

Site Survey for the Giant Segmented Mirror Telescope

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ABSTRACT

The Giant Segmented Mirror Telescope (GSMT), along with other proposed Extremely Large Telescopes (ELT's) with apertures over 20-m, is likely to impose rather different site selection criteria than those for existing large telescopes. Advantageously, remote-sensing techniques allow rather more objective comparisons than was possible in the past, and the general task is aided by numerical modeling and new ground-based measurement techniques. In recognition of the difficulty of the site-selection process, co-operation between the several ELT projects is the norm. A description is given of the site survey for the GSMT, begun in late 1999, and now part of the GSMT studies and evaluation project, run by the Associated Universities for Research in Astronomy (AURA) New Initiatives Office (NIO).

Keywords: telescopes, site-survey

1. INTRODUCTION

A state-of-the-art and very expensive telescope such as the GSMT should clearly be placed on the best possible observing site, in order to maximize the scientific return from the investment. However, aside from determining exactly what is meant by “best”, such a choice is always a trade; apart from meteorological and climatological considerations there are political, environmental and cost criteria that need to be taken into account. These criteria interact, and for any given site their relative importance will change with time, quite possibly in an unpredictable way.

It is essential to define and prioritize the site requirements based on the priorities flowing from the science requirements combined with knowledge regarding the interaction of the GSMT design with the site properties. Because the telescope parameters will continue to be defined and refined through the early stages of the project the site selection process needs to be staged, proceeding from a general collection of information in the first stage, to detailed testing of a single site in the final stage. This final stage should continue throughout construction, and interface seamlessly to the site measurements required in the commissioning and operations phases. A major difference between the GSMT and earlier telescopes will be the reliance of the GSMT on Active and Adaptive Optics (AO); as a consequence, atmospheric turbulence versus height as well as cirrus cover must be well understood, and the effects of wind-loading will be a critical issue..

2. METHODOLOGY

Past site surveys can provide valuable guidance. The most important lesson is that even well funded and multi-year surveys, of which the best example is that conducted by the European Southern Observatory (ESO) to identify and evaluate a site for the Very Large Telescope (VLT)¹, spend more effort on characterization than identification, since the process of conducting even initial tests on multiple sites is very expensive and time-consuming. This would argue for the initial selection process for the GSMT site to use remote-sensing methods as much as possible. Importantly, long-term climatology changes are not well understood. The well-known adage that observing sites can only get worse with time is an example, since the typically few-year selection process poorly samples the long term conditions², and given a choice of sites of not too-dissimilar quality, the one chosen may only be ephemerally better than the others. Long-term

changes including “global warming” can significantly change site properties (cloud cover, wind direction), if these are determined by a delicate balance between weather systems. Island sites may be more immune to such effects than continental sites, in general.

The existing best observing sites in the world, judged on the basis of a combination of atmospheric stability and transmission, are of two types: isolated high mountains in temperate oceans (e.g. Mauna Kea, La Palma) or coastal mountain ranges near to a cold ocean with stable sub-tropical anti-cyclone conditions (coasts of Chile, south-west USA-Mexico, Namibia). Continental mountain sites (e.g. in the USA, Uzbekistan, China, India, South Africa) appear not to be as good, although this general evaluation does depend on the weighting of site characteristics - for example, Mt. Maidanak in Uzbekistan has good seeing AND low wind³. There are possibly other high quality sites remaining to be fully evaluated (e.g. the Atlas mountains in Morocco, north-west Argentina).

Most existing observatories monitor basic meteorological quantities such as cloud cover, wind speed and direction, and temperature. With few exceptions, the easily available records consist of mean quantities, and often there are differences in definition, particularly for quantities such as “photometric time”. Thus quantitative comparisons between existing observatory sites on the basis of published measurements is generally difficult. However, existing observatories do provide the location and infrastructure to ease the task of making new measurements.

