GHz. If this is possible, Band 2 would drop to third priority. The frequency intervals of the other bands are reasonable. Band 10 is scientifically quite interesting. It is in the third priority because the technology of THz SIS heterodyne receivers is in an early state, and it will be difficult to make ALMA work at its highest operating frequency. Some delay in the installation of this band will enable the most sensitive receivers to be installed and the telescope performance to be optimized.

Note that Band 1 is in the second priority list, and it must be considered in receiver layout. If it will not be in the main Dewar, then designs for optics that allow a second Dewar, possibly also containing the WVR, should be developed. It is not necessary for the WVR and Band 1 receivers to operate simultaneously.

Total Power Stability. For On-The-Fly (OTF) mapping capabilities, the requisite total power stability is of order 10^{-4} in one second (see Section 6, Appendix D). Stabilizing the gain to this level can be accomplished by selecting components with low temperature coefficients and by regulating their temperature to $\Delta T \leq 10^{-2}$K. Regulating the rest of the electronics in the laboratory to that level will be difficult, and it might be best to use a (temperature regulated) total power detector on the front end for the continuum total power measurements, rather than trying to use the correlator as the continuum detector. The ASAC recommends that this level of gain stability be a goal, rather than a hard specification, pending further study. The over-riding concern is the receiver sensitivity, and better performance should not be sacrificed for stability at this stringent level. However, this level of stability may allow considerable simplication (avoiding nutating subreflectors, see section 6), and we encourage the JRDG to study the issue and report back to the ASAC on the prospects for achieving this level of stability and on possible tradeoffs in doing so.

WVR Specs. These are discussed at length elsewhere (Section 7). The main point here is that this system must be incorporated into the overall design and receiver specifications.

Polarization. Polarization work will be an important part of ALMA research (Appendix C). Strong efforts should be made to have the polarized single-dish beams as stable as possible; consequently, the ASAC recommends that careful consideration be given to placing the 345 GHz receiver on-axis. For linear polarization work the basis state of feeds would ideally be circular polarization. If circular feeds impose important limitations on tuning range or increase significantly the noise temperature, a system for rapid, accurate calibration of linear feeds should be implemented. Obtaining zero and short spacing polarization data is essential. A nutating subreflector has a limited angular throw and introduces varying angles with respect to the optical axis of the primary mirror. The OTF technique proposed for total power observations would be ideal for polarization if the requisite gain stability can be achieved. Finally, the different polarization properties of the two prototype antennas and other polarization properties of the test interferometer and single-dish techniques should be carefully measured as they may be a consideration in procurement decisions (see Section 6).

Calibration Accuracy. The ALMA calibration specification of 1% for absolute intensity is adequate scientifically, perhaps even a bit aggressive. A cold calibration load in the primary Dewar is probably unnecessary.

Receiver Modes. The superb quality of the Chajnantor site and the non-ideal nature of any optical system means that the theoretical improvement in single sideband (SSB) versus double sideband (DSB) receivers may be difficult to realize in practice. DSB receivers are far easier and cheaper to fabricate, especially at submillimeter frequencies, and the ASAC recommends that a careful design study be undertaken that assesses the likely performance loss for DSB operation. If the loss is sufficiently small, considerable cost savings and ease of operation can be realized by adopting DSB systems. The ASAC would like to revisit this question once the SSB versus DSB study is completed. It is very likely that ALMA will become operational with both SSB and DSB receivers. This change in operational characteristics has important implications for the ALMA correlator, and the ASAC also recommends that the initial and subsequent ALMA correlators be designed with both modes of operation in mind. The operating system and software environment may also be affected.

Summary. The ASAC confirms that Bands 3, 6, 7, and 9 have the top priority and should be installed first. While complete frequency coverage is important, we have divided the other bands into second and third priorities. We recommend study of extending the lower end of Band 3 to include 86 GHz. In addition, the JRDG should consider placing the Band 7 receiver on-axis. Designs that accomodate the Band 1 receiver are essential. The "relaxed" WVR constraints may allow the Band 1 and WVR receivers to share a Dewar, and the JRDG should consider such designs. Finally, the ASAC requests a presentation at our next meeting of a detailed plan for the mass production, integration and testing of the ALMA Phase II receivers.

4. System

The ALMA system deals with many aspects of ALMA. We expect to revisit many of these areas in the future. We summarize below our recommendations on the issues addressed at this meeting.

1. The main array should consist of a number of 4 to 6 sub-arrays, but the number of frequencies operating simultaneously will not exceed 3 or 4. At present we could envision 4+1 subarrays. Namely:
   (a) The main interferometric subarray
   (b) Antennas for reconfiguration and baseline determination
   (c) Two subarrays to simultaneously carry out two of the following functions:
      - Secondary subarray at second frequency band
      - Transient event monitoring
      - mm-wave VLBI
      - Testing, repair, receiver warm-up or cool-down, etc.

   (d) The single-dish subarray or an ultra-compact array (if included in the final project).
2. The prototype antennas should be equipped with nutators and stable receivers. The number of ALMA antennas equipped for total power measurements (nutators) should be 4, but this number will be reconsidered after the tests with the prototype antennas. If feasible, the rest of the array antennas should be equipped with receivers of good gain stability ($\Delta G/G = 10^{-4}$ in 1 second). (See also section 3 and 6).
3. Due to its scientific interest (Appendix G), the option of the Band 1 receivers has to be kept. The costs of including this band need more detailed evaluation (See also section 3).
4. A detailed calibration plan, including polarization issues and phase calibration, needs to be elaborated.
5. Doppler tracking will be needed to provide accurate frequency calibrated data.
6. Polarization observations in total power mode with ALMA will impose requirements on the system that deserve a detailed study.

5. Configurations

Within the Configurations Working Group most of the discussion focuses on two major alternatives for the basic array layout: the spiral zoom array concept described by Conway (ALMA Memos #216, 260, 283, and 291); and the "doughnut" array developed by Kogan guided by the goal of achieving minimal sidelobes (ALMA Memos #171, 212, 226, and 247). For both concepts realistic array layouts considering topographic constraints have now been studied (ALMA Memos #292 and 296). Both layouts appear to achieve comparable sidelobe levels, which are of order 6–8% (for snapshots!), with the spiral array producing lower near sidelobes for longer tracks. Consequently, a decision to adopt one or the other design has to be based on a number of factors, including logistics and scientific requirements. For example, guided by experience with the VLA, one might expect that the observers' demand will be highest for the most extended configuration (for maximum resolution) and the most compact one (maximizing surface brightness sensitivity). Such considerations should be included in the choice of array concepts.

A need for model images has arisen and a total of five images will be chosen for use with all simulations. More imaging simulations are necessary for arrays involving baselines up to 20 km, where terrain considerations are the major issue. Given ALMA's excellent brightness sensitivity, imaging of thermal emission from gas and dust with such long baselines will open new vistas. Resolutions better than 10 milliarcseconds will be achieved, which are essential for studies of some of ALMA's key science goals, such as the formation of planets.

As decisions on antenna pad locations have to be made by late 2000, we recommend that the Configurations Working Group report on progress to the ASAC at our next meeting, after which we can make a final recommendation. Since the large size of the working group might be conducive to excessive discussions, intervention by the project scientists might be necessary to warrant a timely decision process.

6. Antennas and Total Power

The prototype antenna contractors have been selected. We therefore concentrated on recommendations for testing procedures and antenna issues that impact other areas. We considered the priorities when testing the prototype antennas. For the prototype tests, we stress the following points.

- It is extremely important to test whether and under what conditions the pointing specifications ($0\farcs6$) are met. Developing observational strategies aimed at optimizing the pointing is an important goal. In particular, one should examine the possibility of installing optical telescopes on all antennas, together with a servo system allowing real time pointing corrections. It seems likely that such systems are only effective if they are planned as part of the system and the committee recommends therefore that a system of this type is considered soon.

- It is also very important to have some method of recovering zero spacing flux using all or part of the array operated in single dish mode (see Appendix D). The committee recommends that a detailed comparison be made of the relative merits of using nutators switching rapidly (10 Hz) and On-The-Fly (OTF) mapping. A decision on the best strategy for ALMA should be made subsequent to these tests. In particular, one should test whether rapid OTF mapping (e.g $30'$ scans in 1 sec with 1 second turn-around) is feasible and whether gain stability ($\Delta G/G$) of order 10^{-4} per second can be attained. Tests should also be made with the water vapor radiometer (WVR) in order to assess the ability of the WVR to monitor atmospheric emission fluctuations. Analogous studies are needed to test how effectively chopping with a simple nutator eliminates atmospheric fluctuations. Equipping each prototype antenna with a nutator will facilitate these studies.

  With this information in hand, it should be possible to decide whether nutators are, or are not, necessary for the array antennas. The general opinion of the ASAC was that if one could reach the scientific goals without using nutators, this was preferable. Thus one should aim at a system that could do an OTF map with all 64 antennas simultaneously.

- Polarization measurements are also sensitive to missing zero spacing flux (see Appendix C), and thus it should be possible to do polarization OTF at at least 2 ALMA frequencies. The decision discussed above (OTF versus nutators) may be different if one is measuring polarized flux and thus a test of polarization OTF is desirable.

7. Water-Vapor Radiometry

Accurate phase calibration is a critical requirement for ALMA, and the baseline design of ALMA uses a 183 GHz receiver (mounted slightly off-axis from the astronomical beam) to measure a strong atmospheric water line. Under various assumptions about the atmospheric pressure and temperature, and the location of the turbulence, the electrical path above each antenna can be derived. Richard Hills and John Richer contributed a report outlining the status of the 183 GHz systems currently in place (Appendix E), and a series of suggestions for the requirements of a second generation system. Christine Wilson presented a report by David Naylor (Appendix F) on an alternative strategy that uses a 20μm photometer to measure water vapor fluctuations in the infrared.

These reports were discussed in detail. The specific recommendations of the ASAC are:

1. The water vapor radiometers are central to the scientific success of ALMA, and the project should ensure that their development is adequately resourced and integrated with all aspects of the ALMA system.

2. The project should design and test preferably two (identical) prototype/pre-production 183 GHz radiometers as part of the Phase 1 project. These should be tested on reasonable astronomical sites when completed. The possibility of putting them on the 12-m prototype antennas at the VLA site during the test interferometer work is highly attractive, and the feasibility of this option should be investigated.

3. The project should adopt a specification for the WVR system as follows: it should correct the atmospheric path above each antenna to an accuracy of $10(1{+}w_v)\,\mu$m on a timescale of 1 second, over a period of 5 minutes and allowing for a change in zenith angle of 1 degree; w_v is the precipitable water vapor in mm.

4. Although it is not possible to put very firm design constraints on the optics, the project should adopt as the specification that the maximum permissible offset between radiometer and astronomical beams be $10'$, and (if possible) smaller for the higher frequency channels.

5. The project should check that the above specifications are sensible and adequate. In particular, the short timescale behavior of the atmosphere should be quantified to ensure that correction of phase on 1 second timescales is rapid enough.

6. There are scientific and productivity gains to be made by correcting the wavefront tilt across each antenna (the so-called "anomalous" refraction). This effect most strongly compromises mosaic observations, and those at high frequencies. However, given that there are large periods of time when this effect will not be a major problem, the ASAC does not recommend adopting such a system as the baseline design at present. Further study of the loss of observing time this effect produces should be made, and this recommendation should be reassessed at future meetings.

7. The baseline design for the water vapor radiometer remains a 183 GHz system. The alternative Canadian solution using 20 μm radiometers should be examined further, probably by the Canadians themselves, and further reports on progress should be brought to the ASAC. In particular, the correlation of the 20 μm and 183 GHz systems should be examined on the JCMT. The main theoretical problems of the 20 μm technique that need to be investigated are its ability to sample the correct patch of atmosphere; its performance in differing cloud conditions; and the accuracy of the path estimation as a function of pressure, temperature, and water vapor distribution.

8. The baseline design should use a cooled 183 GHz radiometer. Whether to cool or not is, strictly speaking, an engineering problem; there was some feeling that although not absolutely required to achieve the required sensitivity, the benefits of cooling in terms of stability and noise probably outweigh the costs.

9. The project should examine the role of the system water vapor radiometers in the following: a) the amplitude calibration system, through their estimates of the atmospheric opacity above each antenna; and b) in single-dish mode observing, where they could be used to estimate the atmospheric emission. The scientific benefits of these techniques, and the extra requirements they place on the system, should be investigated.

10. The project should accelerate its work on understanding the different atmospheric models used by the WVR systems to predict path errors from water line measurements.

11. The location of the WVR is an engineering problem, and the solution likely depends on the degree of cooling required, and the final optical design adopted. There appear to be no show-stopping problems with locating it either in the same Dewar as the astronomical receivers, or in its own cryostat. The optimum engineering solution should be investigated. The ASAC does note that the simultaneous operation at 183 GHz and Band 1 receivers is not a scientific requirement, so it is straightforward to locate these systems in the same Dewar if that makes sense.

8. Future Issues

There are many issues that require ASAC attention in future meetings. We list here those issues that we expect to focus on in future telecons and our next meeting.

- Planning for Phase II. We would like to see a presentation on the plans for managing Phase II, including the procedures and criteria to be used to select between parallel developments. A plan for construction of the receivers (see Section 3) should be presented.
- Configurations. This issue received considerable discussion, summarized in section 5 above, but we plan to revisit the topic after the Configuration Working Group finishes the simulations recommended above.
- Ultra-Compact Array. One very interesting enhancement that Japanese participation might add is an ultra-compact array of smaller, more accurate antennas. The scientific potential of this array will need further elaboration and study.
- Local Oscillator Systems. Developments on photonic systems are still ongoing, and we should evaluate the status of these. In addition, the implications of some of our recommendations in this report for LO systems should be evaluated.
- Software. The planning for software systems is less advanced than in other areas. We would like to hear a presentation on these plans at our next meeting.
- Spectrum Management. Since commercial broadcasting has interest in bands in the ALMA region, we would like to hear a report on the status of efforts to protect these bands.
- Site. We would like a report on the status of site arrangements.

- Outreach. Since the ALMA project still needs to be explained to the larger community, we would like a presentation on the plans for outreach.

9. Summary

We summarize our major recommendations. These are in the order discussed in the text and not in any priority order. More detailed recommendations can be found in the section referenced by the major recommendations.

