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VLBI in Australia—A Review*

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Abstract

After two decades of Australian VLBI (very long baseline interferometry), high-resolution radio astronomy continues to be an active and fruitful research field. The status of Australian VLBI programs in astrophysics, astrometry and geodesy is reviewed and likely future developments are outlined. In addition to research programs with the Australian VLBI network, a number of successful collaborative projects are underway with overseas VLBI observatories. The inception of the Asia–Pacific Telescope will provide an important formal basis for fostering and extending international VLBI experiments in the Australian hemisphere. The APT will also serve a vital function in coordinating ground-based observations when the Soviet and Japanese VLBI space missions, Radioastron and VSOP, are launched in the middle of this decade. However, continued viable Australian participation in VLBI into the nineties will require new wide-bandwidth recording systems and an Australian VLBI correlator.

1. Introduction

In 1960 Bernard Y. Mills left the CSIRO Division of Radiophysics to join the School of Physics, University of Sydney (see Mills 1991, present issue p. 719). Here he undertook the construction of the Molonglo 1-Mile Cross. The result of this single-dish (Parkes) versus synthesis telescope (Molonglo) approach to building radio telescopes produced much controversy in Australia at the time. In October 1990 these two approaches were reconciled when both Molonglo and Parkes joined with the Mt Pleasant Observatory's 26-m radio telescope in Hobart to form a VLBI synthesis array operating at 0·843 GHz. The 'first fringes' on PKS 0537–441 from October 2, 1990 are presented in Fig. 1.

Australia, as the continent with the major astronomy facilities in the southern hemisphere, plays a significant role in high-resolution radio astronomy. In the twenty years since the early seventies, southern hemisphere VLBI observations have revealed a wealth of astrophysically important compact extragalactic and galactic objects in the southern skies. Many of the current imaging programs have grown out of the successful SHEVE (Southern Hemisphere VLBI Experiment) observations of 1982. In addition, the geological stability of the Australian

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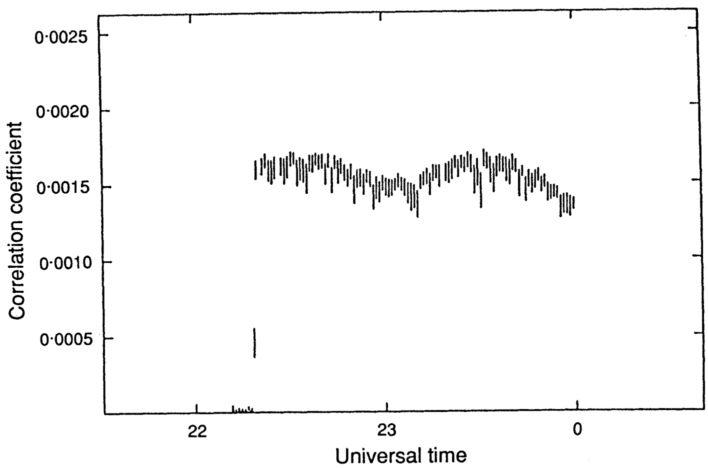

Fig. 1. First VLBI fringes from the source PKS 0537–441 at 843 MHz obtained between the MOST and Parkes telescopes on October 2, 1990 (data kindly provided by John Reynolds and Duncan Campbell-Wilson).

continent has already been utilised in pilot programs of precision geodesy and astrometry. Future availability of domestic wide-bandwidth recording and correlation facilities will greatly improve the sensitivity of VLBI observations. It will also provide compatibility with the space VLBI missions Radioastron and VSOP, to be launched by the Soviet Union and Japan respectively in the mid-1990s.

2. VLBI Capabilities in Australia

The radio telescopes currently used for VLBI in Australia are listed in Table 1, together with their performance operating frequencies and host institutions. The map of Australia in Fig. 2 shows their geographic locations. Even though they were not placed specifically for VLBI imaging there is still an acceptable continent-wide distribution. Fig. 3 shows the *u–v* coverage at 2·3 GHz for Centaurus A (PKS 1322–428) with the seven-antenna array. Observations being made with this array currently produce images with a dynamic range in excess of 100:1.

Considerable use is made of space-tracking antennas for VLBI observations. These have only limited availability outside their tracking duties but, through close cooperation with their host agencies, they have had a significant impact on VLBI in Australia. Successful VLBI has been under way with the Tidbinbilla Deep Space Network (DSN) 26-, 34- and 70-m antennas since the first experiments in the late 1960s (Gubbay *et al.* 1969; Cohen *et al.* 1969). The Alice Springs 9-m antenna of the Australian Centre for Remote Sensing (ACRES) was first used for VLBI in the successful SHEVE campaign in 1982 (Preston *et al.* 1989 and references therein). The most recent addition has been the 15-m Gnangara antenna of the European Space Agency (ESA), near Perth, which is operated in Australia by OTC.

Table 1. Radio telescopes currently in use in Australia for VLBI observations

The T_{sys} values are for their most sensitive frequency

Telescope	Diam. (m)	T_{sys} (K)	T_{sys} (Jy)	Location	Operating frequencies (GHz)	Operator
DSS 42	34	25	125	Tidbinbilla	2·3, 8·4	NASA
DSS 43	70	20	17	Tidbinbilla	1·7, 2·3, 8·4, 12, 15	
DSS 45	34	25	115	Tidbinbilla	2·3, 8·4	
Parkes	64	50	110	Parkes	0·843, 1·7, 2·3, 5·0, 8·4, 12	ATNF
AT CA	6×22	50	500	Narrabri	1·7, 2·3, 5·0, 8·4, 12	ATNF
AT Mopra	22	50	500	Siding Spring	1·7, 2·3, 5·0, 8·4, 12	ATNF
Mt Pleasant	26	60	600	Hobart	0·843, 1·7, 2·3, 5·0, 8·4, 12	U. Tasmania
ACRES	9	450	45 000	Alice Springs	2·3, 8·4	ACRES
Gnangara	15	125	3300	Perth	2·3, 8·4	ESA/OTC
MOST	1600×13	80	100	Molonglo	0·843	U. Sydney

