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An Asian/Pacific VLBI facility

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1. Introduction

The building of an antenna in South-East Asia for use as a VLBI and SETI facility has been proposed. Here I examine the scientific merits of a number of possible sites (listed in Table 1, and shown in Fig. 1) for such an antenna, and evaluate their usefulness for VLBI work. The sites examined here are not restricted to South-East Asia, but include a number of additional sites for comparison.

I will argue in section 3 of this document that, because of the construction of the US VLBA, any Northern Hemisphere VLBI antenna built now would have minimal scientific impact. On the other hand, a VLBI antenna participating in Southern Hemisphere observations could have a dramatic effect on radio astronomy in the next decade. This document is therefore concerned with the performance of VLBI locations for Southern Hemisphere observations.

The number of sites considered precludes a full mapping simulation for each site. Instead, an estimate of the value of each site has been made on the basis of the u-v coverage obtained by including each site in turn.

2. Background

The technique of Very Long Baseline Interferometry (VLBI) offers us the highest resolution views of the Universe currently achievable at any wavelength, and so has been foremost in probing the detailed structure of remote objects such as quasars and active galaxies. For reasons which will become apparent in this report, it has not been so successful at probing the nearest galaxies (the Magellanic clouds) or our own galaxy.

VLBI uses a number of antennas situated typically at distances of hundreds to thousands of kilometres apart. Each antenna observes the same source simultaneously and the data from each antenna are recorded on to magnetic tape. The tapes are then brought to a single central site, where the data are correlated, and, by using fairly powerful image processing algorithms, the array of antennas synthesises the effect of one large antenna covering the area occupied by the array of antennas. Thus a radio telescope with a diameter of thousands of kilometres is synthesised, giving a resolution of milliarcsec -

in other words it would be able to image a radio source the size of a fingernail at a distance of 1000 km.

3. Existing VLBI Arrays

VLBI to date has been dominated by two arrays - the US VLBI Network (USVN) and the European VLBI Network (EVN). Occasionally experiments make use of both these networks simultaneously for the highest resolution and image quality. Each of the arrays is formed from a network of collaborating, but independent, radio observatories who have each made a commitment to allocating some fraction of their observing time to VLBI. The spectacular successes achieved by both these networks, however, have a limitation: since the participating observatories have other worthwhile projects requiring telescope time, each telescope is available for VLBI for only a small fraction of the total operating time.

It was largely in order to overcome this limitation that the Very Long Baseline Array (VLBA) was proposed in the US. The VLBA will be a dedicated array of antennas throughout the United States, running for 100% of the operating time as a VLBI array. It has the further advantage over the USVN and the EVN that the antennas may be located so as to maximise the image quality of the array, whereas both the EVN and the USVN have to make the best of the available antenna locations. Once the VLBA is operational (probably in the mid-1990's) it will dominate VLBI, and other VLBI observations in the Northern Hemisphere will assume only a limited role. This is the basis for the statement in the introduction of this document that a northern VLBI antenna built now would have minimal scientific impact .

There is a further shortcoming, however, of the EVN, the USVN, and the VLBA. All are situated in the Northern Hemisphere (purely because of geographical accident), and cannot observe the Southern Hemisphere of the sky. Unfortunately, in this southern half of the sky lie not only half the quasars, active galaxies, etc., but also most of our galaxy, including its centre, and the nearest galaxies (the Magellanic Clouds). Only a few, restricted, experiments have been performed on the southern celestial hemisphere, and their resulting image quality has been inferior compared to those obtained routinely in the Northern Hemisphere. This is because the current antenna sites are not well-placed for VLBI synthesis.

There are at present only a few radio telescopes capable of observing much of the Southern Hemisphere. This situation will improve to some extent next year, which will see the commissioning of the Australia Telescope (AT). The AT consists of two synthesis arrays. One, the Compact Array (CA), consists of 6 new antennas with baselines up to 6 km, which will produce low resolution but high image quality maps of southern sources. The other, the Long Baseline Array (LBA), consists of the CA operating in a tied mode, together with the existing Parkes 64-m antenna and a new 22-m antenna at

Siding Spring. The LBA will also use, in a collaborative mode, the NASA Deep Space Network's antennas at Tidbinbilla and the University of Tasmania's antenna at Hobart, to give baselines up to 1400 km. The LBA will use Data Acquisition Systems purchased from, and compatible with, the US VLBA, and it will be a VLBI array capable of operating on its own or with other southern VLBI antennas to produce high resolution images, but with limited image quality. Additional antennas in the Southern Hemisphere would increase both the resolution and the image quality, and could have a dramatic impact on our view of the Universe in the next decade.

