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The Revolution in Telescope Aperture

C.M. Mountain and F.C. Gillett
Gemini Observatory, 670 N. A'ohoku Place, Hilo HI 96720

Gemini Preprint # 41

The 40 years that have elapsed since the opening of the Kitt Peak National Observatory have seen several revolutions in astronomy. One such revolution that is often not recognised is the exponential growth in the total collecting area of large telescopes. This revolution, although ultimately driven by curiosity, has come about because of advances in computers, materials and fabrication techniques -- these advances have facilitated the construction of telescopes that are not just bigger, but better as well. The enormous growth in ground-based observational capabilities that will become available over the next decade, combined with future generations of space-based telescopes, should contribute to dramatic changes in our understanding of the Universe. The first hints of this new understanding are already beginning to emerge, giving new directions to future telescope builders.

From the time of Galileo, 400 years ago, we have gained a deeper appreciation of the Universe and our place in it by observing and analysing the appearance of the night sky with telescopes. Seeing the moons orbiting Jupiter convinced Galileo[1] to place the Sun, not the Earth, at the centre of the Solar System. Observations made with the Mt Wilson 50-inch telescope showed that the Sun is in the outskirts of our own Galaxy[2]. Measurements made with the world's first 100-inch and 200-inch telescopes showed that the Milky Way is but one galaxy within an enormous expanding Universe[3,4]. With the 4-metre telescopes on Kitt Peak and Cerro Tololo,

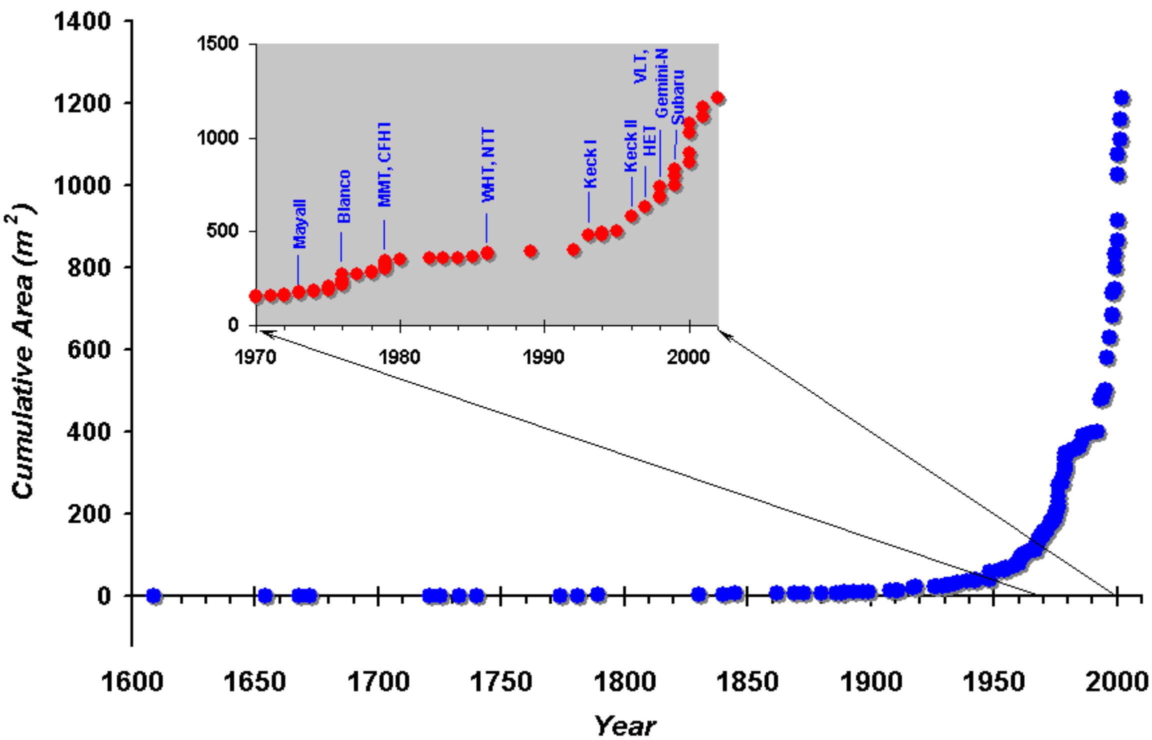


Figure 1 The growth in cumulative telescope collecting area over the past 400 years, with each point representing a completed ground-based telescope. The combination of the ability to manufacture and support large mirrors combined with adaptive optics has given the new generation of large telescopes tremendous scientific gains over the previous 4-m telescopes. For example, an 8-m telescope delivering images of 0.1 arcsec can observe point-like objects at least 20 times fainter than a conventional 4-m telescope delivering 1.0 arcsec images. Will we see such gains in the next generation of telescopes? MMT, Multiple Mirror Telescope; CFHT, Canada-France-Hawaii Telescope; WHT, William Herschel Telescope; NTT, New Technology Telescope; HET, Hobby-Eberly Telescope; VLT, Very Large Telescope; Gem-N, Gemini North Telescope.