- We strongly support continued discussions aimed at including Japan in the ALMA project (Section 2).
- We confirm that the first four bands to be implemented should be Bands 3, 6, 7, and 9. We establish priorities for the remaining bands, but emphasize that full frequency coverage is still desired, including Band 1 (Section 3).
- Polarization studies will be a very important part of ALMA science. We recommend attention to polarization in all aspects, but most importantly in receivers and antenna testing (Sections 3, 6).
- The advantages of SSB operation over DSB operation of the receivers are not so clear. We recommend further study of the tradeoffs and reconsideration of the issue at a future ASAC meeting (Section 3).
- If an ultra-compact array of smaller, more precise antennas can result from participation of Japan, it would add important capabilities. We recommend further study of this possibility (Sections 2, 4).
- The capability for 6 subarrays should be kept, but with no more than 4 simultaneous frequencies (Section 4).
- The Configuration Working Group should complete simulations of different array configurations and testing against a library of test images in time for an in-depth presentation at the next ASAC meeting (Section 5).
- Recovering total power is a major issue for continuum observations of extended sources. This may be best done with OTF mapping if receivers can be built with gain stability of $\Delta G/G = 10^{-4}$ in one second (Sections 3, 4, 6).
- Tests of total power techniques, comparing OTF with gain-stable receivers to nutating secondaries should be made on the prototype antennas. Decisions on equipping the array with nutating secondaries should be based on the outcome of these tests (Section 6).
- The water vapor radiometers are essential and must be integrated into all aspects of the ALMA system (Section 7).

APPENDICES

A. The ASAC Charter

1. The ALMA Scientific Advisory Committee (ASAC) was formed by the ALMA Coordinating Committee (ACC) to provide scientific advice to the ACC, to the ALMA Executive Committee (AEC), and to the Project Scientists. The ASAC will also provide communications to the wider community.

2. To fulfill these goals, the ASAC will take the following steps:

   (a) Hold monthly telecons.

   (b) Meet face-to-face as needed. In the current phase, we plan to meet before each meeting of the ACC. The frequency of meetings may decrease as ALMA becomes more fully defined, but we will probably meet at least once per year.

   (c) Produce a report to the ACC, with a copy to the AEC, before each meeting of the ACC.

   (d) Reply to questions from ALMA project staff and raise issues for their consideration via minutes or "white papers".

   (e) Designate a member of the ASAC to act as liaison to each of the working groups in the project.

   (f) Establish a web site where the community can learn what issues we are addressing and provide input. We will post minutes of telecons and meetings there, as well as reports to the ACC, subject to approval of the ACC.

   (g) Announce our existence and membership in astronomical newsletters, expressing our interest in receiving questions and advice and in giving colloquia about ALMA.

3. We have agreed to the following procedures.

   (a) We will have a Chairperson and a Vice-Chairperson at all times. At the end of each face-to-face meeting, the Vice-Chairperson will become Chairperson and we will elect a new Vice-Chairperson. We expect the role of Chairperson to rotate between North America and Europe.

   (b) Decisions will be made by simple majority. A minority report may be included in the report to the ACC.

   (c) Normally, we will communicate through the Project Scientists, both in receiving questions from the project technical staff and in providing answers. However, direct communication with project staff will be used for clarifications, information, etc. The liaison members are an example of this direct communication.

B. ASAC Liaison to Working Groups

The liaisons to the Working Groups and other organizations are as follows. To implement this system, the Chairpersons of the working groups should incorporate these representatives of the ASAC into their email distribution lists and telecons. When possible and relevant, the ASAC representatives should attend meetings of the working groups. To facilitate this, we have usually listed a representative from each hemisphere.

- Management: Al Wootten, Stephane Guilloteau
- ALMA Liaison Group: Pierre Cox, Neal Evans
- Antennas: Jack Welch, Malcolm Walmsley
- Receivers: Ewine van Dishoeck, Geoff Blake
- Configurations: Min Yun, Roy Booth
- Backend: Rafael Bachiller, Nick Scoville
- Software: Mark Gurwell, Arnold Benz
- Calibration, including Water Vapor: John Richer, Christine Wilson
- System Integration: Dick Crutcher, Karl Menten
- Site: Leo Bronfman

C. Polarization Observations With ALMA

Richard M. Crutcher, University of Illinois, Jack Welch, University of California at Berkeley, Larry D'Addario, National Radio Astronomy Observatory

C.1. INTRODUCTION

Because of its enormous sensitivity and imaging capabilities, the ALMA will be the premier instrument at millimeter and submillimeter wavelengths. Polarization observations will likely be carried out far more frequently with the ALMA than with present telescopes because the sensitivity of the ALMA will make such observations (which always have to deal with signals only a few percent of the total intensity) possible for a much larger set of radio sources. However, polarization observations place significantly more stringent requirements on instruments than do total intensity measurements. Careful consideration of the instrumental requirements for successful polarization observations should therefore be given high priority in the design of the ALMA.

C.2. POLARIZATION SCIENCE

Major scientific areas that will benefit from excellent polarization capabilities of the ALMA include the following:

Star formation. Theoretical and observational work have shown that magnetic fields can play a significant and perhaps essential role in the formation of interstellar clouds, in their evolution, and in the star formation process. Needed are observations of the morphology and strength of magnetic fields in molecular clouds. Techniques available include: (1) measurement of linearly polarized emission from dust grains aligned by magnetic fields; (2) measurement of linearly polarized spectral line emission (both in thermal lines due to the Goldreich-Kylafis effect and in maser lines such as SiO); and (3) measurement of circularly polarized spectral-line emission produced by the Zeeman effect. The first two techniques yield information about the morphology of magnetic fields in the plane of the sky, while the third gives the magnitude of the line of sight component of the field.

Supernova remnants. Synchrotron emission from SNRs is linearly polarized, and the polarization is used to measure the direction and estimate the strength of magnetic fields.

Normal galaxies. Synchrotron emission from the interstellar medium in normal galaxies may be used to map magnetic fields in external galaxies and study the morphology and estimate the strengths of extragalactic magnetic fields. Such studies may lead to an understanding of the amplification of magnetic fields in galactic dynamos.

Radio galaxies. Radio lobes produce polarized synchrotron emission that may be used to map the morphology and estimate the strength of magnetic fields.

Circular polarization observations will probably be primarily Zeeman line work carried out for that special purpose at a small number of frequencies. Certainly the 3-mm CN lines, and perhaps the CCS line at 33 GHz, the 1-mm CN lines, and several SO lines would be of interest. Other lines may of course also prove to be useful as the tremendous sensitivity of the ALMA is exploited. Except for the Zeeman effect, all of the above science drivers for polarization observations with the ALMA involve linear polarization. Requirements on the instrumental polarization are much more severe for continuum linear polarization mapping than for Zeeman observations. Moreover, for many if not most of the observations that will be made with the ALMA, the polarization of thermal dust continuum or synchrotron emission will be of scientific value EVEN WHEN THE POLARIZATION DATA ARE NOT THE PRIMARY PURPOSE OF THE OBSERVATIONS. Thus, optimization of instrumental characteristics of ALMA for routine linear polarization observations would be of the greatest scientific value.

C.3. REQUIREMENTS

Requirements fall into three areas: (1) sensitivity - zero or minimal loss of sensitivity when doing polarization observations; (2) Fourier sampling - ability to obtain and include zero and short spacing polarization data in order to carry out full synthesis mapping; and (3) accuracy - the ability to calibrate instrumental polarization easily and accurately (0.1% or better) over the entire primary beam. We briefly describe these requirements in this section, and in section 4 discuss specifics of instrument design and calibration needed to meet these requirements.

C.3.1. Sensitivity

The very great effort going into giving the ALMA very high sensitivity for mapping of total intensity also will yield high sensitivity for polarization work so long as that sensitivity is not compromised by the instrumental design. The fact that the ALMA will have dual receivers with feeds sensitive to orthogonal polarizations is the first necessary step. But if that system is to achieve its potential for polarization work, the design must have a focus on the effect on polarization of all aspects of the system.

Polarization is usually less than 5%, and over large spatial areas the percentage polarization is 1% or less. Hence, the dynamic range that can be achieved is automatically significantly lower than for intensity observations. In order not to further reduce sensitivity, one would like to be able to map polarization to the limits set by thermal noise rather than instrumental polarization.

C.3.2. Fourier sampling

A large fraction of polarization mapping with the ALMA will be of extended objects. Hence, procedures for obtaining short and zero spacing polarization data that will not degrade the quality of the interferometric data are essential. Single-dish polarization observations have traditionally been done by rotating a polarizer and detecting the total intensity of the time-modulated signal. Because this involves subtracting two big numbers (intensities in two different polarization states) to determine a small number (a Stokes Q, U, or V), it is very difficult to achieve calibrated instrumental sensitivities of 0.1%. New methods of single-dish polarization mapping must be developed for the ALMA.

C.3.3. Accuracy

The goal should be to map Stokes V, Q, and U limited by thermal noise and not by instrumental effects. As a practical matter, the goal should be instrumental polarization effects of $< 0.1\%$, after calibration.

Moreover, this spec must be met over the entire primary beams of the telescopes in order to map over the single primary beam and to mosaic map.

A significant difference between standard intensity (Stokes I) mapping and polarization mapping is instrumental polarization. For intensity mapping, the primary beam is a relatively simple and stable function, so the instrumental response (dirty beam) can be predicted from the UV coverage. Knowledge of that instrumental response can therefore be used to deconvolve it out of the final maps. The instrumental response in Stokes parameters Q, U, and V depends in addition to the UV coverage on the polarized instrumental response over the primary beams of the various antennas, and in general this may vary strongly and in a complicated manner with position in the primary beam, time, pointing position, etc. In order to deconvolve the polarized dirty beams out of the final polarization maps, the polarized dirty beams must be known at the noise level of the maps. If the instrumental polarization due to the antennas is stable in time, one can measure it once and take it out. Time variable instrumental polarization (due to elevation effects for example) requires great loss of sensitivity due to time spent on calibration and/or limitations on polarization fidelity. Failure to know the polarized response of the instrument over position and time is the major limitation on the accuracy of polarization mapping.

C.4. MEETING THE SCIENCE REQUIREMENTS

C.4.1. Instrumental polarization issues

As noted above, science drivers imply that most polarization work will be in linear polarization. The main science driver for circular polarization work is Zeeman work, for which the requirements are less severe (see below). Thus, if it is necessary to optimize the ALMA for observations of linear or circular polarization, the science implies optimization for linear polarization observations. If this is not possible for all bands, consideration should be given to optimization for linear polarization observations at a prime polarization band; perhaps the 345 GHz band is best.

The science goal is that the total instrumental polarization be less than 0.1% without major loss of observing time for calibration. This tolerance cannot be met without calibration, but achieving the closest possible approach to zero instrumental polarization must be a design criterion in order to meet the science goal. Meeting this goal requires consideration of the following areas:

- Absolute polarization of each of two (nominally orthogonal polarization) ports.
- Orthogonality of the polarizations of the two ports of one antenna.
- Uniformity of polarization among antennas of the array.
- Orthogonality of opposite ports between antenna pairs of the array.
- Variation of each of the above with direction of arrival over the main beam.
- Temporal stability of each of the above, short- and long-term.
- Effects of elevation dependence; designs that call for the antennas to be stiff or that allow them to sag with refocusing both require attention to the polarization effects.

Although one often speaks of linearly or circularly polarized feeds, it should be noted that "feeds" are never purely linearly nor purely circularly polarized, though they are often a close approximation to one of these. The mathematics makes it clear that so long as the telescopes have orthogonal polarization receivers, one can derive the full polarization information (i.e., all four Stokes parameters). One can choose any pair of orthogonal polarization states as "basis" states, so that any arbitrary state is describable as a linear combination of them. To be accurate, it is the polarization state of the whole antenna that matters. For most radio telescopes, this includes the main reflector; subreflector; other mirrors (flat or curved); other optical elements (including wire grids and lenses); and finally something to convert the free-space, multi-mode beam into a guided, single-mode wave. The last element is often a polarization-insensitive horn followed by a "polarizer" with two single-mode ports, each coupling to a different polarization of a plane wave incident on the whole antenna. Each of these cascaded elements affects these final two polarizations. Those elements that have sufficient symmetry can be treated as polarization-insensitive. In the simplest case only the polarizer is significant, but in practice the situation is often more complicated.

The sensitivity can be reduced if the polarizer introduces noise, or if a significant fraction of the observing time must be devoted to calibrating the instrumental polarization in order to achieve the required sensitivity. The BIMA system, which has only a single receiver per telescope, employs a transmission polarizer consisting of a grooved dielectric plate in front of the receiver to select the desired polarization basis state; this plate adds significantly to the noise of the system. Second, if the polarization state of each antenna is complicated (for example, if it differs significantly from the desired basis state or varies both in time or over the field of view), a large fraction of the observing time must be spent in calibration, which will significantly reduce the sensitivity. Hence, a design that has the lowest instrumental polarization and the lowest possible, most time stable instrumental polarization will maximize sensitivity.

The optical design is crucial for polarization mapping over extended areas. The best optical system is a "straight through" design, with no off-axis elements or oblique reflections. Both will produce instrumental polarization that varies over the primary beam of the telescopes. If an off-axis system is necessary, careful calibration of its instrumental polarization effects will be necessary. Since this will be time consuming, it will be important that the optical system be kept invariant so that a calibration may be used over a long period of time. It would make sense to choose a primary band for linear polarization work (probably 345 GHz would be best) and optimize the optics of that band for polarization. Again, ideally, this would be on axis. If that is impossible, at least a dual-mirror system should be chosen with reflections designed for the polarization basis state of each channel. Having reflections as close as possible to normal (to the mirror) for the primary polarization band should be a design consideration.

Another issue is whether there is a significant advantage to a choice as close as possible to a linear or a circular basis state, and second, what deviation from a particular basis state may be tolerated without making the calibration less accurate and/or more difficult and time consuming. Although in principle even large instrumental polarization effects may be calibrated, in practice the best approach is to have the polarization state of each antenna to be intrinsically as close as possible to the desired ideal state. In practice, accurate polarimetry must account for the actual polarization state of the antenna; extraordinary efforts to produce a basis state that approaches circular or linear to high accuracy is not important.

