7. Development of New Technology

The science of modern astronomy is closely tied to technological innovation. On the one hand, the desire of astronomers to better understand the universe about us causes them to continually push for more sensitive detectors, higher spectral resolution, and greater angular resolution. On the other hand, technological advances frequently bring new and unexpected opportunities for astronomical research; the growth of radio astronomy from the radar technology developed during the Second World War is an example. The LMT is in the forefront of this tradition. In order for the telescope to reach the desired specifications, innovative technological solutions are required; and, in order to solve the astronomical questions posed in previous chapters, instrumentation with unprecedented sensitivity must be developed.

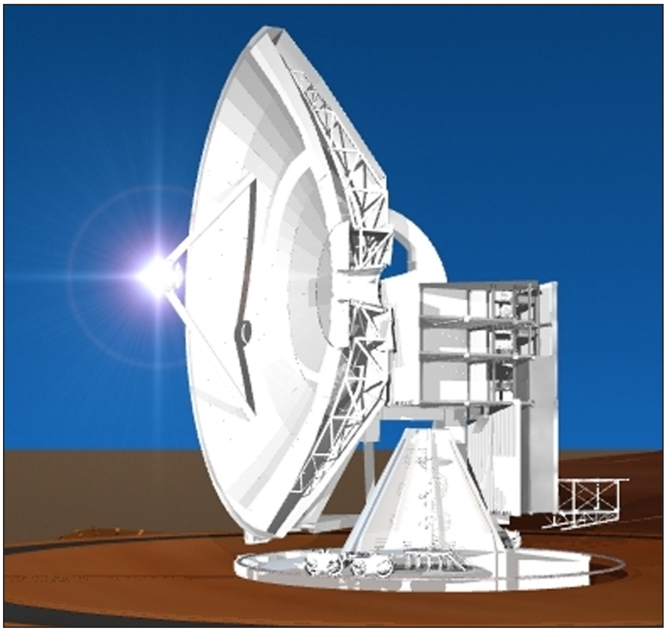

Figure 7.1 Artist's conception of the LMT.

7.1 Active Surface System

For any telescope, it is essential that the figure (precision shape) of the optics be maintained. Because the primary reflector is the largest component in the system, it presents the greatest difficulty. The challenge arises due to gravitational, thermal, and wind-induced deflections of the telescope structure. In order to provide good optical performance, these distortions must be kept to a small fraction (typically 1/20th or smaller) of the wavelength to be observed. For the LMT, this implies a total error budget of 75 microns RMS, of which the primary reflector accounts for about 55 microns RMS (that is, the average deviation from a perfect surface must be less than 55 millionths of a meter, about the diameter of a human hair!).

7.1.1 Correction of Gravitational Errors

Generally, the largest source of error in the surface figure is the deflection of the support structure as it changes its orientation with respect to gravity. The earliest attempts at radio telescope design sought to achieve the necessary performance by designing a structure with sufficient absolute stiffness to maintain the surface figure to within the necessary fraction of the operational wavelength. Unfortunately, the raw gravitational deflections of a structure increase rapidly with size, making this approach impractical for all but the smallest telescopes.

To address this problem, Von Hoerner[1] proposed the use of "homologous" design for radio telescope reflectors. In a homologous design, the structure is not optimized to minimize absolute deflection. Rather, it is optimized so that deflections away from an ideal parabolic shape are minimized. In a perfectly homologous system, the reflector shape is always parabolic for any elevation angle, though the focal length of the parabola may change. Since changes in the focal length of the primary reflector can be corrected by repositioning the secondary mirror, any such deflections have almost no effect on telescope performance. Of course, real telescopes cannot attain perfect homology, but proper design can reduce the effective surface errors by more than a factor of five.

While telescopes have been designed using the principles of homology for many years, the approach is not sufficient for the LMT. The raw deflections of the primary reflector as the elevation angle changes from zenith to horizon are on the order of several millimeters. Even the deflections with respect to the best-fit parabolic figure are a few hundred microns RMS. Since this is much larger than the total error budget for the primary mirror, another approach was needed.

Figure 7.2 One approach to constructing an LMT surface panel.

