The Nançay Decameter Array: A Useful Step Towards Giant, New Generation Radio Telescopes for Long Wavelength Radio Astronomy

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The Nançay Decameter Array, operating in the 10-80 MHz frequency range, consists in two phased antenna arrays in opposite senses of circular polarisation - with a 4000 m^2 effective aperture each -, and a series of powerful spectrum analysers allowing for wide band, high resolution and sensitive spectroscopy of Jovian and Solar Corona radio emissions. Coupled with spacecraft observations (*Voyager, Ulysses, Wind, Galileo, SOHO*) or working alone, it has provided some key information on radiation processes in Solar System magnetised objects. The used antenna concept and the newly developed, digital receiver system are described. Both have demonstrated their ability to solve some of the main difficulties in ground-based observing at decametre wavelengths: struggling against man made radio frequency interference, perturbations from terrestrial ionosphere, low signal to noise ratio inherent to the high sky brightness. Some ideas for future giant decameter radio telescope projects (10^6 m^2 effective area at least) are proposed.

1. GUIDELINES IN DESIGNING THE NANÇAY DECAMETER ARRAY

The Nançay Decameter Array was designed and built in the mid seventies by A. Boischot and his team [*Boischot*, 1980] for studying the impulsive, broadband radio emissions originating from Jupiter and the Solar Corona at decametric wavelengths. Because of the nature of the studied radio emissions, an antenna scheme based on twin compact, filled aperture, phased antenna arrays, made of intrinsic wide band antenna elements, was chosen at the expense of angular resolution capability. The privileged capabilities rather were: i) high sensitivity, by maximising the physical area of the telescope (10^4 m^2 were built, taking into account available resources), ii) wide instantaneous bandwidth (one octave) by using log-periodic primary antenna element and an adequate phasing system, iii) long tracking time, by optimising the phasing system, iv) spectroscopy at high time and frequency resolutions (dynamic spectrum) and v) full polarisation capability, by developing specific, high performance spectrometers.

These uncommon choices are the main reasons of the scientific usefulness of the instrument, in spite of its rather moderate size, as compared to other famous decameter radio telescopes, like the Clark Lake TPT array [*Erickson and Fisher*, 1974] or the Kharkov UTR-2 radio telescope [*Braude et al.*, 1978].

Moreover the Nançay Decameter Array was proven to be quite robust to the pollution by RF interference

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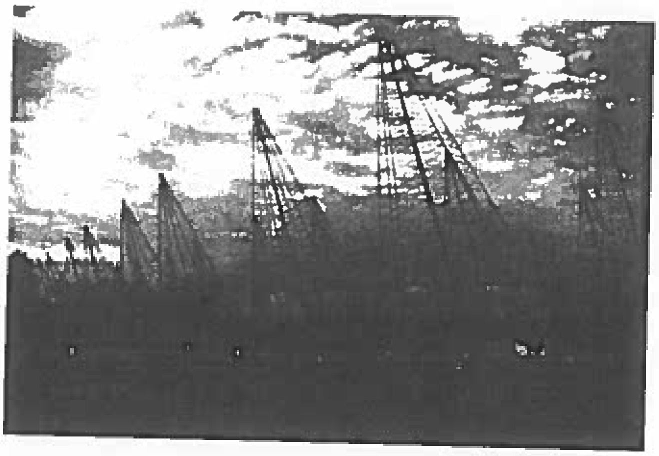

Figure 1. General view of the Nançay Decameter Array, taken from the south-west corner.

and could contribute to the understanding and to the accurate analysis of several propagation effects caused by the terrestrial ionosphere at decameter wavelengths.

In the next sections, the characteristics of the Nançay Decameter array are described, including the receiver system, and some original results are briefly commented. We conclude in delineating some guidelines for the next generation of ground-based, decameter radiotelescopes, that are directly inspired by the lessons from the Nançay instrument.

