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HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY.
5: THE NANÇAY LARGE RADIO TELESCOPE

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Abstract: The large radio telescope (Le Grand Radiotélescope) at the Nançay radio astronomy field station of Paris Observatory was built between 1958 and 1966 on the model of the Ohio State University radio telescope, with which a large collecting area was obtained at low cost. The Nançay radio telescope, with a surface area of 7,000m^2, is a meridian instrument which can observe equatorial sources for 30 minutes on each side of the meridian transit of the source. We describe the origin and the construction of this instrument. We also describe the evolution of the focal systems and give an outline of the first spectral and continuum observations obtained with the radio telescope in the wavelength range 6 to 32 cm.

Keywords: radio telescope, radio interferometer, Nançay, radio astronomy, incoherent scatter

1 INTRODUCTION

Radio astronomy in France started after WWII with small instruments, mostly solar, at the Physics Laboratory of the École Normale Supérieure and at the Institut d'Astrophysique in Paris (see Orchiston and Steinberg, 2007). Thanks to the availability of two 7.5-m Würzburg antennas taken from the Germans, the group at the École Normale Supérieure began galactic radio astronomy in 1954 (Orchiston et al., 2007). Meanwhile, the group at the Institut d'Astrophysique built a 2-element interferometer at the Haute Provence Observatory which was used between 1959 and 1967 to catalogue radio sources at 300 MHz (ibid.). But radio astronomy then ceased at the Institut d'Astrophysique, and the interferometer was dismantled.

In 1953, a field station was established at Nançay, 190 km south of Paris, by the École Normale Supérieure, and the radio astronomy group moved to the Meudon site of the Paris-Meudon Observatory the following year. In 1955, two Würzburg dishes located at Marcoussis, south of Paris, were transferred to Nançay and mounted equatorially on carriages which could be moved along a 1,480m long E-W, 6m wide, railway track, and along a similar 380m long N-S track. This variable-baseline interferometer became operational in 1959, and operated in the continuum at 1,420 MHz (details are in Orchiston et al., 2007). A 169 MHz solar interferometer was put into operation at Nançay in 1956, and a small 3cm solar interferometer which was moved earlier from Marcoussis to Nançay was enlarged in 1958 (see Orchiston et al., 2009).

Elsewhere in the world large single-dish radio telescopes and interferometers were being erected for galactic and extra-galactic studies at about this time. For example, in England the Jodrell Bank 76-m Mark I Radio Telescope was completed in 1957 (Lovell, 1968; 1973), and in Australia the 64-m Parkes Radio Telescope and the Mills Cross at Hoskinstown near Canberra were completed in 1961 and 1965 respectively (see Robertson, 1992; McAdam, 2008). The Cambridge University radio astronomy group was also busy building interferometers (e.g. see Scheuer, 1984; Smith, 1984). The period was favourable for large projects in France, which was under the leadership of General Charles de Gaulle, and it is natural that the radio astronomers there were dreaming of a large instrument for non-solar work. This eventually materialized as the Nançay 'Grand Radiotélescope' (see Figure 1). In this paper we investigate the origin and development of this instrument.[1]

2 INTERFEROMETER OR LARGE PARABOLIC RADIO TELESCOPE?

The French group at the École Normale Supérieure and Observatoire de Paris-Meudon had considerable experience in radio interferometry. As early as 1952 solar fringes were obtained at 3cm by Jacques Arsac and Jean-Louis Steinberg, with the latter proudly announcing "I think we are the first." (Steinberg, 1952; our translation).[2] Several solar radio interferometers were subsequently installed at Marcoussis, and later at Nançay (Pick et al., 2010). It is not surprising, therefore, that at the beginning of 1955 some members of the group proposed to build a large interferometer for non-solar studies, consisting of two 25-m diameter altazimuth-mounted antennas, similar to the Dwingeloo Radio Telescope (see Van Woerden and Strom, 2007), but movable on E-W and N-S railway tracks. The project was unanimously accepted by the radio astronomy group and co-signed by its head, Jean-François Denisse, and by Steinberg who was still at the École Normale Supérieure (Denisse and Steinberg, 1955). The main science driver was to observe the 21cm line of interstellar atomic hydrogen, discovered in 1951 (Ewen and Purcell, 1951; Muller and Oort, 1951), and the scientific reason for an interferometer was as follows (Denisse and Steinberg, 1955; our translation):

> At present, the major problem is to obtain a better resolution in order to solve the problems of structure [of the radio sources] … Since 1946, interferometers have been used in England and in Australia, with two or more antennas on a rather long baseline. Provided that the distance between the antennas can vary in a quasi-continuous way, a two-antenna interferometer is in principle equivalent in resolving power to a continuous antenna with the same total length.

However, at the beginning of 1956 Denisse came up with new ideas when he compared the interferometer with two other options:

(1) a fully-steerable paraboloid, which was rejected on the grounds that "… given the required surface quality [for observing at 21 cm] and the present technical possibilities, one can only build for a reasonable price dishes with a surface smaller than about 900m^2 (a diameter of about 30 metres) …; and

(2) "… a [fixed] parabolic mirror illuminated by a flat mirror movable around a horizontal axis: this is a meridian instrument, less versatile than the other one, but which can be built with a much larger surface area at low cost. (quotations are cited by Darmon, 1981: 42; our translations).

One argument against the interferometer was that

> … taking into account the structure of the ground in Nançay (sand + clay), the cost of the railway track is a significant part of the total cost of the project which is more than 500 million [old] francs … (cited by Darmon, 1981: 43; our translation).

This sum was equivalent to about €10 million in 2008.[3] This new railway track, with concrete foundations, was judged necessary to support the heavy 25-m antennas on their carriages, but the argument was rather weak because the problem of foundations was the same for any type of radio telescope. Moreover, the reservations expressed about steerable paraboloids seem odd since the Jodrell Bank Radio Telescope was almost completed and the Australians had decided to build the Parkes Radio Telescope. A better reason—which was difficult to acknowledge officially—was that French industry was unable or unwilling to build high-precision steerable paraboloids (even though this was possible in other countries), but the radio telescope simply had to be built in France given the political climate at the time.

Meanwhile, the scientific objectives had also changed. Denisse was impressed by the results obtained on distant galaxies with the 5-m Hale Telescope on Palomar Mountain, and in particular by Baade and Minkowski's (1954) identification of Cygnus A with a faint, distant radio galaxy, and he wrote:

> [Cygnus A] is at a distance of 200 million light years. This radio source is more than 1,000 times stronger than most of the other radio sources in which similar objects are certainly present: so on average they must be located 30 times further away, i.e. at 6 billion light years.
>
> This conclusion is also confirmed by the fact that no remarkable optical objects can be seen in the direction of even very intense radio sources, so one must expect that most of them are located beyond the range of large telescopes. (Denisse, 1958: 2; our translation).

