Report of the ALMA Scientific Advisory Committee: September 2000 Meeting

10-October-2000

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1. Introduction

This document reports on the second face-to-face meeting of the ALMA Scientific Advisory Committee (ASAC), held in Berkeley, CA, USA, on September 9 and 10, 2000. During the meeting, presentations on various technical and scientific aspects of the ALMA project were given by ASAC members as well as other parties and discussed by the ASAC. This report summarizes the topics under discussion and presents the ASAC's recommendations.

2. Enhanced ALMA

The ASAC strongly supports the participation of Japan in the ALMA project as a full partner. This participation will enhance the baseline project in important ways. The ASAC considered the following enhancements: addition of the Atacama Compact Array (ACA), ensuring the full complement of receiver bands, additional antennas, and an enhanced spectroscopic capability. The ASAC was asked to prioritize these possible enhancements. While further definition is needed, at this point the prospect of the ACA and complete frequency coverage have the highest priority because they both enable new science to be done. The ACA, a separate array optimized for short spacings, will improve image fidelity for extended sources. Adding receiver bands will give access to all the available atmospheric millimeter and submillimeter windows. Additional array antennas and the enhanced correlator both improve the sensitivity of ALMA, making operation more efficient. The enhanced correlator would also add flexibility to spectroscopic observations in all the receiver bands.

The priorities for the receiver bands and the correlator will be discussed more fully in other sections of this report. Here, we discuss the ACA. The scientific case for the ACA is based on the fact that it will greatly improve the dynamic range and the image fidelity for extended sources. Indeed an array of smaller dishes will add the spacings that lie between the spacings well sampled by the array of 12-meter antennas and those sampled by the single dish, total-power measurements. This addition of spacings is best done with an array of dishes roughly half the diameter of the main array dishes. Based on studies by Guilloteau, Welch, and Morita, there is general agreement on the range of antenna number (10–16) and sizes (6–8 m) for the ACA. Generally, smaller diameters are better for imaging, as long as the minimum spacing is set by antenna size, while larger antennas are better for calibration. Because the receiver cabin must be able to contain the full ALMA receiver complement, it may be efficient to use the 12-m mount design with a smaller dish. Studies are needed to determine the dish diameter at which the minimum separation is limited by mount, rather than dish size. It is also generally agreed that the ACA must be able to operate as a stand-alone array. The ASAC recommends that the ALMA project ensures that the following studies are done in time for reports in January 2001, to be consistent with the timeline calling for a draft agreement for a three-way partnership by February 2001. The studies needed are these:

- a study of how minimum separation depends on dish size for dishes mounted on the standard 12-m mount;
- a study of the effects of dish size, between 6 and 8-m dishes, and of the number and layout of dishes on imaging of several of the standard test images.

The imaging study should include the effects of errors due to noise, calibration, and pointing and be done at representative frequencies where these errors have different relative sizes.

The ASAC should discuss the reports resulting from these studies and finalize scientific priorities for the enhanced ALMA before definition of the enhanced ALMA, currently scheduled for January 2001.

3. Correlator Issues

3.1. The ALMA Baseline Correlator

The correlator of the ALMA baseline project (in the following referred to as “Baseline Correlator” or simply “ALMA Correlator”) underwent its Preliminary Design Review on January 20, 2000. The review panel was impressed with the progress on the NRAO design and the thoroughness with which it has been carried out; the design meets the scientific specifications spelled out in the MMA White Paper “Astronomical Requirements for the Millimeter Array Correlator” by Rupen, Shepherd and Wright (1998).

3.1.1. Design

The ALMA Correlator is being built to accommodate 64 antennas. There are 8 baseband inputs per antenna, each with a maximum sampling rate of 4 GHz (2 GHz bandwidth) digitized at 3-bit 8-levels. The signal is digitized and transmitted over fiber optic cables to the correlator. Station cards provide bulk delays suitable for a 30 km range. At the digital FIR filter, bandwidths and fine delays are set using 4-bit quantization before being passed at 2-bit 4-levels through packetization to the 2-bit 4-level correlator. The resulting bandwidths per baseband input range from the 2 GHz maximum down to 31.25 MHz, providing 512 channels of 31.25 MHz resolution over 16 GHz at the lowest resolution broadest spectral range setting, and 15.3 kHz at the highest full polarization spectral resolution. For single polarization work, 1.9 kHz can be obtained. Details are given in ALMA Memo. No. 194. Power estimates have decreased by 25% from the numbers in the project book, where further details may be found. The cost of the full ALMA correlator will be $13M.

3.1.2. Schedule

The correlator continues to be on schedule, with working test fixtures and FIR filter card in December 2000, working station card, control card and long term accumulator in May 2001. The prototype correlator chip will be delivered in July 2001, followed by the critical design review on July 31, 2001. The minimally populated correlator will be complete by April 2002, with a commitment to a production run of correlator chips in the summer of 2002. A single baseline correlator for the test array, which will replace the test correlator (GBT spectrometer clone) completed in 2000, will be working in the laboratory by the end of 2002 and will be delivered to the VLA site in May 2003. The first quadrant correlator, fully capable of handling 32 antennas will be delivered to Chajnantor on June 16, 2004.

