HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY. 4: EARLY SOLAR RESEARCH AT THE ÉCOLE NORMALE SUPÉRIEURE, MARCOUSSIS AND NANÇAY

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Abstract: The first tentative steps in solar radio astronomy took place during the 1940s and early 1950s as physicists and engineers in a number of countries used recycled World War II equipment to investigate the flux levels and polarisation of solar bursts and emission from the quiet Sun, and sought to understand the connection between this emission and optical features in the solar photosphere and chromosphere. There was also an abiding interest in the terrestrial effects of this solar radio emission. Among these solar pioneers were French radio astronomers from the École Normale Supérieure in Paris. In this paper we review the early solar observations made by them from Paris, Marcoussis and Nançay prior to the construction of a number of innovative multi-element solar interferometers at the Nançay field station in the mid-1950s.

Keywords: French radio astronomy, solar radio emission, École Normale Supérieure, Marcoussis, Nançay, J.-F. Denisse, J.-L. Steinberg, solar eclipse observations, the Arsac Interferometer.

1 INTRODUCTION

Solar radio astronomy was born during World War II, when Alexander (Orchiston, 2005), Hey (1946), Reber (1946), Schott (1947), Slee (Orchiston and Slee, 2002) and Southworth (1945) all independently detected solar radio emission. Military secrecy meant that most of these discoveries remained 'top secret' during the War, and only entered the public domain following the end of hostilities in Europe and the Pacific.

Hey's detection in England and follow-up observations by Appleton (1945) spawned a solar research program at Cambridge immediately after the War (for localities mentioned in the text see Figure 1), while news of Hey's, Alexander's and Southworth's wartime work led to the launch of an ambitious solar research program in Sydney, Australia, under the auspices of the C.S.I.R.O.'s Division of Radiophysics (Christiansen, 1984). For a short time during the late 1940s, smaller Australian solar radio astronomy groups also existed at Mt. Stromlo Observatory and at the University of Western Australia in Perth (see Orchiston,

Slee and Burman, 2006). Canada was also quick to assemble a solar radio astronomy group under Covington immediately after the War (see Covington, 1984). Britain, Australia and Canada all were involved in radar research during the War, and this was a valued catalyst in the post-War development of radio astronomy in all three nations, providing a pool of suitable equipment and talented personnel that could be directed to this new field of science (Edge and Mulkay, 1976; Hey, 1973).

Countries like France and Holland that missed out on these radar developments were not so lucky, yet both nations initiated radio astronomy programs soon after the end of the War (see Denisse, 1984; Strom, 2005; van Woerden and Strom, 2006). This paper investigates the solar radio astronomy program that was carried out by staff at the École Normale Supérieure from 1946, and is the fourth in a series that aims to document significant developments in early French radio astronomy.[1]

2 EARLY SOLAR RESEARCH AT THE ÉCOLE NORMALE SUPÉRIEURE

2.1 Introduction

By the time he was appointed Director of the Physics Laboratory at the École Normale Supérieure (henceforth ENS) in Paris in late 1945, Yves Rocard already knew about Hey's wartime detection of solar radio emission, and saw this as a potential post-War research field. During the following year a radio astronomy group was formed at the Physics Laboratory under the leadership of J.-F. Denisse and J.-L. Steinberg. Others who soon joined the group were J. Arsac, E.-J. Blum, A. Boischot, E. Le Roux and P. Simon. It is important to note that few of these individuals had a background in electronics or radio engineering—unlike many of their counterparts in England and Australia (see Lovell, 1977; Sullivan, 2005)—and none had a background in astronomy (Steinberg, 2001: 513).

2.2 The Solar Observing Program

As in other countries at this time, the fledgling French solar radio astronomy group began by recycling and cannibalising surplus World War II radar antennas and receivers. Initially they erected a U.S. Air Force 1.5m equatorially-mounted searchlight mirror and a 6-element equatorially-mounted Yagi antenna on the roof of the Physics Laboratory (Arsac et al., 1953). The third radio telescope on the roof of the Physics Laboratory was one of the German ex-WWII 3m Würzburg radar dishes that the ENS team adapted for radio astronomy.

The 'searchlight antenna' is shown in Figure 2, and was initially installed so that the radio astronomy group could gain experience in designing and constructing equipment, but its research potential was quickly recognised and it was then used to study variations in solar emission at 9,350 MHz (Steinberg, 2004).

Denisse, Steinberg and Zisler were particularly interested in the terrestrial effects of solar radio emission, and in 1951 they reported on their regular monitoring program at 158 MHz since 1948 and confirmed that some areas with faculae, plages and sunspots were associated with bursts of solar noise (as reported previously by other radio astronomers). They noted (Denisse et al., 1951: 2291; our translation) that

> This emission is characterised by an average level of intensity in the course of a day and by its degree of agitation. Since the importance of these two features is still unknown we have defined the level of radio emission by the mixed index S, representing the sum of its average level and its degree of agitation as outlined in the following table.

Intensity	Agitation	Indices
$p < 10$	Nil or very weak	0
$10 < p < 20$	Average	1
$20 < p < 50$	Strong	2
$p > 50$	Very strong	3

where p = average flux received in 10^{-23} W . m^{-2} (c/s)$^{-1}$

Using these criteria, 74 centres of solar activity were identified during 1948-1950 (inclusive), and these were designated *Type A*, in contradistinction to 65 relatively inactive centres (termed *Type B*). Denisse et al. (1951: 2292) then plotted these centres against the terrestial magnetic index, C, revealing a pronounced maximum in geomagnetic activity 1 or 2 days after the central meridian passage of a radio-active centre of *Type A*, and a distinct minimum in geomagnetic activity 2 or 3 days after the central meridian passage of a centre of *Type B*. They concluded: "The regularity of curves A and B [in their plot] and the persistence of these principal phenomena in the course of each year when considered individually adds considerable weight to the statistical value of these results." (Denisse et al., 1951: 2292; our translation).
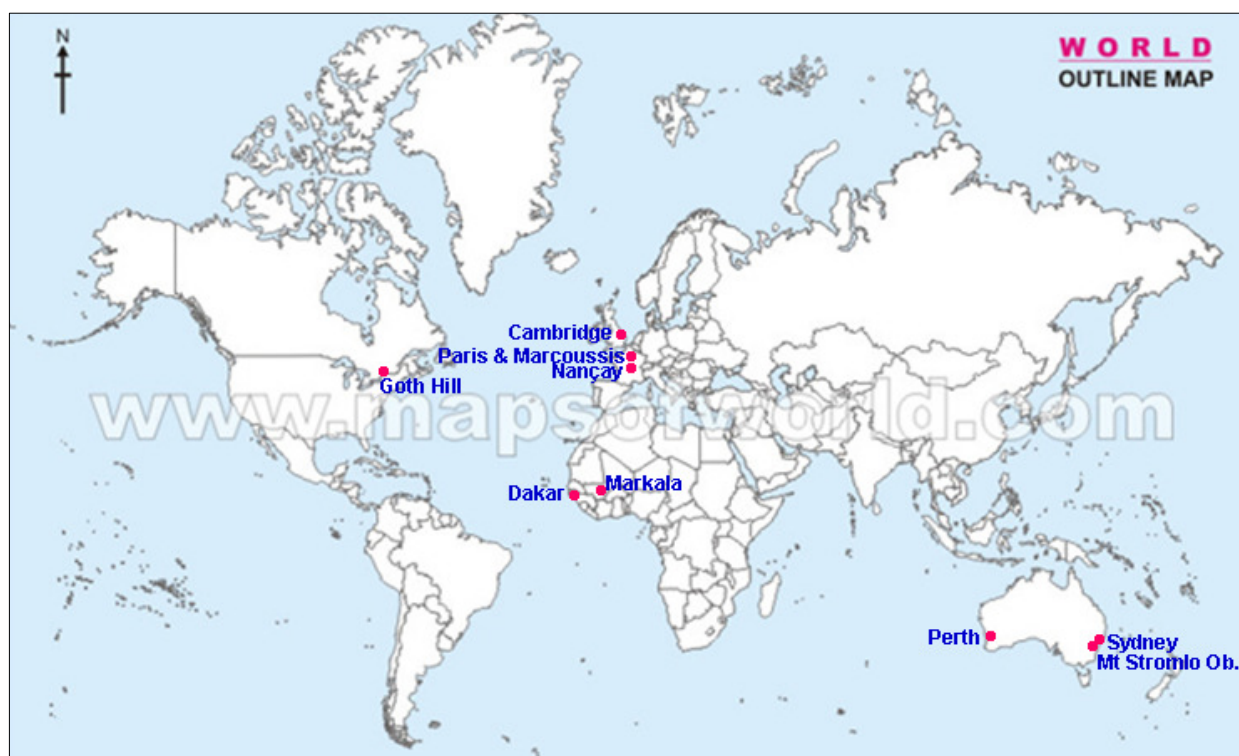

Figure 1: Localities mentioned in the text (outline map courtesy of www.theodora.com/maps, used with permission).

Figure 2: The 1.5m diameter 'searchlight antenna' mounted on the roof of the Physics Laboratory at the ENS in Paris. In the background is the dome of the Panthéon (after Steinberg, 2004: 626).

From June 1954 daily automated monitoring of the Sun at 9,350 MHz was carried out from the roof of the Physics Laboratory in Paris using the 1.5m searchlight antenna shown in Figure 2. In 1955, Kazès and Steinberg published a short paper in which they discussed atmospheric refraction associated with solar observations carried out near sunrise and sunset and how the level of solar emission dropped off rapidly as the Sun approached the horizon towards sunset.

2.3 Solar Eclipse Observations

During the 1940s and 1950s solar eclipses offered a particularly elegant way for radio astronomers to investigate the locations of solar-emitting regions, and those at the ENS observed three different eclipses (for a review see Orchiston and Steinberg, 2007).