Even though it would be impossible to design a steel reflector structure for the LMT that could meet the required gravitational performance, the gravitational deflections are extremely repeatable. This implies that if a system can be designed that could alter the position of the individual reflector panels, then the deflections could be continuously corrected by using a computer. This approach allows the structure to be optimized with respect to weight and stiffness rather than for homology, and shifts the burden of maintaining the accuracy of the reflector from the passive structure onto an active control system. That is, it applies a "smart structure" approach to make use of a few ounces of silicon in a computer chip, together with a collection of actuators, to accomplish a task that is impossible even for many additional tons of steel.

The LMT primary reflector surface is divided into 180 reflector segments, arranged in five annular rings. The innermost ring has 12 segments, the second ring has 24, and the remaining three rings consist of 48 segments each. In the LMT active surface concept, each segment is supported by four linear actuators, one at each corner. Because of the high accuracy required for the LMT surface, it is not practical to share actuators between segments. While this results in a relatively high actuator count (720 actuators for the entire active surface), it has the advantage that the position of each segment can be controlled individually.

While theoretically only three actuators are needed to position a segment, the approximately trapezoidal shape of the segment requires a more uniform support. To achieve this support, the four actuators support a subframe structure, which in turn supports the surface panels at eight interior points. The four-point support also allows for the possibility of slightly warping the panels to compensate for any residual long spatial wavelength errors in each segment.

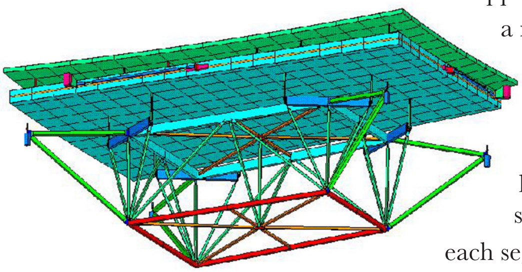

Figure 7.3 Schematic of the segment design for the LMT. The open substructure has actuators to adjust the orientation of the overlying surface panel[2].

Because gravitational deflections are repeatable, they are completely correctable using the active surface system. It is anticipated that the LMT will make use of open-loop correction (i.e., a lookup table) to command the actuators to the necessary positions as a function of elevation angle. While other telescopes have made use of motorized adjusters to help with panel setting (e.g., the Nobeyama 45 m and the JCMT 15 m), and others have used an active surface to extend the operational frequency range of the telescope (e.g., the GBT), the LMT is the first telescope to rely completely on an active surface system to meet its principal operating specifications. As such, it represents an exciting step forward in smart structure technology for radio telescopes.

7.1.2 Correction of Thermally Induced Errors

Another important source of surface errors in the primary reflector is temperature variation in the support structure. As with gravitational errors, thermally induced errors become larger as the size of the telescope increases, because the magnitude of the temperature variation increases with the distance across the structure. The traditional approach to managing thermally induced errors is to minimize temperature variations passively. This is accomplished by coating the structure with a highly reflective paint,

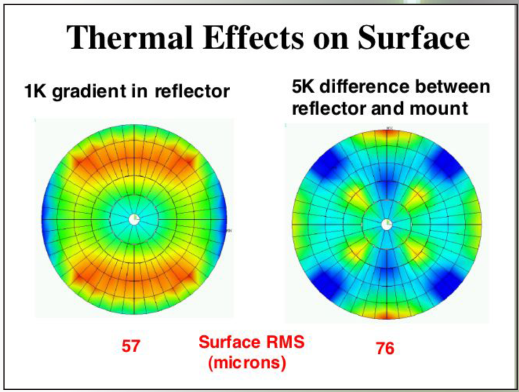

Figure 7.4 Thermal distortions of LMT primary surface in two cases[2].

enclosing the reflector with an insulated cladding, and circulating air throughout the enclosed volume.

The LMT will make use of all of the traditional techniques in order to provide a good baseline thermal behavior. However, because the LMT is already equipped with an active surface system to compensate for gravity, there is an additional possibility to make corrections for thermally induced errors in the surface. To accomplish this, over 100 temperature sensors are installed throughout the reflector truss. The readings from these sensors will be used to calculate the required changes of the actuator positions to correct the reflector figure given the thermal state of the structure. The long thermal time constant of the structure guarantees that such corrections will be slowly varying.

While experimental determination of the corrections is more complicated than for gravity loading, the initial relationship between each temperature sensor and the required actuator commands will be calculated from the Finite Element (FE) model of the telescope structure. As with the gravity correction, the resulting corrections are made using an open-loop lookup table. It is anticipated that significant additional correction can be achieved using this technique, reducing the thermal errors by a factor of about two.