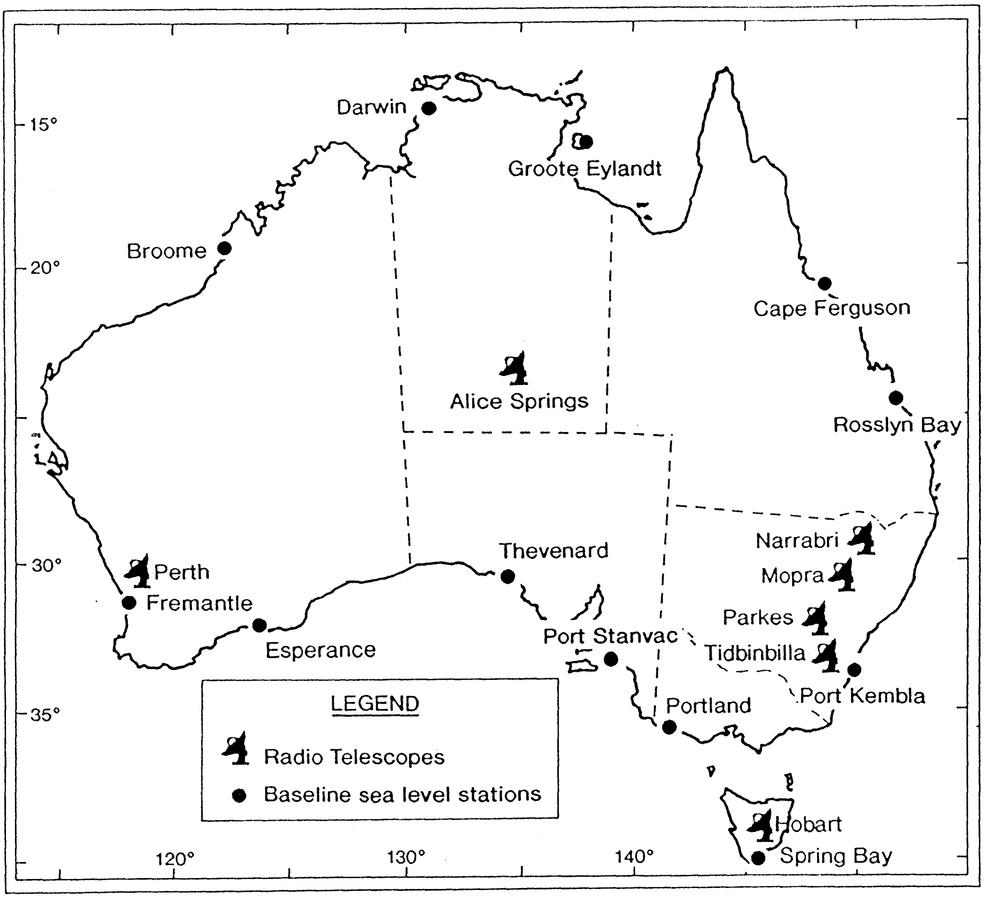

Fig. 2. Geographical location of the seven Australian VLBI telescopes and the location of the baseline sea-level stations (see Section 7*b*) Molonglo is not shown but is 40 km east of Tidbinbilla.

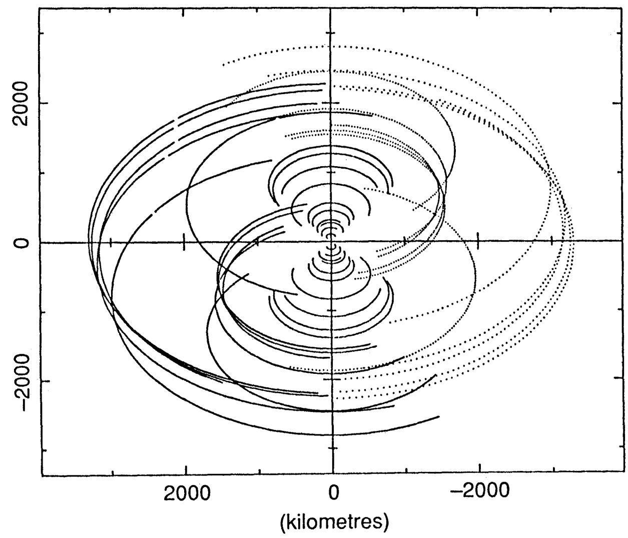

Fig. 3. The *u–v* coverage at 2·3 GHz for the source Centaurus A, 1322–428, for the seven Australian VLBI antennas currently used for the SHEVE program.

These antennas improve the *u–v* coverage considerably but constrain the frequencies to 2·3 and 8·4 GHz. This is an advantage for astrometry and geodesy as these are the internationally accepted standards, but they exclude maser line observations. Outside the space communications frequencies, the set of available antennas is reduced, but valuable observing programs are also under way at 0·843, 1·7 and 12 GHz.

Central to VLBI observations are the recording terminals and atomic frequency standards necessary for independent local oscillator VLBI (Broten *et al.* 1967; Bare *et al.* 1967). The first VLBI recording system in Australia was the narrow-band 14-kHz system developed using standard Deep Space Network recorders, the so-called 'Mk Zero' system (e.g. Gubbay *et al.* 1971) which was soon followed by an NRAO–Cornell 750-kHz Mk I recorder (Bare *et al.* 1967) on loan from the National Radio Astronomy Observatory. These have given way to the now widely available 2-MHz Mk II video-cassette-based recorder system (Clarke 1973), although broad-band Mk III systems (Rogers *et al.* 1983) are also available at Tidbinbilla, Hobart and Parkes. Most were installed as cooperative ventures with a variety of overseas institutions. VLBI in Australia will necessarily remain largely an internationally cooperative venture until domestic correlation facilities become available.

Rubidium vapour atomic standards with a frequency stability of typically 1 part in 10^{12} are readily available and adequate for observations up to 5 or even 10 GHz. For molecular masers the presence of strong unresolved lines allows phase referencing, and observations of the methanol maser lines at 12 GHz have been successfully undertaken with Rb standards (Norris *et al.* 1988*c*). Hydrogen maser frequency standards, with a stability of a few parts in 10^{15}, are in operation at the NASA Deep Space Network complex at

Tidbinbilla. Another, with the support of the US National Geodetic Survey (NGS), has now been installed at the University of Tasmania's Mt Pleasant Observatory near Hobart and a third, with the support of the US Naval Observatory (USNO), at Parkes. In addition, the University of Western Australia has a sapphire-loaded super-conducting cavity oscillator with stability comparable to a maser, available for VLBI at the ESA/OTC site at Gnangara.

The video-cassette-based Mk II recording terminals have seen considerable use in Australia as they provide adequate sensitivity for many purposes and are relatively inexpensive. As a collaborative venture with overseas observatories in 1987, the present Mk II system in Australia was provided to monitor the putative radio remnant of SN1987A following the successful detection of the 'prompt' radio outburst (Turtle *et al.* 1987). Its use for SNR1987A observations will be discussed in more detail later. With no domestic correlator for Mk II data reduction, both the JPL/Cal Tech and NRAO correlators in the United States are used extensively.

