MEMORANDUM TO MEMBERS OF THE NATIONAL SCIENCE BOARD

SUBJECT: Additional Budget Authority to Support Construction of the Rebaselined Atacama Large Millimeter Array (ALMA) Project, Associated Universities Inc. ($176,970,000; award extended an additional 24 months, through FY 2012).

The Atacama Large Millimeter Array (ALMA) is a bold, transformational, and complex global radio astronomy project now under construction near San Pedro de Atacama in the Altiplano of the Chilean Andes. ALMA's array of 50 antennas, with the collecting area of a 85-meter diameter telescope and the clarity of vision of the Hubble Space Telescope, will open new windows on the birth of stars and planets, of galaxies like our own, and of the Universe itself. Beginning as three projects independently conceived in North America, Japan and Europe, ALMA has evolved into the world's first truly global astronomy project.

The original baseline for ALMA dates back to 2002, prior to the formalization of partnerships with Europe and Japan. Activities initiated 18 months ago to put in place a final project baseline are now complete. The new baseline, which requires a significantly higher cost to complete in spite of reduced scope, has been extensively reviewed and verified, both externally and internally, as to cost, schedule and scope. NSF has put mechanisms in place to ensure that this complex international project will proceed to completion within this new budget and schedule.

This memorandum seeks the approval of the National Science Board (NSB) for a proposed amendment to the award from the Division of Astronomical Sciences (AST) to Associated Universities, Inc. (AUI) under Cooperative Agreement AST-0223851 and its successor instruments for the management and operation of the National Radio Astronomy Observatory (NRAO) by Associated Universities, Inc. (AUI). The purpose of this amendment is to increase the budget authority for construction of ALMA by a total of $176,970,000 above the currently authorized level of $344,130,000 (NSB-02-14; NSB-02-114); of this amount, $154,980,000 represents new funding to complete the U.S. share of ALMA construction, an increase of 45%. The duration of the award will also be extended by a further 24 months, through September 30, 2012.

BACKGROUND

In the United States, ALMA began as the Millimeter Array (MMA). With the technical feasibility of millimeter interferometry having been demonstrated in the 1980s, in 1990 NRAO astronomers proposed an array of 40 8-meter diameter antennas, operating at millimeter wavelengths with baselines as long as 10 km. With sensitivity far in excess of any existing millimeter-wave array and angular resolution comparable to that of the Hubble Space Telescope, the proposed MMA would open new windows on the early Universe. It could image the structure of nearby planetary systems as they formed, trace the formation and early evolution of stars, and see galaxies like our own Milky Way to the edge of the Universe and back to the time of their formation. Because of its transformational nature and stunning scientific potential, the MMA was a high priority of the National Academies' 1990 Decadal Survey in Astronomy.

Funding for the MMA began with a four-year MREFC-funded Design and Development (D&D) phase approved by the NSB (NSB 98-96; NSF 01-79) at a total funding level of $32 million for FY 1998 through FY 2001. In approving the D&D phase of the MMA, the NSB directed that international partners be found who were willing to assume at least 25% of the total cost. Because of the compelling scientific opportunity afforded by a large millimeter-wave interferometer, planning was already taking place in Europe and Japan during the late 1990s. ALMA emerged from the coalescence of U.S., European, and Japanese array concepts, and the 2000 Decadal Survey accorded the completion of ALMA a high priority.

By 2002, ALMA had evolved into an array of 64 12m diameter antennas with baselines as large as 15km, equipped with four receiver bands including one to cover the submillimeter-wave atmospheric window

centered around 650 GHz. ALMA's evolution into an instrument with significantly greater collecting area than the original MMA was driven in part by the discovery in the early 1990s of young, molecule-rich galaxies at surprisingly large redshifts; systematically imaging still more distant new-born galaxies would clearly require both more and larger antennas than had been envisioned for the earlier MMA design. The addition of submillimeter capabilities opened access to a rich spectroscopic domain in the interstellar medium of our own and other galaxies, as well as to the far-infrared thermal signature of interstellar dust clouds. However, embedding submillimeter capabilities into the specifications for the array also required antennas with extremely high surface accuracies as well as a high, arid site flat enough to encompass antenna configurations extending over the largest baselines. The site requirements were satisfied beautifully by the 5000-m high Llano de Chajnantor in the Chilean Altiplano near the village of San Pedro de Atacama.