7.1.3 Correction of Errors due to Wind Loading

The final source of primary reflector errors during operation is wind loading. While it can be a significant contributor, this effect is generally more of a problem for pointing. The traditional approach to meeting the surface accuracy specifications under operational wind loading is to rely on the stiffness of the structure to keep the surface within specifications. The LMT also relies on this traditional approach because the analysis results indicate that the surface accuracy can be maintained within budget without additional correction. However, with the active surface system in place it will be possible to make corrections for the steady component of the wind, assuming a measurement of the errors can be obtained.

7.2 Pointing of the LMT

The most difficult problem in the design and operation of large, high-frequency radio telescopes is achieving the required pointing accuracy on the sky. While large telescopes have the advantage that they have a smaller beam diameter, and thus can provide higher resolution images than smaller telescopes, this feature causes three principal problems. Large telescopes present a larger sail area to incoming wind loads, making them more susceptible to wind-induced pointing errors. Their large size also results in a lower natural frequency of the structure, which makes it more difficult for the controller to maintain the desired position in the presence of such loads. Finally, the smaller beam size means that the pointing accuracy must be more precise than for smaller telescopes. Taken together, these problems mean that it is harder to point a large telescope than a small one, and, in addition, the larger telescopes must point to higher accuracy.

The traditional approach to pointing large radio telescopes is to measure and compensate for the repeatable, static pointing errors using a "pointing model." The pointing model is based on a lookup table that is generated by tracking astronomical sources and continuously finding the actual on-sky pointing by peaking up the signal on the source. While the pointing model dramatically improves the on-sky pointing accuracy of the telescope, this approach alone will not be sufficient for the LMT. At its principal operating frequency of 230 GHz, the LMT has a beam size of only 6 arcseconds. As a result, the pointing accuracy requirement is 1 arcsec, with a goal of 0.6 arcsec. The residual errors after applying the global pointing model are expected to be greater than the entire error budget.

To further improve the pointing of the LMT, the basic pointing model will be supplemented in a standard way with local pointing checks. These local corrections require that a nearby pointing source be used to make an additional local correction before moving to the target location for observations. Fortunately, the large collecting area and hence high sensitivity of the LMT ensure that local pointing sources are always available. These additional corrections not only serve to provide a local correction of the pointing model, but also eliminate most of the thermally induced pointing error. The LMT structure is sufficiently massive and well insulated that the time constant of the structure is long. With pointing checks at least every two hours, the thermal contribution to the pointing error can be kept within budget.

To extend the required time between pointing checks and to further improve the pointing, the design takes advantage of the network of several hundred temperature sensors which are part of the Flexible Body Compensation (FBC) system of the telescope. They monitor the temperature of the structure throughout the alidade, reflector truss, and quadrapod legs to allow calculation of the deformation of the telescope for the measured temperature distribution. Initially, these temperatures will be monitored and the actual corrections compared to Finite Element model predictions. Over time, it is expected that a lookup table will be developed that will allow mapping of temperature sensor readings into pointing corrections.

It is certain that the most difficult challenge for pointing the LMT is the external wind loading. Even much smaller telescopes have difficulty meeting this level of pointing accuracy in the presence of wind disturbances, and telescopes of comparable size typically have pointing errors of as much as a factor of 10 too high. The wind causes on-sky pointing errors in two ways: at the position encoders and also because of structural deformations of the primary reflector and its supporting quadrapod.

Maintaining the encoder errors within the required accuracy requires control system performance well beyond what can be achieved with standard telescope controllers. Fortunately, there has been extensive research in improving telescope control, particularly by the deep space network (DSN) control systems group at the Jet Propulsion Laboratory, and these techniques have been applied to the LMT[3]. Experiments on the DSN antennas have shown the feasibility of applying such modern model-based controllers to telescopes, and the LMT antenna and drive control units have been designed to allow implementation of these advanced controllers (Section 7.3). Simulations indicate that the errors measured at the encoder can be corrected, even for dynamic wind gusts, to a fraction of an arcsecond.

