The Large Zenith Telescope project - a 6-meter mercury-mirror telescope

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ABSTRACT

The Large Zenith Telescope is a zenith-pointing telescope with a 6-meter diameter rotating mercury mirror. Located in mountains near Vancouver, Canada, it is expected to see first light in 1998. Equipped with a low-noise drift-scanning CCD camera, the telescope will survey a 17-arcmin-wide strip of sky using a set of medium-band filters. The data are expected to provide spectral energy distributions and photometric redshifts for over a million galaxies which will form a base for studies of galaxy evolution and large-scale structure.

Keywords: telescopes, liquid-mirror, surveys, redshifts, cosmology

1. INTRODUCTION

In recent years, the technology of rotating liquid-mercury mirrors[1–4] has matured allowing the construction of practical working instruments. To date, four 3-meter-class telescope have been built. The 2.7-meter UBC/Laval astronomical telescope[5] was the prototype for three additional 3-meter-class telescopes. Two of these are in operation as Lidar collectors[6,7] and the third, The NASA Orbital Debris Observatory[8] (NODO), is used for studies of space debris.

The NODO telescope is located at one of the best continental sites, near Cloudcroft, NM, at an altitude of 2756 m. The telescope has been in operation for over two years, and its performance has been well characterized.[9] It achieves an image quality limited primarily by atmospheric seeing, with occasional sub-arcsecond images being recorded. The throughput of the telescope is high, and the overall performance is comparable with that of conventional telescopes of similar size. During the period of the night when the sun is too low to illuminate orbital debris, astronomical survey observations are being conducted.[10] These employ a cooled 2048×2048 pixel CCD camera operating in time-delay integrate mode (TDI, also referred to as drift-scanning). This provides continuous imaging of a 20-arcmin wide strip of sky, passing through the zenith, with an effective integration time of 97 sec. Using a set of 33 filters which span the optical spectrum, the telescope has so-far measured several hundred thousand objects to a limit of approximately 21 mag.

2. THE LZT PROJECT

The success of the 3-meter-class liquid-mirror telescopes made it possible to consider the development of the next generation of instruments. While no obvious insurmountable problems exist that would preclude the construction of mercury mirrors of diameter 12 m and up, it was clear that more would be involved than simply scaling up the 3-meter designs. With this in mind, we considered that a prudent approach would be to first develop an intermediate-sized telescope, with an aperture of at least 5 meters, in which new design and construction techniques could be tested.

In November of 1994, a 5-year Collaborative Research Grant was awarded by the Natural Sciences and Engineering Research Council of Canada, to a collaboration between Hickson (PI), Borra, de Lapparent, and Walker, for the

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development, construction and initial operation of a 5+ meter liquid-mirror telescope. With funding totaling approximately $0.5M, the intent was to develop a low-cost instrument, at a local site, which could serve as a prototype for similar, or larger, telescopes to be located at superior astronomical sites.

Even with this restriction, it was clear that a telescope of this aperture, if equipped with suitable instrumentation, could have a significant scientific impact. A portion of our budget was therefore set aside for a wide-field corrector and large-format CCD camera, and a competitive program of astronomical observations was planned.

After selection of a suitable site, construction of the observatory began in 1995. Detailed design of the mirror and telescope systems was undertaken concurrently. Because of its size, and zenith-pointing operation, the telescope was named the "Large Zenith Telescope" (LZT).

3. TELESCOPE SITE

The site for the LZT was selected on the basis of accessibility, infrastructure, and weather records. Within our budget, the most suitable choice was an isolated peak in mountains 50 km North-East of Vancouver, on land owned by the University of British Columbia (UBC). The area is used by the University for a variety of research projects in forestry, biology and environmental studies. It is equipped with a network of roads, security gates, and has a permanent office and staff.

At our site, the terrain rises sharply from the low-lying Fraser River delta to an altitude of 400 m. There are no obstructions to the South, East and West, so the peak lies in a relatively undisturbed airflow. A small telescope was used to observe star images over a period of several nights in the spring of 1995. These indicated a median seeing of 0.9 arcsec FWHM.

