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The MEXART interplanetary scintillation array in Mexico

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RESUMEN

Se reportan los avances en la construcción de un arreglo plano de 64X64 (4096) dipolos de onda completa, con una frecuencia de operación de 140 MHz ocupando un área de 10 000 m^2 (70 m x 140 m) para realizar observaciones de centelleo interplanetario (CIP). Este será un arreglo dedicado de tiempo completo a estudios de CIP donde se espera captar diariamente cerca de 1000 fuentes de radio conocidas. El arreglo se está construyendo en Coeneo, Michoacán (localizado a 350 km de la Ciudad de México, Lat. 19°48' N, Long. 101°41' O y a 1964 m sobre el nivel del mar). El MEXART (por sus siglas en inglés) tendrá algunas características similares al arreglo del MRAO en Cambridge, pero con varias mejoras tales como un mejor sistema electrónico, frecuencia de operación más alta, una parte trasera digital y su ubicación en una altitud geomagnética intermedia (29°). El proyecto MEXART consiste de dos etapas. En la primera se construyó un arreglo prototipo cerca de la ciudad de México, el cual tenía todos los elementos básicos de la antena del arreglo final, pero cubriendo un área menor (1000 m^2) y con una matriz de Butler de 4x4. En la segunda etapa estamos construyendo el arreglo final con la asistencia técnica del NCRA-TIFR de la India. El MEXART será el único instrumento de su tipo en el continente americano y formará parte de una red junto con otros observatorios de CIP en otras longitudes como el ORT en la India y el STEL en Japón. Esta red de observatorios de CIP proporcionará información relevante para el estudio de las perturbaciones de gran escala que se propagan en el medio interplanetario, en particular las que tiene mayor relevancia al clima espacial. Esperamos iniciar observaciones a principios de 2003.

PALABRAS CLAVE: Centelleo interplanetario, técnicas e instrumentación, clima espacial, eyecciones de masa coronal.

ABSTRACT

We report advances in the construction of a 64x64 (4096) full wavelength dipole antenna array, which will operate at 140 MHz, occupying 10 000 square meters (70 m x 140 m) to carry out interplanetary scintillation (IPS) observations. This will be a dedicated radio array of nearly 1000 well known radio sources which is being built in the state of Michoacán 350 km north-west from Mexico City, lat. 19°48' N, long. 101°41' W and 1964 m above sea level. The Mexican Array Radio Telescope (MEXART) will have similar characteristics to the MRAO array in Cambridge, but with significant advantages such as a better electronic system, higher operation frequency, state of the art back end, and location at intermediate geomagnetic latitudes (29°). The MEXART project consists of two phases. In the first phase, we built a prototype radio array near Mexico City, which contained all the basic antenna elements of the final array but covering a smaller area (1000 square meters) and operating with a 4x4 Butler matrix. In the second phase we are building the final array in Michoacán with technical assistance by NCRA-TIFR in India. MEXART will be the only IPS station in the American continent and will be part of a global network of IPS observatories combining measurements with ORT in India and the STEL IPS systems in Japan. Combining data from these IPS observatories will provide important information for solar wind studies and in particular for solar activity associated storms and ionospheric disturbances. We expect to initiate IPS observations by early 2003.

KEY WORDS: Interplanetary scintillation, instruments and techniques, space weather, coronal mass ejections.

1. INTRODUCTION

The onset of geomagnetic activity and ionospheric disturbances due to solar perturbations propagating throughout the solar wind usually leads to disruption of radio communications, damage to power transmission systems and, in space, these disturbances also can perturb satellite orbits (Lanzerotti, 1979; Lanzerotti and Gregori, 1986; Kappenman, 1996: Song *et al*., 2001 and references therein). For these reasons the importance of tracking these interplanetary (IP) events (space weather forecasting) has grown dramatically (Joselyn, 1995; Bravo, 1997; Crooker, 2000; Song *et al*., 2001 and references therein). Coronal mass ejections (CMEs) originating on the front side of the solar disk (halo CMEs) can reach the Earth and cause geomagnetic storms, provided they have appropriate magnetic field orientation. Gonzalez and Tsurutani

(1987) showed that a necessary and sufficient condition for the occurrence of an intense geomagnetic storm is the arrival at the magnetosphere of a large and negative (< -10 nT) Bz component of the interplanetary magnetic field (IMF) intensity of more than three hours duration and most of these geoeffective events are associated with interplanetary counterparts of CMEs (ICMEs) (Gosling, 1993). Space weather studies has become a priority in the space sciences.

Interplanetary Scintillation (IPS) is the random intensity variation of a cosmic radio source of small diameter (<2 arcsec) caused by the diffraction of the wave front as it propagates through random fluctuations in the refractive index of the turbulent interplanetary medium (Figure 1). These phase distortions of the radio wave front are related to the small scale electron density inhomogeneities (Dne) in the interplanetary plasma that produce a diffraction pattern in the plane of the observer and create intensity fluctuations (scintillations) as the diffraction pattern is convected across the antenna by the solar wind (Ananthakrishnan *et al*., 1980; Leinbach *et al*., 1994; Breen *et al*., 1997; Manohoharan *et al*., 1990, 2000). The IPS technique assumes that these electron density fluctuations (Δn_e) are proportional to density variations in the solar wind. The increments in solar wind density and related IPS events may be associated with two general types of large-scale solar wind perturbations: (1) the region around a stream interface between a fast solar wind stream overtaking a slow ambient wind (corotating interaction regions) and (2) the density enhancement associated with solar transient events such as ICMEs or other solar activity. Therefore we can use IPS observations to identify large-scale solar wind perturbations propagating from the Sun to 1 AU (Hewish and Bravo, 1986). The IPS provides information on the large-scale shape and velocity of solar wind disturbances within a range in the interplanetary medium where no other technique is capable to do it.