3.1.3. Options

The correlator PDR panel unanimously recommended a change from 0.25 to 0.18 micron technology for the correlator chip, provided that further experience confirms that this will result in a chip with lower power consumption and lower overall cost. It was recommended that the decision to go to an 8K chip should not be made until a detailed evaluation of the power dissipation of the 8K, 0.18 micron chip was available.

Currently, the project remains committed to the 4K lag/chip 0.25 micron technology, on the basis of expected lower yield for the 8K lag/chip, 0.18 micron technology chip, its higher estimated power dissipation requirements, and the $1.8M higher cost for that technology. The major scientific gain expected for the 8K lags/chip would be that the number of frequency channels would double in every mode, thus increasing the frequency resolution by a factor of 2. Finally, the foundries that can produce 0.18 micron chips are fully booked and prototype chips would not be available until 2002 if this technology were pursued now.

3.2. Future Correlator

The baseline ALMA project includes development work for a 2nd-generation "Future Correlator". Such a Future Correlator should have higher performances than the Baseline Correlator and should take into account the current fast technological progress, e.g. in chips and interconnectivity. As stated at the correlator Preliminary Design Review held in Charlottesville in January 2000, a final commitment for the 64 antenna ALMA correlator should be made by 2003.

On the European side a Digital Hybrid Correlator design is being developed, whereas in Japan an FX design is studied. Both projects are aimed to provide a greater number of channels at the lowest spectral resolution, higher sensitivity, and higher flexibility than the Baseline Correlator. Such improvements should lead to an important increase in the scientific returns of ALMA. As a consequence, ASAC agrees that the development of the Future Correlator is an important part of the baseline ALMA project, and strongly recommends that these studies are continued. Furthermore, the ASAC encourages the European, Japanese, and North American groups to cooperate in their Future Correlator studies.

The ASAC noted with great interest that the hybrid correlator studied by the European team will, by going from full 2 bits to full 3 bits in the correlation process have a 9% higher sensitivity than the baseline correlator, which is the equivalent of adding 9% of collecting area, i.e. the equivalent of 6 additional antennas for a 64-element interferometer. Moreover, the European project is also considering a 4-bit correlation scheme.

The European team solicited ASAC input on various design options, which resulted in the following recommendations:

1. *Spectral resolution*: A highest spectral resolution of 5 kHz is required, corresponding to 0.05 km/s at 30 GHz. This resolution is, e.g., necessary for the observation of lines in cold dark molecular clouds.
2. *Required number of channels*: A total number of 8000 channels is sufficient for most astronomical observations. Observations using multiple sub-bands and polarizations will accordingly have less channels available per subband and/or polarization.
3. *Minimum acceptable dump time for on-the-fly observations*: The specification for the minimum dump time in total power mode is 1 msec. For spectral line observations the minimum acceptable dump time may be chosen to be proportional to the number of channels, e.g 1 msec for 512 channels, but 16 msec for 8000 channels.
4. *Minimum integration period for cross-correlations*: For solar (continuum) observations, minimum integration times of 1 msec are required. For spectral line observations, the fastest integration period should be made compatible with the minimum dump time. In side band separation mode, integration times of ∼120 msec should be possible.
5. *Are on-line WVR corrections necessary?* Yes, but it will be necessary to carefully test the method before eventual implementation.
6. *Sub-arrays*: The specification is that the array can be divided in at least 5 sub-arrays, which are all logically independent and can observe at a maximum of 4 different frequencies. The goal should be at least 16 independent sub-arrays, which is the number provided by the Baseline Correlator.
7. *Flexibility*: Since the Baseline Correlator provides a maximum of 8 sub-bands (total, not per polarization), a reasonable goal for the Future Correlator should be at least 16 sub-bands. Such an improvement would be extremely useful for spectral line surveys of different astronomical objects.

The specifications and goals stated in the above considerations should be taken into account by both the European and the Japanese projects. In summary, the ASAC remarks that the Future Correlator developments should be guided by the goals of achieving (a) higher spectral resolution, (b) a higher number of channels in wide band modes, (c) a significant gain in sensitivity, (d) high configuration flexibility, and (e) lower power consumption.

The ASAC strongly recommends that a comparative presentation of the different correlator concepts that are presently under study (including cost estimates) should be made at a future ASAC meeting.

