Report of the ALMA Scientific Advisory Committee: September 2002 Meeting

October 15, 2002

ALMA Scientific Advisory Committee

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Other Participants

Members of the ALMA Project

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1. Executive Summary

This document reports on the sixth face-to-face meeting of the ASAC which was held September 7-8, 2002. The previous months have seen the achievement of two major milestones for the project, namely ESO Council approval of European participation in the bilateral project and the U.S. National Science Board approval of multi-year ALMA construction. The ASAC was impressed by the progress made on many science-related aspects by the Project and the technical working groups. The visit to the VERTEX prototype antenna, still under assembly at the Antenna Test Facility at the VLA site, was a valuable experience, since it provided, for many of the ASAC members, the first opportunity to see one of the key items of the ALMA Project.

The discussions at the meeting centered on the four Charges from the ACC to the ASAC (see § 5). One charge concerned enhancements to ALMA that would be enabled by Japanese participation. The North American and European ASAC members strongly support the list of enhancements proposed in the Japanese contribution plan, which includes the two top priority enhancements, namely the ACA and Band 10. The ASAC re-affirms its priorization of the ALMA enhancements from the October 2001 ASAC Report and notes that the Japanese plan achieves as much as possible the highest priority items from that report. Another charge concerned the design of the largest configuration for ALMA. The ASAC recommends revising the optimization procedure for the Y+ array, perhaps in combination with the largest spiral array, to give more coverage on intermediate and long baselines.

The remaining two charges concerned the Site Characteristics and ALMA Early Science, and are presented in separate reports in Appendices A & B. The available site data appear to be commensurate with the ALMA scientific mission, design, and mission emphasis of the baseline instrument. The ASAC recommends that dynamic scheduling should be simulated further and a full stringency calculator should be implemented. Additional studies are also needed to determine how the pointing actually degrades as wind conditions worsen, particularly during daytime operation. The main goal of ALMA Early Science should be to demonstrate to *all astronomers* the unique capabilities of ALMA by providing unique scientific results early on, both in continuum and line observations. To meet this goal, the Early Science array should start with at least 6 antennas (preferably 8 to 10 antennas), be equipped with at least 2 receiver bands (including Band 3), and be separated from the telescope's array for commissioning through sub-array capabilities. The ASAC strongly recommends that Early Science should not set the pace of the receiver development and project construction, but should be a natural outcome of the schedule required to meet the full array completion milestone at the specified sensitivities. Both the Site and the Early Science studies identified phase correction as critical if ALMA is to achieve its full potential.

Concerning the front-end, a preliminary plan was presented which envisages the delivery of six prototype receivers for Early Science by February 2008, with limited testing and best efforts performance. This schedule does not meet the Early Science milestone of Q3 2007, nor is it consistent with the ASAC recommendations on Early Science made above. For the production receivers, the ASAC recommendations from earlier reports still hold and, in particular, the ASAC urges the Receiver group to present a study on total power stability at its next face-to-face meeting. The ASAC also recommends that the Project seeks ways to ensure that receiver Band 1 will be part of the enhanced ALMA project.

Regarding software, the ASAC notes the recent progress which has been made in the evaluation of the use of AIPS++ for ALMA, both through a successful reduction of data from the Plateau de Bure interferometer using AIPS++ and through the interim audit of AIPS++ packages. These continuing efforts, together with the planned benchmarking activities, are critical in assessing in a timely fashion how AIPS++

can be adapted to ALMA. Given the many uncertainties involved in the interaction of the AIPS++ and ALMA projects, the ASAC considers that software is still a high-risk area for the ALMA project.

Concerning calibration, the ASAC recommends that the newly appointed Calibration group addresses urgently all the calibration issues for ALMA, with a clear timeline indicating design reviews and decision points, and defines as soon as possible the required minimum hardware. A decision on the dual-load system should be made rapidly, and a framework for the future of the coherent photonic calibration system should be established. In addition, the ASAC urges the Calibration group to include polarization calibration as a vital part of its planning.

Finally, the ASAC recommends that the funding and organisation of the Science IPT be reviewed by the Project.

2. Introduction

This document reports on the sixth face-to-face meeting of the ASAC, held at the Array Operations Center (AOC) in Socorro, USA, on September 7–8, 2002. We thank NRAO for their hospitality during our visit, and for the opportunity we had to visit the Antenna test Facility (ATF) located at the VLA site on September 6, 2002 where we could see the VERTEX North American prototype Antenna still under assembly. During the entire ASAC meeting, it was our pleasure to have with us K.Y. Lo, the recently appointed director of NRAO, who welcomed the ASAC at the beginning of the meeting, and followed actively and with great interest our discussions and deliberations.

In addition to the regular project updates, the program on the first day centered on a discussion of the prototype antennas (see § 7), receiver development (see § 6) and on the responses to the ACC charges to the ASAC, with detailed discussions of the Site Characteristics and Stringency, the Long Baseline Configuration, the aspects of Early Science and the Japanese enhancements. Summaries of our deliberations and recommendations on these charges are presented in § 5. For the Site Characteristics and Stringency, and the Early Science, more detailed studies are given in the Appendices (A and B) to this Report. The program on the second day centered on the software (see § 8), calibration (see § 9) and backend (see § 10) developments. The reports outlining our discussions and the resulting issues are given below, with the overall recommendations summarized in § 11. As to our future meetings, Christine Wilson will become Chair person.

During the visit to the VLA site, J. Kingsley and J. Mangum provided an overview of the current status of the VERTEX prototype antenna and gave a detailed description of the antenna parts. The ASAC could visit the mount and the receiver cabin, and admire the back structure of the antenna. During our visit, a truck bringing the first panels of the VERTEX antenna arrived at the assembly site.

3. Project Status and Management

The ASAC heard reports on the project status, including the status of negotiations with Chile, and project management from P. Vanden Bout, M. Tarenghi, and S. Guilloteau. The bilateral agreement will be signed before the end of the year, and likely at the ACC meeting in Chile in October. Recent progress in infrastructure planning, which was reported by P. Vanden Bout and S. Radford, indicates that the plans are well advanced and appropriate for functioning of ALMA. The current construction plan foresees completion of ALMA construction by Q1 2012.

After the bilateral agreement is signed, the ACC will metamorphose into the ALMA Board and the ASAC is planned to shrink from eight to five members per partner. There was some discussion of the need for broader, partner-based advisory committees when the ASAC itself becomes smaller, both to access expertise in the community at large and as a form of outreach to the community. The future of the Science IPT during construction was also raised during the meeting. S. Guilloteau stated that its budget is likely to be very limited, and that ALMA would need to depend on free (in-kind) contributions to the Science IPT. The ASAC has several concerns about this approach. First, there is a risk that the required contributions will not be forthcoming, as people move on to other new exciting astronomy projects. Second, it weakens the Science IPT: full-time project-funded personnel are much more likely to identify strongly with the project and ensure the required workpackages are completed to a high standard and on-time. Third, the ASAC has in the past provided contributions to the Science IPT's work, and when the ASAC is significantly reduced in size, these contributions will also diminish.

ALMA is a unique project, being carried out by individuals spread over many institutes: for ALMA to build a strong scientific identity, it is important that a strong Science IPT and a strong ASAC are established during Phase 2. Therefore the ASAC recommends that the funding and organisation of the Science IPT be reviewed by the Project in the light of these concerns.