The FY 2002 budget proposed for NSF included $9 million for a fifth year of ALMA D&D, and in August, 2000 the NSB authorized the expenditure of these funds (NSB-01-128). However, the FY 2002 Appropriations Bill signed by the President contained "…$12,500,000 for initial construction of the Atacama Large Millimeter Array (ALMA) radio telescope." In January 2002, the NSB authorized expenditure of the additional $3,500,000 appropriated above the FY 2002 Budget request, as well as the transition of ALMA from D&D to initial construction activities. The total estimated construction cost of the 64-antenna array was $552,000,000 in FY 2000 dollars; using projected OMB deflators, the U.S. share of this cost in actual-year dollars was estimated to be $344,100,000. With a construction start in FY 2002, completion of the array was to occur in 2011.

The early ALMA D&D partnership was essentially a set of parallel, though highly-coordinated, R&D efforts, and it was recognized that if the project were to move into construction, a much tighter project with a simpler partnership interface would be required. The beginning of ALMA construction in 2002 and postponement of Japanese collaboration until 2004 led to a bilateral ALMA partnership between North America (led by NSF) and Europe (led by the European Southern Observatory (ESO)), with the signing of an agreement in February 2003 by the Director of NSF and the Director General of ESO. Later that summer, a Memorandum of Understanding (MoU) was signed by the Director of NSF and the President of NRC Canada, finalizing the terms of Canada's partnership with the US in ALMA. AUI/NRAO serves as the North American Executive for ALMA, ESO as the European Executive.

Japan entered ALMA in September 2004 under the provisions of an MoU signed by the Director of NSF, the Director General of ESO, and the Director of the National Institute of Natural Sciences of Japan. Under the terms of the MoU, the National Astronomy Observatory of Japan (NAOJ) will enhance the original bilateral project by contributing a compact 16-element array of 12 m and 7 m antennas, two additional receiver bands for the full array, as well as a proportional fraction of site and operations costs. Operating in conjunction with the main array of 12m antennas, the compact array will dramatically improve the image quality of spatially extended objects, significantly extending ALMA's scientific capabilities.

As ALMA host country, Chile will receive 10% of the available observing time in exchange for contributing the land on which the array is situated, guaranteeing long-term access to the site, and providing certain immunities and exemptions from import duties to AUI/NRAO and ESO under Chilean law and international treaty, respectively.

Financially, the ALMA partnership is based on the concept of deliverables of fixed value; the completion of tasks and contributions assigned to each partner and not their actual cost constitutes the financial basis of the project. High-level project policy and oversight is provided by the ALMA Board, established in 2003. The Board consists of 10 members, 4 from North America, 4 from Europe, 1 from Japan, and 1 from Chile. The North American membership is made up of one representative each from NSF, NRC Canada, AUI and the North American astronomical community. The Board exercises broad managerial oversight for the project, and provides a forum for the interactions of the partners.

The primary interface between the Board and the project is the Joint ALMA Office (JAO), established with the hiring of the ALMA Director in 2003 and becoming fully operational in 2004 with the hiring of the ALMA Project Manager and Project Engineer. The JAO provides central management, oversight, and decision-making for the project. Situated in Santiago Chile, the office consists of a small support staff under the supervision of the project's international management team.

By the end of calendar 2005, the ALMA project was well underway. The core international partnerships had been finalized along with all necessary construction agreements within Chile. The JAO was staffed and managing the project, groundbreaking had taken place in November 2003, and road, camp, and building construction on the site in Northern Chile were well advanced. Contracts for all the production antennas had been placed, and all the significant technical risk in the project had been retired.