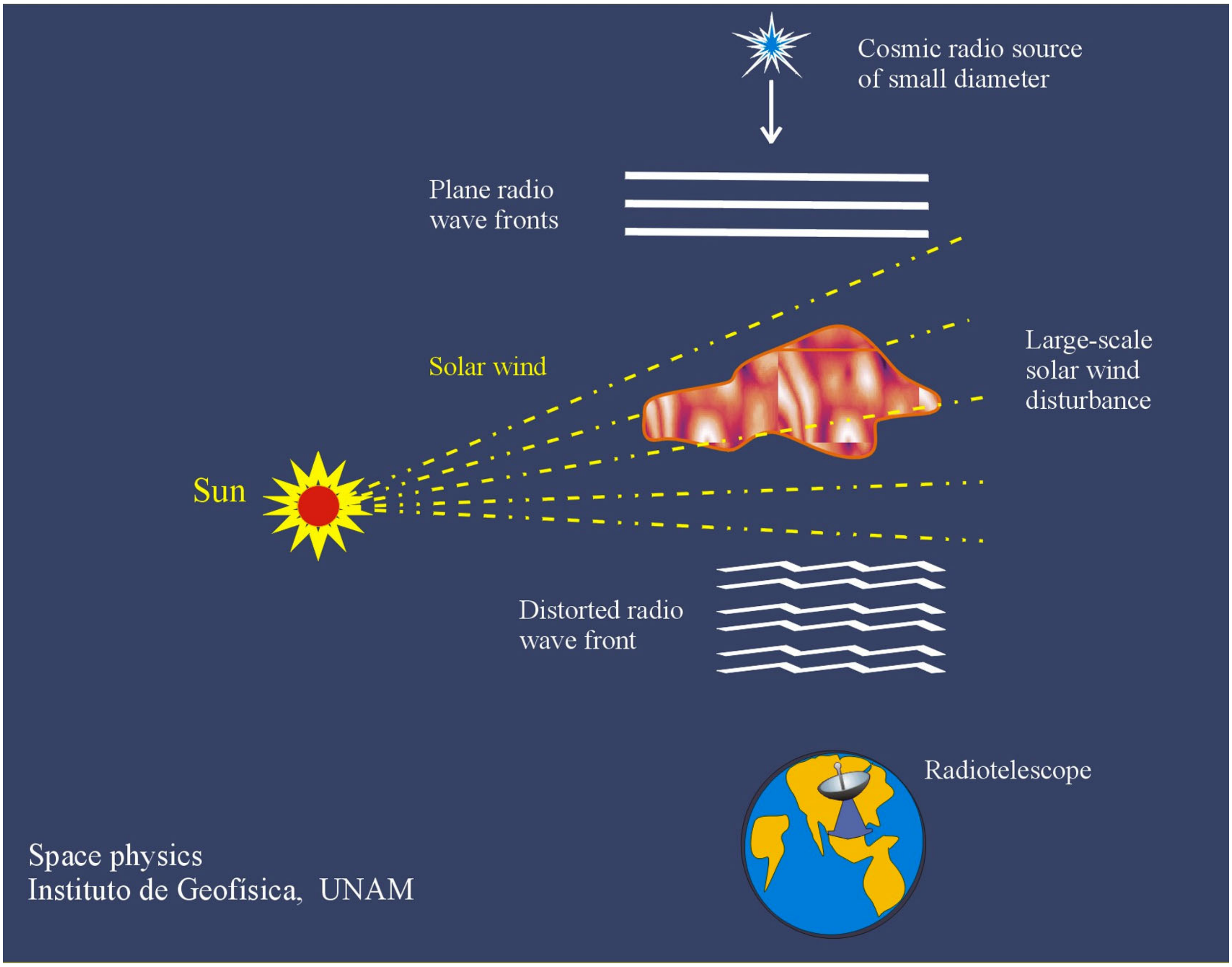

Fig. 1. Scheme of the Interplanetary scintillation phenomenon.

Hewish (1990) suggested that all-sky observations of IPS of extragalactic sources could be used to forecast space weather. In March 1990 the Mullard Radio Astronomy Observatory (MRAO) in Cambridge, UK, began to supply the Space Environment Laboratory (SEL) with automatic measurements of relative scintillation (*g* maps) for about 950 sources for the purpose of testing IPS as a forecasting tool. This experiment obtained mixed results and Leinbach *et al.* (1994) summarized the problems of using a single IPS observing station as a space weather forecasting tool in three points: (1) problems inherent in detecting and analyzing IPS events on graphics that take 24 hours to complete, (2) questions regarding the IPS g-values (e.g., ionospheric scintillation contamination) and (3) difficulties in interpreting 2-D IPS disturbances as 3-D solar disturbances. As they pointed out a solution to these problems is to have at least two stations at different geographic longitudes, which would increase the sampling rate by obtaining two or more IPS *g* maps per day and which also would help to discriminate in some questionable IPS events.

Recently by combining SOHO-LASCO, IPS and *in situ* observations it has been possible to trace the evolution of some fast CME events in the interplanetary medium (Manoharan *et al.*, 2000, 2001). Manoharan *et al.* found that the speed of an ICME decline slowly with distance within 100 solar radii and beyond this point the ICME speed decelerated faster. In these studies the IPS observations provide global measurements of the size and speed of the ICME within a region in the inner heliosphere where there is no other technique that can give us this information. Therefore these new IPS studies have proved to be very useful to infer some characteristics of ICMEs propagating in the inner heliosphere combining data of two different radio telescopes: the Ooty Radio Telescope (ORT) (Manoharan *et al.*, 2000, 2001) and the Solar-Terrestrial Environment Laboratory (STEL) IPS systems (Tokumaru *et al.*, 2000, 2002). These results confirmed the utility of using two or more IPS observatories showing that the IPS technique is a powerful ground-based tool to study the propagation of large-scale IP disturbances approaching the Earth.

Moreover, in recent years much work based on IPS observations has been published on several aspects of solar wind studies, such as:

- The acceleration region (Grall *et al.*, 1996; Breen *et al.*, 2000)
- The large-scale structure of the solar wind (Coles, 1995; Moran *et al.*, 1997, 2000; Kojima and Takimuna, 1990; Kojima *et al.*, 1998; Asai *et al.*, 1998a,1998b; Breen *et al.*, 1999)
- Corotating interaction regions and traveling interplanetary disturbances (Breen *et al.*, 1997; Janardhan *et al.*, 1996; Jackson *et al.*, 1997, 1998; Ananthakrishnan *et al.*, 1999; Gothoskar and Rao, 1999; Manoharan *et al.*, 1990, 2000, 2001; Tokumaru *et al.*, 2000, 2002).