2. DESCRIPTION OF THE NANÇAY DECAMETER ARRAY

2.1 Antenna system

The Nançay Decameter Array (Figure 1) is made of 144 conical helices of the type used at Clark Lake Radio Observatory [*Erickson and Fisher*, 1974], filling a square aperture of about 10^4 m^2. The antenna array is divided in two half parts of 72 antennas (6×12 in East-West and North-South directions, respectively), wound in opposite senses, giving two sub-arrays with the same characteristics but sensitive to opposite circular polarisations. The measured effective area of each sub-array are equal and maximise to 4000 m^2 at about 30 MHz.

2.2 Phasing

In order to maximise both the tracking time and the instantaneous bandwidth of the arrays, a two-stage phasing scheme was used. The first stage uses the fact that each helix antenna is made of eight copper-steel wires wound on the surface of a cone and connected to the output coaxial cable by diode switches; only six wires are used at a time to form the antenna; the other two, diametrically opposite, are left disconnected. By changing the connections through the diode switches, the antenna can be electrically rotated around the cone axis, corresponding to a phase change of the antenna by steps of 45°. In each polarised array, the antennas are arranged in nine groups of eight antennas (2×4 in East-West and North-South), inside which the phases are matched by appropriate connection switches. This first process is chromatic and then reduces the instantaneous array bandwidth from 10-120 MHz to about one octave around the chosen centre frequency. The second phasing stage is achieved by using analogue delay lines between the nine antenna groups (for each polarisation), with an elementary delay step of 0.2m.

The entire array is fully steerable within the broad, 90° half power beam width pattern of the elementary antenna, centred on the antenna cone axis. The axis is tilted 20° South in the meridian plane, to enhance the array gain towards ecliptic directions. The resulting achievable tracking time - with nearly constant gain independent on the frequency over one octave - is ± 4 hours around the meridian transit time, within the –20° to +50° declination range (Figure 2).

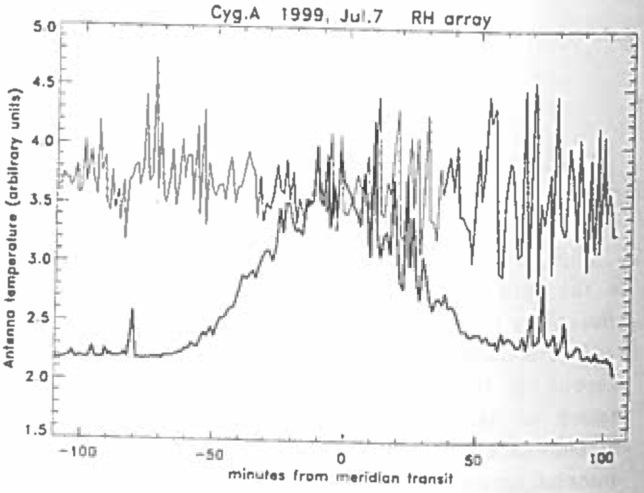

Figure 2. Observation of Cygnus A at 35 MHz. The antenna array was phased with the main beam alternately synthesised in the direction of Cygnus A (source tracking mode, thin curve), then in the meridian plane at the declination of Cygnus A (source drift mode, thick curve). The measurement demonstrates the gain stability of the instrument over the 3 hours tracking time. The broad amplitude oscillations are ionospheric scintillations.

