‘Masterpiece of Engineering’ Rises From the Ashes

Restoring what 150 years ago was the world’s largest clock-driven, equatorially mounted telescope is itself a monumental 21st-century technical feat

By **Trudy E. Bell** (Text Copyright 2018 Trudy E. Bell)

When in 1869 the Great Melbourne Telescope (GMT) in Australia first raised its mighty lattice tube to behold the star-studded southern heavens, the instrument was an engineering marvel.

The reflecting telescope had a mirror 48 inches across, largest in the southern hemisphere and second largest in the world. The speculum-metal (copper-tin alloy) mirror weighed over 2,000 pounds, yet was free of flexure at all observing angles because of a pioneering mirror support system—a design still used in many telescopes. Although it topped 18,000 pounds of moving mass, the telescope was so well-balanced that an astronomer could slew it from horizon to zenith in 20 seconds. It was also clock-driven, able to track an object automatically across the sky.

Despite its technological innovations and great promise, the GMT was dogged by a string of unfortunate circumstances. Technical complications delayed commissioning the instrument, the first observer was relatively inexperienced, the observatory was perennially understaffed, and research observations were continually interrupted by dignitaries wanting to look through the eyepiece. In the 1890s, a major worldwide financial crisis dried up funding both for publication of the GMT’s results as well as for continued observations. The telescope lay idle for most of the first half of the 20th century.

In 1945, it was sold for a nominal sum to the Mount Stromlo Observatory near Canberra. Over the decades, its mount was modified and it was fitted with a series of three slightly larger 50-inch glass mirrors, so it confusingly came to be called both “the GMT” and “the 50-inch.” During each rebuild, more original parts were discarded. Fortunately, by the 1980s, the heritage value of the 1869 telescope was recognized: discarded parts were retrieved and warehoused at the “museum store”—the offsite collection storehouse of the Museum of Victoria (renamed Museums Victoria in 2016).

On January 18, 2003, a fierce firestorm engulfed the Mount Stromlo Observatory. Heated to cherry-red temperatures of 900° to 1,475°F, the steel struts of the modernized telescope softened and slumped, and its borosilicate mirror splintered. For half a decade, insurance companies wrangled while the telescope’s ruins stood unprotected through hot summers and freezing winters.

In 2008, three major Australian organizations banded together for an ambitious goal: to restore the original Great Melbourne Telescope to its former glory in its original telescope house on its original site. Their vision: to have the historic instrument in full working order in time for its 150th anniversary in 2019, but equipped with modern optics—turning it into one of the world’s largest telescopes dedicated to public astronomy education.

The restoration effort is itself an engineering marvel. Among the challenges: whatever existed in the way of original plans and engineering records were consumed in the 2003 Mount Stromlo bushfire (or in an earlier fire in 1952). So, supplied only with diagrams published in one 150-year-old article plus a dozen historic photographs, the restoration team has meticulously reverse-engineered crucial drawings to recreate missing components.

Elements of Design

By 1850, astronomers faced fundamental questions: Just what were all those fuzzy, nebulous patches of dim light scattered amongst the pinpoint stars? Were such nebulae clouds of gas relatively nearby within our own “sidereal system,” perhaps forming solar systems of planets like our own? Or were they distant, independent “island universes” (today called galaxies) so remote that their individual stars could not be distinguished? How did the nebulae repeatedly examined in the northern heavens compare with many others lesser known in the southern? And did any nebulae change over time?

The only way then feasible to answer those questions was to build a gigantic telescope and mount it in the southern hemisphere to complement large northern-hemisphere telescopes.