The IPS technique is used for probing the structure of the inner heliosphere, and several groups around the world regularly make a number of different types of observations. At present there are three different radio telescopes performing IPS measurements. (1) The ORT at 76° East longitude in Ooty, India, which has a single antenna (30 m x 600 m) operating at 327 MHz (Swarup *et al.* 1971; Selvanayagam *et al.*, 1993). This observatory is operated by the Radio Astronomy Centre, Tata Institute of Fundamental Research, India. (2) The STEL multi-antenna system at 138° East Longitude, which comprises four radio telescopes operating at 327 MHz (Kojima and Kakinuma, 1990; Asai *et al.*, 1998a, 1998b). This observatory is operated by the Nagoya University, Japan. (3) The European Incoherent Scatter Radar (EISCAT) which comprises three radio telescopes operating at 931 MHz (Rishbeth and Williams, 1985). The EISCAT is operated by the research councils of seven countries and the transmitter site is located close to the city of Tromsø, in Norway (19° East longitude).

Mexican Array Radio Telescope: MEXART

Forecasting capability for geomagnetic and ionospheric activity may be enhanced by continuous monitoring of interplanetary disturbances via a global network of IPS arrays located at different longitudes to maximize the coverage. A network of ground-based IPS radio arrays which are inexpensive and long term (several decades) compared to satellites, has the potential to provide 24 to 36 hours advanced warning of some events and even a three day warning in some situations. At the present time there is no radio telescope on the American continent performing IPS observations and this produces a significant gap in the daily coverage of solar wind observations. Silvia Bravo promoted and guided the project of building an IPS observatory in Mexico[1]. The project was named *Mexican Array Radio Telescope* (MEXART). The MEXART presented several technical challenges. Because Mexico does not have a background in radio telescope engineering, technical assistance from other institutions has been necessary. Moreover, a project of scientific infrastructure development in Mexico is very complicated due to budget limitations. For those reasons the MEXART project had some difficult moments during the last few years. However, in this final stage we received crucial technical support from the National Centre for Radio Astrophysics (NCRA) - Tata Institute of Fundamental Research (TIFR) in India, which has allowed us to solve most of these problems and to establish a long term collaboration.

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[1] *Silvia Bravo passed away in September, 2000*

We report the advances in the construction of the MEXART, which will participate in a global warning network for impending solar-activity-related geomagnetic storms, combining IPS data from different ground-based observatories at different longitudes such as the ORT in India and STEL in Japan. This global network will improve the tracking of large-scale perturbations that travel from the Sun to the Earth. Combining the IPS data with other solar, *in situ* and magnetospheric observations by several spacecraft (e.g., YOKOH, SOHO, TRACE, POLAR, WIND, ULYSSES, STEREO) and other ground-based observatories, we will improve our understanding of the space weather phenomena. It is important to point out that the IPS observations cover a region in the interplanetary medium which cannot be cover by the corographs and provide a large-scale picture that is not possible to deduce based on *in situ* measurements by spacecraft. Therefore it is necessary to combine the observations.

The MEXART project consists of two phases. In the first phase we built a prototype radio array near Mexico City which contained all the basic elements of the final array. In the second phase we are building the final array in the state of Michoacán with the technical assistance of the NCRA-TIFR in India.

2. MEXART PHASE 1. PROTOTYPE RADIO ARRAY

The MRAO array in Cambridge operated at 81.5MHz and covered an area of 36 000 square meters[2] (Purvis *et al.*, 1987). The MEXART will have some similar characteristics, but with significant advantages such as better electronic components, higher operation frequency (140 Mz) which will allow us to detect the IP disturbances closer to the Sun, state of the art back end based on a digital circuitry, and its location at an intermediate geomagnetic latitude (29°). The latter is important since ionospheric scintillation (which might mimic interplanetary scintillation in some events) is at maximum in the aural oval at high geomagnetic latitudes, diminishes at intermediate latitudes, and rises again toward the geomagnetic equator. Therefore the geomagnetic latitude of the Mexican site (29°) will reduce significantly this contaminating effect. Since in the IPS technique the radial distance from the Sun at which the interplanetary perturbations can be identified depends on the frequency, the MEXART operation frequency will enable the radio array to observe the passage of ICMEs and IP shocks at approximately 20 degrees elongation angle from the Sun[3]. Moreover, the MEXART will probe an unexplored frequency in IPS studies. This band (138.9-140.4 MHz) is protected by the Mexican government for scientific studies in accordance with the Table of National Attributed Frequencies published by the "Diario Oficial" on January, 11, 1999.

Between 1995-1997 we built a prototype radio array having a geometrical area of about 1,183 square meters (137.6 m x 8.6 m) with 64x4=256 elements (full wave dipoles), which was designed by Dr. Michael Thursby of the Florida Institute of Technology (Thursby, internal report, 1994). The array was built at the National Geomagnetic Observatory in Teoloyucan, Estado de Mexico (about 40 minutes driv-

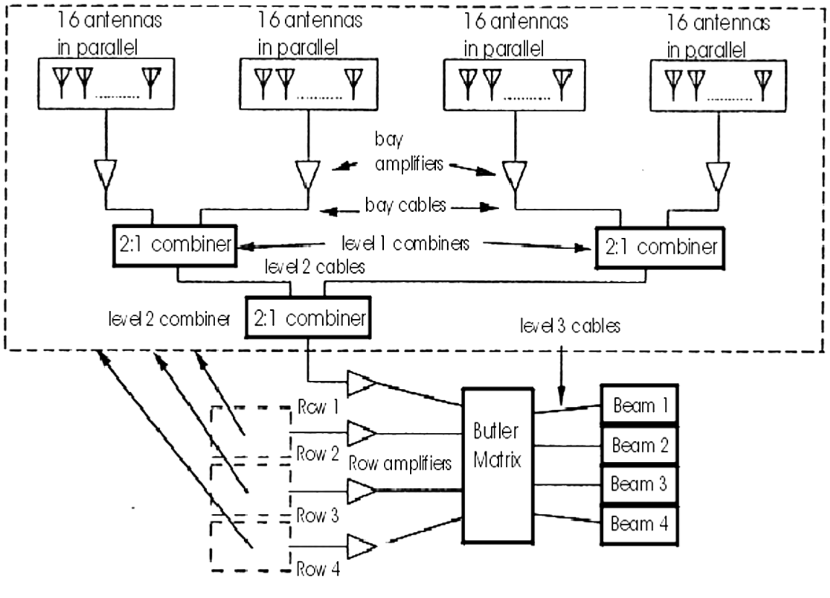

Fig. 2. Block components of the IPS prototype array.

