as short as 5 mm. It will be used primarily for VLBI down to 7 mm wavelength but will have a single-dish spectroscopic capability for observations of interstellar oxygen. The O_2 lines near 60 GHz are of course not observable from the ground because of the severe absorption by atmospheric oxygen. In its present concept, IVS will have an ESA payload launched by the Soviet Energia rocket and will involve NASA tracking stations.

Current Space VLBI observations, of course, rely on the ground networks as well as the space antennas and since the space element orbits the earth, they become truly international employing ground-based telescopes in all continents. Negotiations are currently underway between the ground organizations and the space agencies. With the experience of cooperation in VLBI already gained, we can expect very successful results in the future.

Well into the 21st century, when space VLBI is established, we may see arrays of telescopes in space providing resolutions as fine as 1 microarcsecond. Perhaps it will be possible to measure quasar proper motions!

5. Epilogue

I have already mentioned the grave problems caused in radio astronomy by man-made interference. In many ways this is not surprising because of the extremely small signals received by radio astronomers (the unit of flux density is 10^{-26} watts Hz^{-1} m^{-2}) and the proliferation of communications equipment. At the World Administrative Radio Conference (WARC) where the frequency bands of the spectrum are allocated to the various services, radio astronomers have to fight hard to keep their precious observing bands. This is because commercial and military users are always demanding more and more channels – sometimes for reasons which can hardly be judged to be important. The situation is becoming so critical in some parts of the spectrum (e.g. near 18 cm wavelength), that suggestions to put radio telescopes on the far side of the moon are being taken seriously.

Radio astronomy is vital to our understanding of the universe and must not be squeezed out of existence by commercial demands. We appeal to our scientific colleagues in other disciplines to help expunge the harmful pollution of the spectrum.

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Infrared/Sub-mm Astronomy After ISO (1 μm-0.3 mm)

ISO:	2-200 μm photometry, imaging + moderate resolution spectroscopy at excellent sensitivity
POST-ISO:	High spatial resolution: 1″ at 100 μm → D = 10 m 8 m at 2 μm = 0″.05 for single dish 100 m at 2 μm = 4 × 10⁻³″ for Interferometry λ>200 μm: colder universe at sub-mm wavelengths High spectral resolution: velocity resolved spectra
PLATFORMS:	VLT+VLT Interferometry (λ ≤ 30 μm, λ ≥ 300 m) Large Airborne Telescope (SOFIA; 2.5 m, visible → 1 mm) Large IR/sub-mm telescope in space (FIRST, SM³/LDR λ = 50 → 1000 μm EDISON λ = 2 → 100 μm) Antarctica: ground-based FIR astronomy from Antarctic plateau (e.g. Vostock Station)
INSTRUMENTATION:	Large format, low-noise detector arrays for ground-based (λ = 1 → 30 μm) and space-borne (30 → 300 μm) work Quantum noise limited sub-mm heterodyne receivers
Summary by R. GENZEL, Max-Planck-Institut für Extraterrestrische Physik, Garching bei München, Germany	

