Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005

Lessons for ELTs from the Large Binocular Telescope

T. M. Herbst [1]

[1]Max Planck Institute for Astronomy, Heidelberg, Germany

Abstract: The growth in telescope collecting area is once again stalled at a maximum single mirror size. The lessons of the past, from both the radio and optical/infrared, is that such episodes correspond to the development of multi-element collectors, i.e. interferometers. There are currently several ongoing studies of single-dish Extremely Large Telescopes (ELTs). These efforts are confronting significant challenges, particularly in the area of wind loading, atmospheric turbulence, and cost. This paper presents some musings on how lessons learned with hybrid ELTs, such as the Large Binocular Telescope, can help us address these challenges.

1 The Road to Extremely Large Telescopes

Mankind's growth in understanding of the universe has been a direct result of improvements in our abilities to study it - in other words, growth in the size and quality of our telescopes. However, this growth has inevitably encountered technological challenges, including, for example, the limits of large steel construction for radio telescopes, and the substantial mass and thermal time constant of large glass optics for optical / infrared facilities.

The result has been an episodic growth in telescope size, with brief spurts of dramatic increase interspersed with long periods of stagnation. Figure 1 shows schematically the growth in diameter of radio telescopes over the past century, starting with Grote Reber's original 10 meter telescope in 1937 and culminating in 100 m class facilities approximately 40 years later. Steel structures larger than 100 meters simply don't have the strength and stability to make successful telescopes. As the limits of steel technology became apparent, radio astronomers turned increasingly to distributed, interferometric telescopes. With the advent of the Very Long Baseline Array (VLBA), the new technological limit on the size of radio interferometers is the size of our planet.

Similar technological barriers have affected the growth in optical / infrared telescopes, as indicated in Figure 2. Here, we see at least three significant periods of stagnation in telescope diameter growth. The first, spanning approximately the first half of the twentieth century, resulted from a number of factors. The 100 inch Hooker telescope on Mount Wilson is a classic construction of nineteenth century bridge-building technology, ill-suited to larger diameters and masses. Also, the primary mirror of the 100 inch is essentially window glass, which suffers from bubbles and crystallization problems in very large sizes. Perhaps most importantly, the large coefficient of thermal expansion of ordinary glass renders it useless for large, precise optical surfaces in contact with (varying) ambient temperatures. Finally, both society and technology during the first half of the twentieth century were rocked by two major world wars.

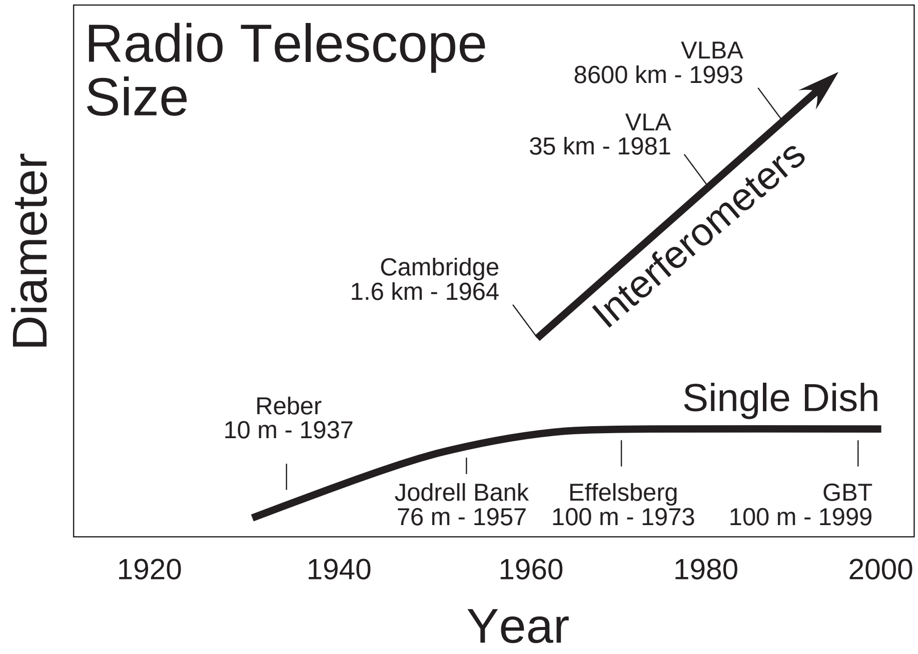

Figure 1: The diameter of the largest radio telescope in the world over the past century. The lower, thick line traces the size of single-dish radio telescopes, while the upper arrow indicates the size of radio interferometers.

