Instrumentation Beyond the Year 2000

Panel Discussion at the XII ERAM in Davos

On the occasion of the XIIth ERAM in Davos, a panel discussion organized on October 11, 1990, was devoted to "Instrumentation Beyond the Year 2000". Such a panel fitted well the general theme of the Davos meeting entitled "European astronomers look to the future", and was also a valuable follow-up to the panel of the previous day on "Cooperation in astronomy in the new Europe" (see a report by P. Léna in the *Messenger* No. **62,** p. 19–20, December 1990).

Four panel members presented their thoughts on "Radio astronomy in the year 2000, and beyond" (R. Booth), "Post VLT optics and telescopes" (R. Wilson), "The future of X- and γ-ray astronomy" (G. Bignami) and "Future far infrared and sub-mm astronomy" (R. Genzel).

Two other panelists had been invited but were not present: A. Finkelstein and A. Labeyrie, the letter having sent some transparencies for a short presentation of an optical very large array.

In the present issue of the *Messenger* we have the pleasure of presenting these contributions.

J.P. SWINGS, Liège (Convener)

Radio Astronomy – Towards the 21st Century

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1. Introduction

Advances in radio astronomy may be related to technical developments in several major areas. Among these I would list increased sensitivity of receivers and receiving systems, extended spectral range to cover the whole of the radio band of the electromagnetic spectrum, higher resolution – spectral, temporal and spatial (angular), together with improved data analysis facilities and techniques.

Radio systems have now reached a high degree of sophistication but improvements are certain in the 2000s especially in spectral range – the extension of the radio band to cover millimetre and submillimetre wavelengths and in angular resolution through VLBI.

2. Sensitivity of Receiving Systems

The performance of a radio telescope and associated receiver is characterized in terms of the figure of merit, G/T, where G is the system gain and T the equivalent noise temperature of the system. The gain of a telescope is given in terms of its area, A, wavelength, l by $4\varrho A/l^2$. This factor is further modified by an efficiency factor, h, related to the efficiency of illumination by the primary feed and the surface accuracy (an rms accuracy of l/20 reduces the gain by a factor of $\sim$ 1.5).

2.1 Large telescopes for the 21st century

Large antennas are required to improve G and at centimetre wavelengths the ultimate size for a fully steerable telescope, in terms of cost, seemed to have been reached in the 100-m Effelsberg antenna. Its design is based on the homology principle where gravity deformations are constrained so that the primary reflector maintains a parabolic shape, albeit with varying focal length. The focal position changes with elevation angle and the primary feed or secondary mirror (when in Gegorian configuration) is moved to compensate. The success of the homology design is demonstrated by the fact that the 100-m telescope is still 30% efficient at a wavelength as small as 7 mm. The homology principle is adopted in most new radio telescopes.

The unexpected collapse of the 300-ft transit telescope at NRAO in W. Virginia has provided the incentive to build another large fully steerable antenna in the USA. This will be the new Green Bank Telescope which will have an unblocked aperture, 100 m in diameter. This will be achieved with an offset design involving a primary/Cassegrain secondary focus arrangement suspended on a large beam above the main reflector (see Fig. 1). I do not expect that there will be any further large telescope in the West, in the early 2000s at least, but we will see the completion of the Soviet 70-m telescope near Sammarkand. This antenna, and the Green Bank telescope will be operated at wavelengths down to 3 mm.

2.2 System temperature

Receiver noise temperatures, T_r have improved dramatically during the past 5 years through the use of high electron mobility transistors (HEMTs), cooled to physical temperatures of around 15 K, and at wavelengths down to about 1 cm, receiver noise temperatures are approaching the quantum limit, T_q. However, the total system temperature, T, has a number of other contributions.

$$T = T_q + T_{cb} + T_{at} + T_{sl} + T_r$$

where T_{cb} is the cosmic background temperature, T_{at} is the contribution from the atmosphere which is most severe at very long (m) and very short (mm) wavelengths due to the ionosphere and troposphere respectively, and T_{sl} represents the noise power picked up in the sidelobes. T_{sl} includes a contribution from man-made interference which has

