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THE LARGE MILLIMETER TELESCOPE (LMT)

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RESUMEN

Se presenta el proyecto del Gran Telescopio Milimétrico (GTM) que será construido por el INAOE en una colaboración binacional con la Universidad de Massachusetts, en Amherst. Este es un ambicioso proyecto que consiste en una gran antena de radio que estará optimizada para trabajar en ondas milimétricas rodeada por una cúpula o radomo y será construido en México y operado por ambas instituciones. El costo del proyecto se estima en 46.4 millones de dólares, con un financiamiento binacional.

ABSTRACT

The Instituto Nacional de Astrofísica, Optica y Electrónica and the University of Massachusetts present a binational project, The Large Millimeter Telescope (LMT) which involves the construction of a 50 m radio antenna. This instrument will operate in millimeter wavelengths with a radome or protective enclosure and will be constructed in Mexico and operated by both institutions. The construction and operation of the instrument has an estimated cost of 46.4 million US dollars; the financing is also binational.

Key words: **SITE TESTING — TELESCOPES**

1. THE SCIENTIFIC LMT PRODUCTION

The millimeter radiation is generated in different processes that take place in the Univèrse. In particular, the rotation of molecules emits and absorbs radiation at such wavelengths, and could be an important tool for measuring velocities, chemical abundances, densities, temperatures, etc. in regions where such molecular compounds are present. Moreover, given the temperatures involved, the thermal radiation in the interstellar matter can easily be detected.

With its projected large collecting surface, and its superior sensitivity to other existing telescopes of its kind, the LMT telescope will have a great impact for its capacity to detect both weak spectral lines, and also radiation sources of extremely low intensity. Some examples of its important potential for research are as follows:

1.1. Spiral Galaxy Structure

The LMT will be able to map the spiral structure of the galaxies with excellent spatial resolution, hence enabling a better understanding of the relationship between molecular clouds and dust emission, as well as with neutral hydrogen and Hα emission, thus enabling the study of the role of the spiral density waves on the star formation history at the spiral arm regions. These observations will allow us to derive the temperature, density, mass and kinematic properties of such regions. The knowledge of these parameters will help us in our understanding of the conditions at which proto-stellar collapse occurs.

1.2. Geometry of the Magnetic Field

Using a polarimeter the LMT will turn into an ideal instrument to study the geometry of the magnetic field in the central regions of dense molecular clouds. Current observational evidence from the external part of the clouds, suggest orderly magnetic fields. Throughout gravitational collapse, magnetic field lines can not be frozen and in order to have the contraction that allows stars to be formed, a magnetic flow must occur.

1.3. Formation of Stars and Planetary Systems

Early stages of stellar formation are characterized by accretion and ejection of material. The magnetic flow carried out by ejection of jets has a definite influence in the evolution of the process. Eventually, it is believed,

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it stops the accretion of material, removing also gas around the forming star. The nature of this wind and its interaction with neighboring material is key to understanding the formation of planetary systems. The low surface brightness of these regions has limited their observation only to the closest objects. The LMT greater sensitivity will allow us to extend the observation of these phenomena to a greater number of stars, at larger distances and for the more recent formation. Millimetric observations in the continuum, with other telescopes, show that is possible to observe rings around young stars, at the distance of the closest regions where active star formation is known to occur; for example in ρ Oph and Taurus. We will be able to analyze the dust implied by excess infrared emission of certain stars to establish limits on the dissipation time of these regions; moreover, with the large gain of LMT we can search for the gas in these remnants. From these observations, we can draw important clues for the formation of objects similar to the jovian planets in the solar system.

1.4. Stellar Chemistry

Chemical composition in interstellar clouds is very important, because these regions contain molecular material widely distributed and of great variability, indicative of fundamental processes that must be studied. The LMT will enable us to investigate molecular and isotopic species of lower relative abundances. This chemistry will shed light on the processes that occur at very low temperature. For example, the incorporation of oxygen and carbon atoms to dust grains as a result of the mixture of solids and gases.