The first of these events was a partial eclipse which occurred on 28 April 1949 when at mid-eclipse the Moon masked just 26% of the solar disk as seen from Paris. This eclipse was observed by radio astronomers from both the ENS and the Institut d'Astrophysique de Paris (see Laffineur et al., 1949, 1950; Steinberg, 1953). Steinberg and Zisler from the ENS used the 3m Würzburg dish on the roof of the Physics Laboratory and a 7.5m Würzburg antenna at Marcoussis near Paris, which operated at 1,200 MHz and 158 MHz, respectively, while Marius Laffineur carried out independent observations at 555 MHz with another 7.5m Würzburg located at Meudon. Successful observations were made with all three radio telescopes, but only results obtained with the 3m Würzburg dish and the Meudon Würzburg antenna were used to generate the eclipse curve shown in Figure 3. On the basis of this curve, Laffineur et al. (op. cit.) concluded that:

1) At frequencies of 555 MHz and 1,200 MHz the radio Sun did not appear to be significantly larger than the optical Sun (a conclusion that was subsequently shown to be incorrect); and

2) "It is necessary to suppose that at least a part of the solar radio emission derived from non-uniform sources distributed over the solar disk." (Laffineur et al, 1950: 339; our translation). These "non-uniform sources" were thought to be associated with chromospheric plages.

The second solar eclipse involving the ENS team occurred on 1 September 1951 but was viewed solely from Africa (see Orchiston and Steinberg, 2007), so it was only on 25 February 1952 that another eclipse was observed from near Paris (Blum et al., 1952). This partial event was monitored at 169 MHz with a 'searchlight antenna' set up at Marcoussis, and the resulting eclipse curve from this site and Dakar—
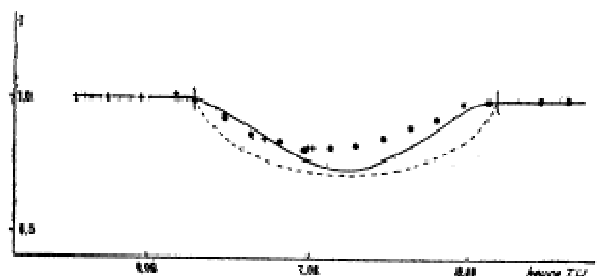

Figure 3: The 28 April 1949 eclipse curve. Dots represent measurements at 555 MHz and crosses at 1,200 MHz. The solid curve indicates the profile expected from a disk of uniform brightness, while the dashed line shows the expected profile if the radio emission derived from an annular ring (after Laffineur et al., 1950: 338).

where the eclipse was total (Figure 4)—confirmed the conclusion following the 1951 eclipse: that at 169 MHz the Sun was non-circular but took the form of an asymmetrical flattened ellipsoid.

2.4 Contributions to Instrumentation and Theory

In addition to observationally-based papers, some of the ENS staff also contributed papers which were solely about radio astronomical instrumentation (e.g. see Arsac et al, 1954; Mosnier and Steinberg, 1950; Steinberg, 1949, 1950, 1952a, 1952b). As Steinberg (2001: 511) notes:

> [Soon after joining the ENS] … I started developing radio receivers. After 4 years of occupation France was very backward in electronics while Great-Britain, Canada, Australia and the United States had many physicists and engineers who had learnt a lot when developing radars during WW II and had many surplus military radars. Fortunately I brought back from Great-Britain the books "Microwave Receivers" and "Vacuum tube amplifiers" from the MIT Radiation Laboratory Series which became our Bible. E.J. Blum joined me within a few months. He knew much more about electronics than I did. I specialized in microwave receivers and he developed the technology of meter wave receivers. We wanted to cover as much as possible of the frequency spectrum. But the frequency bands actually studied were mostly controlled by the availability of the corresponding components.
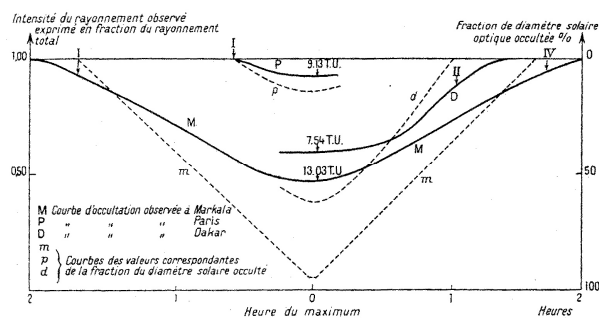

Figure 4: The 25 February 1952 169 MHz Paris (P) and Dakar (D) eclipse curves, plus the 169 MHz Markala curve (M) obtained in 1951 (after Blum et al., 1952: 1597).

A number of the ENS staff members also carried out research on radio astronomical theory. Denisse was the principal contributor, with papers on the role of a magnetic field in the production of solar radio emission (1946; 1947a; 1947b), the relation between solar radio emission and cosmic rays (1949a); the influence of refraction on the emission of radio waves in an ionised medium (1949b); the relation between solar radio emission and sunspots (1949c); the origin of thermal radio emission in an ionised medium (1950b); and the relation between solar radio emission and geomagnetic activity (1952; 1953a; 1953b). In 1956, Denisse also produced a 10-page review paper in which he combined some of his earlier results with those obtained by his Australian counterparts—including a useful account of the various spectral types of solar bursts, as identified by Paul Wild (for a review of this topic see Stewart, 2009). Finally, in 1954 Denisse and Simon published a paper on optical coronal emission and geomagnetic activity.

Meanwhile, in following up their Marcoussis observational papers, Blum, Denisse and Steinberg (1951b) examined the emission mechanisms associated with the small bursts that they believed combined to form noise storms. Their boss, Yves Rocard (1951), took this study further in one of his few escapades into radio astronomy when he published a paper titled "On a coronal radio emission mechanism." (our translation). Having said that, Denisse also teamed with Rocard in 1951, and they published a long mathematical paper where they examined the properties of a shock wave as it traversed an ionised medium. They finish by suggesting that plasma oscillations in the solar corona give rise to intense bursts of solar emission.

In an important paper, Michel Jorand (1955) examined the mechanism of solar radio emission in the corona, and identified the various altitudes at which emission at different frequencies was triggered. His work nicely complemented similar research that was undertaken at this time by the Australian radio astronomers in Paul Wild's 'Solar Group' (see Stewart, 2009).

In a long paper published in 1956 Paul Simon developed Denisse's (1952) earlier work and examined the relationships between solar radio emission and the magnetic properties of sunspots.

Finally, quite apart from research papers based upon their own French observations, Denisse (1950a) also published a 22-page review paper utilising 2,800 MHz Goth Hill data made available by Covington. In this paper, Denisse examines the relationship between sunspots and solar radio emission, and he reviews the theories proposed to account for emission at centimetre, decimetre and metre wavelengths.

3 SOLAR RADIO ASTRONOMY AT MARCOUSSIS

3.1 Introduction

In 1948 (Steinberg, 2001) the ENS established a radio astronomy field station at Marcoussis, ~20 km south of Paris, primarily to serve as a site for two World War II Würzburg antennas acquired by the Physics Laboratory that were to be used for both solar and non-solar radio astronomy (see Orchiston et al., 2007 for details). This radio-quiet environment attracted the radio astronomers at the ENS, and Marcoussis became a base for some solar radio astronomy projects—although solar monitoring continued all the while from the roof of the Physics Laboratory in Paris.

3.2 Solar Observations with one of the Würzburg Radio Telescopes

The first recorded solar research program conducted at Marcoussis was undertaken by Denisse (1952), who studied 167 MHz solar radio emission observed between 1948 and 1950 (inclusive), and related this to sunspot activity. He was able to distinguish two different sorts of sunspots, R-type spots which were connected with radio emission and Q-type spots which were not.

In a further solar study at Marcoussis, Jorand (1953) examined 160 MHz solar emission recorded between 1 September 1948 and 31 March 1951. This was a period of low solar activity, and all Jorand recorded were noise storms, bursts and occasionally outbursts. The noise storms appeared to be associated with sunspots, and accounted for the majority of the emission received during the monitoring period. Jorand pro-

ceeded to study the relationship between sunspots and the solar radio emission, and was able to demonstrate that the emission was more likely to occur when spots were within the narrow window of four days preceding and three days following central meridian passage. This led him to investigate—on theoretical grounds—the height at which the radio emission occurred in the solar corona.

In 1950, during the solar minumum, Blum and Denisse (1950) set out to investigate weak solar emission at two adjacent frequencies, 156 MHz and 164 MHz, using one of the Würzburg antennas. Simultaneous observations were carried out at the two frequencies between 10 October and 10 November 1950, and the incoming signals were recorded on two chart recorders. Comparison of the two chart records revealed the following:

1) Long periods of solar inactivity persisted for many days at both frequencies, but when interrupted by isolated bursts these occurred simultaneously at the two frequencies. However "… the detailed structure of these bursts varies from one frequency to the other and is not identical when considered only 1 or 2 seconds apart. Their durations are variable by as much as several tens of seconds." (Blum and Denisse, 1950: 1215; our translation). Very occasionally pairs of bursts occurred which had similar structures. But these were separated in time by 5-6 seconds, and always appearing first at 164 MHz.
2) In the course of several days, weak solar noise storms were recorded simultaneously at both frequencies, and they occurred when sunspots were present. Superimposed on the noise storm activity were occasional bursts which were indistinguishable from the isolated bursts mentioned above. It was significant that when bursts occurred during noise storms they almost never showed any correlation at the two frequencies (e.g. see Figure 5a).
3) On several occasions during noise storms, bursts were present at 164 MHz but totally absent at 156 MHz (Figure 5b), confirming the earlier impression (gained from evidence presented in 2), above) that the frequency range of bursts which accompanied noise storms was very restricted.