The long-term future of VLBI in Australia clearly resides with the general availability of broader bandwidth recorders and a domestic broad-band correlator. These will allow a considerable increase in sensitivity for astronomical imaging, as well as the wider spanned bandwidths essential for precision astrometry and geodesy, and the broad bandwidths needed to meet the standards for space VLBI in the mid-1990s. Unfortunately, such recorders and their tapes are expensive and their wide disposition in Australia has been limited to those supplied from overseas. Access to overseas correlators remains at best a stop-gap option, with their limited availability restricting outside users, like Australia, to only a few experiments a year.

The Australia Telescope National Facility (ATNF) is preparing to equip its Long Baseline Array (LBA) radio telescopes, Narrabri, Mopra and Parkes, with Canadian S2 wide-band recorders and to build an equivalent wide-band correlator. This will be an important step forward, but it is clear that the LBA has neither the resolution, u–v coverage or dynamic range needed by current VLBI users. Outside the ATNF, a proposal for a Cooperative Research Centre for High Resolution Radioastronomy and Geodesy has been submitted to government in an attempt to fund the necessary infrastructure, staff, recorders and correlator. Participating organisations include the Universities of Adelaide, Sydney, Tasmania and Western Australia, the ATNF and Division of Radiophysics of CSIRO, the Australian Surveying and Land Information Group (AUSLIG) and the US Jet Propulsion Laboratory (JPL).

(a) The Parkes–Tidbinbilla Interferometer

To exploit the practical advantages of real-time operation, considerable use is now being made of the Parkes–Tidbinbilla Interferometer (PTI) which consists of the 64-m radio telescope at Parkes and the 70-m or 34-m DSN antennas at Tibinbilla (Norris *et al.* 1988*b*). This 275-km baseline interferometer has independent local oscillators but a real-time microwave IF link which brings the signals together in the 1024-channel Parkes correlator. This innovative instrument played a vital role in measuring the 'prompt outburst' in SN1987A at 2·3 and 8·4 GHz (Turtle *et al.* 1987). Since then, the PTI has been used extensively in a variety of projects.

While not an imaging instrument, the PTI has still proven immensely valuable because of its real-time operation. It has been used to search for compact cores in a variety of galaxies. Norris *et al.* (1988*a*, 1990) have been very successful in discriminating between Seyfert and starburst galaxies on the basis of the frequent presence of a compact radio core in Seyfert, but not in starburst, galaxies. PTI observations of extremely luminous far-infrared galaxies, ELFs, found radio cores in about one-third of all ELFs with Seyfert-like spectra but they are rare otherwise. This implies that ELFs with a Seyfert-like spectrum are powered by quasar cores, while the other ELFs are more likely to be powered by starburst activity. Maps of the distribution of galactic methanol maser sources have shown that the compact emission features are clustered in regions with sizes of typically 3×10^{15} cm and, in several cases, possess a linear distribution suggesting accretion disks, shock fronts or jets (Norris *et al.* 1988*c*; McCutcheon *et al.* 1988). A proper motion of 49±5 milliarcsec per yr was determined for the Vela pulsar (Bailes *et al.* 1989) in what was to become a successful series of pulsar proper motion measurements with the PTI (Bailes *et al.* 1990*a*, *b*).

The PTI has also been used to search for compact cores in the 34 radio detections (Sadler 1984) from an optically selected complete magnitude-limited sample of ellipticals and S0 galaxies. Slee *et al.* (1990) detected 24 of the 34 sources (71%) with components smaller than 0·1 arcsec in angular size, and sought correlations between the power in the compact core and a variety of observational parameters. Aside from the preferential detection of ellipticals over S0s, 84% to 54%, no significant correlations were found with optical power, radio power from the kpc jets and outer lobes, B–V colours, or NII emission. A strong correlation was, however, found between the core flux densities at 4·9 GHz from the VLA and at 2·3 GHz from the PTI, indicating that all of the cores possessed flat or inverted radio spectra.

(b) The Southern Hemisphere VLBI Experiment, SHEVE

The first Australian VLBI imaging experiment, SHEVE, took place in 1982 with the cooperation of CSIRO, JPL and a number of Australian universities. This was an important first step in the areas of VLBI astrophysics, astrometry and geodesy. These observations provided the first images of about twenty of the strongest compact southern hemisphere Parkes radio sources (Preston *et al.* 1989; Meier *et al.* 1989; Tzioumis *et al.* 1989) and of Sagittarius A*, the compact source at the galactic centre (Jauncey *et al.* 1989*a*). The pioneering SHEVE astrometry yielded 0·1-arcsec rms radio positions of six compact Parkes sources with bright optical counterparts (Jauncey *et al.* 1989*b*). An integral part of the astrometry was to measure the Parkes–Tidbinbilla baseline with 5-cm precision (Harvey *et al.* 1983). In addition, the measured delay and fringe rates from the intercontinental 2·3-GHz survey (Preston *et al.* 1985) were used to provide 0·3-arcsec accuracy positions and optical identifications of many compact southern Parkes radio sources (Jauncey *et al.* 1989*c*).

Since 1982, the SHEVE array has been expanded and now includes the Hobart 26-m and the Gnangara 15-m radio telescopes. The appearance of SN1987A in February 1987 offered the possibility to observe the early expansion of a strong radio remnant immediately after the supernova outburst. Moreover, trans-Indian Ocean VLBI observations, five days after the supernova outburst, had provided a sensitive lower limit to the initial expansion velocity of the radiosphere (Jauncey *et al.* 1988). Accordingly, a 2-MHz MkII system and rubidium frequency standards were installed on all of the SHEVE radio telescopes following generous overseas loans of equipment. In the absence, until recently, of detectable radio emission from the remnant of SN1987A, the VLBI array has been kept in readiness and has operated successfully at a variety of frequencies from 0·843 to 12 GHz. It has been the combination of available recording equipment and the expansion in the number of large or moderately sized radio telescopes available for VLBI that has improved, dramatically, the quality of VLBI images now being made in the south.

