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GOVIND SWARUP, POTTS HILL AND THE KALYAN ARRAY: INDIA'S FIRST RADIO TELESCOPE

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Abstract: India's first radio telescope was the Kalyan Array, a T-configuration solar grating array erected near Bombay (Mumbai) in 1965. This was then used until 1968 to monitor solar radio emission at 612 MHz. The antennas from this radio telescope originally formed the E–W solar grating interferometer invented by the Australian radio astronomer W.N. (Chris) Christiansen, and were sited at Potts Hill in Sydney, a field station maintained by the CSIRO's Division of Radiophysics. In early 1953 Govind Swarup (along with R. Parthasarathy) went to Sydney on a 2-year Colombo Plan Fellowship, and was involved in reducing observations made by this array and a companion N–S grating array. Then, in 1954, Govind and Parthasarathy altered the array so that it could operate at 500 MHz, and they used it to examine the extent of limb-brightening at this frequency. When both arrays became surplus to requirements in March 1955 Govind convinced the Division of Radiophysics to donate the E–W array antennas to the Physical Research Laboratory in New Delhi. This eventually occurred, and after some delay and the transfer of the antennas to the Tata Institute of Fundamental Research in Bombay they were erected nearby at Kalyan.

In this paper I review Govind Swarup's Sydney 'apprenticeship' and his substantial involvement with the Potts Hill E–W solar grating array; his subsequent return to India and intervals he then spent in the USA at Fort Davis (Harvard University) and Stanford University (where he completed a solar radio astronomy PhD); his return to India to found the Tata Institute's radio astronomy group; erection of the solar grating array at Kalyan, and the solar research that was carried out with it; and—finally—how the Kalyan Array was always perceived as a training facility and forerunner to the much more ambitious Ooty Radio Telescope.

Keywords: Govind Swarup, Potts Hill, W.N Christiansen, solar grating arrays, Kalyan Array, coronal emission, radio plages, Ooty Radio Telescope

1 INTRODUCTION

In the years immediately following the Second World War (henceforth WWII) Australia and England, in particular, forged ahead in the emerging field of radio astronomy, where new discoveries became a common occurrence (Sullivan, 2009). By 1954 Australia's reputation was such that the Tenth General Assembly of the International Union of Radio Science (URSI) was held in Sydney (Robinson, 2002), and was hosted by the CSIRO's Division of Radiophysics (henceforth RP), which maintained a number of field stations in the suburban Sydney area, and to the south near the city of Wollongong (Orchiston and Slee, 2017).

One of those who attended the Congress was Sir Kariamanickam Srinivasan Krishnan (1898–1961), the inaugural Director of the National Physical Laboratory (NPL) in New Delhi. During the Congress, he and other delegates learnt about the ground-breaking research being conducted at the radio astronomy field stations with a variety of locally built, often innovative, radio telescopes, by a group of young men with backgrounds mainly in radar and radio engineering rather than astronomy (Sullivan, 2017). Yet they were making waves internationally, in solar, galactic and extragalactic radio astronomy (Orchiston et al., 2021). Delegates also had an opportunity to visit the field stations at Dapto (Stewart et al., 2011a), Hornsby Valley (Orchiston et al., 2015) and Potts Hill (Wendt et al., 2011) and see some of the instrumentation that was discussed in the Congress papers.

Krishnan returned to India mightily impressed by "… the dramatic and remarkable discoveries being made …" (Swarup, 2017: 816), and he determined to establish radio astronomy at the NPL. But there was no one in India trained in radio astronomy, so his solution was to arrange Colombo Plan Fellowships for two young graduates, R. Parthasarathy and Govind Swarup, who would spend two years at RP in Sydney learning radio astronomy from experts. Parthasarathy was from Kodaikanal Observatory, where the Director, A.K. Das (1902–1961), specialized in optical solar astronomy (Bappu, 1961), but wished to expand the wavelength coverage to include radio (Swarup, 2006: 23). Meanwhile,

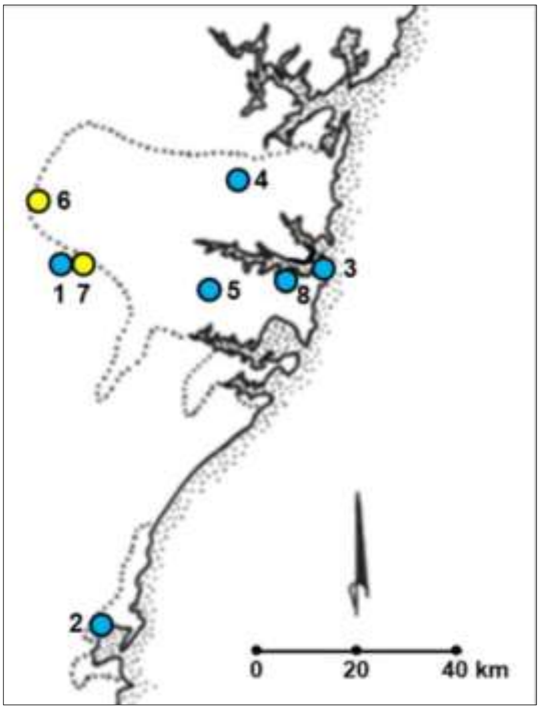


Figure 1: The location of RP's Radiophysics Laboratory (8) and the field stations that existed in 1953 are shown in blue, along with the approximate boundaries of present-day greater Sydney and greater Wollongong (shown by the dotted lines). Key: 1 = Badgerys Creek, 2 = Dapto, 3 = Dover Heights, 4 = Hornsby Valley, 5 = Potts Hill. An earlier field station, Penrith (6), and a later field station, Fleurs (7), are also mentioned in the text and therefore are included here, as yellow circles (map: Wayne Orchiston).

Krishnan's protégé, Govind Swarup, was at the NPL.

Thus it was that in March 1953 Parthasarathy and Swarup arrived in Sydney to start what were effectively their radio astronomy 'apprenticeships', but little could they have imagined at the time that this experience would have a totally unexpected and profound impact on the launch of radio astronomy in India. In this paper I will focus on Govind Swarup's experiences at the RP field stations in and near Sydney, and how the subsequent transfer of an unwanted solar grating array to the NPL would lead to the founding of the Radio Astronomy group at the Tata Institute of Fundamental Research in Bombay[1] and the appearance of the Kalyan Array, India's first radio telescope. I will conclude this paper by reviewing the solar research that was carried out with the Kalyan Array, and how it preceded the design and construction of the Tata Institute's next radio telescope, the innovative Ooty Radio Telescope.

2 W.N. CHRISTIANSEN AND THE POTTS HILL GRATING ARRAYS

2.1 The Sydney 'Apprenticeship'

When Parthasarathy and Swarup arrived in Sydney RP had five operational radio astronomy field stations (see Figure 1), and Table 1 lists the main research programs at these and the associated team leaders. Dover Heights (number 3 in Figure 1) was a former WWII radar station, but all the other field stations were purpose-built for radio astronomy at suitable radio-quiet locations. For overviews of all of these field stations see Orchiston and Slee (2017) and Orchiston et al. (2021).

Head of RP's Radio Astronomy Group was the inspirational Joseph Lade (Joe) Pawsey (1908–1962), an Australian born and educated radio engineer with a Cambridge doctorate (see Goss et al., 2022; Lovell, 1964). Govind Swarup recounts that when Pawsey discovered his interests lay more in experimental rather than theoretical radio astronomy he suggested

> … that I work for three months each in the groups led by W.N. Christiansen, J.P. Wild, B.Y. Mills and J.G. Bolton … [All four] had made important discoveries, and were already acknowledged world leaders in their respective fields. I was to report back to Pawsey every two weeks. S.F. Smerd, a very pleasant man but a tough task master, was asked to co-ordinate my activities and to provide me with guidance on the rapidly-growing literature in radio astronomy. For his part, Parthasarathy was to develop a 10.7 cm solar radio telescope … Then, after the

Table 1: The RP field stations, research programs and team leaders in February 1953 (developed from Orchiston and Phakatkar, 2019: 9).

Field Station	Founding Year	Research Programs	Team Leader	Reference(s)
Badgerys Creek	1949	Discrete sources	Mills	Frater et al. (2013; 2017); Orchiston and Slee (2017)
Dapto	1952	Solar	Wild	Frater and Ekers (2012); Frater et al., (2017); Stewart et al. (2011a; 2011b)
Dover Heights	1945	Discrete sources	Bolton	Orchiston and Robertson (2017); Orchiston and Slee (2002; 2017); Robertson (2017); Robertson et al. (2014)
Hornsby Valley	1947	Discrete sources	Shain	Orchiston et al. (2015); Pawsey (1960)
Potts Hill	1948	Discrete sources	Piddington	Frater and Goss (2011); Frater et al. (2013; 2017); Melrose and Minnett (1998); Orchiston and Wendt (2017); Wendt et al. (2011a; 2011b); Westerhout (2000)
		Hydrogen line	Kerr	
		Solar	Christiansen	
		Prototype Mills Cross	Mills	

first year, Parthasarathy and I would select a joint project. What a great opportunity for initiation into the new field of radio astronomy! (Swarup, 2006: 23).

2.2 Chris Christiansen, Potts Hill and the Solar Grating Arrays

Parthasarathy and Swarup (Figure 2) began by spending three months reading radio astronomical literature, and then Govind was sent to Potts Hill field station, where he would work with Chris Christiansen and Joe Warburton. Established in 1948, this field station (Figure 3) was located beside a metropolitan water reservoir in what at the time was an outer southwestern Sydney suburb (location 5 in Figure 1). This radio-quiet setting allowed solar and non-solar radio astronomy, and Potts Hill soon developed into one of RP's forefront field stations (Orchiston and Slee, 2019; Wendt, 2011b).

Conspicuous in Figure 3 are two orthogonal arrays of parabolic dishes, along the southern and eastern margins of the nearer

Figure 2: Govind Swarup (left) and R. Parthasarathy (right) at Potts Hill field station in 1954. At this time, the 16 × 18 ft ex-WWII radar antenna in the background was being used to survey galactic 21-cm hydrogen emission (after *Illustrated Weekly Times of India*, 14 September 1954).

Figure 3: An aerial view of Potts Hill reservoirs looking southwest, showing the solar grating arrays along the southern and eastern margins of the foreground reservoir. Flat land immediately to the north of this reservoir housed the remaining radio telescopes erected by RP at Potts Hill and used for solar and non-solar observations (courtesy: CSIRO Radio Astronomy Image Archive (henceforth RAIA): 3475-1).

Figure 4: Chris Christiansen (adapted from RAIA: B2842-66).

water reservoir.[2] These were grating arrays, designed by Wilbur Norman (Chris) Christiansen (1913–2007; Figure 4) to observe solar radio emission at 1420 MHz (Wendt et al., 2008b). Figure 5 shows a close-up of the earlier of the two arrays, which eventually would end up in India.

In both 1948 and 1949 Christiansen was among the RP scientists who observed partial solar eclipses from different sites in Australia and used triangulation to successfully pinpoint the locations of those localised regions in the solar corona responsible for the radio emission (Orchiston et al., 2006; Wendt et al., 2008a). After the latter eclipse Christiansen pondered the possibility of determining the positions of these so-called 'radio plages' without resorting to eclipses, and in early 1950 he came up with the idea of the solar grating array.[3] The E–W Potts Hill array was constructed in 1951 (Christiansen, 1953; Christiansen and Warburton, 1953a), and

> … provided a series of 3′ fan beams each separated by 1.7°, which meant that the Sun could only be in one beam at any one time. The array was operational from February 1952, and was used daily for ~2 h, centred on midday, to produce E–W scans of the Sun. These showed up the positions of localized active regions situated low in the solar corona and the motion of these as the Sun rotated … (Orchiston and Slee, 2017: 524–525).