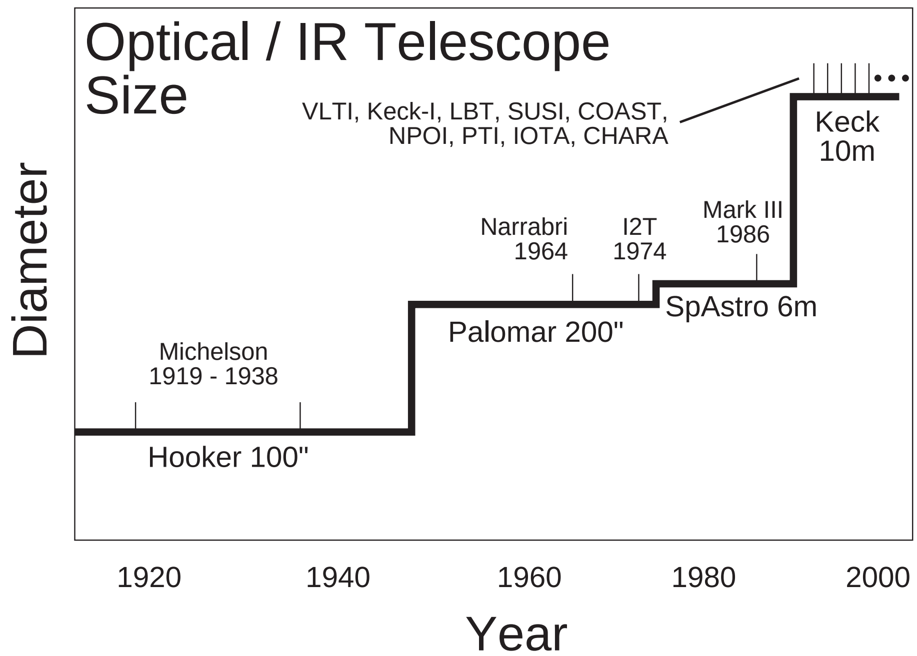

Figure 2: The diameter of the largest optical / infrared telescope in the world over the past century. The thick line traces the maximum size, with the name of the relevant facility appearing below. The vertical tick-marks above the thick line indicate various optical / infrared interferometers developed in reaction to the telescope size limit.

The 200 inch Palomar telescope overcame these technological challenges through a combination of new steel construction methods and the development of Pyrex, a low-expansion glass with considerably reduced bubbling problems, (the telescope did suffer a considerable schedule slip due to World War II, however). The fabricators of the 200 inch also pioneered the technology of mirror light-weighting by casting stiff ribs into the back of an otherwise relatively thin mirror. The Palomar telescope reigned supreme for essentially forty years, until the development of active computer control and very thin, lightweight mirror technologies broke the five meter barrier. These mirror technologies are surprisingly diverse and include such approaches as segmentation, spin-casting, honeycomb light-weighting, and fuse-and-slump fabrication.

As with radio telescopes, Figure 2 clearly demonstrates that optical / infrared astronomers have reacted to growth stagnation by combining individual telescopes into interferometric arrays. And, while we have yet to push the boundaries imposed by the size of planet Earth, the figure unquestionably shows that we are currently in a golden period of growth in large optical/infrared interferometric facilities.

1.1 The Challenges of ELTs

Table 1 summarizes the last one hundred years of development of optical/infrared ground-based telescopes. In every era, astronomers have been confronted with significant challenges to producing larger and larger facilities, and have reacted with innovative technological solutions. Despite these advances, we are unquestionably mired once again in a period of stalled growth in telescope diameter, and the 10 m Keck telescope will be "king of the hill" for at least 25 years.