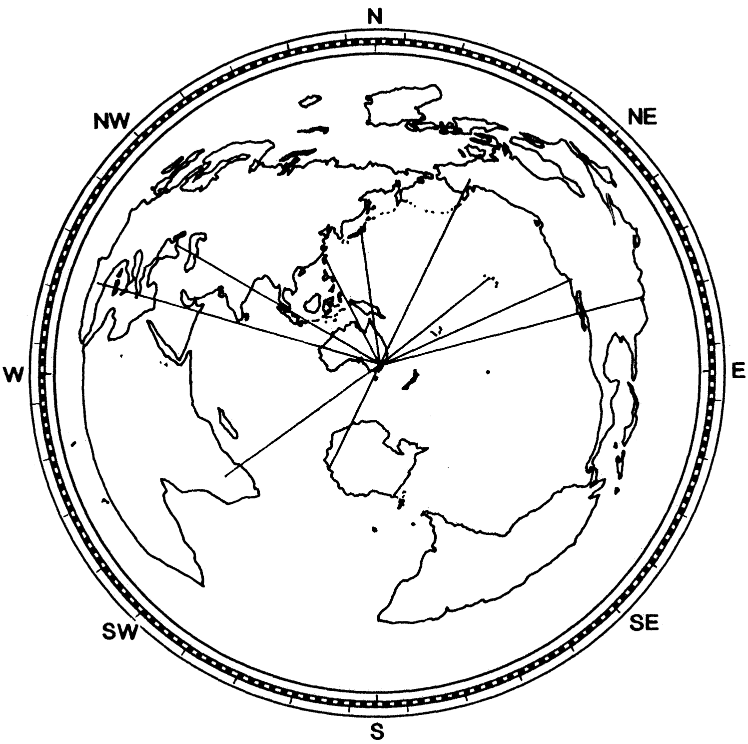

Fig. 4. International baselines over which successful VLBI observations have been made from Australia. For simplicity, all Australian baselines have been drawn from Tidbinbilla.

3. The International Connection

The DSN played an important role in pioneering VLBI observations in Australia, and so there were numerous connections to the DSN sister facilities, particularly at Goldstone California and, in the early days, South Africa [see Gubbay (1988) for an outline of the early days of the Australian VLBI program within the DSN]. Since then, for imaging, astrometry and geodesy, connections to our Asian–Pacific and Indian Ocean neighbours have been both frequent and valuable. Fig. 4 shows the international baselines over which successful observations have been made. Several of these baselines are currently used for imaging, astrometry and geodesy and these experiments will be discussed in more detail below.

An important future step lies in coordinating, more formally, other radio telescopes in our geographic region. While very successful experiments from Australia are separately under way with Antarctica, China, Japan, South Africa, the US and the USSR, high-dynamic-range imaging comes not only with the high sensitivity of wide-band recorders but with the improved *u–v* coverage gained by using Australian telescopes in conjunction with those of all these nations.

A first step towards this goal is the recent formation of the Australia–Pacific Telescope, the APT, to coordinate multi-telescope observations in the region. The APT has a particularly important role at this longitude, as it is the only VLBI network with good *u–v* coverage for equatorial sources in both the north–south and east–west directions. The first experiments with the APT are being scheduled for late 1991. The APT will also provide a good foundation for the future of space VLBI in the Asian–Pacific region.

4. The Space Connection

Ground-based VLBI is limited to a maximum baseline of one earth diameter which, for typical source flux densities, corresponds to a maximum brightness temperature of around 10^{12} K. This limitation was finally overcome in August 1986 with the first demonstration of space-to-ground VLBI technology. Successful observations at 2·3 GHz were made between the 4·9-m antenna on the Tracking and Data Relay Satellite System, TDRSS-E, and the 64-m radio telescopes at Tidbinbilla, in Australia, and Usuda in Japan (Levy *et al.* 1986). Three quasars, 1730–130, 1510–089 and 1741–038, were observed on projected baselines up to 1·4 earth diameters, successfully demonstrating many of the techniques necessary for a dedicated VLBI observatory in space. This was an important precursor for the Soviet, European and Japanese missions, Radioastron, Quasat and VSOP (VLBI Space Observatory Program) respectively, that were being planned at that time.

Later in January 1987 a further 24 sources selected from the intercontinental 2·3-GHz survey results of Preston *et al.* (1985) were again observed with TDRSS, and 23 out 24 were detected on baselines this time up to 2·15 earth diameters (Levey *et al.* 1989). These long baselines gave much better sensitivity to high brightness temperatures than any earth baselines. Brightness temperatures of 1–4 times the 10^{12} K inverse Compton limit were measured for ten sources, suggesting bulk relativistic motion in these sources (Linfield *et al.* 1989) consistent with the explanations of the super-luminal expansion seen in similar sources (Unwin *et al.* 1983). This was the first direct measurement of such large brightness temperatures for extragalactic continuum radio sources, although such values have been inferred for a number of sources from the time scales observed for flux density variations at frequencies less than 1 GHz.

More recently, the same TDRSS satellite has been used successfully at 15 GHz for space VLBI (Linfield *et al.* 1990). These observations were made in February and March 1988 and took advantage of the upgrading of the Tidbinbilla 64-m to a 70-m aperture with improved performance at higher frequencies, as well as of the 45-m high-performance antenna at the Nobeyama Radio Observatory. Despite using an existing spacecraft that was not designed for VLBI, the technique of phase transfer was successfully demonstrated at this frequency. Moreover, 11 out of 22 sources were detected on baselines up to a billion wavelengths, with brightness temperatures similar to that found at 2·3 GHz. This was ample demonstration that there will be large numbers of sources available for investigation by Radioastron and VSOP when they are launched in the mid-1990s.

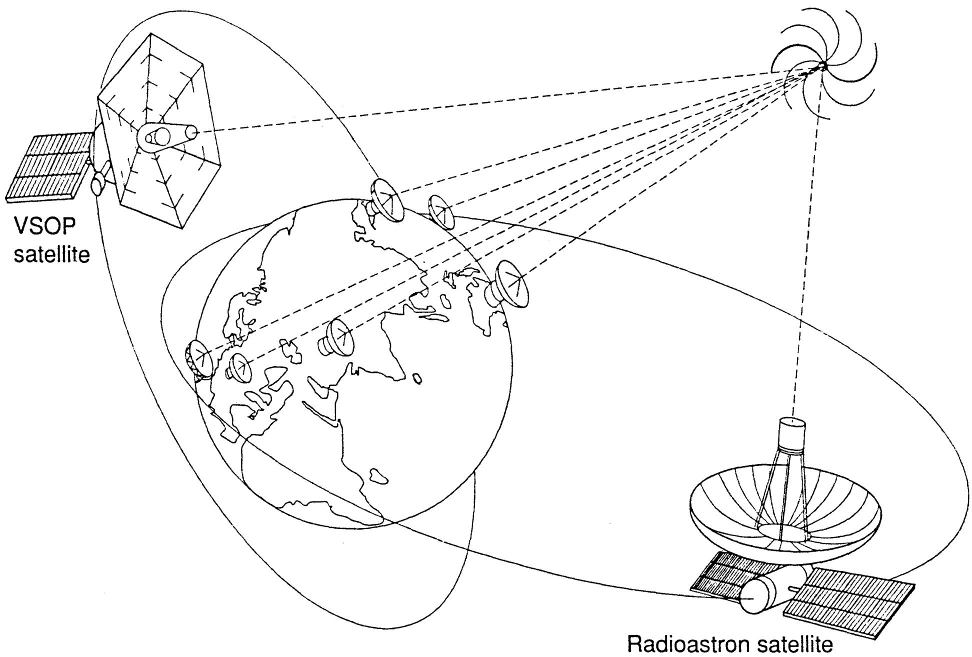

Fig. 5. Artist's drawing of the Soviet and Japanese VLBI spacecraft Radioastron and VSOP in orbit.