An example of successive strip scans obtained between 26 and 30 June 1952 is shown in Figure 6, where one major radio plage is present and varies significantly in intensity in the course of the five days.

Figure 5: A close-up view, looking east, showing the E–W grating array and Chris Christiansen. The array comprised 32 solid metal parabolic dishes each 1.83 m (72 inches) in diameter and spaced at 7 m intervals (courtesy: RAIA: B2976-1).

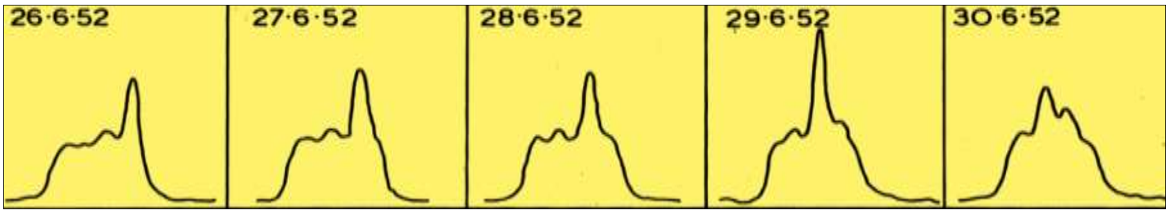


Figure 6: A series of 1420 MHz strip scans of the Sun over a 5-day period in June 1952, showing the development and motion of a prominent radio plage (adapted from RAIA B2849-1).

Then, by superimposing a succession of strip scans and ignoring all of the radio plages, Christiansen and Warburton (1953b) found they could easily determine the level of Quiet Sun emission at 1420 MHz during any given time interval (e.g. see Figure 7).

When Govind first visited Potts Hill field station he saw a second grating array under construction along the eastern margin of the reservoir. This was soon completed, and comprised just 16 equatorially mounted 3.5-m (11-ft) mesh dishes, which produced N–S scans of the Sun. It was then up to Govind to help Christiansen and Warburton create

> … a two dimensional map of the quiet Sun at a wavelength of 21cm, using strip scans obtained with the east-west *and* north-south grating interferometers … (Swarup, 2006: 23; our italics).

Swarup (2008: 195) explained how this was done:

> Using an electrical calculator, I first determined the Fourier Transform (FT) of each of the strip scans obtained at various position angles, plotted the values on a large piece of graph paper, made contour plots manually, determined manually strip scans of the two-dimensional plot at various position angles, calculated the FT of each of these and finally determined the two-dimensional distribution of 21 cm radio emission across the solar disk. Ron Bracewell described short cuts to me for faster calculation of the FTs. Nevertheless, it was a very laborious process, but thanks to Chris' gentle guidance it ultimately led to success!

The outcome of this endeavor is illustrated in Figure 8, and indicated that at 1420 MHz the Quiet Sun was elliptical and exhibited conspicuous near-equatorial limb-brightening (Christiansen and Warburton, 1955), as had been predicted earlier by RP resident solar theoretician Steve Smerd (1950).

There are two important points to note about Figure 8:

(1) As Christiansen (1989) was later to remind colleagues, creation of this figure represented the world's first application of Earth-

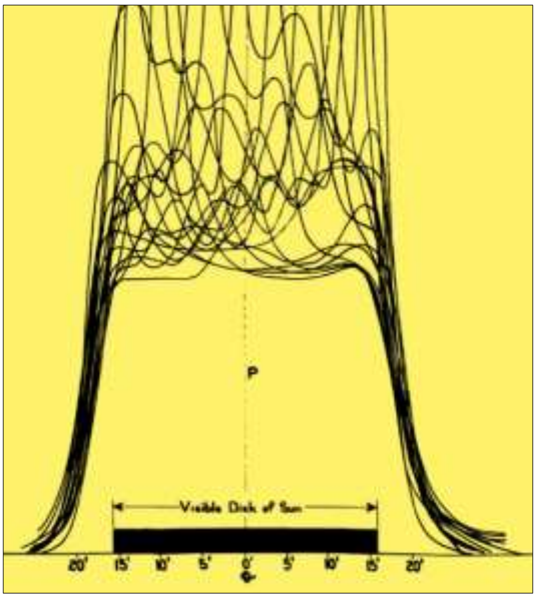


Figure 7: A plot showing twenty individual daily E–W strip scans. The visible solar disk is indicated by the black bar on the x-axis (after Christiansen and Warburton, 1953a: 200).

rotation synthesis in radio astronomy (although this is not widely acknowledged, even today); and

(2) Although Govind played a substantial part in reducing the observations and generating the data used to create Figure 8, at Warbur-

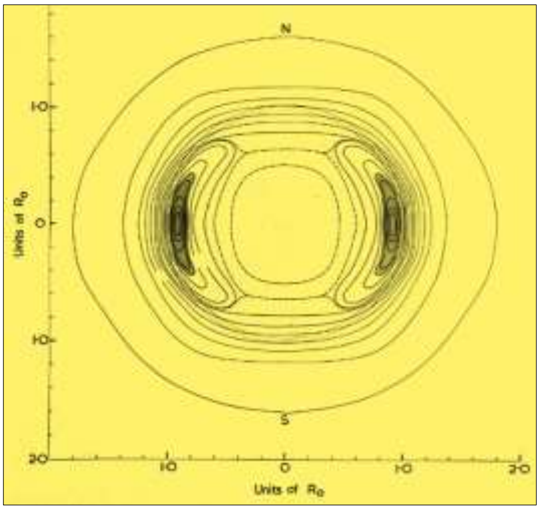


Figure 8: The resulting isophote map of the Quiet Sun at 1420 MHz, showing conspicuous limb-brightening (courtesy: RAIA B3400-3).

Figure 9: Paul Wild, in 1952 (adapted from RAIA B2842-45).

ton's insistence he was not offered co-authorship of the associated paper (G. Swarup, pers. comm., 2008). Instead he was merely mentioned in the Acknowledgements.

2.3 Paul Wild, Dapto and the Solar Radio Spectrographs

After Potts Hill, Govind was assigned to Paul Wild (1923–2008; Figure 9; Stewart et al., 2011b), RP's other major international solar authority. But, unlike Christiansen, Wild was fascinated by burst emission from the Sun, best seen at frequencies below 250 MHz. However, single-frequency observations revealed little about the spectral features of this emission, which in 1948 inspired Wild and his RP colleague Lindsay McCready (1910–1976) to build the world's first dynamic solar spectrograph, which used a simple rhombic antenna. This was installed at a new PR field station at Penrith, 50 km west of Sydney (location 6 in Figure 1; for details see Stewart et al., 2010), and showed "… the ways in which burst intensity changed with frequency and with time …" over the frequency range of 70–130 MHz (Orchiston and Slee, 2017: 540). The results were outstanding, and after analyzing observations made during the first five months alone Wild and McCready (1950) were able to identify three very different spectral types of solar bursts. They named these Types I, II and III. This nomenclature was quickly adopted internationally, and is still in use today (along with Types IV and V, U bursts, J bursts and 'drifting pairs').

In order to expand the wavelength range, a new field station was set up at Dapto, an ideal radio-quiet site near the City of Wollongong 80 km to the south of Sydney (site 2 in Figure 2; Stewart et al., 2011a), and three different crossed-rhombic antennas that recorded emission at 40–75, 75–140 and 140–240 MHz were operational by August 1952 (Figure 10).

Apart from solar research, during sunspot minimum the 40–70 MHz radio spectrograph

Figure 10: The three original antennas and the receiver building at the Dapto field station. Crossed-rhombic antennas were used so that the polarization of the bursts could be researched (courtesy: RAIA 12429-1).

was used from September 1952 to investigate the conspicuous intensity fluctuations of the Cygnus A discrete source caused by ionospheric and interplanetary scintillations (Wild, 1953). Govind's Dapto project

> … was to work with J.A. (Jim) Roberts (b. 1929) and develop a 45 MHz receiver once it was established that this would be preferable to observing over the full 40–70 MHz frequency range (Stewart et al., 2011a).[2]

Nowhere does Govind indicate whether he was actually based at Dapto for this project, or was located at the Radiophysics Laboratory (RPL) in Sydney (i.e. site 8 in Figure 1). I assume he was in Sydney, where most of the Dapto instrumentation was developed and tested. The Dapto field station had facilities to host astronomers for only short stays (of a few days), not for months at a time. Nevertheless, regardless of whether he was based at Dapto or at the RPL, Govind would have been exposed to solar radio spectrographs for the first time, and immersed in what was predominantly a solar research environment. That said, note that this particular assignment was about ionospheric research and had nothing to do with solar bursts—but it did give him an opportunity to design and construct a receiver, experience that would later prove to be most useful.

2.4 Bernie Mills, Potts Hill and the Mills Cross Prototype

After the Dapto project Govind returned to Potts Hill to work with Bernie Mills and Alex Little, who were building an innovative cross-type radio telescope (Mills and Little, 1953). Bernard Yarnton (Bernie) Mills (1920–2011; Figure 11; Mills, 2006) was another one of RP's internationally-recognized radio astronomers, best known for inventing the cross-type radio telescope (see Mills, 1963), which provided a solution for the resolution problem that plagued early radio astronomy. In 1952 and 1953 he and Little were busy constructing a prototype at Potts Hill, as Mills (1976) felt he "… had to convince people it would work, and there were also a number of basic problems I wasn't quite clear about myself which I wanted to experiment with …"

The resulting radio telescope comprised

> … N–S and E–W arms, each 36.6 m (120 ft) in length and containing 24 half-wavelength E–W aligned dipoles backed by a wire mesh reflecting screen (Mills and Little 1953). This novel instrument operated at 97 MHz, and had an 8° pencil beam which could be swung in declination by changing the phases of the dipoles in the N–S arm. The success of the 'Potts Hill mini-cross' was to justify the founding of a new RP field station, at Fleurs in 1954 [where the full-scale 85.5 MHz 'Mills Cross' was constructed]. (Orchiston and Slee, 2017: 534).

The Potts Hill prototype Mills Cross is shown in Figure 12. Govind's project, on this occasion, was to help Mills and Little develop a phase-shifter, "… experience that would prove to be extremely useful later back in India." (Orchiston and Phakatkar, 2019: 17).

2.5 John Bolton, Dover Heights and Cliff-Interferometers

Govind's fourth and final project for 1953 was to work with John Bolton's team from Dover Heights field station (site 3 in Figure 1). British-born and Cambridge-educated John Gatenby Bolton (1922–1993; Figure 13; Robertson, 2017), along with the New Zealander

Figure 11: Bernie Mills in 1956 (adapted from a RAIA image).

Gordon Stanley (1921–2001; Kellermann et al., 2005) and Australian-born Bruce Slee (1924–2016; Orchiston, 2004a), were well known for having solved the riddle of the enigmatic 'radio stars'. Following cliff-interferometer observations made at Dover Heights field station in 1947 and 1948 and from two New Zealand sites in 1948 they were able to demonstrate that the discrete source Taurus A was associated with the Crab Nebula (the remnant of a galactic supernova observed in CE 1054), and Centaurus A and Virgo A with faint distant unusual extra-galactic nebulae (Bolton et al., 1949).

Following this pioneering research, Bolton, Stanley and Slee built a succession of cliff-interferometers with which they detected more than 120 different discrete sources at frequencies of 100 or 200 MHz (e.g. see Orchiston and Robertson, 2017; Robertson et al., 2014).