4. Toward a Three Way Project

The ASAC heard a presentation from M. Ishiguro on the current status in Japan. The Japanese proposal for participation in ALMA was also reviewed. The prospects for obtaining construction funding in FY2004 appear good and design work is proceeding on various items that could be contributed by Japan as enhancements to the ALMA project. More details on the enhancements are given in Section 5.4.

5. Charges from the ACC to the ASAC

In June 2002, the ACC requested the ASAC to assess and evaluate the four following issues:

1. The ASAC is asked to evaluate *all available site* (225 GHz opacity, 12 GHz phase stability, 350 μm and > 1 THz) data for Chajnantor, and to discuss *any significant trends and issues* which may impact the scientific mission, design or mission emphasis of the baseline instrument.
2. The ASAC is requested to make an assessment of *ALMA early science*. What kinds of *scientific data* (including the balance between spectroscopic and continuum data) are likely to be most desired as ALMA begins operations? Based on this probable interest, what are the *commissioning and operational implications* for the array's baseline capabilities, frequency coverage and operating modes?
3. The ASAC is requested to summarize the scientific and technical issues associated with the *long baseline array geometries* currently under consideration and to advise the ACC/ad hoc ALMA Board as to possible *cost, land use, and land access impacts* of which it should be aware.
4. The ASAC is requested to reassess the *list of prioritized enhancements* that Japan should be asked to contribute to the baseline ALMA instrument, understanding that Japanese participation in ALMA is likely to be proposed at a level significantly below that of North America and Europe in the baseline project. The ASAC should take into account the fact that given the schedule, these enhancements are to be contributed by Japan and cannot be redistributed among the partners.

In response to these charges from the ACC, two ASAC subcommittees prepared detailed reports, one describing the weather conditions on the Chajnantor site, including further considerations of the stringency of various observations (see § 5.1 and Appendix A), the second exploring the goals of the early phases of ALMA scientific operations (see § 5.2 and Appendix B). The third and fourth charges were discussed by the entire ASAC and the conclusions are presented in § 5.3 and 5.4.

5.1. Site Statistics and Stringency

The study on site statistics and stringency was presented at the ASAC meeting and is provided as Appendix A. Focusing on the NRAO data, which covers the longest time base, the report includes data on opacity, phase noise (seeing), and wind (which will affect pointing). The stringency (S) is defined as the inverse fraction of the time that a given observation can be made, so that a very difficult or 'stringent' observation can only be done for a small fraction of the time[1]. Several examples of observations were developed, with accompanying requirements on opacity, seeing, and pointing. The site statistics were presented and used to estimate the stringency of the examples. Because the dependence of pointing on wind conditions is not fully known, the wind was included as an either-or criterion: either the wind was sufficiently low that the antenna should meet its primary pointing specifications or it was not. Further study of the effect of wind on the pointing emerged as a key point for further study.

The following conclusions emerge from the study and subsequent discussion by the ASAC.

- There are no indications in the site weather data that the ALMA scientific mission or design needs to be changed.
- There is some correlation between good transmission and good phase noise. However there are significant periods when transmission is good, but phase noise is not very good.
- Examples of ALMA science indicate that most of the exciting science cannot be done without the successful functioning of the phase correction scheme. Making this scheme work will also make the periods of good transmission but poor phase noise usable.
- Determining how the pointing actually degrades as wind conditions worsen will be important in assessing the fraction of time that can be used for different projects. In particular, the effects during daytime need further study.

The ASAC encourages the ongoing study to simulate dynamic scheduling and recommends implementation of a full stringency calculator. Additional studies on the effects of wind on pointing are also needed; data from the prototype telescopes will be very useful for such studies.

5.2. Early Science

A report exploring realistic goals for the early phases of ALMA scientific operations, before ALMA is complete, was presented at the ASAC meeting and is provided as Appendix B. The ASAC has explored realistic goals for the early phases of ALMA scientific operations, before ALMA is complete. Early Science is different from the Science Verification during Commissioning. We recommend that the goals of Early Science should demonstrate the unique capabilities of ALMA by providing unique scientific results early on, in order to show these capabilities to all astronomers. This should be instrumental in involving the community at large in a prompt and efficient use of ALMA. The Early Science should not set the pace of the project, but should come naturally as a result of the progress to match the final deadline within specifications. Unique capabilities of ALMA include sensitivity, access to long baselines early on and the frequency coverage.

From this first study of ALMA Early Science, the ASAC makes the following recommendations concerning the definition and goals of Early Science and its implementation and operation:

- Early Science should start with not less than 6 antennas, and preferably 8 to 10 antennas.

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[1] see also Appendix C of the October 2001 ASAC Report

- Early Science should allow continuum and line observations from the start.
- Early Science should start with not less than two receiver bands, including Band 3.
- Phase correction is essential for Early Science observations.
- Early Science should include polarization as soon as possible.
- The array for Early Science should be separated from the telescope's array for commissioning through sub-array capabilities.
- Additional antennas and/or receivers bands should be brought into the science array as soon as they have been commissioned. In the case of the antennas, it will likely be more efficient in terms of operations to bring them into the science array in small groups of 4, 6, or 8 antennas.
- The ASAC recommends having 1 antenna instrumented with total power mode capability for Early Science, if possible.

5.3. Configuration Issues and The Long Baseline Array Geometry

M. Holdaway has presented his current Y+ configuration which meets many of the scientific and technical requirements, in addition to important logistical benefits. However, the *key* scientific requirement for the Y+ array is the imaging of distant galaxies or protostellar discs on the smallest (sub-arcsecond to milliarcsecond) angular scales. Therefore the ASAC feels that the optimization procedure should be adapted to give more coverage on intermediate and long baselines. In other words, because the goal of the Y+ configuration is to achieve the highest spatial resolution imaging, the optimization criteria for antenna placement is purposely different from that used for the more compact arrays.

- The ASAC recommends running the optimization procedure for the Y+ array again, perhaps in combination with the largest spiral array, to give more coverage on intermediate and long baselines.

The ASAC sees no technical problems for the Y+ configuration: the cable lengths for data transmission are within the technical constraints and good imaging performance is not compromised. This particular configuration presents no problems with land use and land access. The ASAC understands that even minor changes would be acceptable in this regard.

With respect to the more compact configurations, the ASAC is convinced that all the issues have been adequately considered and the project is ready to go forward with the detailed placement of the array pads. The ASAC encourages J. Conway to finalize his report so that soil sampling, and further site work may proceed.

The ASAC is happy with the Japanese progress on planning the ACA (see § 5.4.2) and encourages continued interaction among the configuration teams over the detailed antenna distribution.