Post-VLT Optics and Telescopes

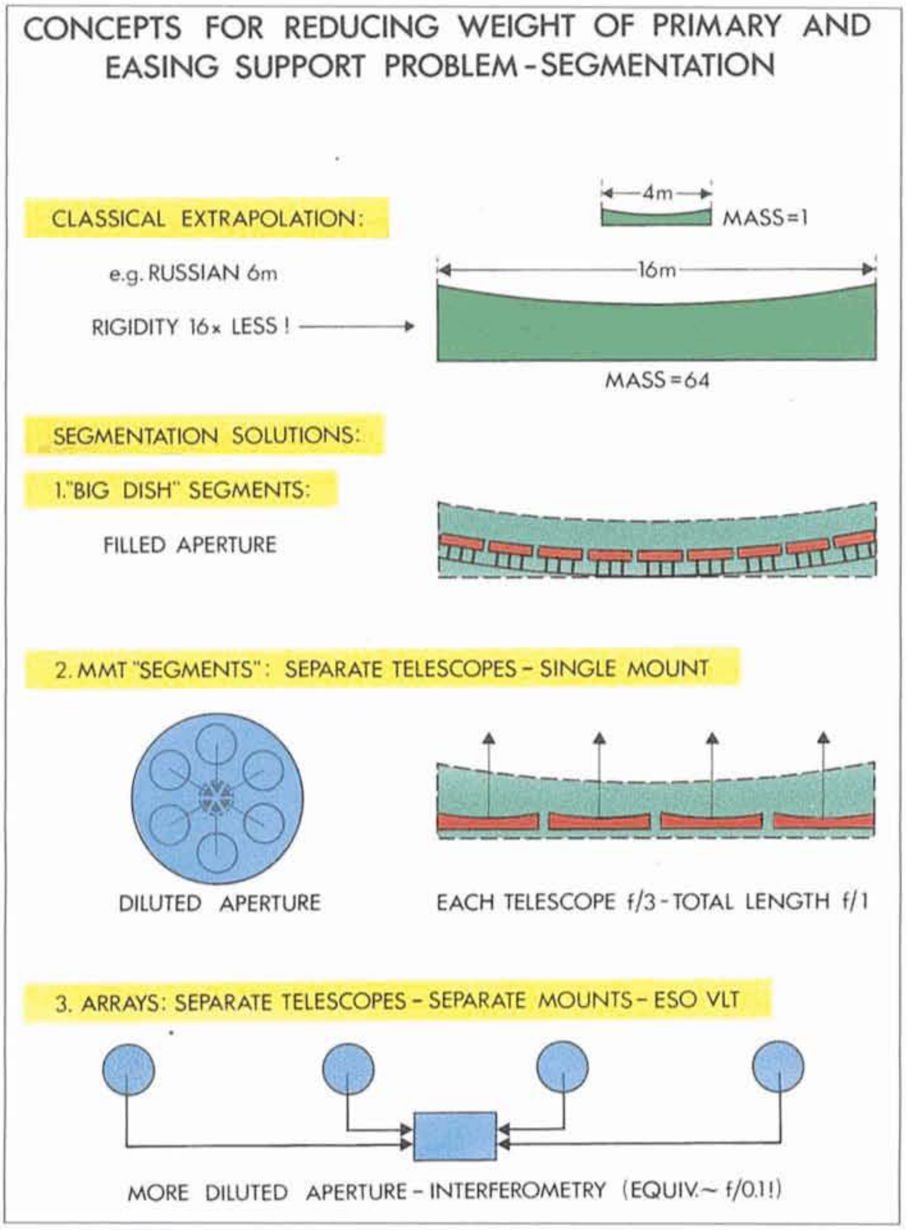
R.N. WILSON, ESO

I would like, in this brief introduction, to stimulate some thoughts and discussion on what the principal directions of optical telescope development will be after the year A.D. 2000.

Ground-based-telescopes will, I believe, continue to play a major role because of recent optics and electronics developments and the cost advantages that accrue from them. *Space telescopes* will slowly gain in total reflecting area and hence in importance, the rate depending on cost, reliability and increased maintenance and user-friendliness.

1. Ground-Based Telescopes

Throughout its long development after the first manufacture about 1665, the evolution of the reflecting telescope has



been dominated by four parameters:
- Size
- Optical quality
- Tracking and pointing (mountings)
- Cost

One will always wish to build the biggest telescope one can afford which delivers high-quality images with corresponding tracking. But there are many cases in telescope history where excessive ambition on the first parameter – size – has led to failure in the technical requirement of the next two and conflict with the third – cost. These failures through over-ambition have led to products of poor cost-effectiveness. The above four parameters will not change after the year 2000: they will still be drivers a century later or, indeed, as long as ground-based telescopes are built.

For about 300 years, the line of development of conventional telescopes had been largely unchanged since the start. Its main characteristics were:
- Monolithic, stiff primaries
- Conventional figuring procedures
- Stiff tubes and mounts with absolute mechanical tolerances. After about 180 years of alt-azimuth mounts, about 130 years of undisputed triumph of the equatorial mount.

In the last 10 or 20 years, each of these aspects has undergone a revolution. These revolutions are a result – directly or indirectly – of the application of modern electronics and computers. I believe these revolutions will determine the further development after 2000 and well into the next century. They will enable the ground-based telescope not only to survive but also to thrive *because of its cost-effectiveness.*

Let us consider the four basic parameters and the impact of these revolutions on them.