A number of factors contribute to the current impasse, including the challenges of adaptive optics and wind loading on large telescopes. For example, adaptive optics simulations show that the atmospheric wavefront error inexorably increases with increasing telescope diameter. And, while this effect depends somewhat on the outer scale of turbulence, ELTs will unavoidably have to have qualitatively more actuators with larger stroke and greater correction bandwidth. Similar calculations of the mechanical response of large telescope structures to wind-loading show a dramatic increase in wavefront error with increasing diameter, and there is currently no clear path to a solution.

A further challenge relates to the cost and scope of the next generation of Extremely Large Telescopes. These projects will certainly transcend the ability of any individual country (or perhaps even group of countries) to construct, support, and operate. Of particular concern is the potentially enormous cost of the telescope enclosure. The largest ELT projects currently under study have either a huge, possibly unbuildable dome, or none at all. The latter option may not be viable if wind-loading proves to be a truly intractable problem.

The lesson of the last century of large telescope building is clear: the success of ELTs will depend on our finding creative technological solutions to these challenges. One obvious way to gain insight into ways forward is to examine early efforts at breaking the 10 meter barrier. The Large Binocular Telescope Project is such an effort.

2 LINC-NIRVANA on LBT: A Transition to ELTs

The Large Binocular Telescope (LBT) represents a transitional facility between the current crop of 8 meter class telescopes and the future Extremely Large Telescopes. It also spans the gap between the single-dish telescopes and dispersed interferometric arrays. With two, 8.4 meter primary mirrors on a single mounting, the LBT provides the equivalent collecting area of a

Telescope	Science Highlight	Challenge	Solution
Hooker 100" 1917 –	identified "spiral nebulae" as galaxies	large reflecting optics	careful fabrication
Palomar 5m 1948 –	discovery of quasars	size, thermal effects	new construction methods, borosilicate glass, primary ribs
Keck 10m 1993 –	brown dwarfs, high redshift universe	size, primary mirror fabrication	active computer control, thin primary, segments
ELTs 2015? –	z=5–10, reionization extrasolar planets?	size, adaptive optics, wind-loading, cost	massive segmentation, laser guide stars, MCAO, control, ?

Table 1: The largest optical / infrared telescopes in the world over the past century. The second column places the telescope in historical scientific context, while the last two columns present the major construction challenges and the strategies to overcome them.

12 meter telescope, and when operated in phased mode, the spatial resolution of a 23 meter telescope.

Figure 3 shows the current (March 2006) status of the LBT. The telescope achieved first light with a single primary mirror in September 2005, and is on schedule for "second light" later this year. Full operation of the LBT, including both adaptive secondary mirrors and coherent combination, is scheduled for mid-2008.

There are currently two instruments under construction that will fully exploit the diameter and collecting area of the Large Binocular Telescope. A group based at the University of Arizona is constructing LBTI, a thermal infrared beam combiner. Current efforts are focusing on a nulling interferometry experiment, but LBTI will allow thermal infrared imaging as well. A second collaboration, based in Germany and Italy, is building LINC-NIRVANA, a near-infrared Fizeau-mode beam combiner with multi-conjugated adaptive optics (MCAO). Fizeau interferometry preserves phase information and allows true imagery over a wide field of view.

Figure 4 explains the general principles behind interferometric imaging with LINC-NIRVANA on the LBT. The individual frames returned from the infrared camera contain 23 m spatial resolution information along the projected baseline, and 8 m spatial resolution information in the perpendicular direction. By combining images taken with different projection ("parallactic") angles, the observer can reconstruct panoramic imagery with the full spatial resolution of a 23 meter telescope.

Producing such imagery forces us to confront challenges that will also face future designers of Extremely Large Telescopes and their instruments. For example, LINC-NIRVANA employs multi-conjugated adaptive optics (MCAO), a technique identified as a prerequisite for effective ELT operation at the diffraction limit. In addition, after the light of the two telescopes comes together, the balance of the optical path, including pupil management and phasing of the primary mirror "segments," is essentially that of an ELT imager. Finally, we will need to actively control multiple optical components in both LINC-NIRVANA and the LBT. Operating

Figure 3: The Large Binocular Telescope in early 2006. This view shows the first-light prime focus camera above the left-hand primary mirror. The beam combining instruments, including LINC-NIRVANA, will occupy the central instrument platform between the two mirror cells.

in this way, both the instrument and telescope have similar physical sizes and control tolerances to that of an Extremely Large Telescope.

