Report of the MMA Cost Review Panel

July 1999

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Summary Report of the Cost Review Panel

The Charge to the Panel and the Organization of the Report

The Division of Astronomical of the National Science Foundation (NSF) convened a cost review panel to review the U.S. Reference Design of the Millimeter Array on July 7, 8 and 9 at the NRAO headquarters in Charlottesville, Virginia. The names of the panel members and their affiliations are given in Appendix 1. The panel members included people with expertise in radio astronomy and people with expertise in the planning, construction and utilization of large scientific user facilities comparable in scale to the proposed Millimeter Array (MMA) project.

Dr. Robert Eisenstein, the Associate Director for Mathematical and Physical Science presented the following charge to the panel during the opening session:

1. Assess the technical feasibility of the proposed approach to constructing the U.S. Reference Design of the Millimeter Array;
2. Determine whether the proposed schedule is consistent with the technical tasks to be performed and the costs projected for the project:
3. Determine whether the management structure in place provides confidence that the necessary planning, coordination, technical- and cost-control, and issue-resolution functions will be performed so as to accomplish the project goals on schedule and within the cost estimate;
4. Evaluate the cost estimate and, based on a detailed examination of its validity evaluate the contingency assigned to each area of the Work Breakdown Structure;
5. Determine whether other approaches or options to the proposed work could result in significant cost savings;
6. Comment on descope options that may reduce costs which would have minimal impact on the scientific capabilities of the instrument.

While the charge did not explicitly request comments on the ALMA project, the Panel notes that the ALMA project and the U.S. Reference Design are very closely linked. Many of the presentations made specific reference to ALMA. During the course of the review the Panel and the NSF agreed that comments and recommendations on the ALMA project would be appropriate. The agenda for the review and a description of the process that the Panel followed are contained in Appendix 2.

This report consists of a summary of the findings of the Cost Review Panel, individual breakout session reports, and two appendices. Each breakout session report evaluates one of the 11 Work Breakdown Structure (WBS) Elements within the framework of the charge. Each breakout session report was prepared by a subset of the Panel following formal presentations by, and discussions with, responsible MMA project staff members designated by MMA project management. Each report was subsequently discussed in executive session before the final draft was prepared. The summary report was prepared after the meeting and is based on the breakout session reports and information that was obtained during discussions with the MMA project staff. In addition to summarizing each of the breakout session reports, the summary report also addresses project management issues that were found to be common to the individual reports.

Response to the Charge

Technical Feasibility of the MMA project:

The Panel found that the proposed approach for the U.S. Reference Design of the Millimeter Array is technically feasible and will meet the scientific goals of the MMA project. The MMA project staff has given extensive attention to all of the technical elements of the project. The designs of most subsystems are sufficiently advanced to give the Panel confidence that the approach for each subsystem was carefully chosen. The Panel did not find any high risk technical designs that could jeopardize completing the MMA project within the proposed cost and schedule or achieving the scientific goals of the project.

The planning for the preferred site (WBS 2.0) is quite advanced and shows that it is feasible to build and operate an array of radio telescopes at Llano de Chajnantor at an elevation of 5000m, with an Operation Support Facility (OSF) located in San Pedro de Atacama at an elevation of 2500m. While the very high elevation of the observatory requires the lower elevation OSF, the relatively small amount of water vapor that the telescope array must see through to reach their targets in space significantly enhances the proposed science program. Indeed, the submillimeter goals of the science program cannot be achieved at a significantly lower elevation. Lower elevation sites in the continental U.S. could not meet the scientific goals of the project for this reason. Even the atmospheric transmission and stability properties of Mauna Kea, at an elevation of 3600m, are significantly inferior to the Chajnantor site. Moreover Chajnantor is the only site with outstanding transparency and phase stability properties, as well as sufficient area to meet the scientific goals of the project. The documentation presented to the Panel, together with the presentations at the review showed that the site could very successfully accommodate the MMA project. Nevertheless the Panel notes that the U.S. and its international partners need to quickly establish agreements with the Chilean Government for the use of the land for radioastronomy. Until that is done it is not wise to begin construction on the Chilean site.

The 12m antenna design (WBS 3.0) presented to the Panel is technically feasible and well conceived. It does not require any major advance in the state of the art and the design could be constructed by a number of telecommunications firms for the estimated cost. At the time of the Cost Review, NRAO had just received bids from four such firms for a prototype 12m antenna, thereby demonstrating the willingness of firms to compete for the order. A production run of thirty or more antennas should provide economies of scale that should lead to reductions in cost relative to the estimate presented to the Panel.

The 12m antenna is expected to be the standard for ALMA, should that project go ahead. The European members of the ALMA consortium are placing procurements for 12m antennas with the same bid specification as the MMA project procurement. This is a valuable step, since it will maintain competitiveness in the antenna procurement process; once the costs of the initial procurements are known, antenna costs will be very well established.

The Panel concluded that the designs of the receivers (WBS 4.0), local oscillator (WBS 5.0); IF system (WBS 6.0), fiber optics (WBS 7.0), and correlator (WBS 8.0) were all technically feasible and do not pose significant technical risks. While some sub-systems are at the limit of the state of the art, they do not go beyond it. These systems could be built for the proposed cost provided reasonable care is followed during design and development (D&D) and production phases. The NRAO staff is aware of the risks that can be encountered during production, and are considering steps to mitigate them. The NRAO staff has in the past built systems similar to the designs described in the U.S. Reference Design, most notably for the VLA, VBLA, and the 12m radio telescope on Kitt Peak. These systems have performed very well. NRAO staff members working on the MMA project have demonstrated the technical capability to design, construct and commission these subsystems. Further, by working with BIMA and OVRO within the framework of the MDC the NRAO staff is maintaining a broad technical overview of millimeter and submillimeter technology. They are also working with Stony Brook on SIS mixers, since Stony Brook has considerable expertise in fabricating SIS junctions.

The Panel notes that MMA project management plans to use NRAO staff to design, fabricate, and test these 5 subsystems. While they plan to outsource the assembly of electronic boards to outside vendors, planned in-house effort to build equipment will place a major burden on NRAO. The Panel notes that the current D&D effort is not yet fully staffed and notes that a strong effort must be made to fill open positions in order to bring the staff to the level needed to maintain the schedule. Should these efforts continue to be understaffed, one or more of the 5 systems could introduce costly delays into the construction project.

The software for control, data acquisition, and data reduction constitute the computing effort (WBS 9.0). The plans for the control software are based on previous experience and the work seems well planned and of low risk. The scheduling and image pipeline software also seem well planned. The cost for these tasks is based on the stated assumptions but the development of this software is of higher risk than the control software. Specifically, the MMA project intends to rely heavily on AIPS++ software for data reduction. Since the AIPS++ effort is not part of the MMA project, a formal memorandum of understanding between the MMA project and the AIPS++ project needs to be established in order to define the deliverables.

The Panel also notes with concern that the MMA pipeline and archiving plans are based on parameters that have not been recently addressed in a scientific context. Given the absence of both a computing requirements document and a computing plan, it was not possible to make a clear statement on the technical risks of all elements of the computing effort (WBS 9.0). The Panel believes that these risks are primarily matters of cost and schedule. NRAO's plan to have a workshop this summer that engages the user community is an important step in addressing this concern.

The Panel believes that the NRAO staff has the technical capability to design, construct and commission an interferometer consisting of 25 or more 12m antennas and their associated equipment, including receivers which cover the submillimeter atmospheric windows. Extrapolating from this U.S. Reference Design to ALMA is largely an extrapolation in the number of elements rather than an extrapolation to a more technically demanding design. The Panel is not aware of any additional technical developments beyond those required for the U.S. Reference Design that could place the ALMA project at risk relative to the U.S. Reference Design.

Project Management Structure and Project Staff Responsibilities

The Panel heard several presentations from the MMA Project Director on the subject of project administration and management (WBS 1.0), and on the methodology that was used to develop the cost estimates described in the formal presentations. The Panel also reviewed the MMA project management plan with the MMA Project Director and Project Manager during the project administration and management breakout session. While the implementation of the plan is at a very early stage of development, MMA project management has made a good start. The management is committed to putting in place a number of formal project management tools, including a Work Breakdown Structure (WBS), a configuration control mechanism, a change control process, an earned value system, a resource-loaded schedule, and tracking systems to measure performance against a baseline. At the time of the review the WBS was quite advanced and had been used to develop the cost estimate presented to the panel. The project staff had also begun to prepare requirements documents and technical specifications for all sub-systems.

