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HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY. 3: THE WÜRZBURG ANTENNAS AT MARCOUSSIS, MEUDON AND NANÇAY

Wayne Orchiston
Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
E-mail: Wayne.Orchiston@jcu.edu.au

James Lequeux
LERMA, Paris Observatory, 61 av de l'Observatoire, 75014, Paris, France.
E-mail: James.Lequeux@obspm.fr

Jean-Louis Steinberg
Paris Observatory (Meudon), Place Jules Janssen, F-92 195 Meudon Cedex, France.
E-mail: chapias1922@orange.fr

and

Jean Delannoy
244 Chemin de Clos-Marchand, 38330 St. Ismier, France.
E-mail: sylv.delannoy@infonie.fr

Abstract: During the 1940s and 1950s ex-World War II 7.5m Würzburg radar antennas played a crucial role in the early development of radio astronomy in a number of European nations. One of these was France, where three different antennas began to be used during the late 1940s. Two of these were associated with the École Normale Supérieure in Paris, and were initially sited at Marcoussis, near Paris, before being transferred to the Nançay field station in 1957. The third Würzburg antenna was used by staff from the Institut d'Astrophysique de Paris, and was installed at Meudon Observatory on the outskirts of Paris. This paper describes the three antennas, lists the personnel involved, discusses the observations made, evaluates the significance of this research in a national and international context, and comments on their current whereabouts.

Keywords: Würzburg antenna, École Normale Supérieure, Institut d'Astrophysique de Paris, Marcoussis, Nançay, Meudon Observatory, solar radio astronomy, galactic radio astronomy, extragalactic radio astronomy.

1. INTRODUCTION

In the first two decades following World War II, Australia, England, France, Holland, Japan, Norway, Russia and the USA all made important contributions in the newly-emerging field of radio astronomy (e.g. see Burke, 2005; Edge and Mulkay, 1976; Orchiston and Slee, 2005; Strom, 2004; and Sullivan, 1984).

A notable feature of these developments in England, France, Holland, Norway and Russia was the role played by 7.5m Würzburg radar antennas (see Dagkesamanskii, 2007; Edge and Mulkay, 1976; Radhakrishnan, 2006; Smith, 2007; Van Woerden and Strom, 2006). At the end of the War, there were more than 600 abandoned Würzburg *Riese* radar antennas in the Channel Islands, France, Belgium, the Netherlands, Germany, Poland, Sweden, Norway and Austria (see http://atlantikwall.info/radar/radar.htm), and so there was the potential for some of these to be salvaged and committed to peacetime research in radio astronomy.

Australia was the only nation prominent in early radio astronomy to place no reliance whatsoever upon these antennas (e.g. see Orchiston et al., 2006), but it is significant that soon after the War ended the 'founding father' of Australian radio astronomy, Joe Pawsey, did in fact investigate the possibility of securing Würzburg antennas and re-locating them to Sydney.

In this paper we investigate the role played by three Würzburg *Riese* antennas in early French radio astronomy.[1] Different localities mentioned in the text are shown in Figure 1.

2. RADIO ASTRONOMY AND THE ÉCOLE NORMALE SUPÉRIEURE

2.1 Introduction

In 1945 Yves Rocard (Figure 2),[2] Director of 'le Service de Recherche de la Marine Nationale', was appointed Director of the Physics Laboratory at the École Normale Supérieure (henceforth ENS) in Paris. During the War, while Professor of Physics at the Sorbonne, Rocard was a member of an underground British intelligence network in France spying on German radar. In 1943 he was secretly flown to Britain where he worked on radar (Steinberg, 2001). There he became aware of the British detection of metre-wave solar radio emission in 1942, and realised that this could be a fertile research field in the post-War era.

Rocard therefore decided to form a radio astronomy group at the Physics Laboratory in 1946. At the time, staff were wandering the corridors of this new facility wondering what sort of research to get involved in, and Rocard independently approached Jean-François Denisse and Jean-Louis Steinberg suggesting they take up radio astronomy—which they previously had not even heard of. Both readily agreed, and they were soon joined by J. Arsac, E.-J. Blum, A. Boischot, E. Le Roux and P. Simon (Denisse, 1984).

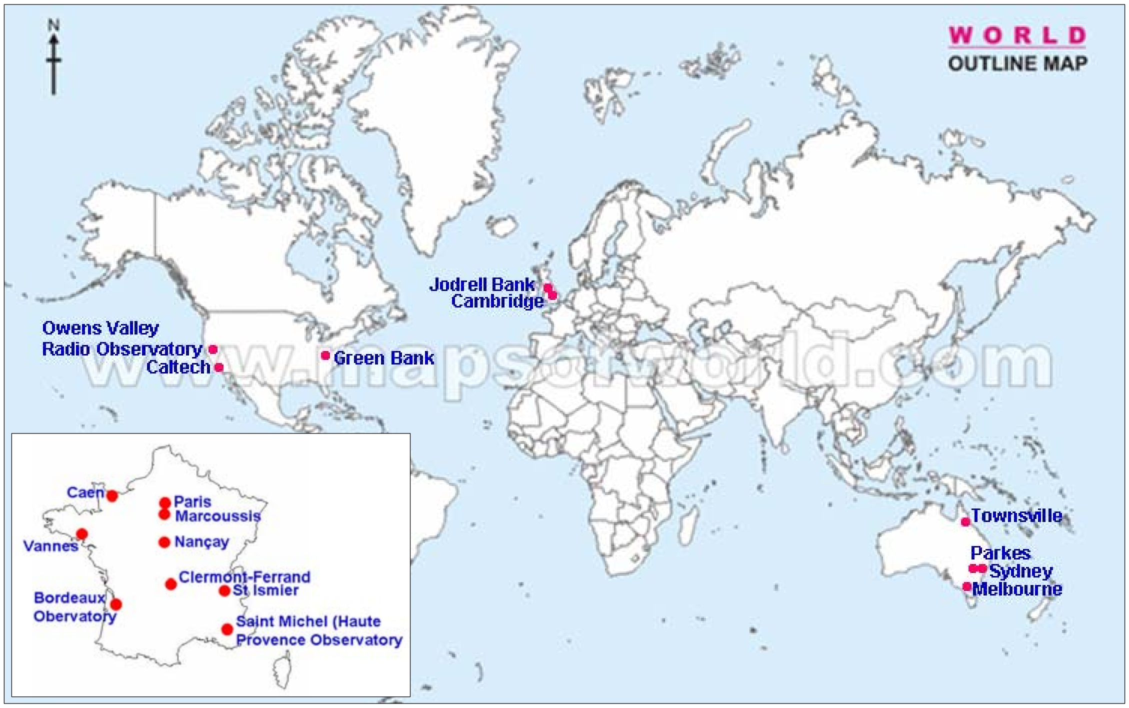

Figure 1: Map of localities mentioned in the text; the inset map shows France (outline map courtesy of www.theodora.com/maps, used with permission).

Figure 2: Yves Rocard, 1903-1992, Director of the Physics Laboratory at the École Normale Supérieure, and 'founding father' of French radio astronomy. This photograph was taken soon after the end of World War II (courtesy: Université Pierre et Marie Curie).

The new radio astronomy team began by erecting a US Air Force 1.5m equatorially-mounted searchlight mirror and an equatorially-mounted array of six Yagi antennas on the roof of the Physics Laboratory (Arsac et al., 1953). The 'searchlight antenna' radio telescope was specifically installed so that the fledging radio astronomers could gain experience in the design and construction of instrumentation (Steinberg, 2004a), although it was subsequently used for solar studies. Denisse (1984: 304) reminds us that

> During the war years, French research had been isolated from the scientific and technical advances that ensured the rapid development of radio astronomy in the Anglo-Saxon world. [So] The first objective of the group was therefore to make up for the delays in the French program.

Denisse (ibid.) mentions that a 3m Würzburg dish was also mounted on the roof of the Physics Laboratory, and Steinberg (2001, 2004a) provides confirmation of this. We know that this radio telescope was used for solar research at 1,000 MHz.

2.2 The Marcoussis Würzburg Antennas

After the War Rocard was quick to appreciate the research potential of the 3m and 7.5m German radar antennas that had been abandoned following the War. At the end of hostilities British forces located three of the 7.5m antennas on the French coast. Realising that these three dishes could not easily be transferred to England, the British decided to give them to the French Army, which subsequently distributed them among the French armed forces. The Navy and one of the other armed forces did not want their Würzburg antennas so Rocard made use of his senior naval ranking and his network of service contacts to lay claim to them.

Steinberg was then instructed by Rocard to mount one of the antennas on the roof of the Physics Laboratory in Paris, so he and Seligman (from the Navy) drove to the railway yards at Sevran-Livry in northern Paris where the antenna was in pieces on four railway wagons. One held the cabin, the mounting was on the second wagon, and the dish—which was divided into three parts—was on the third and fourth wagons. Each wagon listed the weight of its load, and upon totalling these Steinberg came up with an overall figure of ~25 tons for the antenna.

Steinberg immediately advised Rocard the antenna was too heavy for the Physics Laboratory roof so Rocard arranged for it to be erected at Marcoussis, a site ~20km south of Paris which was owned by the Centre de Recherche de la Marine. Rocard had a high position in the Naval Research Department, and Marcoussis was a Naval Research Laboratory. The antenna (which was mounted on a wagon) was installed there on a short set of railway tracks, and later a second Würzburg antenna was placed on a fixed concrete block several hundred metres away.

2.3 Research at Marcoussis

Figure 3 shows the first of the Würzburg antennas installed at Marcoussis. At this time, French radio astronomy focussed on solar research (Denisse, 1984; Orchiston and Steinberg, 2007), and the first serious attempt to carry out research with this radio telescope occurred at 158 MHz on 28 April 1949 when there was a partial solar eclipse visible from Paris.[3] Unfortunately, fluctuations in the noise level of ~20% were recorded before and after the eclipse, which meant that the chart record could not be used to investigate the relationship between the eclipse curve and optical features visible on the Sun's disk at the time (Laffineur et al., 1949, 1950; Steinberg, 1953).

Figure 3: The first of the 7.5m Würzburg antennas mounted on a wagon at Marcoussis and ready for use. Providing an indication of scale is a youthful Jean-Louis Steinberg (courtesy: Observatoire de Paris, Meudon).

By the time the second Würzburg dish was installed, Marius Laffineur from the Institut d'Astrophysique de Paris had developed an electro-mechanical computer drive for a third Würzburg antenna, which was sited at Meudon Observatory, and the ENS contracted him to build a similar drive for the second Marcoussis Würzburg (Steinberg, 2001). Meanwhile, E. Le Roux set to work and constructed a 900 MHz receiver for the first of the two antennas (ibid.), and a stabilised power supply (M. Pick, pers. comm., 2006).

Steinberg (2001: 511) notes that while at Marcoussis the first of the two Würzburg antennas "… was used to observe galactic radiation for the first time in our group …" (cf. Steinberg, 2004b). This occurred between 1954 and 1956 when it was used to study the Galactic Plane at 900 MHz. This project was led by Steinberg, with assistance from three research students from the ENS, J. Delannoy, J. Lequeux and B. Morlet, who were charged with assessing the properties of the Würzburg antenna and 900 MHz receiver and making various measurements. At this time, the Würzburg was essentially the unmodified wartime radar antenna (except for the new radio astronomy receiver and 900 MHz dipole at the focal point), with the original drive and selsyns to measure azimuth and elevation. Lequeux's first task was to prepare a graph that could be used to convert these units to Hour Angle and Declination, and vice versa.

A transmitter located on a hillside a few kilometres distant was used to calibrate the system. The antenna was moved in various directions and the incoming signal strength was measured. Vertical scans were also made to record radiation from the ground and from the sky (for details see Delannoy et al, 1957). For the galactic observations, parallel scans were made with the antenna fixed and centred on a succession of selected positions. As the sky moved through the beam the output was plotted on a chart recorder, which automatically inserted time marks, but the antenna position for each scan had to be written in by hand. Lequeux and Delannoy recall that by present-day standards the manual reduction of these early observations was rather painful!

The initial galactic survey extended from 17h to 21h in Right Ascension, and the results were reported in a paper published in *Comptes Rendus de l'Académie des Sciences* in 1955 (Denisse et al., 1955). This was one of the earliest non-solar French radio astronomy papers (but see the short paper by Blum et al., 1954).

In their paper, Denisse et al. (1955) included an isophote plot of the Galactic Plane at 900 MHz, and this is reproduced here in Figure 4. They also commented that

> The emission at 33 cm, due principally to ionized hydrogen,[4] was observed along the entire length of the galactic equator visible from Paris; until now this result had only been obtained at wavelengths above a metre (from radio sources) and at 21 cm (hydrogen line emission). (Denisse et al., 1955: 279; our translation).

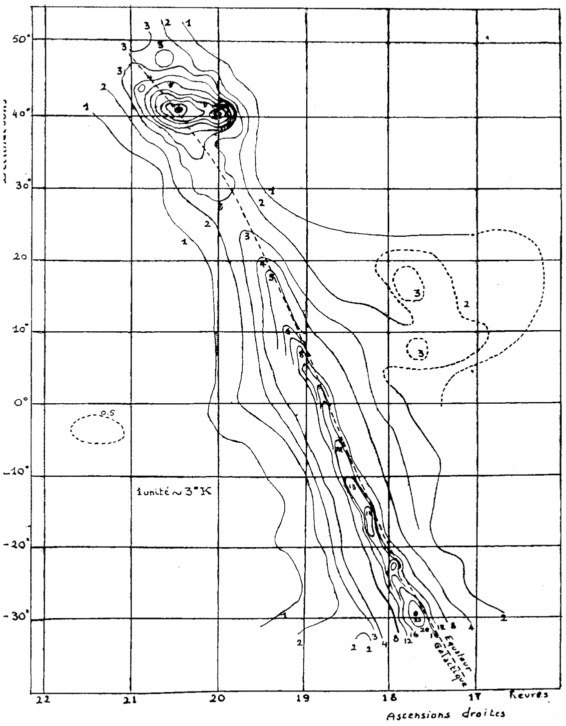

Figure 4: Isophote plot of 900 MHz emission along the Galactic Plane, between R.A. ~16h 30m and 21h 30m, showing a number of discrete sources (after Denisse et al., 1955: 279).

Denisse et al. (1955) also provide a list of the discrete sources detected in the course of the Galactic Plane survey, and these are shown in Table 1. Cygnus A, Cygnus X, Cassiopeia A and Taurus A were well-known to radio astronomers at the time the Marcoussis survey was carried out, but this was not so of Sagittarius A. This discrete source is associated with the Galactic Centre, and although first identified by Piddington and Minnett in 1951 at 1,210 MHz, their paper appeared in a comparatively new Australian scientific journal that was almost unknown to international colleagues.[5] Subsequently, the existence of Sagittarius A was confirmed by McGee and Bolton (1954) and McGee, Slee and Stanley (1955), and although Bolton actually played no part in this research project (see Orchiston and Slee, 2002) the Australian Sagittarius A identification only became widely-known to the astronomical community when the brief report by him and McGee appeared in *Nature*; this occurred just a short time before Denisse et al. (1955) published their French results.

Table 1: 900 MHz discrete sources along the Galactic Plane identified by Denisse et al. (1955).

No.	R.A.		Dec		Source
	h	m	°	′	
1	17	41	07	35	New source
2	17	43	–29	10	Sagittarius A
3	17	47	16	30	New source
4	17	57	–23	00	M20
5	18	15	–15, –18		M17 nebulae
6	20	00	40	35	Cygnus A
7	20	27	40	45	Cygnus X
8	20	35	48	00	New source
9	20	53	43	45	North American Nebula
10	20	57	50	30	New source
11	21	27	–03	30	New source
12	23	24	58	30	Cassiopeia A
13	05	30	21	35	Taurus A
14	05	32	–05	30	Orion Nebula

Denisse et al. (1957) subsequently published a further paper reporting an extension of their earlier Galactic Plane survey at 900 MHz using one of the Marcoussis Würzburg antennas. Their paper includes two isophote plots, one extending from ~19h 30m in R.A. to 6h and the other from 4h to 8h; the former is reproduced here in Figure 5, and reveals the existence of a number of discrete sources. The authors provided a list of the most conspicuous sources, and these are shown here in Table 2. They also included new more precise flux density values for sources 6, 8, 10 and 12-14 listed in Table 1.

Table 2: 900 MHz discrete sources along the Galactic Plane identified by Denisse et al. (1957).