Size

The figure shows the key to increase of size while respecting the other 3 parameters. The key is the abandonment of the full-size monolithic aperture of the primary by the principle of *segmentation* in some form. Whether the segmentation is *direct* (e.g. the Keck 10-m telescope), or *indirect* as in *MMT's* (Multi-Mirror Telescopes: several telescopes on one mount) or *Arrays* of telescopes on different mounts but linked together (e.g. ESO VLT) – this does not change their common aim of reducing the weight compared with a monolithic blank extrapolated with size in the classical way (see the figure). The important difference between these approaches is simply whether the effective aperture is undiluted (direct segmentation), moderately diluted (MMT's) or very diluted (Arrays).

With possible variations and combinations, these three basic forms will dominate the aim for large size after 2000 exactly as they are dominating it today, for we are only at the beginning of the consequences of the electronic revolution.

Optical quality

The revolution is due to active optics combined with modern figuring techniques on the one hand, and adaptive optics to correct the atmospheric turbulence on the other. These two developments are complementary: *active optics* corrects classical telescope errors of manufacturing, mechanical or thermal origin which are fixed or vary slowly; *adaptive optics* corrects the rapidly varying effects orignating, above all, in atmospheric turbulence. While we at ESO see active optics as an essentially solved problem on the basis of the NTT and its routine image analysis, adaptive optics is still in its infancy and not yet available as a general system. It is incomparably more difficult than active optics because of its high frequency bandpass and because of the problems of a reference source within the isoplanatic angle.

Development of adaptive optics will undoubtedly be, together with interferometry, the principal development line in telescope optics after 2000. We shall see whether, by the year 2000, full adaptive correction (i.e. for the full effective bandpass) has been achieved for *the visible waveband and for one single isoplanatic field.* If so, it will be a great technical achievement. If not, it will be the principal area of endeavour followed by extension of the field to more isoplanatic fields. But for even modest fields, the information flow rate, apart from the problems of correction feedback and isoplanatic angle, is formidable to say the least.

For these reasons, search for and investigation of *optimum sites* will continue at an accelerated pace: the most effective adaptive optics is a site where nature has taken as much of the load from us as possible. A further revolution has taken place here, in the scientific understanding of atmospheric optics and the means for proper evaluation of the seeing of sites.

Apart from its intrinsic advantages (see "optical efficiency" below), optimized image quality at optimum sites brings rich advantages in instrument development. The "matching problem" of instrument slit size to pixels has meant that instruments become bigger and more difficult the larger the telescope aperture for a given angular image size of a star. This dilemma is expressed by Bowen's Spectrograph Law:

$$b = S \cdot \frac{Y_1}{206265} \cdot \frac{f_{CAM}}{Y_g} = S \cdot \frac{D_1}{206265} (f/no)_{CAM},$$

in which

b =	width of the slit image on the detector
S =	image size of a star in arcsec at the slit
y_1 =	radius of the telescope entrance pupil (normally, the primary mirror)
y_g =	semi-height of the spectrograph grating
f_{CAM} =	focal length of the spectrograph camera
D_1 =	diameter of the telescope entrance pupil (normally, the primary mirror)
$(f/no)_{CAM}$ =	f/number of the spectrograph camera

Clearly, the smaller the value of the image S, the larger can be the f/no of the spectrograph or the smaller the corresponding value of y_g, determining the size of the grating. High quality imaging benefits all modes of observation, not just direct imaging.

Mounting

The alt-az mounting has returned as the standard because of the revolution in 2-axis tracking. But other forms, perhaps above all various forms of spherical mount, will certainly be further developed in the new century. The domination of the alt-az may have a much shorter life than that of the equatorial. It will be seen, too, whether non-rotational forms of mounting are technically feasible or not. Tracking will be the determinant requirement. Better image quality requires better tracking. In the NTT with its alt-az mount, it is already clear that the tracking requirement (combined with field rotation compensation) is the hardest technical specification to fill.