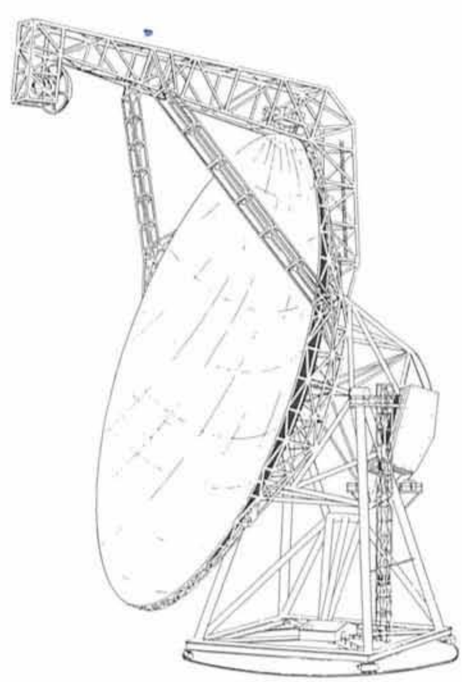

Figure 1: *Diagram demonstrating the concept of the Green Bank Telescope.*

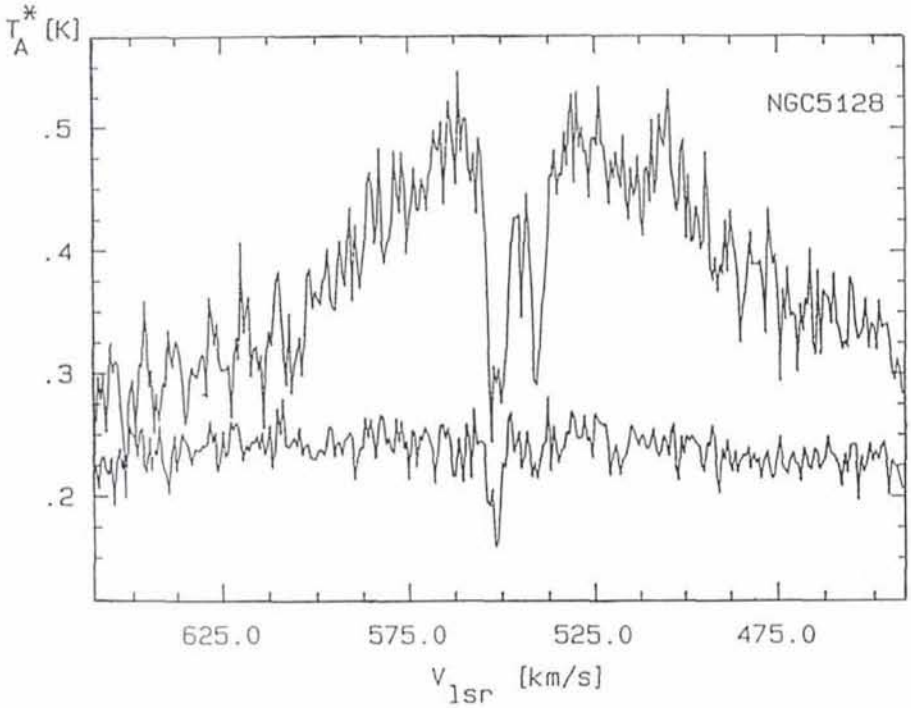

Figure 2: $^{12}CO(1-0)$ (upper) and $^{13}CO(1-0)$ spectra taken towards the central region of Centaurus A with the SEST telescope. The spectra contain broad emission lines continuing outside the spectral window. The line emission is superposed on the nuclear continuum of about 0.2 K. The relatively narrow absorption lines are seen in both ^{12}CO and ^{13}CO. It is clear that it is mainly nuclear continuum which is absorbed by the cold CO gas since the ^{13}CO absorption is deeper than the line emission.

become serious at some wavelengths and will probably become worse in the 21st century. However, minimum noise temperatures of about 20 K are currently achieved at centimetre wavelengths in an interference free environment.

At millimetre wavelengths receiver temperatures should also reach the quantum limit by the 2000s. Much effort is going into replacing the current Scottky and SIS (superconducting) mixers by HEMT amplifiers for 7 mm and 3 mm wavelengths. The extension of SIS technology to even shorter (submillimetre) wavelengths is being actively studied and expectations are high. For observation at millimetre wavelengths, high, dry sites are important to reduce the atmospheric (tropospheric) contribution to the system noise.

