MEMO #8

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DIRECTOR'S OFFICE

December 16, 1989

Dr. Irwin Shapiro
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60 Garden St.
Cambridge, Mass. 02138

Dear Irwin:

Enclosed find the report from the Scientific and Technical Advisory Group for the Submillimeter Array. It took a bit longer than I had hoped to collate and edit the comments from the rather large committee and then circulate a draft for their further input. I believe that the entire committee is very enthusiastic about the project and impressed with the progress to date. We also appreciate your hospitality on our visit to the SAO in late September.

Season's greetings,

Jack

Wm. J. Welch
for the STAG

I Overview

The Scientific and Technical advisory Group for the submillimeter array met on September 21-22 at the SAO in Cambridge. The membership consisted of Dr. Roy Booth from the Onsala Space Observatory, Dr. Roger Hildebrand from the University of Chicago, Dr. Richard Hills from Cambridge University, Dr. William Hoffman from the University of Arizona, Dr. Masato Ishiguro from the Nobeyama Observatory, Dr. A. R. Kerr from the National Radio Astronomy Observatory, Dr. Peter Napier from the National Radio Astronomy Observatory, Dr. T. G. Phillips from Caltech, Dr. N. Z. Scoville from Caltech, Dr. Paul A. Vanden Bout from the National Radio Astronomy Observatory, Dr. William J. Welch from the University of California, Berkeley(chairman), Dr. Gisbert Winnewisser from the University zu Koln, and Dr. Gareth Wynn-Williams from the University of Hawaii. Dr. Reinhard Genzel from the MPI in Garching was unable to attend. During the two day meeting, the committee heard discussions of the plans for the sub-millimeter array in regard to the science which could be done, the overall technical issues, needed receivers, correlator plans, the antennas, imaging problems, and the possible sites. The committee commented during the presentations, contributed to the detailed scientific and technical decisions, and now makes these summary observations and recommendations.

The committee wishes to congratulate the Observatory for planning and organizing the funding for the sub- millimeter array, an instrument which has the potential for addressing a wide variety of problems at the forefront of astronomical research. It was evident from the presentations that considerable thought had been put into the science that could be carried out with the prospective instrument and substantial effort had already been invested in technical planning. However, because the [redacted] out and therefore the corresponding technical specifications are not completely clear, the [redacted] Committee is not able to make firm recommendations between well defined alternatives. Nevertheless, we offer the following general comments on the present state of the planning and some general recommendations.

II. THE SCIENTIFIC PROGRAM

The scientific planning needs some further development. The discussion of the original draft proposal is now somewhat out of date, and it needs to be more focused. Furthermore, it pays inadequate attention to some important areas, such as extragalactic science,[redacted]dust continuum, and[redacted]nterstellar chemistry. There is less a need to develop the scientific case to ``sell" the project; rather, the [redacted] instrument [redacted].

Many more modeling studies of the instrumental sensitivity and the imaging fidelity need to be done before we can make a meaningful statement regarding the track and station placement and telescope/receiver sensitivity specifications. These studies should be done with realistic station locations based on the topology of sites on Mt. Graham and Mauna Kea. It is important to identify areas in which the SMMA will offer unique opportunities beyond just the view of the array as an extension of the millimeter wavelength capability. Great effort should be made to exploit those opportunities at an early stage.

In the following paragraphs, we note a few areas in which it would be valuable to both expand and focus the scientific discussion. These include submillimeter continuum, interstellar chemistry, star formation, and extragalactic studies.

At submillimeter wavelengths it is especially important to study both the continuum emission from dust and its polarization. SAO already has considerable expertise in the relevant science, especially with regard to star formation and the magnetic fields of galactic clouds. At least for the first two or three years of operation, a single wavelength band for continuum should be sufficient since no resonances are expected in the submillimeter, and for $\lambda \geq 300\mu m$ the Rayleigh-Jeans regime is expected. Also, in most cases adequate spectral information can be obtained by supplementing the array data with results from SOFIA and from millimeter-wave arrays. A single band may not be sufficient in the long run, but it is probably a very good starting point.

The array is being designed at just the right time to focus on polarimetry. We now know (but only very recently) that the thermal emission from interstellar clouds is, indeed, linearly polarized to a readily measurable extent, that the polarization provides the best way to determine the configuration of magnetic fields as projected on the sky, and (from $12\mu m$ work) that the polarization maps show structure down to 10 arc sec. But we don't know much more. There is every reason to expect the structure at smaller scales to provide a key to understanding magnetic accretion disks and much more. The first far-IR and SMMA polarization maps with scores of points and with perhaps 10-15 sec resolution (e.g. SOFIA, CSO) will probably begin to appear a little before first light on the array. It is only in the submillimeter that the effects of scattering and absorption have a negligible effect. The 12μ m work referred to above is very good work, but it does require a major correction for foreground absorption.