Then he went on to say that it would be of great importance to obtain the distances of these sources, and that the only direct method for this would be to observe the 21-cm hydrogen line, which had recently been discovered in absorption in Cygnus A (Lilley and McClain, 1956). Thus, "The very large radio telescope which will be constructed at Nançay field station was conceived in order to calibrate the radio universe

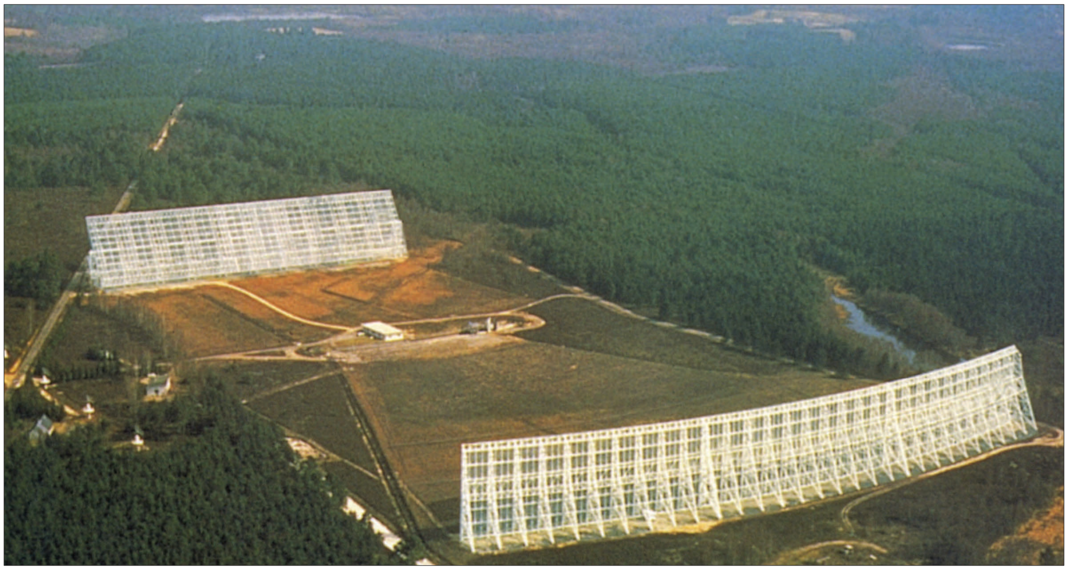


Figure 1: Aerial view of Le Grand Radiotélescope at Nançay.

...” (Denisse, 1958: 3; our translation).

Curiously, Denisse did not explicitly mention observations of the hydrogen line in emission in galaxies, which were to become the main target of the Nançay radio telescope; but H-line observations had been made of only a handful of external galaxies at that time, and presumably he thought that it would be easier to detect the line in absorption. Then he proceeded to say that a very large collecting surface was needed for sensitivity, and also in order to limit confusion when observing faint sources. Confusion was then considered a major topic, being the subject of intense debate between the Cambridge group and Mills’ team in Australia in regard to radio source counts and their cosmological significance (e.g. see Mills, 1984; Sullivan, 1990).

The two-element meridian radio telescope built between 1956 and 1963 by John D. Kraus (1910–2004) and his students at the Ohio State University Radio Observatory was taken by Denisse as a model for the Nançay instrument, because it had a large surface area and had been constructed for a modest cost. This instrument (Kraus, 1986: 86-88) consisted of a fixed curved E-W reflector 110m wide and 21m high, illuminated by a tiltable flat E-W reflector 104m wide and 31m high located to the north. The two reflectors were joined by a flat conducting ground plane, the distance between the mirrors being 153m. Two 1,415 MHz rectangular fixed horns, for observations in the switching-position mode, were placed at the focus of the curved mirror, 18m from its apex. The dimensions of these beams, defined by diffraction, were 40′ N-S and 8′ E-W at this frequency, and they were separated by 40′. The Ohio radio telescope was used for a continuum survey of the whole accessible sky at 1,415 MHz, and later for a Search for Extra-Terrestrial Intelligence (SETI) with a single horn feed which was able to track a source. This novel radio telescope was dismantled in 1998.

Denisse succeeded in convincing his colleagues to adopt this concept rather than the interferometer. Later interviews with several French radio astronomers point to a perceived problem with interferometry which may have played a part in this change of heart: the need to calculate a Fourier transform in order to obtain an image from observations with a variable-baseline interferometer. For example, Arsac said:

> For [radio] interferometry one used Fourier transforms as in optics. Before computers, there was a room at the Institut d’Optique on Boulevard Pasteur in Paris, where ladies were computing Fourier series by hand all day.
>
> Prior to 1958, it was not easy to do interferometry. In 1959, I fought to obtain a computer for the Observatory. This computer [an IBM 650] was purchased and I headed the Computing Centre at the Paris Observatory until 1965. On the other hand there was also a theoretical problem with the [mathematical validity of the] Fourier transform. The theory of distributions outlined by [Laurent] Schwartz at this time allowed us to solve the problem of the Fourier transform. (cited in Darmon, 1981: 44-45).

Remember that these discussions were taking place in 1956, when these problems had yet to be solved.

The choice of a large Kraus-type French radio telescope was approved by the Comité de Direction de la Station de Nançay at a meeting on 29 June 1955. Since the Chairman of this Committee also happened to be the Directeur Général de l’Enseignement Supérieur—who headed a large part of publically-funded research in France—this decision was seen as an official endorsement, and the project could begin.

It is interesting to note that the idea of a large interferometer was not completely abandoned since the Comité de Direction also recommended that a large steerable antenna operating at decimetre wavelengths be built, which would allow very long baseline interferometry (VLBI)[4] and could be used together with the other new radio telescope at Nançay as an interferometer in order to obtain a better resolving power in the N-S direction. This did not materialize because at its meeting on 14 May 1958 the Comité recommended that

> … this construction should be replaced by a relatively cheap increase in the surface area of the two [Würzburg] antennas … [at Nançay, which function as] an interferometer on a railway track: [and] the sum of 4 million francs [equivalent to 65,000 Euros] is proposed for the 1959 budget in order to carry out this transformation. (Comité …, 1958; our translation).

Needless to say, this plan was never carried out. Meanwhile, the idea of using the large Nançay Radio Telescope and a moveable 40-m antenna was revived by French radio astronomers in 1968 (Blum, 1968: 9), but once again without success.

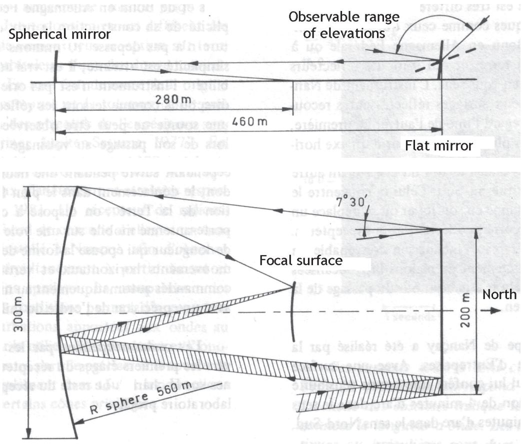


Figure 2: Principle of the Nançay large radio telescope: elevation (top) and ground plan (bottom).

