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EUROPEAN SOUTHERN OBSERVATORY

ORGANISATION EUROPEENNE POUR DES RECHERCHES ASTRONOMIQUES
DANS L'HEMISPHERE AUSTRAL

SCIENTIFIC TECHNICAL COMMITTEE

41st Meeting

Milan, October 30 & 31, 1996

ESO & Millimetre-Wave Astronomy

P. Shaver

ESO & Millimetre-Wave Astronomy

(Prepared by P. Shaver)

1. The Beginnings

ESO became formally involved in millimetre astronomy on 26 June 1984, when it signed a 15-year agreement with Sweden for the installation and operation of the 15m Swedish-ESO (Sub)Millimetre Telescope SEST. A copy of that agreement is attached as Appendix A. The telescope was completed in 1987 and regular scheduled observations began in 1988.

The SEST is unique as the only large (sub)millimetre telescope in the southern hemisphere, and, in addition to providing an important new facility for Europe's mm astronomers it also provided a new observational window for Europe's optical/infrared astronomers. Thus, it has taken its place alongside the optical/infrared telescopes on La Silla to enhance the observational opportunities for the ESO community. It has been a very productive facility, producing front-line science and serving astronomers from over 60 institutes in Europe, including collaborations with astronomers from another 80 institutes world-wide.

2. Recent Developments

A comprehensive review of mm astronomy at ESO was presented at the May 1994 STC meeting (*cf.* ESO/STC-148, "(Sub)Millimeter Astronomy at ESO"). At that meeting the STC reconfirmed its support for millimetre astronomy at ESO and endorsed the recommendations made by a mm working group (Appendix B):

- *"the SEST ... is a productive facility which has been producing results at or near the state of the art ... it supports a large user community ... the relative output is essentially identical with the best facilities ESO has to offer."*
- *"The SEST should continue to be supported. It is the opinion of the committee that SEST will remain an interesting and important part of ESO's programme into the 21st century, and the agreement with Sweden should be extended, when it comes up for renewal."*
- *"The next instrumental developments on SEST should include arrays of receivers for line and continuum observations. In both cases, a nutating secondary will be required."*
- *"The group sees the future of mm wave astronomy as moving toward high resolution and large collecting area through the use of large distributed arrays."*
- *"The Working Group recommends the appointment of a permanent (mm) advisory group."*

The permanent Advisory Group for Millimetre Astronomy was established a month later, with the following composition: P. Andreani (Italy), R. Booth (Sweden), L. Bronfman (Chile), P. Encrenaz (France), M. Grewing (IRAM), F. Israel (Netherlands), L.-A. Nyman (SEST), P. Shaver (ESO), J. Whiteoak (Australia), T. Wilson (Germany; chair). It has since guided the mm developments at ESO.

2.1 SEST

A number of new developments are currently taking place or planned for the SEST. Some of them are summarized below:

On-The-Fly Mapping: The strongest recommendation from the December 1995 meeting of the SEST Users Meeting was for "on-the-fly" mapping, as it can increase mapping speeds (and possibly also data quality) by a large factor. This is now well on the way to being implemented - the first OTF maps have already been made.

New 3, 2, and 1.3 mm Receivers: New 3 and 2 mm receivers were installed on the SEST last year. A new 1.3 mm receiver built by IRAM and Onsala has been shipped to Chile for installation in November; lab tests indicate that that it is one of the best receivers available at this wavelength.

Nutating Subreflector: The Feasibility and Design Study for the SEST nutating subreflector, undertaken by IRAM, has now been completed. It shows that a nutating subreflector system can be integrated into the existing quadrupod. Beam throws up to 12 arcmin are possible, and two-dimensional chopping can be done. FEM calculations indicate that the system should be dynamically well-behaved. The next step is being taken now: a contract for the prototyping, testing, construction and installation of the nutating subreflector. It is expected that the completed system will be installed on the SEST in the first half of 1998.

Bolometer Array: In parallel with the final contract for the nutating subreflector, plans are now being made for the provision of a bolometer array for the SEST. It is intended that this array should be installed on the SEST around the same time as the nutating subreflector.

Heterodyne Array and Digital Spectrometer: The next phase is foreseen to be a heterodyne array for 230 GHz. This would involve not only the array development but also that of a large digital spectrometer: n feeds (pixels) $\times$ m channels for bandwidths from 2 Ghz down to about 100 MHz, with $n \sim 25$ and $m = 1024$. Plans for the spectrometer are only partially formulated but one possibility is that it could be built at the ATNF as part of a proposed Australian-Swedish collaboration in which Australia takes a share of the Swedish SEST time.

1.3 mm Survey: A 1.3 mm CO survey of the southern Milky Way and Magellanic Clouds has recently been started using a new 60 cm telescope near the SEST by the University of Tokyo in collaboration with ESO, the University of Chile, and Onsala (Appendix C).

2.2 The LSA

Concerning a possible large mm array project, the Advisory group made the following recommendations at its first meeting in August 1994:

- *A concept document should be prepared, to serve as a basis for further discussion and as input for a design study.*
- *A design study, supported by IRAM, ESO, Onsala, and other interested European groups, should be initiated.*
- *A joint workshop on Astronomy with Millimetre Arrays should take place next year, in conjunction with the next SEST Users Meeting.*

All of these recommendations have been carried out. A Memorandum of Understanding between IRAM, ESO, OSO, and NFRA concerning a study for A Large Millimetre Array in the Southern Hemisphere was signed on 10 April 1995 (Appendix D). The concept document "LSA: Large Southern Array" was produced in October 1995. And the ESO-IRAM-NFRA-Onsala Workshop on "Science with Large Millimetre Arrays" was held in December 1995 - the proceedings of that workshop have recently been published.