3.3. Enhanced Correlator

If the Enhanced ALMA is made possible with Japan entering as a third major partner, an Enhanced Correlator will be necessary to accommodate the additional 12-m antennas and the ALMA Compact Array (ACA). The design of the Baseline Correlator may be changed to accommodate larger or smaller arrays until production units are begun. Thus, a first option for the Enhanced Correlator would be to modify the design of the Baseline Correlator. This will increase the cost of the correlator by a factor of $(N/64)^{1.6}$, where N is the number of antennas. For example, a correlator for 80 antennas would be 40% more expensive than a 64 antenna correlator and require a few months of additional design time. An obvious second option would be a correlator based on the specifications of the Future Correlator, but the design should accommodate the total final number of 12-m antennas and the ACA. In the latter case, the Enhanced Correlator should be included as part of the Enhanced ALMA project (see section 2). Thus, since budgetary constraints would not be similar to those of the Future Correlator, a larger number of channels could be envisaged for the Enhanced Correlator.

4. Calibration

A number of calibration schemes are under consideration for the ALMA. Good accuracy is expected for frequencies below 300–400 GHz, whereas it will be more difficult at the higher frequencies where atmospheric extinction is high and system temperatures are correspondingly higher. At the lower frequencies where the goal of calibration accuracy of 1–2% may be achieved, small effects are important, including standing waves between lens and mirror surfaces, mixer non-linearities, determination of relative sideband gains, and polarization stability. Among the various schemes being proposed, the possible use of cold loads in the dewar will have a major effect on the overall receiver design. After some discussion, the ASAC reaffirms its recommendation made at the Leiden meeting that there should be no cold loads in the dewar. One reason is that there may be some receiver non-linearity as a result of the significant load intensities. In addition, loads in the dewar may have their accuracy spoiled by lens or window reflections. A general recommendation is that the calibration system be external to the dewar and therefore not play a major role in the design of the receiver dewar.

The problems of standing waves between mirrors are familiar but have largely been ignored in millimeter interferometry because their effects are usually small compared to the typical current calibration accuracies of 10–20%. Because these effects are not stable in time, they must be dealt with as part of the frequent receiver calibration. As an example, the common "chopper wheel" method is simple and attractive and might be adopted, but it will have to be supplemented with additional measurements if it is to be used to measure the effects of the standing waves. Two recently proposed ideas that should be developed further include (a) the use of a semi- transparent vane that could be calibrated directly on an astronomical source and (b) a coherent signal transmitted to each antenna of the array over optical fiber that could measure sideband ratios and bandpass shapes if it is injected at the input of the system. Another scheme, that is currently under development for the BIMA array, uses two loads weakly coupled at the secondary mirror. It has shown good reproducibility and the capability of measuring the standing wave pattern, and the mechanism also provides a natural means for the introduction of the coherent signal. Further tests are planned to determine whether it can produce absolute calibration at the 1% level over a wide bandwidth.

For the coherent signal scheme, it will be important to demonstrate that the accuracy obtained will exceed that of more conventional methods. This system is particularly useful in 3 areas:

1. bandpass calibration
2. sideband gain ratio determination
3. polarization

The first 2 items require proper control of the power vs. frequency, which may be difficult. Baseline ripples apart, bandpass calibration can be achieved on astronomical sources within 1–2% accuracy in a reasonable time at millimeter wavelengths. It will be more difficult to do astronomically at sub-mm wavelengths where the potentially high signal/noise of the coherent scheme gives it an advantage. Measuring the sideband gain ratio is easy at mm wavelengths, but time consuming in the sub-mm region unless the specification is relaxed to about 5% accuracy. Here again, if the coherent scheme can be made accurate to the 1–2% level, its inherent high signal/noise will be an advantage.

Beyond the radiometer calibrations discussed at the meeting, absolute calibration of standard astronomical sources is an important issue. The ultimate limitation of absolute calibration accuracy is the insufficient knowledge of astronomical source strengths, particularly planets. A worthy goal of the array will be to define the relative strength of all such calibration sources, in addition to providing radiometer calibration within 1–2%. If such measurements could be obtained for several planets, atmospheric and surface modeling should be able to provide a consistent absolute scale for each to at least 5% and hopefully better than that.

Our main conclusions are that there should be no cold loads in the dewar, and that the other current ideas, particularly the semi-transparent vane and the use of coherent signals, should be developed further. If the scheme using two loads weakly coupled at the secondary mirror is demonstrated to achieve the required absolute accuracy over a wide bandwidth, then it should also be a contender for the final choice.

5. Water-Vapor Radiometry

Developmental work continues on various schemes to calibrate interferometer phases using measured fluctuations of atmospheric brightness due to water vapor. The effort is divided between observations of the 22 GHz line, on the one hand, and the 183 GHz line, on the other. Although the 183 GHz transition is the one chosen for ALMA (because the line is much stronger and thus better suited to the dry conditions on the site), the 22 GHz experiments on established interferometers are of great value in establishing the phase correction technique.