Two polarization components should be sufficient for the polarimetry. One expects a linear component for optically thin dust emission. This means that the instrument should measure right and left circular polarization, which is well known to be the optimum choice for measuring linear polarization.

Eventually there may be reason to try all four components, but that can reasonably be left to ``phase II" or ``phase III." There is sure to be plenty to do with two components and high spatial resolution.

The SMMA polarimetry offers great opportunities for solar system work, but primarily where the objects can be resolved, as will often be true with the array. Polarized emission from solid surfaces should be substantial, and it will provide important information about the density, roughness, and dielectric properties of the surfaces of solid bodies such as planets, satellites, and asteroids. SAO may have no in-house expertise in this area. It may be desirable to consult someone who has done radar work on the moon at radio wavelengths.

Studies of interstellar chemistry with the array at high angular resolution will be very important, and careful consideration of the requirements for this work will have an important effect on the design of the array. Both the detailed design of the correlator and the tuning ranges of the receivers will be strongly affected by this issue. Particularly because there are multiple receivers to be built for the array, it is essential that the spectroscopic needs be carefully considered at this stage in the design.

Interstellar chemistry is important not only for its own sake, but also because of its implications regarding the physical conditions and evolution of the interstellar medium. A couple of examples will illustrate this point. It is now well known that millimeter wavelength maps show very different distributions in different species. It is only by mapping multiple transitions of individual molecules and observation of transitions of different molecules (e.g., ions and neutrals) that one can hope to understand the physical conditions of clouds in the ISM. A second and more specific example is the composition of the "hot core" in the Orion star forming region. There is a high concentration of Deuterated molecules in the "hot core", a concentration much in excess of the average atomic D/H in the ISM. This excess is unexpected at the high temperature of the "hot core" material, over 200K, and suggests that the present chemical composition is that of the material before star formation began.

There are two other areas of great current interest that merit more detailed attention in the science discussion. First, star-formation regions containing a few solar mass protostars with accompanying disks of 100 AU or so. Can these be detected by the interferometer using the continuum channel? What are the requirements on the instrument? Second, distant or protogalaxies: can these be detected in the continuum? Can they be detected in the red-shifted 158μm CII line? What are the requirements on the instrument? These are two very important topics which could be addressed in more detail and would act as strong drivers for the design.

III. SITES

The committee agreed that the array should be located on a developed site with low atmospheric absorption and that Mauna Kea and Mt Graham were the two best options for further study. The primary criterion in the choice of site should be the number of hours which can be expected in a year when the water vapor content of the atmosphere is below one millimeter. Other criteria, including the lengths of time for which the good conditions typically persist, the stability of the atmosphere, the general weather conditions, the prospects for obtaining construction permits and the costs, should all be evaluated as these would become important in the case that the water vapor statistics do not give a clear-cut choice.

The length of time during which the conditions are good is also particularly important, because the array is intended to do earth rotation syntheses of several hours duration, and this requires several hours in succession during which the atmosphere is dry. Note that if the really dry periods are short, a larger number of antennas will be required so that good operation in "snap-shot" mode is possible. Mapping with a six element array requires a number of hours of earth rotation to be effective. Thus, an early site evaluation will provide a significant input into the design of the array.

As relatively little is known about the atmospheric phase fluctuations on mountain sites, SAO should undertake an investigation of these before the spring of 1991. Although it may be possible to obtain a satisfactory understanding of these fluctuations by indirect methods, such procedures are risky and the results may be unconvincing. A direct measurement of the phase is preferable. The practicality of doing this using a source on a geostationary satellite should be investigated first. Preliminary tests at Nobeyama show that a five or so element array of satellite dishes with some relatively simple electronics observing a satellite can give "seeing" information on a range of size scales.

A simple experiment to test the atmospheric phase fluctuations may be done with two water vapor radiometers, again at several spacings. These could be simple, that is, not scanning devices, possibly pointing towards an optimum elevation angle such as 45 deg. If it is found that there is a good correlation between the radiometric results and those of the satellite interferometer, the radiometers may then be used to study the "seeing" in directions other than toward the geostationary satellite.