The Study Project involves many individuals (including L. Bååth, R. Booth, L. Bronfman, H. Butcher, D. Downes, P. Encrenaz, M. Grewing, S. Guilloteau, R. Hills, F. Israel, J. Lamb, K. Menten, L. Nyman, D. Plathner, A. Otárola, P. Shaver, G. Tofani, M. Torrace, A. van Ardenne, E. van Dishoek, F. Viallefond, R. Wielebinski, and T. Wilson) from a variety of institutes (IRAM, ESO, NFRA, Onsala, Bologna, Bonn, Cambridge, Leiden, Paris, Santiago). The project topics are listed in Appendix D, and a summary of LSA science, technical specs, and possible sites is given in Appendix E.

Scientific Case for the LSA: The scientific case for the LSA was amply documented at a workshop held at ESO Garching last December and summarized in the March issue of The Messenger. The proceedings of that workshop were recently published in the ESO Astrophysics Symposia series ("Science with Large Millimetre Arrays"). 49 papers discuss the science that will be possible with the LSA, ranging from the most distant galaxies to star and planet formation, and 11 papers discuss technical aspects of the LSA itself. Copies of the proceedings have been sent to STC members to accompany this document, and the workshop summary by L. Woltjer is also included here as Appendix F.

LSA Study Project - Recent Developments: Since the last STC meeting there was one meeting of the Study Project in May, and another is being held in October, immediately before the current STC meeting. A range of activities are taking place. The acquisition of site testing equipment is well advanced, and installation on Pampa San Eulogio will take place in October. Very promising atmospheric phase correction techniques are being tested with the Plateau de Bure array. New ideas and technologies for antenna design are being explored, and issues concerning receivers, IF system, correlator, and control/software are being addressed. A tentative plan for the next phase of the study has been outlined.

3. Future Developments

3.1 SEST

In accordance with the recommendations made at the May 1994 STC meeting (Appendix B), the SEST should continue to be operated and maintained at the state of the art for many years to come. The current Swedish-ESO agreement runs until June 1999, and it stipulates that its prolongation is to be discussed two years prior to that time, *i.e.* before June, 1997.

The upgrades currently being made on the SEST, particularly the provision of a nutating subreflector, open the way to a range of new possibilities, and should ensure that the SEST remains a forefront facility for the foreseeable future. At some stage, however, the question as to whether it should be moved from La Silla may have to be addressed. One possibility is Paranal, where it could share the infrastructure being built up for the VLT. Another may be the site of a future millimetre array, which may be more suitable for mm observations; the SEST could either form part of the array, or (perhaps more likely) remain a separate single dish equipped with the latest bolometer and heterodyne arrays.

3.2 The LSA

As foreseen in the Memorandum of Understanding between IRAM, ESO, Onsala and NFRA concerning the LSA project, a combined report of the Study Project is due to be completed by April 1997. This will summarize the work accomplished to date and the activities required in the second phase of the project. These will include establishment and support of several working groups (for site testing, receivers, control/software), continued site testing and the establishment of "rights" on the most promising site, the development of atmospheric phase correction techniques, the hiring of at least two engineers for antenna design and correlator development, and contracts related to antenna design and optical fibre technology. It is proposed at the moment to continue in 1997 with the same budget as in the previous two years, but the activities in the second phase will require an increased level of support.

The LSA may well be the next major project in European ground-based astronomy. As L. Woltjer put it: "The scientific case for such an array is overwhelming ... it is a perfect counterpart to HST, and ... highly complementary to the VLT". It may be located in Chile. For all of these reasons, continued ESO involvement and support at some level would seem appropriate, especially through the critical study phase.

AGREEMENT BETWEEN NATURVETENSKAPLIGA FORSKNINGSRADET (SWEDISH NATURAL SCIENCE RESEARCH COUNCIL) AND THE EUROPEAN SOUTHERN OBSERVATORY

The Swedish Natural Science Research Council, hereinafter referred to as NFR

and

The European Organisation for Astronomical Research in the Southern Hemisphere, hereinafter referred to as ESO

have agreed as follows:

Article 1

NFR and ESO will jointly install and operate on ESO territory on La Silla a 15 m submillimetre telescope which will be referred to by the acronym SEST (Swedish-ESO Submillimetre Telescope) for a period of fifteen years from the date of the signing of this agreement.

Article 2

The capital cost of the SEST (complete telescope + building), estimated as DM 8.600.000 (1983) shall be borne by NFR and ESO as follows:

NFR : DM 3.000.000
ESO : DM 5.600.000

These contributions will be subject to adjustment due to the cost variation specified in the telescope contract with IRAM (Appendix I), and for other items to the approved ESO cost variation. In addition, the two parties will each make available DM 500.000 for the initial receivers.

Article 3

Further organisational and budgetary arrangements not covered in this agreement shall be agreed upon between NFR and ESO in an exchange of letters.

Article 4

The erection of the telescope will take place at La Silla on a site fixed by mutual agreement.

Article 5

The telescope will be a 15 m IRAM telescope as defined in the contract with IRAM. Its specifications shall be agreed upon between NFR and ESO in an exchange of letters. To the extent that the contract with IRAM does not specify a specific IRAM responsibility, the technical responsibility for the telescope during the construction and installation phase will be undertaken by NFR. The technical responsibility for the transport arrangements from Europe to La Silla will be undertaken by ESO.

The design of the building will be fixed by mutual agreement. Its execution will be the responsibility of ESO.

Article 6

The design and construction of the initial receivers for the telescope will be the responsibility of NFR, but the costs will be borne equally by the two parties within the budgetary framework specified in Art. 2.

These receivers will be specified in an exchange of letters between NFR and ESO. Additional receivers may be provided later by the two parties under conditions to be mutually agreed upon.

Article 7

Any alterations to the telescope, the receivers, or the building as specified in Art. 2, 4 and 5 shall be made by mutual agreement.

Article 8

The telescope, the building and the auxiliary equipment, furniture, measuring instruments, etc. remain the property of NFR and ESO in relation to their respective investments for these items.

The parties may agree to insure the properties in which case the cost shall be shared in the same proportion.