The Soviet and Japanese space VLBI missions, Radioastron and VSOP, plan to launch 10-m radio telescopes into earth orbit in 1994 and 1995 respectively. These missions are designed to be complementary in nature. Radioastron will go into a high orbit, 80,000 km apogee height, and will advance the brightness temperature limits tenfold over that achievable from the earth. However, it will provide only a limited imaging capability given the limited *u–v* coverage from such a high orbit. VSOP, on the other hand, is designed to provide much better imaging, but will do this at the more modest resolution that results from its 20,000 km apogee orbit. Fig. 5 shows pictures of both spacecraft in orbit with their 10-m antennas unfurled. Both missions will lead to the formation of radio images with a resolution better than 100 microarcsec at the 1·3-cm shortest wavelength.

Observing wavelengths are 1·3, 6 and 18 cm for both missions, while Radioastron has an additional 90-cm wavelength receiver. The Radioastron receivers are being supplied by Finland (1·3 cm), Europe (6 cm), Australia (18 cm) and India (90 cm). Tracking, data reception and phase transfer outside the Soviet Union and Japan will be provided through NASA by constructing a dedicated 10-m antenna sub-net to be located in California, Madrid, Tidbinbilla and Green Bank (USA). The Australian receiver development is being funded jointly by the Australian Space Office and the CSIRO Office of Space Science and Applications (COSSA).

Participation of the Australian ground radio telescopes is an important component of both missions, as they are essential to achieving high quality images of southern hemisphere radio sources. This participation will provide direct Australian access to space missions costing several hundred million dollars. Space VLBI will achieve an order-of-magnitude increase in angular resolution over ground-based VLBI, and explore for the first time the physical processes taking place in ultra-compact regions such as the accretion disks around the massive black holes thought to reside in the active nuclei of radio galaxies and quasars. As the nearest of these active galaxies, Centaurus A will be a prime target of both missions where a linear resolution of better than one light-day will be achievable.

5. VLBI Astrophysics

By setting up the SHEVE MkII capability and adding the Perth and Hobart antennas, a major continuum imaging program has been initiated at 2·3 and 8·4 GHz. This program is attempting to obtain milliarcsecond resolution images of the strongest southern hemisphere compact radio sources as well as to image a complete sample of the strong peaked-spectrum Parkes Catalogue sources. A short discussion of some of the more interesting sources follows.

(a) Centaurus A

At a distance of 4 Mpc, Centaurus A (PKS 1322–428) is the nearest active radio galaxy and one of the prime targets for VLBI imaging in the southern hemisphere. The SHEVE 1982 image, Fig. 6, shows that this spectacular radio galaxy exhibits structure over angular scales from 6° to 10 milliarcseconds; that is, from 400 kpc to 0·1 pc. Imaging observations at 2·3 GHz are now being made regularly with the SHEVE array in an attempt to follow any dynamic changes that may be taking place in the nucleus or jet. Unfortunately, at this frequency, not only does the true 'core' appear to be totally self-absorbed and undetected, but also the jet appears to be essentially featureless. Successful imaging observations have been made at 8·4 GHz at one epoch only (Reynolds *et al.* 1991, personal communication). Here the core is readily visible and the jet appears to possess several knots whose strength and position may well evolve with time.