5.4. Enhancements

5.4.1. Prioritization of the ALMA enhancements

The ASAC re-affirms the prioritization of the ALMA enhancements as defined and documented in the ASAC October 2001 Report. The priorities were decided on scientific basis only. We remind that the scientific ranking given below was unanimously agreed upon by the ASAC, that within each group of two, the rankings are equal, that the priorities of categories 1–3 are close, and that the items in category 4 are of significantly lower priority than the items in categories 1–3. The prioritization of the enhancements are as follows:

1. *Top priority:* Band 10 and the ACA
2. *Very high priority:* Band 1 and the Second Generation Correlator
3. *High priority:* Band 4 and Band 8
4. *Medium priority:* Band 2 and Band 5

5.4.2. Japanese proposal for the ALMA enhancements

The North American and European members of the ASAC learned with great interest and strongly support the list of enhancements to the baseline ALMA project proposed in the Japanese contribution plan, namely the ACA, Bands 10, 8, and 4, and the 2G Correlator. They note that the contribution plan achieves as much as possible the highest priority enhancements listed in § 5.4.1, and that it does include the top priority enhancements, namely the ACA and Band 10. These enhancements will bring new and important scientific capabilities to the ALMA project. The North American and European members of the ASAC encourage the Japanese efforts to make these enhancements possible in the ALMA project. Should further prioritization of the Japanese contributions be required (e.g., due to financial limitations), the ASAC asks to be involved.

6. Receivers

The receiver presentation focused on the receivers available for early science observations. No presentations were made of the prototype receiver progress, total power stability, plans for production and integration, or WVR progress. On these issues, the ASAC recommendations from the April 2002 report still hold; in particular, the ASAC would still like a presentation on the total power stability of the receivers at its next face-to-face meeting.

The ASAC reiterates that complete frequency coverage should be the ultimate goal of ALMA, and that the cryostat, LO, and IF systems should remain capable of supporting the full ten band receiver suite. As noted in Section 5.4, the ASAC strongly endorses the receiver Bands 4, 8 and 10 proposed by Japan as enhancements to the bilateral project, but notes that the highly ranked Band 1 is not included. The ASAC recommends that the Project seeks other ways to ensure that this important receiver band will indeed be part of the enhanced ALMA project.

The current plan for Early Science (Section 5.2) envisages the delivery and commissioning of eight receivers by Q3 2007. Ideally, these receivers would be production receivers; if some of them are commissioning receivers, i.e. copies of the prototype receiver, it is important that their performance be as close as possible to the final ALMA specifications. One acceptable modification would be for the receivers to contain as few as two of the four baseline receiver cartridges. The preliminary schedule for receiver production presented at the meeting showed delivery of six prototype receivers, with limited testing and best effort performance, by February 2008. A vigorous ASAC discussion of the proposed timescale followed, which led to the first of the following recommendations.

- The ASAC strongly recommends that Early Science should not set the pace of the receiver development and project construction, but should be a natural outcome of the schedule required to meet the full array completion milestone at the specified sensitivities.
- The ASAC recommends that the Project seeks ways to ensure that receiver Band 1 will be part of the enhanced ALMA project.
- The ASAC reiterates its request for a presentation on total power stability of the receivers at its next face-to-face meeting.

7. Prototype Antennas

During the visit to the VLA site, the ASAC was able to see and have informal discussions about the North American prototype VERTEX antenna. Confidentiality agreements make it impossible for any specific comments from the ASAC on the protype to be made in this report. In the meeting itself, the ASAC also heard progress reports on the manufacture of the European and Japanese prototypes. These are expected to arrive at the VLA site in April 2003 leaving approximately 8 months for tests and evaluation prior to the deadline of Jan. 1, 2004. The ASAC concluded that it is is extremely important that the US and European prototype antennas be tested in comparable fashion within this timeframe. In addition, the very exciting possibility of Japan joining the project means that the Project should liaise very carefully with the Japanese project to ensure that its own 12-m prototype can be tested at the ATF in a comparable fashion, and in a timely way. The evaluation includes holography, radiometric, and pointing tests. This will include measurements of the beam pattern, antenna efficiency, and focus translation. The holography should yield estimates of the RMS surface accuracy. There will also be direct tests to assure that the pointing specifications of $0''.6$ for offset pointing and $2''$ for absolute pointing are fulfilled, in particular under high wind conditions.

8. Software

Two reports to the ASAC were presented on the use of AIPS++ for ALMA. A. Kemball and R. Lucas reported on the test results using AIPS++ for the analysis of data from the IRAM Plateau de Bure millimeter array. This test has resulted in the first successful reduction of an IRAM interferometer data set with AIPS++. However, quantitative comparisons between AIPS++ and GILDAS remains to be done; it also appears that the tests required a significant amount of work, and that the learning curve for the IRAM software staff was steep. In addition, the size and the complexity of the test data set was quite limited. The next stages of this test, where non-experts users are encouraged to use the software, will be critical.

In the second report B. Glendenning presented preliminary results of an audit of AIPS++ functions which are required by ALMA. A good fraction of these functions already appear to be in the software; however, the ASAC was not encouraged by the statement that the missing functions would be added over the next 5 years. Given the effort already put into AIPS++ and its generic design, a higher level of compliance was expected at this stage by the ASAC. The ASAC recognizes that these findings are preliminary, and awaits with interest the final results of the audit.

The ASAC is concerned that it has not yet been demonstrated that AIPS++ will meet the stringent performance requirements of ALMA. In this respect, the planned benchmarking tests are critical to evaluating the use of AIPS++ for ALMA. The ASAC is also concerned that the recruitement and training of AIPS++ developers could be a serious problem for ALMA. Finally, although conclusions drawn from indirect evidence can be misleading, the informal feedback from many ASAC members and their colleagues is that AIPS++ is not yet as easy to use nor as functional as is desirable.

Unfortunately the ASAC has no strong recommendation as to how handle this aspect of the Computing work; it is undoubtedly a very complex and key area of the ALMA Project. Since AIPS++ has been chosen by the Computing IPT as a key technology base for ALMA science software, it should be stressed that AIPS++ software was and still is largely developed outside of the ALMA Project. In addition, ALMA represents only a fraction of the AIPS++ activities. How exactly the software system needs of ALMA will be fulfilled by the AIPS++ project is therefore a matter of concern for the ASAC. In particular, the ASAC notes that the planning and progress of the AIPS++ contribution should come under a similar scrutiny as all the other parts of the project. In general, the ASAC would like to emphasize that Software is still a high-risk area for the Project and one that may need further detailed monitoring and review. In mitigation, the ASAC recognizes that the quality of the computing teams and their organisation appears excellent and looks forward to reading the results from the forthcoming IDR and PDRs.

Finally, the ASAC also notes that a strong interaction with the users is needed in the completion of the software. It is mandatory that astronomers take part in the planning, reviewing and developing processes. Therefore,

- The ASAC recommends the creation of scientists/software positions whose function would be to work with software engineers on user interface software from the astronomers' perspective and to assist in software benchmarking, testing, and validation.

9. Calibration

S. Guilloteau presented the current status of calibration work in the project. The ASAC was pleased to see that a Calibration Group had recently formed, with B. Butler of NRAO leading this. The ASAC look forward to working with this group in restating and refining the calibration requirements which affect the scientific capabilities of ALMA.

Although it appreciates that this group has only just started its work, the ASAC remains concerned that a clear calibration plan for ALMA is still lacking. The ASAC recommends that a work plan which addresses all the calibration issues for ALMA, with a clear timeline indicating design reviews and decision points, be established over the next six months. In particular defining the minimum hardware required for calibration seems to be urgent, given the budget pressures in the project. For example, whether there is a need for one or more FTS systems, 60 GHz sounders, polarization widgets, and a coherent photonic calibration signal should be rapidly established. A presentation and/or a paper from the Calibration Group on its plans at the next ASAC meeting would be welcomed and would help the ASAC advise on scientific implications of the calibration schemes under consideration.