Buildings

The trend away from the conventional dome is clear. Cost is not in its favour, but *control of the conditions of the local air* will be the dominant reason for choosing other forms which are also favoured by the alt-az mount. The revolution here was made by the building of the MMT. Apart from external seeing, the local air will be the decisive influential factor in the final optical quality until adaptive optics is available in a general form.

The optimum size of a telescope: optical efficiency

The classical formula for the optical efficiency of a telescope has been known implicitly ever since photography was introduced into observation about 1850:

$$E = k \left(\frac{D}{d}\right)^2$$

where
E = the optical efficiency
D = diameter of the telescope pupil (normally the primary)
d = image diameter of a star
k = transmissivity

Although this formula is simplistic and only really valid assuming adequate pixel sampling and photon-limited observation in certain regimes, its general validity is proven every night by the integration times used at the NTT. More sophisticated criteria are under investigation for the VLT. A general formula reflecting all different observing conditions, above all background limited, would certainly be more complex. Even if the formula above is accepted only as a rough general approximation, its conclusions are striking: if D is doubled, but d is also doubled, there is no gain in efficiency, but a tremendous amount of money and effort has been wasted: huge "light buckets" of low optical quality are not the path of the future.

After the year 2000, the struggle for bigger size will only give higher efficiency if the conditions of the local air can be adequately controlled or compensated by adaptive optics. These factors will dominate the development scene and determine what the optimum (or maximum) size can be. My colleague Richard West mentioned *cost-effectiveness* yesterday. I should like to take this up and emphasize it. The most *cost-effective* telescope (with instrumentation and detector) is the best for a given observation and size is only one of the parameters involved. The astronomical community will have to think increasingly in these terms to make the best use of its resources. Reduction of d may well be more efficient than increase of D.

It may take 50 years or more to "digest" the size range 10-20 m. Until adaptive optics is available in a fairly complete form (wavelength band, frequency band, reasonable field) the optimum size may be < 20 m or even < 10 m.

2. Space Telescopes

In the absence of an atmosphere, the specification of space telescopes is far simpler than for ground-based tele-

"Tours du Monde, Tours du Ciel"

"Around the world, around the sky" is the title of what is probably the most comprehensive documentary film about astronomy ever made. It was produced by a team of French specialists, headed by Robert Pansard Besson and supported by Pierre Léna and Michel Serres (see also the *Messenger* No. 48, page 33).

During more than three years, Mr. Pansard Besson and his crew travelled to all major observatories in the world, ancient as well as modern. The European Southern Observatory provided support during their visit to Chile and the film includes scenes from La Silla, Paranal and Garching. Many other observatories, also in the ESO member states, are shown and astronomers from all over the world have provided live commentary to various passages in the film.

The film is divided into ten "travels" in time and space: (1) The beginning (160,000 years ago); (2) Around the year 0; (3) From the other end of the world (from –500 to 1000); (4) Around the world, around the sky (1000–1600); (5) Venice, Beijing, Paris (1600–1676); (6) East, West (1642–1743); (7) The starry messenger: the light (1743–1880); (8) The visible and the invisible (1880–1950); (9) Towards the giant mirrors (1950–1970); (10) The light and other messengers (1970–1990). Each part lasts slightly less than one hour. The total playing time is therefore almost 10 hours.

The film is distributed on video cassettes (Pal, Secam, NTSC) from: HATIER, 8, rue d'Assas, F-75006 Paris, France (Tel: 49.54.49.54; Fax: 40.49.00.45). It is available with French commentary, and soon also in English.

scopes: they should be diffraction limited, also in the UV.

The real breakthrough will come when assembly and maintenance can be done in space (on the moon?). HST has made very clear the limitations of pre-assembly and control from the ground.

For individual telescopes, active optics is essential and also the simplest and cheapest solution. HST, I think, proves this clearly. Since there is no atmosphere, *no* adaptive optics is required: it is meaningless. But the harsh thermal environment makes active optics even more necessary than on earth. It also becomes easier in the absence of the disturbing effect of local air: In space, the NTT could go immediately to the diffraction limit even in the UV and be maintained there with simple technology.