However, during the breakout sessions panel members consistently found that the documents that define the interfaces between sub-systems were either missing or inadequately defined. In the case of computing, the Panel found that neither a computing requirements document nor a computing plan had been prepared. Except for the antenna specifications, the sub-system specifications were in a very rudimentary state. While the remainder of the project management tools are still being developed, much more work is needed before they can be useful in managing the project. While the upper levels of MMA project management have begun to use formal project management tools, engineers and scientists working on the sub-systems have not, except for the development of the cost estimate. (This is due in part to the fact that a number of key people are holding more than one job in the project, as will be noted later.) MMA project management recognizes that these tools will need to be in place before the start of the construction phase of the project.

The Panel notes that current management plan combines the functions of systems integration and systems engineering into a single position. After reviewing the job responsibilities with the person holding this position, the Panel concluded that the systems integration responsibility involves managing the integration, installation and testing of antennas #1 and #2 at Socorro, and the similar but much larger task for integrating, installing, and testing all project subsystems delivered to the San Pedro OSF and the Chajnantor site.

By contrast, the responsibility of the systems engineer should be to develop, maintain, and distribute all technical documentation and interface specifications; this is a staff function that should report to the MMA Project Director. The Panel does not believe that the responsibilities for systems integration and systems engineering can be combined into one position in a project of the MMA's size and geographic dispersion.

In the short term there is a critical need to add a relatively small number of people to strengthen project management, particularly where one person has more than one critical responsibility. Several key people now hold several critical jobs simultaneously. The roles and responsibilities of the Project Director, project manager, systems engineer, integration/installation manager, project scientist and antenna task leader do not appear to be sufficiently well defined. The persons with these responsibilities should be carrying out these roles out as full time assignments. Instead, many are trying to do several jobs at once. The positions of project manager, project scheduler and systems engineer need to be filled with experienced project management people. If they are not filled, the project management team will not have the ability to manage a project of this complexity and cost.

Project Schedule and Staffing

The high-level schedule, contained in the Millimeter Array, Construction Cost of the U.S. Reference Project, May 1999, was presented to the Panel at the Review. This document was provided to the panel prior to the July 7-9 review and an addendum to that document, dated July 1999, was given to the panel at the review. While the level of effort for the construction phase of the project could be extracted from this document, the level of effort for the early operations phase was not available. The MMA Project Director supplied a crude estimate for early operations costs during the review. This estimate needs to be refined as the ALMA project and host country commitments become more firm over the next several years.

The schedule contained in the above documents defined a seven-year construction schedule beginning in 2001. The construction and early operation funding plan required to support a seven-year schedule is shown in Table I. The panel believes that a funding profile at this level is needed to complete the work within seven years.

TABLE I. MMA project Obligations by Year in Thousands of 1999 Dollars

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Construction	30,540	72,722	42,317	39,756	56,642	59,642	40,971
Early Operation	0	1,500	3,200	6,100	8,500	10,400	13,300
Annual Funding Total	**30,540**	**74,222**	**45,517**	**45,850**	**65,142**	**70,042**	**54,271**

MMA project management plans to staff the project by drawing on resources from NRAO's Charlottesville, Socorro, and Tucson sites, and by creating an observatory staff in Chile. They plan to staff the operations in Chile by hiring Chileans who will be trained in the U.S. during the D&D and early construction phases of the project. Since the capital cost of the U.S. Reference Design for the MMA project is estimated to be somewhat more than twice the cost of VLA after adjusting for inflation, the operating staff needed to support and operate the MMA will probably be somewhat larger than the 200 people assigned to operations at Socorro. The MMA Project Director stated that he expects about 100 people to work at the observatory in Chile, and that the remainder of the needed support will be drawn from NRAO. By the middle of the construction period, the staff in Chile should have reached its steady-state size if serious delays in installation and commissioning are to be avoided.

The number of NRAO staff assigned to the MMA project needs to be increased beyond the current level of 44 people. The project currently has 9 openings that it is striving to fill. The Director of NRAO assured the Panel that these positions will be filled.

The MMA Project Director outlined steps that could be taken to shift NRAO personnel from current Observatory operations to the construction and commissioning of the MMA. The panel notes that the NRAO staff of more than 400 is large enough to provide the support needed by the MMA project, although if this support is provided without the hiring of new staff, it will come at a cost to the current scientific operations and obligations of the Observatory. The Panel did not investigate the impact of such personnel transfers on the ongoing scientific operations at NRAO and it notes that the NSF, NRAO, and its user community must do this. Given the possibility that the budget for scientific operations may decline during the period of construction, a response to such a funding scenario needs to be developed in the near future

The breakout session reports, which examined the staffing of each subsystem, concluded that the schedule for each subsystem is optimistic given the number of staff assigned to each sub-system. Project staff needs to be augmented quickly in a number of areas; these areas are noted in the recommendation sections of the breakout session reports.

When the MMA Project Director was asked to name his greatest problem, he stated that it was staffing. The Panel concurs. The seven-year schedule to complete the U.S. Reference Design of the MMA is achievable only if NRAO is able to assign or hire the required number of people into the project.

On the basis of NRAO's demonstrated accomplishments, which include the construction and operation of the VLA, VLBA, and the 12m telescope on Kitt Peak, the Panel concluded that the NRAO staff has the technical capability to successfully plan and manage the MMA project, provided that the project management staff can be quickly augmented with dedicated people with large project experience, and provided that the size of the technical staff can be brought to the level needed to carry out the D&D phase in a timely manner.

Opportunities for Significant Cost Reductions and Descoping

The Panel was asked to examine whether there were other approaches to the U.S. Reference Design that could result in significant cost savings. Other than basic descoping options, the Panel did not find different approaches that could result in a major cost reduction. The panel notes that there are two options for descoping: One is to reduce the number of antennas. Another is to reduce the number of bands. Both options are feasible and could readily be used to help bring the project cost into line with a fixed budget, should that be desirable. However, since the U.S. and several European institutions are currently carrying out active discussions on a joint U.S.-European array concept based on extrapolating the U.S. Reference Design to larger (12m) and more antennas—the ALMA project—the Panel does not believe that specific descoping recommendations are appropriate at this time.

The breakout session reports describe opportunities for more modest levels of descoping. Such reductions will be important asset in the effort to stop further cost growth.

Total Project Cost

The Panel reviewed the construction cost estimate for the U.S. Reference Design. The construction cost was estimated by MMA project staff to be $343 million in 1999 dollars. The total project cost is obtained by adding the cost for design and development (D&D), $26 million (in then-year dollars), and the estimated cost of early operations, $43.5 million, to the foregoing construction cost. The total project cost in 1999 dollars is then $412 million. Since the MMA Project Director provided the cost of early operations to the Panel Chair after the review was over, the Panel did not review this contribution to the total project cost. While it appears reasonable when compared to the cost of operating the VLA, it should be reviewed in the near future.

The cost of early operations cannot be avoided. Indeed, as soon as the OSF and Chajnantor sites facilities are completed, they must be equipped and staffed as an observatory to assemble and commission into an operating array newly-constructed antennas, receivers, and other subsystems which have been completed and shipped to Chile. There must also be funding for maintaining equipment that has been successfully commissioned during the earlier portions of the seven-year construction phase. If an adequate, properly trained and equipped staff is not in place at the OSF and Chajnantor prior to the arrival of equipment, there will be significant delays and cost overruns in completing the project.

The Panel concludes that the construction cost estimate of $343 million 1999 dollars is sound. Indeed, the Panel believes that the cost estimate is probably conservative. Value engineering can and should reduce the cost estimate once the necessary project management controls are in place.

Likewise, the total project cost of $412 million 1999 dollars, including funding for early operations, is a good estimate for the project scope presented to the Panel. Of course, any increase in scope will increase the cost.