4. SHIVA: A Southern Hemisphere International VLBI Array

The tests to be described here investigate the effect on two arrays of an additional antenna in various target locations. One array consists of all the existing antennas (listed in Table 2) that might be used in conjunction with an Asian antenna to study a Southern Hemisphere source. These include the whole of the US VLBA, the whole of the Australian LBA, together with other antennas in Australia, South Africa , Japan , and China. The European and Soviet antennas have been excluded as their location adds little to these Southern Hemisphere observations. In practice, especially for sources below declination -40^{o}, this array is dominated by the antennas in Australia and South Africa. Indeed, these are currently the only VLBI antennas that can observe a source at declination -80^{o}.

Because of this, we may envisage an autonomous international VLBI array concentrating on Southern Hemisphere observations. This array is here called SHIVA (Southern Hemisphere International VLBI Array), and its kernel would consist of the proposed Asian/Pacific antenna, the Australian LBA, the South African Hartebeesthoek antenna, and, of course, any other observatories who wished to participate. For observations north of declination -40^{o}, collaboration with the US VLBA or other northern observatories would obviously be desirable. SHIVA would be organised along the same lines as the existing EVN and USVN, with the running of the array being directed by a committee of representatives of participating observatories. Each observatory would allocate a fixed block of observing time in advance to SHIVA operations, and then time within those blocks would be allocated and scheduled by a SHIVA programming committee.

As an alternative, we may envisage a much more restricted operation in which the proposed antenna is used with the Australian LBA. For the purposes of the simulations considered here, this is taken to consist of the antennas available for use with the LBA in 1988 (Culgoora, Siding Spring, Parkes, Tidbinbilla, and Hobart) together with two additional antennas (Alice Springs and Perth) which represent desired extensions to the LBA in the 1990's.

In either case, the array should follow the custom already established by the USVN and EVN: time on the array should be allocated to astronomers from any nation, whether part of the network or not, purely on the basis of scientific merit of the individual proposal.

5. U-V Coverage

The quality of a synthesis image depends not only on the number and separation of the antennas of an array, but also on their location. This is conveniently represented on a u-v diagram, which shows the apparent locations of the antennas as seen from the source. The Earths rotation causes these locations to appear as elliptical tracks in the u-v plane. The u-v plane is in the Fourier transform domain of the image, and so the tracks represent the sampled portions of the synthesised aperture. In general the best images are obtained from uniformly sampled u-v planes, and so a synthesis array should be designed to have as few major gaps in the u-v coverage as possible, since any gap will transform to a spatial frequency to which the array will be insensitive. The u-v coverage should also cover as large an area as possible, in order to achieve the highest resolution. Thus the goal of a designer of a VLBI array is to cover as much of the u-v plane as possible (for high resolution), whilst leaving as few gaps in that coverage as possible (for high image quality). The art of designing a good VLBI array is to balance these two factors.

This is illustrated by Fig. 2, which shows the u-v coverage of the US VLBA. It can be seen that at most northern declinations the elliptical paths of the antennas almost fill the central portion of the diagram. This is because the VLBA antennas have been sited deliberately to achieve this effect. The VLBA can therefore be confident of producing high quality images of northern sources with a high resolution. Fig. 1 also shows the relatively poor performance of the VLBA at southern declinations. Although still usable at -20°, the central portion of the u-v diagram is compressed in a North-South direction, leading to a synthesised beam which is severely distorted. By the crucial declination of -28°, the declination of the galactic centre, this distortion is even more significant. By declination -40°, many of the VLBA antennas cannot see the source at all and so the u-v coverage is very poor. The VLBA will therefore be unable to make worthwhile synthesis images at -40°. A few degrees south of this declination, none of the VLBA antennas can see the source at all.

6. The Tests

The target sites are listed in Table 1, and shown in Fig. 1. Four Asian sites (Sri Lanka, Malaysia, Burma, and Thailand) were selected as well as three Pacific sites (Philippines, Fiji, and Papua New Guinea), and an African site (Madagascar).