Weather observations, including solar irradiance, have been recorded by UBC for 15 years. These include observations from a location 6 km E of our site, and should be well representative of the local conditions. From these data, we have estimated instantaneous cloud-free line of sight (CFLOS) probabilities for daylight hours. These range from 0.13 in mid-winter to 0.55 in mid-summer. During the prime extragalactic months of February - May, the mean CFLOS probability is 0.35. The 15-year mean number of yearly sunshine hours for the area is 1417. If we assume that the same CFLOS probability applies at night, the mean yearly number of clear dark hours for 12° and 18° twilight is 986 and 757 respectively. For the four months of March - May, the totals are 356 and 288 respectively. These are long-term averages, large fluctuations can and do occur from year to year. In fact these CFLOS probabilities and numbers of clear dark hours are likely to be underestimated, as they are determined from daytime measurements which would be affected by diurnal convective clouds.

The wind speed is another factor which of particular importance to liquid-mirror telescopes. Although wind speeds exceeding 30 m s^{-1} ($\sim$ 100 km h^{-1}) can be encountered during winter storms, the site is typically calm. The 5-year mean wind speed is only 2.65 m s^{-1} with the prevailing wind direction being South-East through South-West.

4. OBSERVATORY BUILDING

The observatory is sited upon a granitic outcrop overlooking a cliff to the South-West. Following road construction and site preparation, a 7 m $\times$ 7 m reinforced concrete pad was poured directly on the bedrock. With an average thickness of 0.8 m, it provides a massive, stable, base for the telescope. The pad is surrounded by meter-high concrete walls which support the building. These are vibration-isolated from the pad, and the interior area is sealed to provide a containment area in case of any accidental mercury spill. The 7.3 m $\times$11 m main building includes an equipment area level with the top of the concrete walls. A control room, with a separate entrance, is located at the South-East end of the building.

Because the telescope is zenith-pointing, no dome is required. Instead, the roof rolls back on steel tracks to provide access to the sky. The roof is steeply pitched, and clad with metal siding, in order to shed snow. A platform, attached to the roof, provides access to the top of the telescope when the roof is closed and is carried clear when the roof opens. A small exterior building houses an air compressor, and a backup generator. A 2-km power line and transformer were installed to service the observatory.

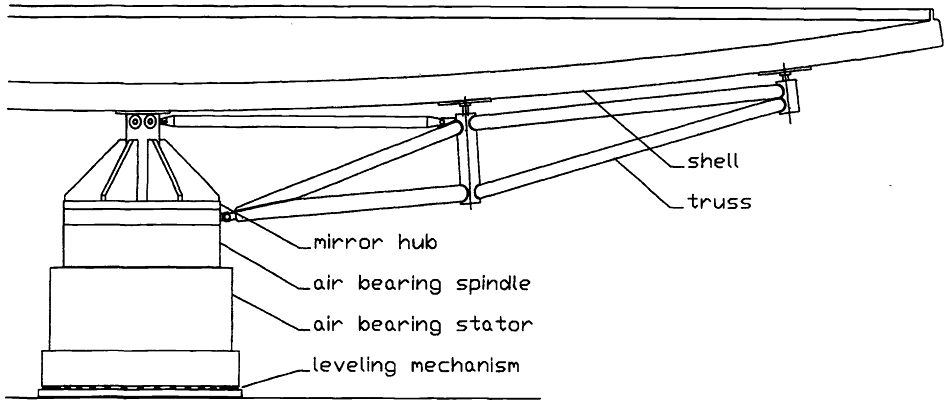

Figure 1. Section view of the primary mirror and support system

5. DESIGN OF THE TELESCOPE

5.1. Primary Mirror

All existing 3-meter-class liquid-mirrors are of a monolithic composite construction, employing a Kevlar skin surrounding a styrofoam and aluminum core.[3] A thin (less than 2 mm thick) mercury layer rests upon a layer of polyurethane formed on the upper surface by spin casting. This makes for a stiff, lightweight structure that is relatively simple to construct. While this design has proven effective for liquid mirrors as large as 3.6 meters in diameter, several considerations suggest that it may not be optimal for much larger mirrors. The surface which supports the mercury needs to be parabolic to within a tolerance of about 100 um. The mirror must retain this shape under large temperature variations, and over a long period of time. The composite materials used in the present liquid-mirrors have large thermal-expansion coefficients, making control of thermal deflection difficult for larger mirrors. A second difficulty is long-term stability. The present mirrors employ plastic materials that are subject to creep.

