Reply to Comments from the Scientific and Technical Advisory Group by the Smithsonian Astrophysical Observatory Submillimeter Array Project

These comments were generated by the Submillimeter Array Project in response to the report from the Scientific and Technical Advisory Group of 16 December, 1989. The response has been arranged and numbered in the same manner as the report.

March 28, 1990

I. SCIENCE

A. Science Goals

We agree with all the suggestions and comments from the STAG regarding the scientific issues. The uniqueness of the submillimeter band is particularly important in view of the existence of several millimeter-wave interferometers and the probable construction of the NRAO millimeter array within the next decade; we expect to emphasize science goals and technical capability for which the submillimeter band offers unsurpassed opportunities. Among these are the atomic carbon lines, high-J lines from common molecules in hot, dense regions, dust continuum studies, and possible measurements of highly redshifted CII emission from starburst galaxies.

We are of course well aware of the potential and importance of continuum studies in the submillimeter wavelength bands. Polarimetry of the dust emission will be particularly important at arc-second scales if disk-like structures are present. Detected polarizations at submillimeter wavelengths are so far at the 2% level. Although polarizations may be higher with higher angular resolution, we plan to design the array with excellent instrumental polarization properties.

Interstellar chemistry is clearly a very important area that the SMA will address. We intend to design the spectral line system to operate simultaneously at as many bands and as many different lines as possible. An understanding of the excitation and energetics of the gaseous environment requires the study of many different transitions of many different atomic and molecular species. The ability to image in the various lines with high angular resolution is a main goal for the SMA since we expect that different transitions will have vastly different spatial morphologies.

With regard to the other two areas mentioned by the STAG, namely disklike structures associated with low mass protostars and distant or protogalaxies, our calculations show that they will be detectable and are appropriate targets for the SMA. Indeed, objects in both of these classes have been studied already in line and continuum by existing interferometers; we expect that the SMA will have significantly greater sensitivity, by virtue of its higher operating frequency, opening a much wider range of objects to investigation.

We are pursuing these and other science topics, vigorously, in order to drive the design of the SMA for the greatest scientific return. For example, we anticipate that in the continuum, protostars and other planetary systems will drive the sensitivity and resolution requirements, stellar clusters will drive the dynamic range requirements, and formation of giant molecular clouds in nearby galaxies will drive the mosaic requirements. In spectral lines, protostars may again drive the sensitivity requirements, dense molecular cloud cores will drive the simultaneous line requirements, interstellar shocks and bright galactic nuclei will drive the angular resolution requirements, while winds and outflows and galaxies will drive the mosaic requirements.

B. Study Plans

Our goal during the design study and beyond, is to continue to develop and refine the scientific requirements imposed on the SMA, based on calculations and modelling, as well as the most recent observations in the submillimeter and other wavelength bands. We will continue to calculate what can be detected and which parts of the instruments are critical for answering the scientific questions. For example, the broadest spectral window requirements will be set by high redshift lines at the shortest wavelengths. The ability to detect these lines will depend not only on sensitivity but also on instrumental stability. We will model such observations to see what can be expected in realistic experimental conditions. We will also model in detail the expected observations based on actual configurations at the possible sites. Imaging, mosaics, and restoration will be studied in order to find what requirements are imposed on configuration and sensitivity.

C. Short spacing problem

We are actively investigating the short spacing problem by trying to gain some theoretical understanding and by making some models of potential observations. The lines of investigation are defined by the limits of practical variations in the array design. For example, in such a small array, a large central element is ruled out by cost. In addition, mapping will be aided by the availability of several large single dishes (CSO, JCMT, SMT), which we hope will be able to supply suitable maps for combination with the interferometer data, in addition to maps from individual antennas of the array.

Possible antenna variations under study include the effect of radomes on limiting the proximity of antennas, and the use of ‘shaping’ to improve the primary beam.

Our expectation, based on the recent work at the VLA, is that wide-field operation of the SMA will be based on the use of suitable deconvolutions to recapture missing spacings, with the aid of single-dish maps from individual elements of the array and other telescopes, where necessary.

The most likely options for changing the instrumental design are in the configuration, where we will look at the station layout (a) at the center of the Y, to see whether we can improve the close-in *uv* coverage, and (b) at the point farther out where the spacings are sufficiently separated that the primary beam is no longer fully sampled. This outer point determines the finest detail that can be imaged in a complex field containing structure over the entire primary beam, as would be needed in a mosaiced image.