A report from the OVRO program described phase correction measurements based on a three channel spectrometer centered on the 22 GHz line. Typical data showed residual errors of 160 microns RMS in delay leading to improved correlation and successful correction of astronomical data obtained concurrently. Regular use of the technique for improving observations is presently limited somewhat by awkward software. Better accuracy seems to be limited by the effects of gain fluctuations on the high receiver temperatures of the ambient amplifiers. Cooled amplifiers are being installed, and the accuracy is expected to improve by a factor of two to three. The system has been demonstrated to operate even in cloudy weather. Another future improvement may be enabled by an addition from the Maryland BIMA group of a multichannel correlation system.

A Canadian group led by McMaster University and the JCMT group at NRC has built a clone of the 183 GHz radiometer systems installed at the JCMT and the CSO. This system is uncooled and uses a flip mirror to switch between sky, warm, and hot loads. This radiometer and the radiometer currently at the CSO will be installed on two of the SMA telescopes in the spring of 2001, where they will be used to extend the tests of the capabilities of the 183 GHz system to a wider range of weather conditions and frequencies than was possible with the JCMT–CSO interferometer. A second Canadian group led by the University of Lethbridge and NRC has designed a novel system to operate on the water lines in the 20 micron region. The prototype device has now been installed at the JCMT for a long-term campaign of tests in comparison with radiosonde probes of the atmosphere. A second device is under construction, which should permit interferometric tests similar to those planned with the 183 GHz systems within the next two years.

A joint proposal from Chalmers and the Cavendish has been submitted to the ALMA management for the development of a new 183 GHz radiometer system. This project will test two options; one is a chopping system, and the other is a correlation detector. The goal is to carry out laboratory tests at the outset, with field tests possible in the future.

In connection with the discussion of the problems of pointing errors early in the meeting, the question was raised whether the WVR system might be able to produce on-the-fly pointing corrections. Pointing errors due to the atmosphere ("(a)nomalous refraction") will limit sensitivity and dynamic range, particularly during the day, and water vapor radiometry is a way to eventually correct for this. At its March 2000 meeting in Leiden, the ASAC recommended that the project press ahead with the basic phase correction scheme using the 183 GHz line, and did not recommend work on the anomalous refraction correction; this was both due to the extra complexity such a system entails, and to the fact that this is only a significant problem for mosaiced observations of extended sources. At the present meeting, because of the greater emphasis on high fidelity imaging of extended sources, the opinion was voiced that this issue should be re-evaluated by the project. The project should thus continue with development of 183 GHz prototypes, but should also attempt to quantify the scientific impact of not correcting for anomalous refraction. There was also a suggestion that the Cosmic Background Interferometer currently operating on the Chajnantor site might already have the necessary data to address this option, and an effort will be made to obtain and study the relevant CBI observations.

The Committee felt that all of these activities were important and urged the various investigators to press on. Accurate phase correction schemes will be the only way to realize the full resolution capabilities of the array. More resources need to be pushed toward all of the schemes under way or planned above and take advantage of any opportunities to test the systems and their ability to correct phase under the appropriate conditions. For the 183 GHz systems, the SMA is clearly a good choice for tests.

6. Receivers

As noted in the March 2000 ASAC report, it is the combination of the antenna performance and receiver sensitivity and frequency coverage that determines the capabilities of ALMA. A further discussion of questions concerning the frequency bands and their priority, the total power stability, the WVR specs, the polarization requirements, the calibration accuracy, and the receiver configurations (principally single sideband versus double sideband operation) may be found therein. Certain of these issues were revisited in September 2000 in the wake of the restriction of the ALMA baseline project to four receiver bands earlier this year, and are discussed further below.

6.1. Frequency Bands

The ASAC reiterates that the goal for ALMA should be complete coverage of the atmospheric windows across the millimeter and submillimeter spectrum. We concur that the four bands to be initially installed on the array should be (in order of increasing frequency) Band 3 (84–116 GHz), Band 6 (211–275 GHz), Band 7 (275–370 GHz), and Band 9 (602–720 GHz). In considering the manner in which additional receiver bands should be added to the array, we note that several enable unique science to be performed that would otherwise not be possible. Table 6.1 presents the ASAC recommendations for the ALMA receiver band priorities grouped by first priority (bands 3, 6, 7, and 9), second priority (bands 1, 4, 8, and 10), and third priority (bands 2 and 5) along with a description of the important science goals to be addressed with the individual receiver bands. We stress that the bands within the groupings are presented in order of increasing frequency only; this is not intended to be a strict priority ranking. As the project moves forward, the ASAC requests continued involvement in the process by which receiver band priority is established.