Govind's task was to help make a highly stable D.C. power supply—yet another talent

Figure 12: A view at Potts Hill looking west. In the foreground is part of the prototype Mills Cross, and in the background are the ex-Georges Heights radar antenna, the 11-m hydrogen-line dish and various instrument huts (courtesy: RAIA 3171-4).

that would prove invaluable once he was back in India. Once again, he was based at the RPL (rather than Dover Heights field station), where most of the requisite instrumentation was developed. Figure 14 shows him at work in an instrumentation room.[4]

So, during the first year of his 'apprenticeticeship' Govind

> … became familiar with international radio astronomy by reading widely; he gained

Figure 13: John Bolton (courtesy: RAIA, Bolton 01).

Figure 14: A 1954 photograph of Govind at work in the RPL, with (left-to-right) John Bolton, Gordon Stanley and Joe Pawsey in the background (courtesy: Hastings Pawsey; cf. Goss; 2014: 5).

> experience in reducing observations; and he constructed equipment that was used for making observations. All this would prove handy in the second year of his 'apprenticeship' when he and Parthasarathy would carry out a major collaborative project. (Orchiston and Phakatkar, 2019: 18).

2.6 1955 and a Major Collaborative Project

Deciding on that major collaborative project was easy. The research intended for the two Potts Hill grating arrays had ended and Christiansen was off to Europe for a year to work with the French radio astronomers in Paris.[5] So, after discussions with Pawsey,

> … Parthasarathy and I decided to convert the Potts Hill EW grating array … from 21 cm to 60 cm (500 MHz), in order to investigate whether the quiet Sun exhibited limb brightening at that frequency. This was predicted by Smerd (1950), but was in conflict with measurements made at Cambridge by Stanier (1950). (Swarup, 2006: 25).

As Govind relates, converting the E–W array so that it could operate at 500 MHz was an interesting exercise:

> Chris explained the intricacies involved in matching the transmission lines of the 21cm grating array, particularly to ensure that the lengths of the lines from the central point of the array to each of the 32 dipoles was within a few mm. This involved a cumbersome procedure whereby a 21cm signal was transmitted from the junction of each adjacent pair of dishes, the signals were received at the dipole feeds of the adjacent dishes using a movable probe, their phase was then measured using a slotted line, and finally appropriate corrections were made to ensure equality of the lengths of the transmission lines to within a few mm. (Swarup, 2008: 197).

Once they had modified the array, Govind and Parthasarathy observed the Sun from July 1954 to March 1955, finding strong evidence of limb-brightening (Swarup and Parthasarathy, 1955a; 1955b). Their results "… agreed with Smerd's [1950] prediction and mimicked the earlier finding by Christiansen and Warburton …" (Orchiston and Phakatkar, 2019: 18). This is illustrated in Figure 15. Swarup and Parthasarathy (1955a: 9) felt they could explain the different curves plotted in the right-hand section of Figure 15:

> Stanier's observations were made near the maximum phase of the solar cycle, while the present observations have been made during the current minimum phase. The discrepancy between the two results could be due either to an actual change in the "quiet" Sun or to errors in Stanier's result, caused by the presence of unrecognized bright areas. Stanier has not given details of the method he used to allow for such bright areas, and without further information it is not possible to decide which alternative is the more likely.

Govind and Parthasarathy (1958) also studied the 500 MHz radio plages, which always were associated with chromospheric prominences and Hα plages and were responsible for the slowly varying component of solar radio emission. These radio plages were not very common given that 1954 was near sunspot minimum, but there were enough

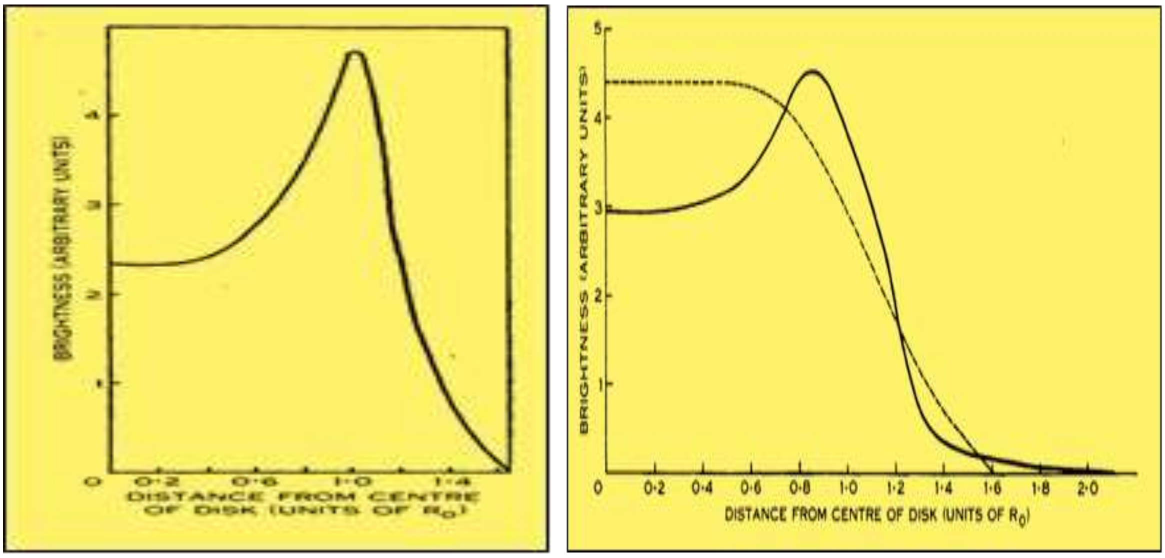


Figure 15: On the left is the radial brightness distribution across the solar disk based on one-dimensional scan observations at 1400 MHz (after Christiansen and Warburton, 1953b: 268). The plot on the right shows the radial brightness distributions at 500 MHz comparing Stanier's result (dashed) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy, 1955: 493).

of them to derive some useful results. For example, Govind and Parthasarathy (1958: 338) found that

> … the emission polar diagram has a half-power width of 6 days, the estimated size of the sources varied from less than 3 to 6 min of arc, the largest value of the derived brightness temperature was 10^7 °K, and for two groups of localized regions the height of the source was derived to be 35,000±15,000 km above the photosphere.

These results were consistent with those obtained by others at similar frequencies. For example, see Christiansen and Warburton (1957) for observations of radio plages with the Potts Hill E–W grating array in 1952–1953.

Swarup (2017: 822) later reported that he and Parthasarathy found this Potts Hill experience inspirational:

> For us, this was a great experience: building dipoles, a transmission line network and a receiver system; making the observations; and finally, carrying out data reductions—not to mention saving my dear friend Parthasarathy from drowning in the Potts Hill reservoir! At the time he was using a bucket to draw some water from the Reservoir so that we could make a cup of tea and wash our faces (after a day of hard work), and he accidentally fell into the water.

2.7 Future Directions: In Australia and India

When Christiansen returned from Paris in early 1956 he announced that he planned to erect a new solar radio telescope at Fleurs field station (Orchiston and Slee, 2017: 547–563), where there was already a full-scale Mills Cross and adequate flat land for another large radio telescope. What he had in mind was a crossed-grating interferometer, which combined some of the features of the old Potts Hill grating arrays and the Mills Cross. It would comprise E–W and N–S arrays each with 32 equatorially mounted parabolic antennas, that could produce daily isophote maps of solar emission at 1420 MHz (for details see Orchiston and Mathewson, 2009). Therefore, the two Potts Hill grating arrays were 'surplus to requirements'. Govind then began thinking of the future development of radio astronomy in India once he returned to the NPL in New Delhi, and during one of Pawsey's visits to Potts Hill he suggested that RP may like to donate the E–W grating antennas to the NPL. Pawsey

> … readily agreed to this suggestion, as did E.G. (Taffy) Bowen (1911–1991), Chief of the Division of Radiophysics … On 23 January 1955, I wrote to K.S. Krishnan about the possibility of transferring the thirty-two dishes from Sydney to the NPL in New Delhi (Swarup 1955). I proposed simultaneous dual frequency observations with a 2,100-feet long grating interferometer using the thirty-two dishes at 60cm and 1.8m. On 22 February Krishnan (1955) replied: "I agree with you that we should be able to do some radio astronomy work even with the meager resources available." (Swarup, 2017: 822).

Bowen and Pawsey then had the CSIRO approve the gifting of the dishes to India under the Colombo Plan scheme, but they insisted that India should cover the cost of their transfer from Sydney to New Delhi—which Govind recalls amounted to about 700 Australian Pounds, a considerable sum in those days.[6]

3 GIFTING OF THE POTTS HILL ARRAY TO INDIA, DELAYS, AND AMERICAN ADVENTURES

3.1 Problems with the Gift

Govind Swarup (2008) returned to the NPL in July 1955,[7] expecting the grating array dishes would follow him, but foreign exchange funding was tight and Sir K.S. Krishnan could not convince the CSIR to approve the transfer from Australia. They countered by insisting that the Australians should pay. Given this impasse, Govind decided to gain further radio astronomical experience, and he and his wife, Bina, went to the USA.

3.2 An American Interlude: Fort Davis and the U Burst

In August 1956 Govind began working as a Research Associate with Alan Maxwell and Sam Goldstein (Figure 16) at Harvard University's Fort Davis radio astronomy field station in Texas (Thompson, 2010), "… in order to study dynamic spectra of solar bursts using the 100-600 MHz swept-frequency radio spectrograph that had just been installed …" (Swarup, 2008: 197).

Alan Maxwell (1926–2021) was head of Harvard's radio astronomy program, and every year he would return to his native New Zealand to spend Christmas with friends and family (Skinner et al., 2022). In December 1956—while he was on holidays—Govind discovered a new type of solar burst, the U burst (Maxwell and Swarup, 1958). An example that was recorded later with the University of Michigan's solar radio spectrograph is shown in Figure 17.

Figure 16: Sam Goldstein, Govind Swarup and Alan Maxwell (left to right), posing in front of the 28-foot parabola at Fort Davis Station (courtesy: Maxwell Family Archive).

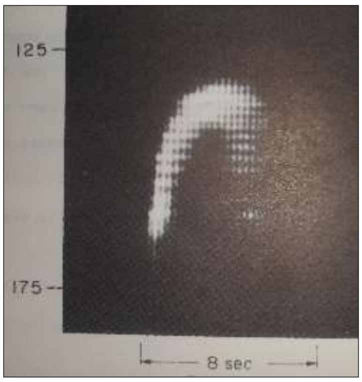


Figure 17: A U-burst recorded by the University of Michigan on 29 November 1956; time is shown on the x axis and frequency (in MHz) on the y axis (after Kundu, 1964: 408).

3.3 An American Adventure: The Stanford PhD

After a year at Fort Davis Govind decided to study for a radio astronomy doctorate in the USA, and after receiving various offers he selected Stanford (Bracewell, 2005) where Ron Bracewell—whom he knew from his Sydney sojourn—was the Professor of Radio Astronomy. In September 1957 Govind

> … began Ph.D. research under the guidance of Australian-born Ronald N. Bracewell (1921–2007; Thompson and Frater 2010), who was in the process of building a cross-antenna interferometer … that would be used to generate daily solar maps at 9.2cm … (Swarup, 2017: 824).

Figure 18: A panoramic view of the 3259 MHz Stanford Microwave Spectro-heliograph Antenna (courtesy: Stanford University Photographic Department, Negative No. 9448).