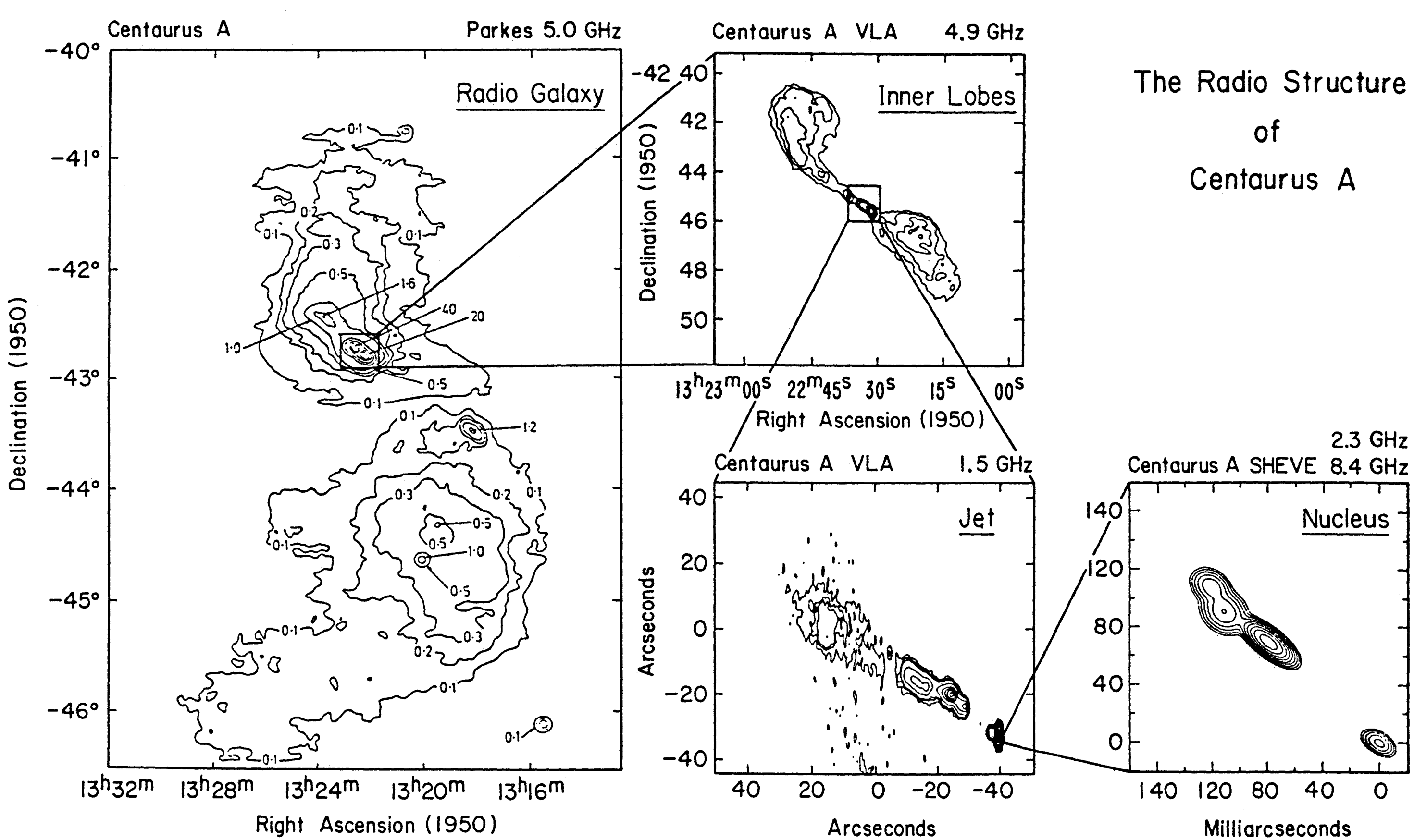

Fig. 6. Radio structure of Centaurus A on angular scales over a factor of 10^6, taken from Meier *et al.* (1989).

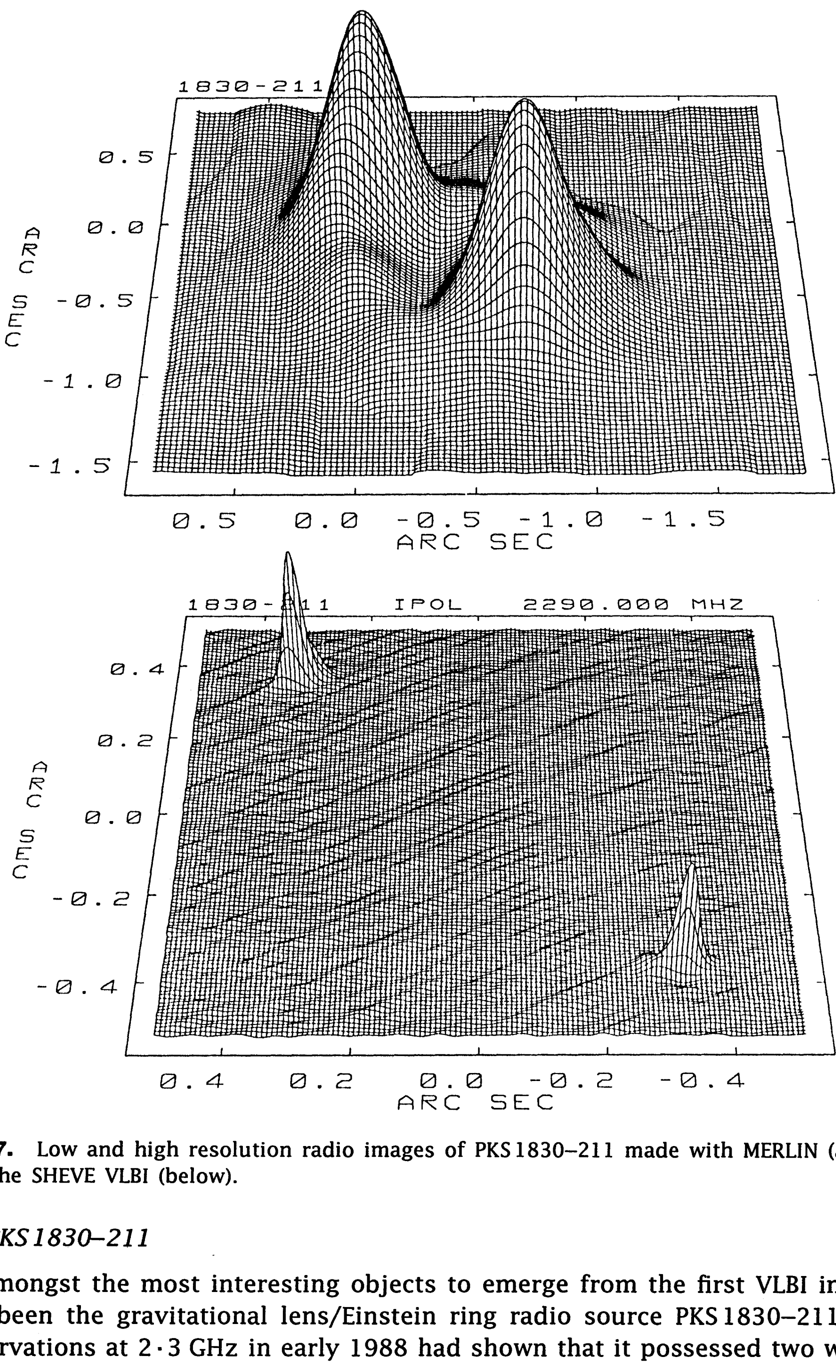

Fig. 7. Low and high resolution radio images of PKS 1830–211 made with MERLIN (above) and the SHEVE VLBI (below).

(b) PKS 1830–211

Amongst the most interesting objects to emerge from the first VLBI images has been the gravitational lens/Einstein ring radio source PKS 1830–211. PTI observations at 2·3 GHz in early 1988 had shown that it possessed two widely spaced flat-spectrum compact components but which accounted for only half of the total flux density. VLA observations by Rao and Subrahmanyan (1988) at 15 GHz had also shown two compact components separated by 1 arcsec, but with the symmetry usually associated with gravitational lensing. MERLIN observations were then undertaken to account for the missing 2·3-GHz flux density, and these revealed the presence of a steep-spectrum complete elliptical ring connecting both compact components (Jauncey *et al.* 1991). The existence of the ring was confirmed with an 8·4-GHz VLA image and its presence virtually confirms the identification with a gravitational lens/Einstein ring. Fig. 7 shows both the 1·7 GHz MERLIN (above) and the 2·3 GHz VLBI images (Jauncey *et al.* 1991), clearly indicating the ring-like structure and the two compact components.