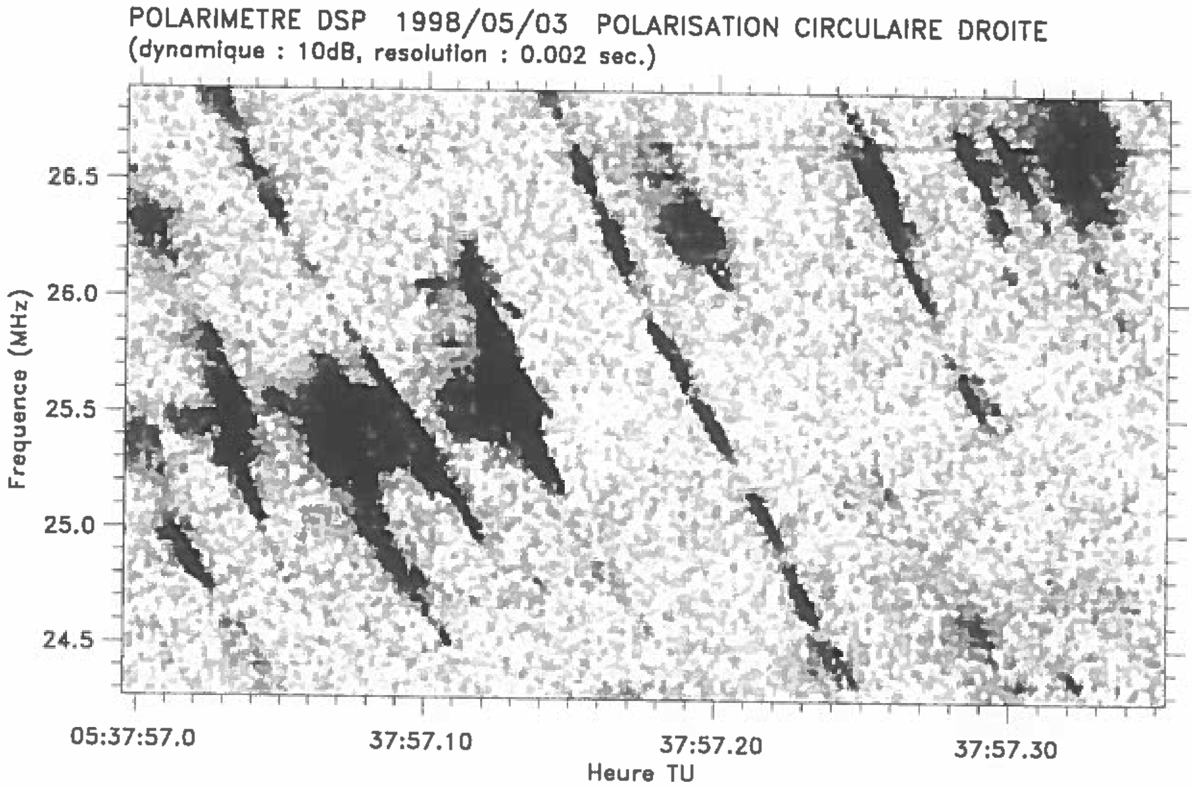

Figure 3. High resolution, real time spectral analysis of Jovian DAM radiation on 1998, May 3, by using the Nançay Decameter Array and the DSP receiver. The time resolution is 1 ms and the frequency resolution 12 kHz. About 300 ms of recorded data are displayed, showing fast drifting structures with 20 MHz/s slope in the time-frequency plane.

2.3 Signal distribution and back-ends.

The phased antenna signal is further filtered - several pass band filters can be selected in HF, depending on the ionosphere and RFI conditions -, then amplified and distributed to the back-end system.

The backend system is made of several spectrometers providing complementary capabilities of spectral analysis. In the configuration operated since mid 1997, three different spectrometers are available.

The overall decameter activity and observing context are recorded by using a wide band spectrum analyser, - the "survey" swept-frequency spectrometer -, which sweeps 400 frequency channels linearly spaced over the full observed bandwidth (10-40 MHz resp. 20-70 MHz for Jovian resp. solar observations), by alternating the sense of circular polarisation every 0.5 second.

Sensitive, high time resolution spectral analysis is provided by an acousto-optical spectrometer, having a frequency resolution of 35 kHz over a bandwidth of 24 MHz with 2048 channel output and a time resolution down to 3 ms.

Finally, the DSP digital spectro-polarimeter [*Kleewein and Lecacheux*, 1999] provides the ultimate spectral analysis capability of the Nançay instrument. Unlike existing analysers, the new machine performs spectral analysis digitally in real-time using digital signal processing (DSP) techniques. Both theoretical study and practical experience have shown that such an approach offers significant advantages over conventional analysers, namely swept frequency analysers, filterbanks, acousto-optical spectrometers or autocorrelators. None of these systems indeed can simultaneously provide wide bandwidth, high time and frequency resolutions, high dynamic range and no loss in sensitivity.