1.5. Planetary Radar

The LMT will be the leading instrument in the field of millimeter planetology using radar. Radar development with the LMT, working on millimeter wavelengths will extend current frequency coverage by an order of magnitude and will produce fundamentally new data of excruciating detail in the solar system. Using high power transmitters, currently available (of about one kW at 94 GHz), the LMT will be able to detect objects such as asteroids within 0.05 AU of earth. Recently, one asteroid of this kind per year has been discovered. NASA's great interest on this search makes us believe that the discovery rate for these objects will increase in the future. Better resolution will allow the observation of more objects using current technology coupled to the LMT. The instrument will permit the observation of irregularities of millimeter scale on planetary surfaces. The LMT radar will be capable of scanning a wide area of the sky, relevant to the observations of comets and asteroids approaching earth. With these capabilities, the LMT will be a powerful instrument that will extend our understanding of the nature of planetary objects.

1.6. Extragalactic Studies

The resolution, sensitivity and mapping speed, both in spectral lines and in the continuum, make LMT an ideal instrument for extragalactic observations. At the distance of the Virgo Cluster, it will allow mapping of the distribution of molecular clouds in a galaxy, measuring directly their dust content. Today, we believe there is a relationship between quasars and galaxies with active nuclei and infrared ultraluminous galaxies. These objects seem to have very large gas densities, as required for intense star formation bursts in active galaxies. It is possible to build a set bolometers for the LMT to look for these objects at great distances. For these reasons the LMT will yield crucial data to understand the spectral distribution of energy of galaxies with active nuclei, thus allowing us to explore the relationship of galaxies rich in gas and dust with centers of star formation in both quasars and active nuclei.

Hence, the LMT will be capable of making new important contributions, from nearby objects such as asteroids and other objects in the solar system, all the way to the most distant objects such as quasars. Its versatility will be unique for at least ten years, when new instruments will be built.

2. THE HUMAN RESOURCES DEVELOPMENT

The highly specialized human resources formation during the project execution is crucial. It is not just the need of increasing the number of astronomers, but also of engineers, because the technological spin offs could be of great importance for Mexico. A part of the project budget is necessary for this strategic task, where the goal is the preparation of more than fifty persons.

The training areas of researchers and engineers are: radioastronomy, mechanical engineering, control, electronics and communications, as well as physics of detectors. 80% of the human resources development program will be for the training of engineers. The methodology to accomplish this goal depends on the subject, but has in common the instruction in practice. The curricular design is an essential part in such program.

Additionally, we look for the involvement of other higher education institutions to share responsibilities in promoting the new knowledge for the technology development. The education in microwave engineering is one of most important items in our consideration. So far, we have the participation of the Facultad de Ingeniería of UNAM, CICESE, of the Universities of Puebla, Nuevo León, Querétaro, and Guanajuato, and of the Technological Institutes of Querétaro, Puebla and Aguascalientes.

The participants' selection process is of great importance. The goal is to work with a universe of around 400 people selected both from the academic institutions and the productive sector. At the end, about 50 persons will be associated to the LMT project execution. Up to mid 1995, in an experimental way, around 230 individuals were informed about the program and 18 persons were selected. Two of them are already studying their Ph.D. in high frequency electrical engineering at the University of Massachusetts.

Within the formal instruction process, the tendency will be to get the Ph.D.; however, in the case of the personnel from companies associated with the project, the training on the job will be the main goal. This scheme requires an accreditation process, planned carefully, where the practice work is recognized as an essential part of the requirements to obtain the degree or diploma of speciality. The institutions will have the necessary flexibility according to this experimental program. Binational committees will evaluate the academic quality of the program. The University of Massachusetts will host around 20% of the candidates for Ph.D. studies.

In a project of like LMT, it is important to consider both the experience and knowledge of persons, in order to select the best qualified students not only from the technical point of view, but also by their ability to meet the challenge of participating in a world class instrument, with strict time limits. At the end of the project less than half of the prepared group will join the LMT operation. The rest of them will work in higher education institutions, where they already belong, or in the private companies where they can develop new products and services.