Cotton (1998; MMA Memo 208) discussed calibration of interferometer polarization data and the merits of linear or circularly polarized feeds. There are a number of strong disadvantages of linear feeds, including especially the facts that p-q (orthogonal polarizations) phase fluctuations can significantly increase the noise in linearly polarized data, that no polarization "snapshots" are possible since extended observations are required to measure calibrator Q and U, and that any p-q phase difference corrupts polarization data. Circularly polarized feeds overcome these disadvantages for polarization work, and have the additional advantages that calibrator polarization only weakly affects gain calibration, that there is good separation of source and instrumental polarization with parallactic angle, and that instrumental polarization can be determined from a calibrator of unknown polarization. If, as argued above, linear polarization science observations will be the most important, having the polarization basis states as close as possible to circular would be best.

Since Zeeman observations are spectral-line observations, the observed polarization is a relative measurement. That is, the circular polarization as a function of frequency must be measured. The most important instrumental polarization effect is beam squint - the pointing of the two circularly polarized beams in slightly different directions. More generally, beam squint may be considered to be the total (including sidelobes) difference in instrumental positional response between the two senses of circular polarization. In the presence of velocity gradients in molecular clouds, beam squint will produce false Zeeman signatures. However, so long as the primary beam squint is not too bad, and especially if it is known and stable, its effects can be calibrated and corrected. Small ($< 5\%$) impurity in instrumental circular polarization and difference in gain between the two polarization channels can be calibrated out using standard Zeeman analysis techniques. Moreover, simultaneous observations of thermal continuum and/or of non-Zeeman spectral lines within the observation window may be used to calibrate the instrumental circular polarization.

C.4.2. Calibration issues

Since the instrumental polarization tolerances will not be zero, what is the best overall strategy for calibration to determine the actual polarization of each antenna? Moreover, besides knowing polarizations of the antennas, it is also necessary to know the complex gains of the receivers. To a large extent, this is the same as is required for observations of sources that are assumed unpolarized or where only total intensity is to be measured. An exception is that polarimetry requires knowledge of the ratio of the complex gains of the two channels, whereas total intensity measurement does not. Conventional astronomical calibration determines the amplitudes of these gains separately (and hence their ratio) provided that the calibrator's polarization is known (preferably unpolarized); it can determine the phase difference only if the calibrator is appropriately polarized (preferable strongly so). What, then, is the best overall strategy for receiver gain calibration?

These points must be considered in the contexts of both interferometer mode observations and single-dish mode observations. The single-dish mode is the more difficult.

For the ALMA, it may be that the engineering reality is that all receivers will be connected to antenna ports that are approximately linearly polarized, and thus a poor approximation to being circularly polarized. MMA#208 states that the principal reason for this is that it allows larger bandwidth; this is roughly true at centimeter wavelengths, but it is not correct for the ALMA. At the shorter wavelengths, various antenna elements besides the polarizer are either impossible to construct or are excessively lossy if they operate on waves that are nearly circularly polarized. An element that selects a single linear polarization with very low loss and very large bandwidth is easily built (a wire grid), whereas nothing similar exists for circular polarization. It is possible to insert a “quarter wave plate” to convert circular to linear polarization with good accuracy over a narrow band, but with some noise penalty due to ohmic losses. Thus, engineering reality may preclude the possibility of having the ALMA optimized for linear polarization by having near-circular polarization feeds, except as a potential add-on, with limitations. It should be clear that this is an engineering limitation and not a decision that optimizes for polarization science.

Many of the difficulties cited by Cotton in MMA#208 would be overcome by having a calibration source of known polarization with a very strong linearly-polarized component (assuming that we are more interested in mapping the linear polarization component than the circular one of unknown sources). Although such things do not exist in the natural sky, it should be straightforward to have one built into each ALMA antenna. One attractive possibility for the calibration of the dual polarization receivers is to provide an intense millimeter wavelength CW signal that can be coupled into the receivers at their inputs. Such a signal could be coupled into the receivers through a small aperture in the middle of the secondary mirror. It could be highly linearly polarized but at a position angle of 45 degrees, so that it couples equally and coherently to both the horizontal and vertical polarization receivers. In this way, it could provide a very accurate relative calibration of the two receivers. A total power spectral correlation measurement would provide both amplitude and phase calibration between the two receivers. Presumably this CW millimeter wavelength signal could be tuned to different frequencies as needed.

A further possibility would be that the same coherent millimeter CW signal could be injected into every front end. For example, the signal might be provided as the beat note between two optical laser signals. In this case, the coherence of the signals would allow the phase (and amplitude) relative calibration of all the receivers, including their two polarizations.

This internal polarization calibration source would of course calibrate the system from the feeds on; instrumental polarization of the primary and secondary reflecting surfaces would have to be calibrated astronomically. In order not to spent excess time on such calibrations, the design should focus strongly on making the instrumental polarization that must be calibrated astronomically as stable in time, elevation angle, and position over the beam as possible.

Obtaining single antenna and short spacing polarization data will be a challenge for the ALMA. A plan to obtain such intensity data by "on-the-fly" mapping with the ALMA antennas should work for polarization also so long as full polarization information is obtained and the system is sufficiently stable. A stability of at least 1 part in 10,000 seems to be necessary, sufficient, and achievable, but this spec needs to be investigated specifically for polarization calibration. A system to cross-correlate the signals from the orthogonally polarized receivers on each antenna in order to produce single-dish polarization data while "on-the-fly" mapping is being carried out should work, but needs to be investigated. A system which requires physical rotation of polarizers should be avoided; it would be difficult to achieve the required accuracy and would be time consuming.

C.5. RECOMMENDATIONS

The sections above describe the science drivers and the required polarization performance of the ALMA. Specific recommendations have been discussed in section 4. However, millimeter-wave polarimetry is not yet a mature field. We therefore strongly recommend that the systems for polarization observations with the ALMA be implemented and tested at the earliest possible time. Use of existing millimeter-wave interferometers is likely to be useful, but implementation of polarization capabilities from the beginning on the first ALMA test interferometer is essential if the ALMA is to fulfill its promise for polarization.

D. Total Power Observing with the ALMA Antennas

Jack Welch, University of California at Berkeley, Darrel Emerson, NRAO, Karl Menten, MPIfR, John Richer, Cambridge

D.1. Introduction

Particularly at the shorter wavelengths, the ALMA will need to do mosaic observing to cover large fields of view. Along with the mosaic pointing, there will need to be total power maps to fill in the interferometric short spacings and produce complete images. It is well known that this is best done with a single antenna that is two to three times the diameter of the interferometer antennas (Vogel,S.*etal*, ApJ, 1984, 283, 655). However, that will not be possible for ALMA; there are no 24m - 36m antennas available that will work well to 0.35mm wavelength. As long as a mosaic of pointings is employed in the interferometry, a single antenna map made with one of the interferometer antennas will suffice in principle (Ekers,R. and Rots,A, 1979, In Image Formation, etc., Dordrecht, Reidel). This is rarely done, largely because the interferometer antennas are not equipped to do it. Tests done at the VLA at cm wavelengths (Cornwell, T. 1988, A&A, 202, 316.) indicate that it should work, and at mm wavelengths in the CO(1-0) line, Marc Pound made a good map of the Eagle Nebula combining a Mosaic interferometer map made with the BIMA array and a single antenna map made with the Bell Labs 7m antenna (Pound, 1998, ApJ, 493L, 113). This capability must be in place for the ALMA antennas. How it is best done may be studied with the prototype antennas.

D.2. Candidate Schemes

There are five schemes that are usually considered for this purpose. The simplest is the on/off pointing method. Here one points at the source for a short integration, perhaps 10-30 seconds, and then at blank sky for the same time, and then takes the difference. The rest of the map results from a sequence of such measurements. For spectral line observations with narrow band widths, the receiver noise is usually large enough that it dominates both the atmospheric brightness fluctuations and the noise due to receiver gain fluctuations in this method, and it works. The second scheme is to use rapid frequency switching for spectral line observing, and this also works. Neither of these procedures will work for continuum measurements. That's obvious for the second method. For the first, the wider bandwidth means that the receiver noise is lower than that due to either the atmospheric brightness fluctuations or the effects of receiver gain fluctuations.

For continuum total power observations, there are three schemes that can be used. The most common method is to employ a nodding secondary mirror. A related alternative is the focal plane chopper. The third idea is On-The-Fly mapping (Emerson, Klein, and Haslam, 1979, A&A, 76, 92). In all three cases, differential ground spillover will be a problem and will probably set the fundamental limit to the accuracy and depth of the continuum single antenna maps.

The nodding secondary, giving a rapid comparison, avoids gain drifts. Its main weakness is that it is difficult to get a throw of more than a few arc minutes. While this will be adequate for some science programs, there are situations where one needs to chop to an "off" position that is 10-20 (or more) minutes away. This is especially the case at the shorter wavelengths where, in the Milky Way, the background dust emission is bright.

The focal plane chopper, on the other hand, can only throw large angles, typically 10 minutes or more.

Other disadvantages for our application are that it is often difficult to have a good balance between the "on" and "off" and the mechanism would probably have to be mounted on each receiver separately, which could be an annoying complication for the ALMA antennas with their many receivers.

The On-The-Fly (OTF) method looks to be the most flexible and simplest, and we summarize its properties and requirements below. Whatever scheme is chosen, the maximum throw will limit the maximum spatial scales in the resulting maps.

D.3. OTF Mapping

The prospects for doing OTF mapping at the Chajnantor site have been discussed in detail by Holdaway, Owen, and Emerson (1995, MMA #137) (HOE). The basic idea is that a raster scan of the object under study will be made with a very rapid turn-around of the scan at the end of each row in a region that is off the source. During the scan across the source, the receiver power is read out at a rate which corresponds to at least the Nyquist sampling of the source structure. That is, at least as often as twice per beam width. Thus, there are many "on" observations across the source with an "off" observation at the end of each row. The "off" observations last about one second during the turn-around at the end of each row. The time on each "on" observation is much smaller.

HOE used the path length fluctuations as measured by the site testing interferometer at Chajnantor to infer the expected atmospheric brightness fluctuations. They were able to work out the magnitude of the fluctuations as functions of both the time and pointing angle with respect to the source. Under the assumptions that (1) the antenna could slew as rapidly as 1^o/second, (2) the antenna could accelerate and decelerate between normal tracking and full slew in one or two seconds, and (3) the correlator could dump the spectral data every .003s, they concluded that OTF mapping should work well at the Chajnantor site. Their Figure 2 shows that the expected receiver noise and atmospheric noise contributions will be about equal at 230 GHz 80% of the time for a scan that is a large as 1^o. For smaller scans the situation is even better.

At the time of the HOE memo, is was not clear whether their assumptions about the antenna and correlator would be met. We now have more information about the array components. The present NRAO design for the correlator will allow correlator read-out at the rate of once every .001 second, which is fast enough to permit OTF mapping of both continuum and line observations (J. Weber, private communication). The planning for the antenna prototype has included studies of the capability of the antenna to carry out the OTF observing. It appears that if feed forward is used in the drive servo design, it will be possible to turn the antenna around at the end of an OTF scan in about one second as assumed by HOE. The maximum smooth scan rate will be at least about 0.5^o/sec, comparable to the 1^o/sec rate assumed by HOE.

One further point that needs to be considered is the required receiver gain stability for the OTF scheme to work. The planned continuum bandwidth of 8 GHz calls for unusually good gain stability. The time between any of the "ons" and the off at the end of the scan is about one second. The gain must be stable over that time interval. The fractional total power noise for one of the "on" measurements is: $\Delta T/T = 2/SQRT(Bt_s)$. B is the bandwidth, and t_s is the time on each source. The 2 is the usual factor due to switching. Here the long "off" time reduces the noise in the subtraction, but it is also about twice as long as the total "on" source observing time. The fractional total power fluctuation due to gain variations is: $\Delta T/T = \Delta G/G$. If we take the scan time to be always one second, then t_s depends on the scan length and the beam width. For scan lengths between $5'$ and $60'$ and beam widths between $25''$ (220 GHz) and $6''$ (800 GHz) the time on source varies between .08 sec and .002 sec. For B=8 GHz, and equating the receiver noise fluctuation to that due to the gain fluctuation, we find a necessary gain stability in the range of 0.8×10^{-4} to 5×10^{-4}. Thus, a receiver gain stability of about 1×10^{-4} over a time scale of about 1 second is required for the receiver. This level of stability can certainly be achieved, but it requires careful attention to the construction of the receiver.

The above argument leading to a gain stability requirement of 1×10^{-4} depends on the relative time on each "on" during the scan being small compared with the total scan time of about 1 second. Thus, the OTF method works best for large scans (M. Wright, private communication). Even for short scans, it will still work reasonably well, requiring a little more gain stability. It will be important to keep the total scan time to be about the same time as the turnaround time, in order that the overall observing be efficient.

Another question concerns the number of antennas that must be used to achieve the necessary sensitivity in the single antenna measurements to equal the corresponding array sensitivity. The answer here depends on the amount of redundancy in the short interferometer spacings. If there is no redundancy in the short interferometer spacings, then, for approximately equal sensitivity in the OTF measurements, the same amount of time must be spent on the single dish map as on any of the array baselines. That means about the same amount of time in the single dish mode as in the array mode. The only difference is in the factor of 2 in the OTF (switched) mode. This implies that a measurement with 4 antennas for the same duration as the array observation would suffice. However, with the likely large redundancy in the short interferometer spacings, much more time in the single dish mode will be required. Exactly how much time will depend on the details of the compact interferometer array. Probably most of the antennas will be required to operate in the single antenna mode simultaneously to produce the uv plane sensitivity comparable to the of the array. The requirement that all the antennas have the good gain stability makes the most sense. It is not a difficult requirement, and it will benefit the interferometer operation as well.

D.4. Summary

The major limitation in the accuracy of the single dish mode will be due to differential spillover in the "on"−"off" comparison. It is difficult to know in advance whether the nodding secondary or the OTF scanning scheme will be more plagued by this. The antenna background is likely to be of the order of 10K. Whether the modulation of this by the moving secondary or scanning across the ground is worse can only be determined by experiment. Thus, it will be important that the prototype antennas be equipped for both kind of observing and tests be carried out. Both good gain stability and chopping secondaries must be installed. It may be possible to test these options on existing systems. It may also be possible to test further the "homogeneous array" operation (array with single dish one of the array antennas) using one of the existing antenna systems.

Another activity that would be important in the near term would be to test the calculations of HOE with atmospheric data taken at higher frequencies. The atmospheric conditions on Mauna Kea are probably close enough to those at Chajnantor that JCMT observations would be useful for this.

