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CHAPTER 20

# The European VLBI Network and Global VLBI

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**Abstract** Current and future characteristics of the European VLBI Network (EVN) are described, and a brief description of the Asia-Pacific Telescope (APT) is given.

## Contents



## 20.1 Introduction

The other major VLBI facility in the world is the European VLBI Network. It currently provides between six and eight telescopes with wideband recording equipment (Mark III or VLBA) at several "standard" VLBI frequencies, and soon will provide between eight and twelve telescopes, depending on observing frequency, with Mark IV recording capability. A major upgrade program for the EVN is underway which includes construction of a 16-station data processor,

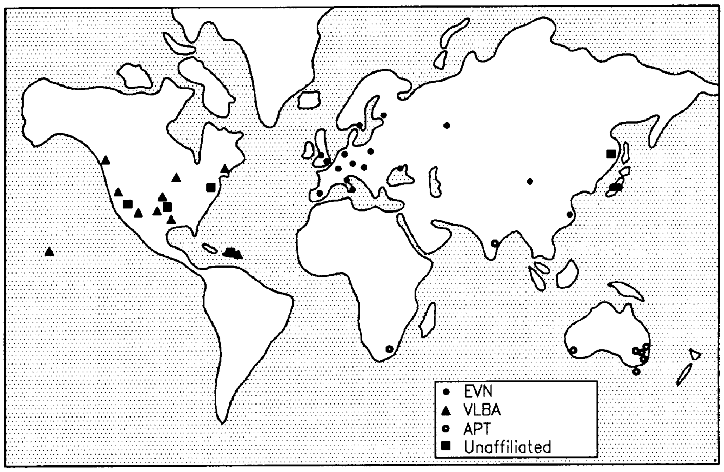


**Figure 20.1:** The world of VLBI: EVN *(filled circles)*; VLBA *(filled triangles)*; Asia-Pacific Telescope *(open circles)*; unaffiliated telescopes *(filled squares)*.

upgrade-conversion from Mark III to Mark IV recording systems, improved user support by specially appointed EVN support scientists to aid in experiment preparation and analysis.

The combination of the EVN and the VLBA is likely to be a frequent mode of operation in the era of large correlators. Such *global* observations, if successful, can provide superb $(u, v)$ coverage for northern sources, and will allow state-of-the-art imaging experiments. In the southern hemisphere, the aptly named Asia-Pacific Telescope (APT) is the vehicle for VLBI observations for one to two weeks every four months. In this chapter, I describe the EVN, its upgrade program and user support, and I will give a brief description of the APT.

## 20.2 The World of VLBI

Figure 20.1 shows a Eurocentric view of the world with the VLBI networks and arrays: the EVN, the VLBA, the Asia-Pacific Telescope, and unaffiliated telescopes. I have designated the VLA and the Green Bank site as unaffiliated, but I expect them to work predominantly with the VLBA.

Figure 20.2 shows the distribution of telescopes in the European part of the EVN in more detail. The telescopes are located in 11 different countries. It used to be said that one joined the navy to see the world, but these days a VLBI astronomer visiting the telescopes in his array gets to see quite a bit of the world as well!

**Table 20.1:** EVN telescopes

| Country | Institute | Location | Diameter (m) | Band (GHz) |
|---|---|---|---|---|
| Spain | National Astron. Observ. | Yebes | 14 | 2.3–43 |
| UK | Nuffield Radio Astronomy Laboratories | Jodrell Bank | 76 | 0.3–1.6 |
| | | | 25 | 1.4–43 |
| | | Cambridge | 32 | 1.4–43 |
| France | Meudon Observ. | Nancay | 300 x 30[1] | 1.4–1.8 |
| Netherlands | Netherlands Foundation for Research in Astronomy | Westerbork | 14 x 25[2] | 0.3 – 8.4 |
| Germany | Max-Planck-Institut für Radioastronomie | Effelsberg | 100 | 0.6–90 |
| | University of Bonn | Wettzell | 20 | 2.3–8.4 |
| Sweden | Onsala Space Observ. | Onsala | 25 | 1.4–5 |
| | | | 20 | 2.3–100 |
| Italy | Istituto di Radioastronomia | Bologna | 32 | 1.4–43 |
| | | Noto | 32 | 1.4–43 |
| Poland | Torun Radio Astronomical Observ. | Torun | 15 | 0.3–15 |
| | | | 32 [3] | 0.3–43 |
| Finland | Metsähovi Radio Research Station | Helsinki | 14 | 22–100 |
| Ukraine | Crimea Observ. | Simeiz | 22 | 0.3–43 |
| Russia | Moscow Power Institute | Bear Lakes | 64 | 1.4–5 [4] |
| China | Shanghai Observ. | Shanghai | 25 | 0.3–22 [5] |
| | | Urumqi | 25 | 0.3–22 [5] |