The five years needed for the construction of LMT are enough time to make this education program possible with a strong practice emphasis. The project budget considers the necessary scholarships. Some enterprises have already stated their intention to pay for the needs of their qualified personnel.

3. PROJECT COMPONENTS

In general, the project is composed of three major areas: the construction of a fifty meter diameter antenna, protected by a radome or a structure that can be opened, with a membrane transparent to microwaves; the integration of the control system for the radio-telescope and; the development of the instruments to detect millimetric radiation.

3.1. Antenna

The antenna has also three basic parts: i) a large parabolic steel structure, covered with an active surface of hexagonal panels of aluminum, or composed aluminum alloy. Each panel will be supported by movable parts allowing for independent adjustments; ii) the secondary reflector, that INAOE has the responsibility to built, also made of aluminum or other materials, and iii) the structure to support the antenna, which has some alternatives now under analysis.

The backstructure is a spaceframe of steel components. Mexican companies with the capacity to build these components have indicated that is possible to manufacture them in Mexico, if they are provided with structural drawings and blue-prints. INAOE has already developed, during the last year, a structural design using finite elements techniques. This capability will allow detailed supervision of the contractor's work during the development of the preliminary and final design studies.

In the first draft, the active surface or the primary reflector contains 126 hexagonal aluminum panels, approximately five meters each in diameter. The panels will be arranged in six nested rings with 6, 12, 18, 24, 30 and 36 panels respectively; the focal ratio of this active surface will be close to 0.4. Each panel is independently controlled by sensors and actuators to correct, in real time, errors caused by thermal and gravitational deformations. Our studies show that this kind of active surface will meet the precision specifications of less than 60 microns rms on the surface and within one arc-second pointing accuracy. Trapezoidal panels have also be considered to reduce the total number of molds needed.

Each panel of the active surface is made of segments mounted over a frame of hardened aluminum. The segments are machined from prestretched thin aluminum sheet, with a curvature approaching the desired value. The final surface is produced by vacuum casting on a precision mold. The manufacturing of the segments and the final panels is a complex and delicate process that must attain a precision of 45 microns rms. INAOE knows no Mexican company with the equipment required to work with this thickness of aluminum sheet or the vacuum cast processes needed to make the panels. INAOE however, will have the technology to measure and determine the correct shape of the panels.

Each of the panels conforming the active surface of the antenna is individually controlled. The system control must be capable of a response with 3 degrees of freedom for each panel (piston, tilt and tip). The first draft of the conceptual design requires 147 actuators, and one sensor for each side between panels for a total 336 sensors. For the final design, the number of actuators and sensors may change. In any case, the control algorithm must be able to handle sensing data redundancy, cope with the sampling speed required, and carry out the high number of operations per second imposed by the active surface. Based on previous achievements in this area, we are sure that the system control of the active surface could be developed by research centers or academic institutions in Mexico. Indeed, there is an team of scientists from INAOE-UMass already working towards this goal. Still remains to be analyzed, the precise mounting points of sensors and actuators on the panels. The solution on these issues is related to the final design of the supporting frames for the panels.

The secondary reflector is a hyperboloidal aluminum surface of about 3 meter diameter and 1000 kg in weight. It must be machined with surface accuracy better than 12 microns. The secondary reflector will have a control system capable of pointing the reflector with a precision better to a 1000 th of an inch. To achieve this precision, one has to use a secondary control unit, based on a laser metrological system capable of measuring the deflections induced by gravity and taking into account thermal effects on the reflector's support.

It is possible to build the secondary reflector at INAOE, in a specialized laboratory already designed. Later on, this laboratory could provide metrology services to the industry in Mexico. The control unit of the secondary reflector was developed for antennas of smaller size that the one consider here. Based on these developments it is possible to adapt them to the requirement of the LMT.

With regards to the configuration, several options have been considered: yoke on king post and wheel on track, where the whole structure of the telescope gyrates around central pedestal. The yoke on king post seems to offer better possibilities.