No.	R.A.		Dec		Source*
	h	m	°	′	
15	20	55	47	00	
16	22	36	64	30	
17	00	20	65	30	Associated with SN1572
18	02	16	62	30	Perhaps HB No. 3
19	03	20	56	00	Perhaps HB No. 7
20	04	51	47	30	Perhaps HB No. 9
21	06	30	05	00	Rosette Nebula

* HB = Hanbury Brown and Hazard (1953).

When discussing the isophote plots, Denisse et al. (1957: 3033; our translation) specifically comment on the

> … distinct non-symmetrical structure that extends between Cassiopeia and the North Pole and which was also observed by E.J. Blum at a wavelength of 1.77m. It is perhaps significant to consider that this extensive source is situated in the opposite direction to the Magellanic Clouds [when viewed] in relation to the centre of the Galaxy.

Later observations by other radio astronomers would confirm the existence of this 'North Polar Spur', which we now know to be the most conspicuous part of the edge of a giant bubble that is also seen in X-rays and is called Loop I. It was probably produced by a series of supernovae and stellar winds from the nearby Sco-Cen OB assocation.

In a final short section of their paper, Denisse et al. provide a fascinating comment on the level of galactic background radiation detected in the course of their 900 MHz survey. They reported that when they observed away from the Galactic Plane

> Our measurements however allowed us to show that the brightness temperature of the sky is less than 3° K and that variations from one place to another are less than 0.5° K. (Denisse et al., 1957: 3033; our translation).

In the light of Wilson and Penzias' later pronouncement this would appear to be a very significant result except that in another more definitive account of this 900 MHz French research, Delannoy et al. (1957: 236; our translation) discuss problems associated with accurately measuring the sky background radiation level and conclude:

> The preceding discussions reveal that the principal error is the one that results from the measurement of ρ (of the order of 8%) and that all we can conclude is that the temperature of the sky at 900 MHz is certainly not greater than twenty degrees Kelvin.

This differs markedly from their initial assessment.

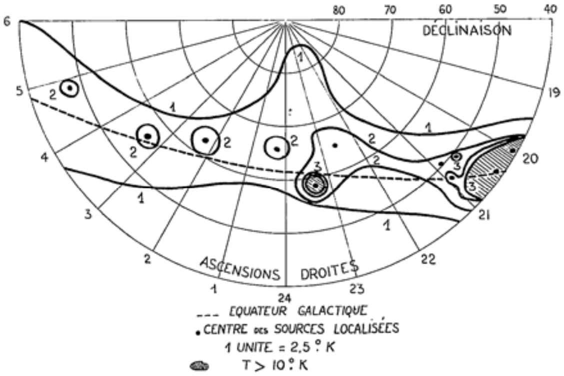

Figure 5: Isophote plot of 900 MHz emission between R.A. ~19h 30m and 6h, showing a number of discrete sources (after Denisse et al., 1957: 3031).

In a perceptive paper published in 1954, Hanbury Brown showed that "… the remnants of supernovae may be expected to form a population of radio sources with characteristics similar to those which have been observed close to the galactic plane." (Hanbury Brown, 1954: 191). This discovery is consistent with the Marcoussis results, with at least three different supernova remnants represented in Tables 1 and 2 (above). The best-known of these is Taurus A, which was first associated with the AD 1054 supernova by Bolton, Stanley and Slee in 1949.

On 24 January 1956 Taurus A was occulted by the Moon, and this event was observed from Marcoussis with a solar radiometer at 169 MHz and with one of the two Würzburg antennas at 900 MHz (Figure 6). Boischot et al. (1956: 1851; our translation) found that at this frequency

> … the influence of the outer [optical] filaments was not negligible. In effect the first contact (arc I in the figure 3 [reproduced here as Figure 7]) occurred at the moment when these started to be occulted and the radio-emitting centre of the nebula at 900 MHz also corresponded rather precisely with the centre of the mass of the most brilliant filaments.

In the days before radio astronomers had access to sub-milliarcsecond resolution, lunar occultations offered a particularly elegant way of investigating the position and structure of any extended radio source that happened to lie along the Ecliptic. Fortunately, Taurus A was one of these.

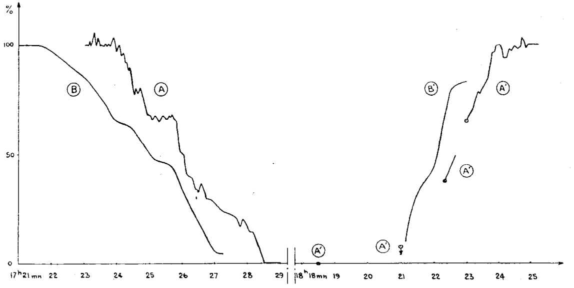

Figure 6: Marcoussis occultation curves for Taurus A obtained at 169 MHz (A-A′) and 900 MHz (B-B′) on 24 January 1956 (after Boischot et al., 1956: 1849).

3. URSI AND THE FOUNDING OF NANÇAY

In 1952, the URSI Congress was held in Sydney, Australia (Bolton, 1953; Kerr, 1953), the first time that this meeting was sited outside of Europe or North America. Australia's selection as the host nation reflected its ongoing research record in ionospheric physics and its role as one of the leading nations involved in the emerging field of radio astronomy. For an interesting recent perspective on the Sydney URSI meeting by someone who was actually there, see Robinson (2002).

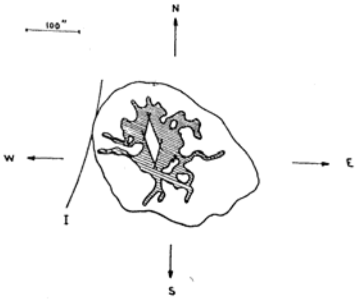

Figure 7: The Crab Nebula showing the distribution of the most brilliant optical filaments (hatched), the envelope encompassing the outer optical filaments, and the centre of the radio emission (the 'trapezium' within the hatched area). Arc I indicates the position of the lunar limb at the time of first contact at 900 MHz during the 1956 occultation (after Boischot et al., 1956: 1851).

Figure 8: 'Chris' Christiansen and his 32-element East-West 1,420 MHz solar grating array at Potts Hill, Sydney (courtesy: ATNF Historical Photographic Archive).

Marius Laffineur from the Institut d'Astrophysique de Paris and Jean-Louis Steinberg from the ENS were the only radio astronomers in the French delegation (but there were others from non-radio astronomy areas). Actually, there was insufficient Government funding for both radio astronomers to attend so Steinberg obtained financial support from a private French electronics firm he did contract work for.[6]

The URSI program included visits to a number of the field stations maintained by the CSIRO's Division of Radiophysics in and near Sydney, and Laffineur and Steinberg were impressed by the Australian radio telescopes that they saw and heard about, particularly Christiansen's 1,420 MHz solar grating array at Potts Hill (see Figure 8, and Christiansen, 1953; Christiansen and Warburton, 1953). They decided that more elaborate French instrumentation was required and that a specialised observatory, with abundant land, and at a radio-quiet site, was essential. A few days after returning to Paris, Steinberg approached Rocard about obtaining such a site. Rocard asked him to prepare a budget, which he did with considerable difficulty. It totalled 25 million in 1952 French francs, which was equivalent to 2.6 million francs in 2001—a truly phenomenal sum. A few weeks later Rocard had a commitment for the funding through the Ministry of National Education, which preferred to finance a large and very visible project rather than dozens of smaller ones. Rocard told Steinberg that he had 25 million francs to spend and to "… do what you want but keep me informed." Later Steinberg (2001: 512) would write: "It was an incredible sign of confidence since all our team were in their early 30s. The sum of 25 million … was enormous as compared to most scientific project budgets." The result was the 150 hectare Nançay field station, 190 km to the south of Paris, which was established by the Physics Laboratory of the ENS in 1953.

At this time the Director of the Paris Observatory, André Danjon, wanted to set up a radio astronomy group at the Meudon branch of the Observatory, for he realised that this new discipline could make important contributions to solar physics and astrophysics. He proceeded to invite Denisse and Blum to join the Observatory's staff, and in 1954 they accepted; soon they were followed by Steinberg and other members of the ENS group. In addition, the Nançay facility was also transferred to the care of the Observatory.

It might seem strange that Rocard was prepared to part with his new field station and to let one of his prize research groups defect to a rival institution, but the fact is that he was non-territorial by nature, and he also was interested in continually developing new research areas. Thus, he had no intention of retaining radio astronomy forever, and at the time of the Paris Observatory initiative he was keen to develop semi-conductor research and needed more space for this in the Physics Laboratory. The final 'crunch' came when he informed the radio astronomy group that he wanted to erect military equipment at Nançay to detect atomic bomb tests. Steinberg vehemently disagreed with this decision and insisted that Nançay remain non-military and accessible to international scholars. This stance did not please Rocard, who made it clear that the era of co-operation was over. He then proceeded to withdraw various facilities from the radio astronomers, and to cut off access to the workshop (although he did allow the workshop to complete the Nançay 2-element 3cm interferometer). It was only when the interferometer was finished that Steinberg and other staff from the ENS transferred to Paris Observatory.


Figure 9: Close up of the two Würzburg antennas at Nançay.

4. PARIS OBSERVATORY AND NANÇAY

4.1 Introduction

When Paris Observatory gained access to the Nançay field station the intention was to erect 1,500m long E-W and N-S solar arrays, and a variable-baseline interferometer for non-solar work, but both projects required several years of design studies so a start was made with smaller instruments, including solar antennas relocated from Marcoussis.

4.2 The Würzburg 2-Element Variable Baseline Interferometer

Eventually the Marcoussis Würzburg dishes were transferred to Nançay, and they were mounted equatorially on a 1,480m long E-W railway track and a 380m long N-S railway track constructed in 1957-1959 (see Figure 9), giving maximal resolutions of 17.4″ and 67″ on the E-W and N-S baselines respectively at 1,420 MHz. Under the very best circumstances, it was possible to measure sources with flux densities as low as 1.4 Jy. Le Roux oversaw the development of this instrument and a new 1,420 MHz receiver (Steinberg, 2001), but the 6m gauge railway track was designed by an engineer from the National Railways.

Most of the electronics were built by Le Roux (see Lequeux et al., 1959), and the only major problem encountered was that the phase was not stable but drifted slowly due to temperature variations, even though a phase-lock system was in place (see Arsac, 1959). Lequeux recalls that when he was fortunate enough to see interference fringes he had to add them together in order to increase the signal-to-noise ratio, and to facilitate this Marc Vinokur built an ingenious integrating 'machine' that sampled the signal every twentieth fringe, converted the analog signal into digital and added the fringe signals together with twenty special electronic tubes developed in England which had phosphorus displays.[7] To input and continuously update the fringe frequency, Lequeux used a frequency synthesizer that he adjusted manually using a navy chronometer and tables! Due to the phase shift, Lequeux's procedure was to integrate separately the first and second halves of each observation, measure the phase shift, and correct for this in the final result. Surprisingly, this worked rather well, but because he could not control the phase all he ended up with was an amplitude visibility curve. Jacques Arsac developed an algorithm that was used to recover a 1-D profile from this alone, but of course this included a directional ambiguity. Calculations were performed on an IBM 650, which was the first scientific computer to be installed at Meudon.

The interferometer became operational in April 1959, and was used for continuum observations at 1,420 MHz; between October 1959 and the end of 1962 these formed the basis of Lequeux's doctoral research. By present-day standards, observing was a tedious affair. Lequeux remembers that for each baseline change he had to move the antennas along the railway track using a cable which was attached to a truck. He then had to measure the positions of the two antennas and plug in the mains power and coaxial cable for the local oscillator reference and the signal at posts that were spaced at 50m intervals along the track. During each observation he would go on foot, by bicycle or in a car (depending on the distance involved) to the two antennas, point them at the designated Right Ascension and Declination, make some electronic adjustments, and then rush back to the central cabin to adjust the delay line and start the integration. On average the integration time was ~1hr.

The first series of scientific observations made with the Nançay facility was an attempt to measure the angular sizes of five different well-known discrete sources, Cygnus A, Sagittarius A, Virgo A, and the remnants associated with supernovae of AD 1572 and 1604. Observations were carried out from April 1959, at 1420 MHz, and Biraud et al. (1960: 116) noted that

> The detection of weak sources is limited by noise, but an integrating system allows us to detect sources whose flux density is as low as 7×10^{-26} w $m^{-2}(c/s)^{-1}$. No phase determinations are yet available, and we measure only the modulus of the Fourier transform of the strip brightness distribution of the source ... measurements have been made with aerial separations in the range 41 λ to 2080 λ (440 m) on the East-West baseline.

The curve obtained for Cygnus A was found to be similar to those derived by other investigators, while Sagittarius A suggested the existence of two sources, with E-W halfwidths of ~28′ and 3.5′ and flux densities of 680 and 280 Jy respectively. Biraud et al. identified the smaller source with Drake's narrow thermal source at the centre of our Galaxy. In this case, the source has an E-W diameter of 8.6 pc, which is similar to the dimensions of the nucleus of M31, and "… we think they are bodies of the same kind. If the radiation of the central source is indeed thermal, with an assumed electron temperature of 10,000° K, we derive an emission measure of 4.4 × 10^{6} cm^{-6} pc and a mean electron density of 960 cm^{-3}." (Biraud et al., 1960: 117). The Virgo A visibility curve was also found to originate from two superimposed sources: "… a halo approximately gaussian in shape with a halfwidth of 10′ and a flux density of 74 × 10^{-26} w $m^{-2}(c/s)^{-1}$, and a very intense and narrow source with an E-W halfwidth of 40″ (if gaussian) and flux density of 112 × 10^{-26} w $m^{-2}(c/s)^{-1}$." (ibid.). The narrow source was thought to be connected with the jet that is associated with the nebula. Although both of the SNRs were detected, an angular size (6′) was obtained for just one, SNR 1572. Its flux density was measured at 39 Jy, while SNR 1604 produced a flux density of ~12 Jy at 1,420 MHz.

Heidmann and Lequeux (1961) also investigated the radio source Hercules A with the Würzburg Interferometer, using baselines from 43 λ to 6,950 λ. The visibility curve suggested two sources with E-W halfwidths of 0.8′, separated by 1.8′ and at a position angle of 98 ± 5°. The flux density was noted as 3% that of Cygnus A, or 42 Jy at 1,420 MHz.

In another paper published in 1961, Lequeux and Heidmann report on their measures of a number of strong discrete radio sources using the Würzburg Interferometer. From a plot of the amplitude of the interference fringes as a function of distance and the resulting integrated brightness distribution in an E-W direction for Cygnus A, they identified the existence of a sharp outer shock front which is separated from the inner regions of the source by an angular distance of between 90 and 108″.

Observations of Virgo A, with an interferometer spacing exceeding 300 λ confirmed the existence of two source components—as reported previously by Biraud et al. (1960)—except that the new interference fringes (Figure 10) indicated two gaussian sources with halfwidths of 23″ and separated by 31″. The source Ophiuchus C (3C 353) was observed and also was found to comprise two adjacent sources, with halfwidths of 74″ and separated by 136″. Hydra A also appeared to be a double source, one component having a halfwidth of 42″, while the other was not resolvable at the longest baseline used for the observations. Bootes A was also unresolved at this spacing, while 04 N3A and 3C 273 produced source diameters of 15.5″ and 21″ respectively.

In 1962, Lequeux (1962a) brought together his accumulated observations made with the Würzburg Variable Baseline Interferometer and published these in the *Annales d'Astrophysique*. This long paper is primarily based upon his doctoral research, and is split into two parts: the first deals with galactic sources and the second with extragalactic sources. In both sections he elaborates on the previously-published findings reported in Biraud et al. (1960), Heidmann and Lequeux (1961) and Lequeux and Heidmann (1961).