Chile, Vera Rubin[5] showed that even the visible matter of galaxies was merely the tip of an iceberg. Vast quantities of dark matter seem to dominate the dynamics of all galaxies and probably the Universe itself. Today's observers, using the Keck 10-m telescopes and the new generation of 8-m telescopes, are analysing the constituents of early galaxies within a few billion (10^9) years of the creation of the Universe[6,7].

This ground-based capability for observing and studying the Universe at optical and infrared wavelengths has grown from Galileo's first telescope, with a collecting area of about 1/2000 m^2, to an ensemble of telescopes that, by the end of this century, will have a total collecting area of over 1000 m^2 (Fig. 1). Of this growth in collecting area, 80% will have occurred in the last 10 years of this century, and will be dominated by the emergence of a new class of 8-m to 10-m diameter telescopes. This tremendous growth in telescope collecting area has been driven by three factors. The first, and most fundamental, is the curiosity-driven willingness to invest in astronomy, inspired by the discoveries of the Past century. Most of this recent investment is in national and international facilities, and continues the trend to internationalise astronomy. The Associated Universities for Research in Astronomy (AURA; the parent body of the National Optical Astronomy Observatories) must take much of the credit for starting these international partnerships, The second factor is the profound revolution in computer and materials technology that has occurred over the past few decades. This has allowed the fabrication of large, high quality mirrors with short focal lengths, and sophisticated computer-controlled telescopes and instruments. Lastly, advances in adaptive optics at near-infrared wavelengths should soon allow us to build large telescopes that are essentially diffraction limited. This will result in sub-arcsecond resolution, like that of the Hubble Space Telescope (HST) combined with the increased collecting area of an 8--10-m telescope.

The challenge of building large telescopes

Before the development of high-performance charge-coupled device detectors, increasing the light-collecting area of telescopes was the main goal of telescope builders. The reason for this is simple: if too few photons per unit area are reaching the detector (which is more pronounced as spatial or spectral resolution is increased), the noise level produced during a given observation will be determined solely by the noise of the detector; in this limit, the signal-to-noise ratio is proportional to the collecting area of the telescope. Consequently, the main challenge that most telescope builders addressed was how to manufacture and support ever-larger primary mirrors to collect more light.

The larger the mirror, the greater is the need for mechanical stiffness to counteract the effects of glass deformation due to its own weight and wind forces. This classically requires more massive mirrors and supports, which in turn result in more structure (steel), and larger protective buildings. All of this adds to the cost of a telescope. The thicker glass of larger mirrors also responds more slowly to changes in temperature, thereby degrading the images both through thermal deformation of the mirror and from the convection of air warmed or cooled by the mirror itself. In fact, it is the combination of large thick mirrors supported by massive steel structures housed in large unventilated domes that has limited the performance of 4-m class telescopes until very recently. Also, in parallel with the drive for greater collecting area came the challenge of

Box 1: Mechanical and thermal deformations

Mechanical. Analytically, the deflection δ (normalised to an observing wavelength λ) of a circular plate due to its own self-weight supported by three discrete points is described by:

$$\delta/\lambda \; \alpha \; \rho D^4 / E \, t^2 \lambda$$

where ρ is the density, D is the diameter, E the Young's modulus and t the plate thickness.

For the case when a uniform pressure P_0 (such as wind) is applied to a circular plate the normalised deformation becomes:

$$\delta/\lambda \; \alpha \; P_0 D^4 / E \, t^3 \lambda$$

In both cases as the diameter of a mirror grows, the thickness, hence mass of the mirror must grow even more quickly to maintain the same stiffness against gravity or wind. Since this approach soon becomes prohibitively difficult and expensive, modern telescope designers have moved towards using thinner and lighter mirrors, using a complex array of supports to maintain the mirror figure against both gravitational and wind forces.

The ratio of ρ/E changes by only ±15% for a wide variety of glassy and glass-ceramic materials used in today's large telescope mirrors[10]. In the future, if the costs can be brought down, large telescope mirrors could be made of Beryllium or Silicon Carbide. The ρ/E ratios of these materials being 5 – 6 times less than glass or glass-ceramics, allowing far stiffer and lighter mirrors than possible with the more affordable materials used today.

Thermal. The susceptibility of the mirror figure to thermal distortion is determined by its thermal properties such as the coefficient of thermal expansion α ($10^{-6}K^{-1}$), its specific heat capacity C ($J\,kg^{-1}\,K^{-1}$) and its conductivity K ($Wm^{-1}K^{-1}$). For a given change in temperature (a thermal transient), the thermal distortion experienced by a mirror is proportional to the ratio:

$$\alpha \, C \, \rho \, K$$

where ρ is the density of the mirror ($10^3\,kg\,m^{-3}$).