3.2. Protective Enclosure

The radome is essentially a protective enclosure, designed to eliminate the adverse effects of wind on the active surface of the antenna, thus allowing us to reduce the weight of the support structure compared to an unprotected antenna design. The radome also protects the antenna against the direct solar radiation, but unfortunately induces a thermal gradient difficult to eliminate. This later effect induces panel deformation, making the desired pointing accuracy harder to attain. This problem is yet to be resolved and will require of a significant amount of effort. During the conceptual design INAOE is studying the feasibility of a telescope with a different kind of enclosure: a rotating building with a roll-up screen. INAOE has currently a design under consideration. This rotating building is been considered because of the need to eliminate the thermal effects on the active surface. This problem remains a key factor on the type of enclosure that will be built.

The non-rotating closed radome can be considered as an aluminum structure, which supports a membrane transparent to the millimeter radiation. The combination of membrane and the aluminum structure must stand to winds velocities up to 200 km/hr. There are some materials transparent at the frequency range at which the LMT will work. Among the commercially available, one can point out the ESSCOLAM 6, the Spectra and the Gore-Tex, which are made of Teflon or chemically related materials. For a closed radome, 14000 square meters will be required of this material.

The construction of most of the radome could be achieved by Mexican manufacturing firms, provided one can promote a joint venture with a company with long and proved experience on these enclosures. In the design studies we are particularly interested in a detailed analysis of the temperature gradient generated inside the radome; the thermal effects in the structure must be minimized to ensure proper pointing to the desired accuracy.

3.3. Pointing System

The control system includes all the necessary mechanisms to point the antenna to the elevation and azimuth required for a given observation, with a precision better than one arcsecond. Control systems of this kind are relatively well known; similar systems have been tested on smaller antennas for millimetric radiation and in larger antennas at other wavelengths.

Some error sources are predictable and can be compensated for, such as imperfections on the servos. Non-systematic errors such as gravitational and/or thermal deformations change slowly with time and can be practically eliminated with a good pointing system design. Other rapidly changing errors however, like the ones resulting from servo friction, can not be corrected under any scheme. Of course the measuring system induces other kinds of problems that have to be minimized. The project feasibility studies indicate that it is possible to develop a control system to cope successfully with those challenges; however, pointing remains as one of the most difficult problems to be solved during later stages of the design.

3.4. Instrumentation

The equipment to detect and measure the millimeter wave radiation received by the telescope represents a special chapter, yet to be written in full detail. The instruments under consideration are: heterodyne receivers, spectrometers, bolometer arrays, polarimeters and others. Some of these devices may demand frontier technology, so that receivers in the required frequency ranges (from 100 GHz to 300 GHz) are not yet commercially avaliable; they are under development, at the prototype level, in a few research institutions of USA, Japan and Europe.

Given the important role that communications have nowadays in society, and will have even more in the near future, these developments could be used as a triggering element for an advanced technology center, hosted in an existent research institute; with this incubation process, once the main project needs are completed, a transfer of the technology for commercial applications can be achieved relatively easily. The formation of such a group will be possible because the University of Massachusetts already has important groups in high frequency electronics. INAOE will have a laboratory with the capacity to design, build and measure parameters in circuits of high frequency. Such laboratory will start functioning in June 1996.

Since the commercial opportunities open for millimeter wave equipment are very important, there is an additional attracting factor to participate in this field. At the present time, the market for microwave devices, in the spectrum range that goes from a meter to a centimeter in wavelength, is around 70 billion dollars a year. A broader coverage of the electromagnetic spectrum, extending up to 340 GHz will induce new communications tools, that will impact daily society life even deeper; consequently, the market for high frequency equipment will expand rapidly. Many communications devices depend on the microwave use: TV programs transmitted by satellite, cellular phone structures that are continuously expanding, data and telephone calls transmitted by microwave relays, airplane safeguards, ships and other transportation vehicles guided by intelligent microwave systems, etc. In a report from the Ministry of Telecommunications of Japan it is stated that in the year 2000, 7% of the total production of radio equipment will correspond to millimeter wave equipment, reaching 13% by the year 2010, with a minimum market volume of 10 billion dollars. It is our intention that mexican firms will share part of that market.