Table 1: Summary of Receiver Band Priorities

Band no.	Frequency Range (GHz)[a]	Science drivers
3	84–116	Bulk of low-excitation lines, SiO 86 GHz maser, high-z CO, dust SED
6	211–275	Bulk of medium-exc. lines, dust SED, high-z CO and dust search, [CII] $z = 5.9$–8.0
7	275–370	Bulk of medium-exc. lines, dust maps, polarization, high-z dust search, [C II] $z = 4.1$–5.9, o-H_2D^+ and N_2H^+ at 373 GHz
9	602–720	High-exc. lines, warm gas, dust SED, [C II] z=1.6–2.2
1	31.3–45	Sunyaev-Zeldovich, free-free, synchrotron, heavy molecules, SO at 30.0 GHz
4	125–163	Many low-exc. lines, H_2S at 169 GHz, CO $z \approx 0.6$–0.8
8	385–500	[C I] 492 GHz, HDO 464 GHz, CO 4–3, [C II] $z = 2.8$–3.9
10	787–950	[C I] 810 GHz, CO 7–6, dust SED, [C II] z=1.0–1.4
2	67–90	Low-exc. lines deuterated molecules, high-z CO
5	163–211	H_2O 183 GHz, $H_2^{18}O$ 203 GHz

[a] Frequency ranges as given in *Specifications for the ALMA Front End Assembly*, Draft 1.4, August 31, 2000.

[b] The top 4 bands are the highest priority bands, the next 4 bands are the second priority bands, whereas the last 2 bands are the third priority bands. Within each group, the order is in increasing frequency.

Space for all ten receiver bands should be included in all cryostat designs, and the LO and IF system designs should remain capable of supporting the full receiver suite. We recommend that the JRDG consider carefully the achievable receiver coverage for band 1; specifically, to investigate the cost/performance trade-off for increased bandwidth designs. Extending the frequency coverage to lower values, would improve the overlap with the Enhanced VLA and would bring new science capabilities to ALMA. We also note that Zeeman splitting observations of the 30.0 GHz transition of SO has the potential to allow magnetic field determinations.

Careful inspection of Table 6.1 shows that some important spectral lines have frequencies that are not within the formal limits of any of the ALMA receivers. We therefore ask the Joint Receiver Development Group whether the relevant bands could be stretched to cover the lines in question, i.e., band 4 to 169 GHz and band 7 to 373 GHz.

6.2. Other Issues

The ASAC re-iterates its earlier recommendations on various other important ALMA receiver issues:

- *Total Power Stability*: See March 2000 ASAC Report
- *WVR Specifications*: These are discussed in section 5. We simply note here that a robust WVR system is critical to the success of ALMA. The present baseline is for an uncooled design, but further research will be required to determine whether such systems can in fact meet the scientifically mandated specifications.
- *Polarization*: Again, the ASAC recommends that careful consideration be given to optimizing the polarization properties of the 345 GHz receiver for both continuum and molecular line work, and that the different polarization behavior 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.
- *Calibration Accuracy*: The ALMA calibration specification of 1% is adequate scientifically, perhaps even a bit aggressive, but, as discussed in section 4 might be difficult to achieve at submillimeter wavelengths. A cold calibration load in the primary dewar is unnecessary.

6.3. Recommendations: Receivers

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. The ASAC requests to be involved if any further prioritization is needed. We recommend study of extending the lower end of Band 1. The ASAC again requests a presentation at its next meeting of a detailed plan for the mass production, integration and testing of the ALMA Phase II receivers.

7. Polarization

7.1. Introduction

Polarization observations are one of the important science drivers for the ALMA telescope. One of the most important areas where polarization observations will play a significant role is star formation. Probably mosaic mapping of extended polarized emission will dominate polarization work. Therefore, optimization for such observations is crucial.

The March 2000 ASAC report proposed the requirement for 0.1% polarization mapping fidelity after calibration. Although synchrotron polarization is often $> 10\%$, polarization of dust emission seems typically to be $< 5\%$. Hence, requirements for dust polarization determinations are more stringent than in the perhaps more familiar synchrotron polarization case. Also, simply detecting polarized dust emission is insufficient; position angles must be measured to a high degree of significance. For example, interstellar turbulence can lead to tangling of magnetic field lines and therefore to a dispersion $\Delta\theta$ in the position angles of polarized dust emission. Measurement of $\Delta\theta$ can lead to an estimate of magnetic field *strengths*, since the degree of field tangling depends on the ratio of magnetic to turbulent energies, and turbulent energy can be estimated from spectral line widths. For 1% polarization of dust emission, an uncertainty at the 0.1% level implies a 1σ uncertainty in position angle of about 6°, about the largest uncertainty for the results to be useful.

This requirement of 0.1% polarization fidelity after calibration does not lead directly to specifications on receivers, since the combination of instrumental polarization induced by receivers and antennas both play a role, along with the procedures for calibration. We discuss these separately.