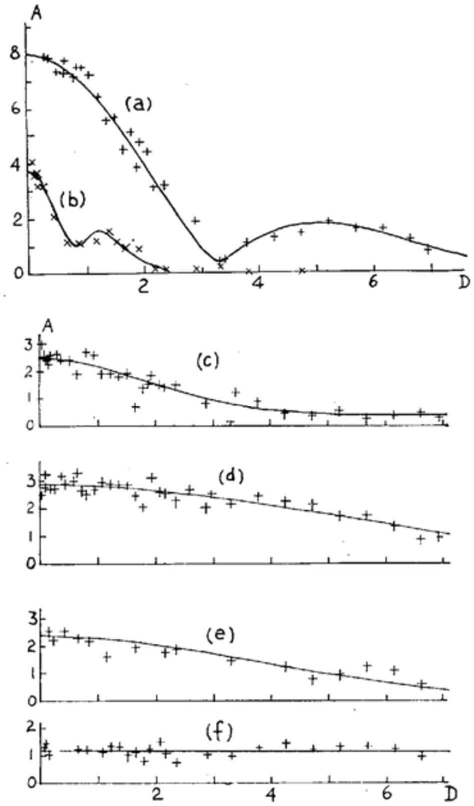

Figure 10: Plots of amplitude (A) of the interference fringes as a function of interferometer spacing (D, in 1000s of λ) for Virgo A (a), Ophiuchus C (b), Hydra A (c), 04 N3A (d), 3C 273 (e) and Bootes A (f) (after Lequeux and Heidmann, 1961: 806).

Lequeux begins by presenting visibility curves for eight different thermal galactic radio sources known to be associated with HII regions, and these are shown here in Figure 11 (the W series of sources being from Westerhout's 1958 catalog).[8] Meanwhile, source flux densities and E-W dimensions are listed in Table 3.

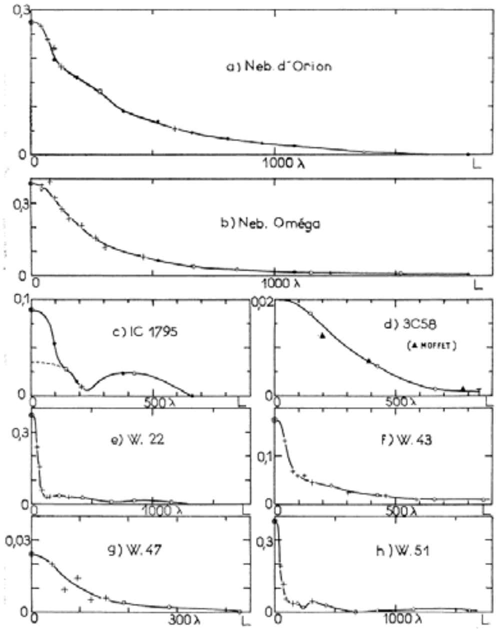

Figure 11: Visibility curves for selected galactic radio sources (after Lequeux, 1962a: 224).

Table 3: 1,420 MHz galactic thermal sources observed at Nançay (after Lequeux, 1962a: 226).

Source	Identification	Flux Density	E-W Dimensions
3C 58[7]	----	30 Jy	5′
IC 1795	IC 1795	134 Jy	18′; double source, each 3′ and separated by 7.6′
Orion Nebula	NGC 1976	410 Jy	complex, ~4′
W22	NGC 6357	555 Jy	broad 34′, narrow 3′
Omega Nebula	NGC 6618	570 Jy	complex, ~5.8′
W 43	----	270 Jy	broad 33′,narrow 5′
W 47	----	35 Jy	broad 20′, narrow 5′
W 49	3C 398	84 Jy	very complex, ~20′
W 51	----	560 Jy	broad 40′, narrow 3′

From the Orion Nebula curve in Figure 11 Lequeux derived an E-W size of 4′, and when he compared his E-W profile for this source with the model developed by Menon (1961) for the same frequency, "The accord between the observations and the model can be considered excellent, except at large distances from the centre where the observational results and the model are both uncertain." (Lequeux, 1962a: 226; our translation). In addition, Lequeux (ibid.) confirmed the values for the electron density and the emission measure reported by Menon.

Some of the other sources listed in Table 3 display a feature that was found to be common for galactic thermal sources: they "…are in general composed of an intense small nucleus superimposed on an extended component." (Lequeux, 1962a: 221; our translation). This is indicated in the extreme right-hand column in the Table.

Table 4 lists non-thermal galactic sources observed at Nançay, and contains four known supernova remnants (the two SNRs and Taurus A and Cassiopeia A) plus two other sources.[9] Visibility curves for all six sources are shown in Figure 12.

Table 4: 1,420 MHz galactic non-thermal sources observed at Nançay (after Lequeux, 1962a: 228).

Source	Flux Density	Spectral Index	Diameter
SNR 1572	43.5 Jy	– 0.7	broad ~8′, narrow ~1.8′
IC 443	170 Jy	– 0.4	40′
Taurus A (Crab Nebula)	880 Jy	– 0.26 ± 0.03	3.9′ × 2.7′, P.A. 126°
SNR 1604	12.7 ± 1.5 Jy	– 0.7	2.2′
W 44 (3C 392)	180 Jy	– 0.5	broad ~16′, narrow ~4′
Cassiopeia A	2450 Jy	– 0.78 ± 0.02	4′

The results for Taurus A (associated with the Crab Nebula and SN 1054) were very interesting in that they indicated an elliptical source with a similar orientation to its optical counterpart. This is shown in Figure 13, where the 101 MHz isophote of Mills (1953) is also included. Lequeux (1962a: 230; our translation) concludes that "… it seems that decisive progress will not be possible on the theory of the Crab Nebula until one can arrange for reliable isophote plots at several frequencies to be obtained with a resolution of at least 30″ in two directions."

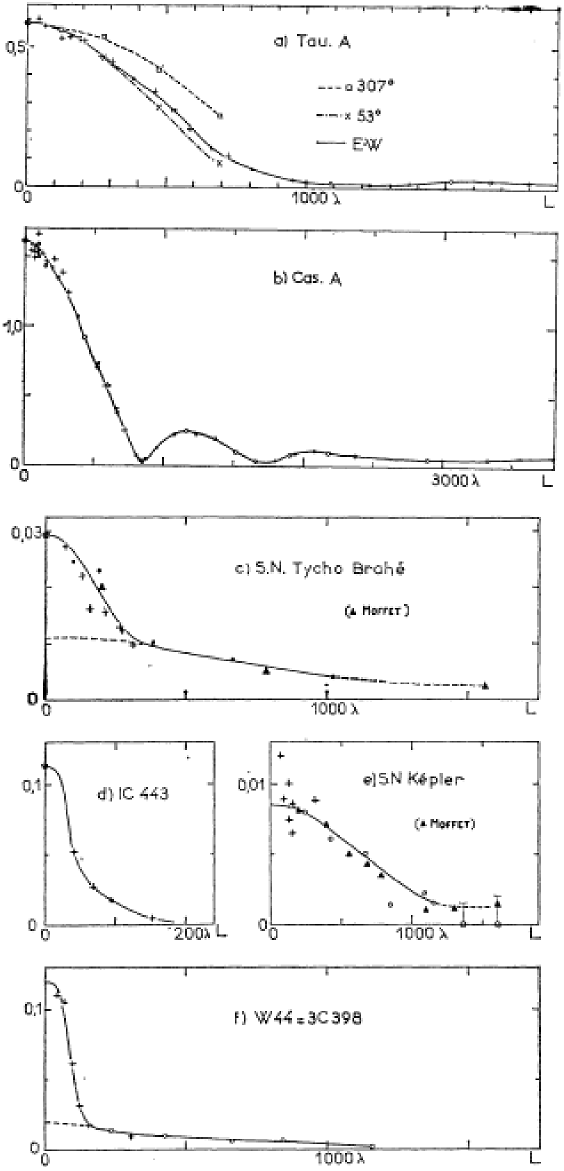

Figure 12: Visibilty curves for selected non-thermal galactic radio sources (after Lequeux, 1962a: 229).

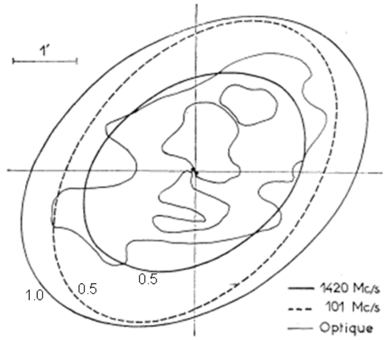

Figure 13: A comparison of the optical continuum of the Crab Nebula and 101 MHz and 1,420 MHz isophotes for Taurus A (after Lequeux, 1962a: 229).

Cassiopeia A is the only other SNR in Table 4 for which there was a relative abundance of data at 1,420 MHz. Lequeux (1962a: 230; our translation) found that

> The dimensions and form of the radio source do not vary with frequency: the visibility curve at 1420 MHz does not differ significantly from those that have been obtained at 127 and 3000 MHz … However we do not find in our measures the "depression" of the visibility curve observed at 127 MHz for interferometer spacings of the order of 500 λ; it is true that this effect is limited by experimental errors in the 127 MHz measures.

Lequeux derived a spectral index of –0.78 ± 0.02 for Cassiopeia A (Table 4), and noted that while certain authors expect that the slope of this spectrum and those obtained for other SNRs will decrease with the passage of time, this is very unlikely. He also showed this source to be a thin spherical shell, and adopting the principles advanced by Shklovsky calculated that its annual decrease in flux is 1.7%.

Of the remaining sources in Table 4, Lequeux (1962a: 233; our translation) specifically mentions that W44 has "… a complex structure that has some analogies with the supernova of Tycho Brahe [i.e. SN 1572]: but the report of its dimensions and the flux density values of its components are not the same."

In his long 1962 paper, Lequeux assigns a separate section to his observations of Sagittarius A, the discrete 'source' located at the centre of our Galaxy. The Nançay observations confirmed the existence of two small sources, as reported earlier by Biraud et al. (1960). The 1962 paper contains revised flux densities of 730 and 300 Jy for these two sources, and also indicates that they are superimposed on a large non-thermal background source measuring about 1° × 2°. The low elevation of the Galactic Centre above the horizon at Nançay and the shortness of the N-S interferometer baseline only allowed for fringes to be obtained inclined by –19° and +19° with respect to the N-S direction, which was a limitation on the 2-D description of the course. However,

> These measurements show that the large source is highly asymmetrical: if one can visualize an ellipse with an axis in the Galactic Plane its diameter is 50′ in the direction of the Plane and 17′ in the perpendicular direction. In contrast, the small source appears to be circular … (Lequeux, 1962a: 234; our translation).

Lequeux (ibid.) proceeded to compare and contrast his measurements with those obtained by Pariiskii at other wavelengths and at higher resolution, and he then combined all the observations to prepare spectra for the two sources. The smaller intense source at the very centre of the Galaxy was found to be thermal, while the larger nearby source exhibited a non-thermal spectrum (see Figure 14). Lequeux then proceeded to compare and contrast his observations with those published by Drake who, with a resolution of 6′ × 6′, detected four different sources (which he labelled A and B_1, B_2 and B_3). In the light of our present very detailed knowledge of Sagittarius A accumulated through VLBI and with the VLA, it is fascinating to read about these early formative investigations of this region.

The final section of Lequeux's classic paper deals with extragalactic radio sources observed at Nançay with the Würzburg Variable Baseline Interferometer, and begins with the following warning: "Despite the accumulation of a very considerable number of observations, our knowledge of the extragalactic radio sources remains rudimentary." (Lequeux, 1962a: 236; our translation). Table 5 lists the 25 different sources that Lequeux investigated, along with their 1,420 MHz fluz densities and diameters, plus details of source structure, and their spectral indices. Some of the material in this table was reported previously in the papers by Heidmann and Lequeux (1961) and Lequeux and Heidmann (1961).

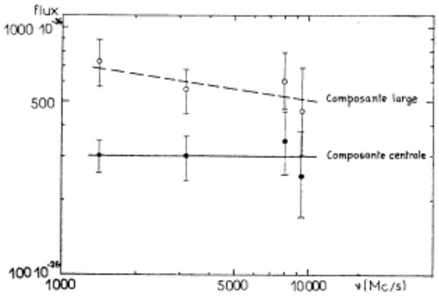

Figure 14: Spectra of the two components of Sagittarius A (after Lequeux, 1962a: 234).

The dual nature of Virgo-A was confirmed, with the two components referred to as the 'radio halo' and 'radio jet', respectively. Revised flux density values for the two components of 80 Jy and 120 Jy were reported, and dimensions of 10′ × 5.5′ were obtained for the size of the 'halo'. Figure 15 shows the visibility curve obtained for the 'radio jet' and its E-W profile; the latter suggests a double structure that is right at the limit of resolution of the Nançay interferometer. In trying to interpret the jet, several different models were investigated, but the solution of the numerical analysis was inconclusive: "None of the models gave a double structure or results that were compatible with our observations, but [despite this] we are still convinced that the jet is double." (Lequeux, 1962a: 238; our translation). As a first approximation, Lequeux (ibid.) suggested the existence of two similarly-sized sources 23″ in diameter and separated by 31″, with individual flux densities of 65 and 55 Jy.

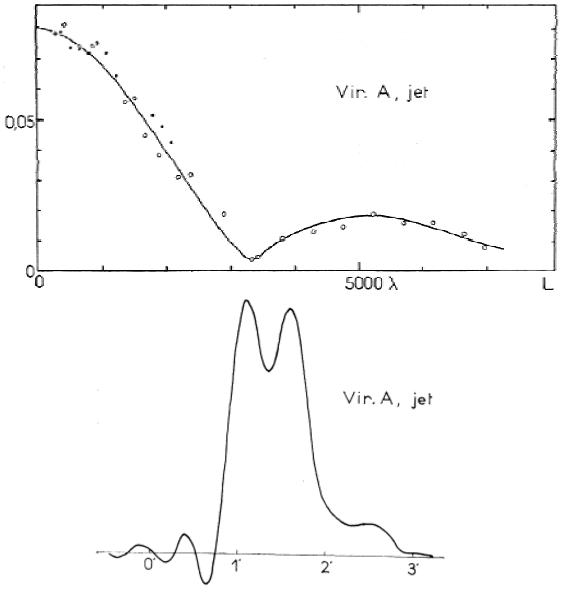

Figure 15: Visibility curve for the Virgo A jet and its E-W profile (after Lequeux, 1962a: 239-240).

Table 5: Extragalactic sources observed at Nançay (after Lequeux, 1962a: 237).

Source	Flux Density (Jy)	E-W Diameter	Structure	Spectral Index	Comments
3C 33	11.00 ± 1.5	Double	Each component <20″ diameter with E-W separation of 1.1′	0.74	Optical identification
3C 48	15.0 ± 2.0	See text	See text	0.55	Optical identification
3C 66	10.0 ± 3.0	Double?	Complex; large component >10′	0.55	Optical identification; double source, flux of small source 3.3 ± 0.6 Jy.
NGC1275*c* *a* *b*	9.0 ± 1.0 3.9 ± 1.5 7.5 ?	<12′ <2′ ? 30′ ?		---- 0.55 ?	See text
3C 98	10.5 ± 2.5	Complex	Large component 3′, small component <30″	0.65	Optical identification; double source
3C 111	13.5 ± 2.5	Double		0.73	
3C 123	45.0 ± 2.0	Double	Each component 5″ diameter with E-W separation of 2.5″	0.66	
3C 134	9.8 ± 1.3	39″ ± 14″	Double, almost N-S	0.95	
3C 147	18.9 ± 1.5	<10″		0.37	
3C 161	12.0 ± 1.5	<10″		0.67	Complex structure
3C 196	12.0 ± 1.0	<5″		0.79	
Hydra A	39.0 ± 2.0	Halo	Large component 42″ diameter and flux 31 Jy, small component 10″ diameter and flux 8 Jy	0.87	Perhaps a large halo
3C 273	37.5 ± 2.0	Double	Diameters of components ~4″ with E-W separation of 14″	0.44	See the earlier result in Lequeux and Heidmann (1961)
Virgo A	200	Halo	Halo 10′ × 5.5′, position angle ~70, flux density 80 Jy; double jet, components 23″ with 33″ separation at position angle 285 ± 15°; flux densities of 65 and 55 Jy	See text	Traces of structure and a halo
Coma A ………D …… . C	3.8 ± 0.5 3.0 ± 0.5 7.5 ?	<1′ <1′ ~40′ ?		0.42 ± 0.15 0.55 ± 0.15 ?	See text
3C 286	13.4 ± 0.7	8″ ± 4″		0.43	
3C 295	17.7 ± 0.6	<5″		0.65	Optical identification
Hercules A	45.0 ± 2.0	Double	Components 47″ diameter with 111″ separation at position angle 98 ± 5 ; flux densities of 25 and 20 Jy	0.96	Optical identification
3C 353	54.0 ± 4.0	Double	Components 74″ diameter with 136″ separation; flux densities of 36 and 18 Jy	0.68	Optical identification
3C 380	13.7± 1.2	12″ ± 5″		0.75	
Cygnus A	1500	Double	Components 25″ diameter with 106″ separation at position angle 110°; flux densities of 830 and 600 Jy	0.81 (after 2,000 MHz)	Components with extremely sharp edges extending along the same axis, with the point of emission between the two components
3C 409	13.0 ± 0 9	18″ ± 6″		1.00	Perhaps double
3C 433	9.9 ± 0.9.	16″ ± 5″		0.84	Optical identification
3C 444	10.5 ± 1.5	Double	Components ~15″ diameter with 24″ separation	0.7?	Optical identification
3C 452	7.5 ± 2.0	Complex		0.83	

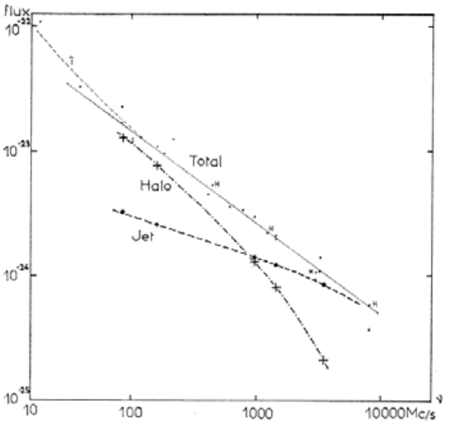

Figure 16: Spectra of the components of Virgo A (after Lequeux, 1962a: 242).