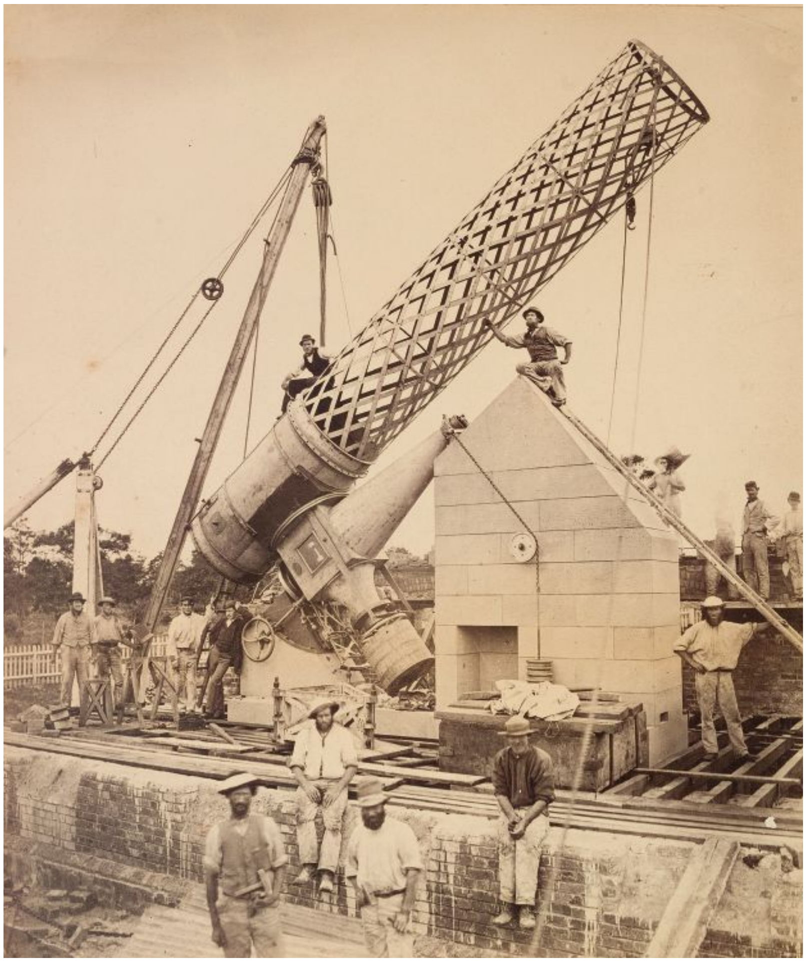
In late 1852, the British Association for the Advancement of Science and the Royal Society of London jointly appointed a Southern Telescope

Remains of the modernized 50-inch telescope at Mount Stromlo Observatory near Canberra after a firestorm in 2003 stood out in the weather until 2008. *Photo: Steve Roberts.*

Committee, consisting of the British Empire's leading astronomers, to study potential locations and designs.

The committee selected the Dublin, Ireland, firm of Thomas Grubb. Grubb was engineer to the Bank of Ireland, for which he designed and built complex engraving machinery for printing banknotes; he also designed and built experimental apparatus for scientists. Grubb grasped optics as well as mechanics: he was possibly the first to use ray-tracing to design microscope lenses and he held at least one optical patent.

To allow an astronomer to observe from on or close to the ground instead of atop a high platform in the dark, the committee chose the Cassegrain focus: incoming starlight would bounce off the concave 48-inch primary mirror, converge up to a smaller convex secondary mirror, which would direct it back downward again through a hole in the center of the primary to an eyepiece behind the mirror [see diagram on following pages].



Above: The Great Melbourne Telescope was assembled in Australia in early 1869; then, its protective house with a roll-off roof was put up around it. The lower third of the GMT's tube was boiler plate (wrought-iron plate of the standard used for manufacturing steam boilers) while the upper two-thirds was a cylindrical lattice of riveted iron strips. *Image: Museums Victoria.* **Below:** Trial reassembly of the GMT was far enough along for photos to be taken in late 2014 to aid in fundraising for the restoration project. All five of the restored pieces from Mount Stromlo are shown: cube, upper cone, bell housing, and quadrant on the supporting pier; the declination axle is lying in the foreground (partially cropped out at the bottom of the photo). *Photo: John Robinson.*

Innovative Optics

By 1853, Grubb had fleshed out the Southern Telescope Committee's astronomical specs into an innovative optical and mechanical design. The entire back of the mirror was supported at all observing angles by a 48-point system of equilibrated triangular levers—a "flotation" system invented by Grubb but perfected by his brilliant young son Howard.