The design of this radio telescope was important given later developments that would take place in India. The Stanford Microwave Spectro-heliograph Antenna

> … comprised NS and EW arms in a cross configuration, each containing sixteen solid metal 10-ft parabolic 'dishes' spaced at 25-ft intervals. It was designed to operate at a wavelength of 9.2 cm, with a pencil beam of 3.1 arcminutes. (Bracewell, 2005: 75).

The array is shown in Figure 18, and is described in Bracewell and Swarup (1960). On 1 January 1961, soon after obtaining his PhD degree, Govind was invited to join the University as an Assistant Professor.

Figure 19: Dr Homi Bhabha, 1909–1966 (wikibio.in).

3.4 The Dream to Set Up a World-Class Radio Astronomy Facility in India

Apart from Govind Swarup, at that time there were two other young Indians working in radio astronomy in the USA, Dr T.K. Menon (at the National Radio Astronomy Observatory) and Dr Mukul Kundu (University of Michigan), while T. Krishnan was at the University of Sydney (working with Christiansen). All four met at the IAU General Assembly in Berkeley in August 1961 and discussed the idea of returning to India, forming a radio astronomy group, and initially conducting solar research using the thirty-two dishes donated to the NPL before setting up a very high-resolution radio telescope of a novel design.[8] In September they converted their ideas into a formal proposal (Menon et al., 1961), and sent this to five major scientific organisations and agencies in India. All five replied,

> … but the most encouraging and highly supportive was from the great visionary scientist and a dynamic organizer, Dr Homi J. Bhabha … [Figure 19; Chowdhury, 2016], Director of the Tata Institute of Fundamental Research (TIFR) in Mumbai. He sent a cable to all four of us on 20 January 1962: "We have decided to form a radio astronomy group stop letter follows with offer ..." (Bhabha 1962). (Swarup, 2006: 27).[9]

Meanwhile, the CSIRO in Australia had eventually relented and agreed to pay for transportation, and the Potts Hill antennas were now in storage at the NPL in New Delhi.

Further correspondence between Govind and Homi Bhabha followed, and Govind ended up resigning from his Stanford post and after visiting radio astronomers in Leiden, Meudon and Bologna returned to India on 31 March 1963 and started working at the TIFR two days later. He mentions that "After spending 10 years abroad, I was returning to India with a dream to set up a world class radio astronomy facility here." (Swarup, 2014b: 432). From the start, he found "The facilities and the general ambience of TIFR were most impressive. I found my discussions with Bhabha very stimulating." (Swarup, 1991: 76–77).

Soon after Govind's arrival, transfer of the Potts Hill antennas to the TIFR was arranged,[10] and India's first radio telescope was on the drawing board. But first Govind had to find staff for his new radio astronomy group, and train them. In August 1963 J.D. Isloor and V.K. Kapahi (1944–1999)—both recent graduates from the Atomic Energy Establishment Training School (AEETS)—joined Govind's group, as did R.P. Sinha and S.H. Damle (also from the AEETS) and a recent M.Tech. graduate, D.S. Bagri, in August 1964. That same year, both N.V.G. Sarma (1931–2008) and M.N. Joshi (1933–1988) resigned from the NPL in order to join the TIFR radio astronomy group. They were joined by T. Velusamy in 1965, and by V. Balasubramanian and S. Ananthakrishnan in 1966. Finally, Govind had the manpower to build a radio telescope and mount a viable research project. But this was to be very much an on-the-job learning exercise for these budding new radio astronomers and radio engineers. History was repeating itself, but this time they were the 'apprentices' and Govind was the master. That said, in early 1965 he was joined by another 'master', Mukul Kundu (Figure 20) who, prior to returning to the USA in 1968, "… provided considerable support for the [Kalyan Array] project." (Swarup, 2008: 200). He and Govind were the only ones from the 'gang of four' offered appointments by the TIFR who actually took up the offers at this time (although Menon did so later, before also returning to the USA—*ibid.*).

4 THE DESIGN AND CONSTRUCTION OF THE KALYAN ARRAY

4.1 Design Options

By the time he joined the TIFR Govind had been tutored by Chris Christiansen and Ron Bracewell, two of the luminaries of international radio astronomy, and had gained valuable experience with linear and crossed solar grating arrays and with a solar radio spectrograph. He also was able to improve on the methodology of his mentors. For example, while working at Potts Hill he

> … noticed that the procedure adopted by Christiansen for phase adjustment of the grating array was time consuming. Based on this experience, I later developed an innovative technique at Stanford in 1959 for phase adjustment of long transmission lines and paths in space. [And] In a bid to improve on the method used by Christiansen to make a 2-dimensional map of the Sun from strip scans, I suggested to R.N. Bracewell in 1962 a revolutionary method for direct 2-dimension-al imaging without Fourier transforms. Bracewell and Riddle developed the method for making a 2-dimensional map of the Moon using strip scans obtained with the 32 element interferometer at Stanford. The method has since revolutionized medical tomography. (Swarup, 2008: 194).

Figure 20: Dr Mukul Kundu, 1930–2010 (courtesy: Govind Swarup).

Govind specifically mentioned these developments in his paper "… to show how new ideas often are developed by necessity and have their origin in prior experience!" (*ibid.*).

Armed with 32 metal parabolas, he had three basic options for India's first radio telescope:

(1) A linear array, thereby mimicking the original Potts Hill E–W grating array;
(2) A cross, similar to the Stanford Cross, of which he also was familiar; or
(3) A T-shaped array.

Notwithstanding his personal familiarity with the first two options, Govind selected the third, and later mentioned that in fact back

> In September 1957, soon after joining Stanford, I made a detailed study of a Cross antenna versus a T-shaped antenna and showed that both provided the same resolution but that the latter, *although more economical*, was much more sensitive to phase errors, which resulted

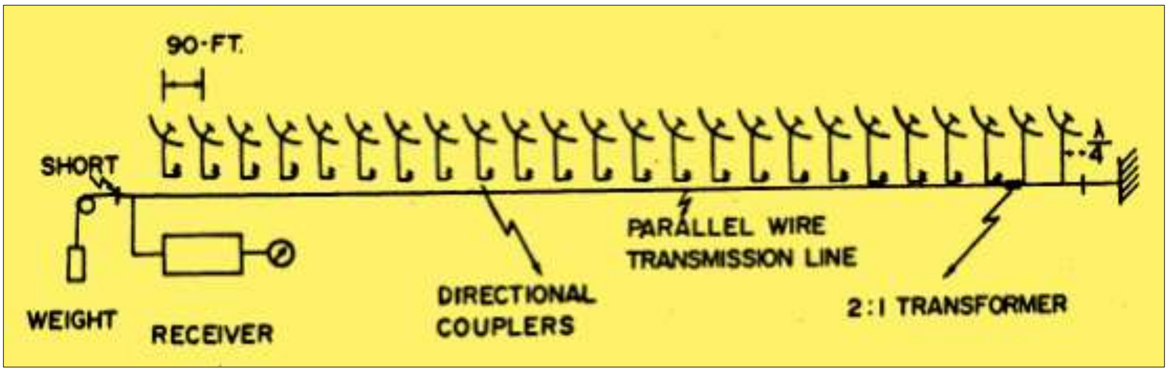


Figure 21: A schematic diagram showing the arrangement of the 24-element E-W array (after Swarup et al., 1966b: Fig. 1).

> in spurious sidelobes. (Swarup, 2008: 197; our italics).

Notwithstanding the side-lobes issue, Govind probably chose the T-configuration because it would be cheaper to build, an important factor given the economic situation in India.

In his first published paper mentioning this new Indian radio telescope, which appeared in a journal with the distinctly non-astronomical title, *Nuclear India*, Govind described it as follows:

> This radio telescope, designed at the [Tata] Institute, consists of 32 parabolic dishes, each 170 centimetres in diameter. Twenty-four dishes have been placed along a 640 metres [2,100 ft] long east-west line and the remaining eight along a 275 metres long north-south line. (Swarup, 1965: 5).

The 24 dishes were placed 27.4 m (90 ft) apart, and the eight N–S array dishes 36.6 m (120 ft) apart (Swarup et al., 1966a). The N–S array was at the eastern end of the E–W array. Figure 21 provides a schematic of the E–W array. The E–W and N–S arrays operated as two separate interferometers, and gave rise "… to a number of narrow fan-shaped beams corresponding to the principal maxima of a grating." (Swarup et al., 1966a: 775). Papers reporting the first scientific results indicate that the Kalyan Array was built in stages, the E–W array first, followed by the N–S array, and that the E–W array was used for observations while the N–S array was still under construction (e.g. see Swarup et al., 1966b).

The frequency chosen for this array was 612 MHz, or about 49 cm wavelength (Swarup et al., 1966a), "… because at present there exists a considerable uncertainty in the known characteristics of the decimeter wavelength radio emission." (Swarup, 1965: 5). The new Indian array would have a resolution of 2.3 minutes of arc in an E–W direction and 5 minutes of arc in a N–S direction (*ibid.*), and

> Near the normal directions to the arrays, the adjacent beams of the gratings are separated by 61.4 and 45.8 minutes of arc, for the east-west and north-south interferometers respectively. Since the solar disk has a diameter of about 32 minutes of arc only, there exists only one beam in the direction of the sun at any time. With the rotation of earth, the sun is scanned successively by various beams giving rise to a series of one-dimensional strip scans across the sun. (Swarup et al., 1966a: 775–776).

Later, Swarup (2008: 194) would write that the pioneering developments in the 1950s by his mentor Chris Christiansen would lead

> … to the construction of many major solar radio telescopes around the world, including the 21cm Chris Cross antenna at Fleurs, near Sydney (Christiansen et al., 1957; Orchiston, 2004[b]), the 9.1cm Stanford Cross antenna in the U.S.A. (Bracewell, 2005; Bracewell and Swarup, 1961), radio interferometers at 7.5cm and 3.2cm in Japan (Tanaka, 1984) … the 120cm Miyun Radio Telescope in China, the 10.7cm solar radio interferometer in Canada (Covington, 1984), 3.2cm and 1.7m solar arrays in France (Denisse, 1984), and a 107cm solar grating array near Lake Baikal in Russia (Salomonovich, 1984).[11]

All of these were contemporaries of the Kalyan Array, but Govind and his colleagues pointed out that "The construction of this radio telescope in India also fills a gap that existed in 24-hour radio observation of the sun." (Swarup et al., 1966a: 776). We should note that it also filled a gap in the wavelength coverage since it was the only radio telescope to operate between the 21 cm (1420 MHz) Chris Cross in Australia (see Orchiston and Mathewson, 2009) and the 107 cm (280 MHz) grating array in Russia.

4.2 Selecting a Site

The TIFR was located in the city of Bombay, which was unsuitable for an expansive radio telescope that required an area of flattish (preferably level) land in a radio-quiet environment. Yet it needed to be accessible for staff living in Bombay. One of the radio astronomy team members, J.D. Isloor (2022) recalls that through colleagues that had previously done cosmic ray research there, Govind's group heard about an area of flat land 11 km from Kalyan Railway Station near an abandoned airstrip that had been used by the Indian Air Force during World War II.[12] In a straight line, the location was about 50 km northeast of the TIFR headquarters in Bombay (Figure 22) and was investigated by the TIFR radio astronomers. Their sketch map (Figure 23) pinpointed the intended location of the array relative to nearby villages. These were some distance away and were inhabited by agricultural labourers and some vegetable growers. They did not have electricity, so there was no problem with electrical noise pollution (Isloor, 2022).