The device that has been developed can operate down to a time resolution of one millisecond with 1024 frequency channels over an instantaneous bandwidth of 12.5 MHz, including full wave polarisation measurements (Figure 3). The measured linear dynamic range for broadband noise is higher than 60 dB. Thanks to its high dynamic range, its excellent selectivity and accuracy, this receiver immediately appeared as a real

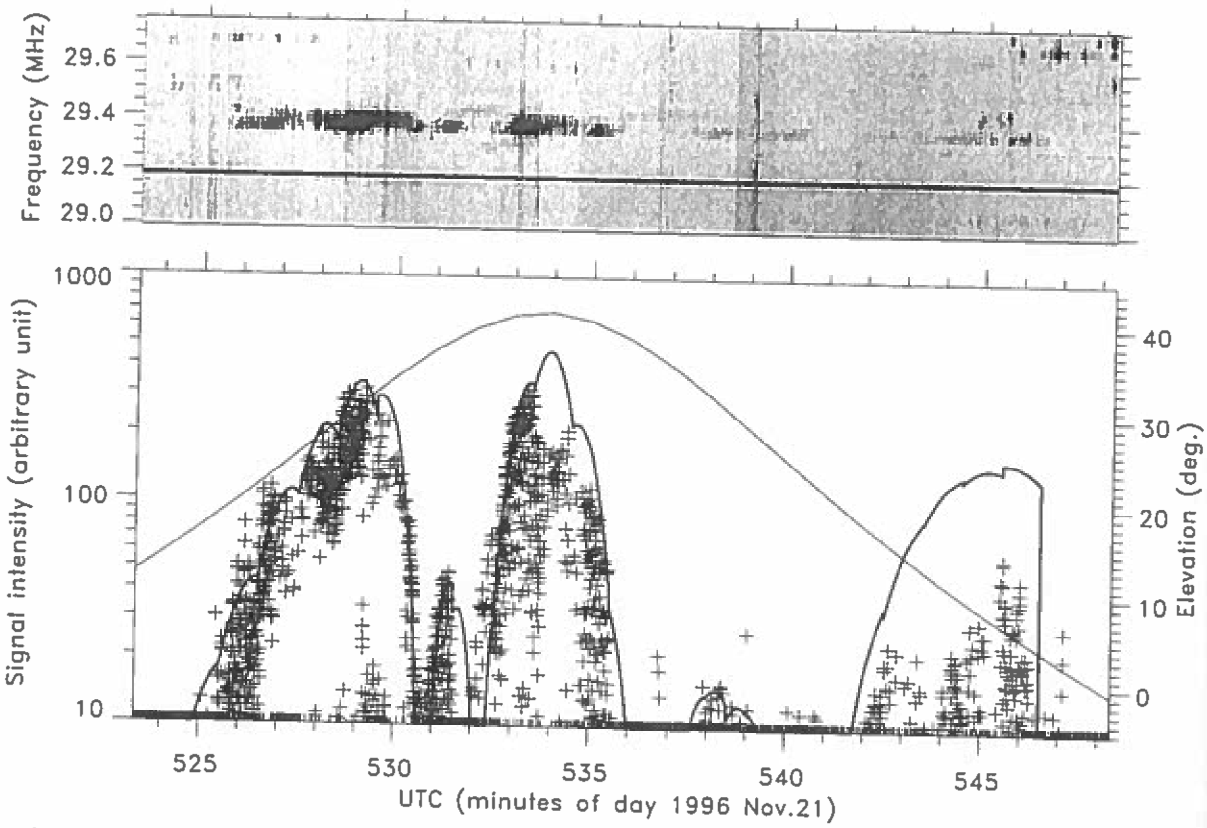

Figure 4. Check of the phasing of the Nançay Decameter Array by using Earth orbiting, radio emitting satellite as reference signal. The used satellite is the radio amateur satellite RS 15, launched in 1994 along an elliptical orbit (1800/2200 km , 2 hours revolution period). The used signal comes from the downlink transponder at 29.357 and 29.397 MHz (5W power) and the typical path duration above Nançay is 25 mn. The displayed example was a check of the backward lobes of the Nançay Decameter Array, by using a low elevation orbit (culmination at 41° elevation towards the north-north-east). The synthesised main beam was pointed along the satellite trajectory and changed every 1 mn. The signal was recorded with a bandwidth of 10 kHz and a time constant of 0.25 s. The top panel (dynamic spectrum) displays the variable intensity and bandwidth of the transponder signal. The bottom panel displays the excellent agreement between the recorded amplitude signal vs. time at 29.36 MHz (crosses) and the computed, expected response of the array (full line). Note that the signal is not corrected for the satellite spin (about 9 s. period) and that the satellite direction went out the available range of delay lines. The attenuation by ionosphere is visible after minute 542, but the signal could be tracked down to the horizon (the RS-15 elevation above horizon is given by the light line, right scale).

improvement, in particular regarding the RF interference problem.