Regarding amplitude calibration, the ASAC was pleased to see the semi-transparent vane system had made progress, with a preliminary ALMA design available, and that there were plans for construction of a prototype on a millimeter dish. Although already tested as a prototype at BIMA, the status of the dual load system is less clear, and the ASAC recommends that a decision on this system be made rapidly by the Calibration Group.

The ASAC also recommends that a framework for deciding on the future of the coherent photonic calibration system be established as part of the calibration group's planning.

Finally, the ASAC reaffirms the unique scientific value of accurate polarization measurements from ALMA, and urges the calibration group to include polarization calibration as a vital part of its planning; polarization calibration should be included in the overall plan presented to the ASAC at its next meeting.

The ASAC makes the following recommendations concerning the Calibration:

- The ASAC recommends that a plan which addresses all the calibration issues for ALMA, with a clear timeline indicating design reviews and decision points, be established over the next six months.
- The ASAC recommends that the minimum hardware required for calibration be established over the next 12 months, or as soon as is practicable.
- The ASAC recommends that a decision on the dual-load calibration system be made rapidly by the Calibration Group.
- The ASAC recommends that a framework for deciding on the future of the coherent photonic calibration system be established as part of the calibration group's planning.
- The ASAC recommends that the calibration group include polarization calibration as part of its planning, and present a report to the ASAC at its next meeting on progress in defining a definite plan for polarization calibration.

10. Correlator

The ASAC heard a report by D. Sramek on the progress concerning the Backend subsystem. A PDR on the Backend was held in April 2002 in Granada, and the corresponding report will be available by October 2002. Good progress is being achieved in the design of the 6 elements which constitute the Backend, i.e. IF downconverters, digitizers, data transmission system, photonic LO, low-frequency LO and timing distribution, and baseline correlator.

In order to meet the stability requirements, it is assumed by the backend group that the instrument will not be changed during a target-calibrator cycle. This seems a reasonable assumption to the ASAC for most of the astronomical observations. However some particular observations (e.g., planets) could need some changes in the correlator configuration. Those changes will be further studied by the Calibration Working Group.

The current schedule for the Backend development fits well with the general schedule of the project. Nevertheless, the ASAC would like to stress that:

- The 1-baseline prototype correlator should be delivered to the ATF by the end of 2003, since interferometry with the prototype antennas is foreseen for the beginning of 2004.
- ALMA Early Sciences activities are foreseen to start by Q3 2007, so the ASAC will like to know in detail the capabilities offered by the portion of the baseline correlator which will be available at the ALMA site by that time.
- The ASAC continues to encourage the collaborative efforts of the several groups working on the ALMA Backend in Europe, North America, and Japan towards establishing the optimal design of a Second Generation (2G) Correlator for ALMA.
- A progress report about the development of such a 2G Correlator (in particular, about the activities within the frame of the ALMA Baseline Project) should be presented to the ASAC at its Spring 2003 meeting.

11. Summary

The major ASAC recommendations are summarized below. These are in the order discussed in the text and are not in any priority order. More detailed recommendations can be found in each section.

1. In the area of Site and Stringency (see § 5.1), the ASAC encourages the ongoing study to simulate dynamic scheduling and recommends implementation of a full stringency calculator. The available site data appear to be commensurate with the ALMA scientific mission, design, and mission emphasis of the baseline instrument.
2. The ASAC has the following recommendations concerning ALMA Early Science (see § 5.2):
   (a) Early Science should start with not less than 6 antennas, and preferably 8 to 10 antennas.
   (b) Early Science should allow continuum and line observations from the start.
   (c) Early Science should start with not less than two receiver bands, including Band 3.
   (d) Phase correction is essential for Early Science observations.
   (e) Early Science should include polarization as soon as possible.
3. Concerning the design of the largest configuration (see § 5.3), the ASAC recommends running the optimization procedure for the Y+ array again, perhaps in combination with the largest spiral array, to give more coverage on intermediate and long baselines.
4. The ASAC re-affirms the prioritization of the ALMA enhancements as defined and documented in the ASAC October 2001 Report. The North American and European members of the ASAC encourage the Japanese efforts to make the enhancements outlined in their proposal, namely the ACA, Bands 10, 8, and 4, and the 2G Correlator, possible in the ALMA project (see § 5.4.2). They note that the contribution plan achieves as much as possible the highest priority enhancements documented in our previous report.
5. The ASAC has the following recommendations concerning receivers (see § 6):
   (a) The ASAC strongly recommends that Early Science should not set the pace of the receiver development and project construction, but should be a natural outcome of the schedule required to meet the full array completion milestone at the specified sensitivities.
   (b) The ASAC recommends that the Project seeks ways to ensure that receiver Band 1 will be part of the enhanced ALMA project.
6. The ASAC recommends the creation of scientist/software positions whose function would be to work with software engineers on user interface software from the astronomers' perspective and to assist in software benchmarking, testing, and validation.
7. The ASAC makes the following recommendations concerning the Calibration (see § 9):
   (a) The ASAC recommends that a plan which addresses all the calibration issues for ALMA, with a clear timeline indicating design reviews and decisions points, be established over the next six months.
   (b) The ASAC recommends that the minimum hardware required for calibration be established over the next 12 months, or as soon as is practicable.

   (c) The ASAC recommends that a decision on the dual-load calibration system be made rapidly by the Calibration Group.
   (d) The ASAC recommends that a framework for deciding on the future of the coherent photonic calibration system be established as part of the calibration group's planning.
   (e) The ASAC recommends that the calibration group include polarization calibration as part of its planning, and present a report to the ASAC at its next meeting on progress in defining a definite plan for polarization calibration.

8. The ASAC continues to encourage the collaborative efforts of the several groups working on the ALMA Backend in Europe, North America, and Japan towards establishing the optimal design of a Second Generation (2G) Correlator for ALMA (see § 10). A progress report about the development of such a 2G Correlator (in particular, about the activities within the frame of the ALMA Baseline Project) should be presented to the ASAC at its Spring 2003 meeting.

9. Finally, the ASAC recommends that the funding and organisation of the Science IPT be reviewed by the Project in the light of the concerns described in § 3.

APPENDICES

A. Report of the ASAC Subcommittee on Site and Stringency

A.1. Introduction

The ACC charged the ASAC to address the following issue:

The ASAC is asked to evaluate all available site (225 GHz opacity, 12 GHz phase stability, 350 micron and > 1 THz) data for Chajnantor, and to discuss any significant trends and issues which may impact the scientific mission, design or mission emphasis of the baseline instrument.

This issue was considered closely related to the considerations of stringency that have emerged from our thinking about operations and scheduling. Consequently, the ASAC asked that the definition of stringency be considered as part of this work.

The ASAC appointed a committee to address this issue, consisting of five ASAC members (Neal Evans, Chris Wilson, John Richer, Seiichi Sakamoto, and Diego Mardones), Simon Radford, Selby Cull (a summer student at NRAO-Tucson), and Robert Lucas. The ASAC members have supplied sample experiments that explore the parameter space of stringency. Radford and Cull have analyzed the site statistics. Lucas has considered the effect of these considerations on the ALMA simulator (delivering stringency estimates) and dynamic scheduler (incorporating stringency into the scheduler).