3. Spectral Range – Bridging the Gap Between Radio and Infrared Astronomy

The discovery of interstellar molecules and their importance in stellar evolution has been a major driver in the development of millimetre/submillimetre radio astronomy. The spectral transitions observed are, in the main, rotational transitions which have their ground state lines at these wavelengths. Molecular emission is now detected in nearby galaxies and, with improvements in sensitivity, in not so nearby galaxies (e.g. CO has been detected in a galaxy with a redshift, $z = 0.163(1)$) thus giving us information on stellar evolution in these extragalactic systems. Figure 2 shows interesting observations in the CO line of the southern galaxy Centaurus A from Eckart et al.

However, molecular studies are not the only reason for pushing to higher frequencies. At wavelengths of about 1 mm it becomes possible to observe emission from interstellar dust. This emission is optically thin and readily interpreted – in fact, measuring the dust emission from galaxies at 1 mm may become the standard technique for measuring the masses of most galaxies(2).

Finally, the extension of the spectral range for continuum measurements on quasars and radio galaxies is also very important. In particular, the observation of radio quiet quasars is of great interest, for it is in the submillimetre or far infrared that their emission must turn off.

3.1 Telescopes for millimetre/submillimetre astronomy

The importance of astronomy at the shortest radio wavelengths is shown by the large number of telescopes built or planned. 14 telescopes with diameter greater than 10 m have been listed by Booth(3) and several more are being built.

The largest instruments are the Nobeyama (Japan) 45-m antenna and the 30-m telescope in Pico Veleta (Spain) of the Institute for Radio Astronomy at Millimetre wavelengths (IRAM), the French-German institute based in Grenoble. The latter telescope is operating regularly at a wavelength of 1.3 mm. As we have seen, dry mountain sites are important for the shortest wavelengths since tropospheric water vapour severely attenuates the signals and its emission degrades receiver perfomance. Therefore 2 telescopes for use at submillimetre wavelengths have been built on Mauna Kea in Hawaii (altitude 4000 m) (the Caltech 10.4-m and the James Clerk Maxwell Telescope (JCMT), a 15-m telescope operated jointly by the UK, the Netherlands and Canada) and a third, the Swedish-ESO Submillimetre Telescope (SEST), has been constructed on the ESO site of La Silla in Chile (altitude 2300 m). This telescope is important because of its coverage of the southern skies. In addition, the Max-Planck-Institut für Radioastronomie in collaboration with the Steward Observatory in Arizona is building a 10-m submillimetre telescope on Mount Graham in Arizona.

Most of the millimetre telescopes use the homology principle in their design. An important new step for the next decade could be the inclusion of a phase corrector plate or a deformable subreflector to further compensate for non-homologous gravitational (and even wind) deformations.

3.2 Millimetre wave arrays

Several arrays have been constructed for high-resolution mapping using the aperture synthesis technique. In particular we cite the Hat Creek array of three 6-m antennas and the Caltech 3 × 10 m array at Owens Valley. Both arrays are operating at 3 mm wavelength (where they have angular resolution ≈ 1 arcsec) and plans to extend their frequency coverage to 1.3 mm with an increased number of elements are going ahead. A Japanese array of five 10-m antennas has been built at Nobeyama and an IRAM 3×15 m element array is now operational on Plateau de Bure in the French Alps. Again both instruments will be upgraded by the addition of more elements to increase their speed during the next few years.

Further millimetre/submillimetre arrays for the 2000s are planned. NRAO will probably build a large millimetre array near the VLA site in New Mexico and the Smithsonian Astrophysical Observatory is working on a submillimetre array which will be built on Mauna Kea. Finally, now ESO has chosen Cerro Paranal as the site for the VLT, some of us are interested to investigate the possibility of building a millimetre/submillimetre array on the plateau to the south of the peak. This would be a significant complement to the Australian telescope for southern hemisphere observations.

3.3 Further technical developments

Galactic Molecular Clouds may be up to 10–15° in angular extent but can contain components or structural variations on scales of less than one arcsecond. The same applies to the overall molecule structure of galaxies. Thus, to map them fully even with a 10-m telescope (beam width at 3 mm ≈ 1.5 arcmin) is a time consuming process. For this reason focal plane arrays (radio cameras) are being developed for single antennas which will improve the mapping speed by an order of magnitude. Such an array with eight beams is operational on the 12-m NRAO Kitt Peak telescope(4).