Structural deformations are more difficult to correct, because there is no direct sensing of the error. To address this, the LMT design includes additional components in the Flexible Body Compensation (FBC) system. These include biaxial tilt meters at each elevation bearing, an optical telescope near the center of the primary reflector, and additional direct monitoring (via a laser system) of the position of the secondary reflector. The goal of the FBC is to combine the information from these sensors to provide additional real-time corrections in the presence of wind loading. In their analysis, the telescope designer (MAN Technologie) estimated that the FBC could provide the necessary corrections for most cases, with the exception of load conditions that introduced a pointing error parallel to the elevation axis. While there are still significant unknowns in correcting pointing errors caused by wind-induced structural deformations, the sensors will allow direct monitoring and comparison of on-sky pointing errors and those predicted by the FBC. It is expected that, over time, an increasing degree of correction will be possible.

7.3 LMT Monitor and Control System

Modern large telescopes are complex distributed systems, consisting of devices and instruments that must be controlled in a coordinated scheme to perform scientific tasks and collect corresponding data. The status of these devices must be monitored in real time to ensure safety and scientific integrity. We have devised a reusable, automatically generated software system for the LMT that simplifies the implementation of its monitor and control system. The described system takes advantage of advances in computing technology to facilitate the development of control software, ease the integration of new devices and instruments, and shorten the path to scientific production.

7.3.1 General Approach

The traditional approach to creating a monitor and control system has been to implement individual device level controllers and then attach them to a client/server system to achieve the desired coordination. The problems in this approach are twofold: complexity and inflexibility. Synchronization and communication protocols must be implemented, and any upgrades or additions require code modification and perhaps even design changes.

Our solution for the LMT is to automate the creation of a framework for monitor and control by describing the system components in XML, the extensible markup language[4] and then *automatically* generating source code for extendible base classes and user interfaces. This enables the monitor and control system to be both flexible and adaptable, and greatly simplifies the design. It also allows the system to be reusable in many different problem domains.

To simplify the coordination mechanism among the different subsystems, we have employed a global state system for the communication model. A single global state object containing references to all of the components of the system is described in XML and corresponding source code is automatically created to implement global object access. The use of XML in astronomy was initiated by work done at NASA's Goddard Space Flight Center[5].

7.3.2 Object-Oriented Design and Automation

The LMT consists of a large number of complex control systems: the main axes servo system (16 motors in azimuth, 4 motors in elevation), the subreflector positioner and wobbler, the active surface panel actuators (720 actuators), and the tertiary optics (large flat mirror and several additional smaller mirrors). In addition, the LMT has a collection of scientific instruments such as receivers, spectrometers, and data acquisition systems.

Since the telescope system naturally comprises real-world objects, an object-oriented design for the monitor and control system logically follows. Each subsystem can be defined as a software object with attributes that describe the properties of the real object and methods that alter the state of these attributes. Due to the complexity of the LMT system, the traditional approach of hand coding the classes describing the objects is both tedious and repetitive. Automation is highly desired to eliminate unnecessary labor and ensure a common syntax.

XML provides the desired automation through a set of rules for structuring data such as spreadsheets, address books, and configuration parameters. This simplifies the computer's task of generating and reading data, and ensures that the data structure is unambiguous. The properties of each telescope subsystem are specified in an XML configuration file. Each such file describes an object class, including field types and access methods. These XML files are processed to automatically generate extensible base classes and communication methods in C++ and Java; and IDL interface definitions to generate CORBA communication code. CORBA[6] is the acronym for Common Object Request Broker Architecture, a vendor-independent architecture and infrastructure that computer applications can use to work together over networks. Using the standard protocol IIOP, a CORBA-based program from any vendor, on almost any computer, operating system, programming language, and network, can inter-operate with a CORBA-based program from the same or another vendor, on almost any other computer, operating system, programming language, and network.

The LMT XML to monitor and control compiler (LMT-XMLMC) is a software tool that, given a set of XML configuration files, creates extendible base classes and user interfaces to form a framework for monitor and control. The software was designed around radio telescopes but can be used to monitor and control any system with similar requirements. The LMT-XMLMC compiler processes the XML configuration files, and generates Java, C++, JNI, and CORBA base classes, as in Figure 7.5. Java is the language of choice for user interfaces. JNI, the Java Native Interface, is the native programming interface for Java; it allows Java code to operate with applications and libraries written in other languages, such as C or C++. The use of JNI is not practical outside of a local area network (LAN) due to bandwidth limitations, hence CORBA. By using the Java

Foundation Classes and Swing GUI components, the deployment of user interface applications is greatly simplified and a customizable look and feel is permitted without relying on any specific windowing or operating system.