Mechanically, Grubb was one of the first to break with past practice of giving large telescopes wooden altazimuth mounts: mounts that rotated horizontally and vertically. Instead, he designed an equatorial mount: he tilted the vertical axis to an angle parallel with Earth's axis of rotation, giving the telescope a polar axis. That allowed the telescope to track an object across the sky using a single axis (the polar axis) to counteract Earth's rotation. The GMT became the world's largest equatorially mounted telescope.

For rigidity, Grubb specified that the telescope be of cast iron and other metals. Each end of its polar axis was to be supported on bearings atop a stone pier (in a mounting style today called English cross-axis). Mass-produced precision ball and roller bearings were still in the future. So Grubb designed a system of axial and lateral counterbalances loaded by weights hanging on cables to reduce up to 99% of the bearing friction on both axes, allowing the astronomer single-handedly to move the telescope quickly from one celestial object to another. Moreover, a weight-powered clock drive could keep a celestial object centered in the eyepiece for up to two hours at a time.

Father and Son Engineers: Thomas Grubb (1800-1878), top, was an Irish optical and telescope engineer. His youngest son, Sir Howard Grubb (1844-1931), below, joined him in the family business. He is credited with perfecting the submarine periscope during World War I and inventing the reflex rifle sight, still widely used around the world. He was knighted by Queen Victoria in 1887. *Image below from the collection of Ken Launie.*

Shortly after the committee approved Grubb's design and started to set up procedures for letting the contract, the Crimean War broke out and matters stalled—for a decade. The plans were revived essentially unchanged in the 1860s when Australians in high places became keen to establish a grand southern telescope in Melbourne, the capital of the British colony of Victoria—now wealthy because of a gold-mining boom and aspiring to be a world center of culture and learning.

By then, Grubb was overwhelmed with other contracts. So he handed the southern telescope project to his capable 21-year-old son Howard, who dropped out of engineering studies at Dublin's Trinity College to shoulder the project that helped make his own name.

The work was dangerous, capable of killing Howard or his workmen at any time. One early task was casting two 48-inch mirror blanks of speculum metal. By mid-1866, a peat-fired furnace, heated iron and stone mold (complete with central core to form the hole for the Cassegrain focus), and annealing oven were ready. Workmen poured more than a ton of molten white bronze "at full red heat" in 16 seconds, and chain-dragged the mold and liquid mirror into the annealing oven, where it cooled gradually over 24 days. A few months later, the process was repeated, yielding two 48-inch speculum-metal disks (dubbed A and B).