Unlike the mechanical properties of glasses and glass-ceramics, this ratio can vary considerably as is shown in the following tabulation (the lower the number the less the thermal distortion resulting for a given temperature transient).

Material	**Thermal Susceptibility to Distortion**	
	$\alpha \rho$ **C / K**	**Normalized to glass**
Glass	15.68	1.000
Pyrex (borosilicate)	3.67	0.234
Fused quartz (fused silica)	0.67	0.043
Ultra Low Expansion glass	0.04	0.002
Zerodur	0.15	0.010
Aluminum	0.36	0.023
Beryllium	0.17	0.011
Silicon Carbide (CVD)	0.22	0.014

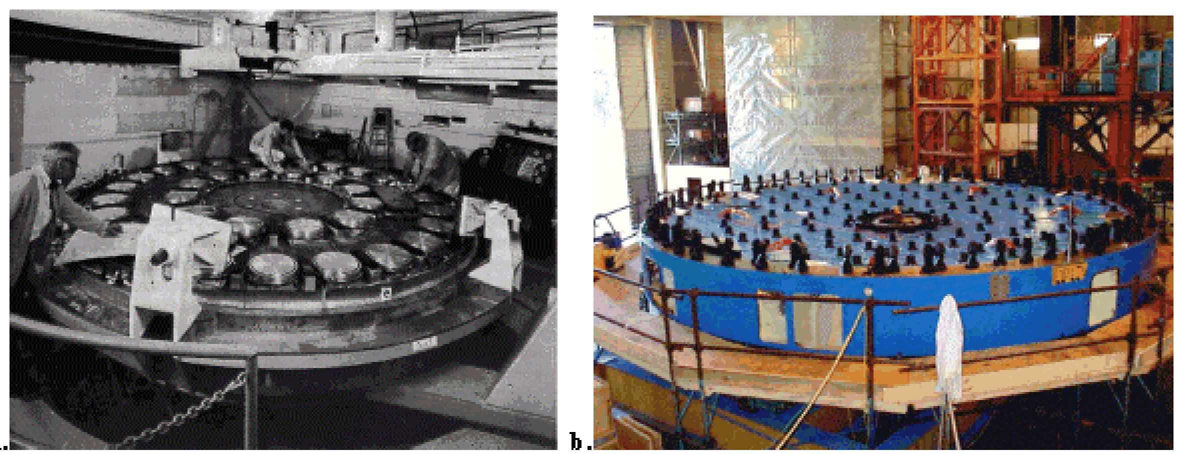
Typical values for these materials are taken from Yoder[6], the precise ratio depends on the exact type and grade of material under consideration.

building mirrors with ever shorter focal lengths, mainly to reduce the escalating size (and cost) of the telescope and enclosure. This requires deeply curved mirrors, which until recently have been very difficult to produce with the surface accuracy required by astronomers.

The Palomar 200-inch telescope ushered in the modern era of large optical instruments, exploiting the most sophisticated battleship-building techniques of the day. By the 1930s, telescope builders were also beginning to obtain a quantitative grasp on the problems of manufacturing and supporting large mirrors[8]. The Palomar group hoped to offset some of the effects of gravitational deflection and thermal distortion (Box 1) by moving away from a solid glass. Instead they cast deep pockets in the back of the mirror blank, producing the first large structured mirror. Although the mass of the mirror was accordingly reduced, the Palomar mirror still needed a distributed support system based on a series of levers that changed the support forces as the telescope tracked across the sky. As there were no reliable analytical methods to describe a structured mirror supported on a number of points, the support system had to be adjusted empirically once the telescope had been assembled, even to the extent of adding four fisherman's scales to the system at the last moment[9]. To avoid the thermal distortion problems that plagued the plate glass mirror of the earlier Hooke 100-inch telescope, the Palomar designers hoped to use fused quartz for the 200-inch mirror blank. However, because casting a fused quartz blank of this size proved problematic, they chose the newly developed Corning material, Pyrex (borosilicate glass). The susceptibility of Pyrex to thermal distortions is less than one-quarter that of plate glass, although markedly inferior to fused quartz.

Fifteen years after the completion of the Palomar telescope, AURA started work on what would be the second-largest telescope in the world - the Kitt Peak 4-m telescope (KPNO). Its twin would be placed in the Chilean Andes at the Cerro Tololo Inter-American Observatory[11]. Despite the time interval, the design of the Kitt Peak 4-m telescope was tied to concepts developed for the Palomar 200-inch telescope. The Kitt Peak primary mirror weighed 13.6 tonnes, compared with Palomar's 14.5 tons. It used a large equatorial yoke, and a telescope tube with Serrurier trusses to hold the secondary and primary mirrors, resulting in a structure weighing over 300 tons[12,13], compared with over 530 tons[9,14] for the Palomar telescope. There were also significant innovations in the mirror and its support system, which laid the groundwork for today's large telescopes. First was the availability of a fused quartz blank with a thermal stability five times better than that of Pyrex. The mirror was manufactured as a solid disc with an aspect ratio (diameter to thickness, *D/t*) of 6.6:1. Equally important was the arrival of computers and hence the ability to model accurately the physical properties of large mirrors in any orientation[5]. The first step towards actively controlling the shape of a telescope mirror had thus been taken (Fig. 2).