The simplest model for PKS 1830–211 has the steep-spectrum ring as the lensed image of the jet and the two compact flat-spectrum components as separate images of the core of the background object. Here part of the jet is exactly aligned while the core is slightly displaced. As the source is so strong, ~10 Jy, and is known to be variable, VLBI observations have the potential to determine the lensing mass distribution in detail, as well as to follow changes in the structure and determine the time delay between the two images and hence the Hubble constant.

(c) SNR1987A

In late 1990, observations at 0·843 GHz with the Molonglo Observatory Synthesis Telescope (MOST) detected steadily increasing radio emission from the remnant of SN1987A at the mJy flux density level (Turtle *et al.* 1990). The remnant has since been the subject of several PTI and VLBI observations at 0·843, 1·7 and 2·3 GHz but no significant detection of a compact component has been made. The weak radio source is also resolved with the AT compact array at 8·4 GHz on the 6-km baseline (Staveley-Smith *et al.* 1991), indicating an asymmetric structure around 1 arcsec in size, significantly smaller than the OIII ring seen by the Hubble Space Telescope (Jakobsen *et al.* 1991).

Accurate registration of the AT structure of the radio remnant on the HST OIII optical image is essential to determine the exact relationship between the radio and optical emission. This is being sought through repeated VLBI astrometry observations at 2·3 and 8·4 GHz on the Tidbinbilla–Hobart baseline of the nearby active radio star HD32918. This star, only 6° from SNR1987A, is extremely active and is included in the HIPPARCOS Input Catalogue. Radio and optical positions, and proper motions accurate to ~1 milliarcsec, will soon provide the necessary precise 'tie' between the VLBI radio position reference frame and the HIPPARCOS optical frame, and hence between the HST and AT images.

If the remnant continues to increase in flux density, as has been found since August 1990 (Turtle *et al.* 1990; Staveley-Smith *et al.* 1991), then it may indeed become one of the strongest radio sources in the Large Magellanic Cloud. As the remnant increases in flux density, VLBI measurements may become sufficiently sensitive to take images of the detailed interactions of the expanding shock wave with the surrounding stellar wind, as originally intended when the MkII array was set up. This will be greatly aided by introducing the AT Mopra antenna late in 1991 and moving to lower frequencies, as both will provide the angular resolution suitable to the remnant size.

(d) Circinus X-1

X-ray, optical, infrared and radio observations indicate that Circinus X-1 (B1516–569) is a binary star system at a distance of 10 kpc. Circinus X-1 shows intense, variable radio flares that are nearly coincident in time with the 16·59-day periodic X-ray flares (Haynes *et al.* 1978). VLBI observations at 2·3 GHz undertaken in 1980 showed that the flaring component was unresolved on the 275-km Parkes–Tidbinbilla baseline throughout the flare, but totally resolved on the Australia–South Africa baseline (Preston *et al.* 1983). At 10 kpc this implies a linear size of 15–150 AU and an expansion velocity for the flaring component of no more than 0·1*c*. However, at a galactic latitude of only 0·04°, this large apparent size, even when the flare was only a few hours old, is probably due to interstellar scattering. Determination of an accurate, 0·3-arcsec rms, radio position from the VLBI observations led to the unambiguous optical identification with a faint, very red, galactic stellar object (Argue *et al.* 1984).

6. Astrometry

VLBI astrometry has two major thrusts. The first is to obtain reliable optical identifications of compact radio sources based on radio–optical position coincidence alone. The second is to select those strong compact sources to establish a southern hemisphere VLBI radio astrometric reference frame of high accuracy, <5 milliarcsec rms, from dual-frequency 2·3- and 8·4-GHz VLBI observations. This VLBI radio reference frame will then form the basis for a precise tie with the optical reference frame also determined with milliarcsec accuracy by HIPPARCOS. Along the way, the VLBI reference frame also provides calibration sources for the southern high-resolution radio telescopes like the MOST and the AT.

(a) Reliable Optical Identifications

The southern 2·3-GHz VLBI survey was carried out between the Tidbinbilla and Parkes 64-m antennas in Australia and the 64- and 26-m antennas at Goldstone in California, and between the Australian antennas and the 26-m antenna of the Hartebeesthoek Radio Astronomy Observatory in South Africa (Preston *et al.* 1985). Radio positions were determined by analysing the observed time delays and fringe rates of those sources that were detected on these 8×10^7 wavelength baselines. In a series of papers (Morabito *et al.* 1982, 1983, 1985, 1986) radio positions with an accuracy of ~0·3 arcsec rms were derived for several hundred compact radio sources. In the southern sky optical identifications were sought from the UK Schmidt SERC J survey films. Optical positions were measured with respect to SAO Catalogue stars and objects within 3 arcsec of the radio position were claimed as identifications (Jauncey *et al.* 1989*c*). South of declination −20°, to the 22·5-magnitude limit of the SERC J survey, 91% of the sources with VLBI positions are identified, 79% with QSOs, 5% with galaxies, 4% with BL Lac objects, 1% with faint objects that were not obviously QSOs or galaxies and a further 2% as possible QSOs.

(b) Precision Southern VLBI Radio Reference Frame

Compact extragalactic radio sources, quasars and active galactic nuclei, are at great distances and are thus ideal objects to provide a quasi-inertial celestial position reference frame. Radio positions of such objects can be determined with milliarcsec accuracy using VLBI techniques. The first pioneering astrometric radio measurements south of declination −40° were made in Australia in 1982 as part of the SHEVE program (Jauncey *et al.* 1989*b*). In the southern hemisphere, further accurate VLBI positions are needed to form a dense primary reference frame for the new generation of high-resolution radio and optical telescopes like the MOST, the AT and the HST.

Several active collaborative VLBI astrometry programs are under way in and from Australia in collaboration with the US Naval Research Laboratory, the Bureau des Longitudes in Paris, JPL and the Communications Research Laboratory at Kashima in Japan. The first results from these programs have led to a dramatic increase in the number of Parkes radio sources with positions to a precision of about 10 milliarcsec (White *et al.* 1990; Harvey *et al.* 1991) with a sky density close to that for such sources in the northern hemisphere.

An important precursor to these programs has been the single-baseline surveys to select those sources possessing compact components that make them suitable position calibrators. Nine hundred sources were examined in the most extensive of these surveys (Preston *et al.* 1985) undertaken at 2·3 GHz on intercontinental baselines between South Africa, the US and Australia. More recently, both the PTI and Tidbinbilla–Hobart VLBI have been used to select those sources that possess compact cores but no extended structure on scales larger than 0·1 arcsec.