Each site was examined for its effect on (a) SHIVA, and (b) the seven-station LBA (Culgoora, Siding Spring, Parkes, Tidbinbilla, Hobart, Perth, and Alice Springs) at five negative declinations (-80°, -60°, -40°, -28°, and -20°), chosen to represent 20° steps through the Southern Hemisphere, together with the important Galactic Centre declination of -28°. Positive declinations were not tested as the northern sky is adequately observed by northern VLBI arrays.

7. Results with SHIVA

Figure 3 shows the u-v coverage which results from adding an antenna at each of the target sites to SHIVA. The left-hand column shows the coverage from existing and planned antennas, and each column to the right shows the effect of a particular additional antenna. Each row represents one of the five declinations of interest.

Looking first at the top two rows of the left hand column (no extra antennas), it can be seen that the existing antennas leave gaps in the u-v coverage above and below the central region, and to the top right and bottom left. Comparing this with the other columns, it can be seen that Madagascar adds almost nothing, Fiji and Papua New Guinea fill in the spaces near the centre, and all the Asian sites, particularly Malaysia, fill in the spaces further out. The Philippines site is nearly as good as the Asian sites. Thus we may conclude that our capability, using all possible antennas, to observe these declinations, including the galactic centre, would be significantly enhanced by the addition of antennas either close to Malaysia, or in the Fiji/Papua New Guinea region, or in both regions.

Looking now at the lower rows, we can see that Malaysia, Thailand, and Sri Lanka continue to enhance the u-v coverage as far south as -60°, but add nothing at -80°. Of these three, Sri Lanka gives the best u-v coverage at southern declinations. Only Fiji gives a comparable improvement, and also has the added advantage of giving considerably better coverage at -80°.

8. Results with the Australian LBA

Figure 4 shows the u-v coverage which results from adding an antenna at each of the target sites to the LBA. The left-hand column shows the coverage from existing antennas, and each column to the right shows the effect of a particular additional antenna. Each row represents one of the five declinations of interest.

Looking first at the left hand column, it can be seen that the existing antennas have good u-v coverage in the central region, except for the extreme southern declinations at which an annular region is unfilled. Thus the function of additional Asian/Pacific antennas in this case would be to increase the resolution, rather than the image quality.

The remaining columns shows that any of the additional sites would increase the resolution. However, Madagascar, while giving the highest resolution, leaves large gaps in the u-v plane which would degrade the image considerably.

Both the Asian sites and the Pacific sites give a valuable enhancement to the u-v coverage, but the Pacific sites leave fewer gaps in the u-v coverage than the Asian sites, whilst the Asian sites give a higher resolution. Of the Pacific sites, Papua New Guinea gives better u-v coverage near the centre, while Fiji gives higher resolution. Both Papua New Guinea and Fiji are superior to the Philippines. The annular gaps in Fiji's coverage could be filled in by additional Australian mainland sites.

Of the Asian locations, Burma gives the poorest coverage, largely because of its high latitude. Sri Lanka, Thailand, and Malaysia give comparable image qualities, with Malaysia giving marginally better coverage than the other two.

Thus we may conclude that the capability of the LBA to observe southern declinations, including the galactic centre, would be significantly enhanced by the addition of antennas in any of the Asian sites, or a site in the Fiji/Papua New Guinea region, or both.

9. Construction

Here I consider construction of the VLBI equipment only as a factor which might affect the location. and do not consider SETI equipment, buildings and physical plant, or manpower. The choice of equipment should depend not only on the obvious factors of cost and availability, but also, to avoid the necessity of 're-inventing the wheel', on the extent to which any particular piece of equipment is already in use at VLBI observatories, and is in current production. Thus equipment such as the antenna, receivers, and local oscillators would ideally be chosen from those currently being built for the US, Japanese or Australian observatories. The Data Acquisition System would necessarily be identical to that developed for the VLBA. This system, which is also being used for the Australian LBA, is likely to become the 'industry standard', and render the older types (e.g. MkII and MkIII) obsolete.

Thus the choice of equipment to be used for construction is effectively pre-determined. Any of this equipment would be suitable for use in any of the countries considered, with the proviso that much of the state-of-art electronics (e.g. the recorders used for Data Acquisition) has been developed in the US, and so must be authorised for export by the US Department of

Defense. This authorisation will obviously depend on political factors which are outside the scope of this document.