However, building telescopes significantly larger than 4-5 m had to wait at least 15 more years: successful scaling of the available techniques beyond this size range was accepted as inconceivable both in terms of engineering viability and cost.



a. b.

Figure 2 Comparing primary mirror support systems from 1974 and 1998. **a**, The actively controllable mirror support system for the KPNO 4-m telescope, designed to support a 13.6-ton mirror with an aspect ratio (*D/t*) of 6.6. This can be compared with **b**, the Gemini fully active support system, which has been designed to support a 20-ton meniscus mirror with an aspect ratio of 40.5. An important step towards today's modern telescopes came when the Kitt Peak 4-m designers realised that mirror support systems could be active. Having the ability to predict the optical effect of a support force meant that the designers could conceive a system of several adjustable support points which, when moved in unison, could actually change the shape of the optical surface in a controlled way, thereby improving the image.

Optical telescopes 8- 10 m in diameter

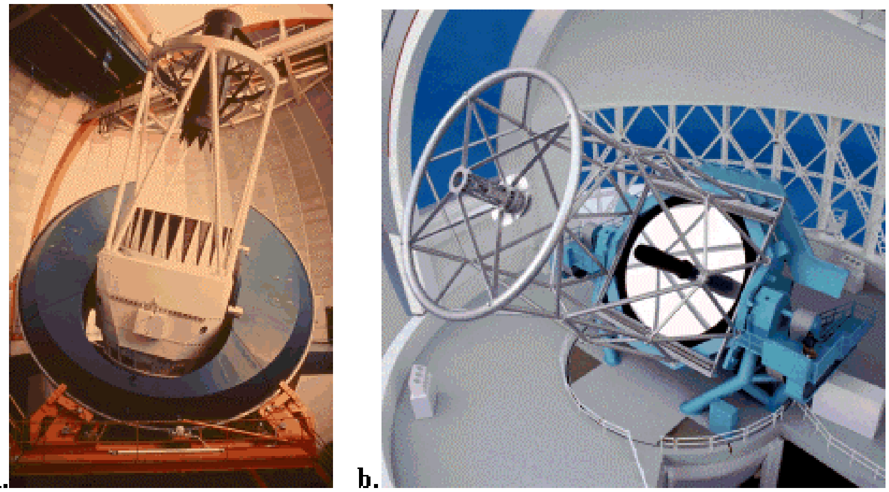
The key design feature for the 8-10-m class telescopes was to greatly increase the ratio *D/t* of the primary mirrors to reduce the mass of the mirror, the supporting telescope and the surrounding structure. The availability of analytical models opened the way to understanding the detailed performance of these lighter mirrors and telescope structures and the active systems needed to support the mirrors. Computers also enabled the precise control of the altitude-azimuth telescope mounts, techniques pioneered by the radio astronomy community. These techniques were successfully extended to optical telescopes by the UK's 3.8-m Infrared Telescope (UKIRT)[16] and University of Arizona/Smithsonian Institution's Multiple Mirror Telescope (MMT) in 1979[17]. Telescope designers were released from the Palomar legacy.

In the 1980s, KPNO and the Universities of Arizona, California and Texas initiated the study of a number of new telescope approaches[18,19]. The University of California at Berkeley began investigating the fabrication of 10-m primary mirrors from individual segments of low-expansion glass, which would lead to the two Keck telescopes. Edge sensors attached to each mirror segment would feed corrections to 180 actuators controlling the 36 polished hexagonal segments, ensuring that the entire ensemble would behave as a single mirror" with an effective aspect ratio for the glass of 133:1. The University of Texas at Austin adopted a fixed, segmented primary and a movable secondary for its rather radical Hobby-Eberly telescope[21], after initially investigating a meniscus design for a 300-inch telescope.

The University of Arizona began developing large, structured mirrors made from borosilicate glass[22]. At 16 tonnes an 8.4-m diameter structured borosilicate mirror weighs almost the same as the Kitt Peak 4-m mirror and the Keck 10-m primary mirror (14.4 tons of glass). However, the modern demand for superb image quality still means that these types of mirror require a distributed and active support system. Arizona has adopted a matrix of 164 active, computer-controlled supports for the 8.4-m primary mirrors[23] of its Large Binocular Telescope.