The site was deemed to be ideal, although it initially lacked running water and electricity. After a lot of paper work the land was acquired from the Government, and a bore was drilled which produced good water. A small temporary hut was built on the premise and a security guard installed. Trees were planted and watered, and electricity was connected (after negotiations with the State Electricity Board). At the time, the J.D. Isloor was a young graduate and Govind's first graduate student, and he remembers working at the site and the excitement of setting up India's first radio telescope. He recalls:

> The site was not easy to reach in those days. I remember leaving my home early in the morning. A TIFR jeep used to pick me up from near Vile Parle railway station and take me to Kalyan. (*ibid*.).

4.3 Construction of the Kalyan Array

Construction of the Kalyan Array began in March 1964, and timing was critical since the plan was to involve the Array in the International Years of the Quiet Sun (IQSY), in 1964–65 (Pomerantz, 1963). The Array became operational in the nick of time, but Govind pointed out at the time that "… observations will be continued even after 1965 and perhaps for a complete solar cycle of 11 years." (Swarup, 1965: 6). As we shall see, this would prove to be an optimistic projection.

A number of critical changes had to be made to the old Potts Hill design so that the rebadged array could operate in the Northern Hemisphere, and at a different frequency. For a start, the mountings for the parabolas had to be modified, and this redesign was accomplished by Mr Isloor (2022), who also designed the metal pillars that supported each of the mountings. Figure 24 shows a close-up of the new mounting and the supporting pillar. When observations were made, in order to track the Sun the right ascension of each parabola was "… changed manually every 32 minutes using a simple system of pegs and holes which is attached to the polar axis of each dish." (Swarup et al., 1966a: 776).

In linking the various antennas in the two arrays, Govind decided not to use the same transmission line systems that he encountered at Stanford and Potts Hill:

> A novel feature of these multi-element interferometers is that a simple travelling-wave type of transmission line has been used for connecting the various parabolic dishes to a receiver which provides multiple-beams and thus allows rapid scans of the sun. (*ibid.*).

Govind and his collaborators provide further details:

> A single pair of parallel-wire transmission line[s] consisting of two hard-drawn copper wires of 0.3 inches diameter runs along the entire length of each interferometer. Each line is tied to a fixed support at one end, and is attached to a heavy weight of about 1500 lbs, through a pulley system, at the other end. (*ibid.*).

The dishes in the two arrays were joined to the transmission lines by

> … quarter-wave directional couplers … which are suitably adjusted so as to illuminate the arrays uniformly … Each coupler is supported by two teflon insulators which are placed [a] quarter-wavelength apart and are mounted on tubular poles fixed to the ground. The parallel-wire lines slide through the teflon insulators. Since the parallel-wire lines are attached to a heavy weight at one end, and also the directional couplers are fixed with respect to the ground, the length of the lines between adjacent elements remains constant inspite [*sic*] of temperature expansions of contractions of the copper wires. (Swarup et al., 1966a: 776–777).

Figure 25 shows the second author of this paper adjusting the transmission lines.

Govind (1965: 6) pointed out that

> The design of the Tata Institute solar radio telescope differs from the existing

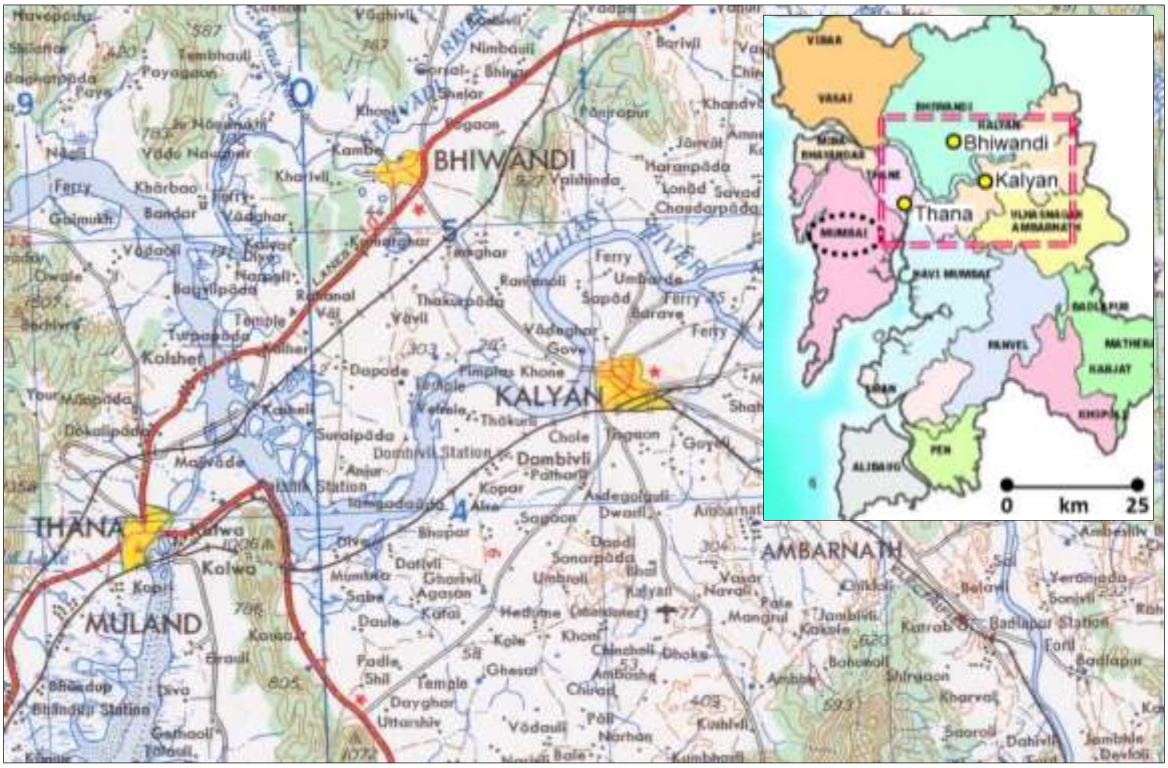


Figure 22: A 1955 topographical map showing Kalyan, the railway from Bombay, the abandoned WWII airstrip (due south of Kalyan, and about two thirds of the way to the edge of the map), and nearby villages Navali and Khoni (courtesy: NCRA Archives). The insert map on the right shows the location of the 1955 map (the red 'box') and Kalyan in relation to Bombay—the upper pinkish area, adjacent to the coast, where 'Mumbai' is circled (source: https://en.wikipedia.org/wiki/Mumbai_Metropolitan_Region#/media/File:Mumbai_Metropolitan_Region.jpg; map modifications: Wayne Orchiston).

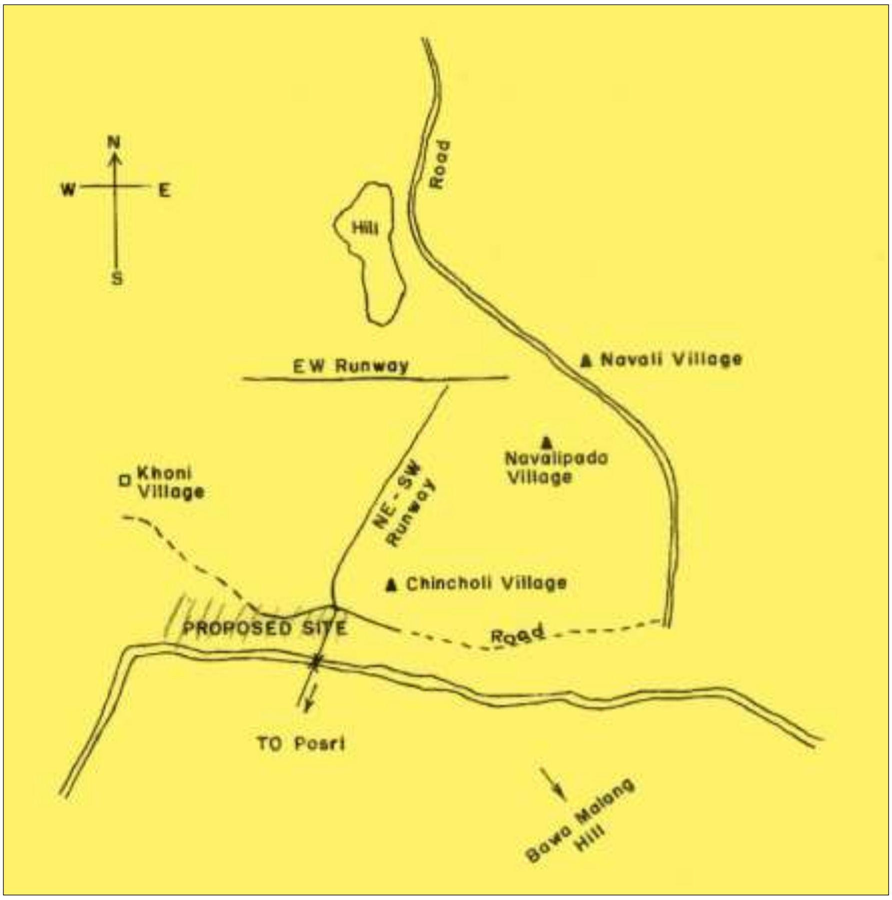


Figure 23: A sketch map showing the proposed site of the Kalyan Array in relation to the abandoned NE–SW runway (which is now a road), local villages and immediately to the north of a predominantly E–W aligned local stream. Aerial photographs show that the Kalyan Array site is now occupied by a Bhabha Atomic Research Center facility (courtesy: NCRA Archives).

Figure 24 (above): A close-up of one of the Kalyan Array antennas showing the equatorial mounting and support pillar developed by J.D. Isloor. In this photograph V.K. Kapahi can be seen adjusting the transmission line (courtesy: NCRA Archives).

Figure 25 (right): A close-up of one of the Kalyan Array antennas showing J.D. Isloor adjusting the transmission line (courtesy: NCRA Archives).

> radio interferometers in that a single dispersive system of radio transmission line has been used for both east-west and north-south arrays. This should allow us to obtain [an] instantaneous one-dim-ensional picture of the sun. This feature will be of value in studies of the rapidly varying phenomena that occur at the time of large solar eruptions, and is likely to be widely used in future solar radio inter-ferometers.

Once the design of the array and its precise location on the site were finalized, Govind borrowed a theodolite from the Indian Institute of Technology in Bombay, and on a few convenient nights surveyed a North-South line using observations of Polaris (Isloor, 2022). From this it was easy to survey an E–W line.

When it came time to actually erect the individual antennas in the array along with the associated transmission lines,

> Thanks to the excellent workshop and other facilities of TIFR, they could be set up within a record period of about 18 months and became operational in April 1965 (Swarup, 1991: 77).

Figure 26 shows the E–W arm of the completed array. According to data provided in Figure 27, prior to construction the all-up cost of the completed array was anticipated to be Rs. 155,000. To place this figure in perspective, the Nagaland Act 4 of 1964 (1964) stipulated that as from 25 January 1964 the salary of the Chief Minister was set at Rs. 1,500 per month, and each Minister of state at Rs. 800 per month. So, the annual salary of the Chief Minister was Rs. 18,000. While Bombay Government salaries would certainly have been significantly higher than those of Nagaland, this exercise indicates that financially, erection of the Kalyan Array was a non-trivial affair, notwithstanding the fact that all of the antennas were donated by the Australian Government.