Among all the possible methods to obtain the total power data for the array, the OTF scheme is the simplest and least expensive, and it appears that it should work. The main requirement is a fractional receiver gain stability of about 1×10^{-4} in a one second time interval for all the antennas. There should be no difficulty in achieving this.

E. 183GHz Water Vapour Radiometers for ALMA

Richard Hills and John Richer, Cambridge

E.1. Introduction

This is a discussion document setting out the options for performing atmospheric phase corrections by means of radiometry. There is a great deal already written on this subject. In particular, the relevant memos and other documents have been summarised on the ALMA web site at

`http://www.alma.nrao.edu/development/cal_imaging/phasecal.html`

E.2. Status of current 183 GHz phase correction experiments

The JCMT-CSO single-baseline interferometer was the first to demonstrate phase calibration using the 183 GHz line, using equipment built by Martina Wiedner, Richard Hills and colleagues. Only a limited quantity of data were gathered but the results (ALMA memo 252) were encouraging and suggested that even an uncooled system could provide effective phase calibration at submillimetre wavelengths. Single baseline interferometry at JCMT-CSO is no longer a supported mode of operation, so further observations would be difficult though not perhaps impossible to arrange. It is however possible that two SMA antennas can be equipped with 183 GHz systems, using the radiometer currently at CSO plus a clone of it being built in Canada by Christine Wilson and the HIA. It is unclear when this experiment might produce results on Mauna Kea, but access to a large set of data in a variety of atmospheric conditions would certainly be useful in establishing the capabilities of the technique.

On the Chajnantor site, two further 183 GHz radiometers are in operation; these were built as a collaboration between Onsala and Cambridge and are very similar to the Mauna Kea systems, again using uncooled DSB mixers and three roughly 1-GHz wide filters. These two independent systems are aligned with the twin 11-GHz site testing interferometers, with their beams matched as well as possible using newly designed mirrors. The intention is to see how effectively and for what fraction of the time it is possible to use the 183 GHz systems to correct the 11GHz atmospheric phase measurements. It is possible to estimate the height of the turbulence from the lag between the two 11 GHz phase measurements (which are obtained by looking at different satellites) together with information on wind speed and direction. This will be important in establishing how strongly the quality of radiometric phase calibration depends on the turbulent scale height, both in practice and through models.

Initial results for both the lag estimates and radiometric phase calibration have been obtained in the past 2 months, although operational difficulties (principally power outages, and the difficulties in performing system upgrades and receiver tests on site) have restricted the quantity of data so far obtained. Work on analysing the existing data and on improving the measurements will continue as a high priority, with the goal of producing a report in about 6 months.

Although the results from these more detailed studies will be needed in order to answer some of the questions, we need to have an initial set of specifications for the ALMA radiometer system and a baseline design for inclusion in the plans and cost estimates. We do in fact have sufficient information to provide much of this information already. The following sections summarise our current thinking on the requirements and the design choices.

E.3. Design Considerations for the ALMA water vapour monitors

E.3.1. Requirements

The first question to be decided is whether we wish to correct just the phase error in the interferometric signal or whether we should also plan to take out the tilts in the wavefront across the individual dishes which cause pointing errors. (The latter effect is sometimes called anomalous refraction, although it is only anomalous in the sense that it would not occur if the atmosphere were uniform.) Correcting such pointing errors with radiometers was discussed by James Lamb and Dave Woody in MMA Memo 224. In each case we then need to set detailed requirements. We need to decide the path length error allowed as a function of integration time, weather conditions, zenith angle (z) and change in z. For pointing corrections, we need to set the required accuracy (which should be a term in pointing error budget) again presumably as a function of weather and z. The rms path error given as the goal in existing documents is 38.5 fs which is 11.5 micrometers of path. Note that, at this level, the loss of correlation from this cause is only 5% at 950 GHz and 0.7% at 350 GHz, so this is setting the goal very high. (Compare these to the transmission losses of about 70% and 20% for these same frequencies with 1 mm of water vapour.) No reference is made to whether this figure degrades in less than ideal conditions, but is clear that it can be allowed to without seriously affecting the data. A more realistic goal would be to multiply the above figure by $(1 + w_v)$ where w_v is the amount of water in the path in millimetres. The time allowed for achieving this accuracy is also not presently specified. We have generally been assuming that this refers to a one-second timescale, but we really need to look more closely at the data to see if we are justified in going as fast as this. (Note that the question of whether the correction is applied to the phase in real time or the data taken with short dump-times and stored for later processing has only a small effect on the radiometer requirements but quite large implications for the software.) A "systematic (avg)" error of 8.4 fs is also quoted in Larry D'Addario's Phase Stability Specification Note. We believe this is not relevant because any systematic or slowly varying errors in the atmospheric phase correction will be taken out by the observations of calibration sources. For the same reason, it seems to us that the longest timescale that we need to worry about for the radiometers are a few minutes. (We will presumably observe calibration sources much less often than we would if we were using only them to remove atmospheric phase fluctuations, but there seems to be no reason to do it less often than say once every 5 minutes. Note that this implies that the phase stability of the rest of the system must be maintained for at least this length of time. We can, if necessary, move further and use brighter sources than is planned for fast-switching phase calibration. Presumably the same observations will generally be used to check the pointing and/or the amplitude calibration.) It is however essential that we can measure the atmospheric term accurately as we move from source to calibrator. This is certainly more difficult if there are large changes in the total water in the path and/or ground spillover (although it is only the dish-to-dish differences in these effects that are important). At low elevations it would be beneficial to look for calibration sources that are closer to the target in zenith angle than in azimuth, i.e. to search in an elliptical patch of sky. The key sensitivity number is that at the optimum frequency the change in brightness temperature is $\sim 15/w_v$ mK per micrometer of added path. This suggests that a radiometric precision of order 150 mK (corresponding to 10 microns of path) would be sufficient in good conditions. Given bandwidths of ¿100 MHz and an integration time of 1 second, this looks reasonable, even for a room temperature mixer, for which Tsys of 1500K should be possible.

For antenna pointing corrections a suitable budget allocation is 0.3 arcsec rms (in dry conditions). This is a wavefront slope of 1.5 microns per metre, which leads to a figure of 9 microns when taken between two points 6 metres apart on the dish. The measurement is however now a difference between two numbers and it probably has to be measured in shorter times than the interferometric phase. This looks marginal with a single uncooled mixer. Studies of the existing site data (e.g. MMA Memo 223 and references therein) show that much of the observing time will be seriously affected by single dish pointing errors: the overall median seeing is about 1 arcsec compared to the specification for the antennas of 0.6 arc seconds. More study is needed of how fast the pointing fluctuates and how the bad seeing correlates with the other conditions. The obvious conclusion at this stage is that we do need to correct the pointing and that we should assume that this needs to be updated once per second. (With a wind speed of several metres per second and a 12-metre aperture, we can obviously expect some pointing changes on timescales as short as this, but the bulk of the power will normally be a periods of more like 10 seconds.) Note that this has to be done in real time and that we will therefore need to use an algorithm that anticipates the error for a time about one second ahead of the most recent reading.

Other requirements: Compatibility of interfaces (CANbus, etc.) Minimum interference with other systems. A special problem is leakage of the LO and its harmonics into other systems via various paths e.g. out of the feed and by reflection off the subreflector. It is unlikely that we can suppress these completely. The LO's should therefore be locked to system clock so any interference is at an accurately defined frequency. The design should use the fixed reference frequencies already provided at each antenna. We might add a requirement that the LO can be shifted by a small amount so that any interference can be moved away from a critical line.

Suggested baseline spec: $10(1+w_v)$ microns of path and $0.3(1+w_v)$ arc sec of pointing over a 5 minutes of time and 1 degree in z, with 1 sec time resolution.

E.3.2. Basic technical approach

The obvious options are line measurements at 183 GHz, 22 GHz, and in the mid-infrared (10 or 20 microns), or measurement of the (sub)mm continuum as for example used at IRAM.

The latter is unlikely to provide accurate enough path estimates and could not easily accommodate a wide range of conditions.

22 GHz is now essentially ruled out by the size of the optics. The feed would be 250 mm diameter to measure the interferometric phase and at least 500 mm for correcting the pointing. Sensitivity would in any case be problematical - a cooled system would certainly be required.

The use of infra-red radiometers is a new suggestion from Dr David Naylor (Lethbridge, Canada). The principle is essentially the same as with the millimetre radiometers but uses water vapour emission bands in the mid-IR. The system uses detectors cooled to 77 K. We could not use the telescopes optics so to measure the pointing corrections we would probably need either several detectors per dish or some optical relay system to give an appropriate spreading of the beam. The initial report on sensitivity and stability looks encouraging, but questions such as how much the results are affected by the temperature and pressure in the fluctuating layer and the effects of cirrus clouds have yet to be investigated. This needs to be done before we can judge whether this might be a viable option for ALMA. Meanwhile the baseline should remain 183 GHz.

E.3.3. Mixer or HFET?

183 GHz HFETS will probably be available but will be expensive, noisy and with poor short-term stability. The baseline should be to use mixers.

E.3.4. Cooled or uncooled?

The main advantages of cooled systems are sensitivity and stability. It would also be easy to provide a cold reference load. There is however some concern about how one would calibrate out losses in the Dewar window, especially if there is a possibility of getting dirt or water on it. External optics would almost certainly still be required for the pointing system and it might be possible to introduce some additional calibration signal there. With cooled systems, the radiometer will essentially take up one complete slot in a Dewar and the development path will interact strongly with the main receiver programme. It will also take up some of the cooling power budget (IF amps, windows, connections, etc.) and there would be greater likelihood of LO power leakage.

An uncooled system is clearly simpler, and should cost less to develop and build. Uncooled Schottky mixers can be obtained commercially and are robust and stable.

We therefore believe that an uncooled system should be adopted as the baseline. Assuming, however, that the goal of correcting the pointing is confirmed, there is some question as to whether sufficient sensitivity can be obtained with an uncooled system. Until this is established the cooled option should be kept open as the backup.

Digression on cooled systems:

E.3.5. SIS

If we use SIS mixers, these will have to go in the main Dewar and will presumably be based on the ALMA band 5 mixers. Sensitivity is then excellent and stability almost certainly acceptable given a suitable switching scheme. One can argue that no significant development effort on the mixers is required. The standard IF choice is not ideal (1 to 9 GHz would be better), but we could live with it. For example the LO could be at about 180 GHz so that the upper-sideband IF range of 4 to 12 GHz would correspond to line offsets of 0.7 to 8.7 GHz. The lower sideband would not be used and would have to be rejected at about the 25 dB level. The mixers would provide a certain amount of sideband rejection and this could be enhanced by having a waveguide filter at the input to the mixer, since the operational frequency is fixed. Although there will naturally be strong resistance to giving up one of the astronomical "slots" (or making the Dewar larger and more complicated), this option is sufficiently attractive that it should probably be kept open for the present. A straw-man design for it could be worked up and costed but no development work seems to be needed now.

We should also consider here the possibility of using the astronomical band-5 receiver to do the radiometry. Given the high sensitivity it might be possible to obtain sufficient accuracy from the shape of the line plus perhaps frequency switching, in which case it should not be necessary to compromise the astronomical performance of the receiver by adding additional switching components inside the Dewar. Another option would be to insert a 45-degree polarising grid into the beam when selecting this mode. This would make it possible to use the two polarisation channels as a cross-correlation receiver. This should also provide a way of doing sideband separation. This would of course mean that correction would not be available when using this receiver for astronomy. (Under good conditions, however, it might be possible to do the water vapour measurements with the band-7 receiver using the 325 GHz water line.) Some additional electronics for generating the LO and processing the IF would need to be added. Extra optics would be needed to do the single-dish pointing corrections and these would have to be inserted into the beam to select this mode.

An important additional consideration is that using an SIS mixer should give sufficient sensitivity to provide a correction for the water vapour emission when making total power observations with another receiver. One can see that this should be possible from the fact that, for 1mm of precipitable water, the extra emission ΔT_b for a given Δw_v is several times stronger between 181 and 185 GHz than it is at say 345 GHz.

Again these options seem sufficiently attractive that they should be explored in more detail. The interactions with the rest of the system are nevertheless a substantial negative factor. If nothing else we would be compelled to have band 5 available on all antennas from day 1, which may not coincide with the astronomical priority.

E.3.6. Cooled Schottky

The advantage of using a cooled Schottky system is that it could be housed in a separate Dewar with the band 1 receiver (if that is the outcome of other discussions) where it could be cooled to 15 –20 K. The interactions with the more critical part of the receiver system would then be reduced. It would however probably be necessary to undertake a new development to obtain suitable mixers and we are not clear what performance could be obtained. The IF amplifiers would probably play a major role here and it may again be best to use the ALMA 4 to 12 GHz ones. If we decide to use a Dicke switch (see below) then we would probably need to develop a suitable coolable switch. This option should be considered further if detailed planning for a band 1 Dewar is undertaken.

Finally in this section, we should note that very compact and relatively cheap refrigerators are now available which could cool a simple radiometer to say 70K. Although reliability might be an issue, it may turn out that this is the most cost-effective way of getting the necessary sensitivity if it cannot be obtained with an uncooled system.

E.3.7. Form of switching

For an uncooled system, there seems little chance of obtaining 0.1 K stability with a total power system given a system temperature of at least 1000 K. (Note that we can get some relief because we are observing a line and are to a considerable extent only concerned with the differences between frequencies. We believe that some form of comparison with a load of known temperature will however be necessary.) We should therefore plan to use either a Dicke switch or a continuous-comparison radiometer which takes the difference between the sky temperature and a temperature-controlled load. For the pointing correction we also need to take the differences between different parts of the aperture. Many options are available but we clearly wish to select the simplest, cheapest and most reliable that can do the job.