Article 9

ESO shall undertake to provide those utilities necessary for basic functioning of the telescope and initial receivers, e.g. water, electricity, heating, liquid helium, etc. However, when during the time allotted to NFR special receivers are installed which have a much larger consumption of utilities than the receivers available as standard observatory instrumentation, ESO may charge NFR for this.

Article 10

NFR will provide a team of five persons full time, including the Scientist in charge of the telescope. NFR and ESO shall establish the necessary arrangements for the payment of salaries and site supplements to these persons, but the cost will be borne by NFR.

ESO will provide a team of three persons full time and support personnel in mechanics, digital electronics, etc., equivalent to one person full time.

ESO or NFR may request on the basis of duly justified reasons the replacement of a staff member provided to the project by the other organisation. Such a request would be jointly discussed before a final decision.

Article 11

ESO has the responsibility for the maintenance of the building, the day-to-day maintenance of the telescope and associated computer, and shall bear the corresponding costs.

Article 12

The maintenance of the receivers mentioned under Art. 5 shall be the responsibility of NFR. The costs of replacement parts and of NFR personnel beyond that mentioned under Art. 9 shall be shared between ESO and NFR in proportion to their annual share of the observing time.

Article 13

The costs of accidental damage to the telescope associated with the operation shall be borne by ESO and NFR in proportion to their annual share in the observing time.

Article 14

Individual observers may provide and install their own receivers, subject to the agreement of NFR and ESO.

Article 15

All observers and personnel shall be subject to the internal rules of ESO. They will receive transport in Chile, board and lodging on the ESO premises on terms and conditions agreed upon by NFR and ESO.

Article 16

ESO will have the right to 50% of the observing time and NFR to 50%, which latter figure then also includes what otherwise would have been the Swedish share of the ESO time, so far as possible evenly distributed over the seasons. Decisions with regard to this distribution shall be taken in mutual agreement.

Article 17

NFR will inform ESO about its observing programmes and observers in due time. Possible conflicts in this area will be resolved by mutual agreement.

NFR, in agreement with the Director General of ESO, may invite observers and personnel of other countries to share its observing time. Such observers and personnel shall have the same rights and obligations as observers and personnel of NFR.

Article 18

Two years before the termination of this agreement, NFR and ESO shall discuss its prolongation.

Article 19

Should essential circumstances and conditions underlying this agreement change or cease, both parties will enter into negotiations with respect to a revision of this agreement, fully or part.

Article 20

In case of termination of the agreement, ESO and NFR will decide about the disposition of the telescope, the receivers and the building in mutual agreement.

Article 21

All and any dispute which could arise between ESO and NFR out of or in connection with the interpretation or application of the present agreement and which could not be settled by way of direct negotiations will, unless the parties agree on another method of settlement, be submitted at the request of one of them to a Court of Arbitration consisting of three members, i.e. one arbiter appointed by ESO, one arbiter appointed by NFR, and a third one elected unanimously by the two others who cannot be an official of the Organisation nor a Swedish subject and who will chair the Court.

The application to institute arbitral proceedings must contain the name of the arbiter appointed by the plaintiff's party; the defendant's party will have to appoint its arbiter and communicate his name to the other party within two months from the date of receipt of the application to institute arbitral proceedings. Should the defendant's party not notify the name of its arbiter within the above mentioned period, or should the two arbiters not agree upon the election of a third arbiter within two months from the last arbiter designation, the arbiter or the third arbiter, according to the case, will be appointed by the President of the International Court of Justice upon request of the most diligent party.

The Court of Arbitration shall convene in Munich and decide on the basis of the terms of the present contract and subsidiarily the terms of German law. The tribunal will establish the rules of procedure. Its decisions will be imposed upon the parties and are incontestable.

In witness whereof the undersigned have signed this Agreement.

Onsala, 26 June 1984

For the Swedish Natural Science Research Council

Ingvar Lindqvist

Professor I. LINDQVIST

Huvudsekreterare, NFR

For the European Organisation for Astronomical Research in the Southern Hemisphere

On behalf of:

Giancarlo Setti

Professor L. WOLTJER

Director General of ESO

Extract from the Minutes of the STC Meeting, 5-6 May 1994:

The future of (sub)millimetre astronomy at ESO

P. Shaver presented a report on (sub)millimetre astronomy at ESO (STC-148). S. Beckwith presented the recommendations of the SEST Working Group (Annexe 10). Members of this group were: P. Andreani (Italy), S. Beckwith (STC, chair), R. Booth (Sweden), L. Bronfman (Chile), P. Encrenaz (France), M. Grewing (IRAM), P. Hall (Australia), F. Israel (Netherlands), P. Shaver (ESO) and T. Wilson (Germany). The recommendations were supported by the STC. In particular, it was agreed that the Director General would appoint a permanent advisory group for the SEST.

Recommendation paper to the ESO STC
(SEST Working Group, Draft 28.04.94)

The SEST Working Group met on 19.04.94 to discuss the future of SEST. The Working Group consists of ten members, most of whom had used SEST. The discussion concerned the relative output of SEST to date, probable future directions, and technical recommendations to ensure that the facility is competitive into the next century.

A survey of the science, done by SEST shows that it is a productive facility which has been producing results at or near the state of the art in a wide number of subfields. It supports a large user community. This user community is both active and satisfied with the access SEST has provided them for mm wave observations. The use of the telescope has leveled but not declined, and it is clear that, compared with other ESO facilities, the demand for time, the access, and the relative output are essentially identical with the best facilities ESO has to offer, including the NTT and the other large optical telescopes. This is one reason why SEST should be continued, since there is no obvious fall-off in the demand or output from the telescope.

The group sees the future of mm wave astronomy as moving toward high resolution and large collecting area through the use of large, distributed arrays. It was the consensus of the Group that, over a two decade time period, a very large mm array would be constructed by Europe, the United States or Japan, and that the science drivers justifying this array are compelling enough to ensure that mm wave astronomy will undertake some of the most interesting current problems in astronomy. Two readily identifiable examples are the study of very high redshift objects, particularly very young or primeval galaxies, and the study of newly born stars and young planetary systems. To this end, it was deemed vital to maintain a European facility such as SEST, so that a wide community can participate in these future developments. The aforementioned examples are currently addressed mainly by other telescopes owing to instrumental limitations of SEST.