Thus, the Java base classes are used to drive the Java user interface, the C++ base classes drive the real-time system device drivers and controllers, the JNI classes enable communication between the Java and C++ classes on the LAN, and the CORBA classes enable communication between the Java and C++ classes among any computers. In addition, the LMT-XMLMC compiler creates a single object in Java and C++ that contains references to all of the elements of the system to implement a global state system. Any object can read the state of any other object by acquiring a reference to that object from the global state object.

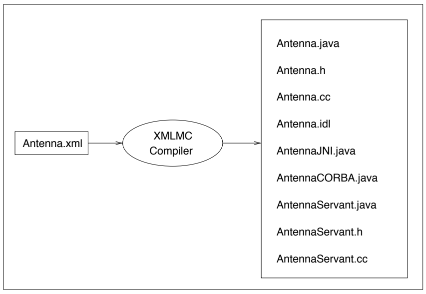

Figure 7.5 The LMT XML-LMC Compiler[7].

To guarantee a consistent look and feel to the LMT monitor and control system, a set of XML configuration files are used to describe the user interface and layout of the monitor and control panels. An example is shown in Figure 7.6.

7.3.3 Global State System

As mentioned above, a global state system is used to facilitate access among the different system components and simplify the communication protocol. The more common approach to telescope control is to define communication paths between the different subsystems and implement a message/data passing scheme to achieve the desired coordination. However, this approach produces a very complex communication problem for information exchange among the telescope subsystems.

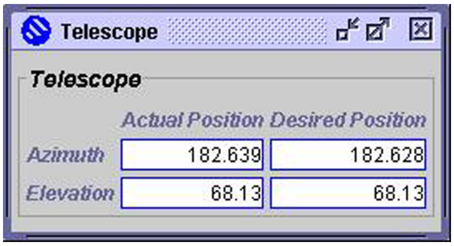

Figure 7.6 A sample LMT monitor and control panel[7].

In contrast, with the LMT global state system each subsystem posts its state to the global state and retrieves the state of other subsystems from the same global state. A finite state machine controller coordinates the activities between the different subsystems through that same global state. This approach is illustrated in Figures 7.7 and 7.8. The only requirement to make this approach feasible is that for each element in the global state, only one writer can exist. This ensures that two or more processes cannot simultaneously write or update a given element. On the other hand, an unlimited number of readers can access the same global state element.

In a distributed computing system such as the LMT, a replicated shared memory system is used. Replicated shared memory is implemented by installing an individual memory board in each computing system and interconnecting these memory boards using a fiber optic link. Memory writes to a replicated shared memory board at one computer are instantly sent to all other replicated shared memories on the network. When direct access to the replicated shared memory is not available, as in remote observing, a CORBA server is used to provide access to the shared memory.

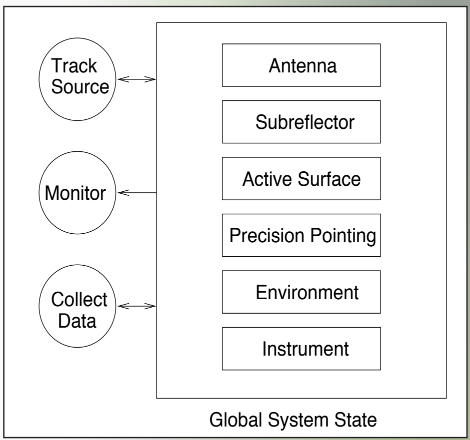

Figure 7.7 Global state approach[7].

Choosing the correct computing environment for the LMT was a difficult task. The final choice was to use a host/target system: a Sun workstation running Solaris, and a VME-based Motorola PowerPC embedded computer running VxWorks, one of the market leaders in real-time operation systems. While the purchase cost for VxWorks remains high, the direct mapping between Unix and VxWorks and the wide availability of device drivers in that environment justifies the initial cost.

7.3.4 LMT Monitor and Control System

The system described so far is used to build the LMT monitor and control system (LMTMC). The LMTMC is composed of several modules including an observing tool, monitoring tools, a finite state machine controller, and a scheduler.

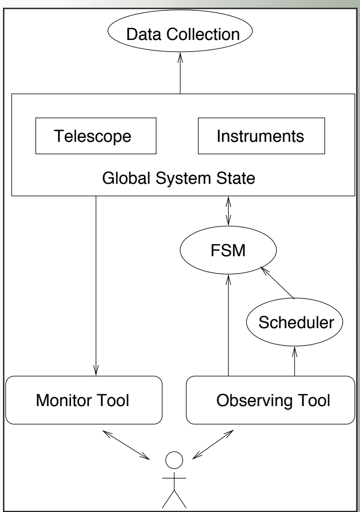

Figure 7.8 The LMT monitor and control system[7].