3 BUILDING THE FIRST SECTION OF ‘LE GRAND RADIOTÉLESCOPE’ AT NANÇAY

The plan was to build a French radio telescope modelled on Kraus’ instrument (see Figure 2), but on a considerably larger scale. The mirror would be a portion of a sphere 300m wide, 35m high and of 560m radius, while the tiltable plane mirror would be made of ten 20m × 40m elements in parallel, giving a surface 200m wide and 40m in the other direction. Both surfaces would be made of metallic mesh. An important change with respect to the Ohio design was that the tiltable mirror would be located not far from the centre of the sphere (actually 460m from the surface) and that the plane would be somewhat distorted on the E-W edges, by displacing slightly the axes of the two ex-

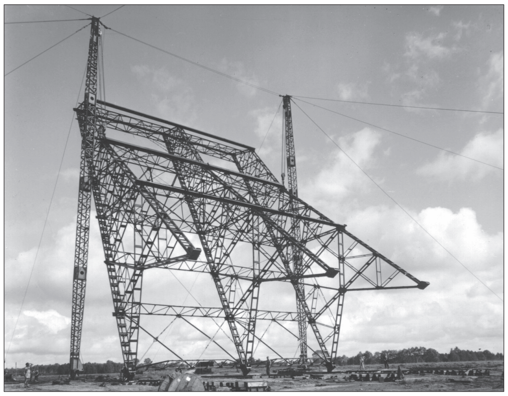


Figure 3: Two 10m-wide elements of the fixed mirror, which were assembled on the ground, are hoisted together.

treme elements on each side with respect to the axes of the six central panels. This configuration was calculated by Arsac and François Biraud, and is similar to that of the optical Schmidt telescope where the spherical aberration is corrected by a deformed plate located near the centre of curvature of the spherical primary mirror. For the radio telescope, this would give a diffraction-limited image on a curved focal surface (of 280m radius) concentric with the spherical mirror, allowing observations to be made of sources up to 7.5º on either side of the meridian plane. By tracking the path of the image of a source on this focal surface, it would then be possible to integrate its flux for an hour for a source located at Dec. = 0°, and for longer for sources with other declinations.

There are advantages and drawbacks to this design when compared to that of a fully-steerable parabolic antenna.

The main advantage is the low cost per unit area. Another one is the easy accessibility and lack of weight limitation for focal equipment.

The main disadvantage is the fact that this is a meridian telescope with an integration lime limited to about 30 minutes on either side of the meridian crossing. This makes the scheduling of the telescope difficult, with a poor time-efficiency, and the limitations in hour angle in practice forbid VLBI with other radio telescopes. Also, the elongated lobe renders measurements of linear polarization almost impossible, and makes it difficult to compare Nançay results with those obtained with circular antennas. Because the focal antenna is close to the ground, some thermal noise from the ground enters through the side lobes if special care is not taken. Kraus solved this problem by covering the ground with a flat reflecting surface, but this is expensive, and runs the risk of creating ‘ghosts’ of strong sources. Similarly, the focal horn ‘sees’ in its main lobe whatever happens to stand behind the bottom of the plane mirror when this is inclined. At Nançay, these significant contributions to the system noise were only drastically reduced in the late 1990s when appropriate measures were introduced. A final disadvantage of the two-mirror design is that it would be extremely expensive to replace the reflecting surfaces by better ones for observations at shorter wavelengths, whereas this is common practice with large steerable paraboloids.

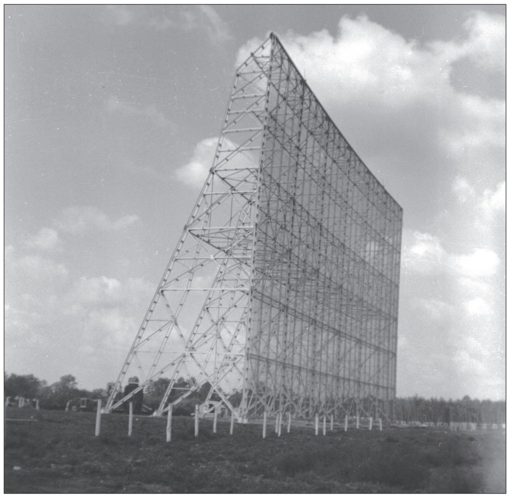


Figure 4: The first section of the fixed concave mirror is completed.

It seems that the limitations of a meridian radio telescope were underestimated in the beginning, and that the other disadvantages of the design were completely overlooked. The low cost per unit surface area was the decisive argument, as can be seen from the following, somewhat naïve, statement:

> The voluntary limitations on the universality of the large Nançay mirror will render its usage secure. Moreover, it could fit in this way within the present scientific budget of France. It is in a way a cousin of the 1.97m [sic] Rosse [optical] reflecting telescope which was built a century earlier than its universal brother, the 1.93m reflector at Haute Provence, because one accepted its limitations around the meridian. (Heidmann, 1961: 49; our translation).

It turned out to be very easy to obtain a substantial amount of money for the new instrument: 155 million francs (equivalent to €2.9 million in 2008) were assigned in the budget for 1957. Three million of this total was used for preliminary studies including tests in wind tunnels, and contract submissions were then invited from French companies. Surprisingly, only one answered positively, and this was the Compagnie Française d’Entreprises (CFE), which was created by Gustave Eiffel around 1880 as Entreprises Métropolitaines et Coloniales, and then merged with the Moisant-Laurent-Savey Company, only to be purchased by Usinor-Sacilor in 1959. The CFE had considerable experience in large concrete and metal constructions, and the Director of its Industrial Department, Jean Roret (1925–2005), was personally interested in the radio astronomy project. A contract with CFE was signed in December 1958 for 152 million francs (€2.5 million), and work started in their Rouen plant and at Nançay in May 1959.

This contract price was only sufficient to build the first section of the radio telescope, one-fifth of the total, consisting of a fixed 60m × 35m portion of a spherical mirror and two tiltable flat panels covering 40m × 40m in total. This was supposed to be completed within 14 months. A further amount of 32 million francs (€500,000) was obtained in 1960 for the buildings, the first focal antennas, the receivers and an electrical generator, the local municipal power supplies being insufficient for moving all ten panels of the completed radio telescope at the same time.

Figures 3, 4, 5 and 6 illustrate the erection of both mirrors. The reflecting surface, a square wire-netting initially foreseen as an 18mm × 18mm mesh but finally realised as a 12.5mm × 12.5mm one, was fixed to steel cables which were attached to the structure and were adjustable. This structure was completed by the end of 1961, with a slight delay. The surface of the concave mirror was checked by the Division des Travaux Spéciaux of the Institut Géographique National (IGN), headed by J. Commiot, and found to be significantly better than the contract specifications: 5-6mm r.m.s. instead of the required 10mm. A fixed set of parabolic antennas was installed at the focus for 21, 13 and 6cm, with small antennas and uncooled receiver front ends, mixers and intermediate-frequency amplifiers at their foci (Figure 7). On 23 January 1962 the radio telescope was officially inaugurated, with several speeches, including one by Denisse as head of the Nançay field station. One can sense there was some bitterness when he spoke about the 64-m Parkes Radio Telescope (which had just been completed):

> [When our Nançay radio telescope was decided] … the Australians were studying the present paraboloid at Parkes which at the same time is both accurate and has an imposing surface area: 3,000m^2. At the present time it is certainly the best radio telescope in existence, and it is operated by a staff of exceptional quality. (Denisse, 1962: our translation).