In addition, imaging analysis techniques such as the maximum entropy method are being developed which utilize all the information (spatial and velocity (frequency)) in the spectroscopic data and impose natural constraints such as positivity to achieve the highest available resolution(5). Further, techniques combining interferometer and single telescope data and mosaicking several fields of view are providing large-scale maps with the resolution of the interferometer (≈ 1 arcsec)(6). These techniques are only possible with the use of large fast computers but are already producing a wealth of detail on the molecular clouds and hence the star formation process.

3.4 Submillimetre telescopes of the future

In order to bridge the final gap between the submillimetre far infrared regions of the spectrum it becomes essential to place telescopes above the earth's atmosphere since its transmission becomes extremely low at these wavelengths. Some balloon-borne telescopes are under development and a telescope is regularly flown in a high flying aircraft – the Kuiper observatory. These are all relatively small telescopes and they are not entirely free of atmospheric attenuations. Thus to achieve a significant development in the 500 GHz to 1 THz spectral region it becomes essential to place a telescope in space.

An important project, the Far InfraRed and Submillimetre Telescope (FIRST) has been defined as a cornerstone in the ESA programme, Horizon 2000. This 4.5-m antenna will be launched sometime after the turn of the century. In the USA a more ambitious project, the large deployable reflector, LDR, has been proposed. This telescope will be a composite reflector, of 20 m in diameter. It will be realized only well into the 2000s. At least 2 more smaller satellite-borne submillimetre telescopes for observations in the 500 GHz region are in the design phase. These are SWAS a 50-cm antenna to be launched as part of the explorer series in the USA and MOSES, a combined astronomy and aeronomy project being studied by a Swedish-led team of European astronomers. If they successfully pass all the study phases, both will be launched in the mid-90s.

Although in the distant future, the larger projects are of great interest since they open up regions of the spectrum where the bulk of the dust emission is to be seen. In addition, high excitation lines of molecules and fine structure lines of abundant atoms are to be found. As an example of the importance of this region, about one per cent of the luminosity of the bright star burst galaxy M82 is emitted in the 61-micron line of oxygen(2). Observations in this line will give a totally new set of data for such objects.