2.4 Calibration

Accurate polarisation measurements require a good knowledge of the antenna response and continuous control of their performances.

The balance of the two polarised antenna outputs can be achieved by replacing antenna signals by a pair of stable noise diodes through a 4 × 10-dB steps programmable attenuator. Absolute amplitude and check of gain linearity are further provided by switching receiver inputs against a reference noise diode calibrator, through a 64 × 1-dB step programmable attenuator. These measurements are periodically carried out and recorded during each observing sessions (the typical period being one hour), in particular those of the survey receiver: a recent examination of all the calibration records available since 1990, has shown an excellent overall stability (within a fraction of 1 dB) of the instrument characteristics over the past ten years.

Check of the array phasing is regularly done by using celestial radio sources. Unfortunately, only a few radio sources (Cygnus A, Cassiopea A, Taurus A) are

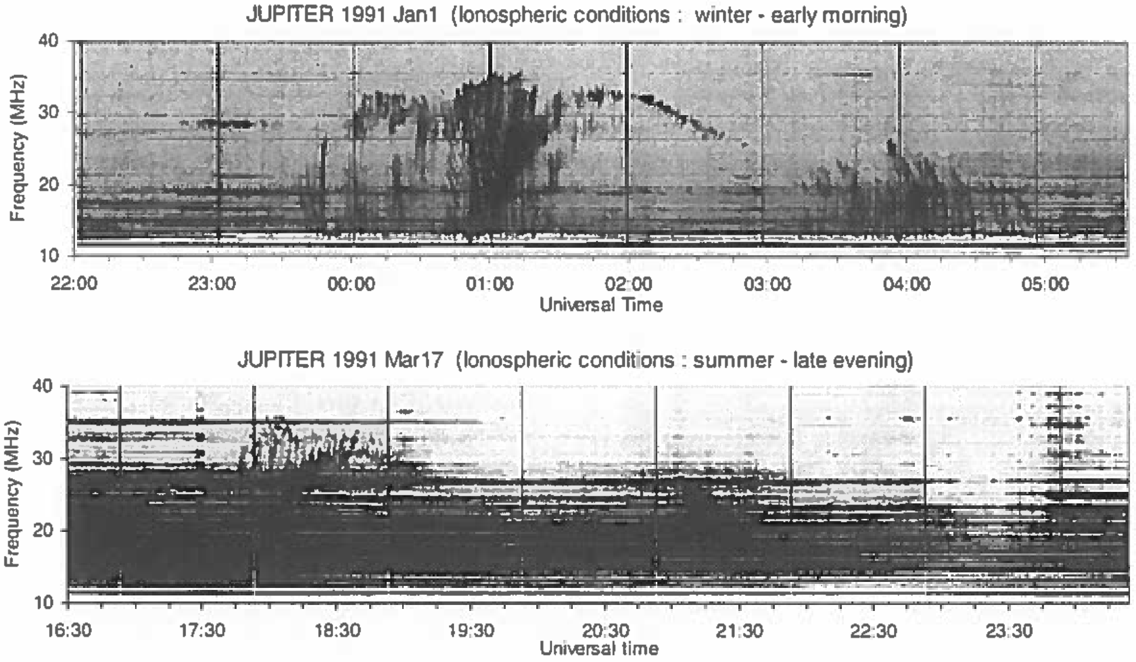

Figure 5. Examples of Nançay wide band records of Jupiter decametric emission illustrating the changing conditions of observations, occurring at decameter wavelengths. The top panel displays typical night time, winter observation in transparent ionospheric conditions : the Jupiter radiation can be followed down to the lowest analysed frequency. The bottom panel shows day time, summer observation in very bad ionospheric conditions and high RFI level : Jupiter is barely visible, especially below 25 MHz, although accurate measurements are still possible after adequate data processing. The one-hour spaced, vertical strikes are calibrations.

available with a signal level high enough to provide accurate calibration. An alternative method was developed by using radio amateur satellites (Figure 4).