The committee decided to retain the definition of stringency in the Fall 2002 ASAC report:

$$S = t_a/t_p,$$

where t_a is the total available time and t_p is the total time during which the conditions for the observations are met. After discussing the available site statistics, we decided to estimate S based on the NRAO site statistics on $\tau(225)$, ϕ_{rms}, and wind speed accumulated since 1995. While there are other data from Pampa La Bola, the time base is shorter, so we deferred incorporation of those data.

The wind data are used to ask whether the primary pointing specifications are met; that is, we restrict ourselves to an either/or decision. If the wind is less than 6 m s^{-1} in the daytime or 9 m s^{-1} in the nighttime, we assume the pointing specification of 0.6 arcseconds to be met. This simple assumption is satisfactory for now, but it should be reassessed once the actual performance of the antennas is determined.

The yes/no wind criterion leaves two continuous variables. While there are diurnal, seasonal, and longer trends, we focus on the aggregate data over the period since 1995. Diurnal and seasonal trends are clearly present, as shown below; these may need to be considered in detailed planning. It is possible to compute S from the fraction of the time that both $\tau(225)$ and ϕ_{rms} are less than given values. We will show the joint distribution function for these two quantities in the last two figures. S will be the cumulative function computed from these distribution functions. We also supply relations to relate the effective seeing angle ($\theta(see)$) to the phase noise. We also discuss improvements due to the water vapor radiometers and/or fast switching.

Next we present the example observations. The site statistics and stringency results are presented in the following section, followed by a discussion of the effects of phase correction. Then there is a discussion of the consequences for software and conclusions.

A.2. Examples of Observations

1. This will be a modest stringency experiment. Detect absorption by molecular line against the continuum of a disk. The model is the detection of formaldehyde at 1.3 mm in IRAS4A by Di Francesco et al. 2001, ApJ 562, 770. Using IRAM, they detected H_2CO absorption at 1.3 mm of $T_b = 10$ K against a continuum of 3000 mJy. They used a velocity resolution of 0.16 km/s. This provides the best evidence for infall, but it is currently only possible for the few brightest sources. To generalize the result and to study the infall velocity field in detail, we would like to do similar experiments on sources with 10 times weaker disks with velocity resolution of 0.05 km/s. Thus we need rms noise of 0.1 K for 10 sigma detection. This could be done with modest spatial resolution, such as 1". Then we estimate the rms noise for 1 km/s resolution at 1.3 mm to be 0.29 K in 1 min. That indicates 168 min or 2.8 hours to achieve rms noise of 0.1 K with spectral resolution of 0.05 km/s and spatial resolution of 1". Since we are working at 1.3mm, the constraint on tau is very modest, say less than 0.1. Seeing constraint is also modest at say 0.5". Pointing just needs to meet spec. With the equations given below, the seeing constraint translates to a measured $\phi_{rms} = 3.2\,\mathrm{deg}$.

2. This will be about the highest stringency. We want to map a disk at the highest possible resolution. That means going to 0.35 mm in the largest array. Some probably out-of-date calculations indicate that we get a beam of 8.6 mas or 1.2 AU at 140 pc and can detect 71 earth masses of gas plus dust in 1 min. So we need the best tau and seeing, with great phase correction, and pointing in spec. Using the Matsushita conversion to 875GHz, we need $\tau(225) < 0.043$ to get $\tau(875GHz) < 1$. To get down to say 8 M_{earth}, we need these conditions for 1 hour. Let us say that we need $\theta(see) = 5$ mas. This translates to $\phi_{rms} = 0.12\,\mathrm{deg}$.

3. A deeply dust enshrouded super star cluster may only be detectable in the mm/submm continuum. To clearly identify such a cluster requires a spatial resolution of roughly 1 pc at a distance of 10-20 Mpc for typical cluster-containing galaxies. So we need angular resolution of 0.01-0.02$''$ and sufficient sensitivity to detect a dust signal that is equivalent to at least 10^6 and preferably 10^5 or 10^4 solar masses of gas. At 850 microns, this requires us to detect a source of 50-250 μJy at, say, the 5 σ level in continuum. Primary stringency requirement: atmospheric stability to get 0.01-0.02$''$ resolution at 850 microns. This translates to $\phi_{rms} = 0.26\,\mathrm{deg}$, and we take $\tau(225) = 0.1$ as our requirement.

4. A large population of faint submillimeter sources have been identified in the past 5 years using large single-dish telescopes. However, follow-up studies of this population have been limited because the poor angular resolution makes it difficult to identify optical and near-infrared counterparts. Obtaining accurate positions for these faint submillimeter sources should be easy with ALMA. For example, suppose we wanted accurate positions for 100 sources with 850 micron fluxes around 3 mJy. To get positions to roughly 0.1$''$ would require a resolution of 1$''$ and a signal-to-noise of about 10. To achieve this requires only 10 seconds per source with the full ALMA (20 minutes total plus overheads) or roughly 7 minutes per source with a 12-element "early" ALMA (11 hours total). These observations require moderate $\tau(225)$ ($< 0.1 - 0.15$) and moderately good seeing ($\phi_{rms} = 2.1\,\mathrm{deg}$). This experiment might be possible even if the seeing in not within the primary specification.

A.3. Site Characteristics

A.3.1. Background

On a high altitude (5050 m) plateau near Cerro Chajnantor in the Andes of northern Chile, the ALMA site is one of the best known locations for astronomy at millimeter and submillimeter wavelengths. Atmospheric conditions at Chajnantor have been studied extensively during the ALMA development phase and have been reviewed elsewhere (Radford & Holdaway 1998, Radford 2002). NRAO installed an instrument suite in 1995 April and ESO installed complementary instruments in 1998 June. On Pampa la Bola, about 8 km NE of the ALMA site, the Japanese installed monitoring instruments in 1996 June and the ASTE telescope in 2002 February. The NRAO and ESO instruments include a 225 GHz tipping radiometer, two 11.2 GHz interferometers, two 183 GHz line radiometers, a 350μm broadband tipping radiometer, and meteorology instruments. In addition, two groups have measured the atmospheric brightness at submillimeter wavelengths with Fourier Transform Spectrometers at Chajnantor (Matsushita et al. 1999, Paine et al. 2000).

At both 225 GHz and 350μm, the atmospheric transparency at Chajnantor is better more often than at Mauna Kea (Fig. 1). Only the South Pole enjoys comparable conditions (Radford & Chamberlin 2000, Radford 2002). At Chajnantor, the transparency shows significant seasonal and diurnal variations. Conditions are consistently good from April through December but deterioriate during January, February, and March (Fig. 2). In northern Chile, the summer months are known paradoxically as the "Bolivian winter" because a shift in the atmospheric circulation patterns draws moist air over the Andes from the Amazon basin. There is considerable year-to-year variation in the severity of this summer season. Even during the worst months on record, however, the median 225 GHz optical depth at Chajnantor, $\tau_{225} \approx 0.3$, is comparable to good conditions at many established observatories for millimeter wavelength astronomy. Diurnal transparency variations (Fig. 3) lag behind the solar cycle, with the best conditions occurring around sunrise. The diurnal variations are weaker during the winter than during the summer.