3 Lessons Learned: From LBT to ELTs

What insights can we gain for ELTs from LINC-NIRVANA on the Large Binocular Telescope? Specifically, are there lessons to be learned which can alleviate the major obstacles to ELT development?

The Large Binocular Telescope breaks the 10 meter diameter mirror barrier by employing a nonconventional entrance pupil, one consisting of two separate, large mirrors. While other facilities, such as VLTI and Keck-I, also have multiple apertures, they are not wide field imaging telescopes – that is, they do not allow true (i.e. Fizeau) imagery. What the LBT demonstrates is that we can, indeed, perform conventional imaging and spectroscopy with unconventional pupils, splitting the collecting area and allowing flexible operation.

Distributing the entrance pupil also mitigates the wind-loading problem, since we know how to control wind forces on individual, 10-meter-class apertures. The spin-cast, honeycomb structure of the LBT primaries provides stiffness, yet the mirrors are lightweight (15 tonnes) and rapid in their response to changing ambient temperature (thermal time constant *ca* 20 minutes).

Perhaps most importantly, a nonconventional entrance pupil allows huge savings in the cost

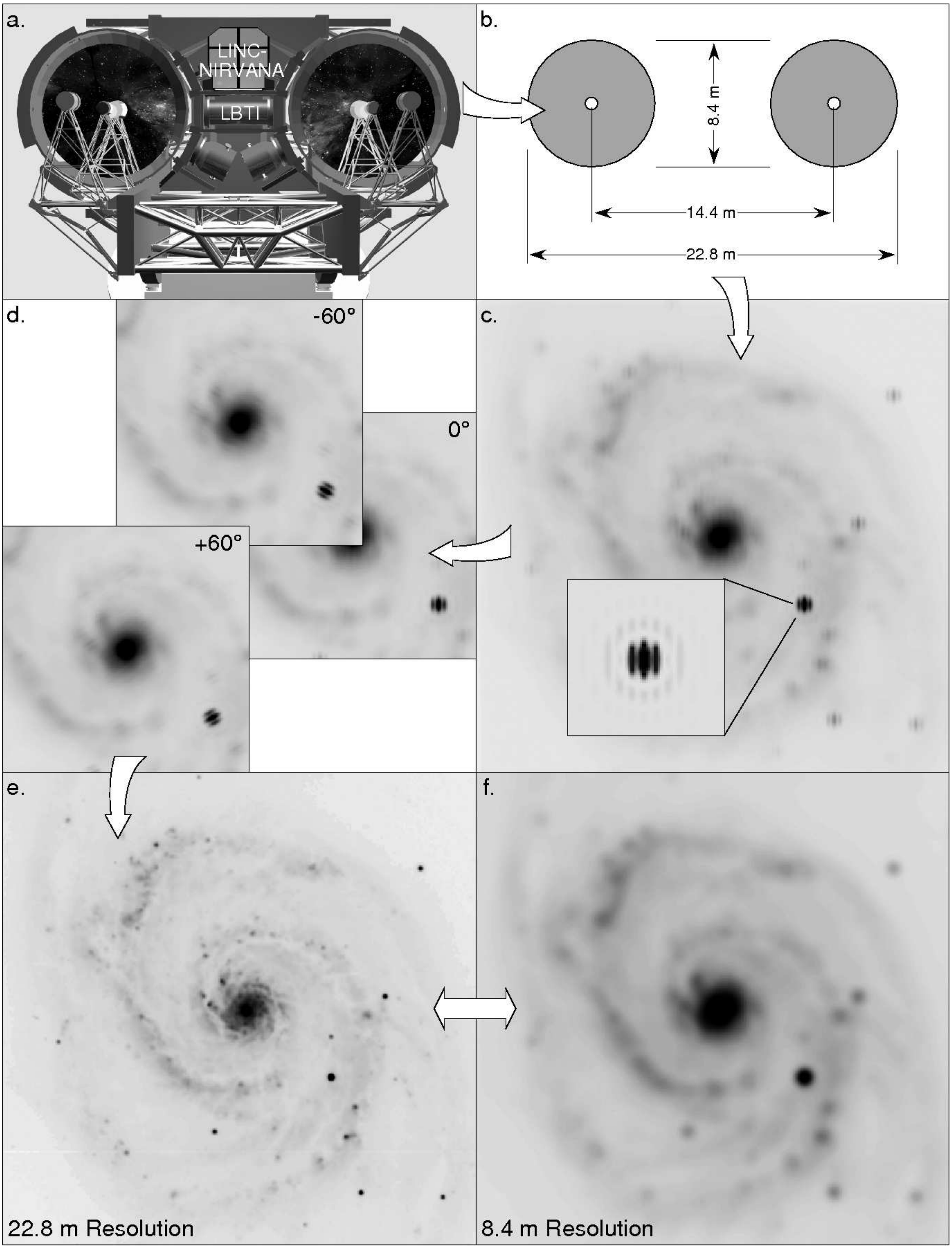

Figure 4: The principle of Fizeau imagery with LINC-NIRVANA on LBT. The entrance pupil of the telescope (panels a, b) creates a hybrid point spread function consisting of an 8.4 meter airy disk crossed by high angular resolution fringes (c). By taking several exposures at different parallactic angles (d), the observer can reconstruct the full 22.8 meter spatial resolution image. A comparison of panels e and f dramatizes the improvement over single-telescope operation.

and complexity of the telescope enclosure. Historically, the cost of ground-based facilities has increased rapidly with the primary mirror diameter, but the major driver has, in fact, been the price of the enclosure The conventional wisdom is that cost scales as $D^{2.6}$, although this relation was established in the era of "small" 2-4 meter telescopes.

With its linear array of entrance pupils, the 23 meter Large Binocular Telescope has an enclosure which is essentially the same size as that of a 3-5 meter telescope of conventional design. The history of radio interferometry suggests that, for a small number of individual antennae, a linear topology is the optimal configuration for a telescope array. This in turn suggests that the cost of both the telescope and enclosure of a multi-element ELT should scale *linearly* with diameter, rather than as the *cube* (or 2.6 power). Of course, the collecting area of linear distributed pupils does not increase as the square of diameter in the usual way.