Remote sensing techniques, particularly from satellites, have greatly advanced in the past 25 years, as has hydrodynamic modeling of wind-flow over topography, at a variety of scales. Use of these techniques should allow the dispassionate identification and comparison of sites, and easy re-evaluation if the weighting of the comparison criteria change. If sites can truly be pre-selected in this way, then the expense of the time-consuming initial site identification phase should be reduced. Databases allowing the global evaluation of such important parameters as earthquake probability, volcanic activity, atmospheric dust content, and light pollution are available. The Meteosat and GOES series of satellites provide cloud cover and water vapor column measurements. Meteorological data on a 3-D global grid, used as input to operational meteorological models, have been collected for 45 years and in principle can be analyzed to determine wind speeds and direction, temperature changes through the night, and possibly mean turbulence profiles. We have funded remote sensing analyses to supplement existing databases, as detailed below. The use of Geographical Information Systems (GIS) as a tool for storing, combining, displaying, and evaluating large volumes of descriptive data has been proposed⁴. Multiple data planes (e.g. longitude, latitude, value) are readily manipulated via use of a GIS.

3. COOPERATIVE SITE TESTING PROGRAMS

There are several new-telescope projects in the early stages, apart from GSMT. The Overwhelmingly Large (OWL) Telescope Project (ESO) and the California Extremely Large Telescope (CELT) Project are for telescopes of similar size to GSMT, with roughly similar site requirements. Collaborative and complementary work is advantageous to all parties. The Atacama Large Millimeter Array (ALMA) and Large Millimeter Telescope (LMT) projects are more advanced, with sites already chosen. ALMA will be sited in the Chajnantor Science Preserve, Chile, while the LMT is being built at Sierra Negra, near Puebla, Mexico. Both sites are high altitude, chosen for their extreme dryness during a large fraction of the year. Cornell University is planning to build a 15-m telescope optimized for the mid-IR on a peak above the ALMA site^{5,6}, while the University of Tokyo is interested in installing a 6.5-m telescope in the same area. The Universidad Nacional Autonoma de Mexico (UNAM) has developed concepts for a 6.5-m segmented mirror telescope, with site nominally San Pedro Martír in Baja California, Mexico. All these sites are worthy of consideration for the GSMT; the GSMT itself may well be some combination of the above-mentioned projects!

The GSMT sites team has deliberately chosen to geographically restrict their efforts to the characterization of potential sites in the continental Americas plus Hawaii. This decision is a consequence of the limited resources available, the already-existing superb sites in these regions, and the stated intent of ESO to consider sites in other continents for the OWL project. The extensive site characterization of Canary Island sites should be mentioned in this regard¹⁸.

Within the Americas plus Hawaii, there are three areas to be considered: the southwestern USA and northern Mexico, northern Chile, and the summit of Mauna Kea. These regions contain many existing observatories, amounting to 80% of

the world's telescopes with apertures larger than 3 meters, and all twelve telescopes with apertures larger than 6.5-m that are presently operating. Relevant characterization work has and is proceeding at existing facilities – e.g. the sodium layer measurements required as part of a new Multi-Conjugate AO (MCAO) facility for Gemini South has been carried out on Cerro Tololo in 2001, while the extensive weather and site monitoring by ESO at La Silla and Paranal are relevant also for any new facility contemplated at or near these sites.

TABLE I: GSMT Site Parameters

Top Level	Parameter	Remote Measurement	Local Measurement	
Atmosphere	Cloud	Satellite	confirm	Radiation (daytime)
	Precipitable Water	Satellite	confirm	Humidity, weather station
	Turbulence	model	Yes	MASS Profilometer, GSM, Scidar, DIMM, Balloons
	Wind	model?	Yes	Ground, near-ground, weather station
	Sodium layer		Yes	Cerro Tololo, for Gemini
	Climate stability	Model		
Location	Altitude	maps, etc		
	General Topography	maps, etc		
	Local Topography	maps, etc	confirm	
	Temperature		Yes	Weather station
	Seismic activity	Yes		contracted study
	Volcanic activity	Yes		contracted study
	Snow, Rain	some	confirm	
	Ground layer turbulence	model	Yes	SODAR?
	Geology		Yes	contracted study
Pollution	Light	model	Yes	
	Air	some	Yes	Particle counter
Others	Accessibility	maps	confirm	
	Ownership	public record		contracted study
	Mining rights			contracted study
	Utilities	maps	confirm	
	Environmental issues			
	Cultural issues			
	Population predictions			
	Industrial development			
	Political issues			
	Construction phase issues			
	Operation phase issues			