At KPNO, in Europe and in Japan, studies looked at the feasibility of using thin meniscus mirrors with aspect ratios (*D/t*) of 40:1 or higher, using new materials such as Coming's Ultra Low Expansion Glass (ULE) or Schott's glass-ceramic, Zerodur, which have essentially a zero coefficient of thermal expansion at room temperature (less than 1 in 30 x $10^{-9}K^{-1}$). Today the four 8.1-m VLT telescopes[24] at the European Southern Observatory (ESO), the 8.3-m Subaru[25] telescope and the two 8-m Gemini telescopes[26] all use meniscus mirrors weighing ~20 tons. These mirrors are supported against gravity and wind deflections on a matrix of between 120 and 264 active supports (see ref. 27 for a good review of mirror support techniques used in large telescopes).

Despite this diversity in mirror technologies, a common theme is the move to faster -- that is, smaller -- focal ratios. (The focal ratio, or f-number, of the primary mirror is the focal length of the mirror divided by its diameter.) Shortening the focal length of the primary mirror shortens the telescope tube length and reduces the size, and hence the cost, of the telescope domes (Fig. 3). For example, the domes enclosing the Keck 10-m telescopes and Gemini 8-m telescopes are



a. b.

Figure 3 The 4-m Mayall telescope (**a**) compared with a model of one of the Gemini 8-m telescopes currently under construction (**b**). Both telescopes are housed in enclosures of roughly the same size (32m and 33m in diameter, respectively), and the moving weight of both telescopes is about the same; the Kitt Peak 4-m weighs 340 tonnes and the Gemini telescope 315 tonnes. The Gemini telescope also illustrates the new approaches being taken with large telescopes. To reduce thermal seeing effects, the only structure above The primary mirror is the lightweight telescope structure supporting an active secondary mirror In addition, the Gemini enclosure incorporates large vents to ensure that the mirror, telescope structure and enclosure are well flushed by ambient air during night-time observing. During the day the entire enclosure is air conditioned to maintain the telescope structure near the night-time air temperature (0ºC on mountain sites such as Mauna Kea).

comparable in size to the domes housing the Kitt Peak 4-m telescope and the Yerkes 40-inch refractor.

However, the difficulty of polishing and testing a large mirror so that it can produce good images is a strong function of its departure from a spherical section[28]: the larger the departure, the greater the fabrication difficulties. Two-mirror (primary and secondary) telescopes typically use either parabolic or hyperbolic primary mirrors. For the Palomar f/3.3 mirror, the parabolic surface differed from that of a perfect sphere by only 32µm, which was within the capabilities of polishers in the 1930s[9]. But as the mirrors get larger, a similar departure from a sphere would require a longer focal length, greatly increasing the size and cost of the telescope. Modern polishers have developed a range of computer-controlled polishing and testing techniques for producing faster primary mirrors of very high precision. The University of Arizona is pushing this technique to produce large mirrors with focal ratios of f/1.2 or less[29,30]. The deviation from a sphere for an f/1.2 8-m mirror is measured in millimetres (1.19 mm) rather than micrometres.

In addition, the active support systems used in the telescope can correct any large-scale errors, and polishers can now concentrate on local smoothness. The result is 8-m diameter mirrors that can perform near the diffraction limit[31] at optical wavelengths. To get some sense of how smooth these mirrors will be on their support systems, if one were to enlarge the mirror to the size of the Atlantic Ocean, the largest wave would be no higher than a foot (30 cm).

With the faster telescopes has come another requirement for modern computer analysis and control techniques. For the 8-m f/1.8 optical systems to remain diffraction-limited at 2.2µm, the secondary mirror has to remain in alignment on the optical axis of the primary mirror to within ~50µm. To remain in focus, the primary to secondary spacing has to be maintained to within ~2.5µm over a distance of 12m[29]. These alignment tolerances become even smaller as the focal ratio of the primary mirror is reduced. Using computer models and image measurements to control the position of the secondary mirror and the shape of the primary mirror precisely, gravitational deflections, thermal distortions and wind buffeting of the telescope can all be actively corrected, keeping an 8-m f/1.8 telescope diffraction limited as it tracks across the sky.

To give some indication of how well modern telescopes can 'break the cost curve', the Kitt Peak 4-m telescope cost $10M at its completion in 1973[13]. In 1998 dollars this is approximately equivalent to $26M. With an expected cost growth scaling law[32,33] of $D^{2.5}$-$D^{2.8}$ this would translate into an 8-m telescope costing between $147M and $181M. Keck and Gemini have spent approximately $88M on each of their 10-m and 8-m telescopes (these costs exclude instruments and ignore differences due to inflation), so these new technologies have resulted in significant cost savings.