Assuming the existence of bigger diffraction-limited telescopes in space after the year 2000, they should be unbeatable for direct imaging of deep, faint objects until a complete solution of adaptive optics is available. Even then, the complete absence of atmospheric turbulence and absorption are bound to give the edge on space observation for direct imaging. However, cost-effectiveness will still mean many observations will be better performed by ground-based telescopes. Space is also the natural environment for interferometry whose success on earth is closely linked to, and dependent on, the advances in adaptive optics.

Wide-field telescope projects in space have been mentioned at this conference and will certainly be carried out. The quality requirements will be far higher than those of any existing ground-based Schmidt telescopes.

Ideas and technologies that will remain a phantasy for high quality ground-based telescopes may be investigated and become a reality in space, e.g. plastic film reflectors with a fixed (dc) or slowly varying active corrector for small fields. Maybe "longer" telescopes may come back since "length" in a weightless environment is of less consequence. The technical possibilities are far wider than for ground-based telescopes.

3. Optical Design Developments

Optical design solutions for telescopes are effectively worked out: it is most unlikely that new design solutions will emerge. Developments will come rather from advanced technologies to realize known designs with higher precision.

X- and Gamma-Ray Astronomy Beyond the Year 2000

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Astronomy should progress in a balanced way. This simple statement needs no proof beyond the simple reflection, for example, on the importance for cosmology of the joint radio, optical and X-ray studies of extragalactic sources. Thus, in view of the impressive progress now being planned for the turn of the century at all wavelengths, both from the ground and from space, it is logical to think also of the goals of high-energy astronomy, in X- and gamma-rays.

Celestial objects happily carry on emitting their energy at the wavelength they please, but astronomers have to worry about how to do astronomy with photons that are widely different in their interaction/detection processes. For example, there is a basic difference between X- and gamma-ray photons: while X-ray photons can be focussed by a sufficiently smooth surface, gamma rays cannot because their wavelength is small compared to the interatomic distances in solids. Thus, X-ray astronomy can, and must, rely on focussing telescopes (of ever increasing throughput and angular resolution) and clever focal plane detectors for doing both imaging and spectroscopy of the X-ray sky. This has been the winning recipe introduced by the Einstein Observatory, currently used in the ROSAT mission, and also adopted by the "great observatories" in X-ray astronomy of the end of this century: NASA'S AXAF and ESA's XMM.

To speculate realistically on the future of X-ray astronomy beyond such great observatories, means to think of what more can be done using the same technique. Firstly, the optics. Of course, high throughput, essential for high sensitivity, means light-weight material, with all the technological complications involved. Very high (i.e. sub-arcsec) angular resolution will also be mandatory for matching the source positioning at other wavelengths. Such high resolution should be maintained over a wide enough field of view, in itself a big challenge, only now being seriously tackled; but not yet solved. Finally, the focal plane detectors should afford an excellent spatial resolution, so as to correctly oversample the telescope's PSF, but, most importantly, should also have a very high spectral resolution, since accurate spectroscopy will remain a key issue in the X-ray astronomy of the future.

It is difficult, at the moment, to imagine an X-ray observatory with the above characteristics without thinking of a "bigger and better" combination of AXAF and XMM: high-throughput (tens of thousands of cm^2), optics with high resolution (sub-arcsec) over square degrees FOV, suitable imaging detectors, and spectroscopy with resolving power in the several hundreds. However, it is also difficult to imagine how such a mission could be designed and realized in the current framework of research from space, given the financial and practical constraints within which national and international Space Agencies have to move. No concrete sign for the birth of an idea of such a mission exists at present.

A possibly even more realistic approach would be to specialize missions by splitting the science objectives. For example, a pilot mission centred on high-resolution, wide-FOV imaging, dedicated mostly to extragalactic work, is currently being studied in the context of an Italy-U.S. collaboration, with manageable dimensions and reasonable budget. Complementarily, a mission dedicated to high-resolution spectroscopy of selected sources could capitalize on the wealth of imaging results presumably available in X-ray astronomy by the end of the century.

For gamma-rays, on the other hand, the situation is quite different. Because of the severe limitations posed by the physics of the detection process as well as by the intrinsically poor astronomical signal-to-noise situation, gamma-ray astronomy is only now leaving the exploratory phase, with the imminent launch of GRO, the first gamma-ray Great Observatory. On the eve of such a