Comments on the Impact of ALMA on the MMA project

While the Panel was not asked to comment on the ALMA project, it notes that this is the project that NRAO and the NSF are actually planning to build. The Panel concludes that a millimeter array based on 25-30 12-meter antennas could be built and put in to operation for somewhat more than $400 million 1999 dollars. A more ambitious project would, of course, cost more.

The Panel notes that should ALMA go ahead with the European signatories to the ALMA MOU, European staff members would have to be incorporated into the upper levels of the ALMA project management. This prospect has already created a significant impediment to recruiting people for the unfilled managerial positions in the MMA project: Should NRAO fill all the positions needed to create a management organization that can carry out the necessary planning, coordination, technical- and cost-control, and issue resolution functions, it is very likely that the senior project staff would have to be changed once the ALMA project is approved by the participating nations. Such a restructuring of the project management can be minimized if people from prospective partner institutions are recruited into the unfilled positions. However, the Panel recognizes that there could be some disruption once an international agreement is reached. In any case, it believes that it would be better to fill open positions quickly rather than wait to reach a final international agreement.

Recommendations

The Panel developed its recommendations in two steps. Each breakout session working group developed its own report. Recommendations for each WBS element are thus contained in the reports of the individual breakout session working groups. These recommendations span a wide range of technical, cost and schedule issues which are specific to the particular WBS element. While these recommendations do not all have the same level of urgency, the panel believes that each should be reviewed by MMA project management.

The Panel notes that in three days—even long days—a panel such as ours cannot reach the level of expertise acquired by the MMA staff over the decade that they have been thinking about the project. Nevertheless, in those three days we did uncover certain issues common to many WBS elements. These common areas are all related to project management. These form the basis of the overarching recommendations which follow. Our first two recommendations address the importance of quickly reaching agreement on the management framework of the international partnership for the ALMA project and the scope of that project. The Panel believes the NSF must take the lead in implementing these recommendations. Our third recommendation is directed at filling out the project management team. It is of great importance and of equal weight with the first two. Our remaining recommendations are directed toward NRAO and the MMA project management. However, we note that without adequate funding and guidance from the NSF, these recommendations cannot be carried out in a timely manner.

Recommendation I: We urge the NSF, with help from NRAO and AUI, to rapidly advance the creation of an international partnership that can successfully finance and manage the construction and utilization of the ALMA project. The next two steps that need to be taken before the end of 1999 are: the international partnership needs to agree on a well-defined project scope and associated total project cost, and must formulate a preliminary high level management plan for the ALMA project organization.

Comments: The Memorandum of Understanding (MOU) for joint participation in the design and development phase of the ALMA project, signed on June 10, 1999 by NSF and the European organizations, is a major step in this direction. The cooperation between NRAO and their European counterparts on the design and development of key technical elements has already produced a common bid specification for the antennas. Once an approximate funding level that the international partners can propose with confidence to their governments is agreed upon, the technical scope of the project can be defined. A specific total project cost will also provide ALMA project staff with a target against which the cost of their designs can be measured, and will provide an incentive for seeking cost reductions. A preliminary high level management plan will allow the recruiting of key project personnel to extend to European Institutions.

Recommendation II: We recommend that NSF and NRAO revise the technical specifications for the subsystems of the U.S. Reference Design so that they are compatible with the ALMA project. We further recommend that the total project cost target for the U.S. Reference Design be fixed at the $412M described in the report.

Comments: This is not a recommendation to fix the total cost for the ALMA project at $412 million, since the determination of the available funds is the responsibility of the governments represented in the international partnership. However, it is our hope that adopting this figure will make the already-completed work of the U.S. MMA project team more relevant to a potential ALMA project. It will also make it possible to set the stage for a cost reduction campaign. This will allow the project cost estimate to become more firm and will give the NSF and its international partners greater confidence in its accuracy. Adopting a totally different total project cost would introduce a significant delay in starting a cost reduction campaign.

The 12m antenna design adopted by the international partnership for ALMA should be also made the standard for the U.S. Reference Design.

Recommendation III: MMA project Management should quickly define and fill top management roles with additional experienced staff. The responsibilities and roles of the project director, project manager, systems engineer, integration/installation manager, project scientist and antenna task leader should be made more definite and the persons occupying these redefined positions must carry out these roles as full time assignments.

Comment: It would be desirable if people working in partner European institutions filled some of these positions. We also note that most, if not all, of the people who are currently filling these roles should participate in the creation of the high-level ALMA management plan alluded to in Recommendation I. The primary need to is to put in place a management team capable of dealing with the full range of issues the ALMA project will face.

Recommendation IV: The MMA project team should refine and fully develop a WBS and cost estimate for a project based on ALMA subsystem specifications having a total project cost of $412M.

Comment: This will primarily involve specifying an appropriate number of 12m (not 10m) antennas for the U.S. Reference Design project, and making appropriate adjustments to the number of receivers, correlator channels, and antenna pads. The Panel anticipates that the MMA project team will reduce the number of 12m antennas to 25–30 in order to bring the total project cost to $412 million, thus conforming with Recommendation II.

Recommendation V: The MMA project team should explicitly identify all of the critical staffing needs required to execute the D&D, construction and early operations phase of the project. We further recommend that a staffing plan that embodies those requirements be prepared by the spring of 2000, so that the staffing plan can be reviewed as part of a baseline review at that time.

Recommendation VI: The MMA project team should give a high priority to defining and controlling technical specifications, the interfaces between subsystems, and the testing and acceptance procedures. In addition, we recommend that they formally document the scientific requirements of the project, and define and document a process of adhering to those requirements. We further recommend that the MMA project team advance the *Project Book* to maturity so that it can be used as a definitive statement of the MMA configuration. The Panel also recommends that the MMA project team prepare a computing requirements document and a computing plan.

Once all of this documentation has been prepared and approved the project should be put under strict configuration control.

Recommendation VII: The MMA project team should seek design efficiencies and opportunities for cost reduction within the framework of the redefined project scope and the reference design Total Project cost.

Comment: The Panel notes that it will take at least a year to implement all of these recommendations. The Panel envisions that first two recommendations should be achieved by the end of the year, the third recommendation should be implemented by the spring of 2000 and the last recommendations should be implemented in roughly one year. Once all of the recommendations have been implemented a baseline review of the project should be held.

Breakout Session Reports

WBS 1: ADMINISTRATION AND PROJECT MANAGEMENT

Panel Members: G. Sanders, R. Goldsmith, J. Peoples, G. Robertson, M. Roth, D. Tenerelli (participated by phone)

Findings: The MMA project presented two documents to the review panel describing the construction cost and schedule of the U.S. Reference Project. These include a listing of the project Work Breakdown Structure (WBS), the project schedule, a summary of the cost estimate, as well as a volume including a one-page detail sheet for each WBS element. The summary cost for MMA is $343 million for construction, with $25.9 million *[sic]* for the D&D phase, totaling $368.5 million. This cost is increased from the May 1999 cost estimate by several new design choices and by an alternate treatment of contingency costs.

MMA management described the evolution of the project's scope and cost estimate from the original 1990 proposal. The original proposal was based upon 40 8-meter antennas, covering 3 millimeter-wave bands, and sited at Socorro, NM. Site studies, site characterization, and new physics opportunities since 1990 have led to a much more powerful array concept. Now sited at the very superior site in Chile, with 9 bands now extending into the submillimeter region, the current U.S. Reference Design includes 36 10-meter antennas. The current cost estimate is based upon a more systematic use of estimating techniques typical of large projects in the early stage of development. This has led to a substantial increase in the cost estimate. Given the short duration of the D&D phase, and the available budget, some D&D activities will be completed in the early construction phases of the project.

MMA management described the plan for staffing the construction project relative to the existing staff in NRAO. It was acknowledged that the large size of the MMA project burdens the NRAO staff and impacts ongoing NRAO activities. It was further acknowledged that some critical skills are in short supply. The MMA plan includes some redirection of existing staff, some curtailment of ongoing activities and some hiring of new staff.
A plan was presented for staffing and organizing the top-level management team of MMA, and for the redefinition of some of these job assignments.