4. SITE SELECTION FOR THE LMT

4.1. General Conditions

The topographic and climatic characteristics of several regions in Mexico allow the existence of sites with adequate physical conditions, to locate an instrument that works at millimeter wavelengths. Several parameters must be considered in the selection process, among which are the following:

1. The altitude over sea level should be more than 3000 meters.
2. The prevailing humidity, during extended periods of the year should be as low as possible.
3. The southernmost possible latitude to have access to the southern sky.
4. To be as near as possible to a reasonable road access. The length of a road to be constructed should not be longer to 15 or 20 kms, considering its high cost.
5. To have the possibility to get energy power, water and other services.
6. The chosen site must be near an urban center that could host a research center.

The millimetric radiation is absorbed mainly by water vapor; for this reason it is necessary that the amount of precipitable water in the local atmosphere should be quite small. The maximum desirable is about 3 mm, during long periods throughout the year. The presence of high clouds, like cirrus, does not have the same effect because water is in the form of ice, that does not stop the radiation in the millimeter wavelength range.

4.2. A Preliminary Selection

The Secretaría de Agricultura y Recursos Hidráulicos counts with meteorological data from 3,400 stations, at least since 1935. The corresponding information has been published in the Mexican Republic Water Atlas, edited in 1976. With this important information, 165 possible places located in regions with low pluvial precipitation have been carefully analyzed for the site selection.

In each of those 165 pre-selected places, their main characteristics were registered. The final database contains 34 parameters for each site, including information of the nearest meteorological stations, like relative humidity values, precipitation, temperature, clear days, evaporation, etc.; besides, there are other kind of data like the nearest services, accessibility and the range of seismicity. With this database it has been possible to generate a list of convenient mountains not just because their meteorological parameters but also taking into account the cost and availability of the basic infrastructure.

4.3. The Measurement System

The parameter measurement process of the pre-selected sites is based in the use of satellites images from GOES and NOAA, with the purpose of knowing the cloud range and to identify the specific effects produced by the meteorological phenomena, present in the national territory. Radiosounding has also been used in the site selection study.

Of the initial list of 165 sites, at present, the work is concentrated in the mountains mentioned before. In these sites, we have installed radiometers at 215 GHz, thermohydrographs, and other instruments.

TABLE 1

SITES UNDER STUDY

Site	Altitude	Parameters State	Date
San Pedro Mártir	2980m	Baja California	Sep. 16, 1995
Teotepec	3550m	Guerrero	Sep. 30, 1995
Banxhu	3190m	Hidalgo	Mar. 30, 1995
Sierra Negra	4540m	Puebla	Aug. 23, 1995
Tehuacán	2850m	Puebla	Mar. 11, 1995
La Laja	3100m	Querétaro	Jun. 22, 1995
Real de Catorce	3180m	San Luis Potosí	Sep. 23, 1994
Cofre de Perote	4200m	Veracruz	Jun. 3, 1995
Concepción del Oro	2830m	Zacatecas	Feb. 15 -Jun. 30, 1995

At the present time, after a few months of measurements, the best sites seem to be San Pedro Mártir and Sierra Negra.

5. AN INTERNATIONAL PROJECT

The Instituto Nacional de Astrofísica, Optica y Electrónica and the University of Massachusetts are working together in a binational project to build a 50 meter telescope. This instrument will operate in millimeter wavelength and it will be the largest of its kind in the world. The telescope will be located in a dry high mountain site over 9000 ft, in Mexico. This project is unique in that its cost is several times the average cost for scientific projects in Mexico because of both; the amount of the investment, and the technological challenges involved.