NSF MANAGEMENT AND OVERSIGHT

NSF management and oversight of ALMA have evolved with the project. The Staff Associate for ALMA in the Division of Astronomical Sciences (AST) is the primary point of contact for the project. The ALMA Project Advisory Team (ALMA PAT) includes members from across NSF, including AST, the Directorate for Mathematical and Physical Sciences (MPS), the Office of General Council, the Office of Legislative and Public Affairs, and the Office of Budget, Finance and Award Management (BFA); the Deputy for Large Facilities Projects (LFP) serves as a member of the ALMA PAT, and the DLFP and staff from BFA's Division of Acquisition and Cooperative Support (DACS) assist in reviewing critical subcontracts. The Staff Associate for ALMA is in continuous contact with the project and serves as the conduit for monthly reporting by AUI, the North American Executive, to the Deputy for LFP; written reports are frequently supplemented by in-person briefings. NSF's active participation on the ALMA Board ensures that the agency can raise issues and concerns with the partners on a regular basis. In addition, senior management staff in MPS have taken a strong interest in ALMA, meeting with the President of ESO Council and the ESO Director General, and attending recent meetings of the ALMA Board. Both MPS staff and BFA staff, including the Deputy for LFP, have attended meetings of the ALMA Management Advisory Committee. The extensive reviews of the proposed new project baseline have led to further improvements in project governance and oversight, including strengthening the ALMA Board's efficiency and supervision of the full international project, increasing the frequency of NSF reviews of the North American project, and improving the frequency of agency communication with ESO Council and the funding agencies which support ESO itself. NSF reviews of the North American project will occur at roughly 6-month intervals, and will focus initially on issues flagged by the external reviews, including implementation of the Project Management and Control System, and site issues.

REBASELINING

The ALMA Board initiated rebaselining of the bilateral project in the fall of 2004 under the direction and oversight of the JAO Project Manager. The project was at that point sufficiently mature that the baseline budget and schedule established in 2002, prior to the signature of the bilateral ALMA Agreement, could be refined based on experience. The rebaselining process took approximately one year, scrutinizing cost and schedule throughout the project, assessing technical and managerial risk, and, ultimately, revising the assumptions on the scope of the project.

Even before the process formally began, initial information on the antenna procurement indicated that a 64-element array would likely turn out to be prohibitively expensive and that the project would have to sacrifice scope to keep the revised cost within bounds. The ALMA Board asked the ALMA Science Advisory Committee (ASAC) to consider the impact of a reduction in the number of antennas on the array's level I science goals. In a parallel study, in early 2005 NSF asked the National Academies'

Committee on Astronomy and Astrophysics (CAA) to examine the issue as well. The ASAC concluded that the number of ALMA antennas should not fall below 50, the CAA that ALMA would retain its scientifically transformational character with as few as 40 antennas. For specificity, the new baseline plan developed by the JAO assumed a 50-antenna array, but it explicitly incorporated the differential cost and schedule impacts for as few as 40, and as many as 64, antennas.

By late summer 2005, only the North American Executive had signed an antenna production contract, and the rebaselining estimate due for delivery to the ALMA Board in early September assumed that identical antennas would be purchased by both project Executives. Just before the rebaselining documents were delivered, however, ESO completed its antenna vendor selection process and chose a second manufacturer to produce another of the ALMA antenna prototype designs. The new baseline cost estimate could not be revised to reflect this change in time to meet the early September delivery deadline. A subsequent addendum (the "delta baseline") addressed the additional costs of a two-antenna bilateral array.

Results: The net result of the rebaselining process, after refinement, addressing the implications of two different antenna designs, and implementing some cost reduction options deemed not critical to the science, was a total estimated cost for a 50-element array that required an increase of just under 40 percent over the original projections (in actual year dollars). The new baseline included a thorough analysis by project management of the reasons for the cost increase.

The largest single increase relative to original budget occurred in the cost of the antennas (which comprised about one-third of the original project cost), followed by increases in site and systems engineering/integration costs. The antenna increases were driven in part by slippages in the procurement process during a period of rapidly rising global commodity prices: signing of the production antenna contracts was delayed by the need for further prototype tests and because of the complexity of coordinating the antenna procurement in the U.S. and Europe. Increases in the cost of site preparation reflected a booming Chilean economy and related currency fluctuations.