The observing tool provides the means for the user to create observing programs. These observing programs can then be executed on-line or submitted to the scheduler for optimal execution. They can also be saved to or loaded from a file, and can be manually edited using any text editor. Each observing program must contain scheduling constraints, target positions, a receiver, a backend instrument, and a data collection method. In turn, the observing tool generates commands to control the different subsystems based on the observing program. The observing tool can also be used to deliver commands directly to the system in a more interactive manner for both scientific and engineering purposes. Other resources made available to the telescope user include source and line catalogs, weather conditions, online help, map configurations, and estimates of time overheads.

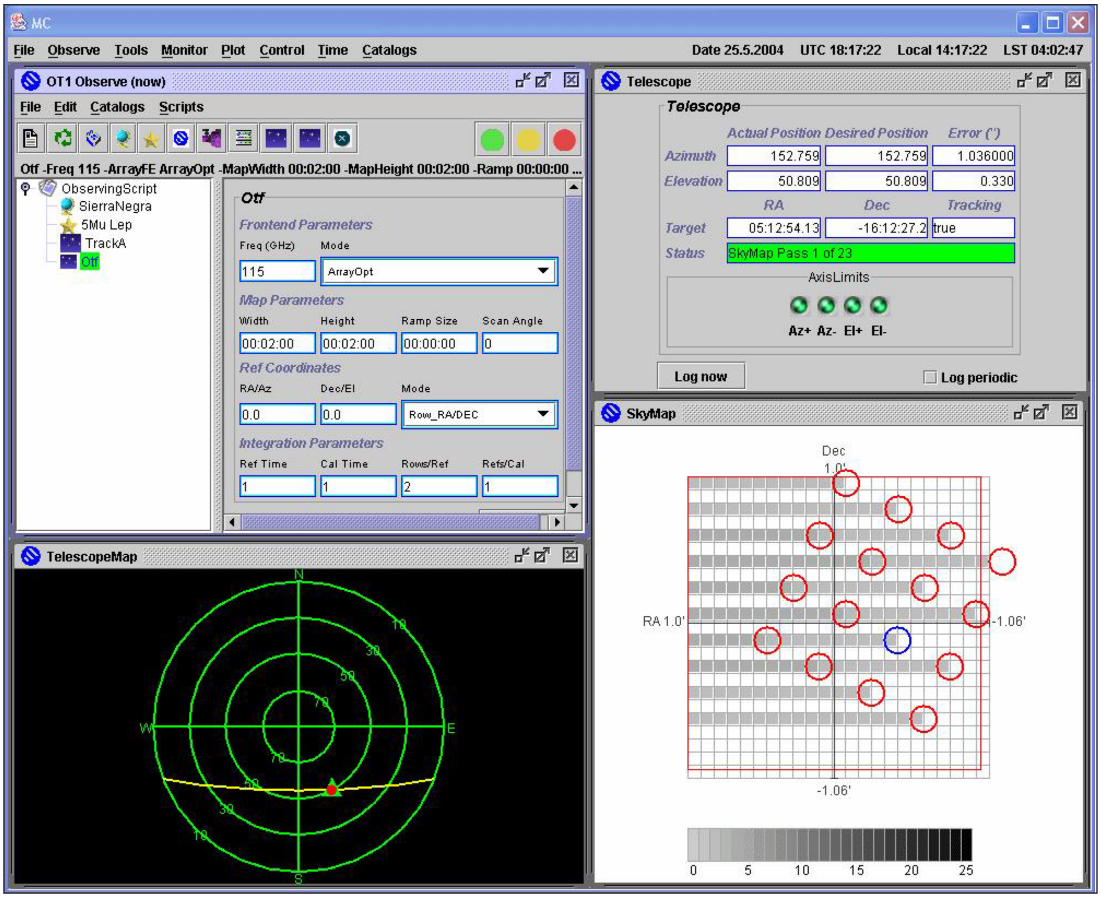

Figure 7.9 Monitor and control panels for the LMT[7].

A finite state machine (FSM) controller translates the observing programs into desired telescope and instrument states. It steps through the science program and executes each command while monitoring the error state of the system.