Blum, Denisse and Steinberg (1951a) subsequently carried out a further analysis of the observations at 164 MHz. They found that on days of very weak solar activity isolated bursts were generally widely separated in time, so that it was easy to determine the amplitude and duration of each individual burst. The strongest bursts had fluxes of between 2×10^4 and 2.5×10^4 Jy and lasted from 0.1 to 0.4 seconds. Having said that, sometimes groups of bursts occurred in the course of 2 or 3 seconds. In contrast, during periods of greater solar activity, the level of emission could fluctuate for several hours, and

> … one is led to believe that this type of [noise] storm is produced by the superimposition of bursts similar to those that are observed on days of relative non-activity. (Blum et al., 1951a: 389; our translation).

3.3 The 2-Element Interferometer

The first new dedicated solar radio telescope at Marcoussis was erected towards the end of 1952 and operated at 9,350 MHz. It consisted of

> … two cylindrical-parabolic antennas with a half-power beamwidth of 2° in the vertical plane, 20° in the horizontal plane. These were positioned along an East-West baseline and the distance between the antennas could be rapidly changed. The incoming radio emission was transferred via a wave-guide to the receiver … (Alon et al., 1953: 301-302; our translation).

Solar monitoring was carried out during the first six months of 1953 with a view to establishing the precise nature of limb brightening at 9,350 MHz. Earlier French solar eclipse observations offered two different models, one where at totality a uniform annulus located at 1.07 $R_\odot$ contributed 16% of the solar emission (curve A in Figure 6) and the other where the annulus was positioned at 1.04 $R_\odot$ and contributed 12% of the solar radiation (curve B in Figure 6). However, the Marcoussis observations proved ambiguous in that they could be used to support either model.
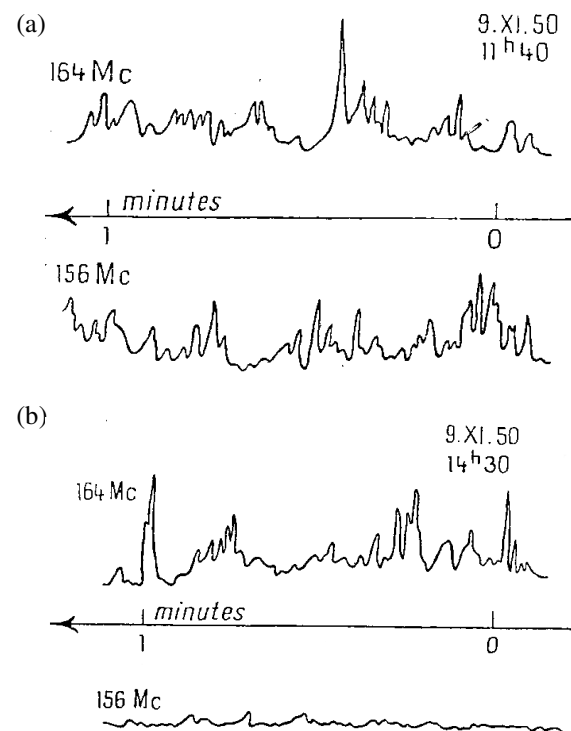

Figure 5: (a) Solar bursts recorded at 156 MHz and 164 MHz on 9 September 1950; (b) An absence of solar bursts at 156 MHz later the same day (after Blum and Denisse, 1950: 1215).

In the last three months of 1954 this radio telescope was used for another solar research program when Alon et al. (1955) investigated the one-dimensional distribution of radio brightness across the solar disk. First they derived a visibility curve for the Sun and then by making a Fourier transform of this curve they were able to calculate the integrated brightness of emission across the solar disk, perpendicular to the celestial equator (cf. Machin, 1951; Stanier, 1950). This is shown in Figure 7, where emission associated with a secondary lobe of the interferometer is apparent to the right of +1. On the basis of this Figure, Alon et al. (1955: 597; our translation) concluded that the diameter of the radio Sun, at 9,350 MHz, clearly exceeded that of the optical Sun, and that "The central part of this curve and the adjacent sloping edges are compatible with the existence of limb-brightening." Both of these conclusions confirmed earlier results obtained from French solar eclipse observations.
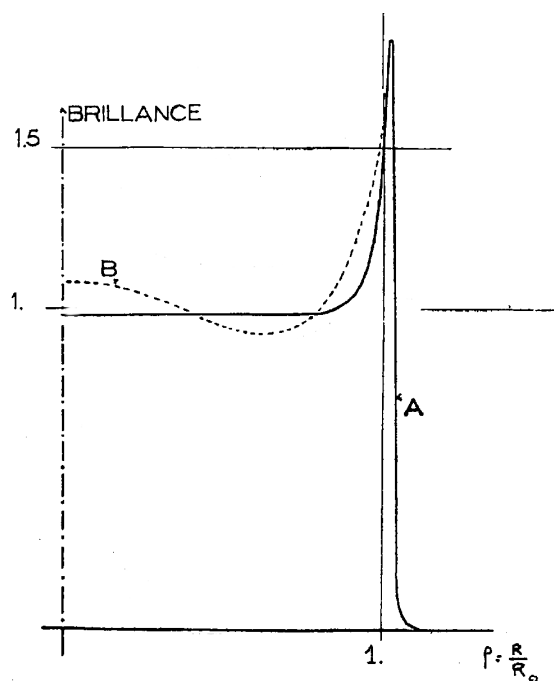
Figure 6: Alternative models (A and B) for limb-brightening at 9,350 MHz, developed from French solar eclipse observations (after Alon, Arsac and Steinberg, 1953: 301).

Finally, we should note that this 2-element interferometer has one further 'claim to fame' in that it inspired Jacques Arsac—one of the authors of the above studies—to develop a more elaborate interferometer (as discussed in Section 3.4 below).

3.4 Arsac's Non-Redundancy Array

Jacques Arsac (1955) pioneered the use of multi-element interferometers in French radio astronomy. Although he was well aware of Christiansen's East-West solar grating array at Potts Hill (Sydney), Arsac decided to take an independent approach, one which involved incomplete arrays:

> We stud[ied] incomplete arrays built with identic[al] antennae placed at abscissae equal to integer multiples of a same length, and deduced [i.e. reduced] from an uniform array by suppression of some of the antennae. With 4 antennae, 6 harmonics of same amplitude may be transmitted. It is impossible to get a constant spatial band pass with more than 4 antennae. Absence of one harmonic in the spatial band pass may introduce errors impossible to correct. (Arsac, 1956: 67; English abstract).

Arsac's primary inspiration came from French optical developments in interferometry, and in a long paper that was published in three installments he discussed
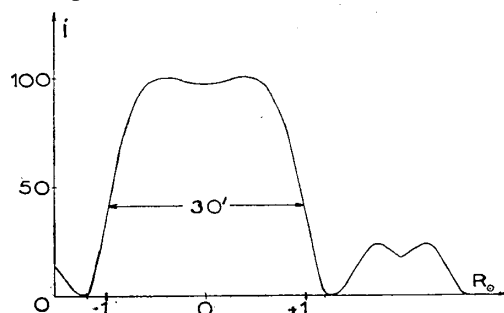

Figure 7: The integrated brightness of 9,350 MHz emission across the solar disk, based on interferometer observations (after Alon, Arsac and Steinberg, 1955: 597).

the concept of interferometry in a radio astronomical context (Arsac, 1956). His ultimate objective was to construct an array that would provide information on the one-dimensional distribution of emission across the solar disk.

Arsac's final result was the 'Arsac Interferometer', which was installed at Marcoussis in 1955 (Figure 8). This novel array comprised four solid metal antennas 1.1m in diameter and of 60cm focal length "… placed in positions 0, 1, 4, and 6, in a manner to supply six spatial frequencies of equal amplitude without redundancy." (Denisse, 1984: 304). The array operated at 9,350 MHz, and each antenna had a beamwidth of 2° in the plane of the meridian and 7° in the horizontal plane.

In addition to operating the non-redundancy array as an interferometer, because the grating lobes of the interferometer were separated from each other by 1°, it was possible to obtain six traverses of the Sun during each day's observations and obtain a chart record of the distribution of radio emission across the solar disk. Figure 9a shows the record obtained on 3 February 1955, while in Figure 9b the same scans obtained on three successive days have been superimposed. These two figures show that radio plages were absent at this time (the Sun was at sunspot minimum), thereby allowing an accurate determination of the mean base level of emission from the quiet Sun at 9,350 MHz. Similar determinations of this base level of emission at 1,420 MHz and 500 MHz, derived from observations carried out in Australia at about this time, were published by Christiansen and Warburton (1953) and Swarup and Parthasarthy (1955).

Soon after it was operational the Arsac Interferometer was transferred to Nançay, but although the promise was there—as clearly evidenced by Figures 9a and 9b—it was never used to produce any useful scientific results. Denisse (1984: 307) explains why:

> … the ingenious concept of the "Arsac network [= array]" could not be used then: the small dimensions of the antennas limited sensitivity and the technology did not permit, at that time, the accurate phase adjustments which the system required.

Monique Pick (personal communication, 2007) recalls that when she joined the Paris Observatory radio astronomy team at Nançay she and Arsac spent some time trying to rectify the phase problems, but in the end they had to admit defeat.