**Notes:** [1] equivalent diameter, 94 m [2] equivalent diameter, 93 m [3] expected to be in operation in early 1995 [4] upper limit to the frequency range may extend to 8.4 GHz [5] upper limit to the frequency range may extend to 43 GHz

## 20.3 The European VLBI Network

Most VLBI observations in Europe are carried out by the EVN, formed in 1980 by a consortium of five of the major radio astronomy institutes in Europe, the *European Consortium for VLBI.* The EVN and the Consortium have grown to include nine institutes with twelve telescopes in eight western European countries as well as associated institutes in Poland, Russia, Ukraine, and China. Operation of the EVN is on a part-time basis, for a maximum of 17 weeks per year.

Table 20.1 lists the telescopes in the EVN by country in west to east order, and gives information on the diameter (or equivalent diameter for arrays) and the VLBI frequency range possible with the optics and surface accuracy. The receivers available now, and the dates for when a particular receiver will be available are shown in table 20.2.

Detailed information about the EVN antennas and their performance are available on the Internet, and access to this information is described in the thrice yearly EVN Call for Proposals.

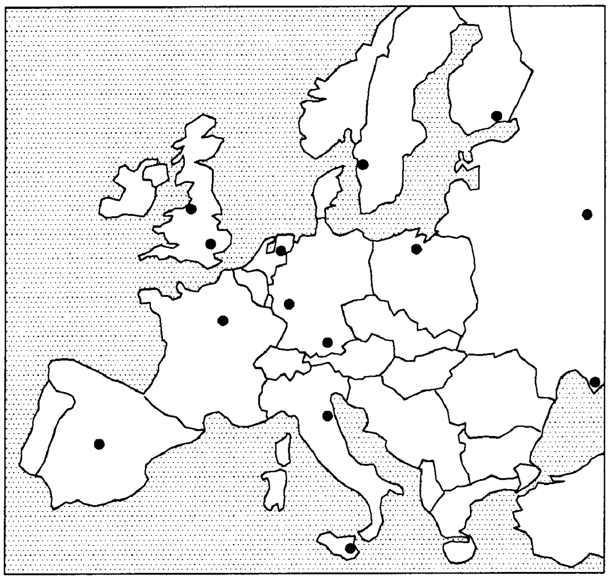

**Figure 20.2:** The European VLBI Network

## 20.4 $(u, v)$ Coverage for the EVN Alone

The $(u, v)$ coverage is one of the fundamental figures of merit of an interferometer. Considerable effort went into the optimum placing of the VLBA antennas for $(u, v)$ coverage (see chapters 4 and 8). No such license was available for the EVN; we take the telescopes where we find them.

Figure 20.3 depicts the $(u, v)$ coverage of the EVN at frequencies up to 8.4 GHz, which is the upper limit for the Westerbork array. Ten telescopes are included: Jodrell Bank, Cambridge, Westerbork, Effelsberg, Onsala, Bologna, Noto, Torun, Urumqi, and Shanghai (all with Mark III or VLBA recording systems). I have not included the Simeiz telescope in Ukraine in this diagram. Maximum baselines of 8700 km are achieved, leading to a fringe spacing of 0.8 milli-arcsec at 8.4 GHz. The $(u, v)$ coverage shows the effect of the northern locations of most of the EVN elements; it becomes more one-dimensional the closer the source is to equatorial. A telescope near the equator between western Europe and the South African telescope at Hartebeesthoek would help solve this problem.