10. Operation

The operation of a VLBI facility can be broken down into a number of steps.

10.1) Allocation

Observing proposals must be solicited from the astronomical community, and then awarded ratings for scientific merit by a panel of referees, also drawn from the community. This requires a host organisation with the necessary experience, infrastructure, and communications with the rest of the astronomical community. Either the US VLBA or the Australian AT would be suitable host organisations.

10.2) Scheduling

The successful proposals must be merged into a single sequence of observations, and sent to each participating antenna. This is most conveniently done by sending a machine-readable schedule, either via electronic transmission or by floppy disk, which can drive the computer controlling the antenna and data acquisition system. The scheduling must therefore be done from somewhere with good international communications.

10.3) Observing

Observing can be conducted by local engineering and technical staff. The issue of what additional infrastructure (e.g. a college, University, or research establishment) is needed at the observing site is obviously a complicated one, and outside the domain of this brief document. However, it should be noted that a major part of the logistics of running the antenna will involve the regular international shipment of massive consignments of magnetic tape, and so good international communications must be readily available.

10.4) Correlating

Only one correlator is needed for the entire array, and VLBI correlators of suitable capability are those of the US VLBA and the Australian LBA. Either of these could be upgraded at a small incremental cost to process data from additional stations. Given the geographic proximity, the Australian correlator would seem to be most appropriate.

11. Conclusion

Construction of a dedicated VLBI/SETI antenna in the Asian/Pacific region would considerably enhance the global capability to observe the southern half of the sky, including the galactic centre, and could have a major impact on radio astronomy in the next decade. To maximise this impact, the antenna should be located either in the region of Thailand, Malaysia, and Sri Lanka, or else in the Papua New Guinea/Fiji region of the South Pacific.

From the point of view of VLBI performance alone, the best location of all is in Fiji. If, however, it is necessary to locate the antenna in Asia, then either Sri Lanka or Malaysia give the best performance, with Thailand running a close third.

Any one of these sites will substantially increase our capability to observe the southern half of the sky. To make most effective use of such a facility, it should be placed in the kernel of a network of southern observatories (here called SHIVA) which would assume responsibility for scheduling and coordinating observations. Time on SHIVA should be available to astronomers from any part of the world, and should be allocated on the basis of scientific merit of submitted proposals, in the spirit of international cooperation already established by VLBI.

The correlation of data from SHIVA should be done on an existing VLBI correlator. The correlator of the Australia Telescope appears well-suited, both because of its technical compatibility (the AT is using standard VLBA data systems) and because of its location.

All of the countries considered above have international airports with regular flights by leading airlines, so that transport of tapes should not be a problem. Electronic communication is likely to be less reliable in some cases, so that it may be preferable to schedule in advance using floppy disks.

In summary, the construction of a VLBI facility in the Asia/Pacific region appears both feasible and timely, and would make a major impact on the capability of the astronomical community.

TABLE 1: TARGET LOCATIONS

Country	Capital	Latitude °	Latitude '	Longitude °	Longitude '	Population (Million)
Sri Lanka	Colombo	6	56	79	58	13.9
Burma	Mandalay	22	00	96	10	32.2
Thailand	Bangkok	13	45	100	35	45.1
Malaysia	Kuala Lumpur	3	9	101	41	12.6
Madagascar	Antananarive	-20	0	47	0	8.5
Philippines	Manila	14	0	120	0	46.0
Papua New Guinea	Port Moresby	-9	30	146	30	3.0
Fiji	Suva	-18	12	178	30	0.6

TABLE 2: EXISTING AND PLANNED VLBI ANTENNAS

Location	Country
Pie Town, NM	USA
Kitt Peak, AZ	USA
Los Alamos, NM	USA
N. Liberty, IA	USA
Fort Davis, TX	USA
Brewster, WA	USA
St. Croix, VI	Virgin Islands
Owens Valley, CA	USA
Mauna Loa, HI	Hawaii
New England	USA
Culgoora	Australia
Siding Spring	Australia
Parkes	Australia
Tidbinbilla	Australia
Hobart	Australia
Alice Springs	Australia
Perth	Australia
Nobeyama	Japan
Shanghai	China
Hartebeesthoek	S. Africa

Note: Included here are all the antennas of the US VLBA and the AT LBA. Excluded are the non-VLBA stations in the USA, and European and Soviet stations. Inclusion of any of these would not affect the results presented here.