It appears that the dynamic range of mosaiced images is critically dependent on the array pointing and we are working to understand this, in order to define our pointing specification. As a necessary part of this study, we are analyzing probable astronomical targets to determine the required performance and expected dynamic range.

II. SITES

A. Testing

We still plan to choose a developed site and are looking closely at Mauna Kea and Mount Graham. The Antarctic was rejected for such a complex instrument because of the difficulty of operation. Recently we have been looking into the possibility of operating in Chile, although most of the presently developed sites have fairly poor sky transparency.

The primary criterion for comparing sites will be sky transparency, as recommended by the STAG, but we have changed the criterion from one based on precipitable water vapor (PWV) to one based on a measured opacity at 225 GHz. This is because, to first order, the opacity depends on the product of PWV and pressure, rather than PWV alone, while opacity is the relevant factor in the operation of the array. A second reason is that it is better to base the decision on a directly measured quantity, rather than one inferred from measurements.

We still plan to use as our criterion an opacity level which emphasizes the very best transparency. Current models suggest that the an opacity of 0.05 at 225 GHz corresponds to approximately 1 mm PWV at an elevation of approximately

10,000 feet. The preliminary data from the NRAO meter on Mauna Kea and similar data from South Baldy show only small amounts of time at such low opacities (5-10 %) and we might be subject to quite large sampling fluctuations. We therefore propose to use an opacity level of 0.075 at 225 GHz, corresponding to approximately 1.5 mm PWV, at which level we expect to fiid about 10~30 % of the time acceptable. For comparison, this corresponds to an opacity of 1.5 at 850 GHz, which is about at the limit for worthwhile operation. On Mauna Kea, we plan to use the 225 GHz data directly measured by the NRAO radiometer, and on Mount Graham, we plan to use the 23 GHz data measured by the team at the University of Arizona. In both cases, historic radiosonde data will be used to correct for any sampling bias, (a) on the scale of years, to ensure that the survey time was not exceptional, and (b) on the scale of days, to compensate for periods when the radiometers were not in operation.

As a second criterion, we will consider the length of time periods for which the opacity is low, although we will give this less weight than phase fluctuations, if these can be measured successfully.

As recommended by the STAG, we have pursued the possibility of making direct phase measurements, and have located a suitable beacon signal at 11.7 GHz on the satellite GStar A2, located at 105° W. Calculations indicate that the power level is sufficient to make measurements at the level of 0.01 mm r.m.s., if the systematic errors can be controlled. A design has been completed for an interferometer which could observe this signal, and components have been ordered. We expect to complete the first version of the system by the end of March 1990 and to install it on Mauna Kea by late spring, if no serious bugs are found. A second copy will be constructed in time for the winter observing season on Mount Graham. Although these systems will not be in operation for a full year on either site, we expect that they will be present during a sufficient sample of good weather in both cases. In view of the expectation that this measurement will be successful, we are not pursuing the recommended option of comparing readings from pairs of radiometers.

Until some preliminary phase data are in hand, it is premature to choose a criterion for comparing sites, but we expect that it will involve the fraction of time at which imaging better than some specified angular resolution is possible.

B. Weather

We are taking steps to collect weather records for the two sites, and where possible, to correlate them with measured opacities and phases.

C. Configurations

It is likely that the easiest size of array to build on either site will have maximum baselines of around 500 - 600 m. On Mount Graham, this is a fairly firm limit set by the need to stay close to an already cleared road, while on Mauna Kea the limitations are mainly topographic. The need for long baselines will become clearer after the phase measurements are in hand. With radio seeing comparable to that at existing sites, the longest baselines would not often be useful, but it might be expected that better conditions will prevail on mountaintops. A Y will used in any case, but the arms may not be exactly straight. At both sites, the possible addition of other large submillimeter telescope(s) to the array will provide the ideal combination of slightly longer baselines with larger sensitivity. We will consider the presence of these telescopes when laying out the configurations, but we expect that other considerations will be more pressing in determining the layout.

We will not consider the availability of these other dishes in making the site comparison, since we cannot rely on obtaining a large fraction of their time. We will, however, consider the constraints imposed by the environmental and topographic limitations of the sites, both for the initial array and for possible future extensions.