The project also classified the cost increases by underlying cause, attributing approximately 45% of the total baseline cost increase to factors stemming from the unanticipated scope of management requirements for a project involving a partnership of equals constructing a complex scientific instrument in a nation thousands of miles from the partners. Setting up and operating the JAO in Chile, implementing the Project Management and Control System (PMCS), and delays associated with efforts to coordinate the AUI-ESO antenna procurement process and to bring Japan into a fully trilateral partnership are key examples of unanticipated management scope. The next three growth drivers – price increases for commodities, unanticipated consequences associated with the remoteness of the site, and underestimates of the complexity of the ALMA instrument (notably in the systems engineering and integration area) – are individually much smaller, with each estimated to have contributed around 15% of the total cost growth.

EXTERNAL REVIEWS

The ALMA Board initiated a review of the revised ALMA baseline shortly after it was delivered. A panel of twenty distinguished international scientists and project managers reviewed the rebaselined project on October 13-16, 2005. The panel was chaired by Dr. Steven Beckwith, Director Emeritus of the Space Telescope Science Institute. The "delta" baseline arising from the decision to utilize two antenna designs in the bilateral array was reviewed by a subset of the same panel on January 26, 2006. Both reviews included ALMA Operations and the transition from early operations to a full operational steady state, and focused on the full international project. NSF staff from AST, MPS and BFA attended the reviews to ensure NSF interests and concerns were properly addressed.

NSF took the initiative to conduct a separate review of the rebaselined North American project plan, budget, and management on January 31 – February 1, 2006. This allowed NSF to probe more deeply into the management and costs for the portion of the project it was funding. Professor Donald Hartill of Cornell University chaired an 11-member panel made up of astronomers and senior project mangers. As in the case of the earlier review, the panel reviewed both construction and operations. NSF staff from AST, MPS and BFA participated.

Summary of Review Conclusions: Both the Beckwith and Hartill reviews reached remarkably similar conclusions as to the strength of the project and its new baseline plan.

Both were enthusiastic about the readiness of the project and its scientific promise. The Hartill panel stated that the "*the National Science Foundation [should] go forward with [this] project.. The technical readiness of the project is very high and construction is under way*", and then asked and answered, "I*s the project organized, staffed, committed, and positioned to complete the ALMA NA project within the proposed new baseline? The answer to the best of our judgment is 'yes'."* The Beckwith panel stated that *"The science capability of ALMA remains compelling. As designed, ALMA will be one of the most important next generation facilities for astronomical research and will remain so for several decades…ALMA's technical readiness level is high. There is little risk that the project will be delayed because of technical issues.*"

With respect to cost and completeness, the Beckwith panel indicated it believes *"ALMA can be built to the current cost estimate, assuming resources are available…[provided] that the execution of the program is robust at all levels of the project."* The Hartill panel agreed, stating that "*…project costs are understood and…the schedule while tight can be met with careful management.……The construction cost growth of the ALMA project is understood."*

Regarding the management structure and oversight of the project, the Hartill panel commented that the [ALMA] "*… management structure that is in place gives confidence that the needed performance level will be met. The…structure is working well and must continue to do so in order to deliver the project on cost and schedule. The qualifications and commitment of the current team provide the best assurance that this situation will continue…The ALMA project management structure has made significant progress in reducing the delay for making high level decisions (as evidenced by resolution of the antenna testing problems and the Chilean local hiring issue)"*, and stated that *"[t]he level of talent of the ALMA team is very high."*

The two committees disagreed somewhat on the maturity of the operations plan, with the Beckwith panel stating that "[t]*he estimated operations costs appear to be adequate and not excessive. At an annual rate of approximately 7% of the capital investment cost, the cost is comparable to that of other astronomical observatories scaled to the size of ALMA."* The Hartill panel's view was that *"…operational plans for ALMA are at an early conceptual stage and will need considerably more work before a solid cost estimate can be developed. The initial cost estimates presented to the Panel seemed to be reasonable."* Both panels agreed that the operations plan is at an appropriate level of maturity for the current stage of the process. NSF will watch further development of the operations plan closely over the next year.