The effect of including the Simeiz telescope (Crimea) and the Ussurijsk antenna near Vladivostok in eastern Russia is shown in Figure 20.3. The gaps in the $(u, v)$ coverage seen in figure 20.3 are largely filled in for the northern declination sources. Simeiz presently has a Mark III terminal on loan from NASA, and it is hoped that a wide-band recording capability can soon be installed at Ussurijsk.

At 22 GHz, the composition of the EVN changes to include the Metsähovi telescope (and Yebes in 1996), and Westerbork drops out. The $(u, v)$ coverage (fig. 20.5) is comparable to that at the lower frequencies, although gaps appear for lower declination sources. At 43 GHz, the situation is less clear. The performance of the two Chinese telescopes is as yet unknown at this frequency, and the funding for receivers at Jodrell Bank, Cambridge, Noto, and Torun is not yet assured. If these questions are all resolved in the affirmative, figure 20.5 also represents the coverage at 43 GHz.

## 20.5 $(u, v)$ Coverage for the EVN+VLBA

Making full use of the VLBA correlator (and in the future the new EVN correlator, see section20.7) allows us to construct VLBI arrays with superb $(u, v)$ coverage for high-dynamic range imaging observations. As an example, figure 20.6 shows the coverage for the EVN (Jodrell Bank, Cambridge, Westerbork, Effelsberg, Onsala, Bologna, Noto, Torun, Urumqi, Shanghai) and the VLBA at $\nu \leq$ 8.4 GHz. The coverage is very similar at 22 GHz.

## 20.6 EVN Sensitivity

### 20.6.1 Current Performance

In table 20.3, I calculate the sensitivities for the EVN using the expressions given by Craig Walker in chapter 8. Note that the record bitrate at 92 and 49 cm is limited by the amount of spectrum free of interference. The range of zenith SEFDs reflects the inhomogeneous nature of the EVN in terms of collecting area and receiver/feed performance. In general the current performance of the EVN, as measured by the image noise, is a factor of 2 to 3 poorer than the VLBA at the same wavelength. However, the high baseline sensitivity for baselines involving the large diameter telescopes in the EVN is extremely useful in detecting and mapping weak sources, and in phase referencing observations involving weak calibrator sources. The sensitivity values in tables 20.3 and 20.4 assume equal weights for all data points–a more optimum weighting scheme may lead to greater image sensitivity, particularly for relatively simple sources.

### 20.6.2 Expected Performance by 1997

After the upgrade from Mark III to Mark IV and improvements to receiver performance are carried out at EVN telescopes, the sensitivity at each wavelength will increase substantially. Table 20.4 gives the results. Again, the record bitrate

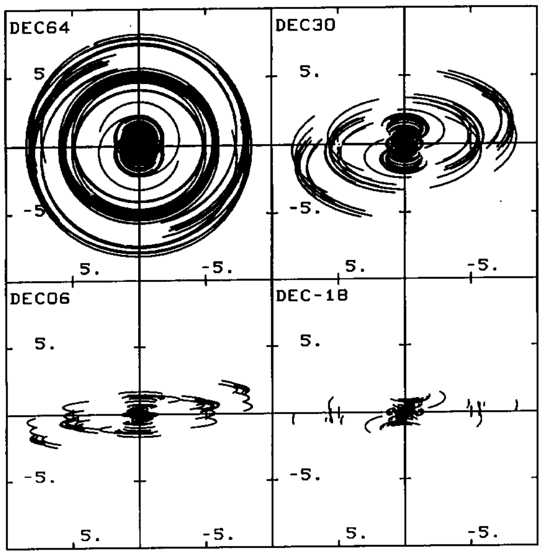


**Figure 20.3:** $(u,v)$ coverage of the EVN at $\nu \leq 8.4$ GHz. Telescopes in the array are Jodrell Bank, Cambridge, Westerbork, Effelsberg, Onsala, Bologna, Noto, Torun, Urumqi, and Shanghai. Units are $10^3$ km.