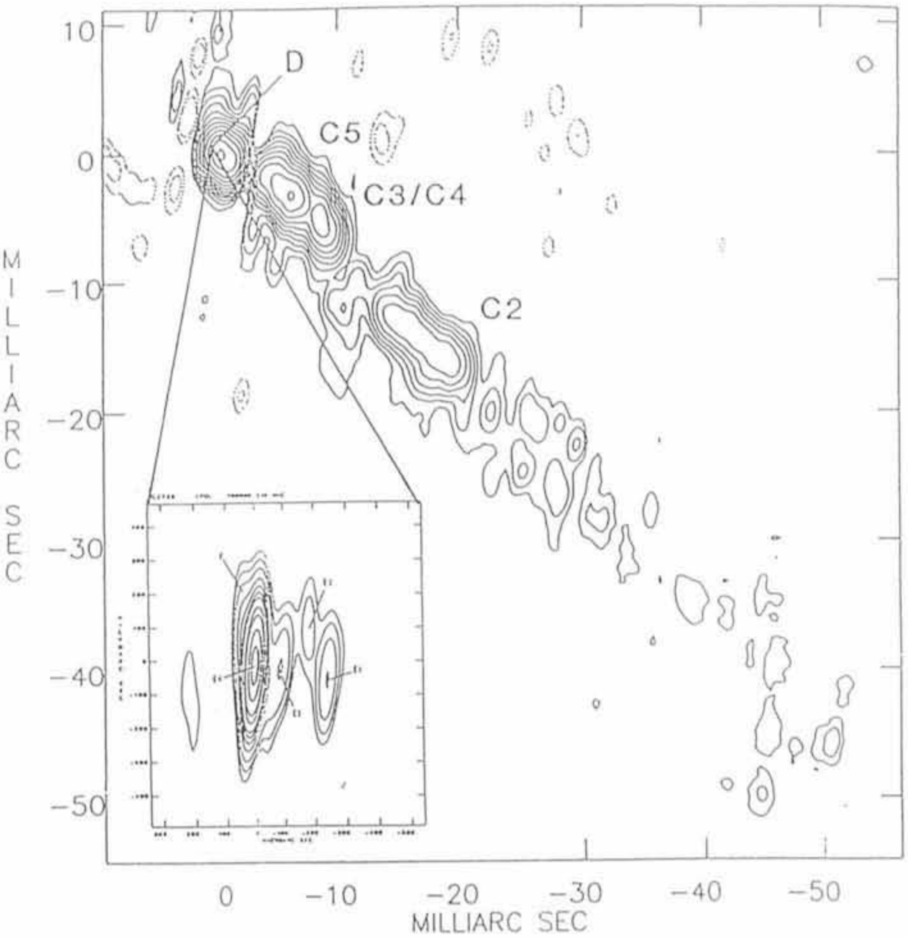

Figure 3: *A VLBI map of the central region in the quasar 3C273. The resolution (FWHM) is 0.″001. The lowest contour level is 0.05 per cent of the peak. The high dynamic range in this map makes it one of the best maps ever made from VLBI data (from Zensus, Bååth, Cohen, 1988). Inserted is a map from a recent VLBI experiment at 3 mm wavelength showing the core (component D) in much finer details. The resolution of this map is 0.″00005 (from Bååth et al., 1991).*

4. Improvements in Angular Resolution – VLBI

4.1 Current status

Despite the inherent limitations imposed by diffraction at long wavelengths, radio astronomy provides the highest angular resolution in astronomy. This is achieved through very long baseline interferometry (VLBI) where widely spaced radio telescopes, often in different continents, simultaneously observe radio sources to create interferometers with resolution (= wavelength/baseline) as fine as 50 microarcseconds. This is more than 2 orders of magnitude finer than the space telescope. Even at this resolution there are still unresolved components in the core of a typical quasar or active galactic nucleus.

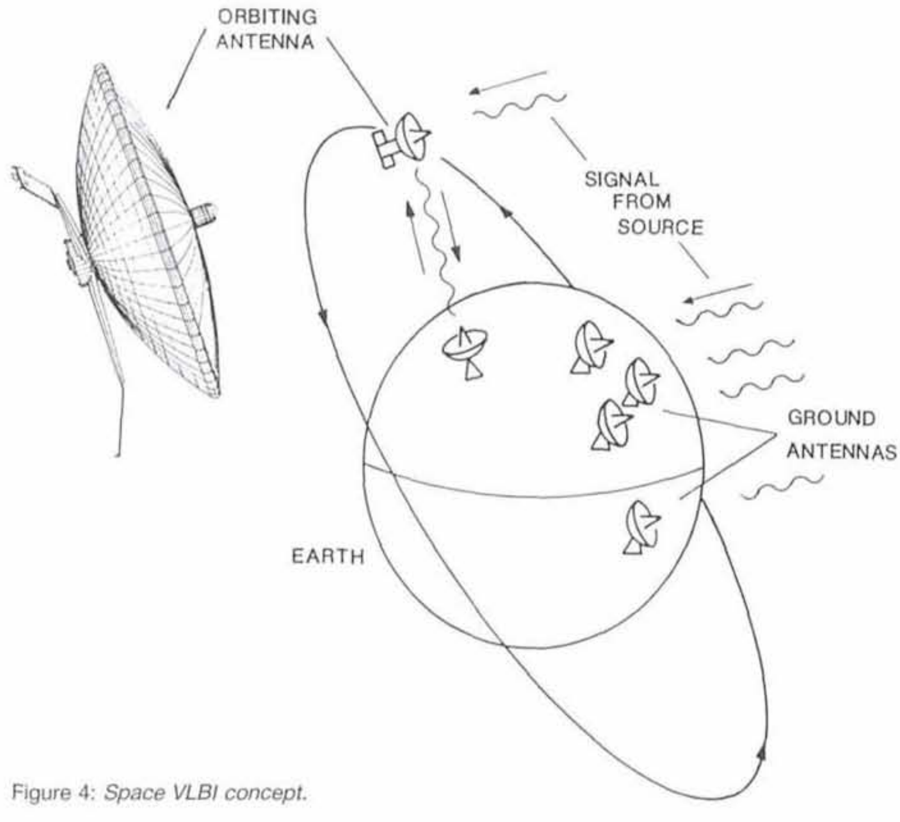

Figure 4: *Space VLBI concept.*

Since the cores of these nuclei are believed(7) to contain the central energy supply for the radio source, with a massive object (black hole) dominating the gravitational field in the "transrelativistic domain" (10^{15}–10^{18} cm) inside the so-called broad line region, VLBI observations with the highest resolution and over a wide frequency range are extremely important.