Both panels pointed out the criticality of managing the project to schedule. The Hartill panel stated that *"[t]he proposed funding profile needs to be maintained if the project is to be constructed for the new baseline cost,"* and noted the dependence of the project on the performance of all partners with work on the critical path: *"In the complex environment that the ALMA project is working in, delivery performance of the partners is crucial to the success of the project."* These concerns were echoed by the Beckwith panel, which stated: "*The [new baseline] cost assumes that the project…will be executed to schedule. Poor schedule discipline and [especially] delays in antenna integration could increase the overall project cost."* The panel also pointed out the cost vulnerability of the project to delays in implementing an early operations plan.

Both panels also expressed concern about contingency, though in varying degree. While the Beckwith panel stated that *"[t]he detailed project plan is realistic and contains adequate detail and contingency for cost and schedule in most areas,"* it also noted that the adequacy of the contingency would depend critically on the ability of project management to react quickly to cost challenges that will arise. By contrast, the Hartill panel's concerns were more general: *"[T]he level of contingency remains a concern. Every effort needs to be made to increase this, without increasing the current estimated total project cost. The project has begun an approach that would lead to a contingency in the 25 to 30% range which would give high confidence for on-cost completion."*

Both panels pointed out the central role which the ALMA Board must play if the project is to maintain cost and schedule discipline, with the Beckwith panel being particularly critical of what they saw as the Board's history of delayed decision making. The Hartill panel – which met some three and a half months after the Beckwith panel – took particular note of the efforts the ALMA Board had made to institute improvements in process and oversight and to assert clearer ownership of the project.

In sum, the reviews concluded that the rebaselined ALMA is scientifically compelling and technically ready, that the project has identified all necessary scope, and that construction can be carried out within the total project cost envelope. The nature of the earlier cost escalations is now well understood and the revised baseline incorporates needed safeguards against future escalation.

DIRECTOR'S REVIEW AND ANALYSIS

The Directorate for Mathematical and Physical Sciences, Division of Astronomical Sciences, and Large Facilities Projects Management and Oversight in the Office of Budget, Finance, and Award Management synthesized the rebaselining results and review conclusions for the Director and Deputy Director of NSF at a special half-day review chaired by the Deputy Director on March 2, 2006. The central concern of the review was whether, and on what basis, NSF should continue its participation in ALMA. Several options were considered.

A 50-antenna array with same baseline and receiver band specifications as the original ALMA concept was determined to be the appropriate path forward. This choice balances fiscal prudence with the critical need to maintain U.S. participation in a global research project of immense scientific promise. As originally conceived, the 64-antenna ALMA array was to provide precise, high-speed images of the millimeter and submillimeter-wave sky at angular resolutions of 0.1 arcseconds or better, offering a clarity of vision surpassing that of the Hubble Space Telescope. ALMA would have the ability to image interstellar spectral lines in galaxies like our own Milky Way at distances of 10 billion light years or more, and would reveal the kinematic and chemical structure of solar-mass protostellar disks in the nearest interstellar clouds, detecting the gaps in those disk cleared by accreting protoplanets. With a 50-antenna array, these primary goals remain within reach. With fewer, as noted by the ALMA Science Advisory Committee, they are at serious risk, and the performance of the array (in imaging speed, for example, which goes as the square of the antenna number) will decline more steeply than costs are recovered by eliminating antennas.

The critical issue is thus whether NSF can be confident that the rebaselined 50-element array will meet the new schedule and budget. Based upon the external reviews and ongoing interactions with the project to monitor its progress, MPS and AST staff, with the independent concurrence of the Deputy for Large Facilities Projects, concluded that ALMA can be completed within the funding profile shown below.