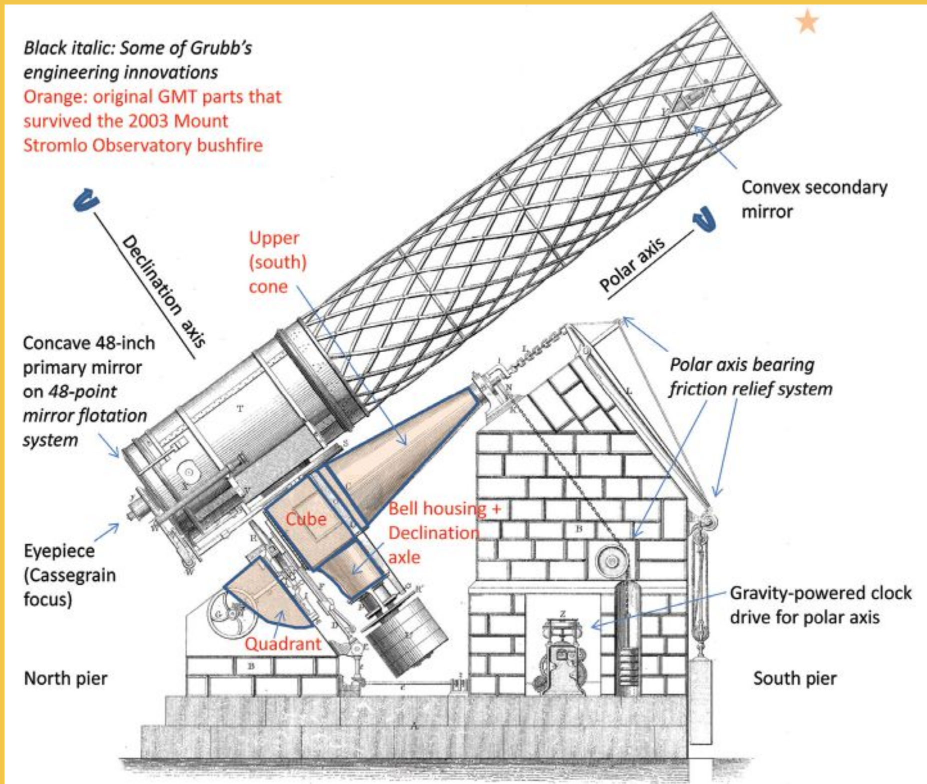
A Tough Grind

Meanwhile, Howard Grubb oversaw the construction of a mechanical two-ton mirror grinding and polishing machine (MGPM), belt-driven by a one-horsepower steam "donkey engine." Disk A was supported face-up on the flotation mirror-support system in its cell, immersed in a water bath that kept it at an even temperature. Then, using a slurry of grinding compound of successively finer grit, steel arms applied about 100 pounds of sideways force to move a rotating metal tool slowly back and forth across the mirror's front surface in an irregular, constantly changing elliptical path, so that no one area became overworked. After three months, two million strokes, and many optical tests, mirror A developed the desired highly polished concave paraboloid surface. Then, it was time to grind, figure, and polish mirror B.

Speculum mirror A was tested by examining challenging celestial objects in October 1867; in early 1868, mirror B and the entire rest of the telescope were completed, assembled in the Grubbs' factory yard, and ready for inspection. A subcommittee from the Southern Telescope Committee was delighted how the movements of the equatorial mount with its weight-relieved bearings were "surprisingly smooth and steady" and how some faint stars in nebulae used as tests for the optics were "dazzling." After minute inspection of the GMT's every mechanical and optical detail, the committee came "unanimously to the conclusion that it is a masterpiece of engineering."

The telescope was sent south by ship, along with the MGPM for periodically shining away tarnish that inevitably accumulates on mirrors of speculum metal;

everything arrived in Melbourne in November 1868. Local workmen erected bluestone (basalt) piers by New Year's Day (in Australian summer), assembled the telescope in place, and then built the walls of the GMT House around the instrument. Instead of being surmounted by a rotating drum or dome, the entire gable roof of the GMT House rolled off on rails to the south so the astronomer observed in the open air. By mid-1869, the Great Melbourne Telescope was ready for astronomical work.



A modified diagram of the GMT as published in *Philosophical Transactions of the Royal Society of London* in 1868 illustrates some engineering innovations by the Southern Telescope Committee and the Dublin telescope maker Thomas Grubb. It was the largest equatorially mounted telescope in the world (English cross-axis style). Grubb's counterpoise system for minimizing frictional loads on the bearings allowed the telescope to be slewed easily by one person and to be clock-driven to compensate for the rotation of the earth. Other innovations included the 48-point mirror support system to avoid flexure at different observing angles, and the use of the Cassegrain focus so the astronomer could observe from floor level. Although Grubb did not invent all these features, he was the first to combine them for such a large instrument. The few parts colored in orange also went through the 2003 bushfire at Mount Stromlo Observatory. *Image:* Phil.Trans.1868; *annotations by Trudy E. Bell*

Phoenix from the Ashes

Fast forward through the twentieth century: after the 2003 Mount Stromlo fire, it dawned on several Victorians that with volunteer labor, the stored original parts, the burnt remnants at Mount Stromlo, and new optics, the GMT could be reconstructed. Representatives of Museums Victoria and the Astronomical Society of Victoria (one of the largest astronomical societies in the world, now 1,000+ members strong) began negotiations with Mount Stromlo management and other relevant organizations.

In 2008, after insurance issues were finally settled, three organizations signed a formal memorandum of understanding: Museums Victoria (which owns the telescope parts plus restoration resources), the Royal Botanic Gardens (which manages the original GMT House on its original site), and the ASV (which has ample volunteer retired labor with needed optical and engineering skills and time). To acquire a modern mirror and reconstruct missing parts, the entire GMT restoration was initially projected to cost about $3 million (in Australian dollars), requiring grants and fundraising. In November 2008, the mangled 50-inch telescope at Mount Stromlo was disassembled and trucked back to the museum store. There, every Wednesday, ASV volunteers work on the GMT in ample space that includes a 10-ton capacity overhead gantry crane and a machine shop.