7.2. Receiver requirements

For technical reasons, the ALMA receivers will apparently be nominally sensitive to orthogonal linear polarizations. Let the signal from an astronomical object measured at the two orthogonal directions be X and Y. Then one may derive Stokes parameters as follows: $Q = X - Y$, $U = XYcos\phi$, $V = XYsin\phi$, where ϕ is the phase difference between the X and Y components of the signal. Systematic errors in Stokes U and V will be only linearly sensitive to the gain calibration of X and Y since X and Y occur as a product, but will be very sensitive to the phase calibration of the two receivers, something that is necessary for interferometry anyway. This discussion assumes that the two receivers are truly orthogonal, but if they are not the difference from a 90° phase difference can be calibrated. But Stokes Q will be extremely sensitive to the gain uncertainty between X and Y; a gain error of 1% means a 100% error in a 1% polarization signal. Maintaining the difference between the gains of the two orthogonal receivers to better than -30 dB in order to achieve 0.1% polarization fidelity would be extremely difficult.

One way to overcome this problem is to insert a phase rotation device into the optical path such that the receivers detect opposite circular polarizations, R and L. This pushes the extreme sensitivity to the gain uncertainty into Stokes $V = L - R$, but means that both Stokes Q and U are derived from products of R and L, with the phase uncertainty rather than gain uncertainty dominating. Although this approach has been considered by the receiver group, it has major disadvantages. The phase rotation device (e.g., a quarter-wave plate) would introduce mechanical complications, would increase noise temperatures, and would yield circular polarization only over a relative small bandwidth.

One alternative solution for deriving accurate measurements of linear polarization with linearly polarized feeds is to take advantage of the fact that the position angle of the feeds will rotate on the sky due to the alt-azimuth mounting of the antennas. In practice, this is a poor solution, since it yields highly variable polarization fidelity over the uv plane. For snapshots, there will be little rotation. For sources transiting near zenith, rotation of position angle will be very rapid, with very little integration time for Stokes Q and U in many uv cells.

A somewhat related approach (suggested by Johan Hamaker; see Astron. & Ap. Suppl., 143, 515, 2000) is to have the orthogonal feeds at mixed orientations on various antennas. Thus, if on half of the antennas the linearly polarized feeds were rotated by 45° with respect to the other half, half (say) of the antennas may at any one instant derive Stokes Q from $X - Y$, while the other half would derive Q from $XYcos\phi$. During source tracking, position angle rotation would change this such that the situation would be more complicated, but the mathematics of inferring the four Stokes parameters from this situation is well known. It does mean that in many uv cells the derivation of Q (say) would be dominated by $X-Y$; without excellent receiver gain calibration the fidelity of the Stokes parameters would be highly variable across the uv plane. Nonetheless, this approach would make it possible to make polarization maps of high fidelity even without accurate receiver gain stability or calibration, with loss of some sensitivity due to having to assign low weights to individual Stokes parameter visibilities derived primarily from $X-Y$ information.

If both receiver gain and phase can be very accurately calibrated, it should be possible to derive all four Stokes parameters from orthogonal linear feeds with common orientation, with acceptable loss of fidelity in the Stokes parameter derived from $X-Y$. An example of a careful investigation of deriving Stokes parameters with such a system is the study by Heiles (Arecibo Observatory Technical Memo 99-01, available on the NAIC web pages). Heiles employed a Mueller matrix formalism of the polarization properties of the Arecibo system and measured the Mueller matrix elements. Off-diagonal matrix elements describe undesirable polarization properties, such as leakage of Stokes I into Stokes Q (m_{QI}), but if these off-diagonal terms can be accurately determined, accurate Stokes parameters can be derived. It of course helps that these terms be as small as possible, which is the requirement for a good hardware design and implementation. The Arecibo L-band wide receiver system has nominally orthogonal linear feeds whose signals are combined in the Arecibo correlator to produce the four Stokes parameters. The system has a correlated calibration source used to calibrate the gains and phases of the two receivers. Although the Arecibo system is a single dish rather than an interferometer, considerations for polarization work are similar, and are the same when single dish mapping with ALMA antennas, which will be essential for much polarization science, is considered. Heiles showed that with a system carefully engineered to produce good uncalibrated polarization results and with a stable calibration source available, excellent results may be obtained. He found that the error in determining the m_{QI} matrix term (with Q being derived from the difference $X-Y$) was only twice that in the m_{UI} term (with U being derived from the product).

A design for a bandpass calibration system presented by D. Emerson at the present ASAC meeting could also be used for polarization calibration of the receiver. This would consist of an amplitude and phase stable signal that would be broadcast into the receiver, so one could essentially continuously calibrate the gain and phase difference between the two nominally orthogonal receptors on each antenna. Based on the Heiles memo of his calibration of the Arecibo system using a similar calibration scheme, this system should make it possible with ALMA to derive the four Stokes parameters with sufficient accuracy.

Either, mixed orientation orthogonal feeds or the signal injection design, seems capable of ensuring accurate polarization calibration and both should be studied in the future.