The lessons of LBT are more mixed in the area of instrumentation, however. Our experience in developing the LINC-NIRVANA imager has demonstrated that there are few shortcuts available to simplify the task of equipping ELTs with imagers and spectrographs. In order to preserve the full collecting area and spatial resolution of nonconventional telescopes, the instrument builder must still provide a scaled version of the entrance pupil, and this implies large, perhaps actively-controlled, optical systems. Also, adequately sampling a wide, near-infrared, field of view at the diffraction limit of an Extremely Large Telescope inevitably involves a large focal plane and costly detectors.

Figure 5 shows one simple way to extrapolate the LBT to an ELT. While this telescope is little more than a cartoon, it demonstrates the clear lessons for ELTs that we can learn from the Large Binocular Telescope. First, it breaks down the challenges of adaptive optics and wind-loading to 8-meter-size bites, which we know how to solve. Second, it provides very flexible, high-angular-resolution, true imagery. Finally, it provides a clear path to breaking the cost curve for the enclosure of an Extremely Large Telescope.

Note that the exploitation of unconventional entrance pupils is very much a mainstream concept. Figure 6 illustrates how this strategy has allowed us to push past traditional size restrictions for telescopes operating at radio and mid-infrared wavelengths. In the case of the Nançay radio telescope, the collector has essentially the same collecting area, but twice the spatial resolution of the largest, fully steerable antenna. The unconventional pupil of the James Webb Space Telescope allows a 6.6×3.6 meter primary mirror to be launched within the limited shroud diameter of an Ariane 5 rocket. If all goes well, the "ear" segments will fold out, producing a conventional 6.6 m diameter primary. If the deployment fails, the JWST operators will still be able to synthesize the full 6.6 m spatial resolution, albeit with a penalty in sensitivity and observing efficiency.

The approaches taken with the Large Binocular Telescope have already permeated the community of Extremely Large Telesocope builders. Most prominently, the 20/20 design concept developed at the University of Arizona draws heavily on the heritage of LBT to overcome the challenges of wind-loading, adaptive optics, and cost of an ELT. While the future of 20/20 appears uncertain at this time, many of the concepts of both 20/20 and LBT are embodied in the Giant Magellan Telescope, which is scheduled for completion in 2016.