Comments: The WBS, schedule and cost estimate for MMA construction, as presented, is a good start on a framework for further development of the MMA project. The WBS should be edited to support the 'rollup' of subsystem costs actually used by NRAO. The format for collecting the basis of estimate is sound.

The methodology used for estimating risks and identifying contingency funds is a useful technique and encourages detailed attention to risks. It can support the judgements that must be made by experienced project leaders.

The cost estimate of $368.5 million (FY1999) including $26 million for the D&D phase appears to be conservative. As the project design is further developed, it should be possible to identify cost reductions through design and production efficiencies, and value engineering.

In order to establish the scientific capability of the MMA, antenna systems must be commissioned and turned over to an operating entity as they are completed. Thus, the operating costs of the MMA will actually commence as the final years of the construction are carried out. The project should clearly identify the early costs required to establish the operational capability of the observatory in Chile and to operate a progressively larger array of antennas through the first period of large-scale scientific operations. Along with the D&D costs, the construction and early operations costs represent the total cost of the project.

It is essential that project and subsystem scope be fixed, through timely decisions on technical options, through resistance to potential improvements once system baselines are established, and through consistent and firm management to the project baseline.

The team must commit to designing and building to the agreed upon cost and schedule.

Project management tools and controls must be rapidly brought to completion and used throughout the project by all subsystem groups. Refining the cost estimate and schedule must be continued vigorously.

There do not appear to be any technical, cost or schedule showstoppers in the U.S. Reference Project, and risks can be managed by acceptable compromises.

The U.S. Reference Project schedule appears to be plausible. Options to shorten some production duration, such as antenna production, should be considered with a view to reducing project costs. Critical paths should be clearly identified and brought under the focus of project management. Some critical paths, such as SIS mixer production, should be examined for possible increments in staff and support, or examined for potential fallbacks, such as phased implementation of late system components.

The review committee continues to be concerned by the staffing requirements needed to successfully execute the MMA program. Building a robust staff to execute the project must be a very high priority. This should include vigorous recruitment outside the existing, experienced NRAO staff. Efforts to fill open positions should be pursued with urgency. Critical skill positions should be filled at market rates despite existing compensation schedules. NRAO should maximize industrial participation in fabrication activities in order to reduce the in-house staff requirements.

Unifying the MMA project team across the several NRAO sites, and redirecting dedicated and experienced staff from the operation of existing NRAO instruments to a highly paced, deliverable-oriented construction project will be a challenge. Such unification requires sharing goals in addition to developing a coherent flowdown of requirements and attention to interfaces and system tradeoffs that is widely understood. The MMA project is an overarching goal for the NRAO with great scientific promise.

Recommendations: NRAO should:

- Define and fill the top project management roles with additional experienced staff. An experienced project manager should be recruited. The definition, roles and responsibilities of the Project Director, Project Manager, System Engineer, Integration/Installation Manager, Project Scientist, and Antenna Task Leader must be made more definite and the persons occupying these roles must carry out these specific roles as full time assignments. Adequate staff must support these positions. There must be sufficient attention to defining the baseline, measuring performance, defining and controlling specifications, defining and controlling interfaces, testing and acceptance, definition and adherence to scientific requirements, and management and surveillance of contractor activity.

- Refine and fully develop the WBS, along with its integrated, resource-loaded schedule and cost estimate. The MMA project should seek design efficiencies and exploit opportunities for cost reductions. NRAO should establish the total project cost including the construction cost, and the cost of early operations up to first large-scale scientific operation.

- Complete the staffing plan to explicitly identify all of the personnel required to execute MMA construction

- Advance the Project Book to the maturity required so that it can be used as a definitive statement of the MMA configuration. The MMA configuration should be put under strict configuration control.

WBS 2: SITE DEVELOPMENT

Panel Members: G. Robertson, J. Baars, M. Roth

Findings: Mark Gordon presents a well-developed and detailed site development cost estimate in MMA 199902-010, a publication dated February 24, 1999. A supplement dated June 24, 1999 describes the changes to bring the estimate into agreement with Bob Brown's report *Construction Costs of the U.S. Reference Project,* dated May 1999. These changes primarily reflect the adjustments in the estimate developed by a Chilean Architectural/Engineering (A/E) firm, those required by scope changes (reduction in antenna pads from 145 to 130) and contingencies based on risk assessments consistent with other MMA WBS estimates. The Chilean firm selected to prepare the estimates is familiar with the region of the proposed MMA site and is highly regarded by the mining industry in that area.

The recommended staffing appears appropriate except for the lack of supervisory and administrative people to provide oversight and quality assurance for construction contractors. Most of this effort could be accomplished by Title III services from the design A/E firm; however, some additional MMA staff should be on-site during construction. One person is currently included in the June estimate.

The two-year construction period recommended by the Chilean A/E firm is appropriate for the project. Remote site construction should be accomplished in a single, continuous endeavor under one contract for efficiency and cost effectiveness.

The recently awarded contract to research alternatives to optimize the response to power surges caused by fast switching is commendable.

The major uncertainties affecting site development are: (1) which building and construction standards and codes will used; e.g., U.S., Chilean, or European and (2) agreements to define land use, permits, customs requirements, taxes, etc.

Comments: The amount and quality of the research accomplished in developing the site preparation estimate are impressive. The sole-source selection of a local A/E firm, familiar with the region and the type of construction involved was very appropriate. The response to each element of the charge to the panel is positive for WBS 2. Descoping the number of antenna pads from 145 to 130 resulted in significant cost savings. Other cost reduction possibilities are discussed in the cost estimate document.

Recommendations: NRAO should:

- Carry out additional research on code selections; e.g., placement of electrical and fiber optic cables (duct banks, direct burial, overhead).

- Reach early resolution of agreements with Chilean Government on land use.

- Consider flexibility in management staffing offered by including some family housing at OSF.

- Add staffing for Construction Quality Assurance on site (both MMA and local hire through Title III).

- Consider providing facilities during construction to accommodate transition to operations; e.g., shops, test equipment, etc.

WBS 3: ANTENNAS

Panel members: P. Swanson, J. Baars, R. Blundell, J. Hewitt

Findings: The 36 antennas were costed by NRAO by three independent methods: parametric cost curves, estimates from manufacturers and a grass roots, in-house design. There was good agreement between the manufacturers and in-house models. The parametric model was about 30% lower. Costs were presented for the antennas, antenna transporter and personnel for contract monitoring, testing and installation in Chile.
The antenna industry is large and well established. It should be possible to find a suitable company to manufacture the antennas. In fact, NRAO has four bids in response to an industry solicitation. The bids have not been opened at the time of the cost review so the review board was not able to evaluate this information.

The presentations by NRAO gave the board a strong feeling that the technical feasibility was high and that several examples of antennas of this class are in use throughout the world.

Comments: Written questions were submitted after the first presentation. The questions and answers by NRAO follow:

Is there enough time for testing the prototype antennas before the production antennas need to be built?

Answer: The schedule is optimistic. Any delay in delivery of the prototypes would eat into the 1.5 years allocated for prototype testing and possibly delay the production antennas. The backup position would be to delay the start of the production antennas and produce more antennas per year.

Are antenna fast switching and radiometry both necessary?

Answer: Yes. The 183GHz radiometry may not work, making fast switching necessary. The fast switching is a small cost increment in the total antenna cost.

Will holography give surface accuracy measurements necessary for 700 GHz?

Answer. Yes, it should work and has been demonstrated at other telescopes (*e.g.,* by the SMT at 38 GHz, and the SMA at 92 GHz).

The following comments were made during the review board deliberations in response to the specific charge made to the board:

The antenna concept is sound and technically feasible. The schedule is consistent with the tasks to be performed. However, late delivery of the prototype could delay testing and require a compressed delivery schedule. The production schedule of eight antennas /year is feasible. Some manufacturers apparently wanted a faster schedule. The eight/year rate is based on the overall project needs so it seems unlikely that the antenna production could ever delay the rest of the project. The management structure is adequate for the job. Key people have been identified. The task leader, who has excellent credentials, is committed to .75 time; three more full-time people were named.