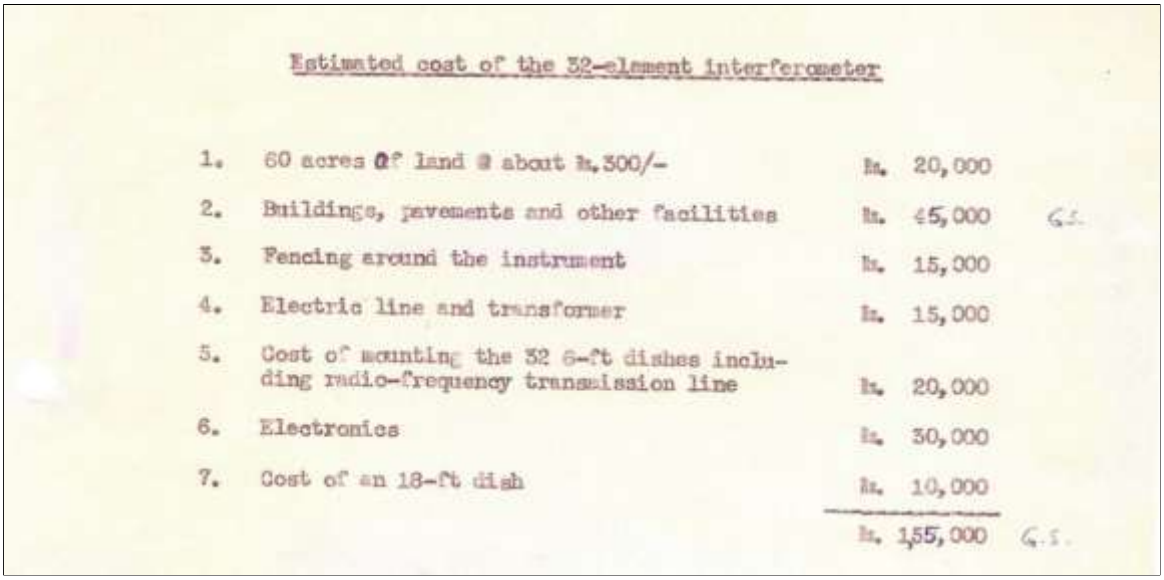
5 SOLAR OBSERVATIONS, 1965–1968

After reviewing the extent of limb-brightening of the Quiet Sun at 1420 MHz in 1953–1954 back in Australia, a time of sunspot minimum, Christiansen and Warburton (1955: 486) reported that

> Further measurements will be required to determine whether there are significant changes in the brightness distribution during the course of a solar cycle. From visual observations this would be expected, and we must wait until the cycle moves away from its minimum phase before we can verify the changes which have been predicted.

Sadly, circumstances decreed that the Kal-yan Array also would become operational during sunspot minimum, but this also open-ed up other research opportunities. Near sunspot minimum bursts were comparatively rare, especially at frequencies above 250 MHz, so there would be an opportunity to explore radio plages (the sources of the slow-ly varying component) and limb-brightening, as well as any bursts that may occur, and to compare the Indian results with those obtained

Figure 26: A view looking towards the west, showing part of the E–W arm of the Kalyan Array (courtesy: NCRA Archives).



Estimated cost of the 32-element interferometer

1.	60 acres of land @ about Rs.300/-	Rs. 20,000	
2.	Buildings, pavements and other facilities	Rs. 45,000	G.S.
3.	Fencing around the instrument	Rs. 15,000	
4.	Electric line and transformer	Rs. 15,000	
5.	Cost of mounting the 32 6-ft dishes including radio-frequency transmission line	Rs. 20,000	
6.	Electronics	Rs. 30,000	
7.	Cost of an 18-ft dish	Rs. 10,000	
		Rs. 1,55,000	G.S.

Figure 27: Govind Swarup's listing of the estimated costs associated with purchasing land and establishing the Kalyan Array. Note that in the end the planned 18-ft dish was not built (courtesy: NCRA Archives).

with those obtained by other researchers at other frequencies.

5.1 The Quiet Sun and Limb-Brightening

Sinha and Swarup (1967: 41) remind us that "… in the radio spectrum the limb of the quiet sun is brighter in the equatorial regions than near the pole." In fact, this was the first solar project Govind worked on when he was at Potts Hill field station in Australia and is illustrated here in Figure 8.

In 1950 RP solar theoretician Steve Smerd had predicted the extent of limb-brightening at various frequencies, based on prevailing knowledge of the solar corona and temperatures of 3×10^4 and 10^6 K for the chromosphere and corona respectively—see Figure 28. As we have seen, observations at

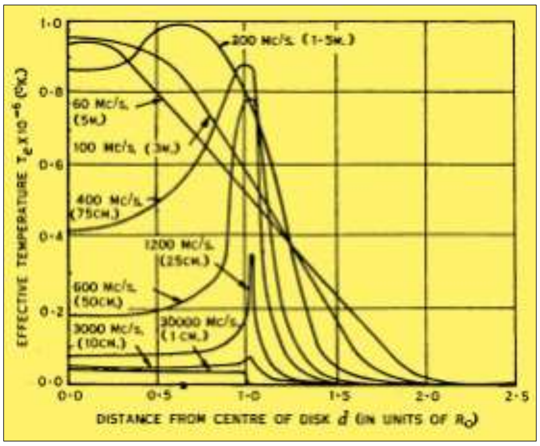


Figure 28: Plots of the predicted variation of the effective temperature with distance from the centre of the solar disk at different radio frequencies (after Smerd, 1950: 46).

Potts Hill by Christiansen and Warburton and later by Swarup and Parthasarathy were in agreement with Smerd's predictions. However, there were conflicting results reported by O'Brien and Tandberg-Hanssen (1955) at 500 MHz, so Swarup and his Kalyan team were keen to examine the evidence for limb-brightening at 612 MHz.

Swarup et al. (1966a) published "A calculated two-dimensional distribution at 610 MHz … [and] Its east-west strip was found to be in good agreement with the observations made during June-July 1965." (Sinha and Swarup, 1967: 41). Meanwhile, Figure 29 shows the north-south strip scan of the Quiet Sun obtained with the Kalyan Array in November 1965, where, as expected, there is a total absence of polar limb-brightening. The theoretical curve "… agrees reasonably with the observations although the latter still shows a somewhat higher tail." (*ibid.*). The authors suggest that this tail could be caused "… by scattering of radio waves by irregularities in the solar corona … but the possibility of its arising from higher side lobes of the antenna cannot be eliminated." (Sinha and Swarup, 1967: 41–42).

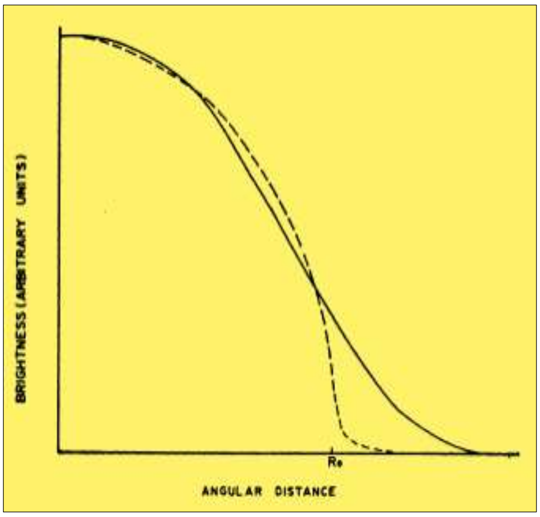


Figure 29: A plot of the 610 MHz one-dimensional brightness of the Sun in the polar direction as observed in November 1965 (the solid curve) compared to the theoretical curve (the dashed line) (after Sinha and Swarup, 1967: 41).

5.2 Radio Plages and The Slowly Varying Component

Solar observations at Kalyan began with the E-W array, while the N-S array was still under construction. Figure 30 shows 16 superimposed daily scans of the Sun, obtained in June–July 1965. The half-power widths of two radio plages seen during this period, and two other strong sources visible in March-April 1966 were found to be 8.8, 9.3, 8.3 and 9.2 arc minutes respectively.

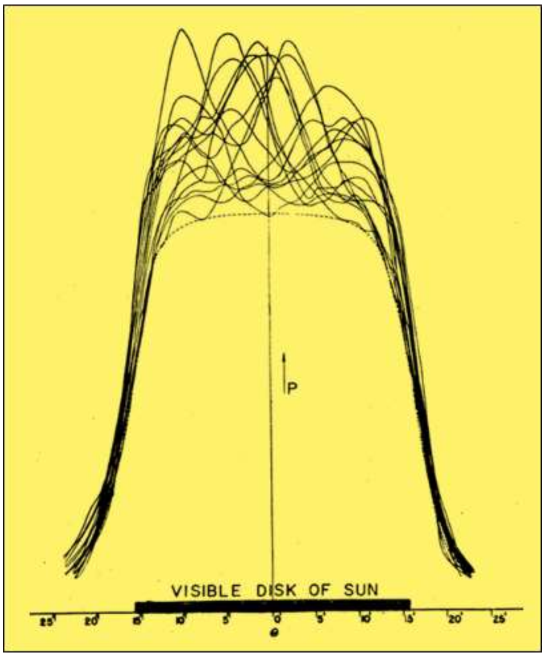


Figure 30: Superimposed daily scans of the Sun obtained with the Kalyan E-W Array during June-July 1965, relative to the diameter of the visible Sun. The dotted line indicates the level of Quiet Sun emission (after Swarup et al., 1966: 910).

During the period from June 1965 to February 1967 Swarup et al. (1968) found that after removing the estimated Quiet Sun level from the strip scans, the half-power widths of the sources of the slowly varying component varied from about 7 minutes of arc to about 14 minutes of arc. The histogram of the size of the sources showed a skewed unimodal Gaussian distribution with 61% of all sources between 8.5 and 11.5 minutes of arc (see Figure 31). The brightness temperatures of these sources were found to vary

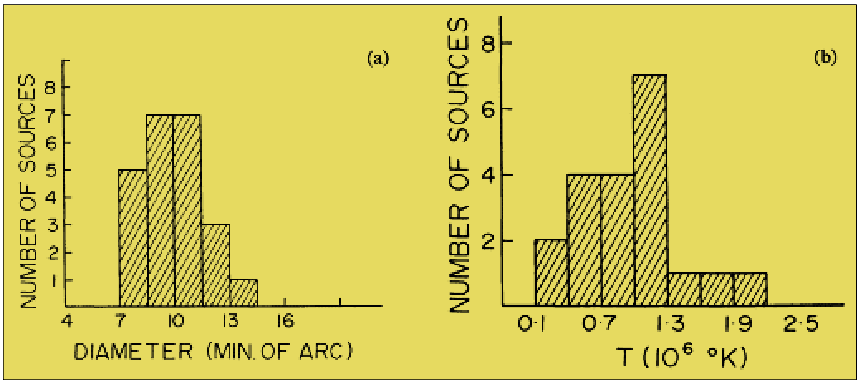


Figure 31: The distribution of (a) angular size, and (b) brightness temperature of the sources of the slowly varying component (after Swarup et al., 1968: 581).

between 0.1 × 10^6 K and 2.3 × 10^6 K (Figure 31), with the brightness temperature directly proportional to sunspot area (see Figure 32).

Swarup et al. (1968: 582) also found

> The centre-to-limb variation of the flux density of three isolated sources as they moved across the Sun's disk was determined from the observations of March–May, 1966. The directivity is found to be steeper than cosine law.

These three sources were found to be between 40,000 and 65,000 km above the photosphere (*ibid.*).

5.3 Bursts

Between March 1966 and March 1967 the Kalyan Array recorded 11 solar bursts, but most of these lasted for less than 10 minutes and thus were seen on only a few successive scans. However, on 18 January 1967 there was a long-lasting burst that appeared on the strip scans for more than 4 hours.