The site selection [redacted] The project needs to define the telescope configuration soon and investigate how to site and transport telescopes on the actual terrain on Mauna Kea and Mount Graham. A 1km long straight-armed Y configuration may not fit onto either mountain without unacceptably steep gradients.

The array is sufficiently different from any other instrument that has ever been built on Mt. Graham or Mauna Kea that a long approval process for either site must be anticipated. It is important that this process start now so that when the data is in hand to allow the choice of a site based on scientific considerations, the political and economic realities can be folded into the decision.

The cost premium of building on Mauna Kea compared to a continental site may be worse than currently expected. Information on construction costs can be obtained on recently completed and currently active construction projects on the mountain.

IV. RECEIVERS

The project management should be congratulated on having recognized that the receivers will be probably the most challenging component of the interferometer and on having made an early start on the problem. We wish to emphasize that the receiver problem is likely to exist throughout the lifetime of the project, and receiver development plans should always have the highest priority. Here are detailed comments and suggestions regarding the receivers.

1. MIXERS

It is known that SIS receivers perform well up to perhaps 400 GHz using existing junction technology, but it is not yet clear whether they will be acceptable at higher frequencies. The possibility of using SIN fundamental or harmonic mixers should not be overlooked.

Above about 400 GHz it is planned to use a quasi- optical mount because of the difficulty of making waveguide components. The only quasi-Optical SIS mixers reported to date are the bow-tie and log-spiral types. No one has yet been able to operate on a telescope with the excellent laboratory results reported for the first spiral mixer, so some caution seems appropriate before making too much of a commitment in that direction. There should be at least a parallel effort on waveguide mixers, despite the mechanical difficulties.

One argument sometimes given in support of planar (non-waveguide) mixers is their suitability for close-packing in focal plane arrays. In view of the already enormous correlator requirements for the multi- antenna array using simple receivers, it seems likely that, for the foreseeable future, focal-plane array receivers on the SMMA would be practical only for dedicated continuum receivers.

2. JUNCTION FABRICATION

Despite the existence of sixteen or so groups which have successfully made SIS receivers, there is still have no reliable source of generally available junctions suitable even for millimeter mixers. This is an indication of the difficulty of making suitable junctions with consistently high quality.

Because of their very high quality, robustness, and reproducibility, $Nb/Al-Al_2O_3/Nb$ junctions are now rapidly replacing lead-alloy junctions, and can be expected to operate as SIS mixers up to about 400 GHz. Possibly they will be useful up to 900 GHz, but that remains to be demonstrated. Present junction development for the SMMA is focussed on $Nb/Al-Al_2O_3/Nb$ junctions to be made in Prof. Tinkham's laboratory in the Harvard physics department. While this work on overlap junctions is valuable and should be continued, it is risky to rely completely on the in-house effort for the SMMA receiver junctions. The project ~~should seek at least one~~ additional source of junctions. Support of another university group or a commercial supplier, for example, could bring a more concerted effort to bear on the fabrication of suitable junctions. (Several groups make $Nb/Al-Al_2O_3/Nb$ junctions, and also NbN-based junctions.)

3. LOCAL OSCILLATORS

Suitable local oscillators for the higher frequency receivers do not exist at present. It is hoped that by the time they are needed other groups will have developed suitable designs. However, it is possible that the particular tuning and reliability requirements of the SMMA may make SAO the driving force behind the necessary LO development.

Gunn oscillators followed by frequency multipliers appear the most practical approach. The frequency multipliers will probably have whisker-contacted GaAs Schottky varactor diodes, and are likely to be the least reliable components in the whole array. The sole US source of suitable diodes for such multipliers is UVA. Some work is under way at UVA to develop planar varactor diodes and integrated multipliers for millimeter and submillimeter wavelengths. Compared with present millimeter multipliers, these should have greater bandwidth and reliability, and fully electronic tuning may eventually be possible (present millimeter Gunn/multiplier combinations typically have 4 or 5 mechanical tuners).

For these reasons it would seem wise to ~~support relevant~~ varactor or multiplier research at UVA, thereby guiding their efforts into areas relevant to the SMMA, while ensuring a supply of their present (whisker-contacted) varactors for in-house work.

4. IF AMPLIFIERS

Commercially available IF amplifiers do not have the lowest noise possible with commercial HEMT's. Steps should be taken to persuade a commercial source to improve their design, or else the possibility of obtaining amplifiers from other research groups should be investigated.