The cost is probably somewhat conservative. The board felt there would be a high likelihood of success within budget and schedule. The 27% reserve is adequate and can probably be reduced after a fixed-price contract is signed and the first production model is tested. There were no obvious options to save dollars, although it was felt that there should be some clever way to exploit the large numbers of identical components to be made.

There were only two obvious descope options identified – reduce the number of antennas and/or reduce their size. It was strongly felt that the number of antennas should be reduced first, since they could be restored later. If the antenna size were reduced it would be a permanent reduction. It was also recommended that a relaxation of surface figure not be a descope option.

Recommendations:

- There was only one recommendation by the review board. The first production antenna (#3) is the most problematic since it will likely be made by a different process than the extensively tested prototypes. There should be some additional testing process to determine if the first production antenna meets all of the specifications.

WBS 4: RECEIVERS

Panel members: N. Erickson, R. Blundell, G. Chin, P. Swanson

Findings: The integration and test activities at the Tucson facility are pretty well thought out, although lots of hiring is needed, and we think the projected staffing level is low. A large labor force is available in the *[Tucson]* area for technicians, although the competition for labor may push up pay scales. There is a minimal staff in engineering at present.

The production schedule seems optimistic but possible, both at Tucson and at the CDL. The SIS wafer suppliers at UVa and SUNY seem reasonably secure. While the present production rates are erratic, only one good wafer is needed for each band above 100 GHz, and so this does not represent a large burden on the suppliers.

The majority of receiver work is on the receiver inserts at Tucson. This work is not overly dependent of actually receiving mixers from the CDL, and so the two groups do not need to synchronize their production plans. Testing of complete inserts is obviously dependent on receiving mixers and this task can not be permitted to fall too far behind, but sufficient schedule contingency is planned.

The engineering staff at CDL seems very tight for all of the SIS design work, but may be adequate for the job. There is a total reliance on 2 key people, which seems a high risk.

Comments: The 183 GHz water vapor radiometer (WVR) needs a place in the focal plane; its only logical location is in the dewar as another insert. Eliminating one receiver band would permit this without other major disruption. There appears to be no space for the 22 WVR GHz feed.

Support for astronomy operations at the 12m is a longstanding obligation of the Tucson group, although much less of a burden as time goes on. If continued, even at a low level, this is likely to conflict with MMA development. Is a phase out of support *[for the 12m]* practical?

The required production rate of SIS mixers at the CDL is 3 times the highest rate achieved at present. While a major step up, this seems within a range that is achievable without major disruption.

The cost of mixers averaged over the bands is about $48K each while for LO multipliers the cost is about $10K each. These parts are sufficiently similar in both machining difficulty and assembly that we would expect prices less than a factor of two apart. This does not provide a high level of confidence in the budget estimates, although the average may tend to work out. By comparison, the cost of HFET amplifiers seems exceptionally low at about $7K each, although this is an area where the CDL has considerable production experience and infrastructure. These costs should all be reviewed on a common basis of assumptions.

One complete receiver band is required simply to cover a few GHz near 70 GHz. An HFET receiver could probably be built to cover 75-116 GHz with fully acceptable performance, and a complete band could then be saved with the sacrifice of only 8 GHz *[i.e, the range 67-75 GHz]*.

Recommendations:

- The critical nature of the SIS design effort seems to require an additional experienced receiver engineer for the CDL.

- A second test dewar is needed at Tucson to keep up the production testing of receiver inserts, particularly if there are any production delays at the CDL.

- An extra test dewar set is needed at Chile as well, since receiver inserts will be sent to the site without integration into the full receiver dewar.

- A descope option to eliminate the 31-45 GHz band may help reduce a lot of engineering effort, since it helps to fit all the parts within the dewar by eliminating a large feed horn. This band also has a complex (and unique) IF system, although receiver itself is simple.

- The decision on whether to use HFET vs. SIS receivers in the 90-116 band should be made very soon. All of the data needed to make this choice would appear to be available without further testing. Since the decision is based upon the suitability of using the receivers for total power continuum measurements, a better (cost-effective) alternative might be to dedicate a single antenna equipped with bolometers to the task.

- Eliminating 67-75 GHz, and redefining a new 75-116 GHz band using HFETs could eliminate one receiver in an apparently very cost effective descope.

- The project should look into the use of MMIC amplifiers for all of the HFET bands. Wafers with all of the needed designs will go out for fabrication soon, and the cost to NRAO would be about the same for complete amplifiers on MMIC chips as for discrete HFET chips. There should be no loss in performance, and significant cost savings seem possible, given the much-reduced complexity of MMIC amplifiers.

- A relaxed specification on receiver performance as it applies to the worst case of individual elements, will not hurt the overall array, as long as the averaged noise specification is met. This will greatly enhance the yield. This applies to specifications on IF bandwidth, SSB/DSB operation and receiver noise temperatures. For early operations, almost any receiver performance may be accepted.

WBS 5: LOCAL OSCILLATOR

Panel members: D. Hartill, G. Chin, N. Erickson

Findings: The local oscillator system for the MMA is based on similar systems in use at the VLA and at the 12-meter telescope at Kitt Peak. The central Hydrogen Maser frequency standard drives a series of frequency synthesizers to provide the needed reference frequencies, which are then transmitted over optical fibers to the individual antennas. At each antenna, these reference signals are used by a synthesizer to generate four driver frequencies which are then used by individual driver-multiplier units to provide the nine local oscillator signals for the receiver front end mixers. The MMA local oscillator system extends the frequency range by a factor of two, compared to the present 12m system.

Comments: Conventional aspects of the design including the reference oscillators seem to be well in hand.

The cost estimates presented to the Committee appear to be adequate for a well managed project. However, by way of comparison, the unit cost of the high frequency multipliers of the local oscillator system appear to be at least a factor of two less than the unit cost of the mixers for these frequencies. Since the diodes are of similar difficulty to manufacture compared to the SIS mixers, it is difficult to understand this difference in estimated cost. Given the difficulty of the design of the high frequency multipliers, a focused effort is needed to provide operational devices in time for the production of the local oscillator systems for the individual antennas.

The interfaces to other parts of the receiver system seem to be ill defined. For example, multipliers for the LO will leave the CDL as tested components but will be untested in the actual configuration that they will be used in the receiver modules.

The RF aspects of the local oscillator system are near the state of the art. As such, the availability of trainable engineers and technicians with sufficient technical expertise is a question. This may be a cost issue in terms of premium salaries.

Because of the difference in unit pricing noted above, there is a significant possible call on the contingency assigned to this category.

Recommendations:

- To avoid a potential major cost growth in the local oscillator system, especially in the high frequency bands, a full time person should be assigned to lead this development.

- NRAO should establish agreed upon milestones to monitor progress on the development and production of the local oscillator system, especially the high frequency components.

- NRAO should explore the use of outside consultants to assist in the development of the challenging high frequency multipliers.

WBS 6: IF

Panel members: A. Whitney, D. Hartill

Findings: The design is straightforward and there is little technical risk.

Cost estimates are based primarily on commercial components such as amplifiers, mixers, and filters. There is adequate contingency.

There is a plan to test IF electronics in a low-pressure chamber to ensure adequate thermal management.

Comments: Total-power stability is major concern; needs to be better than SIS receivers, which are likely to limit the stability.

Thermal noise is $2x10^{-4}$ in 2 ms with an 8 GHz bandwidth. The total power requirement for "on the fly" mapping is being studied. A few parts in 10^{-5} in 10 minutes may be required; obtaining this stability may require temperature control of the electronics.

Recommendations:

- NRAO needs to measure receiver total-power stability in order to determine how stable IF electronics need to be in order not to limit the overall performance.

WBS 7: FIBER OPTICS

Panel members: B. Snavely, T. Kirk, A. Whitney

Introduction: There are three separate fiber optic subsystems in the U.S. Reference Design Project:

- Intermediate Frequency (IF) Data Channel,
- Local Oscillator (LO) Distribution System, and
- System Monitoring and Control.

Dan Edmans presented a clear description of the three subsystems using diagrams that had been provided to the Panel. These schematic diagrams reflected several important decisions, i.e. assumptions, made to permit costing of the Reference Design Project. These assumptions may change for the as-built system. The most important of these decisions are that the IF system is digital, as opposed to an analog alternative, and that the LO system is electronic, as opposed to a photonic alternative.