Swarup et al., (1968: 583–584) found the

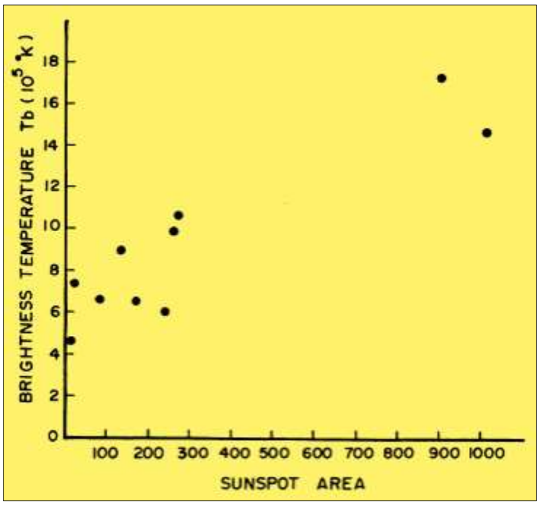


Figure 32: A plot of the brightness temperature of the sources of the slowly varying component vs sunspot area (after Swarup et al., 1968: 582).

angular width of the burst sources was generally "… about 3 min of arc; three sources, however being less than 1.5 min of arc wide. The maximum size recorded was only 4.9 min of arc." Assuming the sources were circular, the brightness temperatures varied between 10^6 and 10^8 K. Unfortunately, none of the bursts was observed near the limb, so the heights of the sources of the burst could not be determined.

In the case of the long-lasting burst of 18 January 1967,

> An interesting feature … was the peak of the burst source (situated 4.5 min of arc West of the central meridian) did not coincide with the peak of a source of slowly varying component … However, the position of the burst agreed well with that of a source of slowly varying component at the shorter wavelengths of 21 cm and 9.1 cm observed at Fleurs and Stanford respectively. (Swarup et al., 1968: 584).

This is illustrated in Figure 33. No obvious change was noticed in the position of the source during the outburst, and its size remained constant at 3 ± 0.5 minutes of arc. (*ibid.*).

5.4 Other Planned Kalyan Array Projects

In the Conclusion to one of their 1966 papers, Swarup et al. (1966a: 779) mention that

> The sun has been fairly quiet during the present series of observations covering the last six months of 1965 … [but the Kalyan Array will] be used later for high resolution studies of type IV radio bursts.

Type IV radio noise storms were discovered by the French radio astronomer Andre Boischot at Nançay field station in 1957 (see Pick et al., 2011), and

> … were rare continuum events, characterized by a high-intensity broadband featureless spectrum and linear polarization. They lasted from around half an hour

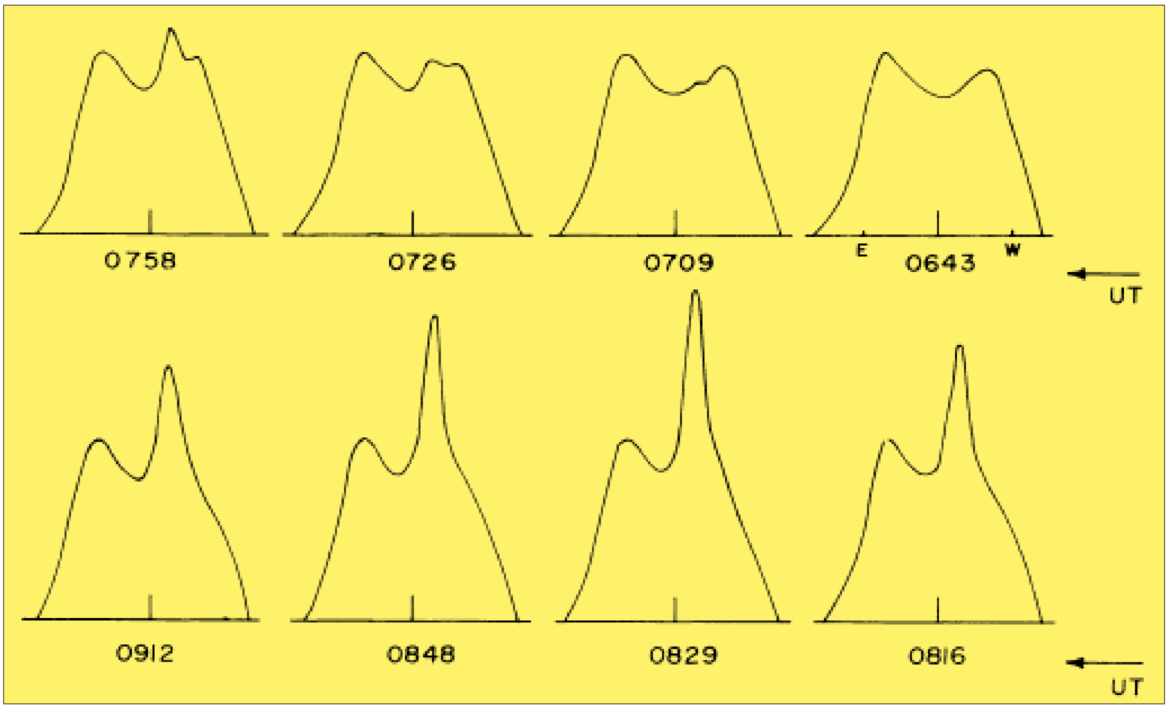


Figure 33: Selected strip scans showing the long-duration burst of 18 January 1967 (after Swarup et al., 1968: 584).

> to six hours, and generally occurred after Type II bursts (but not *all* Type II bursts). (Orchiston et al., 2021: 121).

In fact, the Kalyan investigation of Type IV emission never happened, which is probably just as well because already by 1965 it was realized that these rare events were much more complex than originally thought (e.g., see Pick et al., 2011: 70–72). Single frequency observations—as envisaged by Govind's group—would have had little impact. Instead, once the Ooty Project was underway, the whole TIFR radio group was involved in this and the Kalyan Array was closed down.[13]

6 DISCUSSION

As a radio astronomer, where did Govind Swarup derive his inspiration from? During his formative years Chris Christiansen,[14] Alan Maxwell and Ron Bracewell (in that order) all played a part, introducing him to solar research. And, through Christiansen, he learnt about grating arrays, through Maxwell solar radio spectrographs and through Bracewell crossed grating interferometers. It was only natural, then, that Govind foresaw the launch of radio astronomy in India in a solar content:

> In February 1955 I proposed setting up a '2100-foot-long 32-element interferometer to operate simultaneously at 60-cm and 1.8-m wavelength' for studying the Sun …

using the 32 dishes from the E–W array at Potts Hill (Swarup, 1991: 75). But by the time he, Krishnan, Kundu and Menon proposed the formation of a new Indian radio astronomy group in September 1961, they

> … suggested building a solar radio interferometer in the first instance and soon thereafter a large 'Mills Cross' for operation in the metre-wavelength region, in which the sky was relatively unexplored. (Swarup, 1991: 75–76).

Yet even at this time Govind was not satisfied and wanted to aim for something more innovative because he "… felt the capabilities of a Mills Cross for extra-galactic work was somewhat limited." Inspired, perhaps, by Pawsey's (1960) advice to "Be Original. Try, if possible, to develop ideas which one or more of you have originated …", and always on the lookout for exciting new research opportunities, Govind (2008: 199) recounts how when he returned to India from the USA in March 1963

> … there was a raging controversy between the Steady State and Big Bang Cosmologies. In June 1963 I suggested measuring the angular sizes of hundreds of extragalactic radio sources to arc second accuracy by lunar occultation observations in order to test the predictions of the two theories. For this purpose, I proposed the construction of a large parabolic cylindrical antenna placed on a suitably inclined hill in South India, so as to make its axis of rotation parallel to that of the Earth (Swarup, 1963). This concept was enthusiastically supported by Kundu

Figure 34: A section of the Ooty Radio Telescope (courtesy: National Centre for Radio Astrophysics, TIFR, Pune).

> and Menon, and Dr Bhabha approved the proposal …

So Govind came up with the concept of the Ooty Radio Telescope in early 1963, well before the Kalyan Array was constructed, and he reports that it was in January 1965—when the Kalyan Array was still under construction—that "… Ramesh Sinha and I located a suitably-inclined hill at Ooty in southern India …" (Swarup, 2008: 200). Construction of the novel Ooty Radio Telescope (Figure 34) occurred in the late 1960s (e.g., see Swarup, 1986).

Govind therefore saw the Kalyan Array as a stepping stone to the Ooty Radio Telescope. It was Professor M.G.K. Menon, Dean at the TIFR, who advised him to set up the solar array first (Swarup, 2014b). This offered a chance for those in the new TIFR radio astronomy group to gain experience in radio telescope design and construction and then in observing, analysis and publication before he, Ananthakrishnan and Balasubramanian embarked on the design and construction of India's first home-grown radio telescope at Ooty.[15]

Had the Kalyan Array not been perceived as a 'stepping stone', and had India intended making a long-term all-out assault on solar radio astronomy, then the history of radio astronomy in India would be very different. And in that case, perhaps there was more scientific mileage to be had from spectral analyses of solar burst at lower frequencies. But this would have demanded sophisticated new expensive instrumentation, like the radio spectrographs at Caltech (Young et al., 1961); Dapto (Stewart et al., 2011a); Fort Davis (Thompson, 2010); and the Universities of Colorado (Boischot and Warwick, 1959), Michigan (Haddock, 1958) and Oslo (Elgaroy, 1961),[16] whereas Govind was already *au fait* with higher frequency grating arrays and the Stanford Cross, and had access to the Potts Hill antennas. As we have seen, they served as an excellent starting point for Indian radio astronomy.

7 CONCLUDING REMARKS

In this paper I have recounted how Govind Swarup's exploits in Sydney in 1953 and 1954 led directly to the emergence of radio astronomy in India. Yet Swarup was not the first Indian to venture overseas in search of a radio astronomical career. That distinction must go to Mrinal Kumar Das Gutpa, who in 1950 went to Manchester University where he completed a PhD thesis on *The Measurement of the Apparent Angular Diameter and Structure of Cygnus I and of Casseiopeia I* under the guidance of Hanbury Brown (Das Gupta, 1954; Sullivan, 2009: 519). Das Gupta may have been India's first radio astronomer, but after he returned to the Institute of Radio Physics and Electronics at Calcutta University he did little to establish the radio astronomical reputation at that University anticipated by his mentor Professor Sisir Kumar Mitra (Choudhuri and Chatterjee, 2021).[17]

In contrast, Swarup came home to India and was instrumental in establishing radio astronomy at the TIFR and building the Kalyan Array, which was a forerunner to the Ooty Radio Telescope, and subsequently the Giant Metre Wave Radio Telescope (Ananthakrishnan and Balasubramanian, 2021). Through the innovative home-grown radio telescopes that he, Ananthakrishnan, Balasubramanian and others in the TIFR Radio Astronomy team developed and the cutting-edge research carried out with them, radio astronomy quickly became one of the flagship programs of the TIFR (e.g. see Choudhury, 2016: 183–192; Swarup, 2014a; 2021; Swarup et al., 1991), and the Institute and India were able to build an international reputation in this field. Furthermore, the Tata experience was the catalyst that led to the establishment of viable radio astronomy research programs at other institutes, but especially the Raman Research Institute and the Indian Institute of Astrophysics in Bangalore and at the Physical Research Laboratory in Ahmedabad (Swarup, 2014a: 94–104). So, although Das Gutpa may have been India's first radio astronomer, Govind Swarup should be recognized as 'The Father of Indian Radio Astronomy' (Orchiston and Phakatkar, 2019; cf. Choudhuri, 2021; Choudhury, 2016: 192).