It is true that at this time the French radio astronomy group was still small and busy using the various solar instruments at Nançay. Moreover, the construction of the new radio telescope was only overseen by a single mechanical engineer, Marcel Parise (Figure 8).

Furthermore, an unexpected problem arose: pointing of the tiltable panels, as measured on their axes, was largely in error. Not only was the measuring equipment inadequate, but there was also some distortion when the panels were inclined (and there was no computer to perform the structural analyses at this time). The problem was completely beyond the comprehension of the CFE staff, and it was agreed that it had to be solved by the radio astronomers. This was done by attaching graduated rulers perpendicular to the mesh along one of the edges of the panel, and observing them with a small telescope equipped with a graduated vertical circle attached to the rotation axis. This way the distortion was measured, and a correction was then applied through a mechanical cam inserted between the end of the axis and the encoder. The encoder was supplied by Ferranti Ltd., a UK company.[5]

During the measurements, another problem was discovered: the distortion was not the same when the inclination increased or decreased, pointing to mechanical hysteresis in the panels. This forced the panel to always move in the same way, with increasing inclination. It remained to be seen if the inclination of the edges of the panels where the measurements were performed was representative of the average inclination of the whole surface. This was checked by IGN staff, who used a theodolite to measure from the ground the positions of nine points of the panel surface for different inclinations. The results were satisfactory, but it was discovered that the surface, which was

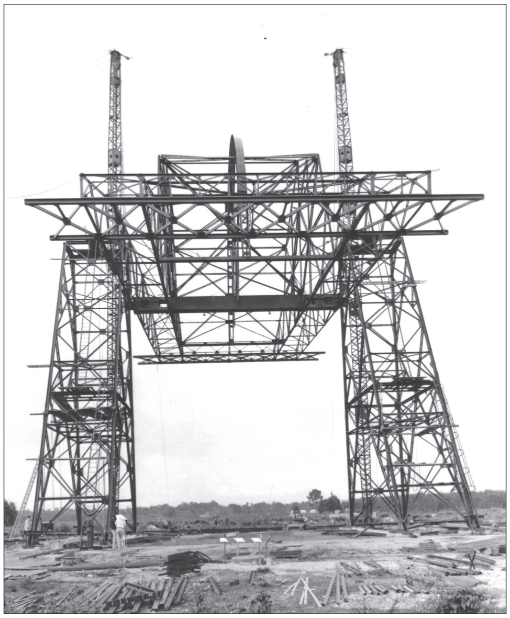


Figure 5: One 20m-wide panel of the tiltable mirror, which was assembled on the ground, is hoisted into place.

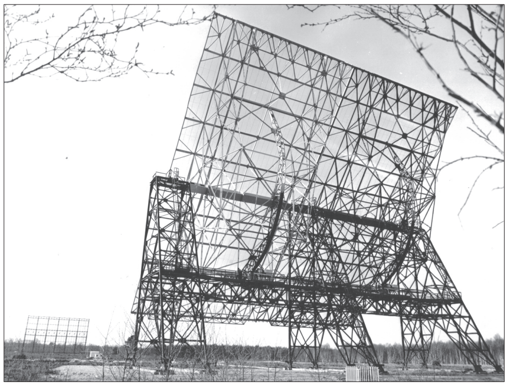


Figure 6: The first completed section of the tiltable flat mirror. Each panel is driven by a pinion acting on a chain placed along the half-circle.

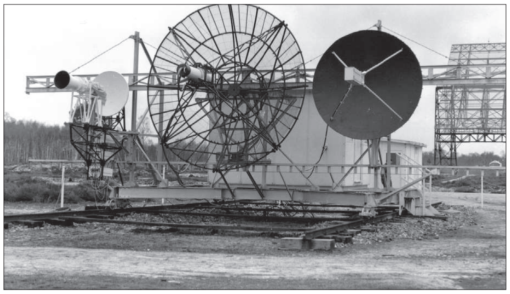


Figure 7: The focal equipment of the first section of the radio telescope. The focal diffraction spot forms on paraboloids which concentrate the radiation on circular horns followed by the high-frequency stages of the receivers (see, also, Figure 8). The intermediate frequency signal is sent to the focal laboratory shown at the back of this photograph. The whole is moveable on N-S rails for focussing. From left to right are devices for 6, 21 and 13cm respectively. The tiltable mirror in visible in the background.

Figure 8: Marcel Parise adjusting the focal system for 21cm.

approximately flat for an inclination of 45º, became concave in the N-S direction by 8mm at the middle of the panel for an inclination of 90º, while it became concave by 5mm in the E-W direction. The usual rule of thumb that the deviations of the final wave surface should be better than $^1/_{10}$ of a wavelength for good results showed that the Nançay Radio Telescope should be good at 21cm and 18cm, fair between 9cm and 13cm and quite poor at 6cm.

With a few exceptions, all of the measurements, analyses and designs of the new instrumentation were done by Steinberg and Michel Ginat, with help from James Lequeux and a few others (Steinberg, 2004). It is only upon reading Ginat's Ph.D. thesis (1966), which is devoted to this work, that one realises just how complex and difficult this task was.

Once the final section of the radio telescope was operational, some continuum observations were made of extended galactic sources at 1,430 MHz and 2,315 MHz (Bottinelli and Gouguenheim, 1964; Heidmann, 1965) and of a few large galaxies at 1,430 MHz (Heidmann, 1963). But since the rest of the radio telescope was then under construction, this effectively prevented further observations from being made.

4 THE COMPLETION OF THE RADIO TELESCOPE

Given the success of the first section of the radio telescope it was relatively easy to raise the money for the rest of the instrument. A new contract was set up between the Ministry of Public Education and the CFE and the construction proceeded without any major problems. Figure 9 illustrates a step in the erection of the second part of the radio telescope. The completed instrument was officially inaugurated by the President of the Republic himself, General de Gaulle, and the Minister, Christian Fouchet, on 15 May 1965.

Of course it was necessary to calibrate the inclination of all of the panels in the same way as for the first two, and this lengthy process was only finished in 1966. This work, along with other geodetic measurements, was the subject of Ginat's Ph.D. thesis (1966). Also, in order to save money, encoders were only installed on the axes of panels 2, 5, 6 and 9, and the other panels were slaved to these master panels

Figure 9: The fully-tiltable mirror during construction.

thanks to a simple but effective electromagnetic proximity system designed by Biraud: panels 1 and 3 to panel 2; panel 4 to panel 5; panel 7 to panel 6; and panels 8 and 10 to panel 9. The pointing of the panels and the necessary controls were designed by the staff, especially by Ginat and Steinberg. Despite the passage of the years, this system is still working at present, after only minor changes.