In VLBI it is impossible to connect the interferometer elements directly, so at each telescope the receiver must be provided with a phase stable local oscillator, usually locked to a hydrogen maser frequency standard (short-term stability a few parts in 10^{-15}). There must also be a means of synchronizing the clocks at each of the telescopes and a device (tape recorder) for storing the received signal and precise timing information. The VLBI system is completed with a playback system for correlating the recorded data. VLBI has been described in ref. (8).

VLBI at centimetre wavelengths is now well organized. The world's radio telescopes regularly combine to form two networks, one in the USA, and one in Europe, which sometimes operate separately but often together as a "World Array" consisting of ≈ 15 telescopes. The aperture synthesis technique is employed and sophisticated image processing software enables images of radio sources to be produced with dynamic range ≈ 1000:1.

4.2 Recent developments

Several developments are in progress: A detected array of telescopes for VLBI is being constructed in the USA. This Very Long Baseline Array (VLBA) will consist of ten 25-m diameter antennas optimally spaced across the USA from the Virgin Islands to Hawaii and a dedicated processor for playback.

In Europe where more telescopes will join the VLBI network, we must build a bigger processor centre and we have applied to the EEC for funding – so far with only limited success.

In Australia a new interferometer network, the Australian telescope (AT) was dedicated recently. It consists of an array of telescopes at Calgoora near Narrabri, Siding Spring near Coonabarabran and at Parkes. These telescopes will operate together with the NASA antenna in Tasmania and a telescope at Hobart in Tasmania to form a north-south array with baselines ranging from 100 to 1500 km. This array will extend the VLBI technique to observations of low declination radio sources only visible from the southern hemisphere.

Finally, VLBI at millimetre wavelengths has recently reached maturity with the production of the first good quality radio source maps at both 7 mm and 3 mm. Figure 3 is a map of the quasar 3C273 at a wavelength of 6 cm(9). The insert is a 3-mm map obtained with a network of millimetre telescopes: Onsala (20-m), U.Mass (14-m), NRAO Kitt Peak (12-m), Hat Creek, Berkeley (6-m), Caltech (10-m), and Nobeyama, Japan (45-m). The resolution is 50 micro arcsec and corresponds to about half a light-year linear resolution at the distance of 3C273(10).

4.3 The future: space VLBI

The size of the earth and the position of the available telescopes limits the resolution in VLBI to ≈ 300 μ arcsec at cm wavelengths and 50 μ arcsec at 3 mm, thus to further probe the unresolved components in radio sources it is necessary to have one or more telescopes in space. Space VLBI has more advantages than simply that of increased resolution. It can enable us to achieve the same resolution at say a wavelength of 1 cm as we do on the ground at 3 mm, thus enabling us to examine the spectral properties of the non-thermal emission mechanism producing the observed compact components.

The major difference between Space VLBI and terrestrial VLBI is the use of a phase transfer radio link to convey the reference frequency from as precision frequency standard on the ground to the spacecraft (it is not envisaged currently that the frequency standard will be onboard the spacecraft) and a network of telemetry stations to track the spacecraft and receive the astronomical data by means of another radio link, see Figure 4.

Space VLBI is not simply a figment of our imagination! It has been demonstrated in 2 experiments by a US-Japanese-Australian group led by scientists at JPL who used an antenna of the Tracking and Data Relay Satellite System (TDRSS) in configuration with the NASA 64-m diameter antenna in Canberra, Australia and the 64-m diameter antenna of the Japanese Institute for Space and Astronautical Science at Usada(11).

Three dedicated space VLBI projects have been proposed: QUASAT(12) – a collaboration between ESA and NASA to put a 15-m antenna into an orbit with apogee 30,000 km; RADIOASTRON(13), a Soviet project to fly a 10-m antenna out to 75,000 km; and VSOP(14), a Japanese project to put a 10-m antenna into an orbit with an apogee of 20,000 km. QUASAT, although highly regarded scientifically, was rejected by ESA on grounds of cost; the other two projects seem certain to be realized before the mid-1990's. We are also studying a second-generation space VLBI mission for the next decade, the International VLBI Satellite, IVS. This will be a 25-m spaceborne antenna operating at wavelengths 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, SM^3/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