4 EARLY SOLAR RADIO ASTRONOMY AT NANÇAY

4.1 Introduction

Through its growing international reputation in ionospheric research and in radio astronomy Australia made a successful bid for the 1952 URSI Congress, which was held in Sydney (Bolton, 1953; Robinson, 2002). Laffineur from the Institut d'Astrophysique de Paris and Steinberg from the ENS were the sole radio astronomers in the French delegation, and they were particularly impressed by the radio telescopes they saw during visits to the CSIRO's Division of Radiophysics field stations at Dapto, Hornsby Valley and Potts Hill in or near Sydney.[2] Of special interest were the solar spectrographs that Paul Wild and his colleagues had erected at Dapto (Stewart, 2009) and the 1,420 MHz solar grating array constructed by Christiansen's group at Potts Hill (Wendt, Orchiston and Slee, 2008).
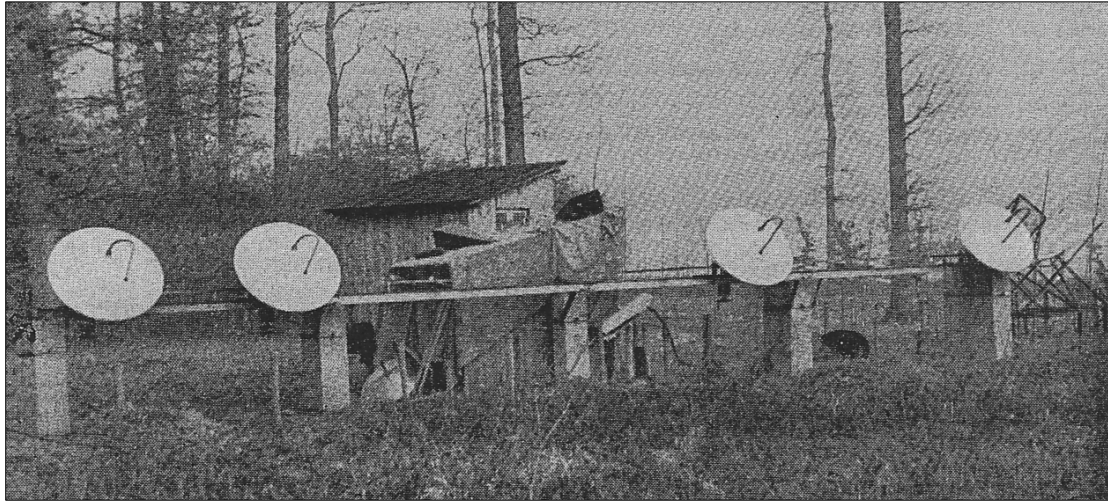
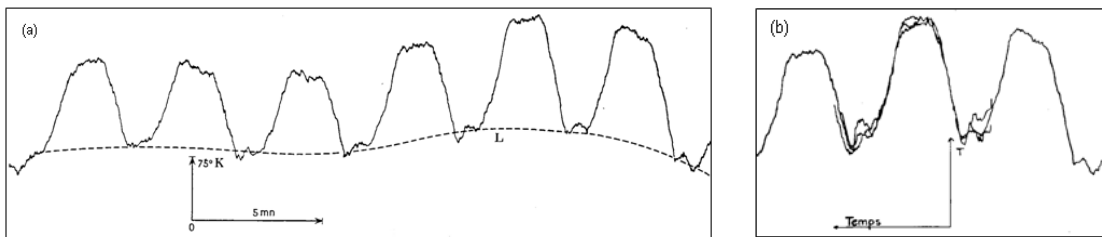Figure 8: The Arsac Interferometer at Marcoussis (after Arsac, 1956: 406).

Figure 9(a): Six scans of the Sun taken with the Arsac Interferometer on 3 February 1955; Figure 9(b): Superimposed solar scans taken on three successive days (after Arsac, 1956: 409).

Laffineur and Steinberg returned to France convinced that similar instruments were required for French radio astronomy. Steinberg's first action was to approach ENS Director Yves Rocard about the establishment of a dedicated radio astronomy field station at a radio-quiet site, and this led to the founding of Nançay in 1953. One year later the radio astronomy group was transferred from the ENS to the Paris Observatory (see Bourgois et al., 1989).[3]

4.2 The Two 'Searchlight Antenna' Radio Telescopes

One of the simplest radio telescopes at Nancay comprised two 'searchlight antennas', one of which was fixed (see Figure 10) while the other was moveable and mounted on a railway track. Each was attached to its own 9,350 MHz receiver. Simultaneous observations were carried out with both antennas and were compared, but the two antennas were never configured so that they could be used as an interferometer. Steinberg and Ilya Kazès used this system to investigate solar scintillations (see Kazès and Steinberg, 1957), and were able to show that these originated in the Earth's atmosphere (Kazès, 1957).

4.3 Kundu's 2-Element Interferometer

In 1956 Mukul Kundu began research for a D.Sc. at Nançay, setting up an interferometer comprising two 2m diameter equatorially-mounted dishes located on an east-west baseline (see Figure 11). The spacing between the two dishes was 60 metres. Figure 12 shows a schematic diagram of the receiving system. Kundu used this interferometer to study the size, brightness distribution, polarization and evolution of localised sources of solar radio emission at 9,350 MHz (i.e. a wavelength of 3.2 cm).

In order to measure the brightness distribution of localized solar sources, Kundu devised an interferometric system where the distance between the two antennas would change continually in the course of a day. This was the first two-element interferometer that used Earth rotation synthesis in one dimension. The reception pattern of such a system is a series of fringes, where the angular separation, dH, measured in the equatorial plane varies as a function of hour angle, H, is given by

$$dH \propto \lambda / D \cos H \qquad (1)$$

where λ is the wavelength (3.2 cm) and D is the distance between the two antennas (60m). By using two antennas which remain pointed on the Sun all day, observations could be made at different values of H, thereby exploring different regions of the Fourier spectrum of the angular brightness distribution of the source without altering the separation of the antennas.
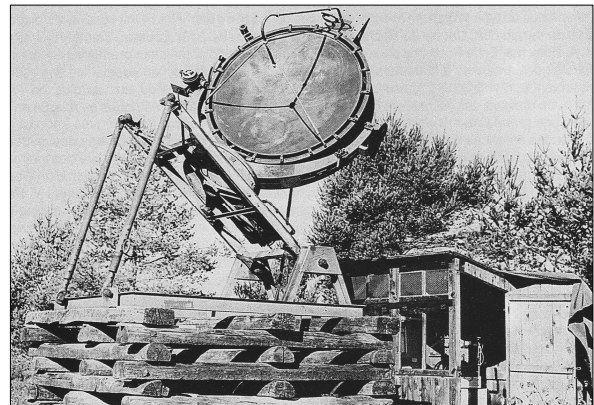

Figure 10: One of the two 'searchlight antenna' radio telescopes at Nançay (after Bourgois et al., 1989: 6).
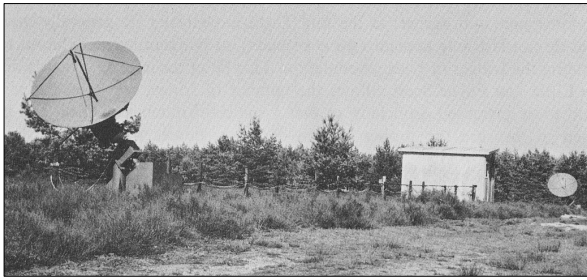
Figure 11: An image of the two antennas constituting the 'Kundu Interferometer' (after Steinberg and Lequeux, 1963: 66).

The resolving power varied continually from sunrise to noon and symmetrically during the afternoon. Therefore, it was possible to measure several Fourier components provided the orientation of the source relative to the fringes did not vary in the course of the day. The resolving power varied between 1.9′ and 6′ at the solstices and 1.8′ and 20′ arc at the equinoxes. When it was decided to carry out polarisation measurements, crossed feed horns were installed at the foci of the two antennas (Figure 13).
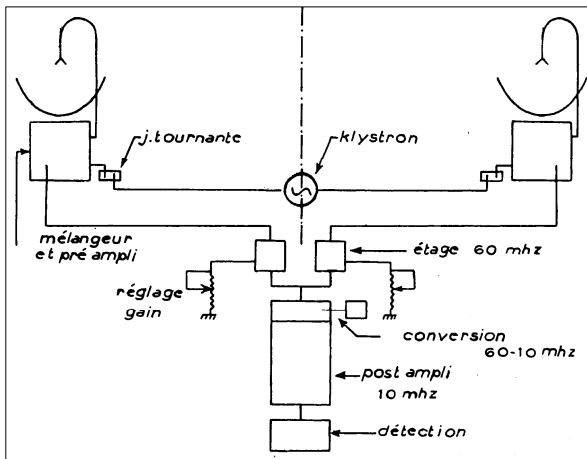

Figure 12: Schematic diagram of the interferometer/receiver system (after Kundu 1959b: 13).
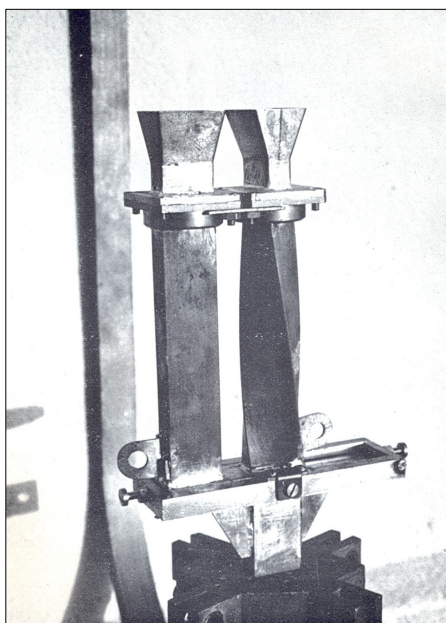

Figure 13: Two crossed feed horns whose E-vectors are perpendicular to each other (after Kundu, 1959b: facing 94).
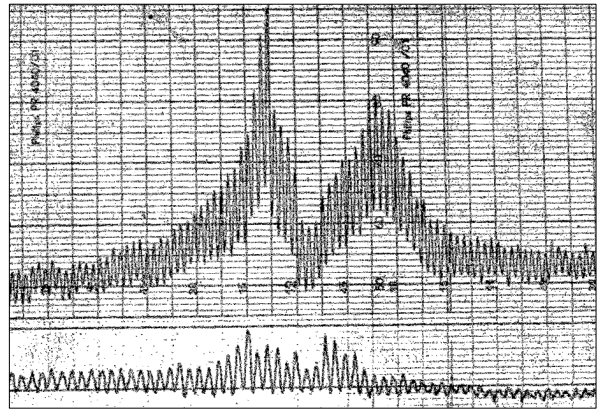

Figure 14: Chart records of the 25 January 1957 (top) and 17 January 1957 (bottom) outbursts (after Alon et al., 1957: 1728).