There was a consensus that improvements in the telescope and receivers could bring these problems within the reach of SEST and ensure that the telescope and the community addressed scientific questions at the state of the art.

Several new spacecraft or suborbital missions will require a European mm telescope to allow preparation and followup. The ISO mission, scheduled for launch a year and a half from now, will return data in the submm, much of which will require further observations with mm wave facilities, including SEST. SOFIA, which is a proposed US-German collaboration, will be asking for a new start in 1996. SOPHIA and SEST will work together in addressing problems concerned with far-infrared and mm astronomy for ten to twenty years. Finally, FIRST will be the last major cornerstone in ESAs Horizon 2000 programme. It is important that the European community, which must then take the lead in submm science, remain active throughout the intervening period to ensure maximum return on this large investment.

To these ends, the Working Group makes the following recommendations to the STC:

1. That SEST continue to be supported. It is the opinion of the committee that SEST will remain an interesting and important part of ESO's programme into the 21st century, and the agreement with Sweden should be extended, when it comes up for renewal.

2. The next instrumental developments on SEST should include arrays of receivers for line or continuum observations. In both cases, a nutating secondary will be required to realize the gains possible with the array detectors. Therefore, a design and cost study for a nutating secondary should be undertaken immediately.

3. Design and cost studies should be undertaken to provide estimates for the cost of

   (a) line receiver arrays with new backends,
   (b) bolometer arrays.

   It seems unlikely that both developments can take place within the current budget, but a proper cost study may help decide which short term developmental direction should be taken. The science to be done on line or continuum emission is equally interesting.

4. To effectively use the capabilities brought about by new instrumentation, it will be important to ensure that

   - the pointing is accurate and reliable,
   - the surface accuracy of the telescope is well understood and possibly improved,
   - that the receivers, bolometers, and backends are sufficiently reliable to relieve the on site staff of unnecessary maintenance requirements.

5. There is also a long term desire to look into the possibilities of service or remote observing. The Working Group had insufficient time to understand the costs involved in these observing modes. Furthermore, it was felt that the overall productivity of the on site team would have to be increased through reorganization or possibly a reallocation of resources to different areas, if any new work is to be undertaken. Therefore, the Working Group recommends that these areas now be explored by a study group appointed specifically to look into the details.

6. Unlike most other major facilities, SEST currently has no advisory group to routinely monitor the management of the facility. This is a particular problem for SEST, because SEST is a different kind of facility than ESO normally operates. Therefore, the Working Group recommends the appointment of a permanent advisory group which will, at a minimum, report to the STC and perhaps also to the Swedish community.

The committee discussed the possibility of moving SEST to Paranal to take advantage of the superior site characteristics, clear weather, and lower water vapour content. Although there is a potential advantage in such a move, we cannot yet make a recommendation, since the costs of the move are unknown, and La Silla is already a good site for millimeter (but not submm) astronomy. In view of the currently succesful operations, it was perceived as not an urgent issue, one that could remain under study for some time.

Agreement

Following the successful Columbia Survey (a collaboration of Columbia University, NASA Goddard Institute for Space Studies, and University of Chile) of the 2.6 mm wavelength, ground state rotational transition of carbon monoxide (CO) in the Milky Way and Magellanic clouds, using 1.2 m diameter radio telescopes based in both the Northern and Southern hemispheres, and

bearing in mind the importance of observations of higher transitions for the full interpretation of the molecular data in terms of the physical conditions in the interstellar gas, and

in the knowledge that the University of Tokyo Radio Astronomy Group has built a 60 cm diameter millimetre telescope for survey observations of CO in its first excited state at a wavelength of 1.3 mm,

the University of Tokyo Radio Astronomy Group, hereinafter referred to as UT,

the European Southern Observatory, hereinafter referred to as ESO

the University of Chile Astronomy Department, hereinafter referred to as UCh

and

the Onsala Space Observatory, hereinafter referred to as OSO

have agreed as follows:

Article 1.

UT, ESO, and OSO will jointly install on the ESO territory on La Silla a 60 cm millimetre telescope for a period of five years from the date of signing of this agreement.

Article 2.

The capital cost of the telescope and its operation shall be borne by UT, although ESO and OSO will assist in the installation of the instrument.

Article 3.

The erection of the telescope will take place at La Silla on a site fixed by mutual agreement.

Article 4.

The initial receiver for the telescope shall be on loan from ESO and OSO, who shall have the right to use it on the Swedish ESO Submillimetre Telescope, SEST, if and when so deemed necessary.

Article 5.

UT will provide an operator for the 60 cm telescope, who shall also be responsible for its day to day maintenance, and that of its instruments, although SEST engineers may give occasional advice and assistance.

Article 6.

ESO shall undertake to provide utilities and support as required for the basic functioning of the telescope, as part of the SEST collaboration.

Article 7.

The observing programme of the telescope shall be agreed by mutual consent of all parties (UT, ESO, UCh, and OSO) and the data shall be published in the name of those parties. Any other participants in the data interpretation and publication must be agreed by the signatories of this agreement or their representatives.

Article 8.

After publication, the data shall be released into the public domain in a manner to be determined by mutual agreement.

Article 9.

Should essential circumstances and conditions underlying this agreement change or cease, all parties will enter into negotiations with respect to a revision of this agreement, fully or in part.

Article 10.

Should a new general agreement between ESO and the Government of Chile be signed, the operation of this 60 cm telescope shall be in accordance with that general agreement.

Article 11.

In case of termination of the agreement, UT shall remove the telescope or be responsible for its disposal within a year.