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[2] *The MRAO stop operating in the middle of 90's.*

[3] *At 81 MHz (MRAO operation frequency) the minimum distance from the Sun is about 0.5 AU, corresponding to 30°.*

ing north from Mexico City) (Carrillo *et al.*, 1997). Figure 2 shows the basic components of the prototype array: antenna, amplifiers, Butler matrix and receivers. The basic element of the prototype array was the full wavelength dipole (l=2.15 m). The antenna had four East-West (E-W) rows and each row had 64 dipoles in total divided in four sections. Each section was composed of a 16 dipole ensemble connected to a parallel transmission line. Figure 3 shows the orientation and dimensions of the antenna, where each E-W row was separated λ/2 along the north-south direction from the next row, and below in the figure there is a diagram showing how each E-W row was divided in four sections. Figure 4 shows the dimensions and details of the ensemble dipoles. The transmission lines were separated 1" employing a PVC tube, this separation was meant to keep the impedance constant (413 Ω) along the whole transmission line. We used copper cable 14 AWG for the dipoles and PVC tubes size $^3/_4$ for the separations. The calibration test of the dipoles (tun-

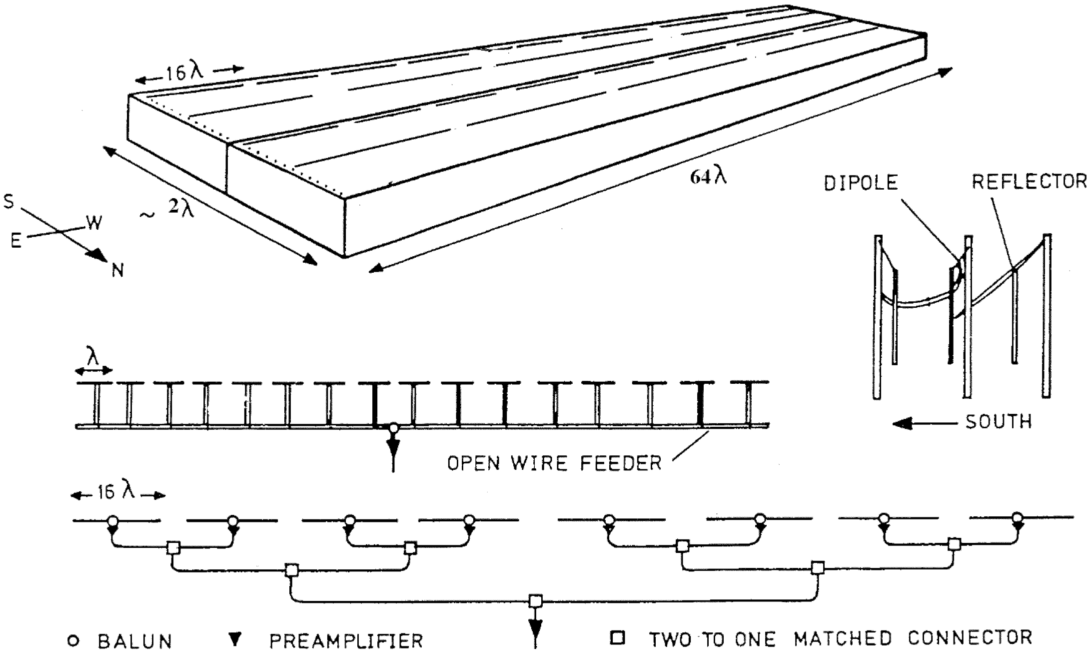

Fig. 3. Dimensions and specifications of the prototype antenna.

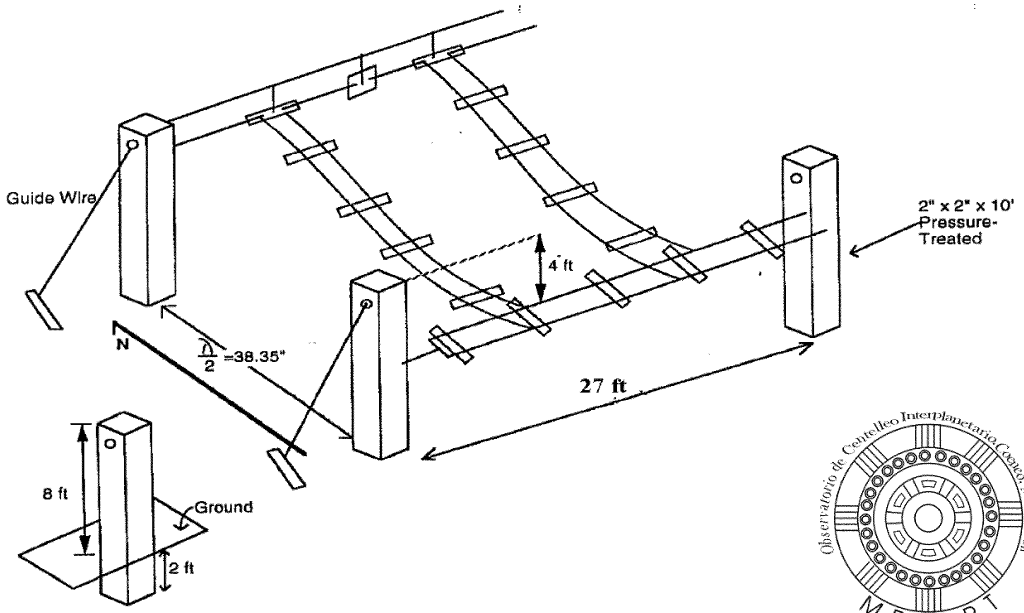

Fig. 4. Ensemble dipoles.

ing the array dipoles at the design frequency 138-141 MHz) was performed using a network analyzer HP 8751A.