Plan the Work, Work the Plan

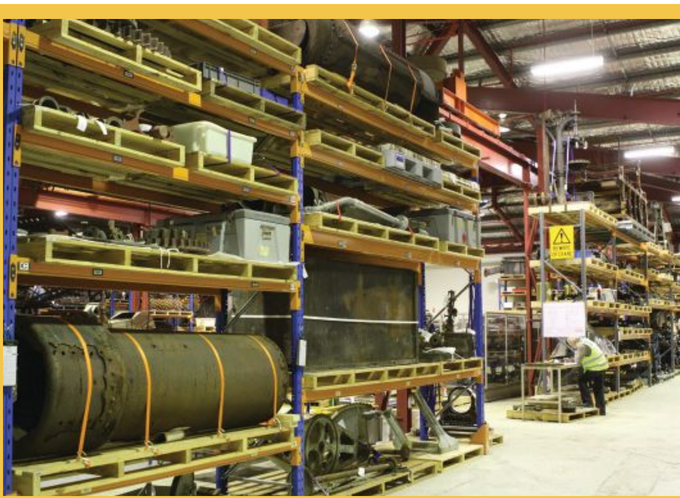
The GMT reconstruction team conceptually divided the work into three phases: Stage 1 was dismantling, drawing, and cataloguing, Stage 2 design and reconstruction of mechanical components, and Stage 3 the provision of new optics and final assembly and installation at the historic site. Because of the daunting magnitude of the project, much of 2009 was devoted to laying essential groundwork for Stage 1.

To document every part, ASV volunteers began building an engineering spreadsheet. They photographed and measured every part to an accuracy of 0.1 mm and weighed larger parts to the nearest 0.5 kg (5 g for smaller parts under 2 kg) so the rebuilt telescope could be properly counterweighted. Some parts could be reused as is. But others clearly needed some repair, modification, or replacement. In those cases, documentation included writing a proposal for the work needed.

The volunteers also drew up a gigantic flow chart to identify critical paths in the restoration project: which sequence of tasks must be completed on time for the entire project to finish on time. Meantime, the three organizations jointly developed a communications strategy—including mission statement, fact sheets, photographs, logo, and website—for seeking publicity and funding.

In 2009–10, the restoration team felt ready to begin dismantling and cleaning. They started with the GMT's heaviest structural component: the giant central 620-kg (1,400-lb) cast iron cube that supported the telescope tube. Attached to it were the south (upper) cone of the telescope's polar axis and the bell housing for the telescope's declination axis [see diagram].

To everyone's surprise and gratification, the nuts and bolts were still in good shape even after enduring the Mount Stromlo bushfire and nearly six years out in the weather, raising hopes for the integrity of other parts. "We grew to relish the sound of the 'crack' as a nut or



Above: At least 70% of the original GMT parts are safely sheltered in the "museum store"—the offsite collection storehouse for large engineering objects of Museums Victoria in Melbourne. Since 2009, a restoration team from the Astronomical Society of Victoria and from the museum has met weekly to document and clean parts, undo 20th-century modifications, and reverse-engineer missing parts, all with the goal of reconstructing the 1869 instrument for public astronomy education. *Photo: Trudy E. Bell.* **Below:** The cube, upper (south) cone, and bell housing of the GMT's polar and declination axes that had gone through the 2003 bushfire had been documented, cleaned, and partially reassembled by August 2014. This heart of the GMT's equatorial mount is suspended by the 10-ton overhead crane of the cavernous workspace at the museum store in about the same orientation as the mount shown at left in the wall-sized photograph of the fully operational GMT taken about 1875. That enlarged image is not decoration; the restoration team relies on it and other 19th-century photographs to obtain crucial measurements and understanding of how the GMT's parts fit together. *Photo: Steve Roberts.*

[machine screw] suddenly began to rotate under our ministrations," recalled ASV volunteer Steve Roberts, who documented the GMT's progress in the project's occasional newsletter aptly named *Phoenix*. "That, and the smell of WD-40 in the morning."