At Chajnantor, the atmospheric phase fluctuations on 300 m baselines are measured at 11.2 GHz by small interferometers observing beacons broadcast by communications satellites. For millimeter wavelengths, at least, these measured fluctuations can be scaled linearly with frequency to estimate the conditions at higher frequencies. For submillimeter wavelengths, however, dispersion at the edges of the windows becomes significant (Holdaway & Pardo 2001), so the measurements provide an underestimate of observing conditions. The phase stability is better in winter (Fig. 4), the diurnal phase stability variation (Fig. 5) is larger than the seasonal variation, the diurnal variation is more pronounced in phase stability than in transparency, and the diurnal phase stability variation more nearly matches the solar cycle than the diurnal transparency variation.

A.3.2. Phase Fluctuations and Seeing

Two methods have been suggested to relate the measured fluctuations to image quality (Table 1). Holdaway and Owen (1995) estimated the highest frequency where the phase fluctuations on 300 m baselines would allow good imaging (30° r. m. s.) or any image reconstruction at all (70° r. m. s.). Masson (1994) extrapolated the temporal structure function of the observed fluctuations to estimate the baseline, $b_{\max}$, where the phase fluctuations at 345 GHz are 1 radian r. m. s. and the corresponding angular resolution limit, or seeing, $\theta(see) = 0.7\lambda/b_{\max} = 0.14'' \ \lambda(mm)/b_{\max}(km)$. Essentially, one is simply limited in resolution by the largest usable baseline. To calculate the largest usable baseline, we first need to scale the measured ϕ_{rms} in degrees to the observed airmass (A), frequency (ν) and baseline (b) from ϕ_{rms} at the site testing parameters ($A = 1.7$, $\nu = 11.2$ GHz, and $b = 0.3$ km). For this report, we use the following: $\phi_{rms}(A, \nu, b) = \phi_{rms}(1.7, 11.2, 0.3)(A/1.7)^{0.5}(\nu/11.2)(b/0.3km)^{s}$ where the phase noise is assumed to increase as the square root of the air mass, linearly with frequency, and with baseline as the power s. We then set the phase fluctuations to the largest allowable phase fluctuations (in the example given here, 1 rad) and solve for b_{max}: $b_{max} = 0.3\mathrm{km}[(11.2GHz/\nu)(1.7/A)^{0.5}(57.3/\phi_{rms}(A, \nu, b)]^{1/s}$. Finally, $\theta(see) = 0.47''\lambda(mm)[(\nu/11.2GHz)(A/1.7)^{0.5}(\phi_{rms}/57.3)]^{1/s}$, where ϕ_{rms} is the value from the site testing interferometer (note however that in some plots, it is already corrected to $A = 1$). The value of s changes with baseline, but we will approximate it here by $s = 0.6$. This is the median exponent on the structure functions of the measured data (Holdaway and Pardo 2001). In Table 1 below, we apply these equations to the case of observing at 345 GHz ($\lambda = 0.87$ mm) at the zenith ($A = 1$); note that the ϕ_{rms} values in the table are already referred to the zenith! The equation becomes $\theta(see) = 0.093''(\phi_{rms})^{1.67}$ One can easily substitute for other observing parameters or assumptions about the structure function.

Most of the time at Chajnantor, phase stable observations are possible only for long wavelengths or short baselines. To achieve the ALMA performance goals, compensation for atmospheric phase fluctuations will be necessary much of the time for millimeter wavelengths and modest baselines and most of the time for submillimeter wavelengths and long baselines.

Because of differences in instrument configuration and other factors, it is more complicated to compare phase fluctuation measurements at different sites than transparency measurements. Nonetheless, a quick estimate based on Masson's method (1994) indicates the median limiting angular resolution at Chajnantor is about twice as good as at Mauna Kea.

Table 1: Chajnantor phase stablility

measured $\phi_{\rm rms}$			$\nu_{\rm limit}$ [GHz]		345 GHz	
	[μm]		30°	70°	$b_{\rm max}$ [m]	$\theta_{\rm see}$
75 %	394	5.3°	63	148	52	2.40″
50 %	187	2.5°	134	313	181	0.69″
25 %	89	1.2°	281	655	625	0.20″
10 %	49	0.7°	510	1189	1691	0.07″

$\phi_{\rm rms}$: r. m. s. fluctuations on a 300 m baseline at 11.198 GHz at 36° elevation over 10 min intervals **referenced to the zenith**. $\nu_{\rm limit}$: frequency limit for observations with specified r. m. s. phase fluctuations on 300 m baselines (Holdaway & Owen 1995). $b_{\rm max}$ [m] and $\theta_{\rm see}$: maximum usable baseline and effective seeing at 345 GHz (Masson 1994) calculated for the median structure function exponent, 0.6 (Holdaway and Pardo 2001).

A.3.3. Correlations

Several atmospheric parameters show significant correlation, but others are only weakly correlated at best. To illustrate these correlations in the presence of substantial scatter, the data were selected on the value of one parameter and then distributions of a second parameter were compiled. The comparisons show westerly winds are stronger than easterly winds (Fig. 6), the transparency is better during colder periods (Fig. 7) and during westerly winds (Fig. 8), and the phase stability is better during weaker winds (Fig. 9). and colder periods (Fig. 10). Despite a tremendous scatter, there is a significant correlation between the transparency and the phase stability. When the transparency is better than the median, the phase stability is about twice as good as otherwise (Fig. 11).

The atmospheric data are recorded every 10 min. To evaluate conditions over longer intervals, cumulative distributions were compiled for the median or the maximum during the interval. As expected, there is essentially no change in the distributions of the medians (Fig. 12). For the maxima, on the other hand, the distributions show a monotonic degradation with interval length (Fig. 13). This is more pronounced for the phase fluctuations than for the transparency (Fig. 14).

In Figure 15, we have plotted the two-dimensional probability density $P(\phi, \tau)$. The contours encircle 5, 10, 15, ... per cent of the total probability. Although typical conditions are of course excellent, there is a significant amount of time with less good conditions. Note especially the relatively long tail on the phase stability distribution. The correlation of τ and ϕ has substantial scatter. We have also shown the joint probability densities (Fig. 16) of the opacity and phase stability when the wind speed is such that the primary pointing specifications will be met (speed is > 6 m/s at day, or > 9 m/s at night time). Note that these wind conditions are met only 56% of the time, so the outermost contour is the 50% contour. Note the substantial growth in the contours, especially outside the 25% contour, when the wind condition is applied. Taken at face value, these statistics would suggest that up to 44% of the observing time could be lost to high winds. This suggestion is overly pessimistic. While the tighter wind limit in daytime was meant to allow for some pointing degradation because of thermal effects, there is a compensating effect: higher wind makes solar heating less localized. Thus, the wind limit may actually not be less in the daytime. If we arbitrarily adopt 9 m/s for daytime as well, only 30% of the time would potentially lost, and much of that is in afternoons, when other conditions also degrade. In addition, the pointing is unlikely to degrade catastrophically as the primary wind limits are exceeded. It will be very useful to characterize the antenna pointing in winds over those limits.