The most basic option is a single mixer with a Dicke switch operating between the sky and a fixed-temperature load. Ideally this load should be at a temperature close to that of the sky brightness at which one obtains the best sensitivity (around 170 K). A modulated calibration signal would also be injected via a coupler on the input. An alternative to injecting a cal signal is to switch between the sky and two loads at different temperatures. This gives more flexibility in the choice of temperatures: something like 100 K and 250 K (spanning the sky brightness range of interest) would be best, but combinations like 200 K and 370 K would also be good. The existing MRAO design uses two loads and an optical switching scheme (a flip-mirror). This works quite well, but for ALMA it would probably be worth developing an all-electronic switching scheme, using ferrites or diode switches, for both reliability and stability reasons. With a single mixer the system would normally run in double-sideband mode and, provided the gain stability was adequate, the sensitivity would be given by the normal radiometer equation:

$$\Delta T = 2T_{sys}(DSB)/\sqrt{Bt}.$$

The next level of sophistication is to use two mixers. With a hybrid before the mixers and a correlating backend one can then arrange that the output is the difference between the sky temperature and the load. The sensitivity improves by root 2 and with appropriate switching we can presumably separate the sidebands as well, although the advantages of doing this do not seem very great. (It would perhaps give better information about any contribution from clouds.) To obtain the gradient in the emission, which gives us the pointing correction, we need to arrange the optics so that the radiometer illuminates a patch on the subreflector, covering about half of it. For a switching scheme the beam then has to be moved around (most naturally as a circular scan about half way out) and the signal put through a pair of synchronous detectors to generate the required error signal. Lamb and Woody suggested a rotating prism to do this but a rotating mirror with its normal slightly tilted with respect to the axis of rotation would also do the job. An alternative is to again use correlation (i.e. continuous differencing) receivers. The most obvious arrangement would be to have 4 horns in a square, which are optically reimaged onto the secondary. The two diagonal pairs are connected to 4 mixers via hybrids in such a way that the outputs are the differences in the sky brightnesses required. A mechanism for switching against loads would still be needed to give the interferometric phase correction. Although these schemes sound complicated, the technology does probably now exist to build such combinations of splitters, hybrids and mixers in a stripline form at these frequencies.

More discussion of these schemes seems appropriate before a choice is made here.

E.3.8. Form of backend

In principle we could scan the LO and use a fixed and very simple IF with just one fixed frequency. Given that we are struggling for sensitivity this seems unattractive. The stability would probably not be good either. We therefore need a multichannel backend. The obvious choices are a set of filters (as in the MRAO and Onsala systems) and an analogue correlator along the lines developed by Andy Harris.

More modelling is needed to determine the number of filters required but it seems unlikely that a great deal of additional information will be obtained by using more than about 4. The bandwidth should increase with increasing offset from the line. It is of course possible to make a cross-correlation filter spectrometer to use with a correlation front-end although twice as many filters are needed.

The analogue correlator form looks attractive as a compact device suitable for mass production. The existing design is limited to about 4 GHz by the analogue multipliers but faster devices are being worked on. An alternative approach using passive detectors is under development at MRAO for CMB work. Because the frequency spacing is fixed, one would need at least 16 lags to cover plus and minus 8 GHz of IF.

We suggest that the analogue correlator be adopted for further investigation with filters as a safe fallback.

E.3.9. Local Oscillator

In order to use DSB systems (or a SSB one with modest rejection) we need to put the LO at the line frequency, 183.31 GHz. First harmonic mixers would require 91.155 GHz, which is easy with a fixed-tuned Gunn. Alternatively it may be more economical to adapt components from the standard ALMA LO system even though the tuning flexibility and phase stability are not required. Fundamental mode mixers are better because there would be fewer LO harmonics and somewhat lower noise. These could be driven with a Gunn plus a doubler, but would need quite a lot of power, especially for several mixers. Using biased mixers rather than self-biasing ones would reduce this problem.

No tuning is needed, except possibly a step of a few MHz to move it out of the way of a particular line. Although with an SSB system one can in principle fit for the frequency, phase locking the LO to the system clock is clearly advisable, so that all the interference spikes are at accurately known frequencies (and with zero fringe rate).

E.3.10. Beam Offsets

It is clearly important that the radiometer samples the same path through the atmosphere as the incoming astronomical signal. It is in fact not possible for these to match absolutely perfectly. (For one thing the radiometer signal is incoherent emission from the water molecules and is therefore sampled by the intensity pattern of the antenna, which is always positive. The path length change is a coherent effect and therefore depends on the amplitude pattern. Molecules in certain locations will not contribute to the phase delay and some will even produce an advance!) The question of how well the beams need to overlap depends on how much small-scale structure there is in the water vapour and how far away it is in front of the aperture. We need more data on the height of the fluctuating layers to make quantitative statements on this.

It is however clear that it is desirable to keep the radiometer close to the astronomical feeds but this is not likely to be a very critical parameter because most of the phase fluctuation is in scale that are considerably larger than the beam. If we can place the radiometer feed in the centre of the ring or cluster of feeds, then the beam offsets are likely to be in the range 3 to 10 arc minutes. This corresponds to distances of 1 to 3 metres at a distance of 1 km, i.e. a modest offset compared to the dish diameter. To illuminate a suitable area on the subreflector to be able to do the pointing correction would require a feed about 75 mm in diameter. It is more likely that a much smaller feed (or group of feeds) would be used which would be reimaged onto the subreflector by an optical relay. The final mirror of this could then be in the central position and it would be advisable to allow about 100 mm clear diameter to accommodate it.

The baseline should be to keep the radiometer beam within 10 arc minutes of the astronomical ones and, if it is practical to do so, make this offset smaller than that for the higher frequency channels.

E.4. Conclusions

The critical issue at this stage is to decide whether we should aim to correct the single-dish pointing errors or not. Once that is determined more detailed specifications can be drawn up and design choices made. It is also important for the SAC to consider the issue of whether options involving use of the astronomical receivers should be kept open or ruled out now as an undesirable approach.

F. An Infrared Water Vapour Monitor for the Correction of Phase Errors in Submillimetre Astronomical Interferometry

David A Naylor, University of Lethbridge

F.1. Features of an infrared system (IWVM) for monitoring atmospheric water vapour content

- Operates near the peak of the Planck function for atmospheric temperatures
- Wavelength range carefully selected to include only transitions from water vapour
- Wavelength range includes mixture of strong and weak lines and therefore samples different heights, in effect yielding an average over whole atmosphere
- Theoretical atmospheric model supported by FTS measurements from Mauna Kea (Naylor et. al. PASP 96, 167 (1984)). Inputs are base pressure and temperature.
- IWVM sensitivity (expressed in terms of μm pwv) improves as the pwv decreases (Fig 1). For example, if the IWVM can detect variations of $\pm 1\mu$m pwv in a given integration time when the atmosphere contains 1mm pwv, it will detect variations of $\pm 0.7\mu$m and $\pm 1.85\mu$m when the atmosphere contains 0.5 and 3mm pwv respectively
- Photoconductive detectors are simple devices offering high speed, sensitivity and stability
- Diffraction limit at these wavelengths allows use of smaller optics
- Design makes calibration intrinsically clean since optical train is identical in all observing modes

F.2. Description of Infrared Water Vapour Monitor (IWVM)

Figure 2 is an image of the unit in operation at the JCMT. The computer and electronics are seen in the foreground, the IWVM in the background. The IWVM uses a plane steering mirror which directs light onto a fast off-axis parabolic mirror at whose focus is an infrared photoconductor detector. A cold bandpass filter located immediately ahead of the detector defines the spectral bandwidth. A cold aperture in front of the filter defines the detector field of view. A reflective chopper produces a 200Hz modulated signal of the atmosphere which is calibrated by pointing the steering mirror to 2 blackbody sources. The detector and parabolic mirror define the field of view on the sky which is chosen such that it samples a patch of atmosphere of similar size as a submm telescope at the scale height altitude of water vapour (~10 m @ 1 km).

In the current design a standard, compact, LN_2 dewar cools the detector. For installation and long term operation on a submm antenna, a closed cycle cooler would be used (eg. Cryotiger) and the IWVM mounted on the outer rim of the antenna (much like a finding scope). The cold space required is rather small ($\sim$ 18 cm^3). The Moon provides an ample signal to align the IWVM (in the Dec 99 run the moon was about first quarter and was easily detected). Once the submm telescope is centred on the Moon it is expected that the IWVM can be aligned to an accuracy of a few arcminutes.

The IWVM can operate in sky-dip or stare modes. In the sky-dip mode the system steps in 0.18° increments from the zenith to ∼70° (corresponding to a range of 1 – 3 airmasses). In the stare mode the system can be fixed at a given zenith angle.

Key components of the IWVM are:

- Infrared detector – 20μm represents the practical limit for MCT detectors operating at 77K. (Si:As detectors would offer a significant gain in sensitivity (several orders of magnitude) but require cooling to ∼12K. When I was approached by NRC to study an infrared solution to phase correction of submm interferometry one of the boundary conditions was a temperature no lower than 77K.) I am discussing with an infrared detector manufacturer ways of improving the performance of the MCT detectors for this application. I believe that the detectors will not be a critical issue.
- Low noise preamplifiers – our group has extensive experience in infrared technology and routinely constructs preamplifiers that out perform those supplied by detector manufacturers. Other aspects of the electronics (eg. chopper controller, lock-in amplifier, analog-to-digital conversion) are standard. No critical items.
- Infrared filter – this is the most critical item. Unfortunately there are no manufacturers currently building filters for this wavelength region. Furthermore, and naturally, any existing 20μm filters were designed to avoid the water vapour lines. Prof. Peter Ade (QMW), with whom I have a long standing collaboration, is currently trying to extend his filter fabrication technology from the 200 to the 20μm range. While the initial attempts have yielded promising results more work needs to be done in this area, in particular the production of smaller scale electron beam lithography masks.
- Optics – the fast off-axis parabolic mirror and the electric discharge machined (EDM) reflective chopper. No critical items.

F.3. Theoretical calculation of radiant power emitted by atmospheric water vapour in the 20μm band above Mauna Kea

- Atmospheric models show that the 20μm flux from H_2O (assuming 1mm pwv) is ∼1 W m^{-2} sr $^{-1}$. Fig 3 shows a theoretical curve of growth (radiance vs mm pwv) for the atmosphere above Mauna Kea, fitted with a 13 order Chebyshev.
- Telescope diameter ϕ = 125 mm. Area=1.23 x 10^{-2} m^2
- Field of view: defined by 10 m patch of sky at an altitude of 1 km, $\theta = 10^{-2}$ rad, $\Omega = 7.85$ x 10^{-5} sr
- Total efficiency, η ∼10% (optics, filters, chopping)
- Power on detector = 1 x 1.23 x 10^{-2} x 7.85 x 10^{-5} x 0.1 = 9.7 x 10^{-8} W
- Detector sensitivity, D*, = 2 x 10^9 cm $\sqrt{\text{Hz}}$/W
- NEP = $\frac{\sqrt{\text{Area}}}{\text{D*}} = 5 \text{ x } 10^{-11}$ W/$\sqrt{\text{Hz}}$
- S/N = $\frac{9.7\text{x}10^{-8}}{5\text{x}10^{-11}} \approx 2000$

- Atmospheric models of flux vs pwv, well described by Chebyshev polynomials, show that this S/N translates to a Δpwv of $\sim 1\mu$m (1σ) detection in a 1 second integration.

F.4. Preliminary discussion of results from Dec 1999 run

- Fig 4 shows the stability of the blackbody reference measurements. Top left: plot of variation in detector signal due to ambient blackbody over one week period. The radiance from this blackbody follows the ambient temperature and so variation in this reading is expected. Bottom left: same for LN_2 blackbody. Each day the detector was allowed to warm up and then refilled with LN_2. The residual variation in this signal is likely due to a slight repositioning error of the LN2 blackbody. Typically 20 scans were obtained for each point in the left plot; the standard deviations of those 20 scans is shown in the right plots. The scan to scan repeatability is around 5mV for the LN2 data throughout the week. It is higher for the ambient data but this reflects the slow change in ambient temperature during the 10 minute scans. These data show that the system is intrinsically stable. Detailed analysis of the system responsivity (calculated from the blackbody temperatures and measured signals) on time scales ranging from 30 secs (a single sky-dip) to a week has shown no evidence of variability, as is expected.

- Fig 5 shows three sky-dips observed during a 50 scan sequence. The 1, 25 and 50 scans are shown from which it can be seen that the atmosphere was drying out. The top graph is given in terms of zenith angle (steps 0.18°), the lower plot in terms of airmass. Each full sky dip takes around 30 seconds.

- Fig 6 is similar to Fig 5 but on a dry and stable night. Since each sky-dip is a measurement of atmospheric radiance over a range in airmass from 1 to 3, then in principle it should be possible to build up an experimental curve of growth (equivalent to the theoretical model (Fig 3)) by combining sky-dip curves taken under different water vapour pwv conditions (since water vapour is the only source of emission in the band). Furthermore, by having an independent measure of the water vapour content of the atmosphere (eg radiosonde) this curve of growth can be calibrated. Unfortunately the weather conditions in Dec 99 were generally poor and often varying and our most stable sky-dips were several hours displaced from the radiosonde launches. Nevertheless, we have developed an algorithm to combine the averages of the most stable sky-dip runs assuming that the atmosphere varied only in water vapour content. This algorithm scales individual sky-dip measurements in terms of airmass (or equivalently pwv amount) minimizing the χ^2 of the overlap regions of individual sky-dip sequences. This analysis is still in progress but our early results are shown in Fig 7 (the x-axis scale is left in terms of airmass but once calibrated would be given in terms of mm pwv). The lower plot shows the result of applying this algortihm to 4 sky-dip sequences (the second and third offset by + and - .1 respectively for clarity); the upper plot shows the 4 traces overlaid. The agreement is remarkable and if we had independent pwv estimates from radiosonde data for the start of each of the sky-dips we would be able to calibrate this curve for direct comparison with our theoretical model.

- During the Dec 99 run Prof. Richard Hills was at the JCMT and kindly showed us how to operate the 183GHz water vapour monitor. On the last night we operated this system while we were pointing at Jupiter. Simultaneously we operated the IWVM with the zenith angle set to that of Jupiter. However, because the IWVM is mounted in front of the windscreen (a part of the building that rotates with the dome, but separate from the telescope) we were not aligned at the same azimuth as the telescope. Nevertheless, the same atmosphere swept through the IWVM beam several minutes later. The results are shown in Fig 8. The lower trace is the 183GHz line-of-sight water vapour. The next three traces are IWVM results (each displaced upwards by .2mm pwv): the first is the raw data (0.1 sec samples), the next is smoothed to 1 sec, the last to 10 sec. Since we have not yet calibrated the IWVM we have used our best estimate model atmosphere for the infrared filter and then scaled our vertical axis. The agreement between the 2 systems is remarkable. Many of the features are evident in both systems while some appear to have shifted slightly during the elapsed time.