Improving image quality

Improving the image quality of telescopes allows us to observe fainter point-like sources. Telescopes are used to observe faint astronomical objects, which are typically much fainter than the instantaneous sky background. For some infrared measurements, sources can be several orders of magnitude fainter than the background resulting from the thermal emission of the telescope. Because of this limit, the ultimate signal-to-noise ratio (for point sources) is related to the physical parameters of the telescope and instrument by the following equation:

$$\frac{S}{N} \propto \frac{(telescope \quad area)^{1/2}}{delivered \quad image \quad diameter} \frac{\eta^{1/2}}{\varepsilon_b^{1/2}} \tag{1}$$

where S is the signal from a faint astronomical object, N is the noise in the background in a given integration time, η is the total system throughput (including atmospheric, telescope and instrument transmissions as well as the detector quantum efficiency), and ε_b is the effective background emission. It is the combination of a large aperture delivering small images that makes the new generation of telescopes so powerful. In addition, the HST, with its 0.1-arcsec or better image quality (at optical wavelengths), has revealed great richness of spatial detail in almost every object that it has observed, from star-forming regions to galaxies within a few billion years of the Big Bang. Historically, most of this structure has been blurred by our atmosphere and resulted in images with five to ten times poorer spatial resolution.

The image quality of a ground-based telescope also has two major atmospheric 'seeing' components. The first, realised through pioneering work at the MMT[34], the Canada-France-Hawaii telescope (CFHT)[35] and by the Subaru[36] group, is that substantial temperature differentials between either the mirror surface or telescope structure and ambient air lead to thermally induced turbulent eddies, which can substantially degrade the 'local' seeing in the environment of the telescope. Modern enclosures are now actively flushed during observing to remove any warm air accumulating around the telescope. During the day the structures are cooled with air conditioning to keep the entire enclosure near the night-time ambient temperature. In addition, a variety of strategies are now used to keep the mirror surface near the ambient temperature[37]. The success of these new approaches in removing the effects of the enclosure, telescope and mirror seeing effects is shown in Fig. 4, from the remarkable 'First Light' results obtained by the ESO LT-1[38].

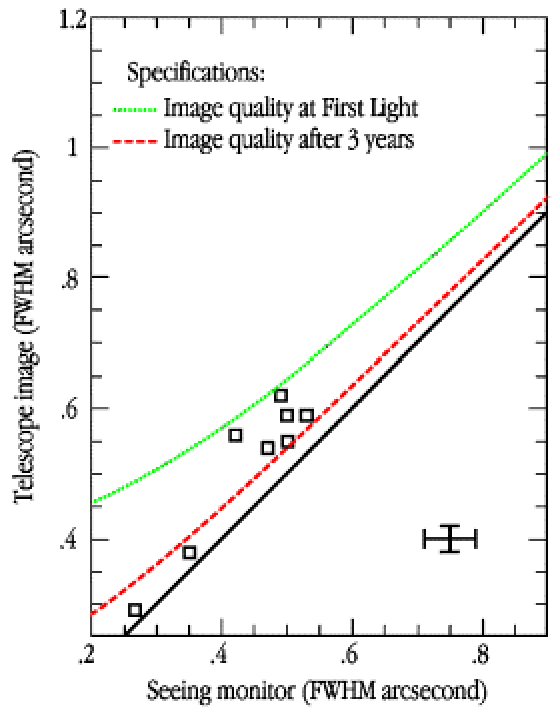


Figure 4 'First Light' results from ESO's first meniscus-mirror 8.2-m VLT telescope. The plot shows the intrinsic site or free-atmosphere seeing (measured externally) compared with the seeing measured by the telescope. Through careful design of the enclosure, telescope structure and mirror thermal systems, at first light the telescope is already delivering almost 'free-atmosphere' seeing. FWHM, full-width at half-maximum. The unity line is shown as solid, with the error bars representing the measurement errors.

The second component is the intrinsic atmospheric seeing due to turbulent cells that pass through the telescope's line-of-sight (typically at an altitude of ~10km). The emerging techniques of adaptive optics can substantially reduce the effects of atmospheric turbulence and offer the promise of another revolution in ground-based astronomy. By using a bright reference star, and more recently an artificial star created by a laser beam from the telescope, fast sensors can detect the phase distortion imprinted on the incoming wavefront by the turbulent atmosphere and apply a correction using a deformable or segmented mirror. The corrected wavefront can then be reflected into the detection apparatus mounted on the telescope (see ref. 39 for a good review of adaptive optics techniques). The potential scientific gains from adaptive optics have been demonstrated using the CFHT[40].

Through careful design and the use of adaptive optics, large telescopes can be built that will be essentially diffraction-limited at near-infrared wavelengths, combining the resolution of the HST with the collecting area of an 8-10-m telescope. This will permit detailed infrared imaging and spectroscopy of the objects observed with the HST. Equation (1) shows why the combination of large aperture telescopes with adaptive optics promises such great gains in sensitivity. If an 8-m telescope can deliver 0.1-arcsec images, the *S/N* advantage compared with the typical 4-m telescope can be over 16; alternatively, this advantage can be expressed as making the same measurement in $(1/16)^2 = 1/256$ of the observing time.