One also had to deal with motion of the carriage (or rather the carriages, as two were constructed), in order to track the displacement of the image due to diurnal motion. This required both a vertical motion and a motion along a curved railtrack, both depending upon the declination of the source. Money was available to build the mechanical and hydraulic parts of the carriages (the motion being secured by hydraulic motors and jacks), but not for controlling the motions, a problem whose difficulty had been underestimated. There was no computer to drive real-time servos so one needed a custom-made computer. The only European firm able to do this at a reasonable cost was Ferranti Ltd., which had also supplied the encoders for the flat mirrors as stated earlier and the control desk of the radio telescope (Figure 10). Lequeux was in charge of defining the needs, writing the contract and following the construction and installation of the drive system. The necessary funds came from a convention (agreement) signed in 1963 between the Paris Observatory and the Centre National d'Études Spatiales (CNES) which agreed to pay, on the basis that artificial satellites would be tracked by the radio telescope (something which never occurred). This was arranged by Steinberg, who was in the process of setting up a Laboratory of Space Radioastronomy at Meudon whilst continuing his work at Nançay, and had excellent relations with the CNES. The position of the focal antenna as a function of time was computed with the IBM 7040 in Meudon, whose output was a punched tape. This tape was sent to Nançay and fed into the Ferranti equipment, which was housed in several big cabinets which filled a sizable fraction of the control room. The total cost was 320,000 new francs (€400,000).

The first H-line receiver was built by Émile-Jacques Blum, with help from Jean Delannoy, Émile Le Roux and Leonid Nicolas Weliachew (Blum et al., 1966), and placed on one of the carriages (Figure 11). This was a correlation receiver, a concept invented by Blum and derived from his studies of interferometers (Blum, 1959). The principle is as follows: if one splits the signal from the antenna and feeds each of two identical receivers with half of this signal, a correlation of the outputs of these receivers will give a DC output proportional to the power received by the antenna, the noises in the receivers being uncorrelated. Thus, the output is essentially unaffected by variations in the receiver gains, which were very troublesome at this time. For this purpose, Blum used a correlator that he originally designed for his solar interferometer (Figure 12). Of course fluctuations in receiver noise are still present, but it can be shown that the signal/noise ratio of the system is comparable to or better than that of the permutation receivers of Robert Dicke and Martin Ryle which were largely in use at this time. A problem with this system is that splitting the antenna signal in a hybrid circuit like a magic T requires an-

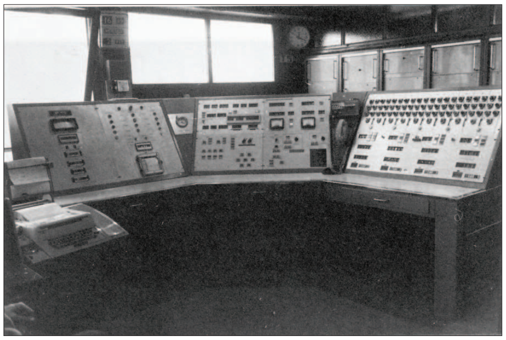


Figure 10: The control room of the radio telescope, circa 1966. The controls on the left activated the generating set for powering the tiltable mirrors; those in the central part controlled the tracking of the focal carriage; and those on the right controlled the motions of the tiltable panels. Notice the panels in the background which housed part of the electronics of the Ferranti equipment.

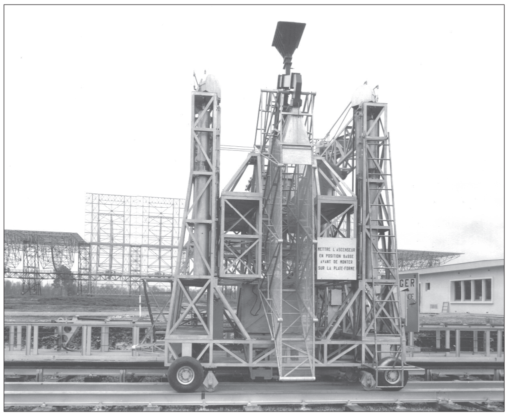


Figure 11: The focal carriage for observing the H-line. The signal is received by a hog horn whose dimensions (2m × 0.4m) match the diffraction spot. Notice the smaller vertical horn which feeds the other input of the hybrid circuit (magic T) of the correlation receiver (see the text, and Figure 13). The cabin contains the front end, the mixer and the amplifier for the intermediate frequency, which is sent by cables to the focal laboratory towards the rear of the photograph.

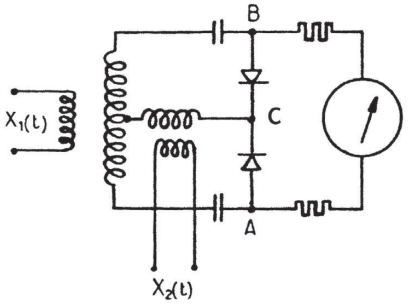


Figure 12: Blum's correlator. $X_1(t)$ and $X_2(t)$ are the input signals from two antennas of an interferometer or from the two halves of the signal of the antenna for a correlation receiver. The voltage between A and C is proportional to $[X_1(t) + X_2(t)]^2$ with a quadratic detecting diode, and that between B and C proportional to $[X_1(t) - X_2(t)]^2$, if the senses of the transformers are well chosen. Hence the voltage between A and B is the difference of these two quantities, which is proportional to $4X_1(t)X_2(t)$, the correlated product.

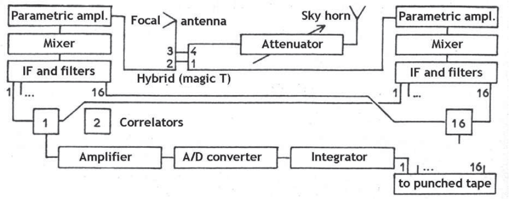
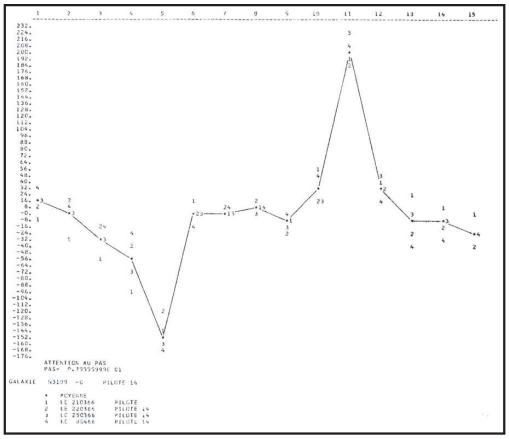


Figure 13: Principle of the 21cm line correlation receiver. For a description see the text.

other input for balancing the impedances (Figure 13). This input comes from a horn which is looking at the sky, followed by a variable attenuator whose noise must balance the noise from the antenna. Another possibility, which has also been used in some correlation receivers, was simply to insert a unidirectional circuit between each half of the antenna signal and the input of the corresponding receiver.

For all these receivers, the incoming signal was sent to the mixer after amplification by a parametric amplifier.[6] The locally-made parametric amplifiers did not work very well and were soon replaced by commercial ones. The first 21cm line receiver was uncooled and had a system temperature of 350K, including 35K of ground noise for low declination sources. It had 15 frequency channels, each 280kHz (59km/s) wide, which were only suitable for extragalactic observations, and a continuum channel 5MHz wide. The signals were digitized and integrated, and the results were entered on punched paper tape. This tape was sent to Meudon and its content was transferred onto punched cards by an IBM 1401 computer, then the reduction was performed with the Meudon IBM 7040, with an output on paper (Figure 14) and on punched cards. This complicated system was replaced in 1969-1970 by a Digital Equipment PDP 8 computer located in the control room of the radio telescope.