7.3. Antenna requirements

The discussion in the previous section has focused on the polarization performance of the receivers. However, the polarization performance of the antennas is equally important. In Heiles' formalism, the Mueller matrix of the antenna must be determined to sufficient accuracy. Moreover, this must be done over the entire primary beam of each antenna, and over sidelobe responses (which are usually highly polarized). Thus, there will be a different antenna Mueller matrix at each pixel in the antenna beam pattern. Determination of these Mueller matrices at every pixel can only be done by careful mapping of the polarized beam pattern of each antenna – hence, it will require astronomical calibration. Such a procedure is very time consuming. If these matrices depend on time, temperature, antenna pointing, etc., the situation is hopeless. The only hope is for the polarized beam of the antennas to be sufficiently stable that the antenna Mueller matrix map over the beam can be derived once (or infrequently) and applied over extended periods of time. Hence, any antenna design considerations that might result in changes in the polarization response of the antennas should be avoided at all costs.

7.4. Recommendations: Polarization

1. The polarization receiver specifications proposed by Larry D'Addario as stated in the Wolfgang Wild memo would appear to be satisfactory so long as other recommendations below are followed. These specs were that either linear or circular orthogonal polarization states are acceptable, with a maximum degree of non-orthogonality and of mismatch between antennas of -20 dB. Because linear receptors appear to be capable of delivering lower system temperatures, linear polarization would be preferred.
2. The proposed special provision for circular polarization capability for band 7 would not be needed, as long as other recommendations are followed.
3. We continue to recommend that band 7 be optimized for polarization work. This means that the design goal should be as clean as possible a polarized beam pattern. One aspect of this recommendation is a design goal of zero beam squint. Although a beam squint (and other polarized beam anomalies) of 3% could be addressed in principle by calibration, it will reduce polarization accuracy and sensitivity. In particular, these effects will be extremely important for single-dish polarization mapping, which will be essential for much of the polarization science that will be done.
4. The Emerson bandpass calibration signal, stable in intensity and phase, should be included in the receiver design.
5. The antennas must be designed and constructed for maximum stability of the polarized beam patterns. Without this, polarization mapping will be difficult if not impossible.
6. Provision for testing the polarization characteristics of the two-antenna test array should be made. This will give the opportunity to test the system hardware and software for interferometer and single-dish polarimetry and identify problems before additional contracts are signed.

8. Configurations

The configuration group has made substantial progress during the last six months. Both the zoom spiral and donut/doubling-ring strawperson designs now fully implement the topographic constraints of the site. A further convergence in the strawperson array design has been achieved by the zoom spiral design adopting the compact array and "3 km" array of the donut/doubling-ring design as the inner and the outer limit of the telescoping design. Memos describing the details of the two competing designs are now available, and reports of other related works can be found at the Configuration Working group web page (`http://www.alma.nrao.edu/development/config/index.html`). The ASAC strongly urges inclusion of the effects of pointing errors in the simulations and recommends that the ongoing imaging studies be completed and their conclusions reported at one of the next ASAC meetings.

A preliminary conclusion from the ongoing imaging study, using the five test images in the Simulation Image Library, is that the two competing strawperson designs have comparable imaging performance. The only fundamental difference between the two arrays is the way they may be operated. The doubling ring array has five fixed arrays and possible hybrids between them and is reconfigured in bursts. The zoom spiral allows the possibility to be run either as a continuously reconfiguring array or to operate as a variable number of fixed arrays with burst reconfiguration. Assuming the two arrays have comparable imaging capability as suggested by the imaging study, the decision of selecting the final design may be then made based on the operational considerations. Upon the completion of the imaging study, a decision based on the joint discussion between the configuration and the site study groups should be reported to ASAC for the formal endorsement.

9. Test Interferometer

The plan for the Test Interferometer (TI) evaluation tasks has been formulated. The goals of the TI are, in order of priority:

1. To evaluate the prototype antennas to determine if they meet the specifications of the antenna contracts.
2. To compare the relative performance of both prototype antennas.
3. To evaluate the ALMA electronics systems.
4. To evaluate the prototype monitor and control system, special observing modes, innovations in electronics systems, etc.

A detailed list of tasks, sequenced to accomplish these goals, has been developed. Refinement of this plan will continue over the coming months, with a concentration on the assignment of personnel resources to the assembled tasks. Several issues, including the status of phase and amplitude calibration systems for the TI, will be revised and/or accommodated in the plan over the next six months. By spring 2001, we would like to have a final plan.

10. The ALMA Site Characterization

10.1. Safety

Visitors to the site are reminded that it is remote, very high altitude with extreme weather conditions, and that it can experience sudden changes in weather. ESO and NRAO agreed in safety rules that anyone visiting Chajnantor must follow. These can be found at `http://www.alma.nrao.edu/info/almasafety.html`. The ASAC urges institutions to bring these rules to the attention of prospective visitors of the site. Site visits should be coordinated with Simon Radford (sradford@nrao.edu) in Tucson and Eduardo Hardy (ehardy@nrao.edu) in Santiago and with Angel Otarola (aotarola@eso.org) in Antofagasta.