4. GSMT SITE DRIVERS

The key measurements for the GSMT are listed in Table I. Weighting will depend on the scientific priorities and telescope technical characteristics, together with any construction or operations restrictions implied. For example, a site at over 5000m may have severe cost implications. The result of this weighting may be very different from existing telescopes - as an example, GSMT will likely have a primary resonance frequency closer to the maximum of the wind power spectrum, and thus be more sensitive to wind-buffeting than the present generation of large telescopes. Survivability issues - in particular the frequency of strong earthquakes, the maximum tolerable wind speed, and the tolerable snow load, are likely to be important issues for the GSMT. It is clear that GSMT will be strongly reliant on AO, even if its scientific use is mostly spectroscopic rather than imaging. Thus the photometric quality and the turbulence properties of the atmosphere will be extremely important. A long AO time constant is desirable for a large telescope, which implies low wind at high altitude and thus prejudice against any site that is covered by the jet stream for a significant fraction of the time.

Our strategy is to collect relevant data for candidate sites in order that a reliable comparison can be made after the scientific and technical characteristics of the GSMT are known. In the early stages, the range of site properties of the “candidate sites” is quite large, reflecting the initial uncertainty in the telescope characteristics.

5. PROCESS AND PRIORITIES

The above strategy translates into the following tasks:

- To proceed with an analysis of present and potential sites in Chile. Parts of this work are collaborations with Cornell, ESO, and the Institute of Astronomy, University of Tokyo
- To work with CELT, Gemini Observatory and the Institute of Astronomy, University of Hawaii to evaluate the large-telescope site(s) on Mauna Kea, and to objectively compare them with candidate Chilean sites.
- To work with CELT, UNAM, and Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) to analyze present and potential sites in the USA and Mexico
- To meet regularly with all interested parties to ensure that accurate and reliable inter-comparisons between regions and specific sites are made, and that the quantities being measured or modeled are those particularly relevant for ELT's.

The above program can be divided into these main activities:

- Compilation of existing databases, and initiation of new remote-sensing studies.
- Procuring, testing and installing site testing equipment at the prospective sites.
- Atmospheric turbulence modeling and measurement for prospective sites and regions.

We discuss these in turn in the following sections.

6. REMOTE-SENSING SURVEYS

6.1 Archival Cloud Cover and Precipitable Water Vapor (PWV) Analysis of Northern Chile, together with a Topographical Analysis

An analysis of Meteosat and GOES-8 satellite (6 and 10 micron channels) data by Dr D.A. Erasmus was completed in April 2001, covering five years spread over 1993-2000 between latitudes 20.5 to 30.5 S in Chile. This includes all the major Chilean observatories. The analysis provides an 8-year baseline, long enough to cover the most recent El Niño and La Niña phenomena as well as several normal years. Within the large area covered by the study, specific sites were identified via a topographical study⁷ that evaluated mountains using as criteria: distance from city lights and mining

operations, altitude, relief, isolation from the surrounding landscape, and summit area size. The best sites based on lack of cloud and on low PWV were identified, and compared to the existing sites⁸.

6.2 Archival Cloud Cover and PWV Analysis of SW USA and Mexico

A second study, funded by CELT and NIO, covers the whole of the US south-west and Mexico, extending as far north as Pike's Peak in Colorado and south to the LMT site at Sierra Negra. This study uses the same data set as the Chilean analysis, and extends an analysis carried out for the Rocky Mountains Observatory Consortium⁹, which used a subset of the dataset to compare sites in Colorado to Mt Graham and Mt Hopkins in Arizona. The results of the new analysis were presented at SITES Workshop II, reported at <http://www.ctio.noao.edu/sitetests/WorkShop2002/meeting.html>.