D. Costs

There appears to be ample information available to properly judge the relative costs of preparing the candidate sites and the funding of subsequent operations. What is more difficult to anticipate is the relative rate of progress that will be possible in light of varying approval cycles, large differences in infrastructure and the like. Thus, there is a large uncertainty in the point at which the array will become scientifically productive.

E. Selection and Approval

We do not expect to take the site approval process for granted at any candidate site. Our current plan is to ask for a preliminary finding regarding the suitability of the proposed sites prior to making a final selection.

In accordance with the committee's recommendation, we plan to make our final selection by spring 1991. By that time we expect to have in hand all the information necessary to make the decision, as well as to initiate construction.

This includes good data on the opacity and weather conditions at each site, preliminary array layouts, measurements of seeing, and plans for the approval process.

III. RECEIVERS

We appreciate the fact that receiver development is, and will continue to be, the most challenging technical aspect of the SMA project. We are still building up the lab, in terms of both equipment and personnel, and would like to emphasize that the facilities toured by the STAG, in September 1989, were just a foundation for a much larger effort that will necessarily develop.

A. Mixers

We are aware of the attractive features of SIN junctions for receiver applications, and are studying their use both as fundamental and harmonic mixers. The test quasi-optical receiver for 345 GHz was initiated only as a means of investigating the quasi-optical approach at a relatively accessible frequency. We are aware of the excellent results from waveguide receivers up to 345 GHz, and expect that the best performance even up to 490 GHz will be obtained with relatively conventional waveguide mixer designs.

B. Junction Fabrication

From the first days of the receiver effort, we have pursued contacts with outside groups making SIS junctions. Specifically, we are now in contact with the following groups: (1) Bell Labs (lead junctions), (2) Cambridge University (niobium), (3) IRAM (lead), (4) TRW (niobium trilayers), (5) U. Texas/Hypress (niobium), (6) University of Virginia (niobium and possibly niobium nitride). Tours of outside facilities indicate that the equipment in the Harvard physics department is of equal quality, and that a competitive in-house effort should be possible when sufficient manpower can be brought to bear.

C. Local Oscillators

We agree with the STAG regarding the desirability of Gunn oscillators followed by diode multipliers. It appears that suitable technology is now available up to about 500 GHz; in fact, sources covering 460 GHz and 490 GHz are in use in our lab. An alliance with the research effort at UVa may make sense in light of the funding limitations at both institutions.

D. IF Amplifiers

The IF frequency for the array has not been chosen, but we are aware of the work done at NRAO in achieving very low noise and broad bandwidth. Consultations with Marian Pospieszalski suggest that a state-of-the-art design can be made available to us to suit our needs.

E. Receiver Optics

We are aware of the general optical requirements, and have made some early efforts in fabricating polarization diplexers and dielectric lenses. Rachael Padman is presently visiting from the University of Cambridge for 3 months and she is working on the optical design for the antennas, including calibration and receiver diplexing. We are in the process of recruiting an expert in microwave optics, who may also help with the optical interface to the telescope.

F. Refrigerators and Cryostats

We acknowledge the importance of early experience with closed-cycle refrigerators. Consultations with various experts at NRAO and Haystack have yielded no clear consensus, but we will nonetheless buy some test units soon. It appears that use of multi-receiver cryostats, similar to the 8-channel NRAO design, is a sensible approach.

G. Receiver Cabin

It appears that a large, non-tipping receiver cabin is preferable. Discussions of these issues are underway with contractors involved in antenna design studies. This aspect of the design is also being considered by Rachael Padman.

H. Manpower

The receiver group will require significant increases in staffing. Particularly in **the critical** early stages, we have been careful to select only the best people, which has necessarily caused staffing to proceed rather slowly. We agree that graduate students can make a valuable contribution, and currently employ two of them with plans for more in the future.

IV. ANTENNAS

A. Retractable cover design

If we are required to protect the antenna, the retractable cover is certainly an interesting option. The firm MAN-GHH is presently working on a study contract to investigate construction of the primary reflector and backup structure from carbon-fiber composites. We have directed them to provide a means for protecting the reflector panels. Their mid-term report illustrates several possible concepts for a protective cover. It is not obvious that a simple straight forward solution exists; however, we will continue to develop these initial concepts in order to attain a satisfactory cover design.