Findings: Based on nearly ten years of relevant technical experience Edmans demonstrated a good understanding of the FO system requirements and alternative technologies for meeting the requirements. He appears well well qualified to lead the FO effort.

We understood that detailed specifications for the interfaces of the FO system with other parts of the MMA system will not be available for, at least, another month. Nonetheless, Edmans has enough information on system requirements to block out the subsystems and choose among alternatives for implementation.

All three subsystems are to be designed at NRAO using commercial components (lasers, amplifiers, multiplexers, transmitters, and receivers). Estimated costs are based on current vendor prices with price projections based on historical experience with similar components. Edmans used particular components from his complete vendor files as examples to trace the derivation of costs used in the cost documents. It should be noted that the components to be used are developed for the highly competitive communications industry, which will assure consistency of availability.

Technical risks for all three subsystems appear to be minimal. Cost risk is associated with the validity of the price models used to project future costs of components. Since there are multiple vendors for critical components the committee felt that the pricing models and contingencies appeared to be reasonable.

The LO system is less well defined than the IF system. Consequently, the technical risk for the LO system, although not high, is higher than that for the IF system. We understood that a decision to use the photonic LO system in the as-built system could, potentially, double the cost of the LO distribution system with respect to the cost estimated for the U. S. Reference Project.

Edmans felt that the planned level of support for the FO effort for duration of the reference project is adequate in terms of facilities and staff. We understood that present staffing is 1 ½ FTE, with the ½ person being a visitor until October 1999. Staffing planned for the construction period, FY ’00 to FY ’07, totals 31.8 engineering FTE years and 45 technician FTE years.

In conclusion, the committee was favorably impressed with Edmans’ grasp of the system and its requirements, his organization of material and documentation, and his confidence and enthusiasm. The FO system presents relatively low technical and cost risk as described for the U. S. Reference Project.

Recommendations:

- The committee recommends that documentation of the interfaces for the FO system be completed in a timely manner.

- The committee encourages the timely demonstration of a functioning LO design since the achievement of all the design requirements is critical to the success of the MMA.

- The committee recommends that appropriate engineering resources be maintained to assure timely demonstration of the performance of the baseline LO distribution system.

WBS 8: CORRELATOR

Panel members: D. Hartill, A. Whitney

Introduction: The correlator system consists of three subsystems, which are referred to as separately named items in the discussion below:

- *Samplers*, which convert the analog IF signals to sampled and digitized replicas
- *FIR filters*, which perform a digital filtering operation on the output of the samplers
- *Correlator*, which performs the actual digital correlation operations

Findings: The MMA correlator is being designed and constructed in two stages. The first stage is to build a test correlator based largely on the existing GBT correlator design. The final correlator will be a further evolution of the basic design incorporating a new VLSI custom correlator chip, and scaled up to meet the demands of the full MMA system.

The test correlator will sample an 800 MHz-bandwidth signal at 1.6Gsamples/sec, which are multiplexed into 16 100-Mbit/sec subchannels for correlation. The test correlator is already well underway and is expected to be completed and tested by the end of 1999.

The operational correlator will sample a 2 GHz bandwidth from each receiver of each antenna at 4 Gsamples/sec, which is then divided into 32 subchannels of 125 Msamples/sec before correlation. A new VLSI chip will be designed for this correlator, each chip to have 4096 lags operating at 125 MHz. NRAO looked into several options for chip design, including gate arrays as well as full-custom chips. Though a gate array can be designed that is functionally acceptable, the power dissipation of each such chip is expected to be ~9W; this significantly exceeds allowable dissipation in the final system, which must incorporate many thousands of these chips. A full-custom design based on a 0.25 μm process, on the other hand, is expected to dissipate <2W, and is likely to operate at the lower target voltage of 2.5V.

At least two sources of design for the new full-custom correlator chip were investigated. UVA has a chip design lab and is interested in the job, but would use ‘canned’ libraries for much of the design and might not have good continuity of design personnel (i.e. graduate students), a situation judged to be a potential problem. The other possible source is to employ the personal consulting services of Mr. John Canaris (formerly of the NASA MRC chip design center at UNM, and currently employed at Phillips). Mr. Canaris is probably the world’s pre-eminent expert in correlator-chip design, having designed several chips in wide use today, including the chip used in the GBT correlator. Discussions with Mr. Canaris suggest that first prototypes could be available for testing as early as 4Q 2000. NRAO will supply Mr. Canaris with the necessary equipment and hardware for design. Mr. Canaris would also subcontract with standard industry sources for fabrication, packaging and testing. Test vector generation will be jointly done with NRAO.

The FIR filter board design appears to be well advanced and adequate. The FIR filter provides a 128-tap filter at the 1 GHz output bandwidth, with more taps at smaller bandwidths.

The development of the 4 Gsample/sec sampler is proceeding more slowly than the rest of the project. This sampler is required to have at least 3 bits/sample (preferably 4) and must meet extremely stringent specifications imposed by high-quality interferometry. Only a preliminary specification exists, and one person at Tucson is devoting an unknown amount of time to this item.

The total correlator system is expected to dissipate as much as 30 kW of power. The expectation is that a forced-air ambient-temperature cooling system (~ -2°C) in Chile will be sufficient for cooling, though active refrigeration may have to be considered if power consumption is significantly greater than the design target.

The various interfaces both to and from the correlator, as well as inside the correlator, are fairly well defined, though not complete.

Comments: The correlator design appears to be entirely adequate for the tasks required of it.

The correlator cost is credible, apart from the potential significant uncertainties in design costs of the full-custom correlator chip.

The proposed schedule is realistic, provided the correlator chip is available.

The functional specification of the new correlator chip design appears to be mature and well thought out.

The cost and schedule for the development of the new correlator chip is heavily dependent on the availability of Mr. Canaris. Should Mr. Canaris not be available as anticipated, both the cost and schedule for the chip development are likely to be heavily affected. If it becomes necessary, for example, to contract with industry for the design, the development cost could balloon to many times the current projected costs.

The FIR filter design is mature and well advanced and appears to be adequate to meet the necessary requirements.

The lack of focus on sampler development is somewhat worrisome. Adequate commercial samplers are not known to be available and development costs are really unknown. Status of the current sampler development at Tucson is not known and there is little indication that management is concerned about this situation. Projected costs for samplers may be significantly low.

Recommendations:

- The sampler development must be given much higher priority and adequate resources assigned. Budget estimates must be carefully re-examined.

- A realistic correlator-chip development and production cost/schedule utilizing standard commercial services should be developed so that the extent of cost/schedule impacts costs is known should the services of Mr. Canaris not be available.

WBS 9: COMPUTING

Panel members: S. Grandi, T. Kirk, J. Hewitt

Introduction: The Computing subpanel met with Brian Glendenning, the computing subsystem manager for MMA. He discussed with the subpanel a number of topics related to computing efforts for the MMA. Brian's personal experience is appropriate for his role in the MMA as he has spent many years in professional computing work linked to radio astronomy. Brian was frank and forthcoming in his views about the MMA computing project and in his answers to subpanel questions and inquiries. He was knowledgeable in the computing areas germane to the needs of the MMA computing project.

Findings: MMA Computing has two main branches: controls software and image processing. There are other, smaller efforts in archiving and "dynamic scheduling" of the array but these were declared not to impact the MMA computing effort significantly. Brian stated that the controls software area was well in hand and would require no major advances in the state of the art. He would be able to build on existing controls software in use by NRAO at two operating facilities, the VLA and the VLBA. The MDC also has two operating millimeter arrays whose controls are germane and applicable to the development of MMA software. It was stated by Brian that the MMA correlator will be the most complex part of the MMA controls system but that it will be simpler than the existing VLBA correlator; as a result, this is not considered an area for software development concern. The subpanel concurred in this assessment but did not have the ability to determine whether the needed effort would be available to accomplish the goals in a timely way.