Another carriage (Figure 15) bore three horns for continuum observations at 21, 11.3 and 6.2cm, and the corresponding receivers. It seems, however, that the 21cm continuum receiver was never implemented, and that the observers simply used the broad channel of the line receiver instead.



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ATTENTION AU PAS
PAS=  0.79999999E 01

GALAXIE   N3109  -C     PILOTE 14

*    MOYENNE
1    LE 210366     PILOTE
2    LE 220366     PILOTE 14
3    LE 250366     PILOTE 14
4    LE  30466     PILOTE 14
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Figure 14: One of the first observations of an extragalactic 21cm line with the completed radio telescope. This is a listing from the Meudon IBM 7040 computer. The 15 frequencies of the multi-channel back end are in abscissae. The positive signal (2K of antenna temperature) is the 21cm line from the galaxy NGC 3109, and the negative one is a residual from the galactic line emission in this 4-hour ON-OFF observation (after Bottinelli et al., 1966).

In 1968 the total cost of the radio telescope with the focal building and all of the auxiliary instrumentation that we have just described was estimated at 15 million francs, corresponding to €16.7 million in 2008. As suggested by a referee, it is of interest to compare this cost with that of contemporary large radio telescopes. This comparison can only be approximate, because of difficulty in obtaining the actual total costs and because of uncertainties in the exchange rates and in the conversion into 2008 Euros. For Jodrell Bank (the Mark I Lovell Telescope) and Parkes the estimates did not include the first receivers and auxiliary equipment, so we added 20% to these estimates. We do not include the Ohio Radio Telescope because this was essentially a home-made instrument. Our results are presented below in Table 1.

These results must be weighted by the shortest wavelength observable with the different radio telescopes. At the time of their completion, Jodrell Bank and Arecibo were worse than Nançay, while Parkes was better. Also, Arecibo has a limited observing range around the zenith, whereas Jodrell Bank and Parkes are fully steerable. Overall, it appears that the choice of a meridian combination for Nançay saved money, but that the best deal was clearly Parkes, a radio telescope which was built by German industry (MAN-Krupp). For political and industrial reasons it was not possible for France to obtain such an instrument.

After the completion of Le Grand Radiotélescope most of the scientists who had worked so hard on its pointing, focal tracking and receivers partially lost interest in the instrument, with the exception of Biraud and Weliachew. Thus, in 1965 Le Roux left astronomy; during 1967-1968 Blum spent a sabbatical year at the NRAO in Charlottesville (West Virginia) becoming familiar with millimetre techniques; and in 1967 Delannoy moved to the Bordeaux Observatory in order to build an experimental 8mm interferometer. Meanwhile, Steinberg worked full-time in his Space Radioastronomy Laboratory at Meudon, and in 1966 Lequeux (with a few colleagues) founded an infrared laboratory at Meudon, before going to Caltech in 1968-1969 in order to observe with the Owens Valley Radio Observatory interferometer. Ginat was killed in a mountain accident on 1 April 1968. Blum had taken over from Denisse as Director of the Paris Observatory's Radioastronomy Department and the Nançay field station in 1964, and he remained in charge until 1973, but he never used Le Grand Radiotélescope, working instead on millimetre receivers. He was succeeded by Lequeux, who occasionally used the large radio telescope but was mostly busy with other tasks, especially (with Blum, Weliachew and Pierre Encrenaz) in setting up a large millimetre interferometer which materialized in 1979 as one of the elements of the German-French-Spanish Institute for Millimeter Radio Astronomy (IRAM).

Presumably all of these scientists were exhausted by the considerable tasks they had to achieve in order to bring Le Grand Radiotélescope to fruition. Denisse understood that building such a large instrument in a difficult industrial climate was at the very limit of the potential of a small group with little technical preparation, and so in 1966 he created the Institut National d'Astronomie et de Géophysique (INAG), with a Technical Division, in order to handle major projects. On the other hand, some members of the staff thought that the Nançay radio telescope would soon be superseded by others, like the Effelsberg 100-m steerable parabola, which was completed in 1972. Whether they were right or wrong will not be discussed here, but long-standing unease was experienced by the staff, which later resulted in a splitting of the Radioastronomy Department into 'millimeter' and 'decimeter' radio astronomers. In any case, the use of Le Grand Radiotélescope was left to the younger generations.

5 IMPROVEMENTS AND USE OF THE NANÇAY RADIO TELESCOPE

As with any new facility, Le Grand Radiotélescope at Nançay has been continually improved over the years. Little has changed to the actual radio telescope itself, but the Ferranti system to tilt the panels and move the focal carriages was replaced by a computer in 1969-1970. Many more changes were made to the receivers and the focal carriages. It is difficult to track all of them, and we will only report on some of them. We will also briefly describe some of the early observations which were made with this radio telescope.

A 15MHz continuum channel and fifteen 60kHz channels were first added to the H-line receiver, and the high-frequency parts were cooled. In 1973 there were thirty-two 60kHz channels and sixty-four 6kHz (1.3km/s) channels, and the receiver temperature was down to 120K in 1975. Unfortunately, the correlated response of each pair of frequency channels turned out to be very sensitive to the shape of the bandpass of these channels, so that chromatism was a problem for line observations. This, together with the cost of having all the electronics in duplicate, led to abandoning this type of receiver and also the parametric preamplifiers around 1985, and they were replaced by cooled High Electron Mobility Transistors (HEMT) in the front-ends. An autocorrelator was substituted for the filter banks. However, many useful scientific results were produced before these changes occurred, in particular the H-line detection of a large number of galaxies (see in ADS the many papers by R.J. Allen, C. Balkowski, L. Botttinelli, P. Chamaraux, B.F. Darchy, E. Gérard, L. Gouguenheim, M. Guélin, J. and N. Heidmann, I. Kazès, R. Lauqué and N. Weliachew).

A new impetus to this major program of the Large Nançay Radio Telescope came from the discovery of the Tully-Fisher Relation between 21cm line width and absolute magnitudes and diameters of galaxies (Tully and Fisher, 1977), which offered a way of deriving distances of galaxies independent of redshift and allowed the Nançay observers to obtain a value of 68 ± 8 km s^{-1} Mpc^{-1} for the Hubble Constant (Fouqué et al., 1990), which is close to the currently-adopted figure of 71 ± 4 km s^{-1} Mpc^{-1} obtained from COBE and WMAP observations.