Alon, Kundu and Steinberg (1957) used the 2-element interferometer to study the diameters of radio plages. By measuring variations in the amplitudes of the observed interference fringes obtained near sunrise and sunset they were able to calculate the diameters of the radio-emitting regions, on the assumption that these were circular and did not vary appreciably in diameter in the course of one day's observation. They found that "… at least 75% of the energy from persistent sources was emitted from regions with diameters of 5′. Nevertheless, active regions were sometimes observed with diameters that were much smaller." (Alon et al., 1957: 1728; our translation). The authors also report observations of two outbursts observed in January 1957 where the fringe patterns (Figure 14) not only allowed them to determine the diameters of the two emitting sources, but to follow their evolution with the passage of time. They found that the 25 January event always had an apparent diameter >1′ while the diameter of the 17 January outburst remained <1′ throughout the course of the observations.

In a paper presented at the Paris Symposium on Radio Astronomy (Kundu, 1959a) and a long paper in *Annales d'Astrophysique* based on his D.Sc. thesis, Kundu (1959b) provides further details of his solar research at Nancay between 1956 and 1958. During these more extended observations, he differentiated radio plages ('persistent sources') from bursts. Radio plages were found to consist of a narrow bright region, associated with a more diffuse region, the corresponding optical phenomenon being a sunspot surrounded by faculae. Kundu found that the diameters of radio plages ranged between 1.5′ and 12′. Those sources with diameters ~1.5′ were relatively intense and their average brightness temperatures could reach as high as 500,000 K, that is, coronal temperatures (see Figure 15). Sources with larger diameters, (i.e. 10′-12′) had temperatures ~100,000 K.
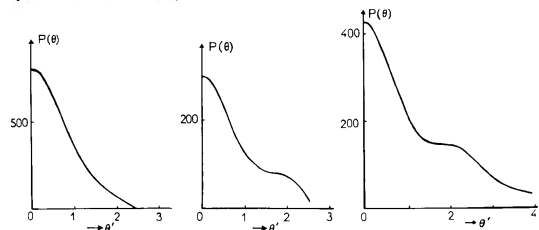

Figure 15: Brightness distributions of three typical radio plage sources; $P(\theta)$ is in arbitrary units and θ in minutes of arc (after Kundu, 1959a: 224).
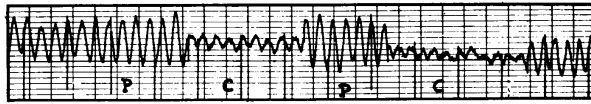
Figure 16: Chart record showing circular polarisation of a radio plage, where P indicates parallel polarisation and C crossed polarisation (after Kundu, 1959a: 233).

This core-halo structure typified radio plages, the core being circularly polarized and the halo unpolarized. The core corresponded to the umbra of a sunspot. The observed coronal temperatures of the brightness peak (core) of a sunspot-associated radio plage implied that the source was optically thick. This finding led subsequently to the conclusion that gyroresonance radiation was involved (see Kakinuma and Swarup, 1962; Zheleznyakov, 1962). In the gyroresonance radiation process, the opacity in the corona is produced by the acceleration of electrons as they gyrate in a magnetic field. The opacity is produced at resonant layers where the frequency matches harmonics of the gyrofrequency: $v = \omega_e$, $2\omega_e$, $3\omega_e$, etc., where $\omega_e = 2.8B$ is the electron gyrofrequency in MHz. Because ω_e is proportional to B, this provided a powerful tool that could be used to measure coronal magnetic fields.

Kundu's doctoral research also showed that the emission from radio plages was sometimes partially circularly polarized (Figure 16), and did not change appreciably in the course of the day. Figure 17 shows a typical example, where the polarized component of the radiation has a diameter <1.5′, while the source of the total radiation is much larger. Kundu's measurements showed that the narrow and bright regions in a complex of sources are polarized, while the more diffuse regions do not contribute to any polarization. The later finding that the polarized component of the radiation from persistent sources increases with eruptive activity on the Sun only served to confirm this result.

The appearance of narrow bright regions was found to be associated with periods of intense solar activity. This is shown in Figure 18 where the average fringe amplitude near noon expressed as a percentage of total solar radiation (this number is a measure of the intensity of the source of diameter less than approximately 2′) is plotted as a function of the number of bursts observed at 9,350 MHz during the same day. There is a good correlation between these bursts and chromospheric eruptions, so the probability of observing eruptions systematically increases with the intensity of narrow sources. Kundu concluded that a persistent source is likely to be an active center—the place of chromospheric eruptions and radio bursts—if it has a very localized bright region <1′ in size at centimeter wavelengths.
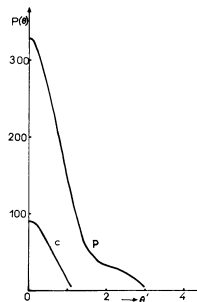

Figure 17: Brightness distribution of Type a sources showing parallel and crossed polarisation. $P(\theta)$ is in arbitary units and θ in minutes of arc (after Kundu, 1959a: 233).
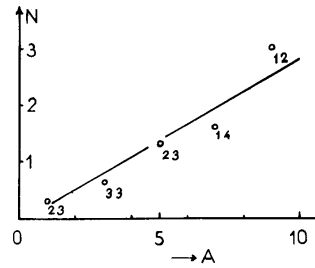

Figure 18: Plot of the average number of bursts observed per day (N) versus the average amplitude of fringes (A) near local noon, expressed as a percentage of total solar radiation. The number of days used in calculating the various points are listed beside the points (after Kundu, 1959a: 225).

In additon to the study of radio plages, between 1956 and 1958 Kundu made a systematic study of solar burst emission at 9,350 MHz, with particular interest in source sizes and their evolution with time.

At this frequency there were at least three distinct types of bursts:

Type a: This is a simple burst, and typically has a duration of several minutes.

Type b: This burst immediately follows a Type a burst, and is indicated by an enhanced level of emission that lasts longer than the Type a burst.

Type c: This burst exhibits a gradual rise and fall which manifests a weak and gradual intensity increase followed by an equally slow decline. The duration of this burst is longer than that of Type a bursts.

Large bursts or outbursts were also observed at 9,350 MHz, but they were rare and often were complex. They were generally associated with bursts of spectral Type IV seen at metre wavelengths (for example, the events of 16 and 20 November 1956, 1 and 3 June 1957, and 3 and 23 March 1958). They were always polarized. Figure 19 shows the evolution of a large 9,350 MHz burst that was associated with a burst of spectral Type IV at 169 MHz.

Kundu was also able to confirm the existence of the bursts of very weak intensity found by Covington at 2,800 MHz (see Dodson et al., 1954), but which he could not prove to be of solar origin (since with a single antenna it is often difficult to distinguish bursts from external interferences or instabilities produced in the receiver). With the Nançay interferometer it was easy to recognize solar bursts because they manifest generally as an increase in the amplitude of the interference fringes. We now know that weak solar bursts, transients and microbursts exist across the electromagnetic spectrum, from microwaves to X-rays.
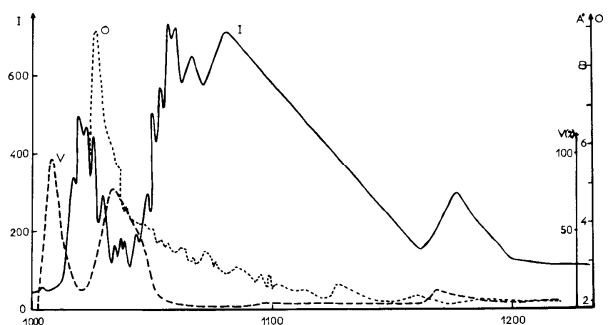

Figure 19: Variations in the intensity (I) and visibility (V) of the 20 November 1956 outburst between 1000 and 1200 UT. Also plotted is the light curve of the associated optical event (O) (after Kundu, 1959a: 230).

Assuming a regular source structure, Kundu used the observed fringe visibility to calculate the effective sizes of the sources of the bursts observed at Nançay. Figure 20 shows a typical simple source (its intensity and fringe visibility). He measured the size of each observed burst at the time of its maximum intensity, and the results are shown in Figure 21 where source diameter is plotted as a function of intensity. It can be seen that source size increases slightly with intensity. Source sizes larger than 2.5′ are rare. Thus, Type a burst sources on average seem to have diameters ~1′ for weaker bursts (with intensities <10% of the quiet Sun intensity), and ~1.6′ for more intense bursts. The source sizes of bursts of Types b and c are shown in Figure 22 where the number of bursts of each type corresponding to a certain visibility is plotted, except for some bursts of Type b whose visibilities correspond to a fringe spacing of approximately 2′. It can be seen that the bursts can be separated easily into two families: Type b bursts have a small visibility and thus a large size, while Type c bursts have a very high visibility, on average 70%, corresponding to small sizes (i.e. ~0.8′). The sources of the large bursts associated with Type IV emission were typically found to be ~2′.
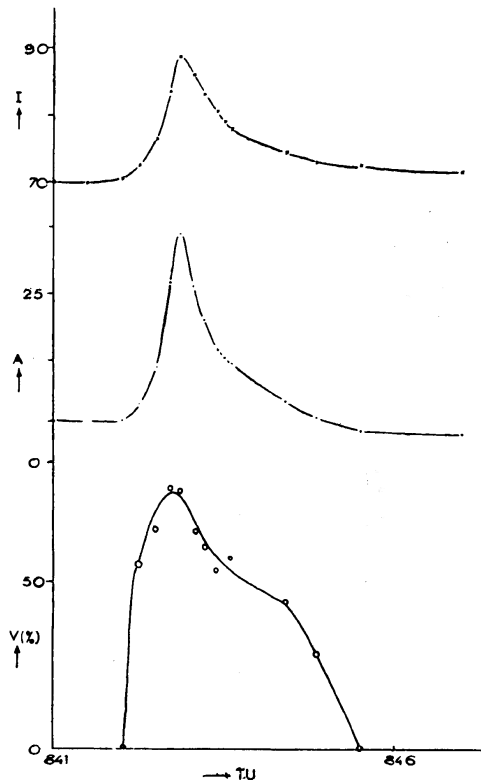

Figure 20: Evolution of a simple burst with time, showing that maximum visibility (V) occurs near the maximum intensity (I). A is the fringe amplitude, and TU is universal time (after Kundu, 1959b: 41).