A.4. Phase correction schemes

The Chajnantor site has, for a ground-based site, excellent transparency and good phase stability. Nonetheless, accurate atmospheric phase correction is a critical requirement for practically all ALMA observations. ALMA will use a combination of fast-switching and 183GHz radiometric measurements to correct for atmospheric phase fluctuations: the phase correction problem is so critical to achieving ALMA's science goals that this apparent redundancy in the project plan is vitally important. Although the solutions in the project plan should achieve accurate phase measurements, correcting atmospheric phase on 10 km baselines at 650 GHz is non-trivial, and is a unique problem for ALMA. How these two techniques will be used together is still unclear, and it likely that this will evolve with experience. The importance of continuing efforts into phase correction techniques cannot be stressed enough if ALMA is to succeed.

A.4.1. Fast switching

There are many very detailed memos, many written by Mark Holdaway, which put together the expected source counts and measured atmospheric fluctuations to estimate the effectiveness of fast switching as a phase correction technique. These are non-trivial simulations to perform, being technically complex and requiring detailed simulation of the observing and data reduction process. Memo 403 nicely brings these results up to date for an ALMA design of 64 12-m antennas. The bottom line is that fast switching, with a few caveats, should work well for ALMA at all frequencies, achieving phase errors less than 25 degrees rms at all frequencies on all baselines. 25 degrees is taken as the phase rms goal as it allows good imaging quality. The total efficiency of fast switching, including losses due to decorrelation and time spent on the phase calibrator, is principally a function of phase fluctuations and airmass, but is typically better than 90% in these simulations. This calculation assumes that one schedules observing programmes based on the current phase stability — i.e one matches high frequency programmes to the periods of highest phase stability. Although this assumption is sensible for first-order models, Figure 15, which shows the poor correlation of τ and ϕ_{rms}, means that a more sophisticated set of simulations would be useful. In particular, we will most likely have to consider both τ and ϕ_{rms}. And it is clear that in periods of good opacity, there is a significant amount of poor seeing.

For example, considering only the best weather ($\tau < 0.05$), the rms phase fluctuations at 11 GHz are 0.95 (25th centile), 1.7 (median), 3.6 (75th centile) and 7.0 (90th centile) degrees. For weather better than $\tau < 0.036$, the corresponding numbers are 0.8, 1.5, 3.0 and 5.8 degrees. For reference, the 10th centile of the entire phase statistics is only 0.83 degrees. In summary, about a quarter of the lowest opacity weather has a phase stability worse than 3 degrees at 11GHz. Bearing in mind that we are likely to be observing at high frequencies in such good weather, these are significant fluctuations: for example, ignoring the dispersive effect, this scales up to 180 degrees of phase at 650 GHz on 300-m baselines. It is unlikely that fast switching will be effective in these conditions, although more simulations are needed to demonstrate this.

A.4.2. Radiometric phase correction

There is much less concrete data from which we can make predictions about the effectiveness of radiometric phase correction techniques. We are heavily reliant at the moment on theoretical models and sensitivity estimates, plus a very small number of results from the JCMT-CSO, and the test systems on Chajnantor. Modeling radiometric phase corrections is even more complex than modeling fast switching, involving as it does detailed atmospheric models, and we have very little quantitative to go on at the present time. Fast switching is the standard technique at cm wavelengths, and the theoretical models seem to be well supported by experimental data. There are few such constraints using the 183 GHz line, as observational results are so scarce. It remains of high importance to the ALMA project that a coherent programme of work on both simulations and real tests is carried out over the coming years.

The project specifications for WVR corrections are established in memos 303 and 352. The aim is to correct the path to each antenna to an accuracy of $10(1 + w_v)\,\mu$m, where w_v is the line-of-sight water vapour content in mm. This correction must be made in one second of time, and be reliable over a 5 minute period, with modest changes in zenith angle or airmass allowed (at the moment the specification is a zenith angle change of less than one degree). At 900 GHz, with $w_v = 1$ this corresponds to a phase error of 22 degrees.

In principle, these specifications, if met by the WVR system, would allow us to phase correct essentially all data to an accuracy of 25 degrees of better, allowing diffraction-limited imaging at all frequencies with high efficiency on all baselines. But this remains a significant challenge to both the WVR hardware and our atmospheric models.

It is important to recall that the possibility of correcting the phase gradient across the 12-m aperture (which effectively adds a pointing error) was not adopted by the project, although should be possible with extra effort and resources.

The advantages of using the radiometric technique in conjunction with fast-switching, rather than fast-switching alone, include

- an increase the integration time on source, both reducing decorrelation losses and reducing wear-and-tear on the antenna drives
- an increase in the correlation amplitude accuracy
- the potential to achieve even higher phase stability, so improving image quality
- the potential to allow efficient use of the very low τ weather when phase stability is poor.

In extreme cases, it may well prove that using the radiometers allow useful observations in very unstable periods when fast switching is ineffective, but this is as yet mere speculation. Unfortunately, all these statements are qualitative. A good deal of further simulation will be needed, and experimental data must be obtained, before they can be quantified.

A.5. Software implications

Requirements have been discussed by the SSR, and are available at

`http://iraux2.iram.fr/%7Elucas/almassr/report-2/report-2-v4r2.pdf` [2]

The sections relevant here are Dynamic Scheduling (3.4) and Simulation (3.8).

A.5.1. Dynamic Scheduling

Programmes will be split into scheduling blocks; the scheduling block priorities will be reevaluated at the end of execution of each block (long programmes will be obtained by repeated execution of the same block). The priorities will include many factors, some trivial (e.g., source visibility), other highly fluctuating like phase rms and system temperature (atmosphere included). Both science rating and stringency will be primary factors.

The SSR required that the dynamic scheduler should be its own simulator, as it can be executed with atmospheric data (as we already have) and a set of scheduling blocks as input, to tune up the formula and coefficients for optimum use of ALMA during a scheduling season:

“The actual formula and coefficients must be tuned for optimum overall efficiency, and agreement with observatory policy, according to the distribution of programme requirements and the weather statistics on the ALMA site. The ordering of programmes according to scheduling probabilities should match that of science ratings, in each range of observing conditions.”

The conclusions of the present report call for treating the system temperatures (or opacities) and the phase rms as truly independent parameters, which had been foreseen. They should both appear as strict

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[2] this link points to a new version of ALMA Software memo 11 that should still be regarded as a draft, until it is formally reviewed at the end of 2002 September; however this text takes into account the reviewers’ comments.

upper limits (e.g., a SB requiring less than 1mm precipitable H_2O and 50μm pathlength rms is not scheduled if either requirement is not met) and through the stringency factor (to make sure this SB is given priority over less demanding ones whenever these conditions are met).

A.5.2. Simulation

Memo 11 formulates requirements on ALMA simulator. The simulator should in principle allow to investigate the use of both fast switching and radiometric phase correction methods, by generating fake data using state-of-the-art atmosphere models, and processing them through the off-line data reduction package.

A.6. Summary

The data presented above lead us to the following conclusions.

- There are no indications in the site weather data that the ALMA scientific mission or design needs to be changed.
- There is some correlation between good transmission and good phase noise. However there are significant periods when transmission is good, but phase noise is not very good.
- Examples of ALMA science indicate that some of the most exciting science cannot be done without the successful functioning of the phase correction scheme. Making this scheme work will also make the periods of good transmission but poor phase noise usable.
- Determining how the pointing actually degrades as wind conditions worsen will be important in assessing the fraction of time that can be used for different projects. In particular, the effects during daytime need further study.
- The ASAC encourages the ongoing study to simulate dynamic scheduling and recommends implementation of a full stringency calculator.