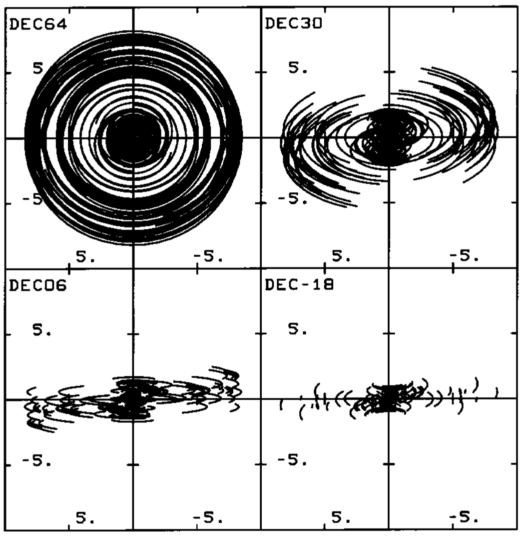


**Figure 20.4:** $(u,v)$ coverage of the EVN at $\nu \leq 8.4$ GHz, including Simeiz and Ussurijsk. See figure 20.3 for the other telescopes in the array. Units are $10^3$ km.

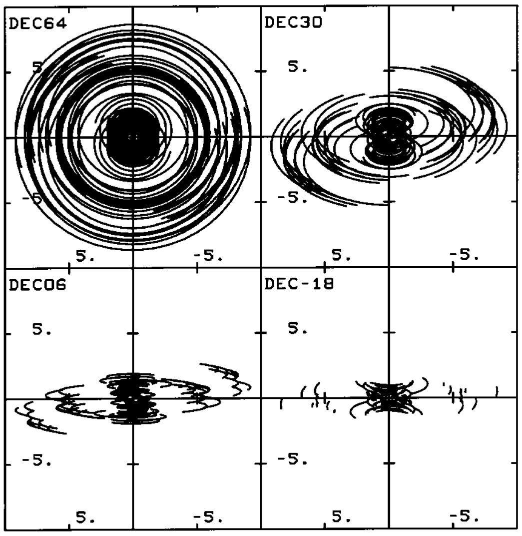


**Figure 20.5:** $(u, v)$ coverage of the EVN at 22 GHz Telescopes in the array are Yebes, Jodrell Bank, Cambridge, Effelsberg, Onsala, Bologna, Noto, Metsähovi, Torun, Urumqi, and Shanghai. Units are $10^3$ km.