Upon combining the Nançay observations with those reported at other wavelengths by Mills, Moffet, Palmer and Pariiskii, Lequeux was able to investigate the spectra of the Virgo A components and show that these exhibited two very different curves (see Figure 16):

> One can see that the spectral index of the jet is constant with a value of 0.33 at frequencies below 2,000 MHz; above 8,000 MHz, where one can utilize reliable flux measures (those of Heeschen which form a coherent group and have been reduced with care, are indicated by the letter "H"), virtually all of the flux originates from the jet; the curvature of the spectrum takes place between 2,000 and 8,000 MHz, let us say mostly near 3,000 MHz. (Lequeux, 1962a: 243; our translation).

Lequeux (1962a) then devotes three and a half pages to a theoretical study of the physical processes associated in the generation of the radio emission from

Virgo A, based in part on the investigations of other scholars.

Cygnus A was another discrete source that was studied in detail at Nançay. From the visibility curve, Lequeux (1962a) derived an E-W profile for Cygnus A (Figure 17) which indicated two components, each ~25″ in diameter and with sharp external edges, separated from one another by 100″, and connected by what has been described as an 'emissive bridge' (Figure 18). The Nançay observations also confirmed that the separation between the two source components appeared to vary with frequency, an interesting phenomenon reported earlier by Jennison and Latham (1959). In his theoretical consideration of Cygnus A, Lequeux (1962a: 248; our translation) states:

> The existence of two components is very common among extragalactic radio sources: Shklovsky (1960*b*) imagines that this structure corresponds to the injection by the galaxy (identified without ambiguity in the case of Cygnus A and in several other cases also) of two clouds of gas containing a magnetic field and relativistic particles. This injection, of which the origin is still unknown (supernovae, magneto-hydrodynamic effects on a large scale?), would occur in two mutually-opposing directions, limited no doubt by the magnetic field of the galaxy and in the intergalactic medium ...
>
> Nevertheless, the properties of Cygnus A do not seem to support this hypothesis: to explain the variations in the source with frequency we have to admit that there is a notable loss of emission in the central regions alone, or by ionizing collisions in the outer regions alone, which appears too arbitary.

After spending almost two pages on a theoretical discussion of Cygnus A, Lequeux (1962a: 250; our translation) concludes: "Of course, the theoretical interpretation of Cygnus A that we have presented (or sketched) is very debatable and it seems premature to subject it to calculation. Many other aspects still require elucidation …"

In his brief discussion of Hercules A, Lequeux confirms the findings reported earlier in Heidmann and Lequeux (1961) and notes that these are in accord with recent results published by the Caltech group. Lequeux (1962a: 251) concludes that Hercules A should be considered a typical double radio source.

The source Ophiuchus C (3C 353) was reported on originally by Lequeux and Heidmann (1961), and in his long 1962 paper Lequeux merely confirms that this is a double source and repeats the parameters presented previously.

3C 33 is another extragalactic source listed in Table 5 with a visibility curve that clearly indicates a double structure. Lequeux (1962a: 251; our translation) concludes that "The E-W separation of the components is of the order of 69″ and their diameters are certainly less than 20″. The fluxes of the two components differ little, by no more than a factor of 2." He notes that his Nançay findings are in accord with those reported by the Caltech group.

Visibility curves were also published for 3C 66, 3C 98 and 3C 111 (see Figure 19), and these three sources are discussed together by Lequeux (1962a). Despite their low flux densities, he considers that all three are double sources, in agreement with results published by the Caltech radio astronomers. Both 3C 66 and 3C 98 seem to comprise a large component and a small component.

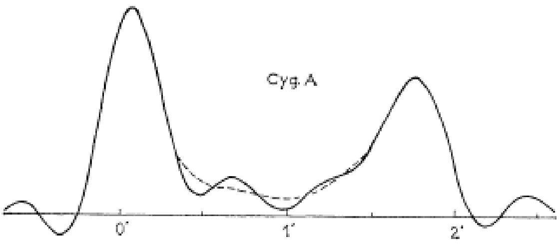

Figure 17: The E-W profile of Cygnus A at 1,420 MHz (after Lequeux, 1962a: 247).

The Nançay visibility curves for 3C 123 and 3C 273 at the maximal interferometer spacing of 7,000 λ show that these sources are still not resolved (re 3C 273 cf. Lequeux and Heidmann, 1961), but data provided by the Jodrell Bank radio astronomers indicate that these are both double sources. Meanwhile, Caltech data also indicate that 3C 134 is a double source, although this structure is not obvious from the published Nançay visibility curve (see Lequeux, 1962a: 252).

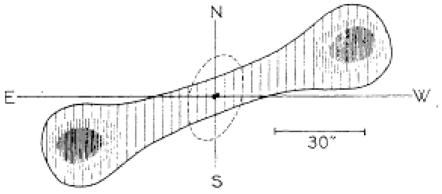

Figure 18: The suggested structure of Cygnus A, with the optical object shown in the centre (after Lequeux, 1962a: 247).

3C 444 is another source investigated at Nançay, and the associated E-W visibility curve

> … indicates a source that is probably double, with an EW separation of about 24″; the diameter of the components, while very difficult to estimate, is without doubt of the order of 15″. (Lequeux, 1962a: 253; our translation).

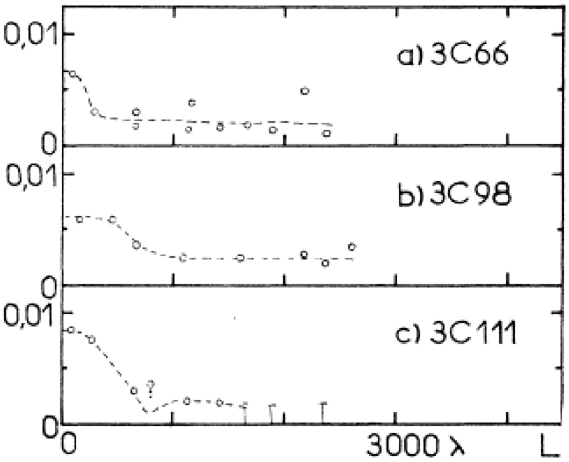

Figure 19: Visibility curves for 3C 66, 3C 98 and 3C 111 (after Lequeux, 1962a: 251).

The region around NGC 1275 in Perseus is a complex one, and observations conducted at Cambridge and Green Bank revealed the existence of three different radio sources. Lequeux's observations at Nançay confirmed this source complexity: in the visibility curve, which is reproduced here in Figure 20,

> … one can see oscillations that correspond to the presence of the small sources *a* and *c*, while the existence of the large source *b* is indicated by the very weak spaced-out measurements. The numbers inserted along the top of the diagram indicate for each measurement the number of fringes which were used in the integration. (Lequeux, 1962a: 255; our translation).

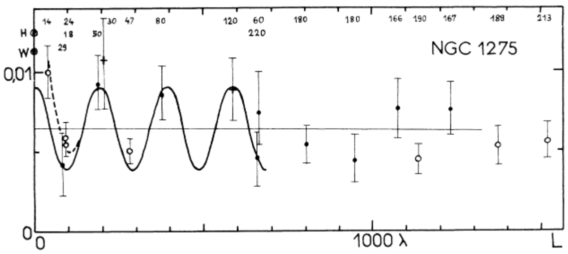

Figure 20: Visibility curve for the region around NGC 1275 (after Lequeux, 1962a: 256).

This visibility curve corresponds to two sources with unequal flux densities, and separated by 18′. Lequeux (1962a: 257; our translation) notes that NGC 1275 is the only known example of a double galaxy where the components are in motion at a relatively high speed (at least 3,000 km/s), and "… this is therefore the only case where we are justified in explaining the radio emission in terms of a collision between two galaxies."

The double nature of Hydra A was already reported by Lequeux and Heidmann (1961), and in his long 1962 paper Lequeux repeats their earlier findings, but within the context of recent results for this source published by Jodrell Bank and Caltech colleagues.

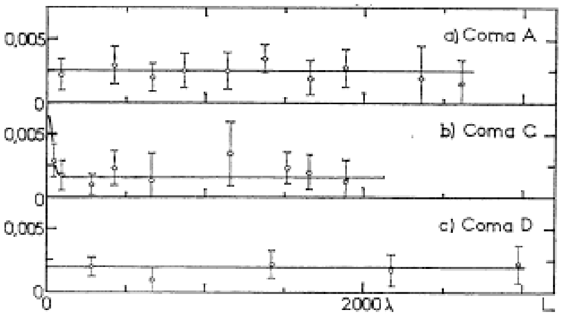

Figure 21: Visibility curves for radio sources in the Coma Cluster (after Lequeux, 1962a: 257).

Large, Mathewson and Haslam (1959) observed the Coma Cluster at 408 MHz and identified three different sources which they designated A, C and D. Lequeux observed these three sources with the Nançay Würzburg interferometer, deriving the visibility curves illustrated in Figure 21. From these, Lequeux concluded (1962a: 258; our translation) that

> Sources A and C are separated by a distance of 68′ ± 12′ … Curve 39 *a* [i.e. a) in Figure 21] is not affected by the presence of source C, which is large, for all the spacings at which we took measurements. To the contrary, in curve 39 *b* [i.e. b) in Figure 21] source A contributes to the fringes with 65% of its flux. Finally, source D … [c) in Figure 21] was well isolated from A and C by our antennas.
>
> One can see that sources A and D are very small: their diameters are certainly less than 1′. One can estimate their fluxes from curves *a* and *c* … [at] respectively 3.8 ± 0.05 Jy and 3.0 ± 0.5 Jy.

Finally, Lequeux (1962a) noted that there were a number of weak extragalactic radio sources studied at Nançay that could not be resolved at the longest interferometer spacing. Visibility curves for nine of these are reproduced here in Figure 22. Subsequent investigations by other astronomers would reveal most of these unresolved sources to be quasars.[10]

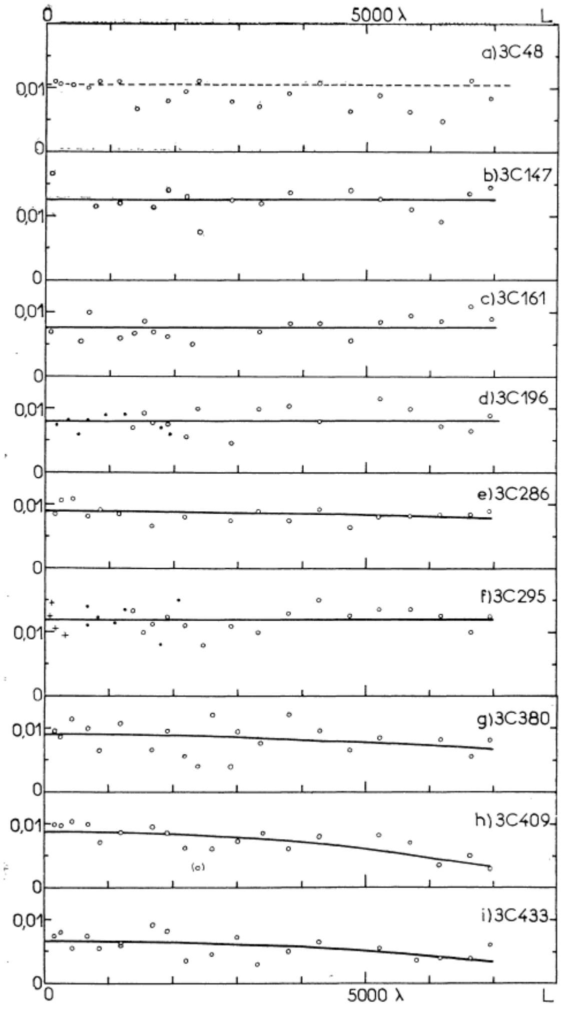

Figure 22: Visibility curves for nine unresolved extragalactic sources (after Lequeux, 1962a: 254).

This brings to a close our discussion of Lequeux's long 1962 paper, but it does not mark the end of the Würzburg Variable Baseline Interferometer at Nançay, which was used for one final research project. In 1962 Lequeux used this radio telescope to measure the 2-D size of the active galaxy, M82. Because of the low flux density (8 Jy) this proved to be very difficult, but Lequeux (1962b) detected an approximately circular source 45″ in diameter, which is much smaller than the optical galaxy. We now know that this source contains many HII regions and many regions of star-formation, hence its relatively flat spectrum.

It should be noted that during the late 1950s and early 1960s there was strong international competition for galactic and extragalactic interferometric observations. This derived, on the one hand, from Jodrell Bank, where they had excellent resolution and sensitivity but lacked absolute phase, and on the other hand, from Caltech, where the Owens Valley Interferometer (comprising two 90-ft dishes) had superior sensitivity and good phase stability but lower resolution than the Nançay Variable Baseline Interferometer could offer. The Jodrell Bank group started early and concentrated —initially at least—on high-resolution observations of a few bright sources (Jennison and Das Gupta, 1953; but cf. Allen et al., 1962). The Owens Valley Interferometer was operational from 1960, and initially it was used for positional measurements that led to the optical identification of a number of extragalactic sources; later it was employed for continuum and H-line observations (see Cohen, 1994).

It soon became clear that the special niche occupied by the Nançay Variable Baseline Interferometer would vanish in the face of competition from the Owens Valley radio telescope, and when the last serious observations were made in 1962 this marked the successful end of its important 13-year contribution to French and international science.[11] Seen in retrospect, the most valuable results obtained with the Nançay radio telescope relate to the structure of Sagittarius A and extragalactic sources like Cygnus A, Virgo A and M82, and to the finding that a number of sources (which subsequently turned out to be quasars) were still unresolved at the highest possible resolution.

5 THE INSTITUT D'ASTROPHYSIQUE DE PARIS' WÜRZBURG ANTENNA

5.1 Introduction

In immediate post-War France there were two active fledgling radio astronomy groups: the larger, vibrant team at the ENS led by Denisse and Steinberg (which we have already discussed) and a much smaller group led by Marius Laffineur[12] at the Institut d'Astrophysique de Paris (henceforth IAP) in Paris. Laffineur was a radio engineer who (just like his ENS colleagues) had to learn his astronomy 'on the run', but his commitment to this new field was such that he ended up putting his solar radio astronomy research conducted in 1948-1950 towards a Doctor of Engineering degree at the University of Paris.

Through the French Army, one of the three 7.5m Würzburg antennas secured by British forces at the end of WWII was acquired by the IAP and from 1948 would become the work horse for Laffineur's early investigations in radio astronomy. In the published version of his doctoral thesis, he describes this instrument:

> The mirror (*pl*. II), of very neat construction was originally intended as a device to track rockets. With a full diameter of 7.45 m, the very rigid paraboloid (*pl*. III) was composed of juxtaposed aluminium beams, covered by square mesh panels. The mesh holes are 10 mm in diameter and between them are strips of metal on average 2 mm wide. The focal distance is 1.70 m.
>
> The vertical distance from the edge of the parabola to the base is 1.90 m, so the focal plane is below the rim of the parabola.
>
> After construction, the surface precision was ± 1 cm, which allows use of the mirror down to a wavelength of 8 cm …
>
> Extending from the base of the mirror is a very rigid steel tube support, with the same axis of revolution as that of the parabola. The 555 Mc/s dipole is attached to the end of a copper tube …
>
> A disk of solid aluminium forms the secondary reflector (*pl*. IV) and is located a quarter-wavelength from the dipole, [and] we have assumed but without checking … that the presence of this reflector reduces the radiation resistance from the dipole to half of its theoretical value … (Laffineur, 1954: 21, 24; our translation).