If we apply the calculations to the examples given in §A.2, we find that experiment number 1 can be done about 30% of the time; if the pointing degrades gracefully, this percentage could be increased. The fourth example could be done about 25% of the time. Neither of the other examples could be done without phase correction in any significant fraction of the time. Assuming that phase correction works to the levels needed, experiment number 2 could be done about 17% of the time and and experiment number 3 could be done 39% of the time (these estimates include only the constraint on τ and assume that the pointing will be acceptable 56% of the time). These examples reinforce the conclusions drawn above.

We suggest that some of the issues raised in this study be pursued as future work. With the existing data, it would be useful to search for rapid time variations in the wind speed, opacity, and phase noise. In particular, rapid variations in phase noise may be ionospheric in origin; these would be less important at high frequencies. If they contribute significantly to the distribution of high $\phi(rms)$, those statistics could be too pessimistic. We recommend further study of the likely effect of wind on the antennas based on the detailed specifications. However, the most important thing will be to characterize the pointing degradation as winds exceed the nominal values for the primary pointing specfications. Finally, we encourage implementation of a stringency calculator based on input requirements and using the available site data. This should be coupled with the ongoing study of how dynamic scheduling will work.

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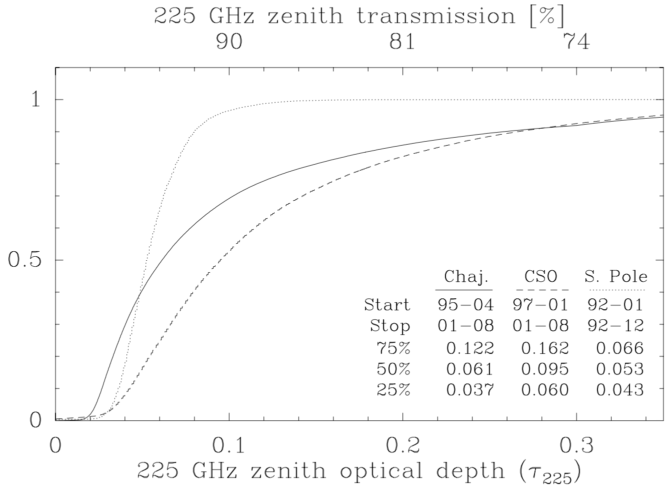

Fig. 1.— Cumulative distributions of the 225 GHz zenith optical depths (τ_{225}) measured at Chajnantor, at Mauna Kea (CSO), and at the South Pole. Adapted from Radford & Chamberlin (2000). The distributions of the broadband 350μm measurements are similar

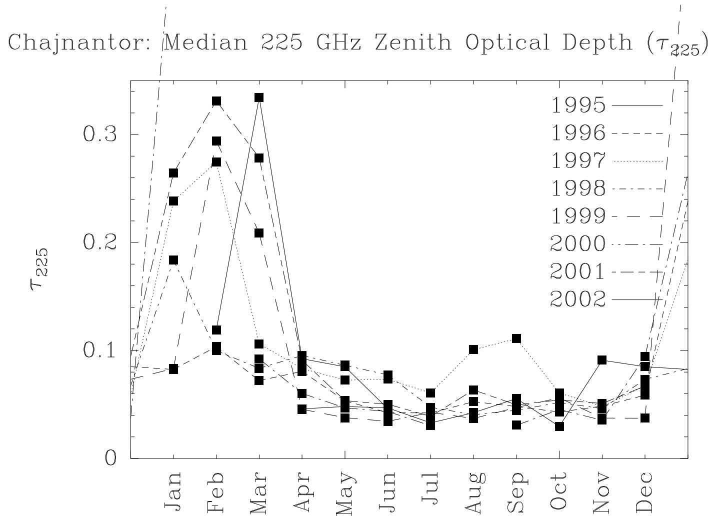

Fig. 2.— Seasonal variation of median measured 225 GHz zenith optical depths at Chajnantor. The variation of the broadband 350μm measurements is similar

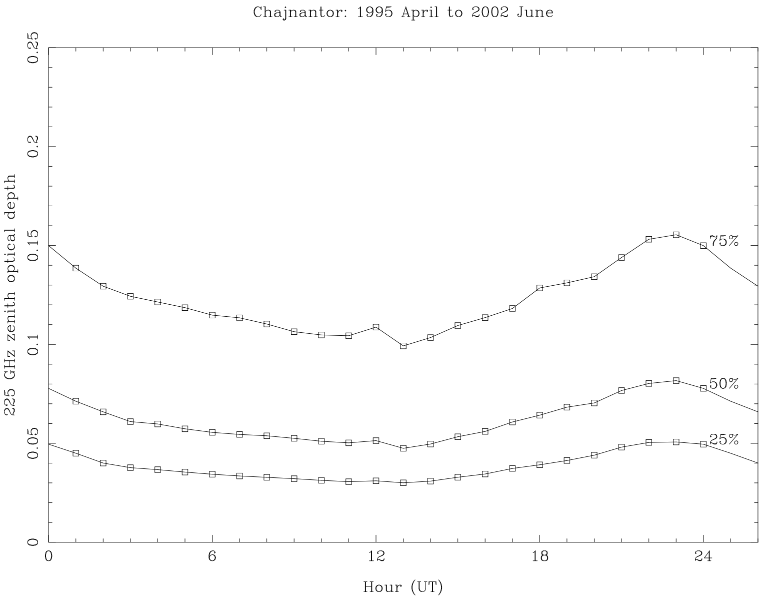

Fig. 3.— Diurnal variation of quartiles of measured 225 GHz zenith optical depths at Chajnantor. Local solar time is UT $-$ $4^{\mathrm{h}}\,31^{\mathrm{m}}$. The variation of the broadband 350μm measurements is similar.

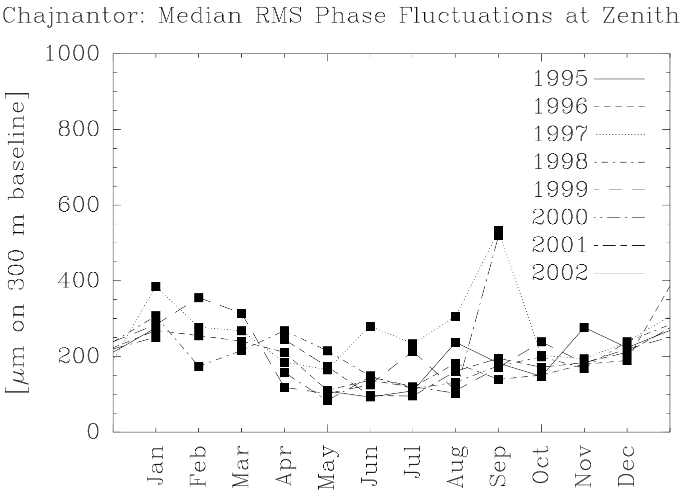

Fig. 4.— Seasonal variation of median measured phase fluctuations at Chajnantor referred to the zenith.