The LMT constitutes the most ambitious scientific project ever undertaken in Mexico. The strategy of the project is to seek a close relationship with Mexican and American companies, so that technological benefits are shared to private industry responsible for carrying on the project. Almost eight years of engineering work in both countries were invested on defining basic concepts and detailing the state of the art research needed to build for the future telescope.

It is clear that the framework of binational cooperation developed will serve as a model for a new way to implement ambitious scientific projects. The construction, the installation and the initial operation of the instrument has an estimated cost of 46.4 million US (1995) dollars; the financing, like the project, is also binational. About 80% of this money will be spent in the construction of the antenna, the radome or protective enclosure, and the required instrumentation. All of these items will be designed and built with advanced technology. The participation of research centers in the project is of special interest.

Following this way, the project will profit from already established binational ties. In short there are three areas where this multi-institutional relationships can profit:

1. Construction of the antenna and related engineering.

It is possible to enlist Mexican companies with proven experience on civil engineering, on structural engineering and and on metal-mechanical engineering. When feasible, it is foreseen that associations with American companies will be formed, particularly on such tasks as: design, basic engineering and manufacture of special parts.

2. Instrumentation and Control.

The project looks for effective participation of research institutions and of certain universities. Building the telescope requires original research of great interest to groups of scientist seeking involvement in prototype construction. The control system for the LMT has important challenges to overcome. Potentially, this area could also be subject to binational financing.

3. Development of high frequency microwave electronics and microwave detectors.

Because the high frequency at which the radio-telescope will operate, the detectors needed are still on the development stage at the laboratory. The project must generate its own suitable infrastructure and human resources for this task. The impact of this technology will be felt in the near future, especially in the field of communications, because of the growing traffic and large volume of data. Also, for the detection of objects with radar using centimeter-sized antennas, made possible by the use of high frequency microwaves.

This project is so vast that one has to consider further aspects. The main issue to obtain financing was that this project should yield benefits to the country, additional to those strictly inherent to scientific excellence. The construction of the LMT should have a legacy of fundamental qualitative expertise. A central goal is aimed at assuring that LMT staff partaking on any of the tasks required to build this complex instrument, spreads out the newly acquired knowledge:

a) To the scientific community as a new alternative, to keep on the trend to expand projects both in quality and quantity in cooperation with other countries. The "megaproject size" has to be understood fully, for future science and technology policy making.

b) Towards higher education to transmit hands on experience with new technologies on electronic processes, control, and precision manufacturing of metal-mechanical parts.

c) To the private sector to get them involved on the process of generating new knowledge in cooperation with research centers.

A new scheme of links between the two sectors will be tried on.

The Mexican participants are: INAOE the chief coordinator of the project; the Universidad Nacional Autónoma de México (National Autonomous University of Mexico), the Servicio Meteorológico Nacional (The Mexican Weather Service) and the Consejo Nacional de Ciencia y Tecnología as head of the academic sector: other academic institutions make important contributions. The US participants are: The University of Massachusetts, chief executive agency; the Advanced Research Projects Agency (ARPA) and the Government of the Sate of Massachusetts, as the two principal funding agencies. At this stage the project also counts with the support of other institutions, such as the National Radio Observatory and the University of Cornell.

The Mexican share of the telescope time, of course, will be opened for the use of the Ibero-American community.

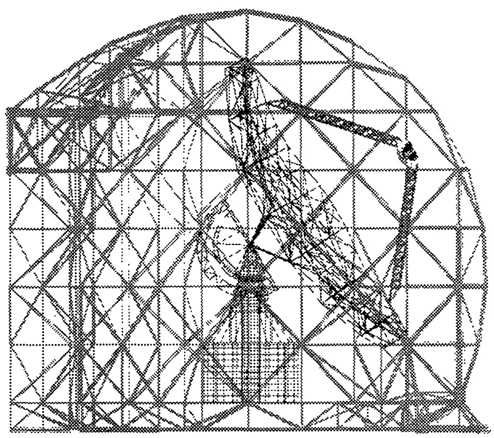

Fig. 1. A schematic cut-out view of the LMT