Everything was carefully cleaned by hand, a tricky task as many painted parts had a toxic red lead undercoat. Moreover, on parts that had survived the Mount Stromlo bushfire, the paint had baked into an almost enameled finish that resisted all chemicals and was slippery under a wire brush: the only technique that worked was lightly tapping with a chisel to spall off the coating in small flakes. (Powered wire brushes were not permitted for use on such historically significant heritage parts.) Finishing the job with a hand-held wire brush and paint stripper threw up "a stinging, filthy spray of solvent, dust, and paint particles against which we [had] to wear protective gloves and face shields," Roberts recalled.

After many Wednesdays of patient, grueling labor, by May 2010 all the beautifully machined surfaces of the big iron cube, cone, and bell housing were gleaming; they and their fasteners were then protected from rust with a thin coat of oil, assigned a number, and stored either inside a numbered gray box or strapped to a pallet with a barcode label.

By early 2012, the team had catalogued all the GMT's parts, cleaned them, understood where they worked in the telescope, and were halfway through photographing them and documenting their condition, function, appearance, and markings. From carefully hand-drawn life-size or scale technical drawings and measurements, ASV AutoCAD expert Campbell Johns produced CAD engineering drawings. Some especially complex parts required multiple drawings: for example, the cube with all its uniquely shaped openings and different sized and irregularly spaced screw holes required no fewer than 12 drawings—one each for the inner and outer faces of its six sides. Every CAD drawing was cross-checked by a different volunteer and Johns corrected the final version in the file server.

Plans for Posterity

All the meticulous steps sometimes felt tedious and exasperating. But the "GMT being an irreplaceable relic of a bygone age" and also public property, Roberts noted, "we should not make any mistakes with heritage materials." Another goal was to leave a complete set of engineering plans for posterity. "The drawings provide a record of the state in which components were found and any changes or alterations made, which is an important part of thoroughly documenting a conservation/restoration project," explained Matthew Churchward, a senior curator of Museums Victoria.

Also in 2012, the ASV team began provisionally fitting cleaned parts back together to plan reassembly. Although they knew how parts they had disassembled fit together, where the hundreds of loose parts in the museum store since the 1980s fit was not always apparent, especially where pieces were missing.

Meantime, the volunteers began searching in earnest for a modern 48-inch mirror. Three promising leads for potential donation of pre-owned mirrors ended in disappointment (including one from the decommissioned Table Mountain Observatory telescope, then in offsite storage of NASA's Jet Propulsion Laboratory in Southern California, which I tried to broker for the ASV in 2012).

In 2013, team members led by ASV member physicist and optical engineer Barry Clark produced a major report identifying restoration needs grouped by type, highlighting needs requiring donation of funds or goods. For a brand new replacement mirror set, Clark's team calculated a Cassegrain configuration with about three-quarters of the original effective focal length and other modern modifications better for both public viewing and for celestial photography and spectroscopy. Their provisional designs were independently verified by the consultants Prime Optics and tweaked using Zemax optical design software.

Last October (2017), Museums Victoria released a formal request for Expressions of Interest (an Australian precursor to a Request for Tender) describing precisely what would be required in the mirror set and other opto-mechanical components, including working replicas of the original eyepieces.

'Press On In the Hope'

Conservatively, the GMT's restoration is about half complete, delayed in part by unexpected engineering challenges. The biggest discovery: the massive cube is slightly distorted. Opposite faces are no longer exactly parallel or perpendicular. They are not off by much—the faces remain parallel within about 2 minutes of arc and the declination axis is about 5 arc minutes from a right angle with the polar axis. But that small divergence is enough to cause excessive runout of the polar drive mechanism (i.e., the polar axis and attached hour circles would not rotate concentrically but would describe an eccentric circle). Moreover, the cube has several fatigue cracks.

So the big question is: If three of the four faces involved are remachined, will the cube maintain enough strength to support over eight tons of moving mass? Will internal reinforcing plates reduce further growth of the cracks? One factor gives hope: in the 1860s, Grubb deliberately over-engineered the mount to be strong and stiff enough to carry the mass of a 60-inch speculum mirror, support system, and tube, should a larger telescope someday be desired. The team is exploring the possibility of fixing the cube's angular errors with shims and steel-filled rigid epoxy gaskets cast in place, with continuous optical monitoring of the corrected angles while the epoxy is setting.