Both external review panels agreed that ALMA remains scientifically transformational and unique; that the new construction baseline is complete and properly costed; the reasons for past cost growth are understood; management of both the central (JAO) and regional projects is excellent; and ALMA's organizational structure is fundamentally sound. Both review panels agreed that the project has retired

almost all outstanding technical risk, and that the signing of the antenna contracts has retired the largest single risk to the project. The contingency provided in the funding envelope is considered sufficient to account for the remaining technical and management risk. Relative to the North American side of the project, the Hartill panel was satisfied by its sample drill-downs, and believes that AUI and NRAO are well-positioned to carry out their responsibilities. Planning for ALMA operations is mature and sufficiently comprehensive for the present state of the project. A final North American operations plan – NSF's share of which will be supported within AST under the Research & Related Activities account – will be completed and peer-reviewed by NSF by the end of January 2007. Preliminary estimates indicate an annual operating cost to AST of approximately $35 million. The ongoing Senior Review will assist AST and MPS in making the programmatic decisions required to provide this level of operational support.

The external reviews identified three primary causes of cost escalation: rising commodities prices; unidentified scope; and the weaknesses in the ability of the international partnership to function smoothly and make timely decisions. The first item was beyond the control of the project and to a large extent has been retired by the signing of the antenna contracts. The second has to do with the pioneering nature of ALMA – the first truly global astronomy project – and, in hindsight, the premature entrance into the construction phase. Both panels were convinced that there is no remaining unidentified scope. The last item, which again has to do with the pioneering nature of ALMA, is not fully retired; however, there are signs of very significant progress in improving overall project oversight by the ALMA Board, with the expectation that this item too will be retired, and improved communication between NSF and ESO has been instituted to see this process to completion and to help bolster the ALMA Board's oversight and ownership of the project.

The recommended increase in project cost is large, both in absolute dollars and as a percentage. However, I am now convinced that the increase is necessary and will be well spent on truly transformational science. Further, I am confident that the project can move to completion on the new schedule and budget with the funding profile shown below, and that proper oversight is in place both within the project and at NSF.

PROPOSED PLAN

The budget required to support NSF's share of a 50-antenna ALMA is shown below. All figures are in actual year dollars. Completing a 50-element array will require $154.98 million in additional U.S. funds, a total which includes a contingency of 25% of the remaining cost to complete. An additional $21.99 million in NSB authority will be required to accept construction funds transferred to NSF by Canada and Japan as compensation for site infrastructure costs and supplied receiver components, requiring new spending authority totaling $176.97 million. The annual spending profile for MREFC funding required by the project is given in the bottom line. It calls for additional funding in FY 2007 above the President's budget request; the need for these funds is driven by the payment schedule of the antenna contract, prudent project contingency, and the need to minimize total cost to complete. The same factors lead to the very large funding level required in FY 2008. NSF will inform the Office of Management and Budget, the Office of Science and Technology Policy, and Congress of this new spending profile and will work with all interested parties to ensure an appropriate spending profile that will neither endanger the construction profile nor spread out costs and schedules. In addition, NSF continues to explore ways to offset some of the increased costs. In particular, the successful completion of currently pending negotiations with a potential new partner would reduce the call on MREFC appropriations by as much as $3 million per year for a total of about $20 million.

	FY 2006 & earlier	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	Total
Current budget profile	190.97	47.89	47.07	37.37	20.98	0.00	0.00	**344.28**
Additional NSF funds requested to complete ALMA	0.00	17.38	55.00	36.38	21.78	21.44	3.00	**154.98**
Total MREFC Funds	**190.97**	**65.27**	**102.07**	**73.75**	**42.76**	**21.44**	**3.00**	**499.26**
Pass-through authority for Canada and Japan	9.64	4.78	3.71	2.19	1.13	0.53	0.00	**21.99**
Requested additional spending authority	9.64	22.16	58.71	38.57	22.91	21.97	3.00	**176.97**
Total requested spending authority	**200.61**	**70.05**	**105.78**	**75.94**	**43.89**	**21.97**	**3.00**	**521.25**

RECOMMENDATION

I recommend that the Board approve the proposed changes to the ALMA project in accordance with the following resolution:

RESOLVED, that the National Science Board authorizes the Director at his discretion to increase the spending authority for the Atacama Large Millimeter Array under cooperative AST-0223851 and its successor agreements, by an amount not to exceed $176,970,000, and to extend the duration of the award by 24 months through September 30, 2012.

Arden L. Bement, Jr.
Director