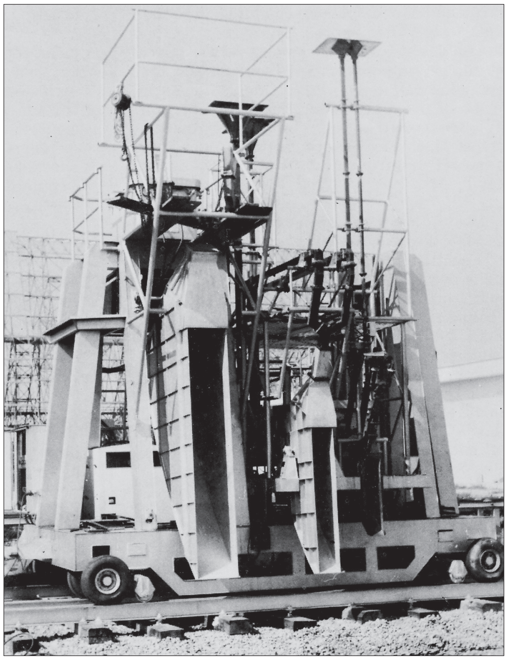

Figure 15: The carriage for the continuum receivers. From left to right are the hog horns for 21, 11 and 6cm respectively. The height of the largest horn is 2m.

There was also an extensive program involving galactic 21cm absorption (Lazareff, 1975; Crovisier et al., 1978), during which many observations of continuum sources were also made. Although more subject to contamination by residual line emission than observations with interferometers, these results were quite useful as a means of measuring distances to continuum sources. One of the original programs was to observe 21cm absorption in front of pulsars whose distances were unknown at the time (Guélin et al., 1969). In this case, the difference between the line seen during the pulse and between the pulses gives a pure absorption profile, hence a relatively good estimate of the distance. This was the beginning of an interest in pulsars, which developed considerably later for the purpose of timing their pulses, and is at present a major program of the radio telescope.

The 21cm line receiver was also used in 1975 and later for observations of radio recombination lines, in particular the 166α lines of carbon and sulphur (Cesarsky et al., 1976). The receiver was used in total power detection instead of the usual correlation mode.

Table 1: Cost comparisons for major early radio telescopes.

Radio Telescope	Date of cost Estimate	Cost (original currency)	Cost (2008 €)	Area (m^2)	Cost per unit area (2008 €/m^2)
Nançay	1968	1.5×10^7 Francs	1.67×10^7	7000	2400
Jodrell Bank	1957	8.4×10^5 £	1.58×10^7	4500	3500
Parkes	1963	1.5×10^6 US$	9.7×10^6	3200	3000
Arecibo	1963	9×10^6 US$	5.8×10^7	70700	800

Figure 16: The focal carriage bearing the 21, 18 and 9cm hog horns in the 1980s.

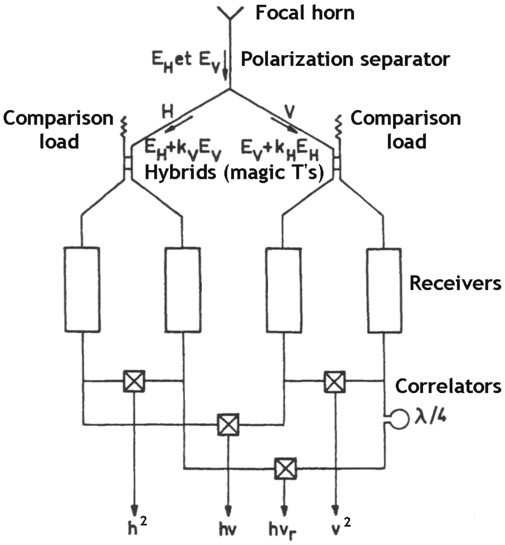

Figure 17: Principle of a correlation-receiver set-up for measuring polarization. The four outputs give the power in the vertical linear polarization component v^2, that in the horizontal one h^2, the product hv, and the product hv_r with a $\pi/2$ phase shift. The fraction of circular polarization in the signal is $2hv_r/(h+v)$.

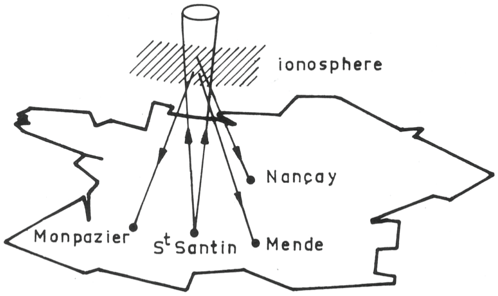

Figure 18: Principle of the incoherent scattering ionospheric sounder. An emitting antenna in Saint Santin near Decazeville sends out a monochromatic wave vertically. The scattered radiation is received in Nançay, and in two other receiving stations equipped with 25m diameter paraboloids near Mende and Montpazier, which were added in 1973.

An interesting event was the arrival at Nançay in 1971 of an 18cm line receiver built in the Soviet Union at the Sternberg Institute and the Space Research Institute in Moscow. This was made possible through cooperation between Intercosmos (the Soviet Space Agency) and the French CNES. The receiver (Paschenko et al., 1971) operated in the frequency-switching mode, and had in its front end an uncooled parametric amplifier on loan from the Max Planck Institut für Radioastronomie in Bonn. The back end had 16 × 20kHz channels 3.6km/s wide. The system temperature was initially 250K, but in 1972 it dropped to 150K thanks to cooling. In 1974 three channel banks were added, each with 32 filters of respective widths 10, 6 and 6kHz. This receiver was used until 1986 when the front-end was replaced by a cooled HEMT one (and the receiver temperature was 40K after this change), and the filters were replaced by an autocorrelator in common with the 21cm receiver. The main program with this equipment was to observe OH-IR stars, OH lines in the Galaxy and OH in comets. These progressively became major programs for the radio telescope, especially the cometary part following the detection of OH in Comet Kohoutek (Biraud et al., 1974; and for a bibliography see Crovisier et al., 2002). Later the radio telescope was turned to external galaxies and several OH megamasers were discovered (Bottinelli et al., 1986).

A 9cm cooled HEMT receiver for observation of the CH lines was constructed in the 1980s for galactic and cometary studies, and these lines were also detected in external galaxies (Bottinelli et al., 1991). For this, a new carriage was built with three focal hog horns working at 21, 18 and 9 cm (Figure 16).

While most of the research conducted with the radio telescope related to line observations, there were also some continuum observations. An early observing program with the continuum channel of the 21cm line receiver was devoted to normal galaxies (de la Beaujardière et al., 1968). The 11cm correlation receiver was used to detect emission from Saturn and Uranus and to obtain an upper limit for that from Neptune (Gérard, 1969). Jupiter and Saturn were observed in 1972-1973 at 21, 11.1 and 6.2cm, with respective system temperatures of about 100, 200 and 300K (Gérard and Kazès, 1973). Biraud made an heroic attempt to measure the polarization of quasars at 11.1cm using a correlation receiver set-up suggested by Blum and represented in Figure 17. The linear polarization could not be observed with any accuracy, but circular polarization was detected in PKS 1127-14 (Biraud, 1969).

One original early program in the continuum was the observation of radio source scintillations due to the heliospheric plasma at 11cm and other wavelengths (Bourgois, 1969, and follow-up papers).