2.5 *Observing methods*

Most of the observations are done in wide band mode, by fast recording of high resolution dynamic spectra (Figure 5). A primary reason is that the decameter radio emissions from the Sun and Jupiter most often occur as broadband, varying continuums. An additional reason is that the dynamic spectrum method is very powerful for disentangling the various RF interference kinds (AM broadcasts and CB, ionospheric sounders, radars, lightnings, etc...) and trying to eliminate them. Powerful algorithms, dealing with signal processing in the time-frequency plane, have been developed and are in use at Nançay for cleaning records from RF interference. An example is given by the successful detection of PSR 0834+06, at the sensitivity level of $10^{-4}\cdot T_{SYS}$, in spite of numerous RF interferences over the 20 to 40 MHz bandwidth (Figure 6).

So far applied in post processing, these algorithms are presently being integrated in the on board software of the DSP receiver, for more efficient usage in real-time.

2.6 *Data distribution and archiving*

The Nançay Decameter Array is fully automatized and can be operated remotely. Tracking information and low resolution dynamic spectrum display are available in real time (through Internet), as an help for multi site, coordinated observations.

Digital data records are produced since 1990 and can be distributed on request. A low resolution quick look data collection (taken from both Jovian and solar surveys) is freely available from the Web.

3. SOME RESULTS (1978-1999)

The Nançay Decameter Array started working in early 1978 near the time of Jupiter's flybys by *Voyager* spacecraft. The Nançay wide band observations of Jupiter (Figure 5) provided useful comparisons with the

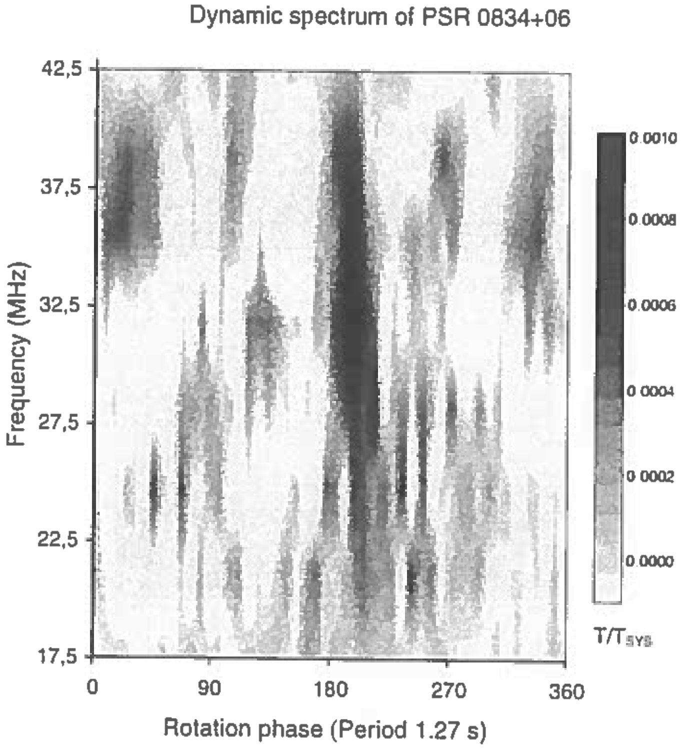

Figure 6. Detection of PSR 0834+06 with the Nançay Decameter Array. The 18-42 MHz band was analysed by the AOS spectrometer with a frequency resolution of 35 kHz and a time resolution of 20 ms. The recorded data were first cleaned from RF interference, then folded and averaged at the pulsar period (1.27 s), and finally corrected for the interstellar dispersion. The integration time is 45 s. The contrast (T/T_{SYS}) of the pulse signal is about 0.001, corresponding to a flux density of 50 Jy. Note the spectral turn over at about 28 MHz In spite of numerous RFI occurring in the wide observed bandwidth, the achieved sensitivity, after data processing, get close of the maximal capability of the instrument.