The second key area of software development for MMA is the creation of an image processing software "pipeline" for use by the radio astronomer users of the MMA. Such a pipeline would accept raw data and automatically produce reduced, scientifically useful, images. In this area, the level of commitment of the MMA project to user-related computing goals and software products was not definite and the path forward not well defined. While many of the image processing techniques and computing algorithms necessary for this pipeline already exist as part of existing software packages (NRAO's AIPS and AIPS++ packages, in particular), new image processing software is required to fully realize the potential of the MMA (*e.g.,* to generate mosaic images).

Research on and development of these new image processing techniques is being done by a separate group within NRAO, the AIPS++ Project, which is not part of the MMA project. Brian asserted that he is responsible for the development of MMA-specific data processing but not for post processing of general image data (such as mosaicing). However, the subpanel saw no evidence of a commitment by the independent AIPS++ group to meet the needs of the MMA or any project management materials such as a task list or time line.

Brian stated that he would welcome the creation of an "MMA Computing Requirements" document that would provide a definite and clearly defined scope for his project efforts. Such a requirements document does not exist at this time. A U.S. Computing Advisory Committee, encompassing both NRAO and user members, exists but was seen by Brian as providing little useful advice to him in carrying out the project; meetings consist mainly of status updates to the Committee on Brian's project progress. Brian also stated that he maintains a connection with the MDC but that this does not provide a close dialog on user computing requirements.

We find that the pipeline and archiving plans and budgets are based on parameters that have not been recently addressed in a scientific context. It appeared to the subpanel that most of the information on potential MMA user computing needs now dates back to a meeting on this subject held in 1995. There appeared to be a lack of concurrence on the part of the MMA project as a whole to the level of commitment that the project should make to the development of user tools. This uncertainty was reflected in Brian's comments concerning his defined project scope in this area.

There was no written computing plan for the project although a work breakdown structure for the software tasks (containing about 40 tasks) was presented and a basic staffing chart for the period 1999 – 2008 was shown. A basic schedule chart for the execution of the WBS tasks has been developed with several appropriate, high-level milestones, but this schedule has not been resource loaded and there were few lower-level details to support the task schedules. When the subpanel questioned him on this issue, Brian indicated that he had plans for these items in his head but that they had not been formalized on paper.

Comments: The subpanel found that the plans for the MMA controls software are based on previous experience and that the budget for this part of the software seems to have been reasonably well planned and of relatively low risk. The scheduling and image pipeline software seems much less well planned and cost-estimated, based not only on the stated assumptions but also in taking account of the significant ambiguities in the current scope of the computing effort. The development of the image pipeline software is of significantly higher risk than the controls software. The subpanel did not see an effective connection between the MMA Computing Project and future MMA users' needs. Establishing and maintaining this connection will be vital for the overall success of the MMA as a user facility. In this regard, the creation of a "MMA Computing Requirements" document to clearly set out the scope of the MMA Computing Project effort will be essential. In addition to the computing requirements document, an "MMA Computing Plan" needs to be created and maintained. This plan will be essential for tracking the progress of the Computing Project and the completion of project activities on-time and on-budget. Specifically, among other things, the data rate from the correlator into the archive, currently specified as 1MB/sec, needs to be re-addressed from the scientific requirements point of view.

Also, the expressed MMA project goal of producing images from a pipeline as the standard observing output product needs to be re-addressed from the scientific requirements and the parameters of the goal quantified. What quality of images needs to be maintained? What percentage of the observations are required to result in scientifically useful images from the pipeline? These and other questions should all be captured in the MMA Computing Requirements document and addressed in the MMA Computing Plan. It has already been demonstrated many times in large, data-intensive science projects that the project's software development is found, at the point of facility turn-on, to be far behind the needed level of performance and unable to meet the needs of the facility users. In recent years, a planning and project-tracking discipline has evolved within the MMA project to address this problem, and that discipline should be incorporated in the MMA Computing Project, starting now.

The subpanel found worrisome the lack of any formal arrangement between the MMA project and the AIPS++ project for the accomplishment of tasks necessary to the scientific productivity of the MMA. Given the long, drawn-out, history of AIPS++, we feel that a firm commitment, backed by NRAO management, should be made to the MMA project by the AIPS++ project and that the AIPS++ contributions be incorporated into the project management formalism of the MMA project.

Recommendations:

- We recommend that the MMA project create an "MMA Computing Requirements" document (MMA-CR) that reflects a concerted effort to contact and understand scientific and user requirements for data, images, operations and other computing capabilities. The MMA-CR should be maintained as a living document.

- We recommend that an "MMA Computing Plan" be formulated and maintained, based on the MMA-CR and embodying the mission of the computing project, and its organization, staffing, budgets, schedules, milestones and computing products. The hardware and software products needed should also be part of this plan.

- We recommend that a formal commitment be made by NRAO management to the MMA project to assure that sufficient resources from the AIPS++ project are provided to meet the scientific requirements of the MMA facility.

- **WBS 10: SYSTEM ENGINEERING AND SYSTEM INTEGRATION**

Panel members: R. Steining, P. Goldsmith, J. Peoples, B. Snavely, D. Tenerelli (participated by phone)

Introduction: In the task definition for the committee, system engineering and system integration were considered as a single function. The committee, however, consider these to be separate and will consider them so in the discussion that follows. We view system engineering as a management tool and system integration as a task.

Findings: The scope of the system engineering function in the WBS is 1½ FTE. The leader has responsibilities elsewhere and devotes only one-half of his time to the task.

The primary function of the systems engineer is to assemble and manage technical specification documents, error trees, and interface control documents. It should be emphasized that the systems engineer does not generate the information in these documents but rather collects and organizes the information for the benefit of the management of the project.

At this time the technical specification documents and error tree, and flowdown to the subsystems, are incomplete. In particular, the interface control document for the antenna is incomplete. Other interface control documents are in a very preliminary state. At this time specifications are traceable to project memos, and not to an integrated error tree.

The scope of the system integration task is the assembly, installation, and testing of project hardware. This task is to be carried out at sites in the U.S. and in Chile.

The plan for integration and testing is based on prior NRAO experience with similar projects. The MMA project intends to carry out the U.S. portion of this function at existing NRAO sites. The systems integration group plans to supply four FTEs at these sites. Additional staff will be provided as needed by the project groups responsible for the hardware.

The plan for system integration in Chile parallels that for the U.S.

The project has not provided a plan or cost estimate for the implementation of a laboratory infrastructure in Chile that is a necessary element for system integration in Chile.

Comments: It was clear to the committee that project management understands the need for the systems engineering function as described above. The committee was pleased to find that the necessary information is readily available within NRAO for implementation of this function. The staff members presently performing this function have multiple responsibilities. Staffing needs to be increased to provide the level of effort necessary for the function.

The committee was pleased with the depth of the understanding of the scope of the system integration task. We do not anticipate that the project will have any difficulty in preparing more complete installation and testing plans. The NRAO has ample prior experience in the installation and testing of similar equipment.
We feel that the plan for integration and testing at U. S. facilities is adequate and that the similar plan for Chile is also adequate provided that the infrastructure and staffing in Chile is available at the time it is needed.

Recommendations:

- The project should separate the system engineering and system integration functions.

- The project should hire a full-time, professional systems engineer and support this function with appropriate staff.

- The project should develop a top-level project requirements document in a timely manner. The requirements for all systems should be traceable to this document.

- The project should develop a verification and testing plan for each system, and each division leader should identify an individual to carry out this function.

- An implementation plan for site technical and support infrastructure for Chile should be developed during the D & D phase of the project.

WBS 11: CALIBRATION and IMAGING

Panel members: A. Rogers, S. Grandi, R. Stiening

Findings: Fast slewing is needed to overcome 1/f noise for the single dish continuum measurements using raster ("on the fly" mapping) scanning of the dish and for atmospheric calibration at the shortest wavelengths. Studies indicate that specified antenna slew rate is high enough that a nutating subreflector should not be needed.

The single dish total power performance is only critical for continuum imaging. There should be no problem with spectral line imaging.

A 183 GHz 64 channel WVR is included (and is budgeted) within the dewar to provide simultaneous WVR measurements with a beam within 10 arcminutes of the observing beam. Exact frequencies/details are not yet decided.

The 25 micron antenna specification was originally based upon image quality requirements at 1 mm; hence, the subsequent decision to include submillimeter wavelengths in the MMA project scope did not impact the antenna specifications.