It should be noted the Le Grand Radiotélescope was also used for a substantial fraction of the time for observing incoherent scattering in the ionosphere, just like the Arecibo Radio Telescope (see Cohen, 2009). This resulted from an agreement between INAG and the Centre National d'Études des Télécommunications (CNET). As shown in Figure 18, a powerful monochromatic beam at 32cm was sent vertically by an antenna located 300km south of Nançay, and the scattered radiation was received by the Nançay Radio Telescope with a hog horn followed by a line receiver

(Figure 19). The two beams of the emitting and receiving antennas defined a volume in which the density and temperature of ions and electrons were measured, as well as the velocity and direction of the wind (thanks to the Doppler effect). The range of elevations explored by changing the inclination of the plane mirror was 95 to 700km.

Between 1995 and 2000 a complete remodelling of the focal installations of the Nançay Large Radio Telescope took place, the so-called FORT Project (for Foyer Optimisé pour le Radio Télescope décimétrique de Nançay). A new carriage (Figure 20) was built on a new railtrack, and the hog horns were replaced by an ensemble of two eccentered concave mirrors feeding one or the other of two corrugated horns according to the wavelength. This system (Figure 21), designed by staff from the CSIRO in Australia (Granet et al., 1997; 1999), completely covers the frequency range 1.0 to 3.5GHz and has low sidelobes. An efficient system of metallic mesh in front of the focal system and behind the tiltable mirror drastically reduces the effects of the ground and the trees behind the tiltable mirror. New front ends were installed in enclosures at 20K and the system temperature is now ~35K over the whole range of received frequencies. A new focal laboratory was built outside the radio beams. All this gave a new life to what is now a venerable radio telescope.

6 CONCLUDING REMARKS

The construction of Le Grand Radiotélescope at Nançay took place in a favourable economic and political climate. But the context was not as favourable when techniques were concerned, because French industry was not prepared to manufacture large metallic structures with any accuracy, and because on-line computers were not yet available. Moreover, the Paris Observatory radio astronomy group only had one mechanical engineer, so this forced the radio astronomers to do work for which they had little training or preparation. To their credit, they succeeded, but they were exhausted by these efforts and the instrument was delayed for two years: although the structure was completed and inaugurated in May 1965, the radio telescope only began working properly at the end of 1967. With its surface area of 7,000m^2, comparable to that of the Effelsberg and Greenbank 100-m diameter paraboloids, it was one of the largest radio telescopes in the world, Arecibo excepted. But unlike its competitors, the Nançay Radio Telescope could not operate below 9cm.

The Nançay site was relatively free of man-made radio interference at the beginning, but like any other, it now suffers badly from this plague. Today, sophisticated techniques are required to allow any sensitive observations, especially at decimetre and meter wavelengths. These techniques are in force at Nançay, but just how long observations will be possible there at these wavelengths is a major question. The Square Kilometer Array (SKA) project, for which the direction of observation will be changed instantaneously as a function of interference, is clearly the way to go for decimetre radio astronomy.

7 NOTES

1. This project was initiated under the auspices of the IAU Historic Radio Astronomy Working Group in 2006, and four papers have been published to date. The first deals with Nordmann's attempt to detect solar radio emission in 1901 (Débarbat et al., 2007);

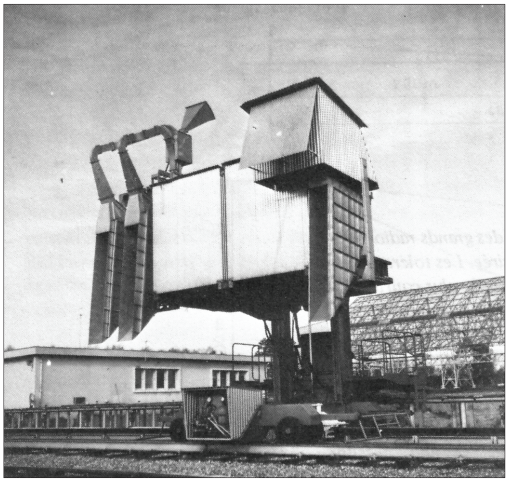

Figure 19: A focal carriage with two radio astronomy hog horns for 18 and 21cm (left) and a hog horn for receiving the signal of the incoherent ionospheric scattering project at 32cm (right), in the late 1970s.

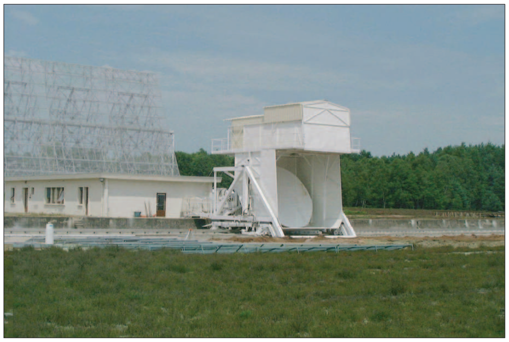

Figure 20: New focal carriage of the radio telescope, circa 2000. The old focal laboratory was still in operation at this time, but has since been replaced by a new one located outside the radio beam.

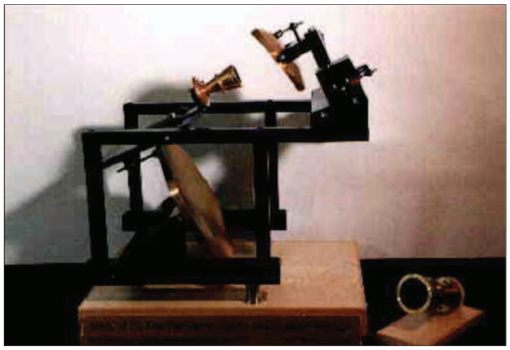

Figure 21: One-tenth scale model of the quasi-optics for the new carriage shown in Figure 20, built and tested by staff from the CSIRO in Sydney, Australia. There are two corrugated circular receiving horns, each one covering approximately half of the total frequency range. One is in position, and the other is lying on the floor.

the second with early solar eclipse observations (Orchiston and Steinberg, 2007); the third with the Würzburg antennas that were at Marcoussis, Meudon and Nançay (Orchiston et al., 2007); and the fourth with early solar research till the mid-1950s (Orchiston et al., 2009). A sixth paper, on post-1956 solar research at Nançay (Pick et al., 2010) will be published later this year and a seventh paper, on the birth of the IRAM project, is currently in preparation.

2. Steinberg was referring to fringes at centimetre wavelengths; all previous interferometry was at metre and decimetre wavelengths.
3. When mentioning the prices associated with the Grand Radiotélescope Project we have tried to convert them into 2008 Euros, based on a comparison of the cost of living at that epoch and in 2008. This conversion was established by the Institut National de la Statistique et des Études Économiques (INSEE), and is available through the following web site: http://www.insee.fr/fr/themes/indicateur.asp?id=29&type=1&page=achatfranc.html
4. This is not explicitly mentioned in the recommendation, but VLBI was just beginning at this time in Canada and the USA, and the French radio astronomers were certainly aware of this.
5. This was one of the few instances where French industry could not supply the required product. Ferranti Ltd. was based in Dalkeith, near Edinburgh, in Scotland.
6. For the concept of parametric receivers see the Wikipedia article on 'Parametric oscillator'.

8 ACKNOWLEDGEMENTS

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