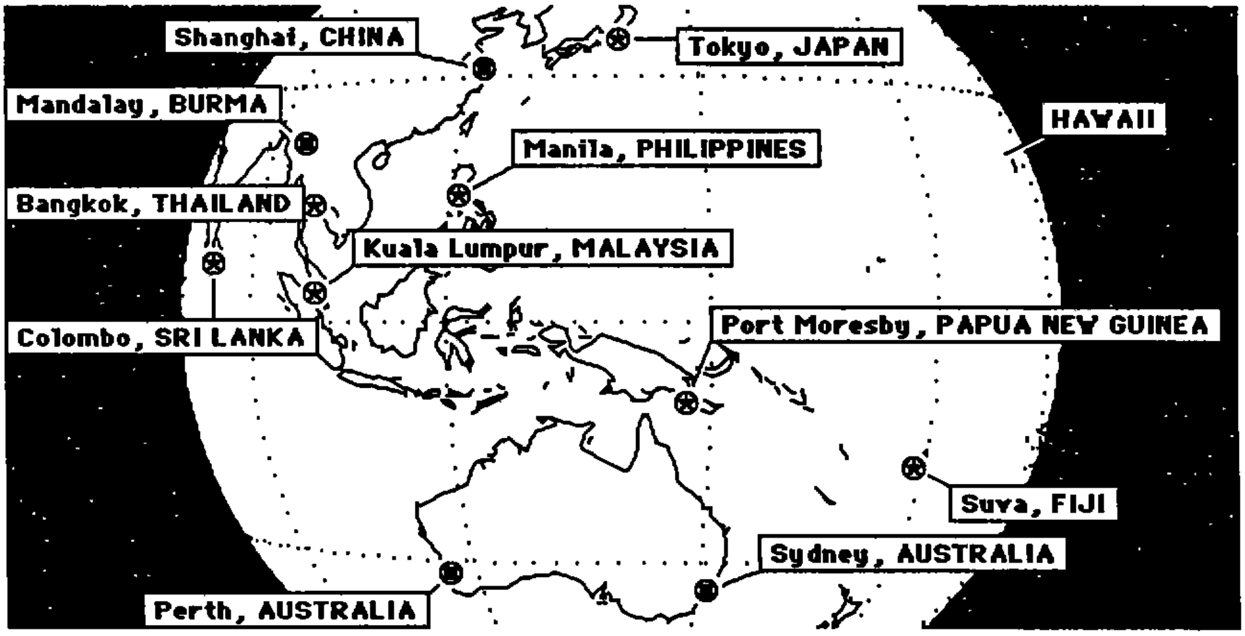

FIGURE 1: ANTENNA LOCATIONS

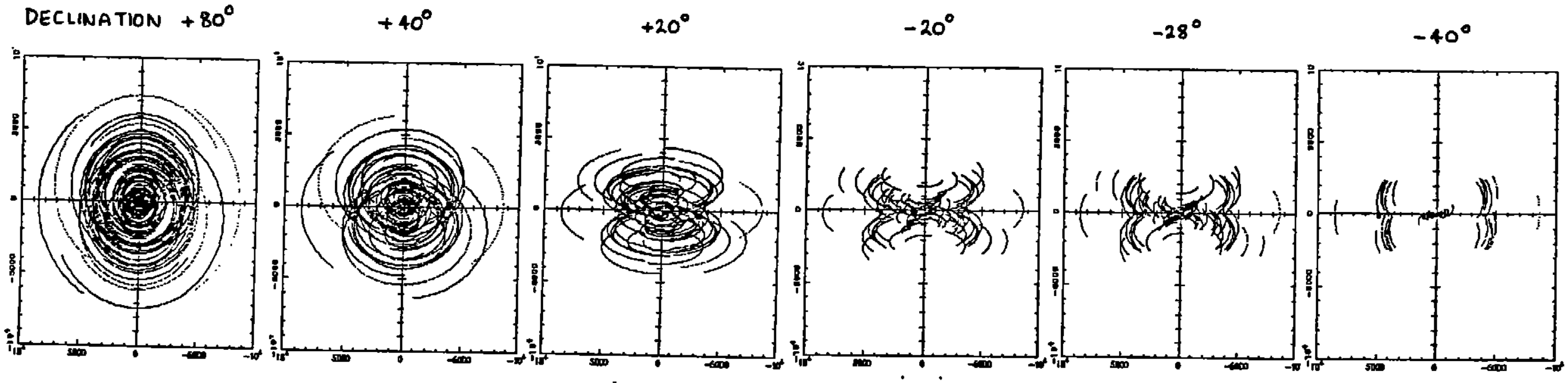