Since the antenna needed a balanced output while the input and output terminals of the preamplifiers were unbalanced, the system must thus be detuned for currents on the outside of the line through a Balanced to Unbalanced Transformer (BALUN) device (Janardhan, 1991). As it is shown in Figure 3 the signal of each section of 16 dipoles (413 Ω) was coupled with the coaxial transmission line (50 Ω) through the balun. The 1:1 balun had a ferrite core with a toroidal shape. The coaxial cable used in the prototype was RG-8U. The signal of each section was amplified using a Low Noise Amplifier (LNA) ZFL-500LN, which characteristics are shown in Table 1. The signal after the first amplification step had an increment of 28 dB.

The amplified signals of each section were added vectorially by a 2:1 power combiner 2:1 ZFSC 2-1W. The characteristics of the combiner are shown in Table 2. The first unit combined the output of 16 dipoles of a row with the 16 adjacent dipoles of the same row. At the end, each E-W row had two amplification steps and two combination steps before sending the signal to the back end.

Table 1

Characteristics of the LNA ZFL-500LN

Frequency (MHz)	Gain (dB)	Directivity (dB)	SWR		N.F (dB)	P_{out} (dB_m)
			IN	OUT		
5.4	27.94	26.5	1.03	1.10	-	8.09
53.3	28.15	27.2	1.09	1.08	1.89	7.94
192.4	28.21	26.9	1.17	1.10	3.03	7.72

The array elements were electrically phased in a Butler matrix, to provide four beams at different latitudes (+/- 10 degrees and +/- 20 degrees with respect to the zenith). Figure 5 shows the diagram of the Butler matrix. The prototype array generated a beam of about HPBW 0.8° along both the N-S and E-W directions. Figure 6 shows the diagram of the prototype receiver. The receiver was of the Dicke type, with a time constant of 1 second.

Figure 7 shows a chart recording made by the prototype array. This observation corresponds to a total power operation mode on date 30/Aug/1996. The radio source is 3C 132, coordinates RA 4:49' and 22° in declination. Note the high electromagnetic noise in the chart. This was a serious problem in the prototype performance, since Teoloyucan is located near a large industrial zone close to Mexico City.

Figure 8 shows a picture of the prototype array. The main results from the prototype array were: the formation of Mexican technicians trained to build up and test a planar array for IPS observations, the acquisition of measuring and calibration equipment and the testing of the design and materials that will be used in the construction of the final array (Carrillo *et al.*, 1996; Guerrero *et al.*, 1997).

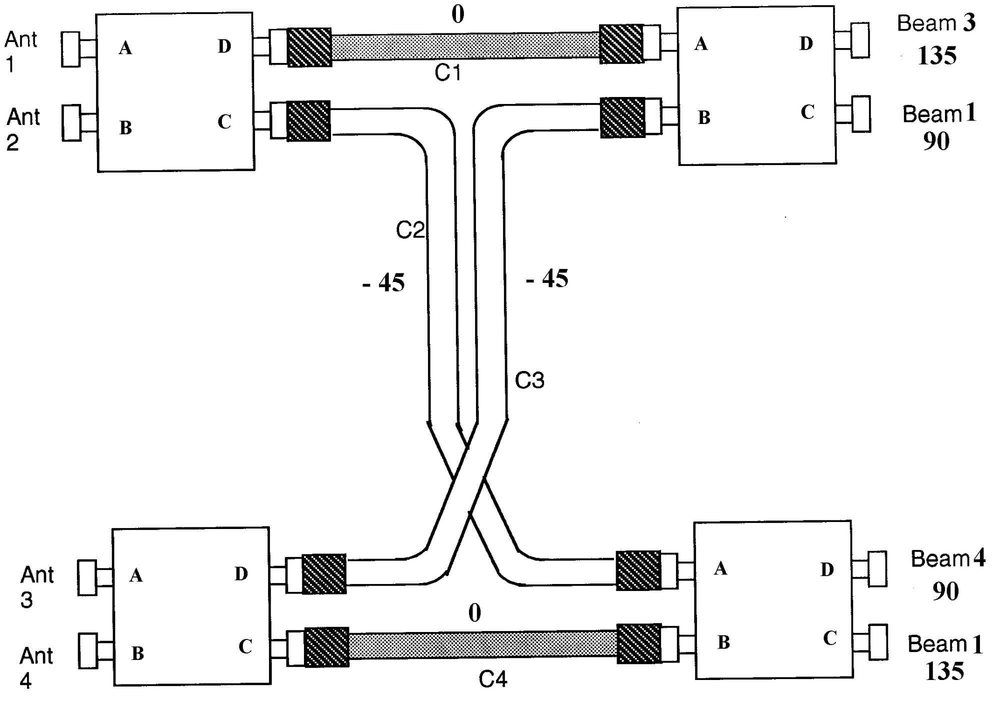

Fig. 5. Butler matrix.

Table 2

Characteristics of the combiner ZFSC-2-1W

FREQUENCY (MHz)	INSERTION (dB) s-1	INSERTION (dB) s-2	AMPLITUDE (dB) 1-2	ISOLATION (dB)	VSWR S	VSWR 1	VSWR 2
100	3.24	3.25	0.01	32.90	1.13	1.15	1.16
146.0	3.24	3.24	0.00	30.74	1.13	1.14	1.15