F.5. Areas of improvement

The early results show that the sensitivity of the IWVM is around 10μm pwv (1σ) in 1 second at ~1 mm pwv. This number is about a factor of 10 worse than theory predicts. The main reason for this is our current infrared filter which is far from optimal. Other problems encountered during this first run with the IWVM include:

- we used a general purpose 12-bit data acquisition system (that we have used in other applications for ease of development). It is clear that more resolution is needed
- analysis of Moon scans has shown that the IWVM was slightly out of focus. Because of the fast optics (f/.9) some of the radiation was not reaching the detector

F.6. Future plans

The first results of the IWVM are encouraging, the system is intrinsically stable and fast (chop 200Hz) and nothing that we have seen to date would speak against the infrared technique as being a very promising approach to phase correction of submm astronomical interferometry. Future plans include:

- procure optimised infrared filter
- upgrade to higher resolution data acquisition system (16 bit)
- now that we know the gains, chop frequency and phase of the lock-in amplifier we plan to integrate all the electronics (including chopper drive circuitry) into one module. This will greatly simplify the connections between the various components and further reduce external noise
- redesign IWVM for remote operation over the Net. We intend to construct a web based interface to the IWVM that would allow us to operate the system remotely, download data in real-time and retrieve data from an onboard archive
- with remote operation capability we are planning a 3-month campaign at the JCMT to perform sky-dips every night within ± 30 mins of the nightly radiosonde launch at 0200 HST. This will allow us to build a statistically significant database to calibrate the IWVM's in terms of mm pwv and revise, if necessary, our model atmosphere. The plan is to operate the IWVM's remotely from Lethbridge requiring minimal assistance from the JCMT staff (eg a TO fills 2 small dewars with LN2 and reboots the computer if necessary.)
- finally, build a clone of the first unit so that we can test the systems on a millimetre interferometer

Note: i) the sensitivity of the IWVM can be increased by using a larger input mirror (eg doubling the diameter to 250mm, which is still practical, increases the sensitivity by a factor of 4). ii) should the cryogenic limit of 77K be dropped, Si:As detectors would allow measurements of water vapour at the 1nm level.

F.7. addendum: A comparison of the IWVM and 183 GHz WVR sensitivities (by C. Wilson)

The theoretical calculations presented above suggest the infrared water vapour monitor (IWVM) should be able to achieve a 1 sigma sensitivity of 1 μm pwv in 1 second. This sensitivity is appropriate for an average pwv of 1 mm; the sensitivity will be 30 percent better when the pwv is 0.5 mm. Now, according to Lay et al. (MMA memo 209), 1 μm of pwv corresponds to 6 μm in the optical path. The currently recommended design goal for ALMA is an accuracy of $10(1+w)$ μm in optical path per baseline, where w is the atmospheric precipitable water vapour (in millimeters). Since the path difference is determined from measurements at two telescopes, this means the accuracy needed at each telescope is about 14 μm of path or 2 μm of pwv when the total pwv is 1 mm. Thus, if the IWVM can achieve the predicted theoretical sensitivity, it should be able to provide the required accuracy.

The preliminary analysis of the results from the first run with the IWVM gives a 1 sigma accuracy of 10 μm pwv (60 μm of path) in one second of integration. In comparison, the uncooled 183 GHz radiometers on the JCMT and the CSO achieved a 1 sigma accuracy of 0.1-0.2 K in 10 seconds (Wiedner & Hills, Imaging 99 proceedings). From the calibration on a day when the pwv was 2.2 mm, this rms corresponds to a 1 sigma accuracy of 20-40 μm in path. In comparison, if we were to average the IWVM data over 10 seconds instead of 1 second, the sensitivity from the first run would be 3 μm pwv or 20 μm in path. Thus, the current IWVM and the current 183 GHz radiometers likely have similar sensitivities.

The expected rms for the existing 183 GHz radiometers from just thermal noise is about 0.06 K; there were substantial fluctuations in the instrumental gain which brought the noise up (Wiedner & Hills 1999). Also, the current plan for ALMA is to cool the 183 GHz radiometers, which will bring the system temperature down by a large factor. As an example, if the system temperature of the uncooled 183 GHz system is 2500 K and that of the cooled system is 400 K, then the thermal noise would drop from 0.06 K to 0.01 K in a 10 second integration or 0.033 K in a one second integration. This means the one sigma accuracy of a cooled 183 GHz radiometer in one second of integration would be 7 μm in path or about 1 μm in pwv. However, this sensitivity is appropriate for fairly wet conditions (2.2 mm pwv; 3.9 K/turn or 4.6 K/mm path). From Figure 2 in Wiedner & Hills (1999), when the atmosphere is very dry (0.4 mm pwv), the sensitivity at the line center rises to 40 K/mm path. If the 183 GHz radiometers for ALMA can measure close to the line center, the sensitivity under these conditions would be 0.8 μm in path or 0.13 μm in pwv. However, at these levels, the sensitivity would likely be dominated by other factors such as gain stability, uncertainty in the altitude of the water vapour, etc. (see Lay et al., MMA memo 209).

In comparison, the expected sensitivity of the IWVM is 4 μm in path (0.66 μm in pwv) with an atmosphere of 0.5 mm pwv and 8.5 μm in path with an atmosphere of 2 mm pwv. (Note that these sensitivities are estimated for Mauna Kea; the sensitivity should be even better at an altitude of 5000 m.) Thus, if the IWVM can achieve the theoretically predicted sensitivity, it could be competitive with the 183 GHz radiometers and should be able to meet the design goals for ALMA.