10.2. Site characterization through Chilean Winter 2000

An array of instruments continues to monitor weather conditions at the Chajnantor site. Data are retrieved, reduced, and placed at the ALMA WWW site for inspection by casual or interested observers.

There are at present a number of opacity measuring devices at Chajnantor, operating over frequencies including 183 GHz, 225 GHz, 492 GHz, 350 microns, 260 microns and 200 microns, and for some of these from different locations, over relatively rapid timescales. Both the Japanese and the Smithsonian have operated FTS devices, for various lengths of time; this gives the best measure of the atmospheric transmission over frequency. These data will be discussed at an IAU Technical Workshop in Fall 2000 in Morocco.

Two memos (176 and 322) compare conditions at the sites. Memo 176 concluded the phase stability is somewhat better on Chajnantor than on Pampa la Bola. Memo 322 found the differences in the basic meteorological data for the two sites to be small. In addition, a Japanese study by Sakamoto et al. compared the 220–225 GHz transparency data for Chajnantor and Pampa la Bola during 1999 August – December. Chajnantor consistently had better transparency.

During the first part of 2000, Y2K concerns, along with the first recorded major lightning strike at Chajnantor, have caused interruptions in the flow of data from Chajnantor, though instruments at Pampa La Bola continued recording data. Tipper data is sparse for January and February, and interferometer data sparse through May. The distributions, etc., are quite comparable to previous summer and autumn seasons.

Recently, the observers at the CBI experiment on Chajnantor have communicated their experiences with the site. Owing to cloud, snow and high winds they have been able to observe 46% of night time during the Altiplanic Winter and about 60% during the last 9 months. Snow drifts on the paved highway and on the dirt road leading to the the Chajnantor area made access difficult for a significant part of 2000.

The ASAC strongly recommends that in addition to the ongoing site characterization studies, information on precipitation and all-sky cloud coverage should be collated. Here, information from the CBI logbooks should provide important subsidiary information. Furthermore, a thorough comparison of the Pampa la Bola and Chajnantor sites should be made using as many contemporaneous data as possible.

10.3. Lascar

According to reports from various sources on the morning of 21-July-2000, the Volcano Lascar had a small eruption of approximately 2 hours of duration (10:30–12:30 local time). The smoke column reached a maximum height of 4,000 m on the crater, which is of low intensity in comparison with similar eruptions registered 15 years ago. The slopes of the crater remain very unstable due to the last great eruption in April of 1993. The recent eruption was clearly visible from Chuquicamata, 150 km toward north, to astronomers at the CBI site on Chajnantor, and to attendees at a gravitational lensing conference in San Pedro de Atacama. According to information of Customs officers of San Pedro de Atacama and Toconao (35 km to the west), the dispersed ash moved toward the northeast, and would not have fallen in Chilean territory. The eruption was accompanied of a small tremor till 10:35 hrs and underground noises. The ALMA seismometer was being refitted with a hardware upgrade and was not present at the site.

The vulcanologists concluded that this event corresponded to a small eruption characteristic of periods of degassing of the volcano, that take place when high parts of the volcanic conduit become clogged. This clogging was preceded by a loss of the height of the smoke column from Lascar during last the two months. It is not clear if this is a small and discrete event or the precursor of greater activity. There was no ash fall on or near the ALMA site, and CBI observations continued throughout the activity.

11. Summary

Here we summarize our major conclusions. For a number of topics, detailed recommendations are included in the appropriate sections of the report.

- The ASAC re-iterates its strong support for the participation of Japan in the ALMA project as a full partner. For the Enhanced ALMA resulting from such a partnership, the possibility of an Atacama Compact Array of 10–16 antennas of size 6–8 meter and adding complete frequency coverage have the highest priority because they both enable new science to be done. Other enhancement options are additional array antennas and an enhanced correlator. With regard to the Atacama Compact Array, we recommend studies of its imaging performance to determine optimum values for the size and number of its antenna elements.
- The project team working on the future correlator solicited ASAC input on a variety of items. Our recommendations are listed in section 3.2.
- Regarding calibration, the ASAC concludes that there should be no cold loads in the dewar. Current ideas, particularly the semi-transparent vane and the use of coherent signals should be developed further. A calibration accuracy of 1% is adequate.
- The ASAC very strongly encourages further work on developing a phase correction scheme using water-vapor radiometry at 183 GHz and 20 microns. Various efforts are under way and should be pursued concurrently.
- The ASAC confirms that the highest priority receiver bands to be initially installed are bands 3, 6, 7, and 9. Second priority bands are 1, 4, 8, and 10, while third priority is assigned to bands 2 and 5. The ASAC requests to be involved in all further discussions on prioritization of receiver bands. We again request a presentation at the next ASAC meeting of a detailed plan for the mass production, integration and testing of the ALMA Phase II receivers.
- A number of detailed recommendations concerning polarization are given in section 7.4.
- A thorough comparison of the Pampa la Bola and Chajnantor sites should be made using as much contemporaneous data as possible.