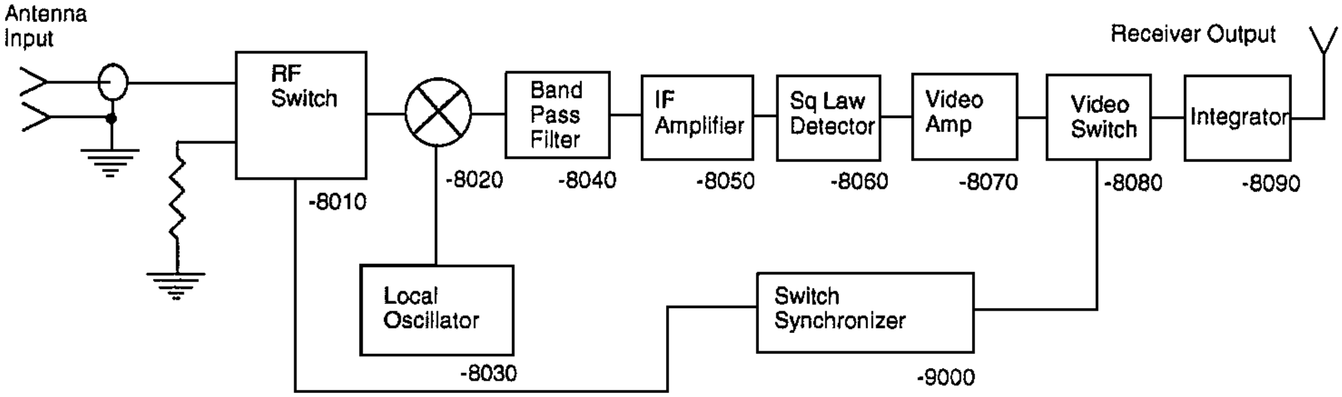

Fig. 6. Receiver type Dicke.

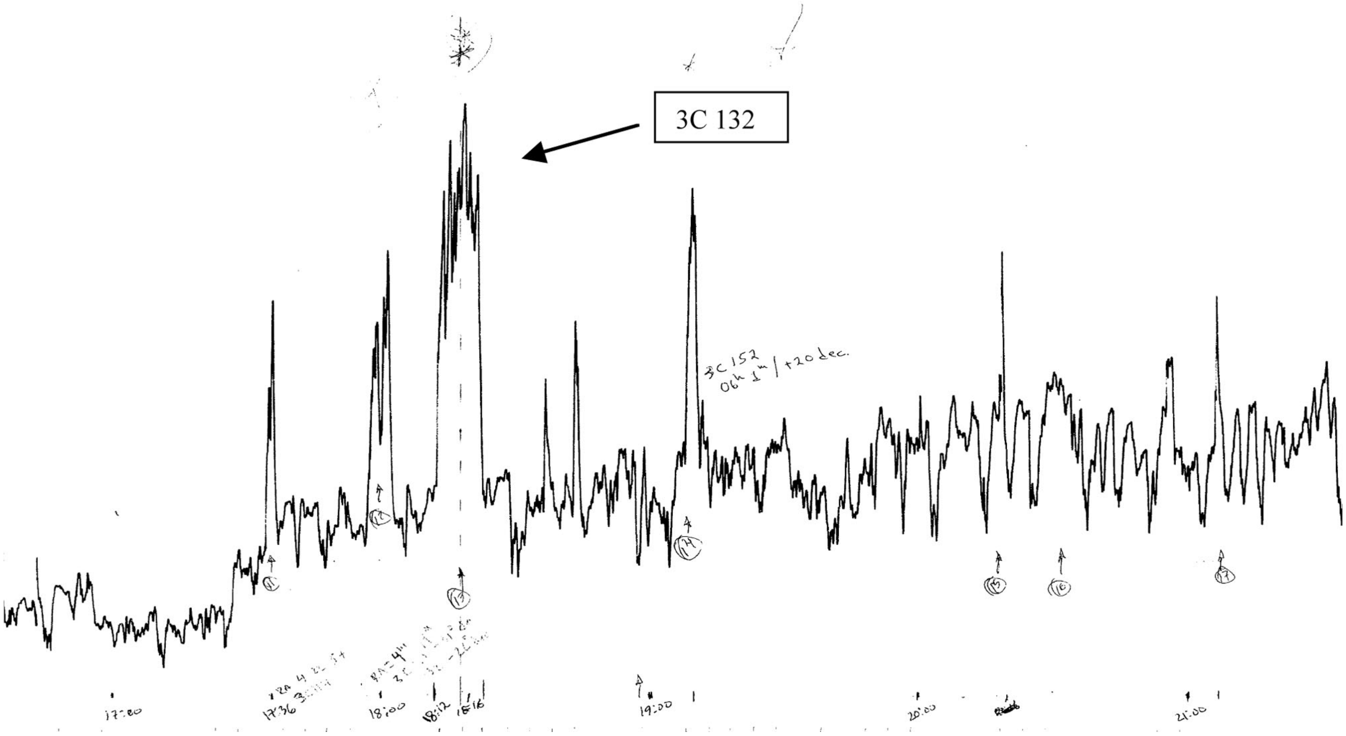

Fig. 7. Chart recording of the radio source 3C 132 by the prototype array.