Looking to the future

The enormous growth in ground-based optical and infrared capabilities becoming available to astronomers over the next decade will dramatically advance our understanding of the Universe. However, hints of the possible direction that future observations might take are already beginning to emerge. For example, recent infrared and submillimetre-wavelength observations[41-43] suggest that the formation of stars and the creation of the first heavy elements in the earliest galaxies might be largely hidden from optical observations[44]. Much closer to home, there has been an invigorated interest in searching for planets around other stars, and for the detailed investigation of extrasolar planetary systems[45]. For the first time in the 400-year history of observational astronomy there is a growing realisation, both in the scientific and public arenas, that we might be able to study "the evolution of the universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA."[46]. What will this require from future telescopes?

To study the earliest formation of stars and the formation of the early precursors to the galaxies we see today will require very sensitive observations. The Hubble Deep Field[47] represents the most sensitive probe of distant galaxies yet achieved. After over two years of work, the Keck 10-m telescope has managed to obtain spectroscopic redshifts of ~65 objects, only a small fraction of the 2,400 identified sources in the Hubble deep field[48,49]. If we could increase the sensitivity by another factor of 10 or 20, about 50% of the remaining objects, many of which could be nascent galaxies, would become accessible to spectroscopy and detailed analysis.

As twenty-first-century astronomers attempt to exploit the recent discoveries of extrasolar planets, modelling[50] indicates that even modern 8- 10-m telescopes will struggle to obtain spectra of Jupiter-mass objects at a distance of only 10 pc. To make progress in this area again requires *S/N* gains of between 10 and 20 times that of contemporary 8-m-class telescopes.

Equation (1) suggests that the only way forward in ground-based observations is to increase greatly the ratio of (telescope area)$^{1/2}$/ (delivered image diameter): control of η and ε_b is rapidly approaching its limit. The options are either a very large telescope delivering diffraction limited images, or an interferometric array of large telescopes. Although optical/infrared interferometers seem an attractive approach, it is hard to achieve diffraction-limited images of the required sensitivity with a sparse array[51]. To achieve *S/N* gains with factors of 10-20, the next large ground-based telescope needs to be an 'Extremely Large Telescope' (ELT) with an effective aperture of at least 30-50 m. The challenge for the next generation of telescope builders who build the ELT will be once again to take on both the engineering and cost obstacles that such large telescopes will present. Scaling the approach from today's innovative 8-m and 10-m telescopes (using a cost growth ratio proportional to $D^{2.7}$), a single 30-50-m telescope could cost between $3.5 billion and $8.0 billion. Unless the costs of a ground-based ELT can be brought to within $1 billion, it might never be built. Consequently, the astronomers and engineers who are contemplating these ELTS, both in Europe and in the USA[52-54], are trying to push today's technological developments even further. Possibilities include exploiting new mirror materials such as silicon carbide or beryllium and perhaps making mirrors faster than f/1.

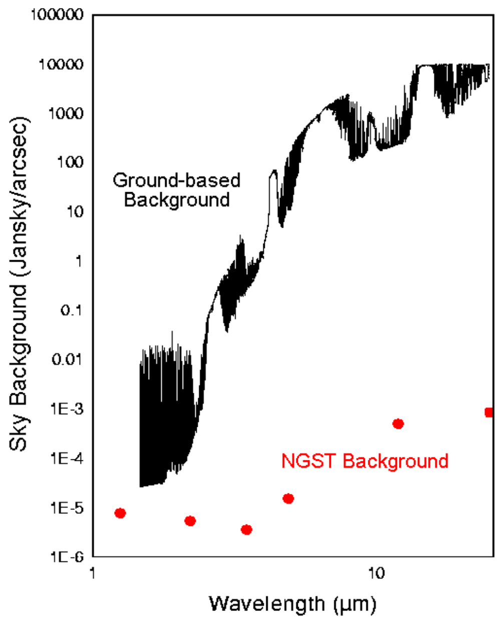


Figure 5 One of The advantages of being in space: a comparison of the sky background from the ground compared with that expected in space.

An alternative is to put a large telescope in space where the sky background levels (ε_b), especially in the infrared, can be reduced by factors of between 10^2 and 10^6 (Fig. 5). For a space telescope of equivalent aperture and imaging performance to a ground-based telescope, this can produce *S/N* gains of between 10 and 1,000. It is this dramatically increased sensitivity that is the principal science driver for the 'Next Generation Space Telescope' (NGST), a 6-9-m telescope that NASA is contemplating launching into space[55].

If NASA can bring the NGST to within a total mission cost (telescope, launch and subsequent operations) of $1 billion, it will compete favourably with any future ground-based facility with at least equivalent scientific capabilities[51]. The approach that NASA is hoping to take might deliver a space-based 6-8-m telescope for about one-fifth of the cost of the 2.4-m HST[56]; this approach might also yield the materials and technologies for the next generation of ground-based telescopes. Perhaps early in the twenty-first century, space-based telescopes and ground-based ELTs will not look so very different, and apart from a large difference in aperture they will probably cost roughly the same.