The monitoring tool is used to oversee the state of the system in real time while observing commands are being executed, and scientific and engineering data are being collected. The purpose of the monitoring tool is to provide a running check on data integrity and proper system operation by displaying the state of the system to the user. This information can include, for example, observation state (schedule step, elapsed time, time to completion), telescope state (position, temperatures, etc.), instrument state (current configuration, bandwidth, sampling rate, etc.), current pointing model, active surface state, subreflector state, weather conditions, error signals, and logs.

7.3.5 Implementation on Existing Telescopes

To prepare for launching the monitor and control system on the LMT, several systems have been built or upgraded to use the LMTMC architecture. These diverse systems demonstrate the reusability and adaptability of the LMTMC framework.

As a first approach to verify the operation of the LMTMC system, a simulator of the LMT was developed. The simulator assumes the behavior of the real telescope and instruments and provides a teaching ground for future users of the system.

The LMTMC software and Sun-Solaris/VME-PowerPC-VxWorks hardware have subsequently been installed for regular use on the Infrared Optical Telescope Array (IOTA) on Mount Hopkins, Arizona, and on the FCRAO 14 m radio telescope in Massachusetts.

7.4 Large Coordinate Measuring Machine

With assistance from the LMT project, INAOE has constructed a Coordinate Measuring Machine (CMM) to carry out dimensional metrology on large work pieces, such as the LMT surface panels and secondary reflector. The machine is of the gantry type: a sliding bridge 8.5 m long is supported at either end by two 10 m, parallel side rails. A saddle rides along the bridge. The combined movement of bridge and saddle allows positioning of a measurement probe within a horizontal (X-Y) plane. Movement of the probe in the vertical (Z) direction is provided by a sliding pillar, which is supported by the saddle.

Figure 7.10 The Large Coordinate Measuring Machine in its laboratory at INAOE[8].

The measuring volume of the CMM is approximately 5 m x 6 m horizontal by 4 m vertical. Maximum test object weight is 30 tons. Approximate machine position can be obtained using rotary encoders on each motor. However, for normal operation the machine uses three orthogonal linear displacement transducers (optical interferometers) to obtain the position of the measurement head with sub-micron resolution.

A linear displacement probe provides 100 mm of linear position information in the vertical direction when attached to the measuring head. This probe is used in a continuous surface-scanning mode, with the probe tip in constant contact with the surface. Coordinate information from the three interferometers (X,Y,Z) and probe (Z) are combined at programmable time intervals while the surface under test is scanned. Continuous scanning is ideally suited to measuring large optical surfaces such as telescope mirrors, where the surface form is generally more important than any constructional details.

The CMM was designed and built entirely by staff and graduate students at INAOE, promoting the establishment of a knowledge base related to large-scale metrology and presenting opportunities for graduate training and the formation of associated technical skills. The machine makes use of traditional engineering concepts, but the unusually large measurement volume requires the development of specialized non-standard techniques for characterization and calibration. The CMM began operating in 2003 and a program of continual improvements makes it an on-going research and engineering project at INAOE. Access to coordinate measuring machines in Mexico is limited to a small number of instruments of small to intermediate size. The CMM is expected to help fill the demand for accurate dimensional measurements on large objects.

The CMM is housed in a dedicated laboratory at the INAOE campus, which is also home to the INAOE large polishing machine. The polishing machine can be used to rectify and polish molds used in the construction of reflector surfaces using composite materials, or to polish mirror blanks directly. The machine is designed to handle blanks of up to 8 m in diameter. The laboratory air conditioning system in combination with thermal building isolation maintain the temperature to within 1°C peak-peak.

7.5 Instrumentation Development

Among the most innovative and important technological advances stimulated by the LMT project are the development of state-of-the-art receiver systems for use on the telescope. Astronomers cannot go to a catalog to buy the instruments necessary to detect the extremely weak radiation from, for example, galaxies forming in the early universe. Instead, they must build their own, frequently working with physicists to develop new technologies or to exploit recent advances. Not infrequently such developments lead to spin-off companies that utilize the new technology for commercial purposes and the benefit of society.

Both UMass Amherst and INAOE have such instrument development groups, and the UMass Amherst team has been very successful in fabricating exquisitely sensitive receiver systems for use on the FCRAO 14 m telescope. The instruments under construction or planned for the LMT are described in the following chapter.

7.6 References

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8. Credit: David Gale, INAOE.