In witness whereof the undersigned have signed this agreement

15 April 1994

For the University of Tokyo
Radio Astronomy Group

T. Hasegawa

Professor Tetsuo Hasegawa

For the European Southern Observatory

Riccardo Giacconi

Professor Riccardo Giacconi

For the University of Chile
Astronomy Department

Professor Leonardo Bronfman

For the Onsala Space Observatory

Professor Roy Booth

Memorandum of Understanding

concerning a study for A Large Millimetre Array in the Southern Hemisphere

Considering that:

- the millimetre waveband is one of the richest in astronomy, unique in containing the peak of the microwave background, the thermal dust emission from protogalaxies and protostars, and the whole panoply of molecular line astronomy, and lies at the crossroads of radio and optical/infrared astronomy
- a large millimetre array which can provide very high sensitivity and angular resolution is one of the highest priorities in radio astronomy today
- such an array will open new frontiers in astronomy such as the study of galaxy formation in the early Universe, and by making objects of all kinds accessible will open up the millimetre range to the entire astronomical community
- such an array requires environmental conditions similar to those required by large optical telescopes, and is best placed in the southern hemisphere where it can complement and enhance the European investment already being made in the VLT

The Institut de Radio Astronomie Millimétrique (IRAM), The European Organisation for Astronomical Research in the Southern Hemisphere (ESO), The Onsala Space Observatory (OSO), and The Netherlands Foundation for Research in Astronomy (NFRA) have agreed as follows:

Article 1.

IRAM, ESO, OSO, and NFRA will conduct a study of the scientific and technical aspects of a large millimetre array in the southern hemisphere. The study will be coordinated by a board comprised of one member from each of IRAM, ESO, OSO, and NFRA, which will agree on tasks and the distribution of responsibilities.

Article 2.

IRAM will serve as host and carry the administrative responsibility for the study and provide the necessary infrastructure, budgetary control and accounting/reporting. The internal rules and procedures of IRAM will apply to all contracts written as part of the study. Such contracts will require unanimous agreement of the board.

Article 3.

IRAM will provide up to two man-years per year for the study, one of whom will be the study manager, and ESO, OSO, and NFRA will each provide DM 90.000 (or the equivalent in manpower) for the first year. The board will oversee the allocation of these funds. Any further contributions, financial or otherwise, will be agreed to and noted in an exchange of letters.

Article 4.

The study will be conducted in a series of stages, with reports to the board at regular intervals, at least every six months. Interim results will be presented in a series of technical reports. A combined report addressing the issues listed in the appendix to this Agreement (MOU) will be prepared by the study manager within a period of two years from the date of signing of this Agreement. It is intended to serve as a basis for further discussions concerning the prospects of funding and constructing a future large millimetre array in the southern hemisphere.

Article 5.

Further organisational and budgetary arrangements not specifically covered in this Agreement shall be agreed upon by all parties in an exchange of letters. Should essential circumstances and conditions underlying this Agreement change or cease, all parties will enter into negotiations with respect to a revision of this Agreement, fully or in part.

Article 6.

In case of termination of this Agreement before completion of the combined report (*cf.* Article 4), all parties will decide about the disposition of the work performed by mutual agreement.

Article 7.

Failing an amicable settlement of any dispute, the parties shall resort to arbitration under the conditions of a Convention, to be concluded by all parties if and when the time comes.

In witness whereof the undersigned have signed this Memorandum of Understanding

10 April 1995

For the Institut de Radio Astronomie Millimétrique

Michael Grewing

Professor Michael Grewing

For the European Organisation for Astronomical Research in the Southern Hemisphere,

Riccardo Giacconi

Professor Riccardo Giacconi

For the Onsala Space Observatory

Professor Roy Booth

For the Netherlands Foundation for Research in Astronomy

Harvey Butcher

Professor Harvey Butcher

Appendix

Millimetre Array Study Topics

1) Site

The site has important consequences on the antenna design and servicing as well on operational costs.

- Identify possible locations
- Obtain quickly rough meteo statistics
  - number of clear days, clear nights, average cloudiness
  - wind speeds, temperature range, humidity
  - most extreme conditions
- Evaluate operational costs
- Perform representative site studies
  - Build 1.3 mm radiometer suitable for atmospheric stability study

2) Antennas

This item is strongly coupled to the atmospheric properties of the site. The study should consider all possible locations in this respect. This is the most original part of the study, since all other items have been (or have to be) considered in the MMA study.

- thermal behaviour
  - open air operation (no radome)
  - surface accuracy under sun illumination
  - pointing accuracy even under sun illumination
  - focus stability
  - stability of the intersection of the axes (which define the baseline length and thus the phase stability of the array)
- survival conditions with respect to environment
  - need for deicing ?
  - need for closed backup-structure ?
  - wind and impact protection ?
- operational conditions
  - wind limit
  - icing/dew deposition on surface
- astronomical specifications
  - error budget for surface, including evaluation of the specifications on financial implications. Main goal is frequency range 70-270 GHz: possible access to the 350 GHz window should be considered, but may be too expensive
  - pointing accuracy
  - focus stability
- Transporter
  - fixed/movable antennas
  - tire equipped transporter ?
  - movable maintenance/assembly shelter ?