Should ground-based telescope builders consider abandoning their terrestrial mountain-top sites and head for space? Perhaps not yet. Many of the scientific issues of the future, such as determining the mass distributions of galaxies, tracing the formation of elements, or the characterisation of sub-stellar objects such as brown dwarfs or extrasolar planets, will demand observations with high spectral resolution of at least $\lambda/\delta\lambda \approx 10{,}000$[57]. For studies of this sort, collecting area will remain at a premium, and the effect of background emission (or lack of it) will be much reduced compared with detector performance. When realistic detector properties such as read noise and dark current are included in the comparisons, the complementary nature of ground-based and space-based telescopes begins to emerge[58] (Fig. 6).

Whatever direction the next ground-based telescopes take, astronomers of the twenty-first century are going to be confronted with some interesting new issues. Rather than having access to ten to twelve state-of-the-art large telescopes, there may only be one or two ELTs (or equivalent) built worldwide, because of the sheer scale and cost of the enterprise. This will bring about a dramatic sociological change in ground-based optical and infrared astronomy, as astronomers adopt the techniques and collaborative methodologies of their colleagues engaged in other 'big sciences' Despite these potentially painful changes, these telescopes, combined with their counterparts in space, could tackle most current problems in astronomy and will undoubtedly get us much closer to achieving our ancient quest of unravelling our origins. However, if history

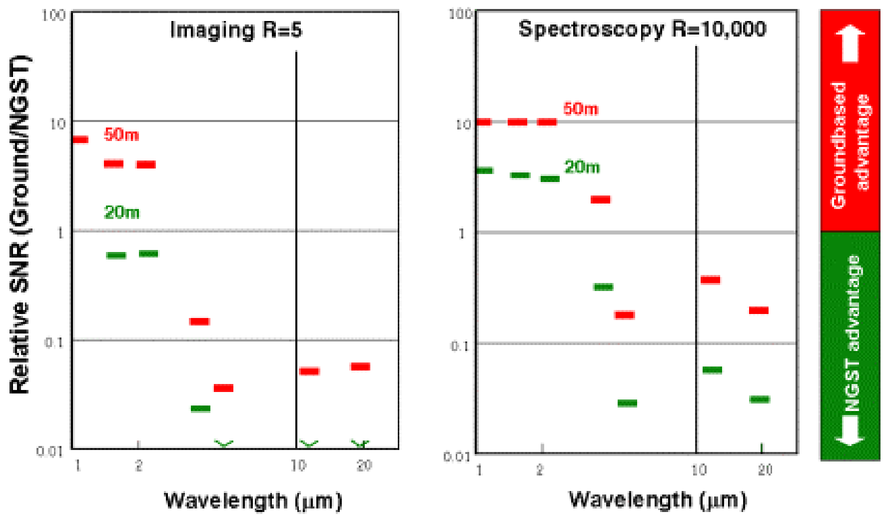


Figure 6. The comparative performance of groundbased 20-m and 50-m telescopes compared to an 8m next-generation space telescope. The relative S/N gain of a 20-m telescope is shown in blue and the 50-m in red, using the methods described in ref.56. The S/N gain (SNR) for a ground-based telescope is plotted as a function of wavelength, assuming NGST makes an observation of a point-like source in an integration time of 4000s achieving a S/N of 10. We assume that the objects we need to observe are very small (less than 0.01 arcsec), such as a star-forming cloud or stellar cluster at high redshift, or a planet around another star. Two cases are shown, a comparison for imaging observations with $R(\lambda/\delta\lambda) = 5$ and the relative performance for a spectroscopic observation with $R(\lambda/\delta\lambda) = 10,000$. For imaging, NGST has a clear advantage over a 20-m in the infrared. For spectroscopic observations, a diffraction limited 20m groundbased telescope has a signal to noise gain of 2 –3 over an 8-m NGST making the same R=10,000 spectroscopic observation at 2.2μm. For wavelengths beyond 2.5μm, NGST offers substantial S/N advantages. In contrast, a diffraction limited 50-m telescope making the same observation, the S/N advantage increases to an order of magnitude greater than possible with a 8-m NGST in the same observation time for any wavelengths up to 3.8μm. Once the observation wavelength becomes greater than 10μm, a 50-m telescope becomes comparable to an 8-m NGST.

is a guide, over the next decade the 8-10-m telescopes will probably uncover whole new classes of problems and phenomena that could cause us to rethink our observational priorities completely.

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Acknowledgments. We thank Marianne Takamiya for producing Fig. 1, and Ruth Kneale for finishing the figures and for work on the text and the references. We benefited from discussions with Larry Barr, Earl Pearson, Larry Stepp and Jim Oschmann.