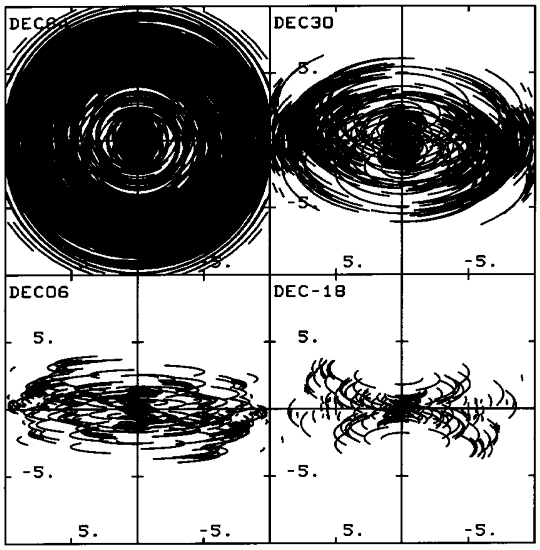


**Figure 20.6:** $(u, v)$ coverage of the EVN+VLBA at $\nu \leq 8.4$ GHz. Units are $10^3$ km.

**Table 20.2:** EVN frequency availability

| | | Observing Bands (GHz) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Telescope | Diameter | 0.3 | 0.6 | 1.4 | 1.6 | 2.3 | 5 | 8.4 | 15 | 22 | 43 |
| Yebes | 14m | | | | | 95 | | 95 | | 96 | + |
| Jodrell Bank | 76m | + | + | + | + | | | | | | |
| | 25m | | | + | + | | + | | | + | p |
| Cambridge | 32m | | | + | + | | + | | | + | p |
| Westerbork | 93m | + | + | + | + | 98 | + | 98 | | | |
| Effelsberg | 100m | | + | + | + | + | + | + | 95 | + | |
| Wettzell | 20m | | | | | + | | + | | | |
| Onsala | 25m | | | + | + | | + | | | | |
| | 20m | | | | | + | | + | | + | + |
| Medicina | 32m | | | + | + | + | + | + | 95 | + | 95 |
| Noto | 32m | + | | | + | + | + | + | | + | p |
| Torun | 15m | + | + | + | + | | + | | | | |
| | 32m | p | p | 95 | 95 | | 95 | | | p | p |
| Metsähovi | 14m | | | | | | | | | + | 96 |
| Simeiz | 22m | + | + | | + | + | + | + | | + | |
| Urumqi | 25m | + | | | + | + | + | + | | 95 | |
| Shanghai | 25m | + | | | + | + | + | + | | 95 | |

**Notes:** * only those EVN telescopes with Mark III or VLBA data acquisition terminals (existing or funded) are included. The EVN Status table distributed via the e-mail exploder gives the availability of acquisition terminals. "+" indicates the receiver is available. "94" indicates that the receiver will be available in 1994. "p" indicates that the receiver is planned but no date is yet available.

differs from wavelength to wavelength depending on expectations of interference-free spectrum space; 2 bit mode is assumed to halve the spectrum space required. The results show that the EVN can in principle achieve better performance than the VLBA; the greater total collecting area in the EVN becoming more effectively used. If the VLBA eventually adopts Mark IV bitrates, the sensitivities of the two arrays will be largely comparable. The remarks on baseline sensitivity and weighting schemes made in reference to table 20.3, apply here as well.

Receiver and feed performance can be further improved. Assuming zenith system temperatures of 100 K for 92, 49 and 1 cm, and 30–40 K for $21 \leq \lambda \leq 4$ cm, and aperture efficiencies of typically 55%, the image noise will range from $\sim 10\mu$Jy per beam at 6 cm to $\sim 55\mu$Jy per beam at 1 cm. Combination of the EVN with the VLBA at 6 cm should lead to an image noise of 8 $\mu$Jy/beam for an 8 h measurement!

## 20.7 EVN Upgrade

A major upgrade of EVN facilities is in progress, made possible by funding from multi-national sources in Europe and from the European Union, and through

**Table 20.3:** Current EVN performance

| Wavelength (cm) | # Tel | Range of zenith SEFD (Jy) | Maximum record bit rate (Mbit/sec) | Range of baseline sensitivity[1] (mJy) | Image sensitivity [2] ($\mu$Jy/beam) |
|---|---|---|---|---|---|
| 92 | 4 | 116–1860 | 20 | 5–56 | 705 |
| 49 | 4 | 70–1600 | 4 | 7–34 | 624 |
| 21 | 7 | 19–900 | 112 | 0.5–14 | 74 |
| 18 | 8 | 19–1685 | 112 | 0.5–25 | 109 |
| 13 | 6 | 250–1942 | 112 | 8–30 | 323 |
| 6 | 8 | 44–992 | 112 | 1–16 | 73 |
| 4 | 6 | 40–2071 | 112 | 2–33 | 267 |
| 1 | 7 | 125–1586 | 112 | 4–27 | 255 |

**Table 20.4:** Expected EVN performance by 1997

| Wavelength (cm) | # Tel | Range of zenith SEFD (Jy) | Maximum record bit rate (Mbit/sec) | Range of baseline sensitivity[1] (mJy) | Image sensitivity[2] ($\mu$Jy/beam) |
|---|---|---|---|---|---|
| 92 | 7 | 93–2000 | 40 | 3–52 | 349 |
| 49 | 7 | 70–1600 | 8 | 4–96 | 651 |
| 21 | 7 | 19–391 | 256 | 0.2–4 | 36 |
| 18 | 10 | 19–698 | 256 | 0.2–8 | 30 |
| 13 | 9 | 44–1526 | 512 | 0.8–12 | 72 |
| 6 | 10 | 29–558 | 1024 | 0.2–3 | 16 |
| 4 | 9 | 40–2071 | 1024 | 0.4–11 | 45 |
| 1 | 11 | 125–1714 | 1024 | 1–9 | 65 |