Despite its key position in the evolution of Indian radio astronomy, until now the Kalyan Array has eluded historical scrutiny. Perhaps this is because of its short-lived existence and because it was merely seen as a 'stepping stone' to the Ooty Radio Telescope (and ultimately the Giant Metre Wave Radio Telescope) and was rapidly eclipsed by the first of these instruments. Yet, notwithstanding its Australian provenance, the Kalyan Array was India's first radio telescope and played a critical didactic role in the early evolution of Indian and indeed Asian radio astronomy (e.g. see Orchiston and Swarup, 2019). It is only fitting that I focus on it in this paper. It is a story that deserves to be told …

There is one final point of interest that I should mention. In his personal tribute to Govind, Professor Debades Bandyopadhyay (2021: 49) describes how Govind

> … had a great plan to build a radio telescope in Kalyani which is about 50 [km] away from Kolkata and where one of the first two IISERs is located. In this connection, he made several trips to Calcutta during [the] 90s. [The] Radio physics department of Calcutta University and Kalyani University were part of this project … However, it did not materialize.

This modest project would have seen Govind's first Indian radio telescope at Kalyan and his last one at Kalyani. Fate decreed otherwise.

8 NOTES

1. In this paper I will use Indian terminology in vogue in the 1950s and 1960s—which is the chronological focus of this study. Bangalore is currently known as Bengaluru, Bombay as Mumbai, Calcutta as Kolkata and Poona as Pune.
2. Note that these two arrays tracked and received radio emission directly from the Sun. Notwithstanding the presence of adjacent water in the reservoir neither array operated as a 'sea interferometer', like those used by the RP scientists at Dover Heights Field Station (e.g. see Orchiston and Slee, 2016: 502–511). At Potts Hill, the margins of the reservoir merely provided the radio astronomers with a convenient cardinally-orientated template they could use when aligning and erecting their arrays, and the presence of an expanse of nearby water was merely fortuitous.
3. More or less simultaneously, Takanori Oshio, Tatsuo Takakura and Shinichi Kaneko from the newly formed Faculty of Science and Technology at Kyoto City University developed the same concept and even presented a paper about it at the 5 November 1950 5th Annual Assembly of the Physical Society of Japan, but they never attempted to construct their array (see Wendt et al., 2017). Christiansen, on the other hand, first outlined the concept of his solar grating array at the 14 March 1950 meeting of the RP's Radio Astronomy Committee, and he went on to build it (and, ultimately, a second one).
4. This photograph appeared in an article in the 10 February 1954 issue of the popular Sydney magazine *People* (Anonymous, 1954), and was first introduced to the history of radio astronomy community by Miller Goss (see Goss, 2014: 5).
5. At this time (January 1955) the French radio astronomers under Denisse and Steinberg at the École Normale Supérieure in Paris had a field station at Marcoussis where they used a 2-element

interferometer to monitor solar radio emission at 9350 MHz and investigate the one-dimensional distribution of radio emission across the solar disk. Meanwhile, Arsac was busy erecting a 4-element non-redundancy array that he used to obtain strip-scans of the Sun at 9350 MHz. For further information about these projects see Orchiston et al. (2009: 179–181).

6. Depending on which criteria are used, 700 Australian pounds equates today (December 2022) to anywhere between AU$27,000 and AU$90,000. Even the lower of these figures is a substantial sum.
7. In some autobiographical papers (e.g. Swarup, 2006; 2017) the date of his return to New Delhi is listed incorrectly as August 1956. This is a typographical error, which, unfortunately, was not picked up prior to publication by Govind or the first author of this paper (who edited the associated journal and the book).
8. At that time India was a young independent nation, emerging from centuries of colonialism, so nationalistic feelings like these were common (Choudhury, 2016).
9. It is ironic that originally the TIFR was not on the circulation list, but in a chance meeting and discussion with M.K. Vainu Bappu, at the eleventh hour, Menon was advised to rectify this (Menon, 2016). It also is important to note that Bhabha had already seen the Potts Hill grating array: Govind records that in 1955, when he and Parthasarathy were working there, Bhabha "… visited the Potts Hill Station of CSIRO near Sydney, where many dramatic and remarkable discoveries had been made … *[His] interest in our work and in the field of radio astronomy was most encouraging*." (Swarup, 1991: 75; our italics).
10. J.D. Isloor (2022) remembers that "The antenna dishes were lying idle at the NPL for some years and we got them from there." In his 1965 paper, Govind states that the dishes were actually "… transferred to the Tata Institute last year [i.e. in 1964]." (Swarup, 1965: 6).
11. Since Govind Swarup wrote his 2008 paper, further historical papers have been published about the Chris Cross (Orchiston and Mathewson, 2009), China's earliest solar arrays (Wang, 2009), the grating arrays at Nançay in France (Pick et al., 2011) and the Japanese grating arrays at Toyokawa (Ishiguro et al., 2012; Orchiston and Ishiguro, 2017).
12. By a happy coincidence, in 1954 the RP Fleurs field station—which Govind never worked at, but may have visited—was also set up on flat land adjacent to an ex-WWII airstrip. Eventually, this field station housed three cross-type radio telescopes that were used for solar, galactic and extra-galactic research (Orchiston and Slee, 2017: 547–562).
13. This would end Govind Swarup's involvement in solar radio astronomy. Although he and Kapahi outlined the way in which a crossed grating interferometer or T-shaped interferometer could be used to obtain "Truly instantaneous images of solar activity …" (Swarup and Kapahi, 1970: 404), this elaboration of the Kalyan Array was never built.
14. Christiansen had a special place in Govind's world:

    > During my stay in Australia, I had close contact with Chris not only academically but also culturally and socially. He was not only my *guru* but became a close mentor and remained a friend for the next fifty years. (Swarup, 2008: 195).

15. This was a major challenge given the situation in India at that time. Thus, Professor Vijay Raghavan (2021: 2), the Principal Scientific Advisor to the Government of India, reminds us that "This was when nothing could be imported, budgets were minuscule and astronomers and engineers had to be trained from scratch." It is also important to realise that Govind at this time also had a much grander vision, of an Indian synthesis telescope:

    > In late 1963 I discussed the occultation project [i.e. the Ooty Radio Telescope concept] with Chris [Christiansen] during a brief visit that he made to the TIFR while he was on his way to the Netherlands. He described the 21cm Westerbork Synthesis Radio Telescope (WSRT), which was under development at the time in the Netherlands. An even less ambitious synthesis radio telescope operating in India at a longer wavelength would have required access to considerably more expertise and technology than was then available in India. Many components would have to be imported, but there was a serious foreign exchange constraint in India at that time. Hence we continued to pursue the cylindrical radio telescope project … (Swarup, 2008: 199).

    Nevertheless, the Ooty Radio Telescope would later evolve into the Ooty Synthesis Telescope.

16. For a useful summary of these and other international solar radio astronomy projects during the 1951–1960 period see Stewart et al., 2011c.
17. Mitra was an international authority on upper atmospheric and ionospheric research and realized that radio astronomy had a promising future, which is why he sent Das Gupta to Manchester.

    After returning to India, Das Gupta remained at Calcutta University through to retirement, and although he quickly built a reputation as an outstanding teacher and populariser of science, "… the expectation … [that he would] establish a strong research group in radio astronomy … was not fulfilled." (Choudhuri and Chatterjee, 2021: 11). Although he did publish a few papers on solar radio astronomy, "... his research made little impact in the field …" (*ibid.*). Later, in a review of Indian radio astronomy, Das Gupta acknowledged the pivotal role of Govind Swarup, "… admitting honestly that his own work done in India was not significant." (Choudhuri and Chatterjee, 2021: 12).

    Choudhuri and Chatterjee (*ibid.*) are puzzled by this, but perhaps a heavy undergraduate teaching load, lack of time for research and adequate funding for instrumentation, and the problem of remaining totally up-to-date in a rapidly emerging scientific field were behind this. Without building a vibrant research group that reached and maintained a critical mass, it was difficult to achieve success in radio astronomy.

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I wish to dedicate this paper to the memory of Govind Swarup, FRS, the 'Father of Indian Radio Astronomy'. Govind and I began collaborative research on this topic, but his passing and the advent of COVID and associated funding restrictions prevented its earlier completion. Having said that, I am particularly grateful to J.D. Isloor, the last surviving member of the Kalyan Array team, for providing me with reminiscences of his time at Kalyan (Isloor, 2022), and to Professor Subra Ananthakrishnan (Electronic Science Department, Pune University) for arranging this. Isloor was Govind Swarup's first student, and saw him in a special light, where G = Genius, O = Outspoken, V = Visionary, I = Intellectual, N = Nationalist (to the core) and D = Doyen of Indian radio astronomy (Isloor, 2021: 30).

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Professor Wayne Orchiston was born in Auckland (New Zealand) in 1943, and has BA Honours and PhD degrees from the University of Sydney. He is employed by the University of Science and Technology of China in Hefei as the Co-editor of the *Journal of Astronomical History and Heritage*. He is also an Adjunct Professor of Astronomy in the Centre for Astrophysics at the University of Southern Queensland (USQ) in Toowoomba, Australia. Formerly, Wayne worked at the National Astronomical Research Institute of Thailand (Chiang Mai), James Cook University (JCU, Townsville, Australia), the Australia Telescope National Facility (Sydney), Carter Observatory (Wellington, New Zealand) and from 1961 to 1968 at the CSIRO's Division of Radiophysics in Sydney.

Over the past two decades Wayne has supervised more than 35 Master of Astronomy and PhD history of astronomy research projects through JCU, USQ and Western Sydney University. Five of the PhDs and one MAstr were on the history of radio astronomy.

Wayne has wide-ranging research interests but has mainly published on historic transits of Venus; historic solar eclipses; historic telescopes and observatories; the emergence of astrophysics; the history of cometary, meteor and minor planet astronomy; the astronomy of James Cook's three voyages to the Pacific; amateur astronomy and the amateur–professional interface; the history of meteoritics; Indian, Southeast Asian and Māori ethnoastronomy; and the history of radio astronomy in Australia, France, India, Japan, New Zealand and the USA.

Recent books by Wayne include *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* (2016, Springer); *John Tebbutt: Rebuilding and Strengthening the Foundations of Australian Astronomy* (2017, Springer); *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (2017, Springer, co-edited by Tsuko Nakamura); *Exploring the History of Southeast Asian Astronomy: A Review of Current Projects and Future Prospects and Possibilities* (2021, Springer, co-edited by Mayank Vahia) and *Golden Years of Australian Radio Astronomy: An Illustrated History* (2021, Springer, co-authored by Peter Robertson and Woody Sullivan). In addition, Wayne has edited or co-edited a succession of conference proceedings. The New Zealand astronomy and the Asian astrophysics books mentioned above both contain chapters on early radio astronomy.

Since 1985 Wayne has been a member of the IAU, and he is the current Immediate Past President of Commission C3 (History of Astronomy). In 2003 he founded the IAU's Historical Radio Astronomy Working Group, and is the current Radio Astronomy Subject Editor of Springer's *Biographical Encyclopedia of Astronomers, Volume 3*. He also founded the IAU Working Group on Historic Transits of Venus, and is the Founding Chair of the History & Heritage Working Group of the SE Asian Astronomy Network.

In 1998 Wayne co-founded the *Journal of Astronomical History and Heritage,* and was the Managing Editor until 31 July 2022 when he passed ownership of the journal to the University of Science and Technology of China. In 2013 the IAU named minor planet 48471 'Orchiston', and in 2019 he and Dr Stella Cottam were co-recipients of the American Astronomical Society's Donald Osterbrock Book Prize for their 2015 Springer book, *Eclipses, Transits and Comets of the Nineteenth Century: How America's Perception of the Skies Changed.*