3) Receivers

- SIS vs HEMT at 100 GHz
  - SIS have better noise figures than HEMT at 100 GHz and can be Single-Side band tuned
  - HEMT have higher instantaneous bandwidth but are inherently DSB but can we utilize this bandwidth ?
- Availability and Reliability of cryogenic systems
  - cooling power and temperature stability specifications
  - size and power requirements
- Fixed vs Tunable mixers
- Simultaneous frequency coverage
  - 2 or more simultaneous frequencies: evaluate impact on sensitivity given the additional optics required and the primary beam mismatch.
  - Can HEMT be used to obtain SIMILAR simultaneous frequencies ?
  - Need and use of the polarisation
  - Impact on ease of maintenance
- Maintenance aspect
  - propose modular concept, and evaluate losses compared to more optimized design

4) Intermediate Frequency transport system

- Define required bandwidth
- Evaluate optical fiber systems
  - for local oscillator phase reference
  - for signal
- Digitized/Analog transport of the signal
- Delay lines: analog or digital?
- Multi-frequency operation

5) Correlator design

- Define goals
  - several flexible identical units
  - one (or more) dedicated continuum correlators + one (or more) dedicated spectral correlators
  - need for cross-polarization ?
  - need for Sideband separation ?
- Evaluate technological possibilities
  - ultra-fast chips
  - many channels slower chips
  - develop and test ultra-fast samplers

6) Control

- Timing control
  - in distributed environment (kilometer size array)
- Walsh switching scheme
  - in Multi-frequency operation

7) Software

8) Atmospheric phase compensation system

- Incorporate in design an atmospheric phase monitoring system based on total power fluctuations.
- Build and test such devices

Science with the LSA

- **Early Universe Studies:** Star-forming galaxies out to $z \sim 20$; timsecale of galaxy formation and evolution, continuum and line observations at high resolution. LSA surveys will be dominated by galaxies at high redshift, and will be the principal means of finding young galaxies in the early Universe. Our own Galaxy would be detectable out to $z \sim 4$ in CO or [CII].
- **Gravitational Lensing:** The LSA will be particularly well suited to studying both strong lensing, cluster arcs, and weak lensing (the shear field), due to its high sensitivity and angular resolution.
- **QSO Molecular Absorption Lines:** A new field, which may make possible measurement of gravitational lens time delays, CBR temperature and isotopic abundances as a function of redshift, *direct* measurement of q_o.
- **Active Galactic Nuclei:** LSA will probe deeply into galactic nuclei because of low synchrotron and dust opacity at mm wavelengths. Used for mm VLBI it will provide microarcsec resolution with unprecedented sensitivity, $T_B \sim 10^2 - 10^6$ K.
- **Detailed Studies of Galaxies:** LSA will provide the same angular resolution at $z \sim 1$ as achieved now for local galaxies, comparable to HST, in molecular lines and continuum. Detailed studies of the central regions of galaxies - molecular tori and rings, nuclear star formation, kinematic (maser) evidence for black holes.
- **The Galactic Centre:** Unobscured study of SgrA* and its environment, gas kinematics (and proper motion studies?)
- **Interstellar Absorption Lines:** Observed in absorption against extragalactic sources -> sample random (unperturbed) clouds, so ideal for unbiased statistical studies.
- **Astrochemistry:** Detailed study of the chemical and physical processes in molecular clouds, molecular abundances, dynamics and evolution of clouds and their interaction with star-forming regions.
- **Protostars:** The elusive protostars are probably best found by virtue of their cold dust emission at mm wavelengths.
- **Young Stellar Objects, Accretion Disks and Outflow Jets:** Accretion from parent molecular clouds, disk dynamics, presence of rings, evidence for planet formation, generation and collimation of jets.
- **Masers:** Interstellar and circumstellar (disk and envelope) maser emission: probes of the chemistry and physics, potential for distance measurement (kinematic or statistical parallax), use as "maser guide stars" to assist in imaging faint circumstellar emission.
- **Stars:** Thousands of stars over the whole HR diagram will be detectable: winds of early stars, photospheres and chromospheres of giants and supergiants, thermal emission from other evolved stars, non-thermal emission from active stars.
- **Supernovae and Supernova Remnants:** Radio supernovae first detectable at mm wavelengths, out to 30 Mpc. Distance determinations from VLBI studies. Detailed study of SN 1987A (shock wave will hit the [OIII] ring in 2005 $\pm$ 3!).
- **Circumstellar Shells around Evolved Stars:** A unique probe of time-dependent chemistry, detectable with LSA out to 6-10 kpc, the distance of the Galactic molecular ring.
- **Solar system Studies:** Composition, isotopic studies, thermal structure, meteorology of planets; size, albedo, and thermal properties of asteriods; dust properties and molecular composition of comets.
- **Extrasolar Planets:** Direct detection marginal, but indirect detection may be possible through precise astrometry with LSA.

LSA Parameters

Wavelength range: a *millimetre* array, operating mostly at 1.3 and 3 mm.

Angular resolution: 0.1" at a wavelength of 3 mm. Required for many of the astrophsical goals and for compatibility with the VLT.

Collecting area: 10,000 m^2. Necessary to achieve adequate sensitivity at the desired angular resolution, and provides the factor of ten increase over existing mm facilities.

Number of antennas: $\sim$ 50-100 for antenna diameters of 11-16 m. (Compare with VLA (27 $\times$ 25 m), GMRT (30 $\times$ 45 m), Culgoora radioheliograph (96 $\times$ 13 m)).

Number of baselines: $\geq$ 1000, for fast, high-quality images.