measurements made by the on board Planetary Radio Astronomy experiment [*Boischot et al.*, 1981], in particular regarding the directivity of the Jovian decametric emission [*Barrow et al.*, 1982] and the understanding of the recurrent features in its dynamic spectrum, linked to the Io-Jupiter electro-dynamic interaction [*Leblanc*, 1981].

Very high resolution spectral analyses of the Jovian decameter radio emission, - not possible so far with instruments on board interplanetary spacecraft because of telemetry constraints -, have been carried out in Nançay, in wide band mode (> 10 MHz) and with temporal resolution down to 1 millisecond (Figure 3). These observations have allowed to characterise several types of very short spectral structures, some being due to interplanetary scattering [*Genova and Boischot*, 1981], other originating in Jupiter's magnetosphere, like the intriguing "S-bursts phenomenon", still not really understood [*Leblanc et al.*, 1980a, 1980b; *Genova and Calvert*, 1988; *Zarka et al.*, 1996].

The capability of measuring the four Stokes parameters of the incident wave has been applied to the Jovian decameter radiation, that was found to be 100% elliptically polarised [*Lecacheux et al*, 1991], with a well defined polarisation ellipse which does not depend on the changing observing conditions [*Dulk et al.*, 1994]. The electron column density of the plasma Io torus could be directly measured [*Dulk et al.*, 1992], leading to a possible method for remotely monitoring the dynamics of this fundamental component of the Jupiter magnetosphere.

Broadband survey of Solar Corona emissions has been carried out in two main directions: studies of spectral fine structures, with phenomenological and theoretical comparison with those occurring in planetary radiations [e.g. *Barrow et al*, 1994]; and spectroscopic study of wide band radio emissions (like solar Type II radiation) linked with developing solar flare and matter ejection out of the Corona (CME) [e.g. *Bougeret et al*, 1998; *Dulk et al*, 1999]. Ground based decametre radio astronomy appears as a powerful tool for defining CME's start time and shock propagation velocity.

Some propagation effects due to the terrestrial ionosphere could be recognised and well understood thanks, in particular, to the broad band spectroscopic capability of the Nançay Decameter Array: an example is given by the modelling of TID focusing effects on decameter radio waves in terms of discrete refractive scattering event [*Meyer-Vernet et al*, 1981, *Lecacheux et al*, 1981]. This kind of scattering effects was later identified on centimetric wavelength pulsar radiation propagating through the interstellar medium [*Fiedler et al.*, 1987].

4. DRIVERS FOR DESIGNING LOW FREQUENCY RADIO TELESCOPES OF NEW GENERATION

From the experience gained in Nançay, we believe that the key characteristics for defining new generation, ground based, low frequency radio telescopes depend primarily on the wanted working frequency range. Above 30 MHz or so, the techniques needed to reach most of the astrophysical objectives remain ordinary radio astronomy techniques and mainly involve imaging capability, high sensitivity and some robustness against RFI. However, below 30 MHz, - which might be the most promising frequency domain for low frequency astrophysics-, difficulties increase dramatically and the primary drivers become the telescope collecting area, the terrestrial ionosphere blockage and the huge amount of RF interference from man made and natural origins.

4.1 *Effective area must be >> 10^6 m^2*

Because of the very high brightness temperature of the sky background ($T_B \approx 10^5$ K at 30 MHz, $\approx 10^7$ K at 3 MHz), which unavoidably limits the system temperature, the only practicable way to achieve acceptable sensitivity is to build a telescope collecting area quite unusual in size: assuming a time-bandwidth product $b \cdot \tau = 10^6$ (e.g. integration time τ=100 s over bandwidth b=10 kHz), the detection of a source of flux density S = 1 Jy with $T_{SYS} = T_B \approx 10^6$ K indeed requires an effective area as large as

$$A_e = 2k \cdot (T_{SYS} / \sqrt{b \cdot \tau}) / S \approx 3\ 10^6\ m^2.$$

Effective area this large implies a telescope configuration based on the concept of filled aperture, compact phased antenna array. The elementary antenna can be a simple dipole or a circularly polarised antenna like the Nançay helices, making the main part of the instrument relatively low cost.