[1] integration time 2 min [2] integration time 8 min

support from several EVN institutes. The main aspects of the upgrade are the construction of a 16-station data processor in Dwingeloo, upgrade of the EVN Mark III recording terminals to Mark IV capability (which includes VLBA modes), and appointment of EVN Support Scientists for users of the EVN and other arrays. A later phase of the project foresees upgrade of the VLBA terminals in the EVN to Mark IV. Receiver upgrades at the EVN telescopes are also in progress (see section 20.6).

The construction of the EVN data processor (scheduled to begin its operation in 1997) is a collaboration between JIVE, Haystack, and NFRA (Netherlands Foundation for Radio Astronomy). JIVE has taken responsibility for the interface between the playback units and the correlator ("EVN/Mark IV Station Unit") and Haystack is developing a new advanced correlator chip, the associated correlator board and a number of the auxiliary boards for the correlator. The correlator board will be used in the EVN correlator and the Mark IV correlators built by Haystack as well as in the new Westerbork DZB backend and the

Smithsonian Sub-mm Array correlator. For the European correlator, the main centers of activity are at Dwingeloo and Jodrell Bank. Dwingeloo is responsible for the overall correlator design, and the detailed design of the data distributor and a number of the auxiliary boards for the correlator, in addition to the overall project management. Jodrell Bank is responsible for the online software for the correlator and the management of the Station Unit contract.

### 20.7.1 Data Processor

The main elements of the data processor are the 16 playback units; the station units which decode the track-based signal streams coming from the playback units, restoring them into channel-based sample streams as if they had never been recorded; and the correlator system which consists of the correlator proper preceded by a data distributor which allows a flexible assignment of signal streams to correlator segments and also does the recirculation to increase spectral resolution.

### 20.7.2 Correlator

The salient characteristics of the EVN correlator are:

1. X-F type.
2. 16 stations (initial implementation; the architecture allows a maximum of 32 stations).
3. A maximum bitrate/station: 1 Gbit $s^{-1}$for 16 stations.
4. A standard mode of Mark IV operation is likely to be 16-station, dual polarization, 2-bit per sample recording at 128 MHz bandwidth per polarization for a data rate per station of 1 Gbit $s^{-1}$. The initial implementation of the correlator architecture allows 4 Gbit $s^{-1}$operation for 8 stations (if we could record at that rate).
5. Spectral resolution better than 1% in full polarization mode for 16 stations. This means 128 complex channels per baseline for each of the four Stokes parameters. Recirculation of the data through the correlator will allow an increase of the spectral resolution by factors of up to 8.
6. Space VLBI compatibility.
7. Sub-arraying for multiple networks and multiple field centers.
8. Pulsar gates for up to 16 sub-bands.

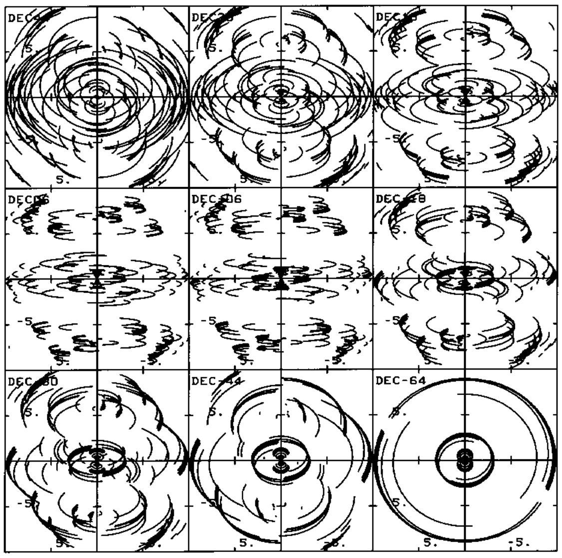

**Figure 20.7:** $(u, v)$ coverage of the APT and western VLBA antennas at 1.66 GHz for sources at declinations of 44, 30, 18, 6, $-6$,$-18$,$-30$, $-44$, and $-64$ degrees. Telescopes in the array are Narrabri, Mopra, Parkes, Tidbinbilla, Hobart, Perth, Hartebeesthoek, Shanghai, Urumqi, Kashima, GMRT, VLBA-MK, VLBA-BR, VLBA-OV, VLBA-KP. Units are $10^3$ km.