Kundu was also able to investigate the evolution of source size during the duration of bursts. For a typical burst of Type a, the apparent size was found to be at a minimum about the time the burst reached maximum intensity. However, complex bursts were observed which sometimes showed a remarkably constant visibility despite great variations in intensity. In such cases the emissive sources would have experienced large variations in brightness without any appreciable variations in size. More complex variations of visibili-

ty during a burst were usually explained by a combination of the three fundamental types of bursts which are outlined on page 183.

As an example, Kundu studied the evolution in intensity and dimension of the complex burst observed on 20 November 1956 which was associated with a Type IV burst at 169 MHz. The intensity and visibility are plotted in Figure 19 as a function of time. The burst began with a precursor at 10:02:27 UT, and at that time the source was practically a point source, the visibility being 90% for a fringe spacing of 2′. The major radio burst began at 10:08 UT, and reached a maximum at 10:12 UT. At this time the visibility was 20%, indicating that the source had become larger. The major burst seemed to go through a period of minimum intensity and small diameter at 10:20 UT, and then the intensity rapidly increased again and reached a broad maximum around 10:35 UT. After that the intensity began to decrease, and this was accompanied by decreasing visibility. Kundu could only explain these variations of intensity and visibility during the burst by assuming the existence of several different radio sources.

The last phase of emission corresponded to a source of very large diameter, which was produced at the same time as the Type IV emission observed at 169 MHz. These emissions varied in parallel at the two frequencies and certainly were of the same origin. We now know that the Type IV burst is a broad-band continuum which occurs in different phases, and covers a wide range of frequencies from microwave to meter-decameter waves.

Since both the Nançay bursts and optical eruptions had their origin in the chromosphere, Kundu found it interesting to compare their intensities and sizes. The dimensions of optical eruptions were found to be smaller than their radio counterparts, with diameters of about 0.5′ and 1-2′ respectively.

The brightness temperature of Type a bursts was found to reach several tens of millions of degrees, so they are probably not of thermal origin, and the same situation was found to hold for the large bursts associated with Type IV emission. Kundu found that the brightness temperature of bursts of the gradual rise and fall type did not exceed 10^6 degrees, and therefore could be of thermal origin.

Kundu also investigated the polarization of 42 of the bursts observed at Nançay, and he found that 26 (i.e. 60%) were polarized, with the degree of polarization generally varying from a few per cent to 50%. Bursts with polarization exceeding 50% were exceptional. Bursts of the gradual rise and fall type were always circularly polarized, while the large bursts associated with Type IV events were weakly polarized. Moreover, the polarized component of the radiation was found to originate from a source whose intensity was weak and almost constant. Kundu pointed out that it was important to note that after a large burst ended it left behind a radio plage which was strongly polarized (>50%) for long periods—for several hours in some cases.

While metric bursts of Types II and III in general were not polarized, the Nançay observations showed that most of the 9,350 MHz bursts associated with these metric bursts were polarized.

5 DISCUSSION

5.1 Scientific Results

While he and his colleagues were busy setting up their first radio telescopes, Denisse also directed his attention to non-observational matters. Consequently, the first papers published by the young ENS solar group dealt solely with theoretical issues. We believe that some of Denisse's papers are important in the overall history of solar radio astronomy, but because they were written in French, at the time they were published they did not reach as wide an international audience as they undoubtedly deserved. For example, in 1946 Denisse published a paper discussing the role of solar magnetic fields in producing what he termed 'gyro-magnetic radiation' (cf. Kiepenheuer, 1946), foreshadowing by several years pronouncements by Ginsburg (1953) and Shklovsky (1953) on synchrotron radiation, while in 1949 he suggested that coronal temperatures of between 2 and 8 million degrees existed in the corona in regions above sunspots (although he seems unaware—at the time—of the earlier papers by Martyn (1946) and Pawsey (1946) where a coronal temperature of 1 million Kelvin was proposed on the basis of theoretical considerations and radio observations respectively).

5.2 Instrumentation

French experiments in solar radio astronomy mirrored overseas trends, where it was quickly realised that dedicated solar instruments offered significant advantages over recycled WWII equipment. Initial experiments focussed on simple 2-element interferometers, but Christiansen's multi-element grating array in Australia inspired Arsac, Blum, Boischot, Gutmann (later Pick) and Steinberg to consider more ambitious designs.

Of all the early radio telescopes discussed in this paper, we believe that the Kundu Interferometer and the Arsac Interferometer stand out as exceptional. Kundu's 2-element interferometer was the first to use Earth rotation synthesis to produce a one-dimensional distribution of solar radio emission, and it made an important contribution to solar physics (see Pick and Vilmer, 2008). In stark contrast, the Arsac Interferometer did not contribute in any meaningful way to solar research, yet this innovative interferometer occupies an important place in the history of radio astronomy in that it paved the way for all future non-redundancy arrays of this type.

5.3 Heritage Considerations

The IAU's Historic Radio Astronomy Working Group is particularly interested in establishing how many of the early radio telescopes used world-wide prior to 1961 have survived, and it is a sad fact that none of the instruments discussed in this paper still exists.

6 CONCLUDING REMARKS

Of the material contained in the various observational papers discussed here, in our opinion the French solar eclipse observations and Kundu's interferometer observations were both internationally significant.

The eclipse observations revealed the shape of the solar corona at radio wavelengths, while other obser-
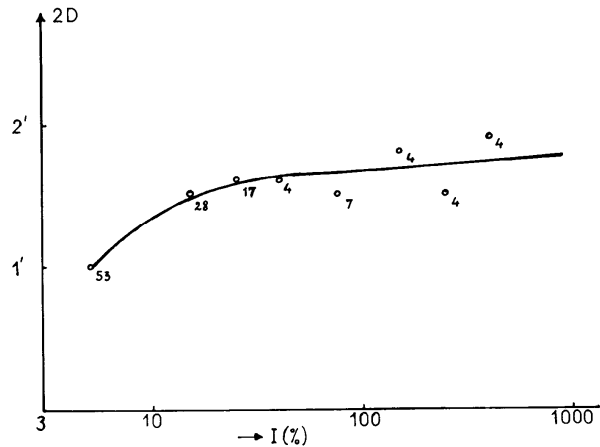

Figure 21: Plot of the average diameter (2D) of bursts as a function of their maximum intensity (I); 2D is in minutes of arc and I as a percentage of total radiation, The number of bursts used in calculating the average for each point is listed beside the point (after Kundu, 1959a: 228).

vations by the ENS team confirmed the finding of previous researchers, namely that limb-brightening occurred at 9,350 MHz (even if their result could not distinguish between the two competing models in vogue at the time). As a result of these investigations and other research carried out at the time, by the end of the 1950s Denisse's group was "… among the most active in the field of solar radio astronomy [internationally], a fact which was demonstrated by the organisation of a symposium on radio astronomy in Paris in 1958 …" (Denisse, 1984: 310).

Meanwhile, observations made with the Kundu Interferometer provided new information at 9,350 MHz on the apparent size, brightness distribution, polarization and evolution of the sources associated with radio plages and bursts, and new clues to their interpretation and their association with corresponding phenomena observed at optical, decimeter and meter wavelengths.

Finally, we must stress that this paper only reviews the early solar radio astronomy at Nançay, which served as a prelude to the construction there of three truly impressive solar research instruments. In 1956 a 32-element East-West solar grating array was completed and three years later it was joined by an 8-element North-South array. Both operated at 169 MHz and were known affectionately as the 'Grand Interféro-
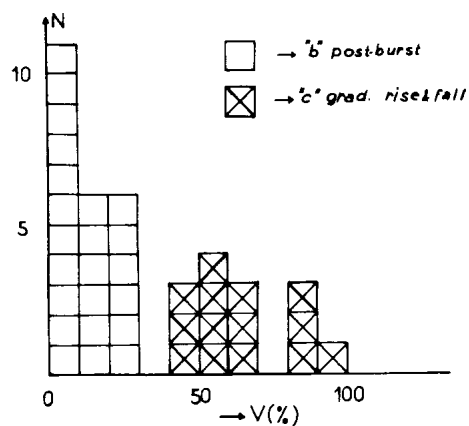

Figure 22: Distribution of the number of bursts (N) of Types b and c as a function of their visibility (V) (after Kundu, 1959a: 229).

mètre' (see Denisse, 1984: 308-309). Meanwhile, the year 1958 marked the completion of another ingenious Nançay radio telescope in the form of a 16-element East-West array which was designed to investigate the one-dimensional distribution of emission across the solar disk at 9,350 MHz (see Denisse, 1984: 307-308). Details of these radio telescopes and their research accomplishments will be the subject of the next paper in this series.

7 NOTES

1. This project was initiated under the auspices of the IAU Working Group on Historic Radio Astronomy in 2006, and three papers have been published to date. The first dealt with Nordmann's attempt to detect solar radio emission in 1901 (Débarbat et al., 2007); the second with early solar eclipse observations (Orchiston and Steinberg, 2007); and the third with the Würzburg antennas that were at Marcoussis, Meudon and Nançay (Orchiston et al., 2007).
2. In 1952, Dapto, Hornsby Valley and Potts Hill were three of the four field stations maintained by the Division of Radiophysics in and near Sydney. The fourth field station was located at Dover Heights. For a review of these field stations, and others established by the Division of Radiophysics between 1946 and 1961, see Orchiston and Slee, 2005.
3. For further details of the establishment of the Nançay field station and the transfer of the radio astronomers from the ENS to Paris Observatory see Orchiston et al., 2007: 225-226.