Figure 23: The 7.5m Würzburg antenna at Meudon Observatory (courtesy: Observatoire de Paris, Meudon).

The original intention was to install this antenna on the roof of the Institute building in downtown Paris, but the load bearing of the building prevented this and Laffineur arranged for it to be located in the spacious grounds of the Meudon Observatory where there was land available (see Figure 23).[13] Dispensing with the original drive, Laffineur developed an ingenious electro-mechanical equatorial computer drive for this antenna. This so-called 'equatorial pilot' (Figure 24), was located in the rotating cabin to the rear of the dish, and

> In spite of this situation, to assure that it can point in a fixed direction in relation to the stars, it is placed on a mobile disk that has a vertical axis that is inclined at an angle of 48° 48′ which corresponds to the latitude of Meudon Observatory ... The vertical axle fixed to the floor is equipped at its upper end with a disk of the same diameter (*pl*. V, *fig*. 1) the two disks being linked by a perforated steel strap. When the cabin and the antenna rotate to some angle around the vertical, the disk supporting the equatorial pilot turns, relative to the cabin by an equal angle and in the opposite direction, thereby assuring the invariability of the direction of the polar axis … (Laffineur, 1954: 25; our translation).

The concept of an 'equatorial pilot' may have inspired the 'master equatorial' that was later installed on the altazimuth-mounted 64m Parkes Radio Telescope in Australia, even though this was of a very different design (see Bowen and Minnett, 1963).

The Meudon Würzburg antenna was to serve Laffineur well, and in introducing his research programs to his colleagues he explains that

> It is in the framework of astronomical research, with the advice, encouragement and kindly support from the French astronomers that we have undertaken this very modest work, in … a vast field of research with the immediate aim the observation of solar emission and of its influence on the as yet unexplored longer wavelengths and incidental observations of the Milky Way at the same frequencies. (Laffineur, 1954: 3; our translation).

5.2 The 1949, 1952 and 1954 Solar Eclipses

Between 1949 and 1954 (inclusive) French radio astronomers observed four different solar eclipses with a view to (a) pinpointing the positions of localized regions responsible for generating solar radio emission, and (b) investigating the distribution of radio brightness across the solar disk. The Meudon Würzburg radio telescope was used to observe three of these events (see Orchiston and Steinberg, 2007).

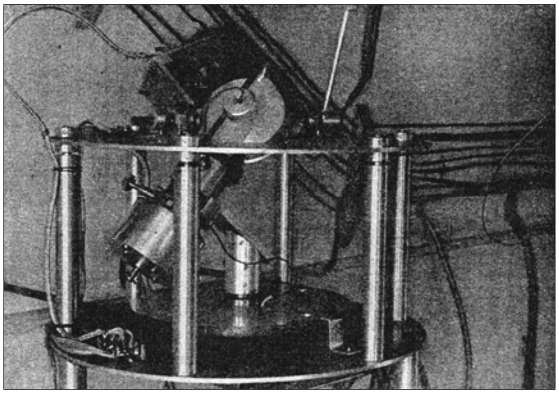

Figure 24: The Meudon Würzburg's 'equatorial pilot' (after Laffineur, 1954: Plate V).

The 28 April 1949 partial solar eclipse was observed at 555 MHz (see Laffineur et al., 1949, 1950; Steinberg, 1953), and the shape of the resulting eclipse curve (Figure 25) was "… incompatible with the hypothesis of a [radio] Sun of uniform brightness." (Laffineur et al, 1950: 339; our translation) or an annular disk of uniform brightness. Rather the eclipse curve suggested that "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." (ibid.). Chromospheric plages were invoked to partially explain this discrepancy, but Laffineur et al. (1950) cautioned that the interpretation of radio data from relatively small-phase partial solar eclipses like the 1949 one generated various difficulties, so the results reported should be seen as provisional.

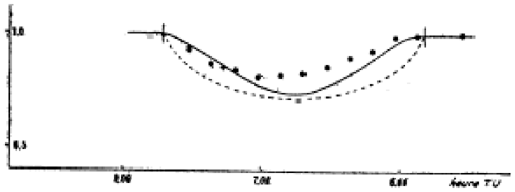

Figure 25: The dots show the 555 MHz 28 April 1949 eclipse curve, while the solid curve indicates the profile expected from a disk of uniform brightness and the dashed line the expected profile if the radio emission derived from an annular ring (after Laffineur et al., 1950: 338).

On 25 February 1952 a solar eclipse was visible in Africa (where it was total) and from Europe (where it was partial), and observations at 255 MHz were made with the Meudon Würzburg antenna. The radio astronomers noted that "At the maximum of the partial eclipse at radio wavelengths, 13 minutes after the optical event, the remaining radio emission was 83% that recorded when the Sun was not in eclipse." (Laffineur et al., 1952: 1529; our translation).

The last partial solar eclipse observed with the Meudon antenna took place on 30 June 1954, and while Laffineur and his colleagues tracked it from the line of totality in Sweden, Begot and Christiansen used the Paris-based radio telescope to observe at both 255 MHz and 545 MHz (Coupiac et al., 1955). Although successful eclipse curves were obtained at both frequencies (Figure 26), no attempt was made to interpret these in terms of localised radio-emitting regions or the shape and size of the radio corona.

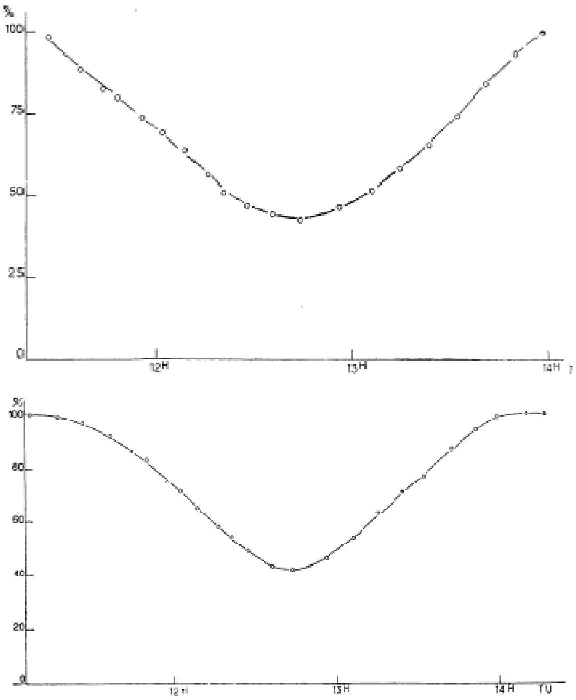

Figure 26: The 255 MHz (bottom) and 545 MHz (top) eclipse curves obtained at Meudon on 30 June 1954 (after Coupiac et al., 1955: 277).

5.3 Other Solar Observations

Between 9 September and 5 October 1948 Laffineur and Jakob Houtgast used the Meudon antenna to monitor the Sun at 555 MHz, and they subsequently reported their observations in *Annales d'Astrophysique* (Laffineur and Houtgast, 1949). From regular observations, they determined a value of T_e = 240,000 K for the quiescent Sun at this time, and compared this with values of 500,000 K and 100,000 K obtained by the Australian radio astronomers, Lehany and Yabsley (1948; 1949), at 600 MHz and 1,200 MHz respectively. In stark contrast was the figure of 10^6 K reported by Pawsey (1946) for 200 MHz, which corresponded with the value predicted—on theoretical ground—by D.F. Martyn (1946). On 24 May 1949 Laffineur (1954: 31) made further observations from Meudon at 555 MHz and obtained a value for the quiet Sun of 524,000 K. Surprisingly, in his paper Laffineur makes no attempt to explain the discrepancy between the 1948 and 1949 results or to correlate these figures with variations in sunspot area.

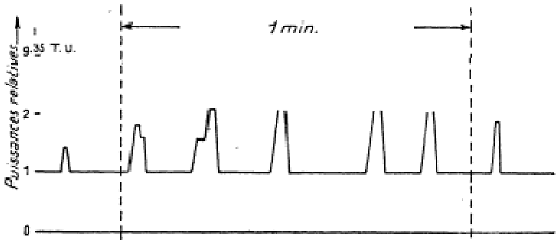

Figure 27: A group of solar bursts recorded at 555 MHz on 16 September 1948 (after Laffineur and Houtgast, 1949: 142).

During their monitoring period in 1948, Laffineur and Houtgast noted a number of occasions on 16, 17 and 23 September and on 4 October when there were significant variations in the level of incident radiation. Most of these came in the form of intense bursts of short duration (i.e. $t \lesssim 1$ min) as illustrated in Figure 27, but of particular interest was the outburst recorded on 17 September, which was also detected by Cambridge radio astronomers at 175 and 80 MHz and was accompanied by terrestrial effects associated with solar flare activity (see Figure 28). The comparative scarcity of bursts at 555 MHz compared favourably with the findings of Lehany and Yabsley in 1947. Observing at 600 MHz, they only occasionally recorded

> Isolated disturbances … mainly of low intensity and fairly short duration. In some instances they were definitely associated with chromospheric flares and sudden daylight radio fadeouts … (Lehany and Yabsley, 1949: 58).

Laffineur and Houtgast also found the events of 4 October 1948 (Figures 29 and 30) of special interest. They reported:

> This was the most disturbed day of this period of investigation (fig. 7 [= Figure 29 here]). During the intervals when there were bursts, the voltmeter was fairly calm (fig. 8 [= Figure 30 here] except towards 15 h 22m, (fig. 8 *a*), before a burst and after the bursts of 15 h 24 up until 15 h 40 (fig. 8 *b*). The intensity varied between 1 and 1.4. The most remarkable disturbance occurred at 15 h 22 m 30 s. The needle of the voltmeter began to quiver, vibrating with a small amplitude and at a frequency that we estimated at 20 periods/second. The frequency of the vibration decreased then in a way continued while the amplitude increased. After the last oscillation (of intensity 2), the deviation remained constant for about 3 seconds then fell back to its initial level. *This phenomenon appears to be due to interference between two coherent beams but with a variable phase difference at the start? If the origin is in the solar atmosphere, which is our belief, [then] this observation is very important.* (Laffineur and Houtgast, 1949: 143-144; our translation; our italics).

As a result of later observations, mainly by Australian and French radio astronomers, we can now associate the various events that Laffineur and Houtgast recorded with bursts of spectral Type III, but we can offer no obvious explanation for the anomalous burst recorded on 4 October.

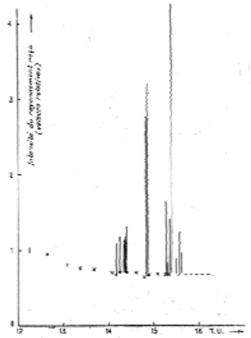

Figure 29: The 555 MHz solar events of 4 October 1948 (after Laffineur and Houtgast, 1949: 145).

Laffineur conducted further observations of solar bursts in 1949, and published these in 1954. A distinct advantage on this occasion was the presence of a chart recorder, so there was no longer any need to manually record individual voltmeter readings. Moreover, the time-constant of the recorder allowed bursts with durations as small as 1 or 2 seconds to be recorded. In another key development, from 1950 simultaneous observations were made at 255 and 555 MHz using the same Würzburg antenna.

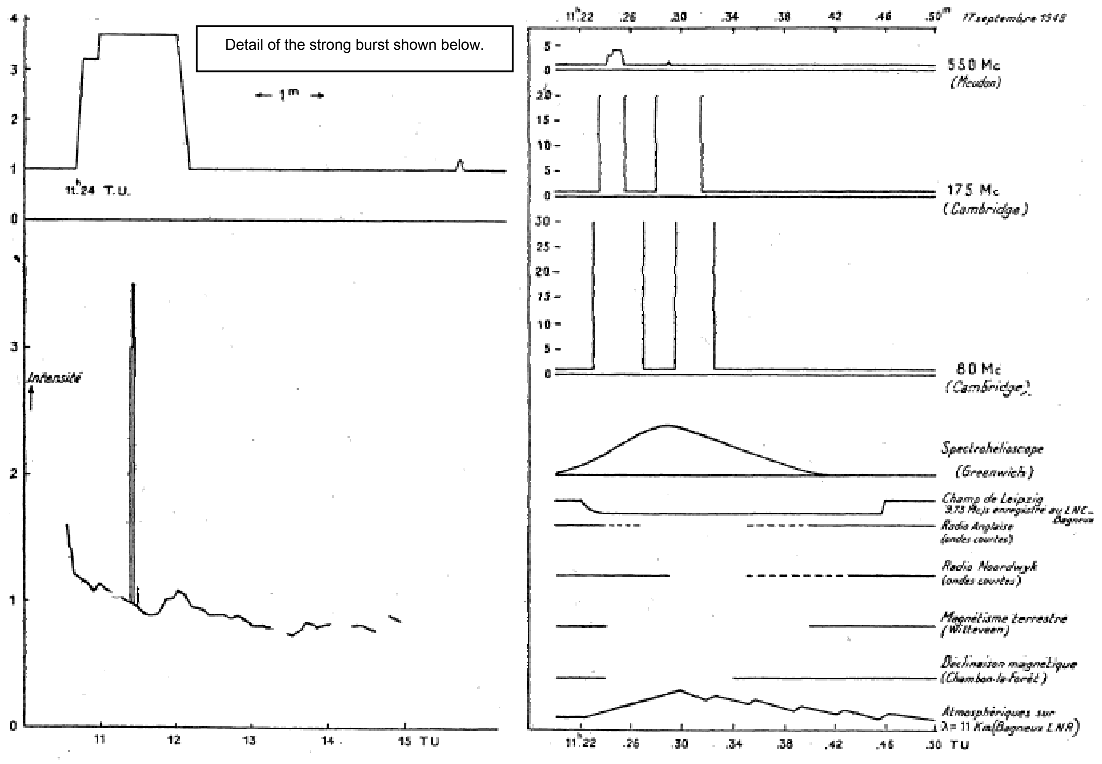

Figure 28: The solar event recorded at 555 MHz on 17 September 1948 (adapted from Laffineur and Houtgast, 1949: 143).

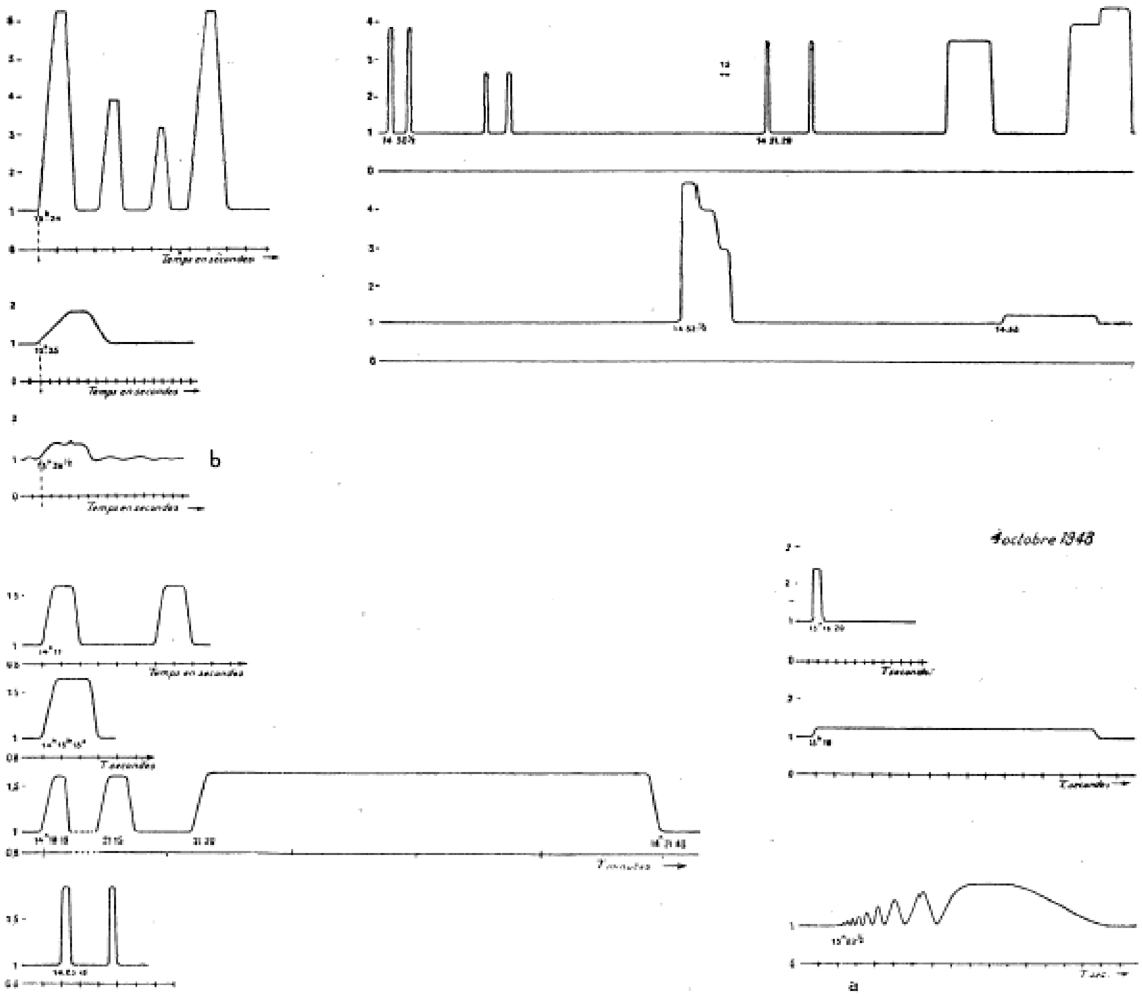

Figure 30: Detailed profiles of some of the 4 October 1948 bursts shown in Figure 29 (after Laffineur and Houtgast, 1949: 146).