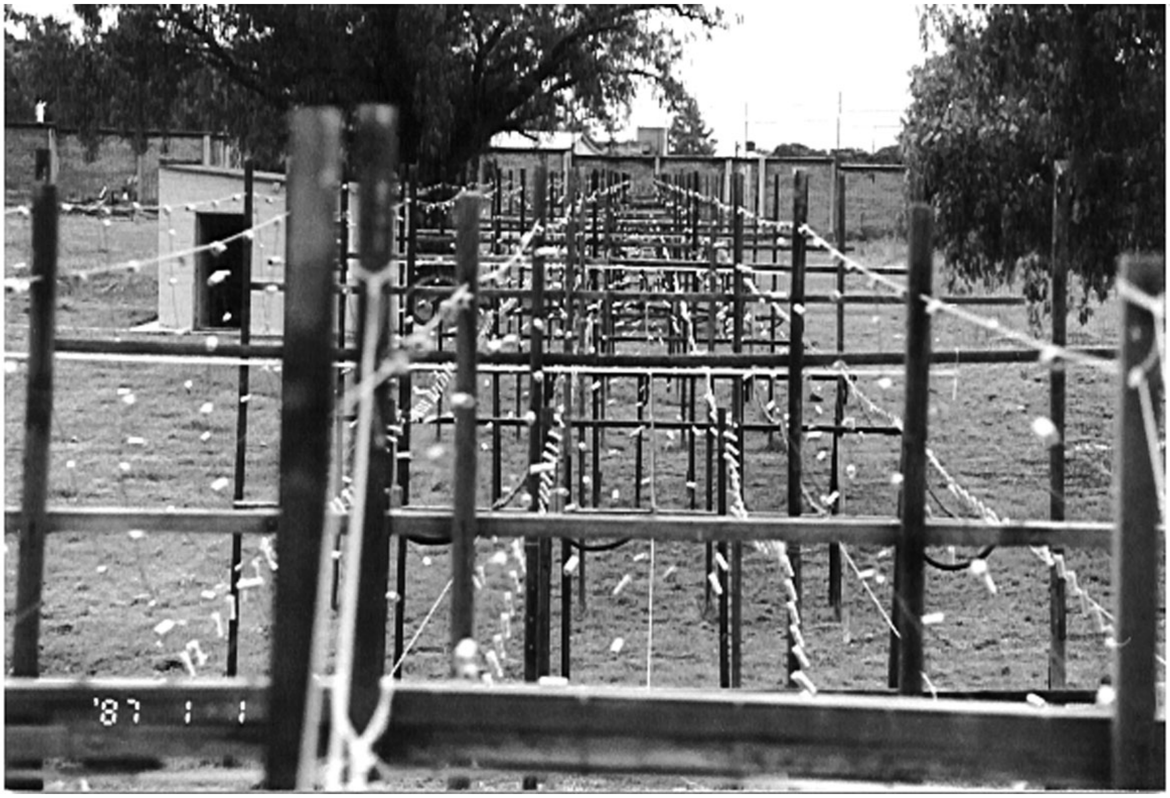

Fig. 8. Picture of the prototype array.

Fig. 9. Map of Mexico and location of the MEXART. The site in Michoacán is at 19° 48' north and 101° 41' west.

3. MEXART PHASE 2. FINAL RADIO ARRAY

The studies of electromagnetic noise in Teoloyucan and locations near Mexico City showed that the final array should be built far away from big cities and factories. Members of the project looked for possible sites in different states. They found a very good location in Coeneo, Michoacán (Figure 9), which presented the lowest level of electromagnetic noise in the band 138.9-140.4 MHz (Carrillo *et al.*, 1997). Figure 10 shows an example of the electromagnetic noise measurements at the site in Coeneo. This measurement was taken using an antenna Yagi Uda with a central frequency of 139.7 MHz, with a spectral resolution of 1 MHz and a bandwidth of 200 MHz. The peaks in the plot correspond to radio and tv stations in Michoacán. The region around the operation frequency has very low levels of electromagnetic noise. This electromagnetic noise monitoring had been performed every three months in the last two years with similar results.

The site is within a small farm community located about three and a half-hours driving from Mexico City (approximately 330 kilometers north-west), and is surrounded by low altitude mountains. There is no extreme weather and the site has good access (Figure 11). Besides, in Michoacán there is the most important group of Radio Astronomy in Mexico (IA-UNAM campus Morelia) and a university (UMSNH) and a technological school (ITM) which are collaborating in the project (González-Esparza and Carrillo, 2001).

The antenna of the final array has the same characteristics as the prototype, but covers a larger area. The full array has 64 parallel E-W rows (each row contains 4 sections of 16 elements). The antenna occupies 10 000 square meters and has 64x64=4096 elements. Table 3 summarizes the main characteristics of the final array.

Table 3

Operation Frequency	**139.65 MHz**
Elongation angle from the Sun	20 degrees
band width	1.5 MHz.
basic element	full wavelength dipole
number of elements	4096
number of E-W rows	64, each row has 64 full wavelength dipoles

The expected sensitivity of the final array is given by (Krauss, 1966):

$$^{1}/_{2}\, S\ A_e = k\, T_a,$$

where S is the flux of the source in Jy, A_e is the effective area of the antenna in m^2 ($A_e = \eta A$), k is the Boltzmann constant and T_a is the minimum detectable noise temperature of the receiver. Large dipoles array made of open wire transmission lines are generally almost 70 percent efficient, with the losses being mainly due to having an incompletely filled aperture, end effects, decorrelation of signals over long rows and mist match (Janardhan, 1991). Using a 0.7 value for the aperture efficiency (η) we obtain that the final array has an expected sensitivity of about 2.5 K/Jy.

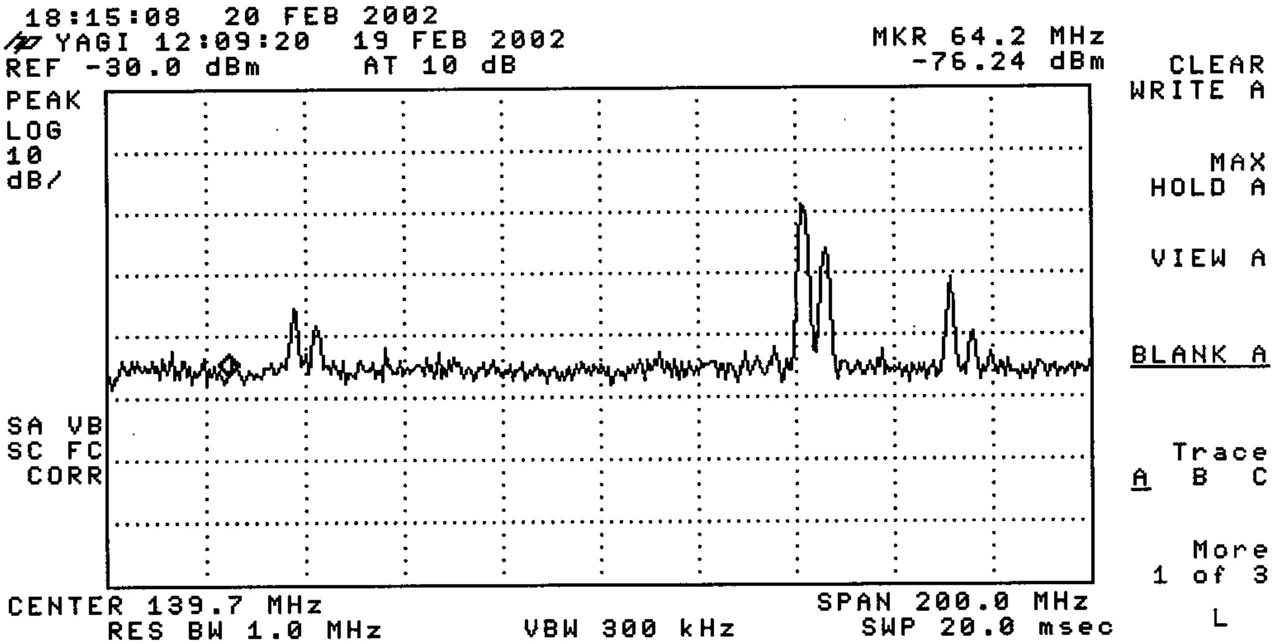

Fig. 10. Electromagnetic noise measurements in Coeneo around 139 MHZ.