FIGURE 2: U-V COVERAGE OF THE U.S. VLBA

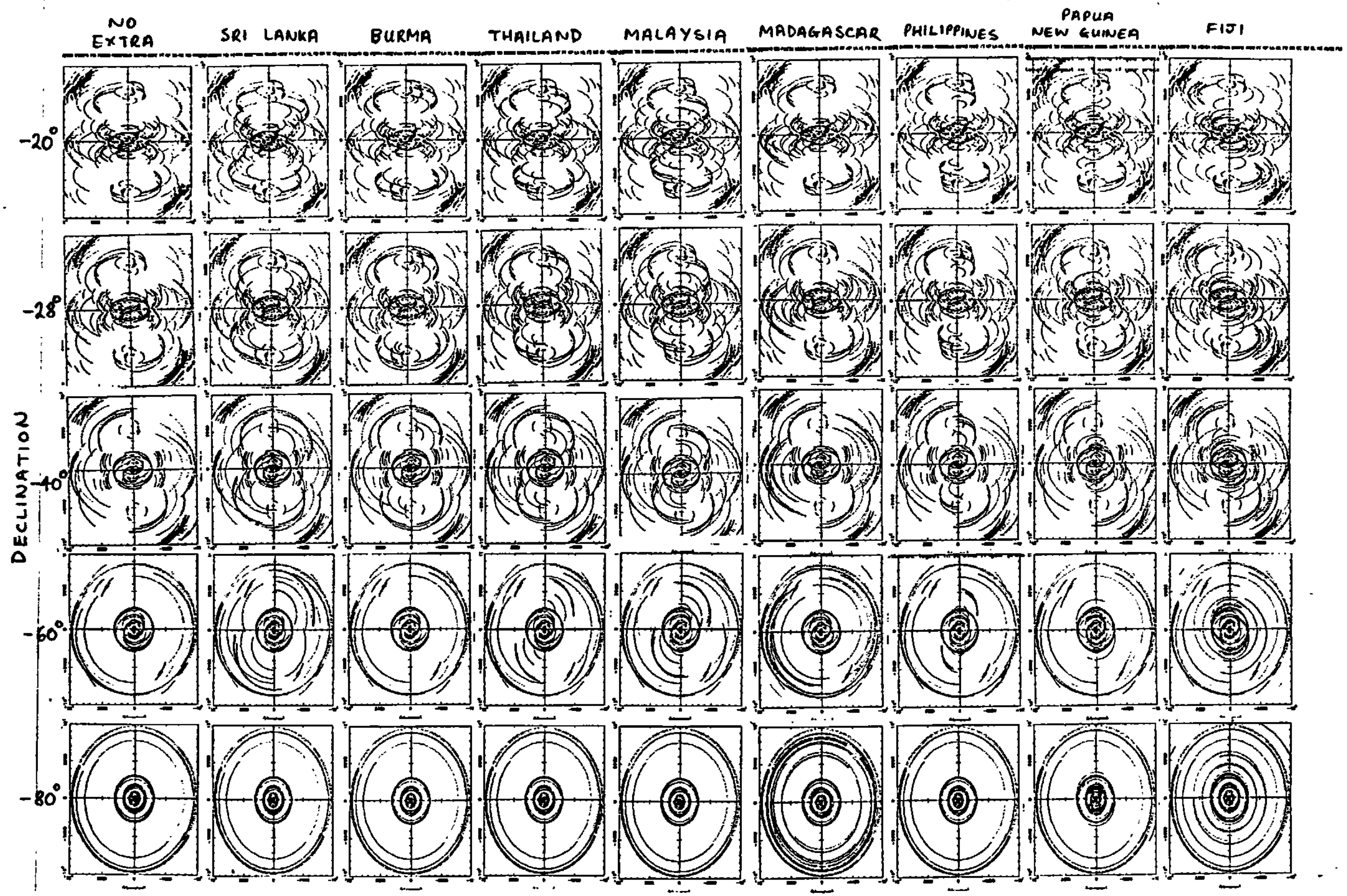

FIGURE 3: THE EFFECT OF ADDING A STATION TO SHIVA