In reviewing the 1949-1950 observations, Laffineur distinguished two different types of solar events, which he termed 'Pointes d'intensité' and 'Sursauts', and although the translated meanings are not the same, British and Australian solar radio astronomers would refer to these as 'bursts' and 'outbursts', respectively. The former lasted for up to 10 seconds duration, while some of Laffineur's 'sursauts' persisted for tens of minutes to more than one hour.

The most notable outbursts or groups of bursts occurred on 26 March, 28 April, 8 May and 17 June 1949 and on 2, 3 and 15 August 1950, and all were associated with solar flares that produced the usual terrestrial effects. All of these radio events are illustrated in Laffineur's paper, and the most interesting are reproduced here in Figures 31 to 34. The major outburst recorded on 8 May 1949 (Figure 32) is reminiscent of the event observed by Payne-Scott, Yabsley and Bolton on 21 May 1947, and it is interesting that there is a 3 minute delay between the start of the events at 73 MHz (as reported by Hey and included in Laffineur's paper) and 555 MHz. Meanwhile, the very numerous nests of bursts recorded at 255 MHz on 2-3 August 1950 (see Figures 33 and 34) would seem to be a good French example of Payne-Scott's'enhanced radiation', which she describes as follows:

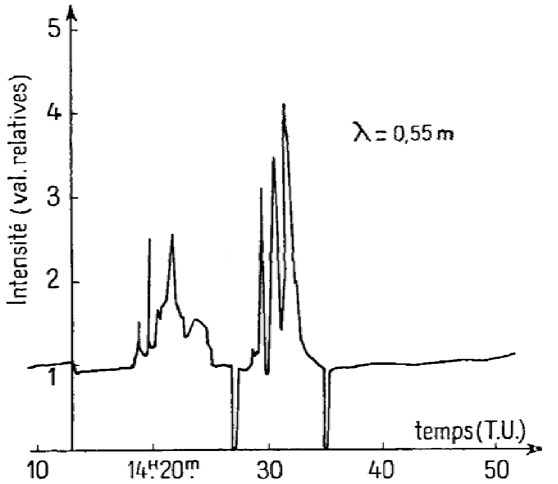

Figure 31: Solar bursts recorded at 555 MHz on 26 March 1949 (after Laffineur, 1954: Plate VII).

> The intensity reaches a high level and remains there for hours or days on end; there are continual fluctuations in intensity, both long-term and short-term. The short-term increases are somewhat similar to [isolated] bursts … but usually have a lower ratio of maximum to background radiation … Superimposed on it may be bursts … There may be short periods

> during which the polarization is indefinite, either because two sources of opposite polarization are superimposed or because the radiation is linearly or randomly polarized, but for the great part of its life the enhanced level shows circular polarization of one sense or the other. (Payne-Scott, 1949: 216-217).[14]

Unfortunately, Laffineur did not have the necessary equipment required to measure the polarization of the solar bursts that he recorded. Meanwhile, Laffineur (1954: 51) claims that the most important difference between the chart records at the two frequencies on 3 August 1950 is that the 555 MHz event commenced 1 minute 10 seconds before its 255 MHz counterpart, but given the plethora of small short-duration bursts visible at both frequencies in Figure 34 we find it hard to support this interpretation.

With access to Meudon Observatory spectroheliograms of Hα and CaII emission in the chromosphere, and the listings of optical events contained in the *Quarterly Bulletin of Solar Activity*, Laffineur was in an ideal position to investigate the relationship between bursts/outbursts and optical activity on the Sun. Assuming a *direct correlation* between optical activity and solar emission, he plotted the distribution on the solar disk of all bursts, groups of bursts and outbursts he recorded in 1949, based upon the positions of supposedly-associated optical activity (see Figure 35). However, there are two problems that he did not address: (1) as Christiansen et al. (1949), and others, had already shown, not all solar emission was associated with obvious optical activity (indeed, during the 1 November 1948 solar eclipse several 600 MHz radio-emitting regions with no obvious optical correlates were found to be located where sunspot groups had existed on the previous solar rotation, i.e. ~25-27 days earlier); and (2) since 600 MHz emission originated from the inner corona, those emitting regions associated with optical features on or near the limb would have been positioned beyond the edge of the optical Sun (e.g. see Christiansen et al., 1949: 515). This latter feature is an important point since many of Laffineur's 'radio-emitting regions' in Figure 35 are located near the limb of the Sun (cf. Laffineur, 1954: 37, Figure 20).

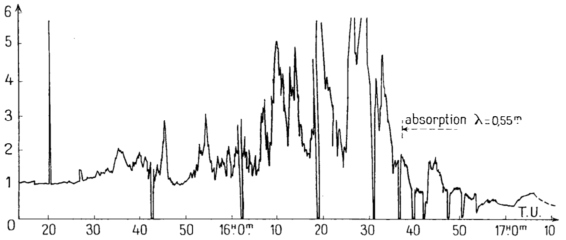

Figure 32: Solar outburst recorded at 555 MHz on 8 May 1949 (after Laffineur, 1954: Plate IX).

Although he did not allow for the aforementioned features, Laffineur proceeded to analyse the latitude, central meridian distance and solar quadrant positioning of his 'radio-emitting regions', and then came up with the following hypothesis:

> In the case occupying us, suppose that the sunspots emit radio emission and that the emission is deflected by the magnetic field so that the preferred emission direction has an angle θ relative to the vertical, towards the East for example. The Earth will then be positioned in the emission cone of those sunspots situated to the East in the northeastern hemisphere and, because of the reversal of polarity, also in those sunspots situated to the West in the south-western hemisphere (*fig*. 21). This explains the distribution that is actually observed.
>
> Without pushing our hypothesis any further, we can insist on the fact that the observed distribution of solar radio emission seems to indicate that the emission is beamed [rather than isotropic]. (Laffineur, 1954: 39; our translation).

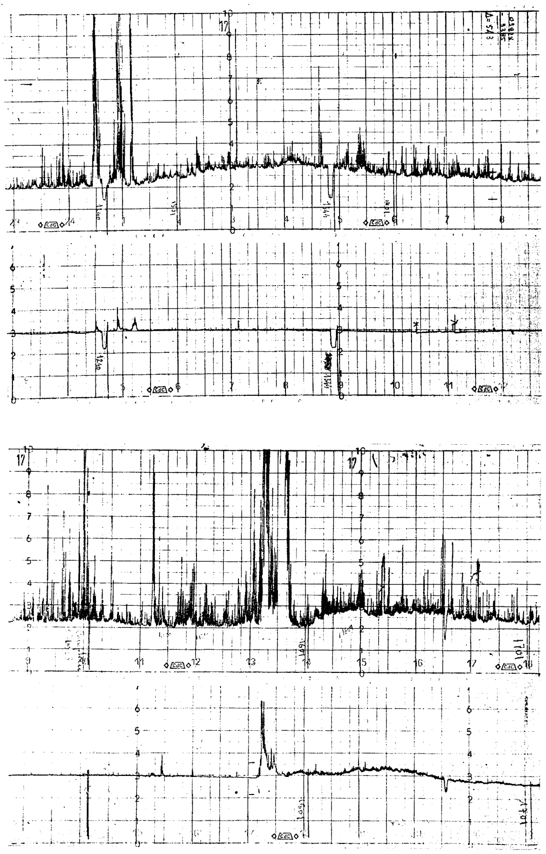

Figure 33: Solar bursts recorded at 255 MHz (upper curve) and 555 MHz (lower curve) on 2 August 1950; top: 12h 15m to 14h 50m; bottom: 14h 50m to 17h 01m (after Laffineur, 1954: 54-55).

In his long solar paper, Laffineur (1954: 4-6) mentions that he made unsuccessful attempts at Meudon to detect solar radio emission at 64 MHz using a half-wave antenna, but in 1947 he used a 64 MHz Yagi antenna at Haute Provence Observatory with some success.

In 1947 he also carried out solar observations with a 64 MHz interferometer comprising two Yagi antennas separated by 80m (or 17λ). Solar bursts were common at this frequency and at this time (e.g. see Payne-Scott, et al., 1947), so it is interesting that Laffineur did not publish any results deriving from these observations. Perhaps he produced results that did not add significantly to the existing body of knowledge, or maybe the observations were merely carried out in order to investigate the relative merits of using different antenna-receiving systems in radio astronomy rather than in a bid to make a serious contribution to solar radio astronomy. We will never know.

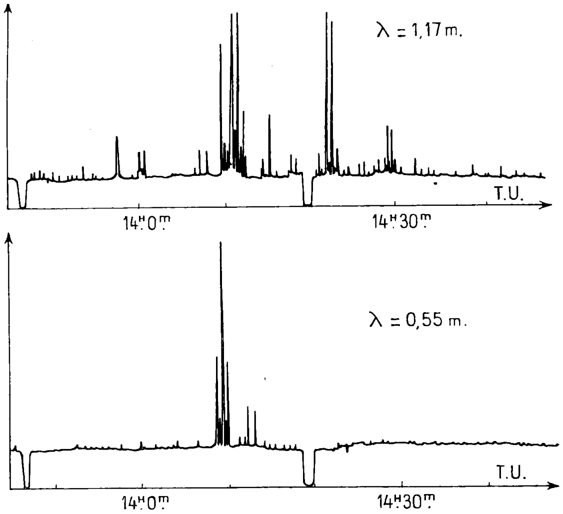

Figure 34: Solar bursts recorded at 255 MHz (top) and 555 MHz (bottom) on 3 August 1950 (after Laffineur, 1954: Plate XIII).

5.4 Non-Solar Observations

At the very end of their 1949 solar paper, Laffineur and Houtgast include a paragraph on their "Observations de la Voie Lactée" with the Meudon Würzburg antenna. They report that the incident radiation at 555 MHz from the Sagittarius region was <3% that received from the Sun (i.e. <75 K), and conclude that "This is a small value, but of the same order of magnitude, as that found by Dicke at much shorter wavelengths." (Laffineur and Houtgast, 1949: 147; our translation).

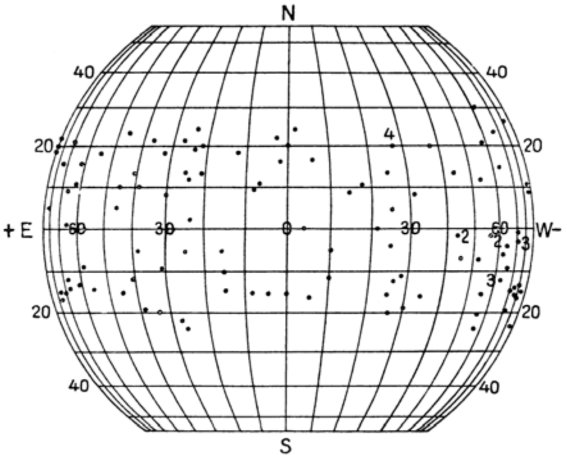

Figure 35: Positions projected onto the solar disk of radio-emitting regions detected at 555 MHz in 1949 (after Laffineur, 1954: 34).

6. DISCUSSION

6.1 The Fate of the Three Würzburg Antennas

Remarkably, all three French Würzburg antennas still exist. One of the two Nançay antennas is now preserved in the World War II Museum in Caen (Normandy). It was given to the Museum in the 1970s, and was installed on a concrete base (similar to the original one) in the dunes at this famous beach. An altazimuth mounting that mirrors the design of the original one is once more a feature of this historic instrument.

The second of the two Nançay Würzburg antennas is still at Nançay, but is slowly deteriorating (see Figure 36). This instrument and its Caen 'twin' played an important role in early French radio astronomy so we believe that it should be preserved at Nançay and used to interpret the early scientific history of the site, while the structural integrity of the instrument still makes this possible.

Of the three Würzburg antennas, the Meudon Observatory instrument made the longest contribution to international radio astronomy, albeit in a modest fashion in its 'twilight years'. In 1962 this radio telescope was transferred to Bordeaux Observatory, where it was provided with an equatorial mounting (Figure 37) and from 1965 began monitoring solar radio emission at 930 MHz for 10-12 hours per day. Operating as a total power radiometer, it continued to provide daily flux density measurements through to 1990. These measurements were simply used to track the Sun's output at 930 MHz; they did not constitute part of a major research program.

Figure 36: The sole remaining Würzburg antenna at Nançay (courtesy, Station de radioastronomie de Nançay, Observatoire de Paris, CNRS/INS).

6.2 Other Galactic and Extragalactic Research at Nançay During the Würzburg Era

One of the major solar radio telescopes erected at Nançay during the 1950s was a 1,550m long E-W oriented 32-element grating array that was inspired by Christiansen's Australian analog at Potts Hill. Operating at 169 MHz, this produced 3.8′ E-W pencil beams 2° apart. Although designed for solar investigations, this high-resolution instrument potentially could be used for a variety of non-solar projects.

The first of these occurred in June 1957 when the Sun passed in front of the Crab Nebula (i.e. Taurus A), thereby providing an opportunity to investigate the structure of the outer corona. Unfortunately, reliable observations were only possible with the Nançay solar interferometer on two different days, June 11 and 13, and a measurable increase in the diameter of the source was noted on both occasions. But more notable was an "… actual *increase* of total flux received from the Crab Nebula on the 13th; this result suggests that refractive processes in the corona might play an important role." (Blum and Boischot, 1957: 206).

Further coronal investigations utilising the Crab Nebula were made in June 1958, and these confirmed both the increase in source diameter and flux density as Taurus A approached the Sun. In Figure 38 the 1957 and 1958 data have been pooled, and it can be seen that both effects commenced when the source was at about $15R_{\odot}$. It is interesting to compare these French results with Slee's conclusion based upon his observations of the same 1957 and 1958 events. In 1957 he carried out fan-beam, pencil-beam and interferometer observations at 85.5 MHz, while in 1958 only fan-beam and pencil-beam observations were made. He reported that

> … the distribution of Crab nebula radiation is markedly affected by refraction and large-scale coronal irregularities. The secondary peak … was recorded in both 1957 and 1958, and suggests the existence of semi-permanent regions in the corona of higher than average electron density. (Slee, 1959: 151).

He also found evidence of short-term changes in the transmission properties of the corona that were possibly linked to the ejection of disturbances from active regions on the Sun's disk.

Figure 37: The ex-Meudon Würzburg antenna at Bordeaux Observatory (courtesy Bordeaux Observatory).

One of the most challenging problems facing radio astronomers in the 1940s and 50s was to identify optical correlates for the many discrete sources found in the course of the various sky surveys. Because of the comparative lack of resolution at radio wavelengths, it was difficult to determine the precise positions of most sources, but instruments like the Nançay 32-element E-W grating array (with its 3.8′ pencil beams) offered some hope. It is no surprise, therefore, to learn that this instrument was used by Boischot (1959) to investigate source positions in the late 1950s. He subsequently published a table containing 25 different sources between Declination +60° and –20°, listing for each the Right Ascension, Declination, diameter or an upper limit to this parameter, the flux density and any correlation that could be made with sources detected by previous investigators.