In order to avoid these problems, a different approach has been adopted for the 6-meter LZT mirror. A shell of composite construction is used to support the mercury, but this in turn is supported by a steel space frame which bears the primary loads and provides rigidity and long-term stability (Fig. 1). The shell is formed from 1.2-meter hexagonal segments bonded together. These segments have molded spherical top surfaces with an 18-meter radius of curvature. The shell is attached to the space frame at 19 axial support points which coincide with the centers and vertices of the individual hexagons. Each axial support can be mechanically adjusted to minimize the departure of the surface of the shell from the desired parabolic shape.

Because the premolded surface is smooth, and matches the desired parabolic shape to within the 100 um tolerance, a surface layer formed by spincasting is no longer needed. Spincasting is a difficult procedure, which sometimes fails to produce an acceptable surface, so its elimination is a nice feature of the new design.

5.2. Bearing and Drive System

In order to obtain the necessary precision and rotational speed stability, a precise low-friction bearing is required. Only air bearings have been demonstrated to provide sufficient performance for astronomical applications. Present mirrors have employed off-the-shelf commercial air bearings, but none of these has sufficient capacity or stiffness for a 6-meter mirror. Consequently, we commissioned the development of a new high-capacity air bearing specifically for large liquid mirrors. This new bearing was designed and manufactured for us by Professional Instruments Co. of Minneapolis. After a two-year development period, the bearing was received and installed in late 1997. Initial tests of this bearing indicate that it should have sufficient capacity for mercury mirrors with diameters as large as 12 meters.

The mirror is driven by a brushless DC motor integrated into the air bearing. The rotor is attached to the air bearing spindle and spins within the stator with no mechanical contact. Rotational speed is controlled by regulating the frequency of the oscillator which supplies the excitation to the field windings. There is no closed feedback loop to the motor, rather, the considerable inertia of the mirror suffices to reduce speed variations to acceptable levels. Observations made with the NODO telescope indicate that good image quality is obtained when variations in mirror speed is less than a few ppm, which is readily achieved by protecting the mirror from the wind.[10] Useful observations with that telescope have been made in wind speeds as high as 15 m s^{-1}. A precise frequency counter gated by the mirror rotation enables us to monitor the period to a level of 10^{-8}.

5.3. Telescope Structure

The structure of a liquid-mirror telescope can be very simple. Although it may be possible for a liquid-mirror telescope to acquire and track objects several degrees or more from the zenith, using a specially designed corrector,[11] our scientific goals can be accomplished by simply observing at the zenith using a drift-scanning camera. There is therefore no need for pointing or mechanical tracking. The LZT uses a prime focus configuration, so all that is required is a system for supporting, positioning and aligning the corrector/detector package at the focus of the primary mirror. For this purpose we have adopted a hexapod configuration. Six stepping motors drive jack screws which adjust the height of the bottom of each hexapod leg with 5-um resolution. By means of a software transformation in the control program, the top-end can be precisely positioned in all six degrees of freedom (focus, x-y position, tip, tilt and rotation). As no motors are needed at the top of the telescope, this avoids one source of heat, and resulting seeing degradation, in the optical beam.

The hexapod elements are made from thin-wall steel tube in order to minimize thermal expansion. The temperature at various points in the structure is sensed by thermocouples and used by the telescope control system which makes frequent small adjustments to compensate for thermal contraction as the telescope cools during the night.