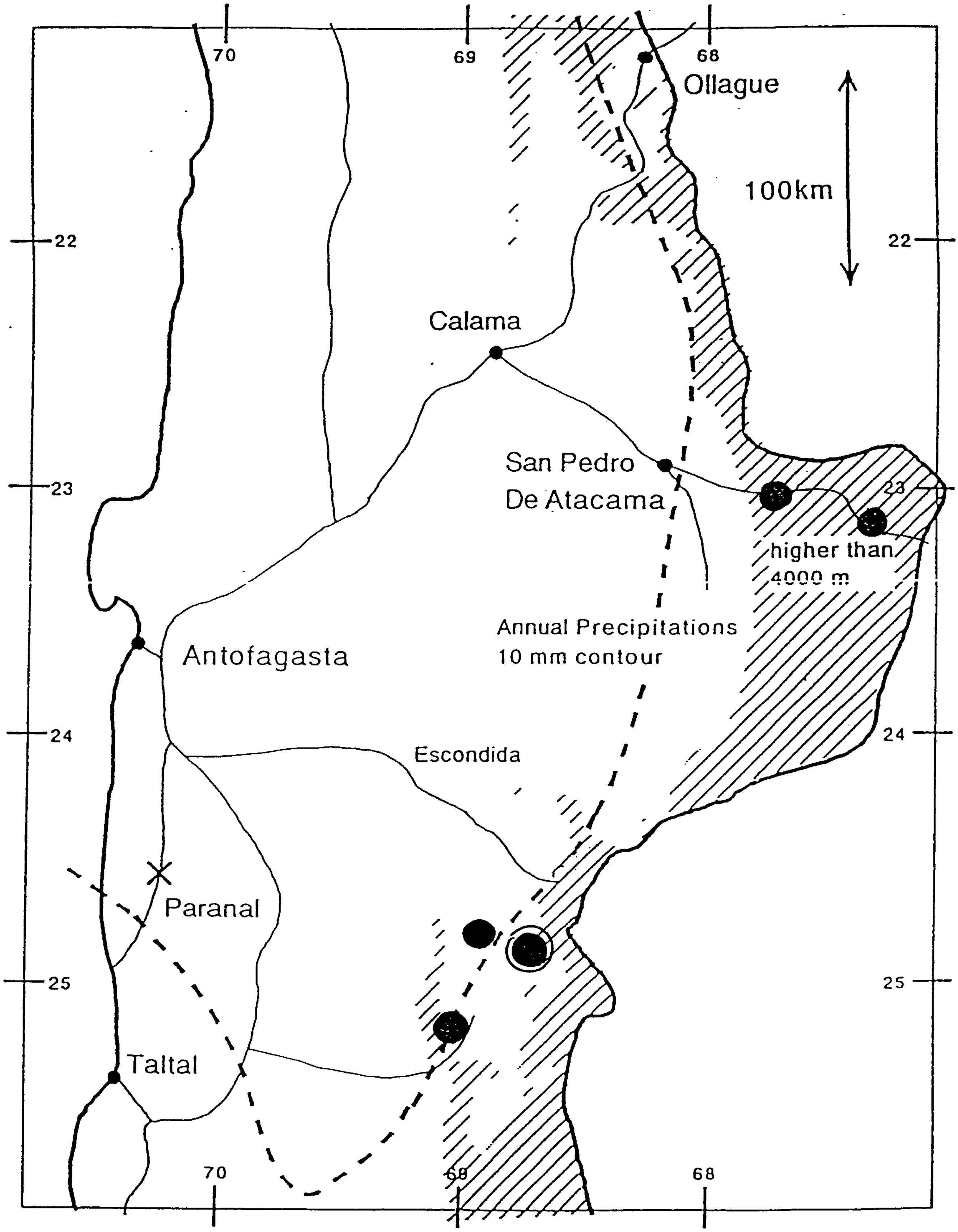
Length of baselines: up to 10 km, to achieve the required angular resolution.

Site: Above 3000m in an extremely dry environment, in the southern hemisphere for compatibility with the VLT.

Cost: $\sim$ 270 M Ecu ($US 340m), projected from IRAM experience.

Table 1. 10-Sigma Sensitivity at 230 GHz in 1^{hr} with $T_{sys} = 100\,K$ and Area = $10^4\,m^2$.

		—— Galactic ——		— Extragalactic —		Continuum
max. baseline	230 GHz beam	resolution at 10 kpc	$10\,\sigma$ at $\delta v = 2$ km/s	resolution at 10 Mpc	$10\,\sigma$ at $\delta v = 20$ km/s	$10\,\sigma$ at $\delta\nu = 2$ GHz
0.3 km	1″	5.0 10^{-2} pc	0.1 K	50 pc	0.04 K	0.2 mJy
1.0 km	0.3″	1.5 10^{-2} pc	1 K	15 pc	0.4 K	0.2 mJy
3.0 km	0.1″	5.0 10^{-3} pc	10 K	5 pc	4 K	0.2 mJy
10. km	0.03″	1.5 10^{-3} pc	100 K	1.5 pc	40 K	0.2 mJy



Some of the sites considered for the LSA (●). Pampa San Eulogio is circled.

Summary Talk of the ESO-IRAM-NFRA-Onsala Workshop

"Science with Large Millimetre Arrays"

11-13 December 1995

Concluding Remarks

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It is interesting to remember that 20 years ago there was still much discussion if there would be small enough structures to resolve with a 1 km interferometer or if large dishes were better suited to study the InterStellar Medium. This finally resulted in the creation of IRAM, a sort of forced marriage of a dish and an interferometer, which has been remarkably successful. By now there is no doubt that as Reinhard Genzel said "you can never have enough angular resolution", and since resolution without enough sensitivity to exploit it is not very useful, the need for large arrays becomes obvious.

The scientific case for such an array is overwhelming. From the nearest planets to the outer reaches of the universe it would have an enormous impact. During this conference we have seen that promising areas of research include the chemistry and dynamics of planetary and stellar atmospheres and of the ISM, star formation, the dynamics and evolution of galaxies, gravitational lensing, the formation of galaxies and cosmology. Surveys in the continuum, in CO and in C^+ will tell us much about evolution in the Universe up to perhaps a redshift of 10 – at least if such high redshift objects exist. Not only will a large array contribute to our understanding in all these areas in a quantitative way, there are also numerous aspects where such an array can lead to entirely new areas being opened up and thereby to unique and qualitative progress.

It is important to note that the array is a perfect counterpart to HST with comparable resolution, but unhindered by dust opacity. Also it is highly complementary to the VLT, as discussed earlier by James Lequeux. Of course, we should evaluate the impact of this array not in the context of today's science, but rather in the one to be foreseen for the period around 2010. But this gives even greater opportunities. HST will have explored the near infrared region by then, while the VLT with its adaptive optics will have attained high angular resolution in the IR windows accessible from the ground.

It appears to be a particularly fortuitous moment to propose an array for the mm region since adjacent communities are developing rapidly: ISO has received 1000 observing proposals, many from "optical" or "radio" astronomers, while the prospect of FIRST has led to the crystallization of an active submm community. Both of these communities will continue to struggle with poor angular resolution (10–30 arcsec for typical wavelengths of ISO and FIRST) for the foreseeable future, and consequently they will much benefit from better images at adjacent wavelengths.