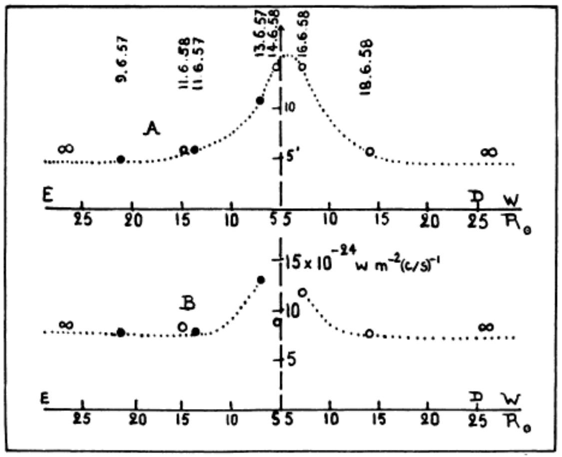

Figure 38: Variations in the apparent diameter (curve A) and flux density (curve B) of the Crab Nebula as it was occulted by the Sun in 1957 and 1958 (after Blum and Boischot, 1959: 283).

By the end of 1961 an eight-element array of equatorially-mounted dishes along a N-S baseline had been constructed at Nançay, and when combined with the original E-W array this offered a powerful new research tool for French radio astronomy. This new cross-grating interferometer (known affectionately as the 'Grand Réseau Interférométrique') operated at 169 MHz, and had a pencil beam with half-power widths of 3.4′ in an E-W direction and 7′ in a N-S direction. In 1961 and 1962 the Indian radio astronomer, Mohan Joshi (1962), used this array to measure the precise positions and flux densities of 112 different radio sources. He found that it was possible to correlate almost all of these with discrete sources already reported in the Cambridge 3C Catalogue (Edge et al., 1959) and the Australian catalog of Mills, Slee and Hill (1958).

Joshi also investigated the controversial position of the galaxy associated with the radio source, Hercules A. Figure 39 shows how the position derived at the Owens Valley Radio Observatory (cross number #1) correlated with Galaxy b, while the Cambridge 3C position (cross #2) clearly favoured Galaxy c. The very close correspondence between cross #3 (the Nançay result) and the Cambridge position leaves absolutely no doubt about the correct identification.

6.3 Paris Observatory, Nançay and 'Le Grand Radiotélescope'

It was inevitable that the two Würzburg antennas at Nançay would eventually be superseded as the quest for improved sensitivity and resolution during the 1950s and into the 1960s saw the emergence worldwide of a variety of new innovative radio telescope designs. These included large single parabolas (as at Jodrell Bank and Parkes), cross-type radio telescopes (e.g. the Mills Cross at Fleurs, in Australia), several different types of variable baseline interferometer (as at Cambridge University and the Owens Valley Radio Observatory), large fixed horizontal cylindrico-parabolic reflectors, and fixed curved collectors using tiltable plane mirrors and moving focal-plane systems. No longer was it adequate to simply recycle World War II equipment!

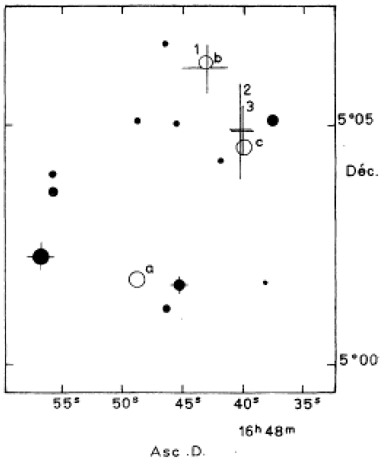

Figure 39: The region of the sky containing the discrete radio source Hercules A. Galaxies are marked by a, b and c and the crosses indicate source positions obtained by the Caltech (1), Cambridge (2) and Nançay (3) groups (after Joshi, 1962: 398).

Like their international colleagues, the Paris Observatory radio astronomers were keen to upgrade their instrumentation, especially following the detection of the H-line. For those involved in non-solar research the final choice lay between a large variable baseline interferometer and a fixed collector with a tiltable plane mirror and moving focal-plane system. The latter option won out and 'Le Grand Radiotélescope' was constructed at Nançay (see Theureau and Cognard, 2004); although it became operational in 1965 it was only used on a regular basis from 1968. It is hoped that the history of this impressive instrument will be the subject of a later paper in this series.

6.4 The Institut d'Astrophysique de Paris and the Saint Michel Interferometer

Those in Laffineur's much smaller radio astronomy group at the Institut d'Astrophysique de Paris also wished to up-grade their instrumentation, but their choice was to erect a 300 MHz 2-element interferometer with each component comprising a fixed horizontal cylindrico-parabolic reflector (Figure 40). The 'Saint Michel Interferometer' was set up at a field station at the Haute Provence Observatory, and began operating in 1959.

Each N-S oriented element was 60m in length and 32m in width, with the wire mesh supported by 128 wooden posts. Tall posts carried lines that supported 80 folded 300 MHz dipoles (Figure 41) 11.29m above the reflector, and each dipole could be electrically phased in order to steer the pencil beam in the meridian plane. The beamwidth was 1.5°. The two antennas were situated at the ends of a 1,100m E-W baseline. Incoming signals from the two elements were channeled into a receiver building (Figure 42) that was equidistant from the two antennas, and phase coherence was achieved by means of a microwave link, the first time such technology was used in French radio astronomy. For further technical details of this radio telescope see Laffineur and Coupiac (1967).

Laffineur and Coupiac mention (1967: 393; our translation) that

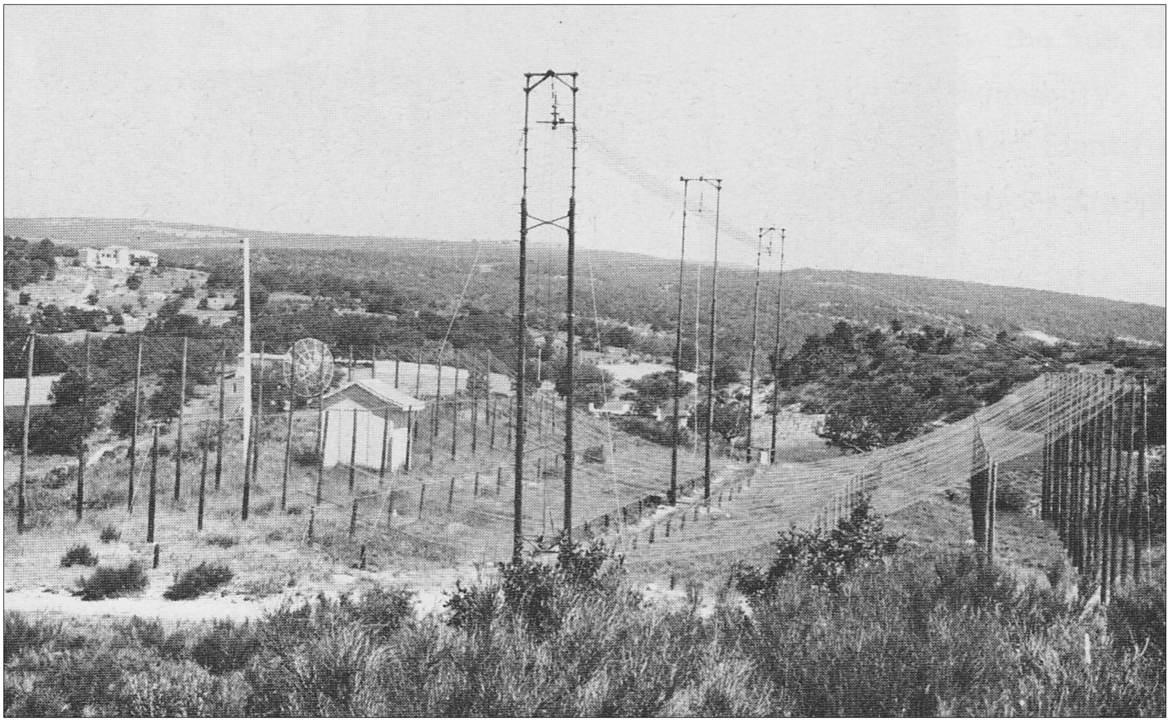

Figure 40: View of the 60m × 32m eastern element of the Saint Michel Interferometer, which was located at the Haute Provence Observatory (after Denisse, 1984: 312).

> The idea of this type of antenna was first developed by one of us [i.e. Laffineur] around 1950 … and has the principal advantage of being extremely economical whilst at the same time possessing two qualities that are favourable for research:
>
> a. — the possibility of being oriented in the plane of the meridian, without having to move the antennas.
>
> b. — good resolving power, comparable to a dish of 30m diameter.

In a telling comment, Laffineur (1961: 203; our italics) mentions that this radio telescope was "Built in 1955 *for instrumental and astronomical research* …", indicating that construction and fine-tuning of the system took several years and that science was not the sole motivating factor in establishing this impressive new radio telescope.

Once operational, the Saint Michel Interferometer was used between 1959 and March 1967 to conduct a survey of all sources >1.6′ in diameter and with flux densities of >9.5 Jy that passed through the beam. Because it functioned essentially as a transit instrument, the procedure was to observe the same strip of sky on three successive days or nights and to record any source interference fringes on the same chart record (e.g. see Figure 43). The maximum fringe amplitude disclosed the source's right ascension and the positioning of the antenna beam its declination.

The resulting Saint Michel Catalogue contained 216 sources that also appeared in the 3C and Revised 3C Catalogues (see Laffineur and Coupiac, 1967: Table I), plus 40 additional sources that were not listed in either of the Cambridge Catalogues (Laffineur and Coupiac, 1967: Table III). Laffineur and Coupiac (1967) also recorded 39 different sources they felt definitely existed which were initially listed in the 3C Catalogue but were removed when the Revised 3C Catalogue was prepared (see Laffineur and Coupiac, 1967: Table IV). Finally, they noted that there were 108 different sources listed in the Revised 3C Catalogue that were not detected with the Saint Michel Interferometer (see Laffineur and Coupiac, 1967: Tabel II); most of these were small weak sources.

The 1967 Laffineur and Coupiac paper marked the last published research contribution from the Saint Michel Interferometer, which is a little surprising given that a follow-up paper on the spectra of the various sources detected at Saint Michel (300 MHz), Cambridge (178 MHz) and with the 85.5 MHz Mills Cross near Sydney would have been a very useful compilation. But it was not to be, and we must presume that Laffineur had other research commitments and priorities.

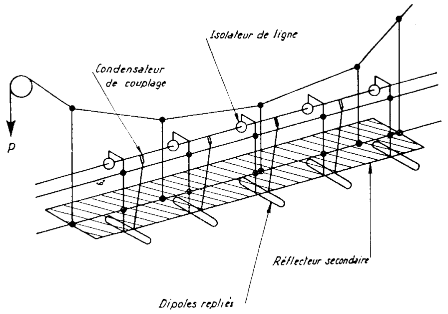

Figure 41: Schematic close-up of a section of the focal plane showing a number of dipoles (after Laffineur and Coupiac, 1967: 395).

Figure 42: The central receiver building, and microwave link tower (after Laffineur and Coupiac, 1967: 394).

We should also observe the sad fact that Laffineur's group received little support from other staff members at the Institute of Astrophysics where the merits of radio astronomy were not fully appreciated, and the fact that Laffineur and Coupiac only used the Saint Michel Interferometer to produce a single catalogue of sources would have served to compound this perception. The truth is that Laffineur was a very good radio engineer, but few important scientific results flowed from the instruments he built. Had circumstances been different and personalities not been a factor, then Laffineur may have been tempted to join the fledgling radio astronomy group at the École Normal Supérieure, and in this supportive intellectual environment he could very well have flourished. Were this the case, the history of French radio astronomy would undoubtedly have a very different flavour!

As it was, when radio astronomy ceased at the Institut the Saint Michel Interferometer was dismantled, so neither of the antennas has survived.

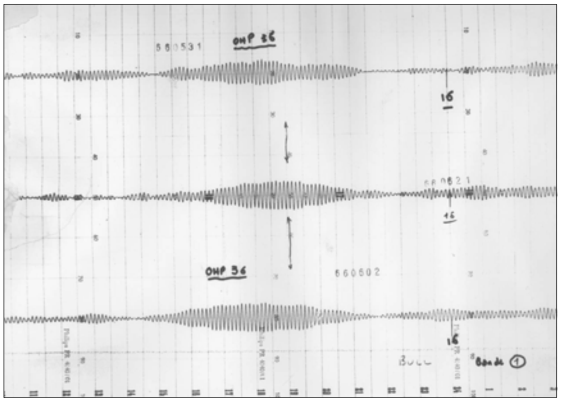

Figure 43: Chart record showing example of three successive days of observations, showing interference fringes from a number of weak sources (courtesy J. Clavier).

7. CONCLUDING REMARKS

In 1945 the defeated German army withdrew from the countries it had occupied, and it left behind a number of military radars. The Würzburg *Riese* radars contained a parabolic mirror 7.5 meters in diameter and could operate at 600 MHz (50cm). Actually their surface shape and structure were both good enough to be used down to 10cm wavelength, but their mount was altazimuth. In many countries these radar antennas contributed to early radio astronomy, and three of them were used in France.

One of the three was mounted at Meudon Observatory by M. Laffineur, who developed an ingenious electro-mechanical computer to point the antenna. Four solar eclipses were observed at 255 or 555 MHz between 1949 and 1954, in cooperation with foreign teams, so that the source regions of the radio emission could be localised and their positions compared with optical features. Laffineur and Coupiac also studied the brightness distribution across the solar disk and measured the brightness temperature of the Sun. The quiet Sun radiation temperature was found to be 240,000 K at 555 MHz. Intense solar bursts were also observed at both frequencies.

The two other Würzburg antennas were mounted at Marcoussis in a French Navy Research Center which was headed by Y. Rocard, who was also the Director of the Physics Laboratory at the École Normale Supérieure (ENS) in Paris. In the immediate post-war years, Rocard was one of very few French scientists who knew about radio astronomy, and he encouraged J.F. Denisse and J-L. Steinberg to build up a research team at the Laboratory and begin investigations in this exciting new field. The first Marcoussis Würzburg, which still retained its original WWII mounting, was fitted with a 900 MHz receiver built by E. Le Roux, and J. Lequeux and Le Roux then used this radio telescope to survey the Galaxy; they detected dozens of discrete sources many of which were new.

In 1953, the ENS group decided to build an observing station which could accommodate 2km long E-W and N-S antennas. Rocard obtained the money within a few weeks, and a parcel of land was found and bought near Nançay, south of Paris. The plan was to build a Christiansen-type cross array for solar studies at meter wavelengths and a variable-baseline interferometer using the two Marcoussis Würzburg antennas for galactic and extragalactic studies at decimetre wavelengths. In 1959 the interferometer became operational, and subsequently many continuum observations of discrete sources were made at 1,420 MHz. The angular resolution was good enough to allow an analysis of the structure of most of these sources. The variable baseline interferometer yielded a large quantity of new data, and resulted in a succession of publications.

Over the years, the three Würzburg antennas not only produced valuable scientific results; they also were used to train researchers and engineers intent on conceiving, building, testing and using new much more powerful French radio telescopes.