In the October–November 2017 issue of the ASV's bimonthly magazine *Crux*, the director of ASV's GMT Section Jim Pollock expressed his midnight fears: "[I]t now appears it will be impossible to complete the GMT restoration in time for the telescope's 150th anniversary of its original installation" in mid-2019. But after more than 20,000 hours of dedicated volunteer work since 2008, "the team will press on in the hope that further funds will be forthcoming and a start on the reinstallation can be made by the end of 2019."

Gratitude is expressed to the following expert sources and reviewers for helpful information, images, and feedback: Roger Ceragioli, Matthew Churchward, Barry Clark, Philip Edwards, Richard Gillespie, Ken Launie, Fred Orthlieb, Steve Roberts, and Matilda Vaughan—and especially to Jim Pollock, who also hosted my all-day visit to the GMT restoration work space.

Selected references

•The most recent authoritative book about the GMT is Richard Gillespie's lavishly illustrated *The Great Melbourne Telescope*, Museums Victoria Publishing, 2011.

•To get a feel for the magnitude of the GMT restoration, see the Australia Broadcasting Corp.'s seven-minute video *www.youtube.com/watch?v=C0KlzIxlKU4* from 2016 (featuring several people helpful to this article), especially beginning around minute 3.

•For sheer first-person drama of casting the GMT's mirrors and other construction, see T.R. Robinson and Thomas Grubb, "Description of the Great Melbourne Telescope," *Philosophical Transactions of the Royal Society of London* 159: 127–161, 1869, available at *https://www.jstor.org/stable/108993*.

•For perspective on how meticulously the Southern Telescope Committee weighed design decisions and risk trade-offs for optics, mechanics, and location, see *Correspondence Concerning the Great Melbourne Telescope. In three parts: 1852–1870* (London, 1871).

•"Report of the Committee on the Melbourne Telescope to the President and Council of the Royal Society," *Proceedings of the Royal Society of London* 16: 313–316 (1867–8). This is the document that pronounced the GMT a "masterpiece of engineering."

•Those hankering for more in-depth engineering details (some quite funny) about the GMT restoration project will enjoy the 11 issues of the project's newsletter *Phoenix* published between June 2009 and April 2015; PDFs can be downloaded from the project's website at *https://greatmelbournetelescope.org.au/newsletter/* . (My attempt to broker a 48-inch mirror for the ASV is summarized in issue #7 (November 2012), pp. 7–8.)

Academic secondary references include:

•Andropoulos, Jenny Ioanna, *Astronomical Publications of the Melbourne Observatory* (James Cook University, 2014) is a two-volume, illustrated Ph.D. thesis topping 800 pages that in part exhaustively reexamines the scientific contributions of the Great Melbourne Telescope.

•Andropoulos, Jenny, and Wayne Orchiston, "Melbourne Observatory and the Genesis of Astrophysics in Australia," *Anglo-Australian Observatory Newsletter*, February 2006: 18–20.

•Gascoigne, S.C.B., "The Great Melbourne Telescope and other 19th-century Reflectors," *Quarterly Journal of the Royal Astronomical Society* 37: 101–128 (1996).

•Gillespie, Richard, "The Great Melbourne Telescope: A Contextual History," in *400 Years of Astronomical Telescopes: A Review of History, Science and Technology* (Springer, 2010 [on CD-ROM and *http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.611.8535&rep=rep1&type=pdf*]).

•Hart, J., et al., "The Telescope System of the MACHO Program," *Publications of the Astronomical Society of the Pacific* 108: 220–222 (1996).

•Hyde, W. Lewis, "The Calamity of the Great Melbourne Telescope," *Proceedings of the Astronomical Society of Australia* 7: 227–230 (1987).

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She is pictured during a visit to Australia, holding an original name plate reading "Grubb 1868 Dublin" before the Great Melbourne Telescope's historic 48-inch speculum mirror (mirror is facing the wall; central hole is for the Cassegrain focus). *Photo: Jim Pollock.*