4 Conclusions

As has happened repeatedly in the past, technological challenges currently limit the maximum diameter of optical / infrared telescopes. And, while telescope builders struggle to break the

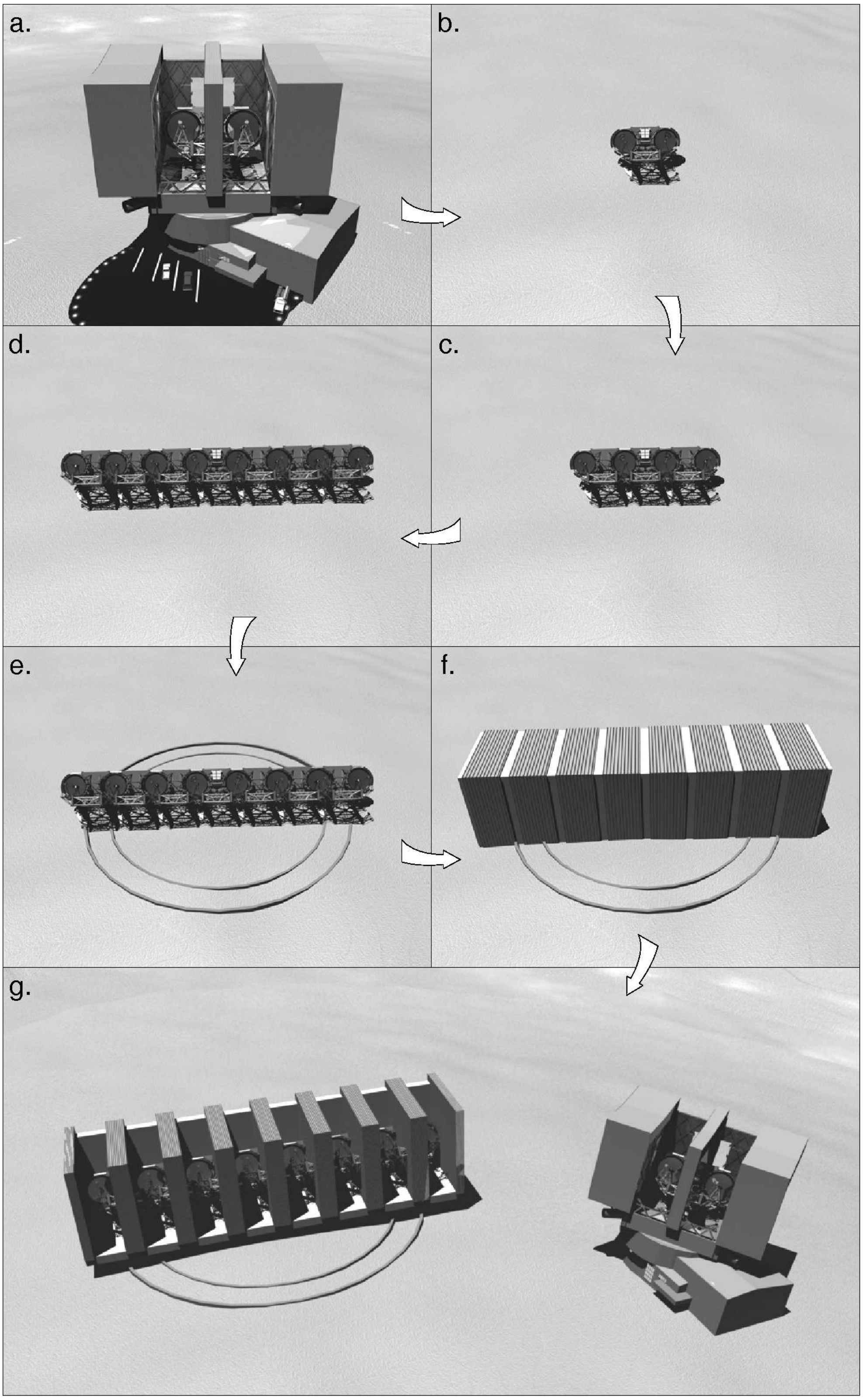

Figure 5: Evolution of the LBT to an Extremely Large Telescope. Simply extrapolating the telescope to a linear array of 4-8 individual mirrors would provide the spatial resolution of a 50 m (panel c) or 100 m telescope (d) Placing the array on an azimuth track (e) and enclosing it (f) completes the telescope. A comparison of the multi-element ELT with the original LBT facility (g) highlights how this strategy can break the traditional cost scaling of large telescopes. To first order, the 100 meter ELT in panel g would cost roughly four times as much as the LBT, since both the number of component telescopes and the volume of the enclosure scale linearly.