8. NOTES

1. This research evolved out of an IAU Historic Radio Astronomy Working Group project to survey surviving early French radio telescopes, and is the third paper in a series documenting early French radio astronomy. The first paper dealt with Nordmann's unsuccessful attempt to observe solar radio emission in 1901 (Débarbat, Lequeux, and Orchiston, 2007), and the second paper examined French solar eclipse observations made between 1949 and 1954 (Orchiston and Steinberg, 2007).
2. Yves Rocard was born in Vannes on 22 May 1903 and died in Paris on 16 March 1992. After studying science at the École Normale Supérieure (ENS), he completed doctoral degrees in mathematics and physics in 1927 and 1928, respectively. He was then responsible for classes—and subsequently for research—at the College of France. In 1939 he joined the Faculty of Science at Clermont-Ferrand, and during the War was active in the French resistance (which is when he became familiar with radar). Immediately after the War ended he became Director of the Physics Laboratory at the ENS, where he nurtured the development of the radio astronomy group headed by Jean-François Denisse and Jean-Louis Steinberg. At this time he was also involved in France's development of nuclear and hydrogen bombs and the construction of the Orsay linear accelerator. As further evidence of his versatility, in 1958 he began a career in geophysics. In 1973 at age 70 he retired from the ENS, but continued to conduct research in magnetism and biomagnetism. He died in 1992. This 'thumbnail sketch' is based on Rocard's published books and the 'Rocard' entry in Wikipedia.
3. Just 26% of the disk was masked at mid-eclipse.
4. Westerhout (1958) later showed that synchrotron emission accounted for about half of the galactic radiation at 1,390 MHz.
5. This was the *Australian Journal of Scientific Research*, which was launched by the Commonwealth Scientific and Industrial Research Organisation in 1948 in order to aid the international dissemination of research work carried out by the Organisation's staff and their university colleagues. While this aim may have been laudable, it took many years for this journal—rebadged as the *Australian Journal of Physics*—to gain international visibility (Sullivan, 2005). To partially offset this situation, the radio astronomers in the Division of Radiophysics were encouraged to immediately publicize their most important findings by means of short papers published in *Nature*.
6. This funding was conditional upon his visiting their Melbourne office during the trip. Steinberg found the office very poorly equipped, and reported on this at the Paris headquarters when he returned to France. They quickly had promotional material prepared in English and sent out to Australia.
7. This project was the mainstay of Vinokur's Doctor of Engineering thesis.
8. One of these sources, 3C 58, was later shown to be a non-thermal Crab-like SNR. Its flat spectrum was the reason that it was thought initially to be associated with an HII region.
9. Subsequently, all six sources were shown to be SNRs.
10. It is important to remember that the identification of the first quasar occurred one year after Lequeux's paper appeared in print (see Waluska, 2007).

11. In 1968-1969, Lequeux used this Californian radio telescope for a systematic study of normal galaxies in the radio continuum, a project beyond the reach of the old Nançay Variable Baseline Interferometer.
12. Marius Laffineur was born in 1904 and died in 1987. He trained in radio engineering and in 1946 joined the staff of the Institut d'Astrophysique de Paris. It was there that he became involved in radio astronomy, and the development of the Meudon Würzburg antenna and solar research carried out with it became the basis of his Doctor of Engineering which was awarded by the University of Paris. After building and carrying out a source survey with the Saint Michel Interferometer, Laffineur became disenchanted with radio astronomy and spent the remainder of his working life organising total solar eclipse expeditions in order to research the solar corona. By the time he retired in 1969 the first signs of Parkinson's Disease were apparent. His final eclipse expedition was in 1970, and he died in 1987. This 'thumbnail sketch' draws on Laffineur's published papers, data in personnel files at the Institut d'Astrophysique de Paris and information kindly supplied by Dr Serge Koutchmy (who worked with Laffineur).
13. Another factor associated with the choice of Meudon was the presence of the solar optical astronomy group there led by Bernard Lyot, who was one of Laffineur's friends.
14. Payne-Scott's 'enhanced emission' is best associated with solar emission of spectral Type I.

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10. REFERENCES

Allen, L.R., Anderson, B., Conway, R.G., Palmer, H.P., Reddish, V.C., and Rowson, B., 1962. Observations of 384 radio sources at a frequency of 158 Mc/s with a long baseline interferometer. *Monthly Notices of the Royal Astronomical Society*, 124, 477-499,

Arsac, J., 1959. Essai de détermination des très faibles diamètres apparents en radioastronomie. *Optica Acta*, 6, 77-98.

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.

Biraud, F., Lequeux, J., and Le Roux, E., 1960. Interference measurements of Cygnus A, Sagittarius A, Virgo A and the supernovae of Tycho Brahe and Kepler. *Observatory*, 80, 116-118.

Blum, E-J., and Boischot, A., 1957. Occultation of the Crab Nebula by the solar corona. *The Observatory*, 77, 205-206.

Blum, E-J., and Boischot, A., 1959. Éclipse de la Nébuleuse du Crabe par la couronne solaire. In Bracewell, R. (ed.). *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press. Pp. 482-485.

Blum, E-J., Denisse, J-F., and Steinberg, J-L., 1954. Influence de l'ionosphère sur la réception du rayonnement galactique de fréquence de 29,5 MHz. *Comptes Rendus de l'Académie des Sciences*, 238, 1695-1697.

Boischot, A., 1959. Résultats préliminaires de l'observation des radiosources à l'aide de l'interféromètre de Nançay. In Bracewell, R. (ed.). *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press. Pp. 492-495.

Boischot, A., Blum, E.J., Ginat, M., and Le Roux, E., 1956. Observation d'une éclipse de la Nébuleuse du Crabe. *Comptes Rendus de l'Académie des Sciences*, 242, 1849-1852.

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

Bolton, J.G., and Stanley, G.J., 1949. The position and probable identification of the source of galactic radio-frequency radiation Taurus-A. *Australian Journal of Scientific Research*, A2, 139-148.

Bolton, J.G., Stanley, G.J., and Slee, O.B., 1949. Positions of three discrete sources of galactic radio-frequency radiation. *Nature*, 164, 101-102.

Bowen, E.G., and Minnett, H.C., 1963. The Australian 210-foot Radio Telescope. *Proceedings of the Institution of Radio Engineers Australia*, 24, 98-105.

Burke, B., 2005. Early years of radio astronomy in the U.S. In Gurvits, L.I., Frey, S., and Rawlings, S. (eds.). *JENAM 2003. Radio Astronomy From Karl Jansky to Microjansky*. PA de Courtaboeuf, EDP Sciences. Pp. 27-56.

Christiansen, W.N., 1953. A high-resolution aerial for radio astronomy. *Nature*, 171, 831-833.

Christiansen, W.N., and Warburton, J.A., 1953. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part I. A new highly directional aerial system. *Australian Journal of Physics*, 6, 190-202.

Christiansen, W.N., Yabsley, D.E., and Mills, B.Y., 1949. Measurements of solar radiation at a wavelength of 50 centimetres during the eclipse of November 1, 1948. *Australian Journal of Scientific Research*, A2, 506-523.

Cohen, M., 1994. The Owens Valley Radio Observatory: early years. *Engineering and Science*, 57, 9-25.

Coupiac, P., Laffineur, M., and Vauquois, B., 1955. Observations radioélectriques de l'éclipse totale de Soleil du 30 Juin 1954. *Annales d'Astrophysique*, 18, 271-278.

Dagkesamanskii, R.D., 2007. The Pushchino Radio Astronomy Observatory: origin and first decade's history. *Astronomische Nachrichten*, 328, 395-404.

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

Delannoy, J., Denisse, J-F., Le Roux, E., and Morlet, B., 1957. Mesures absolues de faibles densités de flux de rayonnement à 900 MHz. *Annales d'Astrophysique*, 20, 222-237.

Denisse, J-F., 1984. The early years of radio astronomy in France. In Sullivan, W.T. (ed.). *The Early Years of Radio Astronomy. Reflections Fifty Years after Jansky*. Cambridge, Cambridge University Press. Pp. 303-315.

Denisse, J-F., Lequeux, J., and Le Roux, E., 1957. Nouvelles observations du rayonnement du ciel sur la longueur d'onde 33 cm. *Comptes Rendus de l'Académie des Sciences*, 244, 3030-3033.

Denisse, J-F., Le Roux, E., and Steinberg, J-L., 1955. Observations du rayonnement galactique sur la longueur d'onde de 33 cm. *Comptes Rendus de l'Académie des Sciences*, 240, 278-280.

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

Edge, D.O., Shakeshaft, J.R., McAdam, W.B., Baldwin, J.E., and Archer, S., 1959. A survey of radio sources at a frequency of 178 Mc/s. *Memoirs of the Royal Astronomical Society*, 68, 37-60.

Hanbury Brown, R., 1954. The remnants of supernovae as radio sources in the Galaxy. *The Observatory*, 74, 185-194.

Hanbury Brown, R., and Hazard, C., 1953. A survey of 23 localized radio sources in the northern hemisphere. *Monthly Notices of the Royal Astronomical Society*, 113, 123-133.

Heidmann, J., and Lequeux, J., 1961. Mesures interférométriques de la radiosource Hercules A à 1420 MHz. *Comptes Rendus de l'Académie des Sciences*, 253, 226-227.

Jennison, R.C., and Das Gupta, M.K., 1953. Fine structure of extra-terrestrial radio source Cygnus I. *Nature*, 172, 996-997.

Jennison, R.C., and Latham, V., 1959. The brightness distribution within the radio sources Cygnus A (19N4A) and Cassiopeia A (23N5A). *Monthly Notices of the Royal Astronomical Society,* 119, 174-183.

Joshi, M., 1962. Mesures précises de position des radiosources à 169 MHz. *Annales d'Astrophysique*, 25, 377-399.

Kerr, F.J., 1953. Radio astronomy at the URSI Assembly. *Sky & Telescope*, 12(3), 59-62, 70.

Laffineur, M., 1954. Contribution à l'étude du rayonnement électromagnetique du Soleil sur ondes décimètriques. *Bulletin Astronomique*, 18, 1-57.

Laffineur, M., 1961. Radio astronomy. *American Journal of Physics*, 29, 198-206.

Laffineur, M., and Coupiac, P., 1967. Un radio interféromètre méridien à liaisons radioélectriques. Techniques et observations. *Bulletin de la Société Royale des Sciences de Liège*, 36, 393-417.

Laffineur, M., and Houtgast, J., 1949. Observations du rayonnement solaire sur la longueur d'onde de 55 centimètres. *Annales d'Astrophysique*, 12, 137-147.

Laffineur, M., Michard, R., 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.

Laffineur, M., Michard, R., Pecker, J-C., d'Azambuja, Dollfus, A., and Atanasijević, I., 1952. Observations combinées de l'éclipse totale de Soleil du 25 Février à Khartoum (Soudan) et de l'éclipse partielle au radio-télescope de l'Observatoire de Meudon. *Comptes Rendus de l'Académie des Sciences*, 234, 1528-1530.

Large, M.I., Mathewson, D.S., and Haslam, C.G.T., 1959. A high-resolution survey of the Coma cluster of galaxies at 408 Mc/s. *Nature*, 183, 1663.

Lehany, F.J., and Yabsley, D.E., 1948. A solar noise outburst at 600 Mc./s. and 1,200 Mc./s. *Nature*, 161, 645-646.

Lehany, F.J., and Yabsley, D.E., 1949. Solar radiation at 1200 Mc/s., 600 Mc/s., and 200 Mc/s. *Australian Journal of Scientific Research*, A2, 48-62.

Lequeux, J., 1962a. Mesures interférométriques à haute résolution du diamètre et de la structure des principales radiosources à 1420 MHz. *Annales d'Astrophysique*, 25, 221-260.

Lequeux, J., 1962b. Observations interférométriques de la radiogalaxie M82 sur 1420 MHz, et comparaison avec objets semblables. *Comptes Rendus de l'Académie des Sciences*, 255, 1865-1867.

Lequeux, J., and Heidmann, J., 1961. Mesures interférométriques de radiosources extragalactiques à 1420 MHz selon la direction Est-Ouest. *Comptes Rendus de l'Académie des Sciences*, 253, 804-806.

Lequeux, J., Le Roux, E., and Vinokur, M., 1959. L'interféromètre à deux antennas à espacement variable de la station de radioastronomie de Nançay. *Comptes Rendus de l'Académie des Sciences*, 249, 634-636.

McGee, R.X., and Bolton, J.G., 1954. Probable observation of the Galactic Nucleus at 400 Mc./s. *Nature*, 173, 985-987.

McGee, R.X., Slee, O.B., and Stanley, G.J., 1955. Galactic survey at 400 Mc/s between declinations –17° and –49°. *Australian Journal of Physics*, 8, 347-367.

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

Menon, T.K., 1961. A model of the Orion Nebula derived from radio observations. *Publications of the National Radio Astronomy Observatory*, 1(1), 1-17.

Mills, B.Y., 1953. The radio brightness distributions over four discrete sources of cosmic noise. *Australian Journal of Physics*, 6, 452-470.

Mills, B.Y., Slee, O.B., and Hill, E.R., 1958. A catalogue of radio sources between declinations +10° and –20°. *Australian Journal of Physics*, 11, 360-387.

Orchiston, W., and Slee, B., 2002. Ingenuity and initiative in Australian radio astronomy: the Dover Heights 'hole-in-the-ground' antenna. *Journal of Astronomical History and Heritage*, 5, 21-34.

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

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.

Payne-Scott, R., 1949. Bursts of solar radiation at metre wavelengths. *Australian Journal of Scientific Research*, A2, 214-227.

Payne-Scott, R., Yabsley, D.E., and Bolton, J.G., 1947. Relative times of arrival of bursts of solar noise at different radio frequencies. *Nature*, 160, 256-257.

Piddington, J.H., and Minnett, H.C., 1951. Observations of galactic radiation at frequencies of 1210 and 3000 Mc/s. *Australian Journal of Scientific Research*, A4, 459-475.

Radhakrishnan, V., 2006. Olof Rydbeck and early Swedish radio astronomy: a personal perspective. *Journal of Astronomical History and Heritage*, 9, 139-144.

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

Slee, O.B., 1959. Occultations of the Crab Nebula by the solar corona in June 1957 and 1958. *Australian Journal of Physics*, 12, 134-156.

Smith, F.G., 2007. Early Cambridge radio astronomy. *Astronomische Nachricten*, 328, 426-431.

Steinberg, J-L., 1953. Les récepteurs de bruits radioélectriques: III. Un radiomètre 1200 MHz et quelques applications. *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., 2004a. La création de la station de Nançay. *L'Astronomie*, 118, 626-631.

Steinberg, J-L., 2004b. Radioastronomie et interférométrie. *L'Astronomie*, 118, 622-625.

Strom, R., 2004. 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 astronomy. *Journal of Astronomical History and Heritage*, 8, 11-32.

Theureau, G., and Cognard, I., 2004. Le Grand Miroir. *L'Astronomie*, 118 (Janvier), 10-16.

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

Waluska, E., 2007. Quasars and the Caltech-Carnegie connection. *Journal of Astronomical History and Heritage*, 10, 79-91.

Web site: http://atlantikwall.info/radar/radar.htm

Web site: http://fr.wikipedia.org/wiki/Yves_Rocard

Westerhout, G., 1958. A survey of the continuous radiation from the galactic system at a frequency of 1390 Mc/s. *Bulletin Astronomical Institutes of the Netherlands*, 14, 215-264.

Dr Wayne Orchiston is a Senior Lecturer in Astronomy at James Cook University, Townsville. His main research interests relate to Cook voyage, Australian 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* (2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan and Jessica Chapman, which will be published by Springer in 2007. He is the Chair of the IAU Working Group on Historic Radio Astronomy.

Dr James Lequeux belongs to the second generation of French radio astronomers, who were physicists rather than radio engineers but still lacked training in astronomy. He started research in radio astronomy with Jean-François Denisse in 1954, and in 1955 completed a Diplôme d'Études Supérieures based on work carried out with one of the Marcoussis Würzburg antennas. In 1959, after completing military training, he commenced Ph.D. research at Nançay with the two Würzburg antennas. He and Jean-Louis Steinberg produced the first French text book on radio astronomy in 1960. After a career in radio astronomy and in various fields of astrophysics, his post-retirement interests turned to history, and his 2005 book, *l'Univers Dévoilé*, is a history of astronomy from 1910 to the present day. James is now affiliated with the LERMA Department at the Paris Observatory.

Dr Jean-Louis Steinberg began working in radio astronomy with J-F. Denisse and E-J. Blum at the École Normale Supérieure after the War. On his return from the 1952 URSI Congress in Sydney, he began developing the Nançay radio astronomy field station, and from 1960 through to 1965 he and M. Parise led the design and construction in Nançay of 'Le Grand Radiotelescope'. 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.

Jean Delannoy completed an undergraduate degree in Physics at the École Normale Supérieure, and in 1959 joined the Paris-Meudon Observatory (after returning from military duty in the Antarctic during the I.G.Y., in 1957-1958). Earlier, he had started working in radio astronomy with J-F. Denisse and J-L. Steinberg. Over the next twelve years he was involved in the development of various radio telescopes at the Nançay field station, and he then spent eight years at Bordeaux Observatory where a small 2-element interferometer was built and successfully tested. In 1979 he accepted the position of astronomer at IRAM (the Institute for Millimeter Radio Astronomy), and moved to Grenoble in 1980. There he helped build precision homological antennas—of 15m diameter and 50 micrometers surface accuracy—for the IRAM synthesis interferometer, until his retirement in 1992.