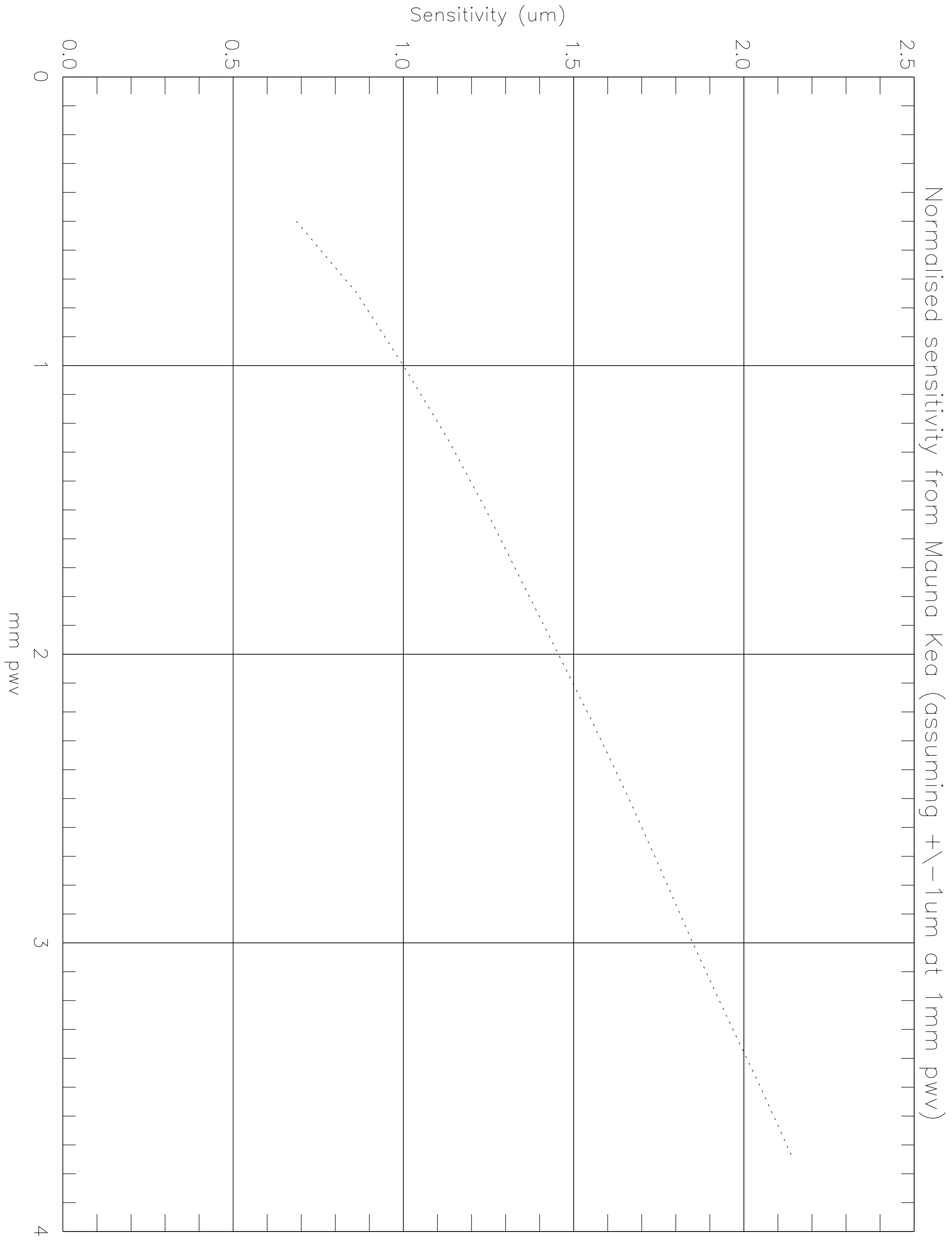


Fig. F1.— IWVM Sensitivity versus Water Vapor

Fig. F2.— Picture of system on the JCMT

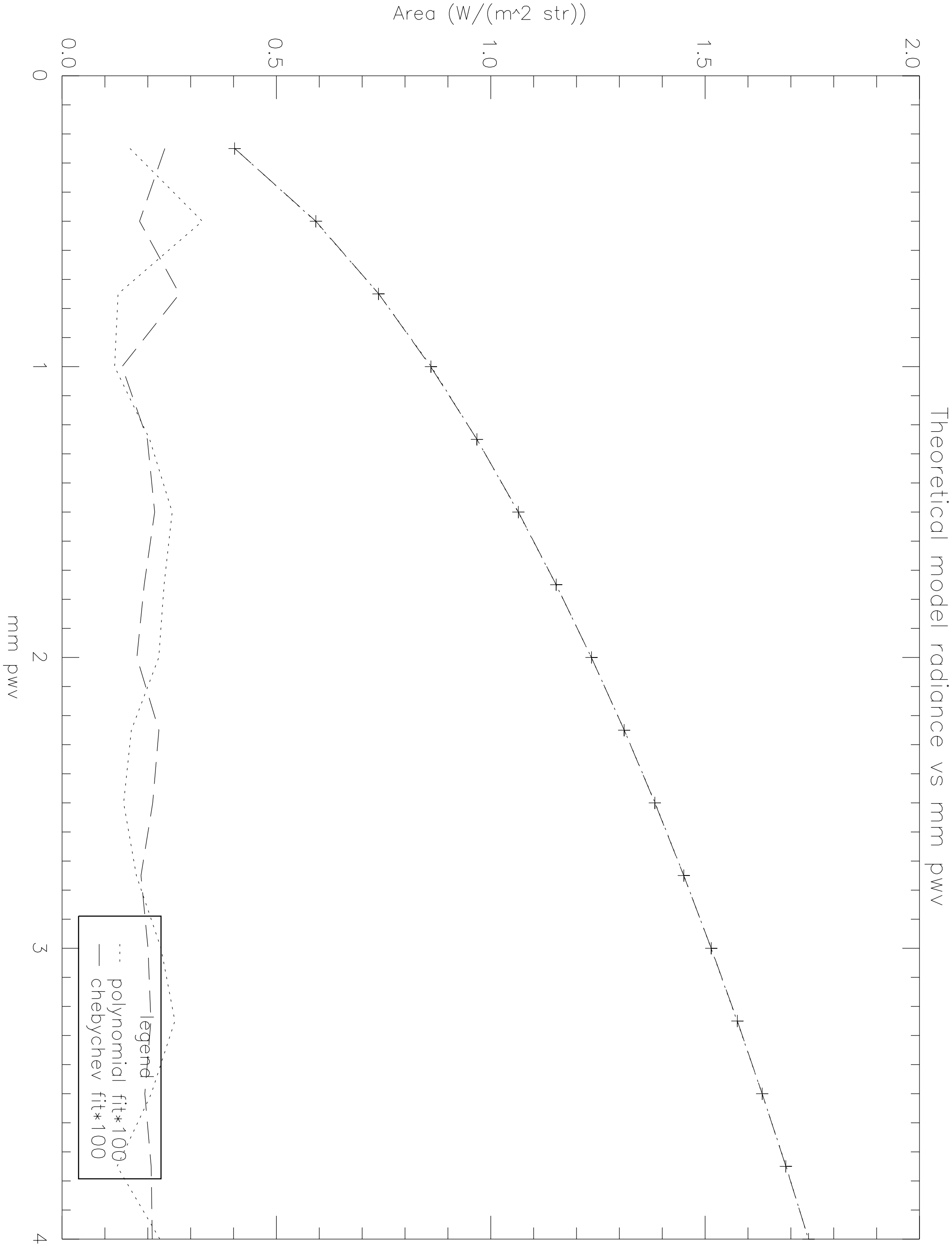


Fig. F3.— Theoretical Curve of Growth

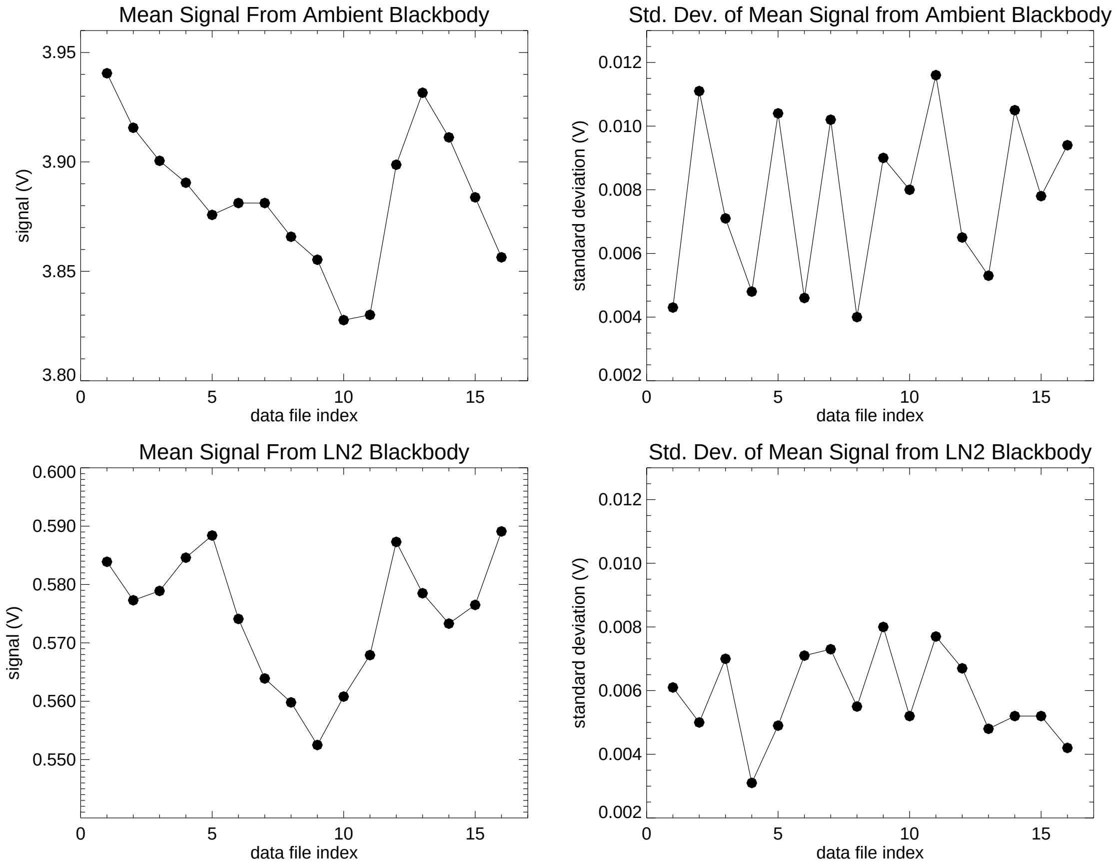


Fig. F4.— Stability of blackbody reference measurements

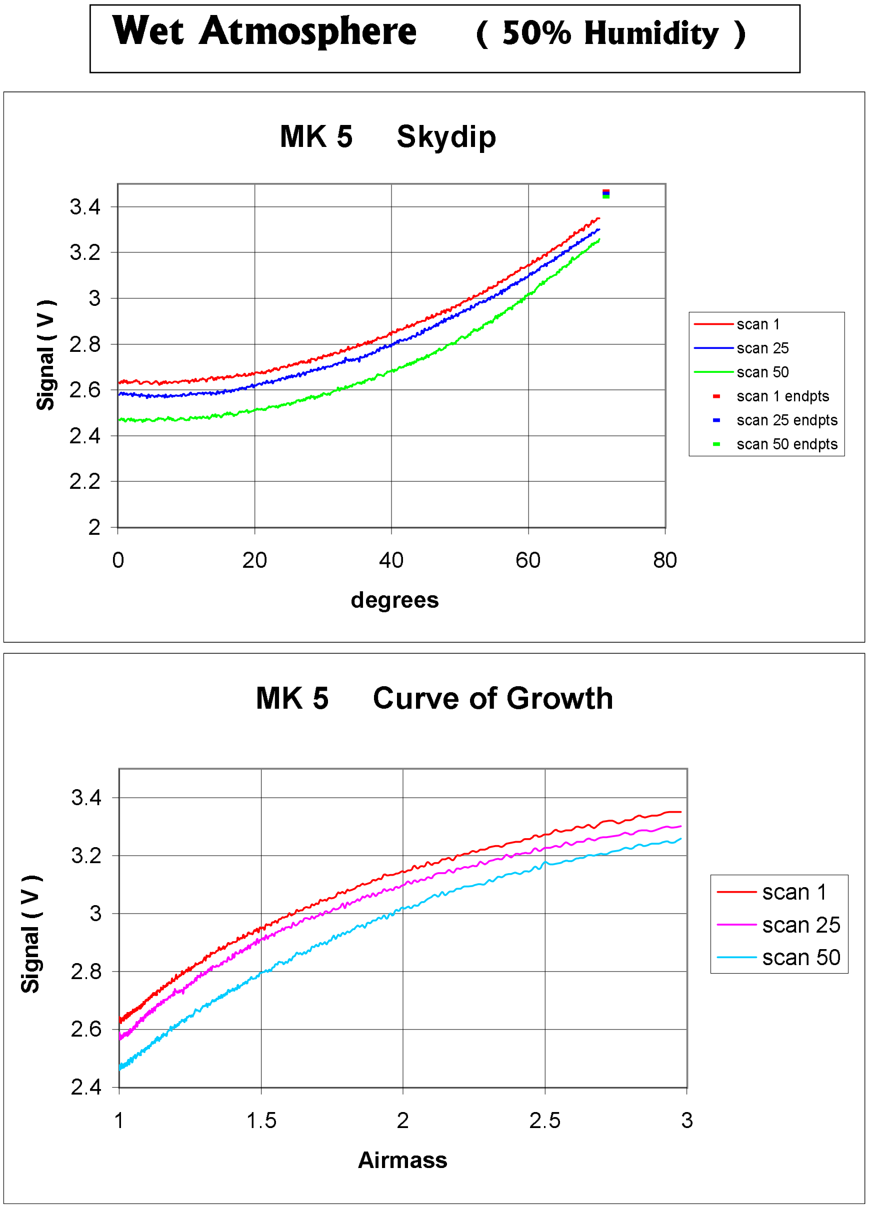


Fig. F5.— Three sky-dips during a 50 scan sequence

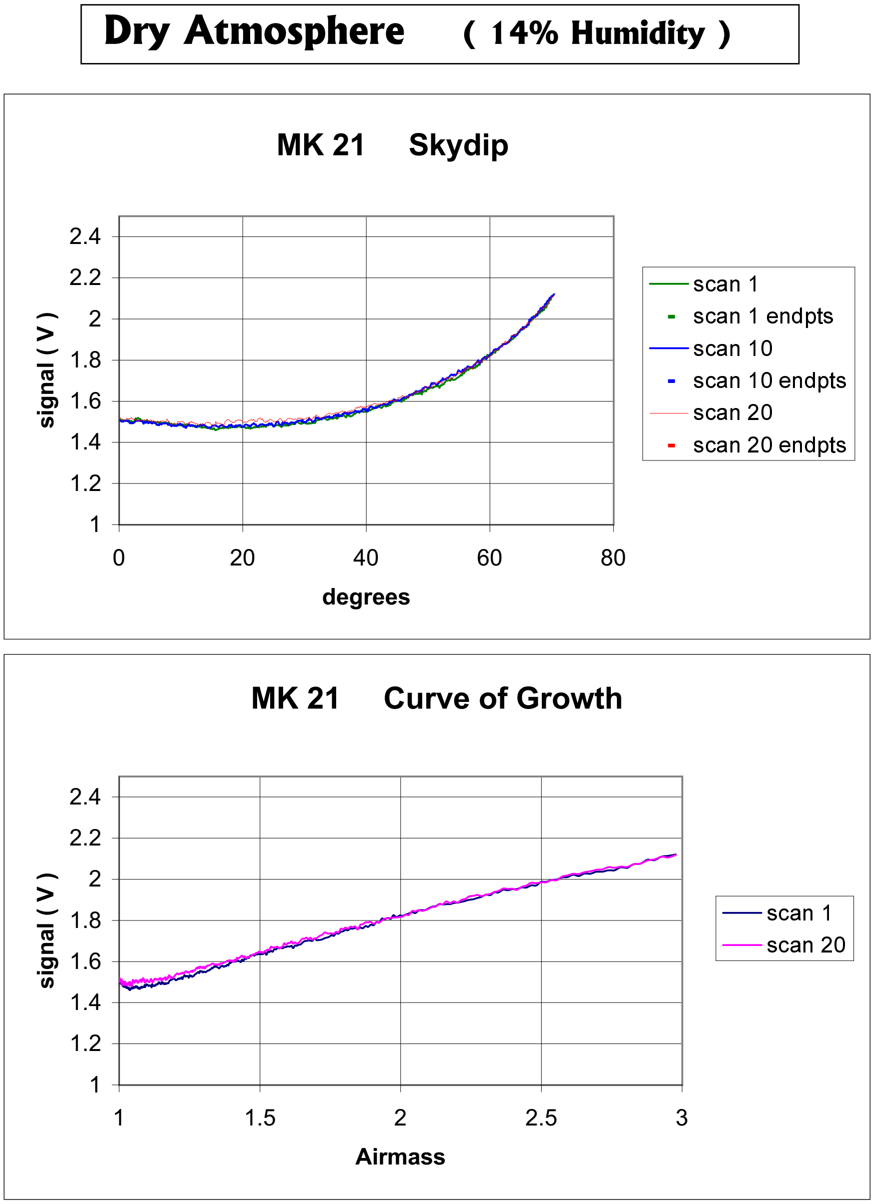


Fig. F6.— Similar to Fig. F5, but on a dry and stable night

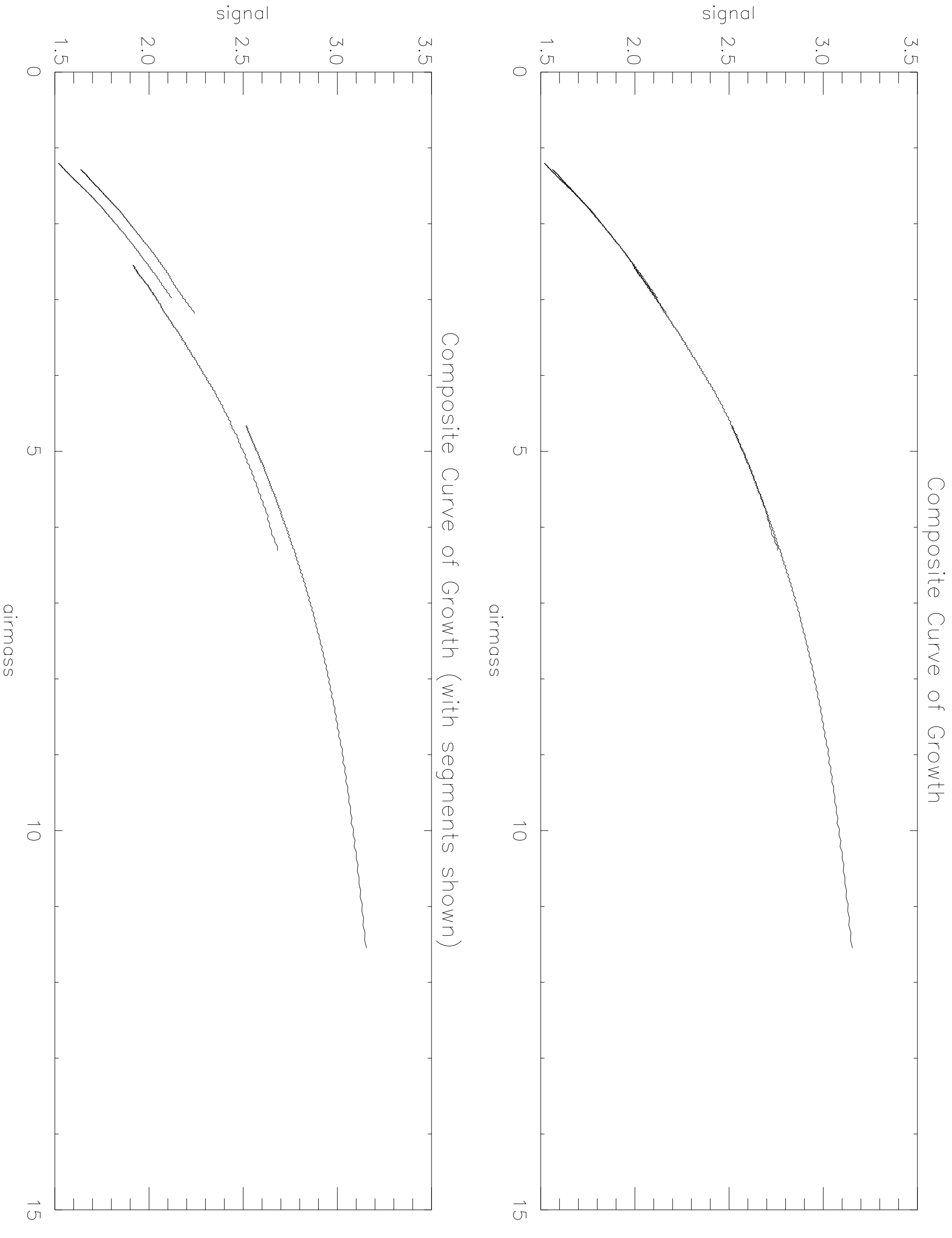


Fig. F7.— Early results of algorithm

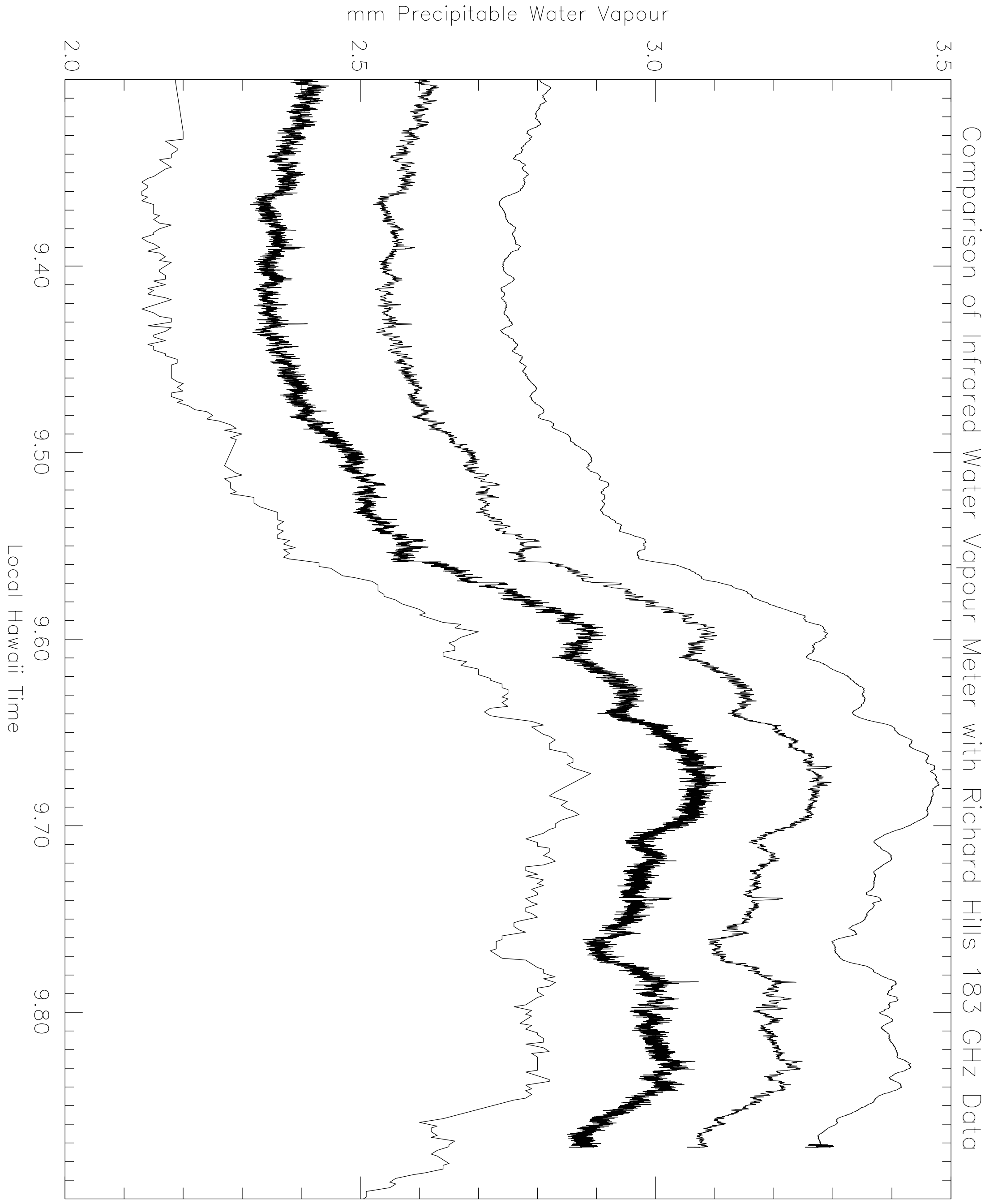


Fig. F8.— Comparison of 183 GHz (lower trace) and infrared system

G. Rationale for Band 1 (31.3-45 GHz) Receivers on ALMA

John Carlstrom, University of Chicago

G.1. Cost

The receivers with today's tedious hybrid amplifier technology and without including the benefit of quantity savings is \$50K per receiver times 64 = \$3.2M. MMICs and quantity savings should bring this cost down considerably.

\$3.2M should be considered a reasonable limit including all other modifications.

I don't believe the \$10M and greater costs that has been floating around.

These are straight forward receivers. For example, 24 similar receivers have been in a small lab at Chicago.

Furthermore, the dewar housing the Band 1 receivers may also include the 70-90 GHz HEMT receiver as well as the WVR receivers. If this is the case, then the incremental cost of adding the Band 1 receivers would be MUCH less than \$3.2M.

I do not believe there is a strong need to have the WVM and the Band 1 receivers working simultaneously. This would presumably simplify the optics.

G.2. Sensitivity of the Band 1 - Incredible

The point source sensitivity of the Band 1 would exceed that of the UPGRADED VLA! There is less total collecting area, but the higher aperture efficiency ($> 2\times$) more than makes up for it. The much better site and cleaner optics helps further.

The field of view of ALMA is 25/12 times larger than the VLA.

For a given point source sensitivity the surveying speed of ALMA will be more than 20 times faster than the upgraded VLA. Interesting in its own right and very important for galaxy surveys, CMB foreground experiments, dust surveys, etc.

ALMA sensitivity will be superb and unparalleled for arcminute scales at Band 1. A simple estimate including ONLY baselines from nearest neighbor telescopes gives 2 μK in one hour and an arcminute beam. There are 2.5×64 nearest neighbors in a close pack configuration. Of course, for imaging it is much better to include all baselines – see simulations. The bottom line is that it is fantastic.

IMPORTANT NOTE: ALMA does not replace the VLA! The VLA has much higher resolution. Together they cover both the N and S hemispheres. The VLA will excell for detailed studies of compact objects (AGN, stellar accretion disks, etc. ALMA will find which objects are worthy of higher resolution studies (eg., survey star forming regions for disks, galaxies, etc.).

G.3. Comparisons with other telescopes

Whenever imaging over scales of $0.2''$ to $10''$ is desired at 31.3 - 45 GHz, there is NO instrument competitive to ALMA, either in existence or planned.

Higher resolution will be best done with the VLA.

Scales much greater than $\sim 100''$ at 31.3-45 GHz will be best done with a number of instruments: i.e., CARMA heterogeneous array, GBT, and dedicated CMB instruments.

Scales larger than $100''$ could be done with ALMA in total power and using mosaicking. I am NOT convinced, however, that the total power will work well for extended low brightness continuum emission (eg., Sunyaev Zel'dovich Effect and CMB work). Nevertheless, there is extremely important work for ALMA to contribute here WITHOUT total power measurements. ALMA will be an ideal probe for the high redshift universe.

The sensitivity of ALMA in its sweet spot ($0.2'' - 100'' \leftarrow$ a big range) is simply incredible.

MORE ON GBT: The one possible direct competition with ALMA for the angular range of $15''$ and larger is the GBT. However, to be competitive a large focal plane array ($\sim$64 elements) at 40 GHz is needed. The single dish radiometers are considerably more complicated and expensive than receivers for an interferometer. The GBT observations will rely on total power measurements, obviously, and thus it is more difficult to reach the low brightness levels. I strongly believe that the interferometric technique is far better. The GBT is also located at a vastly inferior site – atmospheric conditions are likely to severely limit its performance for observations of low surface brightness objects. ALMA outfitted with Band 1 receivers is clearly superior for angular scales up to $\sim 100''$. The GBT, however, may be an ideal way to recover short baseline information.

G.4. Impact on sensitivity to other ALMA bands - None!

To achieve the optimum sensitive for the mm-wave bands, one will want to use a reimaging system - the feeds will not be at the Cassegrain focus. The reimaging could be done with lens, but they would need to be cold to not impact the noise performance. Cold lenses require big dewar windows which would also affect reliability and possibly noise performance. Therefore, most likely highly accurate and large mirrors will be used. This means there could easily be room for the Band 1 pick-off mirror. Including Band 1 should not affect the sensitivity of the mm-wave bands.

Again, in the interest of simplifying the optics. It is not necessary to use the WVM and Band 1 simultaneously.