Note that bandwidths of a GHz or more were discussed at the advisory meeting. Marian Pospieszalski at NRAO has an octave-bandwidth design for 1-2 GHz which looks promising. If an isolator is needed between the mixer and IF amplifier, special development will be needed for such bandwidths or for operation other than at L-band.

5. RECEIVER OPTICS

A number of quasi-optical components will be required between the subreflector and the SIS mixer. These may include: a polarization diplexer, frequency diplexers (for multi-frequency operation and cold-load image terminations), an LO diplexer, refocusing elements, a vacuum window, an IR filter, and an appropriately designed feed. The design of the receiver optics will depend on the specific scientific requirements and will be an important factor influencing the telescope configuration and location of the receiver cabin.

6. REFRIGERATORS and CRYOSTATS

It is important to make an early evaluation of commercial 4K closed cycle refrigerators (Air Products, Sumitomo, Daikin,etc) and buy some for testing, to gain experience with servicing and maintenance requirements, as well as any effects on the receivers of vibration, magnetic fields from the displacer mechanism, or temperature instability. Experience at Nobeyama has shown that at least one commercial unit, the one from Sumitomo, is quite reliable. A possibly more economic approach, which should be investigated at some level, is the in-house construction of a refrigerator. This could, for example, be based on either the NRAO or Haystack design.

The choice of one cryostat containing many receivers versus several cryostats each containing possibly two receivers must be made. By the time a receiver design is ready for use on the array, it should have been so thoroughly tested and evaluated that the design can be frozen. The reliability of SIS receivers with refractory junctions (e.g., Nb-based) appears sufficient to justify putting many in the same cryostat. Perhaps two cryostats could be used, one with the (4) lower frequency receivers, and one with the (4) higher frequency receivers. The design of the cryostat depends to a large extent on the size of the receiver cabin and its location on the telescope.

6. RECEIVER CABIN

The choice of receiver cabin location and size must take into account the size and number of cryostats, and the necessary quasioptical elements. These choices will depend very much on the specific instrumental requirements which are demanded by the scientific program of the instrument. A large, non-tipping room is preferable for accessibility and flexibility. The need to be able to work comfortably in the cabin and bring in extra test equipment cannot be overemphasized on an instrument using so much new technology. The Coude feed arrangement on the Nobeyama telescopes brings the signal conveniently to the antenna base with no apparent degradation in phase stability and signal losses of only 0.5 db. The Cassegrain feed used on the Hat Creek telescopes achieves somewhat lower losses, 0.15 db, but at the price of poor accessibility to the receiver.

7..MANPOWER FOR RECEIVER WORK

The five engineers (of whom one is a full time junction fabricator) may be sufficient in the present early stages of the project, but they will not be sufficient when production begins. Development of receivers for new bands is planned to be concurrent with production of already developed receivers. These five people are responsible for: quasi-optical devices, SIS mixers, SIS junctions, LO's, IF's, and cryostats for 48 or more receivers (6 telescopes times 2 polarizations times 4 frequencies). Success with broadband planar mixers could alleviate the situation somewhat, but in the next few years it seems unlikely. A number of capable technicians could be brought in soon to be ready when real receiver production starts.

Although one cannot count on graduate students handling any appreciable part of receiver production, they may be very helpful in the development work. In fact, this is a good area in which to train Ph. D. students and post-docs. The project should make every effort to attract students, in particular to work in this area.

A general caution is to avoid getting into the situation most of us are in, where the loss of one key individual (e.g. a junction fabricator) could cripple the project. And, of course, maintaining good liaison with other laboratories which are engaged in similar developments is very important.

V. ANTENNAS

The committee accepted the general proposition that recent advances in the technology of high-precision dish antennas had demonstrated that it was definitely possible to build antennas with the necessary accuracy, so that this is not an area requiring major new developments. The requirements for transportability and environmental protection do pose some additional problems for the designer, but the outline scheme with the integrated enclosure and retractable cover looks very promising and should be pursued further.

It will not be easy to obtain an affordable price for the antennas, and the committee feels that it is better to invite tenders against a detailed engineering specification rather than a performance specification. SAO should draw on experience at SAO and elsewhere in contracting for the antennas. They should develop a design in- house or under contract that they thoroughly understand. That is, the structural and electromagnetic analysis should make them confident that the mechanical specifications will yield the desired performance. If necessary, a temporary, experienced antenna consultant could be retained to help in this task. Bidders can be told to bid on their own design or SAO's and that they will be responsible for whichever design they choose. This will yield a better price than simply supplying performance specs and will avoid haggling endlessly on delivery over whether the specs were actually met. Antenna gain and pointing accuracy are not easy to evaluate, especially at the moment when the antenna must be accepted. It will also give SAO much better control over the contractor in that they will be able to speak with authority on the design. The contractor should probably be chosen from among those who have had specific experience in constructing millimeter antennas.