5.4. Corrector Lens and Detector

As with all prime-focus telescopes, a corrector is required to provide good image quality over a wide field. As the telescope will operate in TDI mode, the corrector must also remove distortion. A 4-element corrector lens has been designed for the LZT by Dr. E. H. Richardson. The design provides a 0.4° field with 0.2 arcsec typical image quality (50% EED) over the full optical wavelength range.

A novel feature of the corrector design is that it corrects for star-trail curvature and rate variations. It is well known[12,13] that star images do not move in straight lines at constant rate, and this results in charge spread in the CCD. The resulting image degradation increases with field size and can be very substantial. By employing tilted, wedged and decentered optics, the LZT corrector introduces distortion which compensates for these variations.[14] The result is that the images all move in straight parallel tracks with constant velocity, with a maximum error of 0.06 arcsec. Should the telescope be moved to a different latitude at some time in the future, only one element of the corrector would need to be replaced. The other elements would only require repositioning.

We presently have a low-noise 2048 × 2048 pixel Loral CCD system that was used originally with the UBC/Laval 2.7-meter telescope. While this CCD has low noise and is of good cosmetic quality, it is not thinned an therefore has limited blue response and modest quantum efficiency. We are seeking a larger format thinned CCD for the LZT but as of the time of writing have not yet identified a specific device. We anticipate using either a 2048 × 4096 device with 15 um pixels (0.3 arcsec), or a 2048 × 2048 CCD with 24 um pixels (0.5 arcsec).

5.5. Safety considerations

Any use of exposed liquid mercury requires safety precautions both to contain potential spills and to prevent inhalation of mercury vapor. These hazards are well understood and standard procedures for the use and handling of mercury are followed at all liquid-mirror sites. The primary hazard is from mercury vapor. During startup and periodic cleaning of the mirror, vapor levels are generally sufficiently high that respirator masks are required. Once the surface stabilizes, an oxide layer forms which prevents further evaporation of mercury. For this reason, mercury vapor levels are generally very low, even during operation of the telescope.

6. PERFORMANCE

Table 1 summarizes the main specifications of the LZT, and gives some expected performance figures. The 2048×2048 (24 um) CCD has been assumed. The limiting magnitude has been calculated for broad and medium bandwidths of 200 and 30 nm respectively. The numbers correspond to a 3-σ detection for unresolved objects in a single TDI scan. Images can be coadded over several nights in order to improve the signal-to-noise ratio and provide fainter detection limits.

Table 1. LZT Specifications and Projected Performance

Latitude	49.2881 deg
Longitude	122.5731 deg
Altitude	395 m
Median seeing	0.9 arcsec
Aperture diameter	6.00 m
Primary mirror focal ratio	1.50
Effective focal length	10.00 m
Corrector	4-element refractive
Diameter of corrected field	24 arcmin
Detector	Thinned 2048 x 2048
Image scale	0.495 arcsec/pixel
Integration time	103.62 sec
Detector width	16.89 arcmin
Broadband limiting magnitude[a]	25.4 (R)
Medium-band limiting magnitude[a]	24.4 (750 nm)

a) 3σ detection for unresolved objects in a single TDI scan

A major benefit of TDI operation is the very uniform response that results because all CCD elements in a column contribute to each image pixel. This reduces pixel-to-pixel sensitivity variations by more than an order of magnitude, allowing accurate background subtraction. Typical background fluctuations of less than 0.2% are found in TDI observations using the NODO telescope.[10] A further benefit is that the fringing which plagues thinned CCDs is effectively eliminated in TDI operation.

7. SCIENCE PROGRAM

The primary science program for the LZT is to conduct a deep multiband survey of the strip of sky accessible to the telescope. The main goals are to study the structure, evolution and distribution of galaxies and quasars. Within the survey area, more than a million galaxies and several thousand quasars will be accessible to the telescope. We plan to measure the spectral energy distribution for all objects, and use these to determine the object type and redshift.