6.3 Archival Cloud Cover and PWV Comparison between MK and Chile

CELT and NIO are jointly financing a third study, which will compare cloud cover and PWV statistics for Mauna Kea and Chilean sites. This involves purchase of a new data set, since Hawaii is not included in the field of the images purchased for the western hemisphere analyses. The data set runs from 1997 through 2002, and the analysis is expected to be complete by mid 2003. It will include some improvements over the earlier analyses, particularly relating to the detectability of near ground-level cloud where the ground-cloud temperature difference is small. The opportunity will be taken to re-analyze some of the earlier data sets, to allow a comparison between the best sites in all the study areas.

6.4 Analysis of Cirrus Cloud Transparency at Candidate Telescope Sites

Many of the scientific programs for GSMT do not require completely clear conditions, and laser AO systems may possibly tolerate 10-20% absorption by cirrus cloud¹⁰. A more refined calibration of the cloudy/transitional/clear boundaries determined by the satellite studies could be used in conjunction with the studies above to better quantify the specific fraction of time that laser AO systems could be used. A ground-space comparison by Erasmus & Sarazin is due for completion in 2002, and will lead to an objectively defined and well-calibrated satellite-based indicator of atmospheric transparency at optical wavelengths. For sites measured in the above studies, this calibration could be retroactively applied to the data. This study is being considered for funding in 2003.

6.5 NCEP Re-analysis

The National Centers for Environmental Prediction (NCEP) global re-analysis¹¹ is a large project to reanalyze historical meteorological data from all available sources using state-of-the-art meteorological models. The complete data set covers 1957-2000, with re-analysis fields every 6 hours, on a grid with spatial resolution 1.875 degrees and vertical resolution, in terrain-following co-ordinates, ranging from about 100m near the surface to about 2000m at the 100mb (~17km) level. Data at each level include: temperature, component winds, humidity, vorticity and divergence. For particular observing sites the NCEP data could characterize the wind regime and diurnal temperature changes, and possibly statistical climatology of the vertical turbulence profile. A concern is that the model vertical resolution is too low to provide useful profiles, and that the low spatial resolution will give no information on effects due to topography, except on the largest scale. However, the extent and homogeneity of the database certainly will be able to illustrate trends and changes in the long-term climatological evolution of the meteorological parameters. In order to address whether the NCEP re-analysis can successfully predict vertical turbulence profiles, CELT and NIO are planning to fund a study that will use data coinciding in time with a SCIDAR campaign on Mauna Kea in late 2002. The success or otherwise of this comparison will determine the usefulness of a much more extensive analysis.

7. PROCURING, EVALUATING AND USING SITE TESTING EQUIPMENT

Portable Differential Image Motion Monitors (DIMMs)¹², based on the hardware and software implementation by the Department of Astronomy, University of Washington (Chris Stubbs, Eric Deutsch, and Armin Rest) at the Astronomy Research Consortium (ARC) telescope, have been constructed. They consist of a Meade 10-inch LX-200 telescope, Santa Barbara Instrument Group CCD camera, custom wedge lens and mask assembly. One DIMM has been installed at

Cerro Tololo, two are being used on Mauna Kea, and another is a fully robotic version for remote use, and which initially will be used to characterize the remaining large-telescope site on Cerro Pachón.

Several Monitor Sensors PTY¹³ portable weather stations have been purchased. These contain sensors for wind speed and direction, humidity, temperature, and solar radiation. Data is stored in a data-logger, which can be downloaded at intervals of a few months, and the station is solar powered.