8 ACKNOWLEDGEMENTS

9 REFERENCES

Alon, I., Arsac, J., and Steinberg, J.-L., 1953. Sur la distribution de la brillance radioélectrique sur le Soleil à la fréquence de 9350 Mc/s. *Comptes Rendus de l'Académie des Sciences*, 237, 300-302.

Alon, I., Arsac, J., and Steinberg, J.-L., 1955. Observations interférométriques du rayonnement solaire sur 9350 MHz. *Comptes Rendus de l'Académie des Sciences*, 240, 595-598.

Alon, I., Kundu, M.R., and Steinberg, J.-L., 1957. Dispositif interférométrique pour l'étude des sources solaires localisées centimétriques. *Comptes Rendus de l'Académie des Sciences*, 244, 1726-1729.

André, P., Kazès, I., and Steinberg, J.-L., 1956. Mésure de l'absorption atmosphérique sur 9350 MHz utilisant le rayonnement radioélectrique solaire. *Comptes Rendus de l'Académie des Sciences*, 242, 2099-2101.

Appleton, E.V., 1945. Departure of long-wave solar radiation from black-body intensity. *Nature*, 156, 534.

Arsac, J., 1955. Étude Théorique des Réseaux d'Antennes en Radioastrononie et Réalisation Expérimentale de l'un d'eux. Unpublished Ph.D. Thesis.

Arsac, J., 1956. Étude interférométrique des répartitions de luminances en radioastronomie. *Revue d'Optique Théoretique et Instrumentale*, 35, 65-95, 136-165, 396-413.

Arsac, J., André, P., and Zaccai, R., 1954. Sur les pertes dans les lignes a fils parallèles. *Onde Electrique*, 34, 170-177.

Arsac, J., Blum, E.-J., Lestel, H., and Steinberg, J.-L., 1953. Sur deux radiomètres U.H.F. (160 MHz et 9.350 MHz) et quelques applications radioastronomiques. *Onde Electrique*, 33, 527-532.

Blum, E.-J., and Denisse, J.-F., 1950. Comparaison des rayonnements radioélectriques reçus du Soleil sur deux fréquences voisines. *Comptes Rendus de l'Académie des Sciences*, 231, 1214-1216.

Blum, E.-J., Denisse, J.-F., and Steinberg, J.-L., 1951a. Étude des orages radioélectriques solaires de faible intensité. *Comptes Rendus de l'Académie des Sciences*, 232, 387-389.

Blum, E.-J., Denisse, J.-F., and Steinberg, J.-L., 1951b. Sur l'interprétation des sursauts radioélectriques solaires. *Comptes Rendus de l'Académie des Sciences*, 232, 483-485.

Blum, E.-J., Denisse, J.-F., and Steinberg, J.-L., 1952. Sur la forme ellipsoïdale du Soleil observé en ondes métriques. *Comptes Rendus de l'Académie des Sciences*, 234, 1597-1599.

Bolton, J.G., 1953. Radio astronomy at U.R.S.I. *The Observatory*, 73, 23-26.

Bourgois, G., Gérard, E., Pick, M., and Steinberg, J.-L., 1989. *Histoire du Centre de Radioastronomie de Nançay*. Paris, Observatoire de Paris.

Bracewell, R.N. (ed.), 1959. *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press.

Christiansen, W.N., 1984. The first decade of solar radio astronomy in Australia. In Sullivan, 113-131.

Christiansen, W.N., and Warburton, J.A., 1953. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part II - The Quiet Sun - one dimensional observations. *Australian Journal of Physics*, 6, 262-271.

Covington, A.E., 1984. Beginnings of solar radio astronomy in Canada. In Sullivan, pp. 317-334.

Débarbat, S., Lequeux, J., and Orchiston, W., 2007. Highlighting the history of French radio astronomy. 1: Nordmann's attempt to detect solar radio emission in 1901. *Journal of Astronomical History and Heritage*, 10, 3-10.

Denisse, J.-F., 1946. Étude des conditions d'émission par l'atmosphère solaire d'ondes radioélectriques métriques. *La Revue Scientifique de la France et de l'étranger*, 84, 259-262.

Denisse, J.-F., 1947a. Contribution à l'étude des émissions solaires dans le domaine des ondes radioélectriques ultra-courtes. *Annales d'Astrophysique*, 10, 1-13.

Denisse, J.-F., 1947b. Sur les émissions radioélectriques solaires. *Comptes Rendus de l'Académie des Sciences*, 225, 1358-1360.

Denisse, J.-F., 1949a. Relations entre les émissions solaires radioélectriques et les rayons cosmiques. *Comptes Rendus de l'Académie des Sciences*, 228, 467-469.

Denisse, J.-F., 1949b. Influence de l'indice de réfraction sur les émissions radioélectriques d'un milieu ionisé. *Comptes Rendus de l'Académie des Sciences*, 228, 751-753.

Denisse, J.-F., 1949c. Relation entre les émissions radioélectriques solaires décimétriques et les taches du Soleil. *Comptes Rendus de l'Académie des Sciences*, 228, 1571-1572.

Denisse, J.-F., 1950a. Contribution à l'étude des émissions radioélectriques solaires. *Annales d'Astrophysique*, 13, 181-202.

Denisse, J.-F., 1950b. Émissions radioélectriques d'origine purement thermique dans les milieux ionisés. *Le Journal de Physique et le Radium*, 11, 164-171.

Denisse, J.-F., 1952. Relation entre l'activité géomagnétique et l'activité radioélectrique solaire. *Annales de Géophysique*, 8, 55-64.

Denisse, J.-F., 1953a. Les centres solaires d'activité radio-électrique et leur influence sur l'activité géomagnétique. *Ciel et Terre*, 69, 53-67.

Denisse, J.-F., 1953b. Relations entre les phénomènes solaires et terrestres. *Comptes Rendus de l'Académie des Sciences*, 236, 1856-1858.

Denisse, J.F., 1956. La radioastronomie et l'activité solaire. *Ciel et Terre*, 72, 205-214.

Denisse, J.-F., 1984. The early years of radio astronomy in France. In Sullivan, 303-315.

Denisse, J.-F., and Rocard, Y., 1951. Excitation d'oscillations électroniques dans une onde de choc. Applications radioastronomiques. *Le Journal de Physique et le Radium*, 12, 893-899.

Denisse, J.-F., and Simon, P., 1954. Relation entre l'apparition de la raie jaune coronale et l'activité géomagnétique. *Comptes Rendus de l'Académie des Sciences*, 238, 1775-1778.

Denisse, J.-F., Steinberg, J.-L., and Zisler, S., 1951. Contrôle de l'activité géomagnétique par les centres d'activité solaires distingues par leurs propriétés radioélectriques. *Comptes Rendus de l'Académie des Sciences*, 232, 2290-2292.

Dodson, H.W., Hedeman, E.R., and Covington, A.E., 1954. Solar flares and associated 2800 mc/sec (10.7 cm) radiation. *Astrophysical Journal*, 119, 541-563.

Edge, D.O. and Mulkay, M.J., 1976. *Astronomy Transformed: The Emergence of Radio Astronomy in Britain*. New York, John Wiley.

Ginsburg, V.L., 1953. The origin of cosmic rays and radio astronomy. *Uspekhi Fiz. Nauk*, 51, 343-392 (in Russian).

Hey, J.S., 1946. Solar radiations in the 4.6 metre radio wave-length band. *Nature*, 157, 47-48.

Hey, J.S., 1973. *The Evolution of Radio Astronomy*. London, Elek Science.

Jorand, M., 1953. Le rayonnement radioélectrique des taches solaires sur 160 Mc/sec de 1948 à 1951. *Annales d'Astrophysique*, 16, 151-161.

Jorand, M., 1955. Contribution à l'étude des orages radioélectriques solaires. *Annales d'Astrophysique*, 18, 180-187.

Kakinuma, T., and Swarup, G., 1962. A model for the sources of the slowly varying component of microwave solar radiation. *Astrophysical Journal*, 136, 975-994.

Kazès, I., 1957. Étude de la scintillation du Soleil observée sur la longeur d'onde de 3,2 cm. *Comptes Rendus de l'Académie des Sciences*, 245, 636-639.

Kazès, I., and Steinberg, J.-L., 1955. Étude du rayonnement radioélectrique solaire sur 9350 MHz, au voisinage du coucher et du lever du Soleil. *Comptes Rendus de l'Académie des Sciences*, 240, 493-495.

Kazès, I., and Steinberg, J.-L., 1957. Étude de la scintillation du Soleil observée avec plusieurs antennes sur la longueur d'onde de 3,2 cm. *Comptes Rendus de l'Académie des Sciences*, 245, 782-785.

Kiepenheuer, K.-O., 1946. Origin of solar radiation in the 1-6 metre radio wave-length band. *Nature*, 158, 340.

Kundu, M., 1959a. Étude interférométrique des sources d'activité solaire sur 3 cm de longueur d'onde. In Bracewell, 222-236.

Kundu, M., 1959b. Structures et propriétés des sources d'activité solaire sur ondes centimétriques. *Annales d'Astrophysique*, 22, 1-100.

Laffineur, M., Michard, M., Servajean, R., and Steinberg, J.-L., 1950. Observations radioélectriques de l'éclipse de Soleil du 28 Avril 1949. *Annales d'Astrophysique*, 13, 337-341.

Laffineur, M., Michard, R., Steinberg, J.-L., and Zisler, S., 1949. Observations radioélectriques de l'éclipse de Soleil du 28 Avril 1949. *Comptes Rendus de l'Académie des Sciences*, 228, 1636-1637.