The large effective area of the instrument is also an advantage against the RFI since, in principle, higher the antenna directivity is, lower is the RFI signal contribution, mainly entering through the secondary lobes, as compared to that of a radio source seen in the main beam.

Moreover, the whole instrument might be distributed in several distant sites, in order to decorrelate the local interference and the local effects of the ionosphere, and to provide some imaging capability as well.

4.2 *RF Interference*

With the increase of telecommunications, the RF interference had become a very difficult problem, now faced by all the radio astronomers at any wavelength. Solutions are actively searched, which involve various techniques like i) antenna beam forming (in phased array), ii) ultra linear, high dynamic range electronics (both in front end and back end), iii) real time signal processing (for interference excision), iv) multi-site observing (discrimination of local RFI). Any new generation low frequency telescope must primarily use most of these promising techniques to overcome the RFI challenge. It is worth noticing that RFI level seems no longer very much increasing at decameter wavelengths and, hopefully, might even decrease in the next future.

4.3 *Ionosphere blockage / propagation effects*

The maximum electron plasma frequency (f0F2) of the terrestrial ionosphere is highly variable in a given location. The main variations are due to seasonal (solar illumination) and diurnal (sunset and sunrise) effects, or due to the solar activity. Higher the magnetic latitude is (but less than auroral), lower is the average f0F2: in many sites in Northern hemisphere (Canada, North Europe) or in Southern hemisphere (Tasmania, South Africa), the f0F2 frequency is as low as 5 MHz a notable percentage of the time.

Because of the modern understanding and measuring of the terrestrial ionosphere dynamics [e.g. *Mannuci et al.*, 1998], several propagation effects due to the ionosphere, like absorption, refractive and diffractive scintillations of radio waves, should be modelable and even correctable. Some progress have been done recently in this matter [*Kassim et al*, 1993]. They could be enhanced by additional techniques, like ionosphere tomography by using GPS satellite and calibration of ionospheric effects by using dedicated transmitting µ-satellites.

5. CONCLUSION

There are great promises of low frequency radio astronomy in Planetary Sciences, Solar Physics and Astrophysics [cf. the reviews and contributions by *Kaiser et al.*, *Zarka et al.*, *Bougeret et al.*, *Dulk et al.*, and *Weiler et al.*, this book]. In the latter domain, very few has been done so far at wavelengths longer than 10 meters, and yet this is a domain of choice for the search of non thermal, radio emissions from known or still unknown astrophysical objects.

In spite of its relatively small collecting area, the Nançay Decameter Array, operating in the 3-30 meter wavelength range, has proven to be quite powerful in studying non thermal radiations from Jupiter and the Solar Corona. Its wide instantaneous bandwidth and high resolution spectral analysis capabilities are of prime interest in the understanding of such plasma radiations, and brought some efficient solutions to the radio spectrum invasion by man made, radio telecommunication signals.

The ultimate radio telescope for exploring the electromagnetic spectrum below 30 MHz, will one day be deployed in space, to avoid radio wave blockage by the terrestrial ionosphere. But giant collecting area (>> 10^6 m^2) is required for Astrophysics: premature use of small antennas on spacecraft might be disappointing for galactic and extra galactic astronomy.

In the meantime, building on the ground a new generation, ground based giant radio telescope makes sense. Cheap solutions do exist, based on the concept of phased antenna arrays. The new instrument must include modern digital techniques (massively parallel computing, etc...) to overcome RFI / ionospheric effects problems.

The new instrument could efficiently serve as a useful, low cost demonstrator and be built during the next decade. Then, if scientific promises are still appealing, a more ambitious telescope could eventually be deployed in space or on the far side of the Moon.

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