Because the LZT does not track objects, other than by the TDI operation of the CCD, it will not be equipped with a spectrograph. Rather, the spectral energy distributions of the objects will be determined by photometry through a series of 40 interference filters. A single filter will be used for observations on any given night. After 40 nights, an entire spectrum is obtained for every object. Further observations are then used to increase the signal-to-noise ratio of the data. The filters have logarithmically spaced central wavelengths in order to maintain constant resolution independent of redshift. Their bandwidths are approximately twice the wavelength sampling interval in order to avoid aliasing strong quasar emission lines. Manufactured by Barr Associates Inc., They are image-quality filters with clear diameters of 90 mm and matched optical thickness. Transmission curves for these filters are shown in Fig 2.

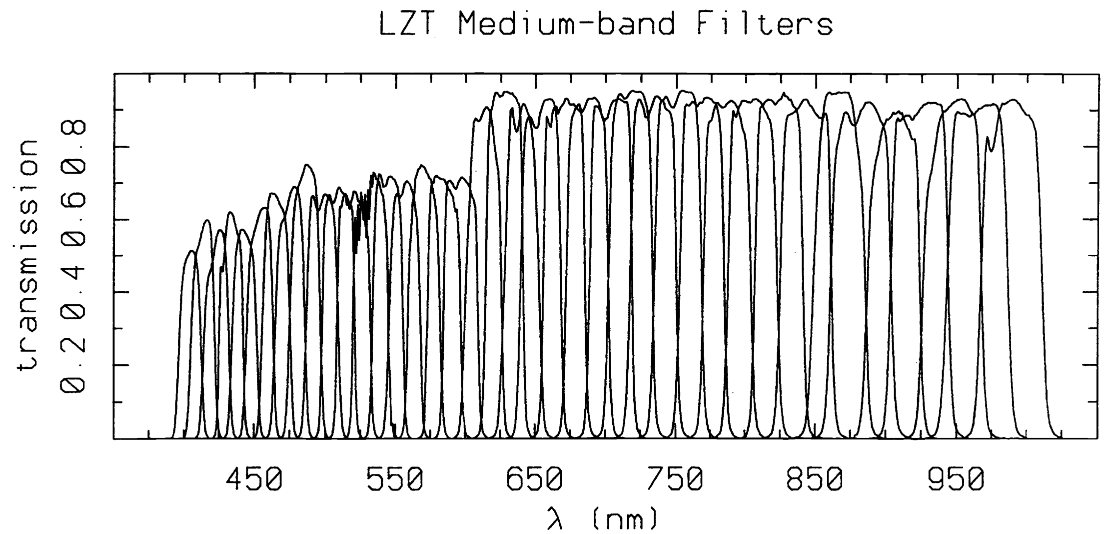

Figure 2. Transmission curves of the LZT medium-band filters

Simulations[15] indicate that galaxy redshifts can be determined from the multiband observations with a typical accuracy of $\Delta z \simeq 0.01$ at a signal-to-noise ratio of 10. This is an order of magnitude improvement over conventional broad-band photometric redshifts. This resolution will allow a direct comparison of the clustering power on large scales with model predictions. The data will also allow a study of the spectral evolution of galaxies over cosmic time scales. The LZT should detect galaxies to a redshift $z \simeq 1$ which corresponds to a light-travel time of order 10^{10} years. Because of passive stellar evolution, galaxies at such redshifts are expected to be about a magnitude brighter (in their rest frames) than their low-redshift counterparts. However, galaxy interactions and mergers may be frequent, and should lead to dramatic changes in the average galaxy population. The multiband-data from the LZT should be well-suited to address these questions.

The multiband survey to be conducted with the LZT is similar the UBC-NASA Survey,[10] which employs the NODO telescope and a subset of the LZT medium-band filters. The data analysis techniques and software pipeline will be similar to the ones used in that survey, which have been extensively tested. The larger aperture, better image quality and more sensitive CCD camera of the LZT should enable us to reach a detection limit that is several magnitudes fainter.

The LZT is expected to see first light by the end of this year, with science observations commencing in early 1999. The survey is expected to take three years, weather permitting. Preliminary results should be available shortly after the first observing season. Additional information on the project can be found on the LZT website (http://www.astro.ubc.ca/lmt/lzt.html).

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