The development of radio facilities follows rather closely that in the optical. The total collecting area of the world's optical telescopes has been doubling every 11 years for much of this century. That of European optical facilities came off to a slow start, but has accelerated over the last 30 years doubling on average every

7 years. These figures are very comparable to those given by Dennis Downes for cm facilities, while the development of mm facilities currently is slower. The great increase in optical collecting area has become possible by a substantial decrease in the cost per m^2 due to the introduction of new technology – in particular active optics. A similar development should be achievable in the construction of a mm array partly by the cost reduction due to the building of a large number of identical telescopes and undoubtedly also by the application of new technology. Of course, the replication advantages would be partly lost if the array would be composed of different types of telescopes (e.g. for mm and for submm) or if the construction time would be stretched out over too long a period.

Optimization of such an array will need much care. To be meaningful it has to be done at a fixed financial envelope and from a broad astronomical point of view. The optimization will involve the frequency range, the diameter of the unit telescopes, the required field of view, the movability of some or all of the telescopes, the altitude and the location of the site. It should also include the operating costs for a decade or so.

The maximum frequency to be achieved strongly affects both the unit telescope cost and the site water vapor requirements, and thereby possibly the necessary altitude. Clearly, at fixed cost an array that aims to function in the 0.3 mm window will be very much smaller than an array limited to 1 mm. The impact of telescope diameter and field of view should be less, but rather detailed technical studies will be needed. Movable telescope are obviously more expensive than fixed telescopes, while also operationally they should add further costs. However, for a proper coverage of the uv plane they have major advantages. Again, detailed studies are needed on the cost factors involved in making the telescopes all movable or only some of them.

Altitude is a major cost factor. Most of us function without too many problems at 4000 m. However, at 5000 m the situation appears to be radically different. This very much impacts the construction costs (installation on the site, building of the infrastructure). It probably even more affects the operating costs. Even at a site like La Silla, ESO has found it difficult and costly to attract qualified engineering personnel, and this would a forteriori be the case at a much higher and more remote place. Location is also important, but almost certainly the Chilean sites are to be preferred. Sites in Namibia probably are inferior to La Silla, while the east side of the Andes is wetter than the west side. Interannual variations may be rather large and daily ones even larger. In comparing a few selected sites it is therefore important to simultaneously measure atmospheric transmission in these, while in the final selection as long a series as possible should be obtained. At Paranal such measurements have been made during six years, and for much of the time comparable data were obtained at La Silla. During the ESO site selection process also numerous data on integrated atmospheric water vapor content and other parameters were obtained by Arne Ardeberg at higher sites further east. These sites were unsuitable for optical telescopes because of higher frequency of cirrus clouds over the Andes, but the extensive data obtained often nearly simultaneously at different locations well deserve to be integrated with the data being obtained now.

The final issue I should address is how to realize the project from a financial and political point of view.

First of all, it is necessary that such a project be supported by a broad astronomical community. This is not yet the case and much "missionary" work remains to be done: presentations at scientific meetings, etc.

A second and rather fundamental point is the relation of the project to ESO. A connection with ESO has three principal advantages: ESO has a good framework for its activities in Chile; even though recently some difficulties have occurred in the relationship between Chile and ESO, these should be regarded as temporary and undoubtedly will have been forgotten a decade from now. Secondly, ESO is engaged in a major project, the VLT, which will be completed very early in the next decade. While the continuing flow of funds to ESO for a subsequent project is not at all guaranteed, it is, nevertheless, clear that it is easier to redirect an existing flow of funds to another project than to start a new flow from scratch. Thirdly, ESO has the experience to deal with large projects, and it is not so simple to build this experience anew.

There are, of course, also problems. First of all, ESO has from a scientific and technical point of view only a limited connection to the mm community, though it should be added that the SEST experience has already improved this quite a bit. Secondly, it is not clear that all ESO member countries would have the same enthusiasm for such a project, while some countries not in ESO, like Spain or possibly the U.K., might wish to participate. The former problem could if necessary be solved by making the array a "special project" in the sense of the ESO Convention. This is a juridical and possibly also politically acceptable option, but it is not very attractive to split the ESO community and also administratively it is cumbersome. In this respect it would also be extremely regrettable if one or more European countries were to join the U.S. project, at least if this were to preclude their later participation in the European one. Unfortunately, this risk it not at all hypothetical.

The other problem could conceivably be solved by an ad hoc contractual arrangement; in the case of Spain, the problem would disappear if the current discussions about a possible ESO membership were to come to fruition.

Another possibility would be to create a joint ESO-IRAM venture. As an example of such an arrangement the European Coordinating Facility for the Space Telescope may be mentioned, which is sponsored conjointly between ESA and ESO. However, this would be more difficult in the case of IRAM because of its different legal framework. Nevertheless, if all partners wish so, there is generally a way to solve such problems.

The final question concerns a broader international cooperation with the U.S. and/or Japan. Considerable obstacles exist to the idea of building one joint array, in part because of the different time scales. Furthermore, industrial policy plays an important part in the funding process. It is not clear that all partners would agree to a 1/3 share, and I do not think that an arrangement like in GEMINI (2×8 m optical, 1/2 U.S.A., 1/2 rest of world) would be attractive for Europe.

However, it would be important to maximize compatibility between the three arrays so that medium baseline interferometry between them would be possible, yielding increased angular resolution.

More immediate than all this is to start work on a detailed technical study of the array, including some studies in industry. A sum of the order of 10 MECU would be needed and perhaps some of this could be found in the European Union. Such a project needs a name. How about LEMMA, for the Large European MilliMeter Array? A lemma in mathematics is an element in a proof, and the array undoubtedly will prove or disprove many hypotheses about the Universe. Should the array finally become really international instead of European only one letter has to be changed.