(c) The Radio–Optical Reference Frame Tie

VLBI observations of active radio stars are also an important component of the radio–optical frame-tie program. The 11th-magnitude limit of HIPPARCOS precludes observations of any extragalactic radio quasars. One means of obtaining a direct tie is through radio observations of the active radio stars that have been included in the HIPPARCOS Input Catalogue. North of −30° declination, White *et al.* (1990) have measured single-epoch positions for two stars, HD26337 and HD77137, on the Tidbinbilla–Goldstone baseline. As noted in Section 5*c*, successful VLBI observations in the far south have already been made of HD32918 in an active state on the Tidbinbilla–Hobart baseline.

7. Geodesy

Over the past two decades VLBI has demonstrated its ability to provide precision trans- and inter-continental geodetic measurements with a repeatability approaching 1 cm. The first precision geodetic VLBI measurements within Australia were undertaken as part of the 1982 SHEVE program. The Parkes–Tidbinbilla baseline was measured with a precision of 5 cm rms from dual-frequency 2·3- and 8·4-GHz VLBI observations of a number of Parkes radio sources (Harvey *et al.* 1983; Stolz *et al.* 1983). At the same time accurate radio positions were determined for six strong southern compact Parkes radio sources (Jauncey *et al.* 1989*b*).

(a) International Links

Geodetic VLBI in Australia is an exciting field that has great potential. Almost a decade has passed since the pioneering SHEVE measurements and, while little has been done domestically, there has been a significant increase in VLBI geodesy measurements from Australia to our Asian–Pacific neighbours. Strong international links have been forged between Australia and Japan, the United States and China through active geodesy VLBI programs. The Australian continental plate is amongst the most tectonically stable and thus forms a near ideal reference platform from which to measure and monitor the tectonic activity of our Asian–Pacific neighbours.

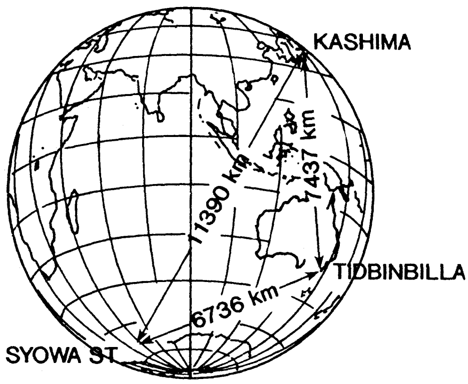

Fig. 8. Global perspective of the Kashima–Tidbinbilla–Syowa geodesy triangle determined from VLBI observations in January 1990.

Both Tidbinbilla and Hobart are active in Asian–Pacific region geodesy. The first joint Tidbinbilla–Kashima–Shanghai (Australia–Japan–China) astrometry/geodesy observations took place on November 30, 1987 in a program to search for reliable VLBI calibration sources in the declination range 0° to –45°. These connections were expanded in January 1990 to include the first successful Japanese-led demonstration measurements from Kashima and Tidbinbilla to the Japanese 11-m multi-purpose antenna at Syowa Station (69°·0 south, 39°·6 east) in Antarctica. The baselines and geometry are shown in Fig. 8. Given the success of these measurements it is expected that they will continue over the next decade to provide a detailed picture of the relative Australian–Antarctic–Japanese plate motions. Mutual visibility constraints make Australian participation essential as the Japan–Antarctica baseline is so long, 0·89 earth diameters, that it is not well determined by direct VLBI measurements.

At Hobart's Mt Pleasant Observatory, the NGS, to complement their northern program, installed a sensitive S/X receiver, hydrogen maser and broad-band MkIII recorder to provide reliable earth-rotation, crustal dynamics and source-position measurements in the southern hemisphere. Mt Pleasant is involved in regular observing programs in the International Radio Interferometric Surveying (IRIS) program as well as the Pacific Plate Motion program with Tidbinbilla, Shanghai, Kashima, Fairbanks, Hawaii and mainland US antennas. Source positions are being determined with milliarcsec accuracy from single-baseline observations between Hobart and Hartebeesthoek in South Africa.

Both the Australian geodesy and astrometry programs are likely to be ultimately limited in accuracy by the lack of knowledge of the structure, and its variability with time, of the southern radio-reference-frame sources. None are perfectly unresolved point-source calibrators, and all possess radio structure that is extended and variable on a scale of a few milliarcsec as shown from the 2·3-GHz survey results (Preston *et al.* 1985). The difficulty arises from the lack of source-structure information on baselines between 3000 and 9000 km in the southern hemisphere. Between Australia and either South Africa or South America there is little land and there are, at present, no radio telescopes. Without these baselines the milliarcsec structure and its variability are only poorly determined and this uncertainty may be ultimately reflected in the final celestial and terrestrial position errors.

(b) The Australian Zero Order Network

Within Australia, some geodesy and astrometry measurements are presently under way between DSS45 at Tidbinbilla, and Hobart. This is also a pilot program to prepare for a more extensive series of VLBI measurements across Australia. The Australian Surveying and Land Information Group (AUSLIG) is planning to set up a Zero Order Network of VLBI centimetric precision reference points located at radio telescopes across Australia. This will be of prime importance in providing the fundamental fiducial network for Australia which will be used for tide-gauge and sea-level monitoring across the continent and perhaps later into the South Pacific. Fig. 2 shows the location of the radio telescopes and baseline sea-level stations. This reference frame will form a network from which to study, in more detail, regional plate tectonics and possible sea-level changes due to changes in the earth's climate.

8. Summary

High-resolution VLBI is an active field of research in Australia with major programs under way in astrophysical imaging, space VLBI, milliarcsec-accuracy radio astrometry and precision geodesy. For this level of activity to be maintained in the long term, three steps will be necessary:

(1) to make available wide-band recorders at all participating radio telescopes;
(2) to make available a wide-band domestic correlator; and
(3) to achieve a significant advance in improving *u*–*v* coverage by collaborating closely with our Asian–Pacific radio astronomy neighbours Canada, China, Japan, the USA and the USSR. Coordinating the Asia–Pacific Telescope should satisfy this requirement.

The wide-band recorders and a domestic broad-band correlator, as well as the wider spanned bandwidths essential for precision astrometry and geodesy, will allow a considerable increase in sensitivity for astronomical imaging. They are essential also to meet the standards for space VLBI in the mid-1990s with the launch of the Soviet and Japanese spacecraft Radioastron and VSOP. In an attempt to fund the necessary infrastructure, staff, recorders and correlator, a proposal for a Cooperative Research Centre for High Resolution Radioastronomy and Geodesy has been submitted to government. The Centre aims at three main research areas—ground-based VLBI, space VLBI, and geodesy—to support the wealth of observational results that would flow freely from properly supported VLBI programs.

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