Lovell, B., 1977. The effects of defence science on the advance of astronomy. *Journal for the History of Astronomy*, 8, 151-173.

Machin, K.E., 1951. Distribution of radiation across the solar disk at a frequency of 81.5 Mc/s. *Nature*, 167, 889-891.

Martyn, D.F., 1946. Temperature radiation from the quiet Sun in the radio spectrum. *Nature*, 158, 632-633.

Mosnier, J., and Steinberg, J.-L., 1950. Sur la distribution spectrale énergétique des fluctuations de sortie d'un récepteur. *Comptes Rendus de l'Académie des Sciences*, 230, 438-440.

Orchiston, W., 2005. Dr Elizabeth Alexander: first female radio astronomer. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth*. Dordrecht, Springer. Pp. 71-92.

Orchiston, W., and Slee, B., 2002. The Australasian discovery of solar radio emission. *Anglo-Australian Observatory Newsletter*, 101, 25-27.

Orchiston, W. and Slee, B. 2005. The Radiophysics field stations and the early development of radio astronomy. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth*. Dordrecht, Springer. Pp. 119-168.

Orchiston, W., and Steinberg, J.-L., 2007. Highlighting the history of French radio astronomy. 2: The solar eclipse observations of 1949-1954. *Journal of Astronomical History and Heritage*, 10, 11-19.

Orchiston, W., Slee, and Burman, R., 2006. The genesis of solar radio astronomy in Australia. *Journal of Astronomical History and Heritage*, 9, 35-56.

Orchiston, W., Lequeux, J., Steinberg, J.-L., and Delannoy, J., 2007. Highlighting the history of French radio astronomy. 3: The Würzburg antennas at Marcoussis, Meudon and Nançay. *Journal of Astronomical History and Heritage*, 10, 221-245.

Pawsey, J.L., 1946. Observation of million degree thermal radiation from the Sun at a wave-length of 1.5 metres. *Nature*, 158, 633-634.

Pick, M., and Vilmer, N., 2008. Sixty-five years of solar radio-astronomy: flares, coronal mass ejections and Sun-Earth connection. *Astronomy and Astrophysics Review*, 16, 1-153.

Reber, G., 1946. Solar radiation at 480 Mc.sec. *Nature*, 158, 945.

Robinson, B., 2002. Recollections of the URSI Tenth General Assembly, Sydney, Australia, 1952. *Radio Science Bulletin*, 300, 22-30.

Rocard, Y., 1951. Sur un mécanisme d'émission radioélectrique coronale. *Comptes Rendus de l'Académie des Sciences*, 232, 598-600.

Schott, E., 1947. 175 Mhz-Strahlung der Sonne. *Physikalische Blätter*, 3, 159-160.

Shklovsky, I.S, 1953. The problem of cosmic radio waves. *Astronomicheskii Zhurnal*, 30, 15-36 (in Russian).

Simon, P., 1956. Centres solaires radioémissifs et non radio-émissifs. *Annales d'Astrophysique*, 19, 122-141.

Southworth, G.C., 1945. Microwave radiation from the Sun. *Journal of the Franklin Institute*, 239, 285-297.

Stanier, H.M., 1950. Distribution of radiation from the undisturbed Sun at a wave-length of 60-cm. Nature, 165, 354-355.

Steinberg, J.-L., 1949. Les conditions de sensibilité maximale des radiomètres hyperfréquence. *Onde Electrique*, 29, 160-166.

Steinberg, J.-L., 1950. Sur la théorie des amplificateurs semidistribués. *Onde Electrique*, 30, 121-127.

Steinberg, J.-L., 1952a. Les récepteurs de bruits radioélectriques: I. Mesure des températures au moyen du rayonnement thermique en hyperfréquences. *Onde Electrique*, 32, 445-454.

Steinberg, J.-L., 1952b. Les récepteurs de bruits radioélectriques: II. Fluctuations de gain de radiomètres, emploi d'une modulation. *Onde Electrique*, 32, 519-526.

Steinberg, J.-L., 1953. Les récepteurs de bruits radioélectriques: III. Un radiomètre 1200 MHz et quelques applications. *L'Onde Electrique*, 33, 274-284.

Steinberg, J.-L., 2001. The scientific career of a team leader. *Planetary and Space Science*, 49, 511-522.

Steinberg, J.-L., 2004. La création de la station de Nançay. *L'Astronomie*, 118, 626-631.

Steinberg, J.L., and Lequeux, J., 1963. *Radio Astronomy*. New York, McGraw-Hill.

Stewart, R.T., 2009. The Contribution of the CSIRO Division of Radiophysics Penrith and Dapto Field Stations to International Radio Astronomy. Ph.D. Thesis, Centre for Astronomy, James Cook University (Townsville, Australia).

Strom, R., 2005. Radio astronomy in Holland before 1960: just a bit more than HI. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth.*. Dordrecht, Springer. Pp. 93-106.

Sullivan, W.T. (ed.), 1984. *The Early Years of Radio Astronomy: Reflections Fifty Years after Jansky*. Cambridge, Cambridge University Press.

Sullivan, W.T., 2005. The beginnings of Australian radio astron-

omy. *Journal of Astronomical History and Heritage*, 8, 11-32.

Swarup, G., and Parthasarthy, R., 1955. Solar brightness distribution at a wavelength of 60 centimetres. I. The quiet Sun. *Australian Journal of Physics*, 8**,** 487-497.

Wendt, H.W., Orchiston, W., and Slee, B., 2008. W.N. Christiansen and the development of the solar grating array. *Journal of Astronomical History and Heritage*, 11, 173-184.

Woerden, H. van, and Strom, R., 2006. The beginnings of radio astronomy in The Netherlands. *Journal of Astronomical History and Heritage*, 9, 3-20.

Zheleznyakov, V.V., 1962. The origin of the slowly varying component of solar radio emission. *Soviet Astronomy - AJ*, 6, 3-9.

Dr Wayne Orchiston is an Associate Professor in Astronomy at James Cook University, Townsville. His main research interests relate to Cook voyage, Australian, French and New Zealand astronomical history, with emphasis on the history of radio astronomy, comets, historically-significant telescopes, early astronomical groups and societies, and transits of Venus. He has published extensively, and has edited the book *The New Astronomy. Opening the Electromagnetic Window and Expanding our View of Planet Earth* (Springer, 2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan and Jessica Chapman, which (hopefully) will be published by Springer in 2010. Until the Rio General Assembly of the IAU Wayne was Chairman of the IAU Working Group on Historic Radio Astronomy.

Dr Jean-Louis Steinberg began working in radio astronomy with J.-F. Denisse and E.-J. Blum at the École Normale Supérieure after World War II. On his return from the 1952 URSI Congress in Sydney, he began developing the Nançay radio astronomy field station, and from 1960 to 1965 he and M. Parise led the design and construction at Nançay of 'Le Grand Radiotélescope'. In 1965, he began developing space research at Meudon Observatory. In 1960 Jean-Louis and J. Lequeux wrote a text book on radio astronomy, which was subsequently translated into English and Russian. In 1962 he was appointed Editor-in-Chief of *Annales d'Astrophysique*, which he and his wife ran until 1969. For the next five years he was one of the two Editors-in-Chief of *Astronomy and Astrophysics*. Jean-Louis has authored or co-authored about 80 scientific publications, and has received several scientific prizes and awards.

Dr Mukul Kundu is presently an Emeritus Professor of Astronomy at the University of Maryland. He was educated mostly in India. Like many young men of his generation at the time, he was anxious to go abroad for higher studies. The 1952 URSI General Assembly in Sydney probably oriented him in the direction of radio astronomy.

Mukul then decided to go to Paris, on a French Government scholarship, with the objective of becoming a radio astronomer. He joined the École Normale Supérieure, and began working at Marcoussis with Arsac and Alon on the Arsac Interferometer. He then constructed the 2-element interferometer at Nançay that contributed solar data for his Doctor of Science at the Sorbonne. After a Post-doctoral Fellowship at the University of Michigan (Ann Arbor), Mukul accepted Professorships at Cornell University, the Tata Institute of Fundamental Research in Mumbai (India) and finally at the University of Maryland, where he was the Director of Astronomy for seven years.

Dr Jacques Arsac began working in radio astronomy in 1952 in the Physics Laboratory of École Normale Supérieure where he developed and used interferometric antennas for solar radio observations at centimeter wavelengths. He also developed the theory of interferometric antennas and the analysis of their performance for various types of observations. From 1956 onward he specialized in numerical calculations, learnt to use electronic computers, and ran the first Paris Observatory computing centre, using it to reduce astronomical data and contributing a lot to computer science.

Dr Emile-Jacques Blum was a retired astronomer from l'Observatoire de Paris. His main interests lay in radio astronomy technology, in particular the design and construction of sensitive receivers. He was deeply involved in various radio astronomy projects: solar eclipse observation in Africa; solar observations at Nançay with a 32-element meter wave interferometer; and the formation of the Institut de Radioastronomie Millimétrique (IRAM) and the building of its interferometer. Emile-Jacques was a Chairman of URSI Commission V, and served as a member of time-allocation committees in the US (at the NRAO), Germany (MPIfR), and in the Netherlands (ASTRON). It is with great sadness that we report that he died on 22 September 2009, long after this paper was completed but before this issue of the *Journal* went to press.

Dr André Boischot joined the French group of radio astronomers in 1954 at the beginning of the Nançay Observatory. He was first involved with Emile-Jacques Blum in the design and construction of the 32-element E-W 169 MHz solar array. He then worked with Le Grand Radiotélescope at Nançay on non-solar projects. Then, he initiated a new program to observe the Sun and Jupiter at decametric wavelengths and was co-investigator on the NASA 'Voyager' radio astronomy experiment where he studied the magnetospheres of the outer planets.