B. Antenna specificatih

We are following the advice of the STAG in developing in-house expertise in antenna design, and have recently hired a lead mechanical engineer. We have a number of contracts with industry to study aspects of antenna design. Our intent is to completely define the antenna's engineering and operational requirements by a detailed performance specification as well as a layout of all the critical physical characteristics. This specification will cover all aspects of the entire antenna system including all its interfaces (site, receivers, etc). It will serve as the antenna's top level document and will list other specifications where specific information is required. We intend to use this specification as the basis for our request for quotation (RFQ) for final design plus construction of the initial antennas. This document will be circulated for comment prior to the RFQ so that industry response to both technique and cost can be meaningful.

The contract for detailed design will include a break point between design and construction at which we and the contractor will agree that the proposed design should meet our requirements. Beyond that point, the construction will proceed according to engineering specifications and the acceptance of the antennas will be based on those specifications.

C. Pointing accuracy

Current state-of-the-art does not permit a design whose pointing error is a negligible fraction of the primary beamwidth; a one arc-second r.m.s. pointing requirement will be difficult to achieve at any cost. We agree with the STAG that we may be forced to relax this requirement under some conditions, but before doing so, we are taking pains to analyze antenna pointing errors in order to obtain the best results. These errors include those associated with the servo itself, errors attributable to the optical path and errors attributable to the mount. Presently, we are trying to identify all sources of pointing error, their magnitude and schemes, where possible, for their correction. This work is being done in conjunction with the imaging studies described above, which will determine the scientific cost of pointing errors.

V. CORRELATOR

We are following the STAG advice in planning not to commit to a particular design until the latest possible moment. to take advantage of developments in technology. The draft report from Haystack has arrived, giving a preliminary costing for a correlator based on the NFRA chip, and a comparison with other chips. We are preparing our reply to this draft and we expect to have a final version in hand in another 2 months.

The required number of channels has been reduced provisionally to 4 sections of 128 channels each, though it is likely that the use of low-speed logic will necessarily provide more channels than this minimum. However, it is easy to reduce the number of channels before processing, by averaging or discarding.

We will estimate the cost of a separate wideband correlator and choose the lowest cost option for the array. It is probably not as cheap and simple as it might first appear to make a very wideband correlator using analog techniques. Cable limitations and considerations of delay line accuracy probably limit any single analog correlator to a bandwidth of about 500-1000 MHz. A very wideband (>2GHz) correlator would then have to be constructed out of a number of sections, and may not be sufficiently cheaper than the digital approach to be attractive, when the extra development effort is taken into account. We will study the bandwidth limitations and costs in detail before coming to a decision.

VI. MANAGEMENT AND SCHEDULES

A. Ample test time

Following the STAG meeting the schedule was changed to permit the arrival of the first two antennas in January of 1994. Firm orders can be placed close to that time for the remaining antennas and still have time to build them. This will allow some feedback on results of the early antenna testing before much metal is cut on the remaining four.

Naturally, we would like to begin operations as early as possible at the site. It is probably true, however, that more equipment has arrived on mountain tops too early than has arrived too late. Much of the cost of construction at these remote sites does not show up until you try to invent things at the site that should have been invented earlier. The modular nature of this apparatus allows us to develop nearly all aspects at a friendly site near Cambridge. The time to move will not be determined by the calendar, but by the passing of a set of readiness criteria proving that the equipment is ready to relocate.

B. Fiber optics capability

We accept the STAG recommendation and will make fiber optics expertise a requirement for one of the engineering hires. Fortunately, these skills are becoming widely dispersed by the communication industry.

VII. GENERAL STAFFING

A. Site crew

The complement of site persons appears to fit our current staffing plan with only minor modification to some of the job descriptions.

B. Crew training

The current plan calls for four of the key site persons to be hired in 1991 and two more in 1992, all to reside in Cambridge until the time to equip the site. This should allow ample time to become familiar with the array.

C. Increased manpower in the receiver lab

We accept the STAG recommendation and are now actively recruiting additional receiver specialists, including a quasi-optics designer

D. Young astronomers

Following the recommendation of the STAG, two additional Post Doc positions were opened on the project and offers have been accepted . In addition, we are actively seeking the involvement of a number of graduate students.