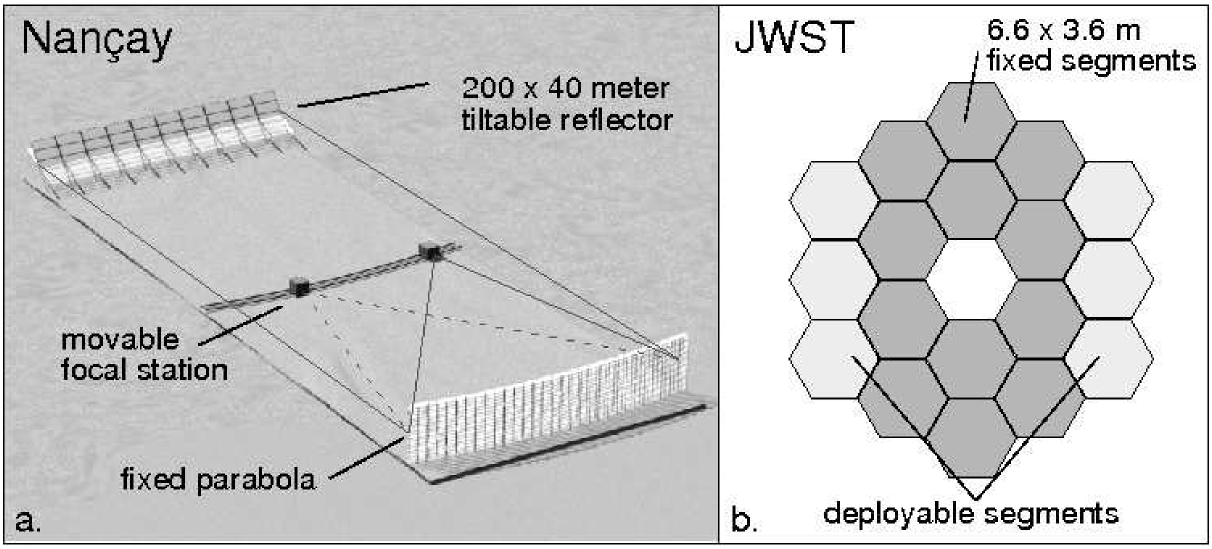

Figure 6: Other unconventional pupils in astronomy. The Nançay radio telescope (panel a) consists of a tiltable, flat reflector, a fixed parabolic primary, and a movable focal station. The primary mirror of the James Webb Space Telescope (panel b) is 6.6×3.6 m at launch. Deployment failure of the two additional sets of 3 segments would still allow observations with the full, 6.6 m, spatial resolution of the telescope.

10 meter barrier, the astronomical community has reacted (again), by pursuing distributed, interferometric, telescope facilities.

Hybrid telescopes, such as the LBT, can provide insight into ways forward in our quest for Extremely Large Telescopes. In particular, the Large Binocular Telescope has demonstrated that we can work effectively with unconventional entrance pupils, splitting the collecting area among individual mirrors that we know how to build. Operated in Fizeau mode, the LBT offers panoramic imaging and spectroscopic capability with few compromises. It is truly the first of the ELTs.

The most significant challenges to ELT development are the feasibility of adaptive optics, the problem of wind loading on the telescope, and the enormous cost of the enclosure. The LBT addresses the first two of these difficulties by reducing them to problems that have already been solved, namely 8 m telescope AO and thick, stiff, primary mirrors. A simple extrapolation of the LBT to ELT scales suggests that cost control is also possible, since for efficient telescope arrays, both the collecting area and enclosure volume increase modestly with diameter.

Acknowledgements

T. M. Herbst is grateful to the conference organizers for spurring the musings contained in this paper. He has also benefitted from discussions and input from Wolfgang Gaessler, Shri Kulkarni and Piero Salinari.