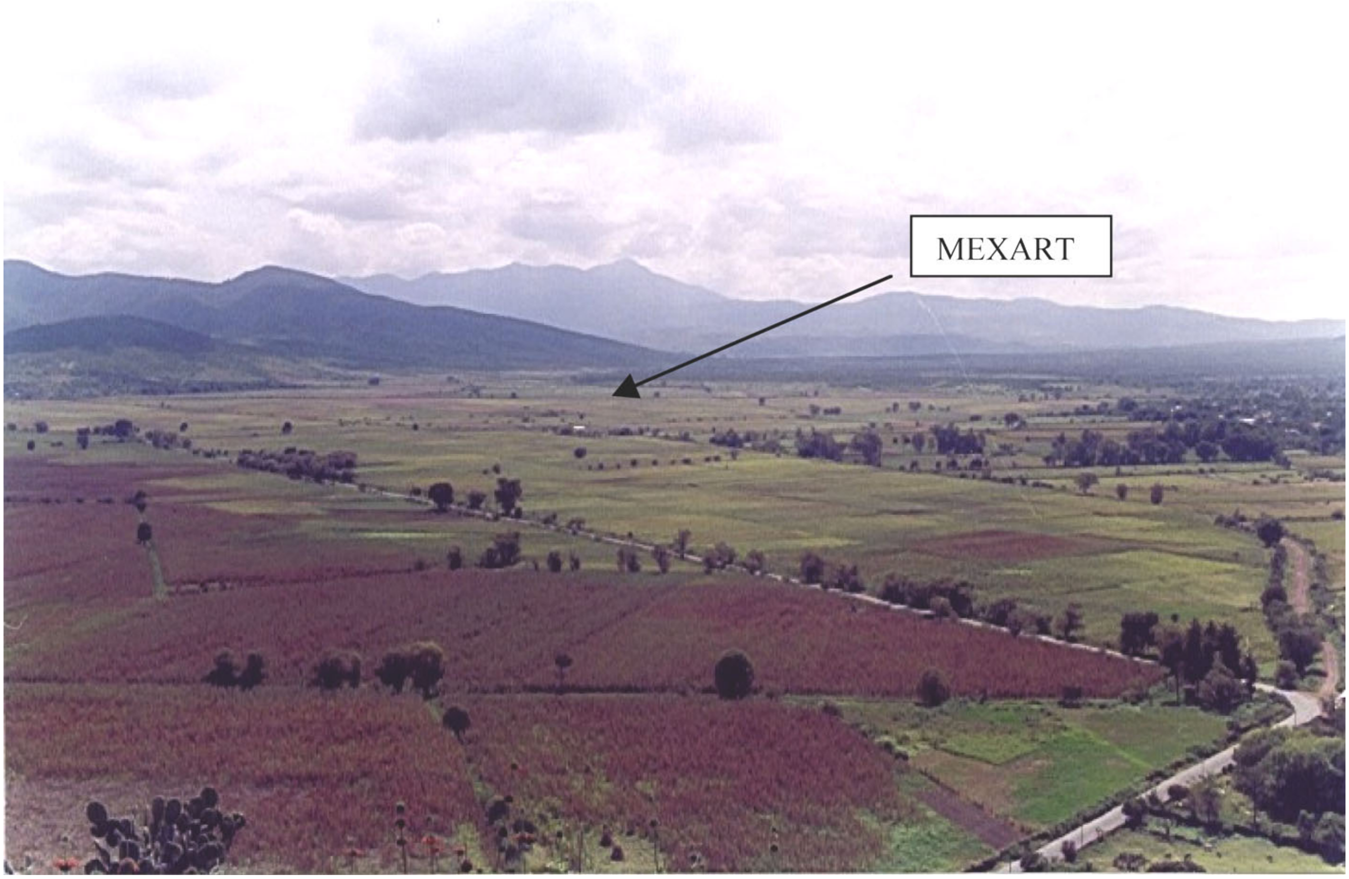

Fig. 11. Panoramic view of the site.

Fig. 12. Picture of the antenna.

General Advances

At the moment of writing half of the antenna has been completed (Figure 12). The amplifiers and combiners are of the same type as the ones used in the prototype , but we will use the BELDEN 9931 Coaxial cable. The receiver system and the Butler matrix are under revision to change the original analogical design to a state-of-the-art digital back end in collaboration with the NCRA in India.

Two engineers from the NCRA visited Mexico between May and August 2002 to review and supervise the design and construction of the array and to perform the calibration tests. The results of this work, reporting the final design of the antenna and the calibration tests, will be reported elsewhere. Based on this review of the overall design by the Indian experts it was decided that the backend of the MEXART should be a modern digital field programmable gate array (FPGA) circuitry. This FPGA circuitry and its software will be designed in the NCRA in India in collaboration with Mexican engineers and will be reported elsewhere. In the future the digital back end could have some modifications to perform other radio astronomic measurements such as pulsar observations or selected spectral line studies.

4. SUMMARY

Space weather forecasting is an important research subject at the present time. In this respect it is always desirable to have simultaneous ground and space-based observations in real time. We reported advances in the construction of the Mexican Array Radiotelescope (MEXART), which will perform IPS studies of solar wind large-scale perturbations operating at a frequency of 140 MHz. The MEXART will participate in a global network with observatories in India and Japan to provide daily *g* maps in real time. The IPS observations provide a global measurement of the size and propagation direction of large-scale perturbations in the solar wind. There is no other technique that can provide this information.

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