G.5. Test phase of ALMA and debugging

The Band 1 receivers will be in a separate dewar from the SIS mixers. They could be used before the much more complicated SIS receivers are installed or when they are being upgraded, etc.

The HEMT receivers are very robust and are simple to operate and maintain.

We have found that the enormous gain in sensitivity when the 30 GHz receivers are installed at BIMA and OVRO (low Tsys; bright point sources, stable atmosphere) allowed us to check out the system at levels not even remotely possible using the mm-wave bands - we are able to tune up the arrays with our receivers. This will also be true for ALMA. I think it will be extremely useful for initial stages of the array. Frankly, I feel this alone is worth the cost (a percent or less of the cost of the total project!). Interestingly, the Q-band (40 GHz) is the only band ready for the testbed interferometer at Socorro.

G.6. Science

- High redshift molecular lines:
  - ground state lines: HCN, HCO+ etc.
  - CO 1-0 ($1.7 < z < 2.8$)
  - CO 2-1 ($4.3 < z < 6.6$)
- High redshift dust emission
- Galactic molecular lines, i.e., SiO, CCS, SO (paramagnetic), HC3N
- Anomalous dust emission (rotating grains?)
- Dust - penetrate high opacity of accretion disks, other extreme optical depth objects
- compact objects - VLBA: ALMA would provide an important southern extension with large collecting area.

G.6.1. Sunyaev-Zel'dovich Effect and secondary CMB anisotropy

SZE detections and images are now robust. The next step is to do large scale blind surveys – these (hopefully) will be done in the next few years.

Arcminute anisotropy is possibly on the verge of detection, but will need ALMA like sensitivity for its characterization.

The next step - just in time for ALMA – will require detailed observations (i.e., high resolution WITH high brightness sensitivity).

See next pages on SZE etc.

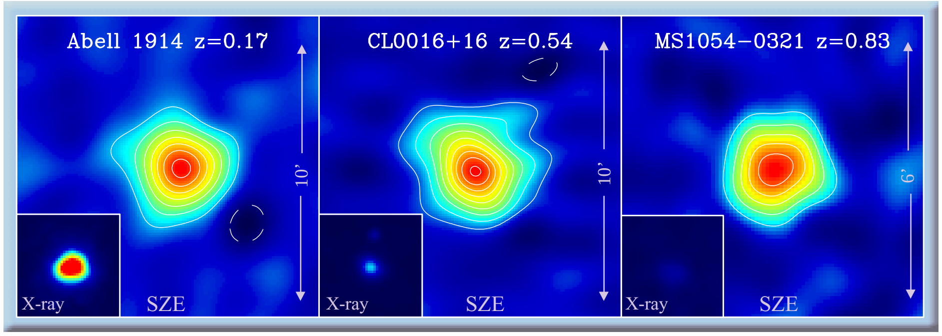
G.6.2. Community support

It seems like a good idea to have the support of the CMB community. Based on the strength of their science they have already been able to push through very large scale projects. Such support could only be helpful for ALMA.

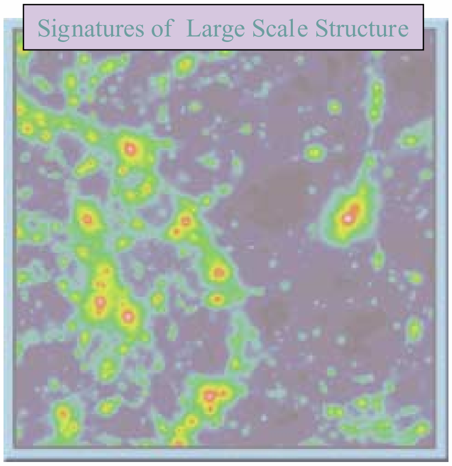
Exploring the Distant Universe with the Sunyaev-Zel'dovich Effect

Hot gas within massive objects interacts with passing cosmic microwave background (CMB) photons, introducing small distortions in the CMB spectrum. The amplitude of this so-called Sunyaev-Zel'dovich effect (SZE) is independent of the distance to the object; thus, SZE observations are powerful probes of the distant universe, which should vastly improve our understanding of the evolution of cosmic structures.

Imaging Galaxy Clusters at any Distance

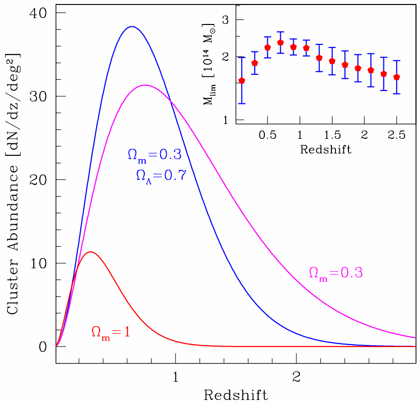


The panel *above* contains SZE images of three galaxy clusters at redshifts z=0.17, z=0.54 and z=0.83 (at z=0.83 the universe is approximately 1/3 its present age). Insets show X-ray images of the same region of each cluster. The SZE signature is comparable at all three distances, whereas the strength of the detected X-ray emission (in fact, any emission) decreases rapidly with distance. SZE observations allow one to study clusters throughout the observable universe!



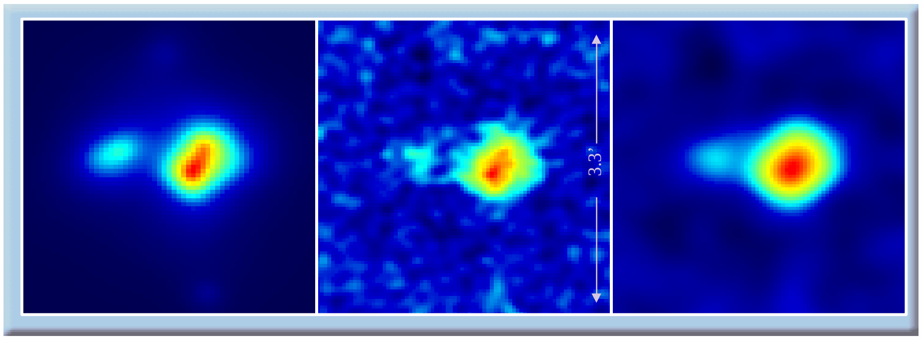
Above is an image of the SZE toward a simulated supercluster of galaxy clusters (red/yellow). Very sensitive SZE observations would enable one to image the intercluster material (green/blue), a diffuse cosmic web which is likely to be the largest reservoir of baryons or normal matter in the universe.

Cosmology and Cluster Abundances



Above is a plot of the evolution of the galaxy cluster abundance for three different cosmological models. The abundance is the expected number of clusters above mass M_{lim} (see inset) within 1 degree^2 on the sky, and these models are tuned to produce the observed abundance of nearby clusters (Redshift z=0). As one probes the high redshift universe it becomes easier to discriminate among cosmological models. The inset shows the limiting mass M_{lim} as a function of redshift for a realistic SZE survey instrument.

ALMA observations of the Sunyaev-Zel'dovich Effect using 30-43 GHz receivers



Theleft panel is the SZE signal from a 2.5x10^{14} M_o galaxy cluster at z=1 from a hydrodynamical simulation This cluster would be detected at 5 sigma confidence level with the Carlstrom proposed SZE survey array. It is expected that approximately 500 clusters of this mass and higher will be detected by the one year survey. The center panel is a four hour observation of the cluster with ALMA at 34 GHz in its ultracompact array. The cluster is easily imaged with high confidence. The right panel is an image made with the same ALMA data after applying a 4 klambda uvtaper resulting in a 22" FWHM beam.

The sensitivity of the high resolution image is 1.5 uJy per 9.7'' beam which corresponds to 14 uK. The tapered image has a RMS sensitivity of 2.8 uJy per 22" beam which corresponds to 2.7 uK !

ALMA will provide critical data on the structure of high redshift clusters. These data will be needed to understand systematics in the SZE cosmic distance scale determination, the baryonic matter density of the universe, large scale structure and its evolution. High redshift clusters are expected to be morphologically more complex than their low redshift counterparts, increasing the need for high resolution observations.

ALMA will provided detailed images of the SZE in filamentary structures, perhaps the largest reservoir of baryonic matter in the universe.