### 20.7.3 User and Technical Support

Each EVN observing proposal is assigned one of several *support scientist* who can aid in all aspects of the project, especially scheduling and data analysis; in addition they monitor the calibration of the EVN.

Technical developments at each of the observatories in the EVN are coordinated by the *Technical Working Group (TWG).* As an example of their role, the TWG currently is coordinating the Mark III–Mark IV acquisition system upgrade in the EVN.

## 20.8 The Asia-Pacific Telescope

The APT is an informal VLBI network in the Asia-Pacific region operating on an ad-hoc basis. At its heart is the Australian VLBI network, a six station array in Australia, and the Hartebeesthoek telescope in South Africa, which carries out VLBI observations for 1–2 weeks every 4 months. Table 20.5 lists the receivers available in the APT, and figure 20.7 shows the potential $(u, v)$ coverage of the APT together with the four western VLBA antennas.

A mixture of recording systems is currently available on the APT including Mark II, Mark III, the Canadian S-2, and the Japanese K4. The most widespread is the S-2 system. The Australian correlator is S-2 based and can

**Table 20.5:** Asia-Pacific Telescope frequency availability

| | | Observing Band (GHz) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Telescope | | 1.4 | 1.6 | 2.3 | 5 | 6.7 | 8.4 | 12 | 22 | 43 |
| **Australia** | | | | | | | | | | |
| Narrabri | 22m | + | + | + | + | + | + | + | p | p? |
| Mopra | 22m | + | + | + | + | + | + | + | p | p? |
| Parkes | 64m | + | + | + | + | + | + | + | + | + |
| Tidbinbilla: | | | | | | | | | | |
| DSS43 | 70m | | + | + | | | + | + | + | |
| DSS45 | 34m | | | + | | | + | | | |
| DSS42 | 34m | | | + | | | + | | | |
| Hobart | 26m | + | + | + | + | + | + | + | | |
| Perth | 15m | | | + | | | + | | | |
| **South Africa** | | | | | | | | | | |
| Hartebeesthoek | 26m | | + | + | + | + | + | + | | |
| **Japan** | | | | | | | | | | |
| Kashima | 34m | + | + | + | + | | + | + | + | + |
| Nobeyama | 45m | | | | | | + | | + | + |
| **China** | | | | | | | | | | |
| Shanghai | 25m | p | + | + | + | | + | + | p | |
| Urumqi | 25m | p | + | + | + | | + | + | p | |
| **India** | | | | | | | | | | |
| GMRT | 30 x 45 m | + | +? | | | | | | | |
| **Russia** | | | | | | | | | | |
| Ussurijsk | 70m | | + | p? | p | | + | | p | |

handle 6 stations with a maximum bandwidth of 64 MHz in continuum mode. There are many spectral line modes including 2048 complex channels per baseline for 1 MHz bandwidth.

## 20.9 Final Remarks

The EVN is a powerful part-time array, and even more powerful in combination with the VLBA. A major upgrade of its facilities, both at individual observatories and at JIVE, is underway. Observations with the VLBA in Mark III mode are possible now, and are planned in VLBA mode by early 1996. The EVN correlator is expected to be operational in late 1997.

The APT is a VLBI network providing access to the compact southern sky. The combination of the APT, EVN and VLBA could give round the clock coverage of equatorial sources with rapidly variable structure (e.g., SS 433).

Proposals for observing time on the EVN+VLBA should be addressed to the Scheduler of the EVN (see Call for Proposals) and the Director of the NRAO. Proposals for the APT should be sent to the Director of the Australia Telescope National Facility and to the Directors of the other telescopes.