There is currently no plan for conventional vane calibration, but this can easily be added.

Comments: The technical feasibility and schedule are fine and cost estimates are well-developed with adequate contingency.

If a nutating subreflector is needed like those on other existing antennas, this should only cost 50k$ per antenna and is within the contingency.

The project feasibility is very good. There is very little technical risk at 1 mm and longer wavelengths. Even if WVR phase calibration works poorly there will still be a large amount of time at which observations can be made at 1 mm. At 230 GHz the atmospheric phase noise on the Chajnantor site is typically less than 1 radian on a 1.6 km baseline for 43 percent of the time.

Recommendations: NRAO should:

- Analyze and summarize satellite phase monitor and WVR data from the site in order to decide on the details of the 183 GHz WVR.

- Carry out early tests of the total power stability using the first antenna at to VLA site, in order to decide whether a nutating subreflector will be needed.

- add a conventional vane calibrator for system temperature measurement and engineering tests in addition to the hot/cold calibrator at subreflector. This addition should not add significantly to the cost.

- Improve plans for calibration imaging activities during pre-operations.

Appendices

Appendix 1: MMA Cost Review Participants

Dr. John Peoples (Fermilab), Chair
Dr. Paul Swanson (NASA JPL)
Dr. Rae Steining (UMass 2 Mass Project)
Mr. George Robertson (Fermilab)
Dr. Thomas Kirk (BNL)
Dr. Jacqueline N. Hewitt (MIT)
Dr. Donald L. Hartill (Cornell University)
Dr. Miguel Roth (Carnegie Institution)
Dr. Ray Blundell (Center for Astrophysics SMA Project)
Dr. Paul Goldsmith (Cornell University, NAIC)
Dr. Neal Erickson (University of Massachusetts)
Dr. Ben Snavely (AIP)
Dr. Alan Whitney (Haystack Observatory)
Dr. Alan Rogers (Haystack Observatory)
Dr. Steven Grandi (NOAO)
Dr. Gary Sanders (CalTech Ligo Project) – MMAOC
Dr. Jaap Baars (UMass LMT Project) – MMAOC
Dr. Gordon Chin (NASA) – MMAOC
Dr. Domenick Tenerelli (Lockheed Martin) – MMAOC

Appendix 2: PROPOSED AGENDA

MMA COST REVIEW
Charlottesville VA
July 7, 8 ,9, 1999

<u>Wednesday, July 7:</u>

8:00 AM	**Executive session:** Welcome and Charge	R. Eisenstein (NSF)
8:15 AM	**Open session:**	
	Welcome and Introductions	R. Eisenstein (NSF)
8:30 AM	The MMA as a User Facility	P. Vanden Bout
8:45 AM	Science Requirements: MMA Discovery Space	A. Wooten/G. Blake
9:15 AM	Technical Requirements for the MMA:	
	The U.S. Reference Design	R. Brown
10:00 AM	Methodology for Developing and Costing	
	The U.S. Reference Project	R. Brown
10:30 AM	Coffee Break	
11:00 AM	**Costing Level-1 WBS Tasks**	
	Project Administration	R. Brown
11:30 AM	Site Development	M. Gordon
12:00 PM	Antennas	P. Napier
12:30 PM	**Executive Session**	
12:45 PM	Lunch (at NRAO)	
1:15 PM	**Open Session**	
	Costing Level-1 WBS Tasks (continued)	
	Receivers	G. Moorey/J. Webber
1:45 PM	Local Oscillator System	J. Webber
2:15 PM	IF System	W. Brundage
2:45 PM	Optical Fiber	D. Edmans
3:15 PM	Correlator	J. Webber
3:45 PM	Coffee Break	
4:15 PM	**Costing Level-1 WBS Tasks (continued)**	
	Computing	B. Glendenning
4:45 PM	System Integration	D. Emerson
5:15 PM	Calibration and Imaging	A. Wootten
5:45 PM	Parametric Cost Summaries	R. Brown
6:00 PM	**Executive Session (30 minutes)**	
7:00 PM	Dinner (for all meeting attendees)	

Thursday, July 8:

8:00 AM	**Executive session:**
8:30 AM	Morning Breakout Sessions:
	Project Administration
	Antennas
	Fiber Optics System
	Local Oscillator
	Calibration and Imaging
11:30 AM	**Executive Sessions:** Reviewer discussion and 1-page summary writing
12:30 PM	**Executive Session (all; working lunch at NRAO)**
1:00 PM	Afternoon Breakout Sessions
	Site Development
	Receivers
	System Integration
	IF System
	Computing
	Correlator
4:00 PM	**Executive Sessions:** Reviewer discussion and 1-page summary writing
5:00 PM	Breakout review group meetings with MMA Division Heads
6:00 PM	Dinner (for all attendees)

Friday, July 9:

8:30 AM	MMA Division Heads' responses to variance reports
9:00 AM	**Executive session:**
	Review and refine written reports for each WBS Level-1 area
11:00 AM	(time approximate)

Exit discussions begin with AUI/NRAO management and MMA Heads

12:00 PM	Working Lunch
1:00 PM	(time approximate) Exit discussions with AUI and NRAO.
	Writing assignments for final report to NSF.
3:00 PM	Adjourn

The Review Process

The panel met with the MMA project Staff and representatives of the NSF and AUI. The NSF participants were Dr. Robert Eisenstein, Director of Mathematical and Physical Sciences, Dr. Hugh Van Horn, Head of the Division of Astronomical Sciences, and Dr. Robert Dickman, Coordinator Radio Astronomy Facilities Unit Division of Astronomical Sciences. Dr. Paul Gilbert of the AUI board attended the review presentations and Dr. Riccardo Giaconni, the newly elected President of AUI, joined the review on the afternoon of the second day. Dr. Paul Vanden Bout, Director of NRAO, also participated in the review. Observers from several countries that are considering participating in the ALMA project also attended the formal presentations and some of the breakout sessions. (ALMA is a proposed international project with U.S. participation, which has the same broad scientific goals as the MMA.)

The formal presentations and the breakout session were organized around the project Work Breakdown Structure (WBS). Each WBS element corresponds to either a subsystem or an integration task. The formal presentations were completed on the first day and the breakout sessions were completed on the second day. Except for Panel executive sessions the meeting was open to all who wished to listen. The presentations for the MMA project staff were excellent and the staff members who participated in the breakout sessions were very responsive to the needs of the Panel. The MMA project staff were very helpful throughout the three days of the review and this made it possible to absorb a lot information about the project in a short time.

There was a formal presentation for each WBS element. Following the completion of the formal presentations the Panel met in executive session and discussed each presentation. It then divided itself into eleven overlapping subgroups, one for each WBS element; these subgroups prepared a set of questions for the MMA project staff which were given to the MMA staff on the evening of the first day or the following morning. After a brief executive session on the morning of the second day, the subgroups met with the appropriate members of the MMA project Staff in breakout sessions corresponding to each WBS element. Following the breakout session each subgroup prepared a written summary of its findings in the form of several overhead transparencies. Each subgroup added comments and recommendations that were responsive to the charge to its findings. The full cost review Panel met in executive session at the close of the second day in order to hear the breakout groups present their findings, comments and recommendations.

The findings, comments, and recommendations of each breakout session were presented to the full panel in the form of overhead transparencies during an executive session on the morning of the third day. These were subsequently revised and given to the MMA Project Director for distribution to the project staff in order to allow them to correct misunderstandings and errors. Following the executive session, the leaders of each breakout group met briefly with appropriate members of the MMA staff and reviewed the corrections and clarifications in their reports.

The summary for WBS 1 was discussed with the full cost review Panel, in executive sessions.

Several members of the Panel, John Peoples, Gary Sanders, and Rae Stiening, briefed Dr. Giaconni and Dr. Vandenbout after dinner on the second day in order to apprise Dr. Giacconi (who was unable to come to NRAO until late in the second day) of the findings which followed the second-day executive session.

The Panel held a closeout session with the MMA project staff following the executive session third day. During this meeting, the Panel presented its findings, comments, and recommendations to the MMA project staff, the representatives of the NSF, and the representatives of AUI and senior management of NRAO.