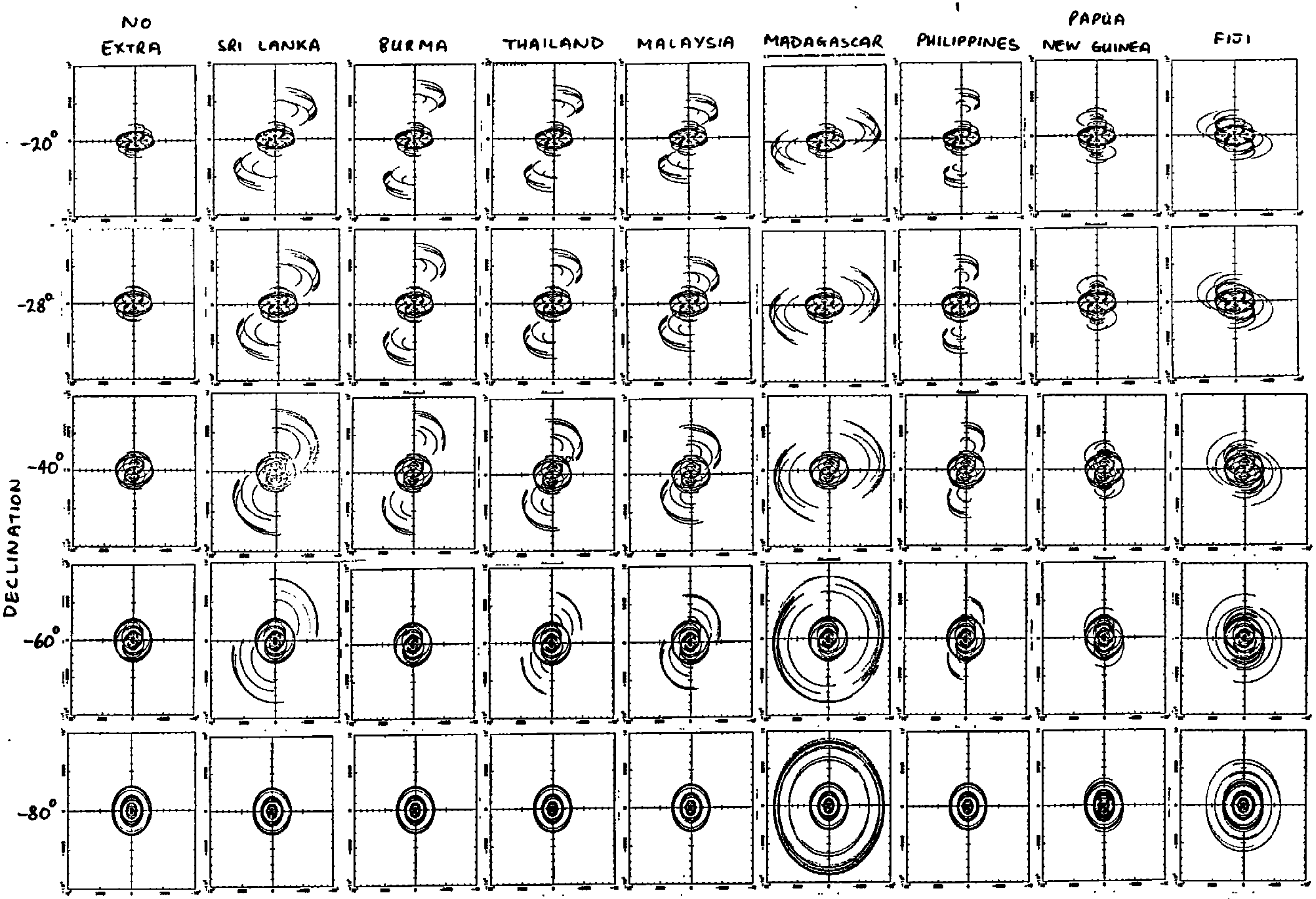

FIGURE 4: THE EFFECT OF ADDING A STATION TO THE AUSTRALIAN ARRAY