The pointing specification of 1 arc second is going to be particularly difficult to meet, and it may be necessary to consider under what circumstances this can be relaxed. Also, the relative merits of mounting the receivers on the dish and in the base of the telescope should be carefully assessed during the study phase.

It is important to be able to place the first order for antennas at an early stage to allow plenty of time for problem solving. One is needed to test the antenna design but two are essential for the development of the other systems, ~~so two should be ordered if at all possible.~~

For the initial construction program the choice of six antennas each of 6 meters diameter has much to recommend it. The committee discussed at some length the advantages of using a larger number of smaller dishes, which would provide faster imaging and reduce the pointing accuracy required on the individual antennas, but concluded that these merits were outweighed by the additional difficulties of calibrating the instrument and of building and maintaining the extra receivers. Here again, it was not possible to draw a firm conclusion in the absence of somewhat more firm scientific requirements.

The design of the array should take into account the presence of other large submillimeter telescopes on the site. For observations of very faint compact objects there would be substantial gains from incorporating these into the array when time is available.

It is very important to consider how to solve the short spacing problem. Most of the sources to be studied will be extended on scales greater than 10 arc seconds, and it is important to understand the relationship of the small scale structure seen interferometrically to the more extended regions.

VI. CORRELATOR

The proposed design, construction, and check-out of the digital correlator by the Haystack correlator group is a good plan. Although it will be a large task, its construction should be straightforward as a result of the ability to adapt existing correlator chips and board design. For this reason, it is felt that the correlator construction ~~need not proceed~~ immediately, thus allowing the adoption of technology developed and implemented elsewhere over the next two years.

~~We strongly recommend that a reduction in the number of channels by at least a factor of two be considered for the initial instrument.~~ There is no point in having more channels than warranted by the instrumental sensitivity, and the large number of channels poses unnecessary burdens on the computing requirements. The necessary number of channels will be found from more detailed studies of the scientific requirements for some important representative observations.

It is very important that a ~~separate wideband continuum correlator be included for maximum continuum sensitivity. In~~ addition to continuum sensitivity, a wideband correlator may permit some bandwidth synthesis. It should have whatever maximum bandwidth the input receiver can manage, at least one GHz if possible. Although the spectral line correlator is useful for continuum experiments when it can be set up with the full bandwidth of the IF, there are times when one needs to be able to measure continuum at the same time that one is observing one or more spectral lines at high resolution. In this case the correlator will not be configured in such a way that it will have good continuum sensitivity, and the separate continuum correlator is important. It is important for both the calibration and in order to maximize the sensitivity on several scientific projects such as dust continuum measurements in protostars and galaxies.

VII. MANAGEMENT AND SCHEDULES

Two key events in the construction schedule are the start of first interferometer tests at a convenient test site near the project office in Cambridge and the start of equipment installation on the mountain top site. The overall construction schedule should be designed to achieve these goals at the earliest possible time. Information from the interferometer tests will be needed to allow the duplication of equipment for later antennas to proceed and for equipment design. On the second point, all telescope projects located on remote, high sites have found that equipment installation and checkout proceed more slowly than expected, so the process should be started as early as possible.

During the design phase a start should be made in building up an in-house capability in fiber optics. High phase stability fiber links and very broad band digital links are a sufficiently specialized technology that this development should not be left until construction starts.

GENERAL STAFFING

1. SITE

The staffing for site testing is dependent to some extent on the site; more support will be required at Mauna Kea.

In principle there is a long time before the site staff need to be chosen. However, taking SEST as a model, it worked extremely well to have the future site people on the Onsala staff for 2 years working on aspects of hardware and software development. They were then exactly the right people to implement these developments on the mountain.

A possible model of the site team would be:

Scientist in charge	1
General support cleaners, 1 secry)	5 (2 cooks, 2
Operators	5
Software scientists/digital engineers astronomy backgrounds)	4 (at least 2 with
RF Engineers	3
Technicians	5

2. CAMBRIDGE TEAM

The present support and development group in Cambridge is a good start and will need to be augmented as discussed above in the Receiver section. In addition, there should probably be a couple of RF engineers to help with the relatively complex technical issues.

It is also very important to try to interest young astronomy and physics students in the project. These are the scientists of the next generation who should grow with the project.