A Turbulence Profiler (MASS – Multi-Aperture Scintillation Sensor)¹⁴ has been recently delivered to CTIO by the Sternberg Institute, Moscow. The instrument measures the characteristic strengths and altitudes of the few dominant turbulence layers, and integral seeing produced by the free atmosphere, from scintillation measurements of a single star. Initial tests have proven very promising¹⁵. Calibration and testing, together with a duplicate instrument being built for ESO, will take place during a SCIDAR campaign at La Silla in July-August 2002, and the MASS will be used during large campaigns on Mauna Kea later in 2002.

Following on from the results of the topographical analysis and the Chile cloud-PWV survey discussed above, we have:

- Installed a weather station on Cerro Honar (5400-m) in the Chajnantor Science Preserve, from October 2000. A week-long DIMM run at the time of weather-station installation, in collaboration with Cornell, was used to test the DIMM operation. The weather station has been in operation for most of the time since then.
- Obtained an expert analysis of mining and property rights on candidate sites.
- Initiated discussions on how to proceed with a prime site for which there are environmental concerns (Inca ruins on the summit).
- Carried out an in-situ inspection for some sites. Given the activity of Cornell in testing the very high altitude sites within the Chajnantor Science Preserve (weather stations on Cerro Negro and Cerro Toco, and regular DIMM campaigns), our plan is to place weather stations on a few sites outside the park, chosen to have less cloudy weather than the Chajnantor sites and altitudes typically ~4500m rather than ~5500m. Later, DIMM and Profiler measurements will be made, initially in campaign mode.
- Initiated planning with CELT for a joint site-testing campaign in Chile, for the CELT telescope.

8. ATMOSPHERIC TURBULENCE MODELING AND MEASURING

Turbulence of the atmosphere occurs on a wide variety of spatial and temporal scales. It can be induced by local topography in the telescope vicinity (ground layer), at the interface between topographically induced local wind flows and the trade winds (typically ~1 km above the site), and at the boundaries of the jet stream, of which the lower boundary (~ 10 km) is the most significant. In order to characterize the turbulence, we need to measure wind profiles and the refractive index structure constant C_n^2 at each site. At minimum, the “classical” measurement of seeing FWHM can be made with a DIMM; however, good seeing is a *necessary*, but not *sufficient*, condition for a GSMT site. A variety of instruments have been used to characterize aspects of atmospheric turbulence, all have advantages and disadvantages.

A complementary approach is to evaluate sites by numerical modeling. Micro-scale (~1m resolution) modeling of the ground layer has been demonstrated for the Gemini telescope sites¹⁶, while lower-resolution 100-1000m meso-scale modeling¹⁷ provides turbulence profiles throughout the atmosphere. It may be possible to model C_n^2 profiles for candidate sites using the NCEP re-analysis, as discussed in 6.5 above.

We have proceeded as follows:

- Held workshops¹⁸ at NOAO in October 2001 and July 2002 to discuss methods and collaborations.
- Funded a wind-flow modeling analysis of Chajnantor sites for Cornell by Dr D. De Young (NOAO) that will serve to characterize the wind flow patterns for the high altitude sites chosen by Cornell as possible

locations for a large IR-optimized telescope. These analyses, based on radar imagery, will be invaluable in our own evaluation of these sites for the GSMT, and as a model for analyses of other sites.

- Funded a post-doctoral fellowship position, to be shared between Dr De Young (micro-scale modeling) and Dr Elena Masciadri, UNAM (meso-scale modeling). Dr Konstantinos Vogiatziz will participate in the numerical modeling of wind flow around and above potential GSMT, CELT and OWL sites, comparing the results to in-situ measurements made by a variety of techniques.

9. WHAT'S NEXT?

GSMT site-testing activities have advanced on several fronts, almost all in collaborations with other groups, meeting at NOAO-organized Workshops (October 2001, July 2002) to exchange results and plan future work. The remote-sensing studies have and will allow dispassionate comparison of western-hemisphere sites. The accent will shortly change to modeling wind-flow and turbulence, and in-situ measurements, for a small number of sites. For the GSMT, the scientific and technical requirements that define the optimal site characteristics should be known by ~2004; our collaborative work with CELT will start on a few chosen sites in 2003.

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