Acta Astronautica Vol. 21, No. 3, pp. 189–196, 1990
Printed in Great Britain.
0094-5765/90 $3.00 + 0.00

INTERPLANETARY SCINTILLATION NETWORK FOR 3-DIMENSIONAL SPACE EXPLORATION IN INDIA†

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(*Received* 17 *May* 1989)

Abstract—Recently, PRL commissioned three large radio telescopes operating at 103 MHz in order to record interplanetary scintillations (IPS) of compact radio sources from Thaltej (Ahmedabad), Rajkot and Surat, as a function of time for the study of solar wind velocity in three dimensions around the Sun between 0.3–1.0 AU. IPS are caused due to irregular scattering of radio waves from quasars by the electron density inhomogeneities in the solar wind that continually blow in three dimensions throughout the heliosphere. When one observes IPS from large number of sources each day, one can determine day-to-day changes in the average 3-dimensional structure of the solar wind velocity. The large IPS telescope at Thaltej would enable us to prepare the so called "*g*-maps" of the sky that would indicate regions of enhanced interplanetary plasma turbulence and their evolution on day-to-day basis. This paper describes the 3-station IPS telescope network in India.

1. INTRODUCTION

Interplanetary scintillation (IPS) is a radio analogy of the twinkling of visible stars. Whereas the latter is caused by the turbulence in the Earth's lower atmosphere, the former is attributed to the solar wind plasma turbulence. The phenomenon of IPS has been explained in terms or propagation of a radio wave from a compact radio source undergoing random scattering due to variations in refractive index in the turbulent solar wind plasma.

The IPS phenomenon was first discovered in the early 1960s by Cambridge (England) radio astronomers[1]. The plane wave front of radiation from a distant radio source is distorted in phase when it emerges from the phase changing screen of electron density inhomogeneities in the solar wind. Figure 1 depicts the IPS geometry. Beyond the Fresnel distance ($Z\mathrm{r} = 2\pi a^2/\lambda$) from the screen the amplitude scintillations build up and they are recorded using sensitive radio telescopes. One can calculate the scintillation index (S.I.), m, for a given source by dividing the rms fluctuations in intensity by the mean intensity of the source and is given by

$$m = \sqrt{2}\,\pi^{1/4} r \lambda \langle \Delta N^2 \rangle^{1/2} (aL)^{1/2} \qquad (1)$$

for gaussian density irregularities under weak scattering condition, where

r = classical electron radius,
λ = wavelength,
a = irregularity scale size,
L = thickness of diffraction screen, and
ΔN = electron density fluctuations.

Apart from day-to-day fluctuations in the S.I. of a given source, there occurs a systematic variation of S.I. as a function of solar elongation, ϵ, which is an angle between the directions of the sun and source as seen from the Earth. As shown in Fig. 2, the mean value of S.I. is low at large elongations and increases systematically as the elongation becomes smaller and smaller. But when a critical elongation ($\sim 30°$) is reached for $\lambda \sim 3$ m, the wavelength of observation, S.I., begins to decrease as the line of sight enters the strong scattering region, thereby causing angular broadening of the source. It may be noted that S.I. is also proportional to the wavelength of observation for gaussian irregularities. So, a compromise has to be made in selecting the wavelength of observation. Thus, if one wants to study the plasma turbulance far away from the sun then one has to select a long wavelength for IPS observation. On the other hand, if one wants to study plasma turbulence closer to the sun, then one has to choose shorter wavelengths for IPS observation. Usually for a wavelength around 3 m, useful S.I. measurements can be made over a weak scattering region from 0.3 to 1.0 AU.

It can be seen from eqn (1) that the scintillation index, m, is a measure of electron density fluctuation, ΔN and hence of the strength of the plasma turbulence in the solar wind. By measuring the scintillation index of several hundred radio sources in different directions around the sun, one can determine the distribution of strong and weak turbulent regions at different helio-latitudes, -longitudes as well as at different radial distances from the sun in a dominant scattering zone. In other words, the IPS technique

†Paper IAF-88-421 presented at the *39th Congress of the International Astronautical Federation*, Bangalore, India, 8–15 October 1988.

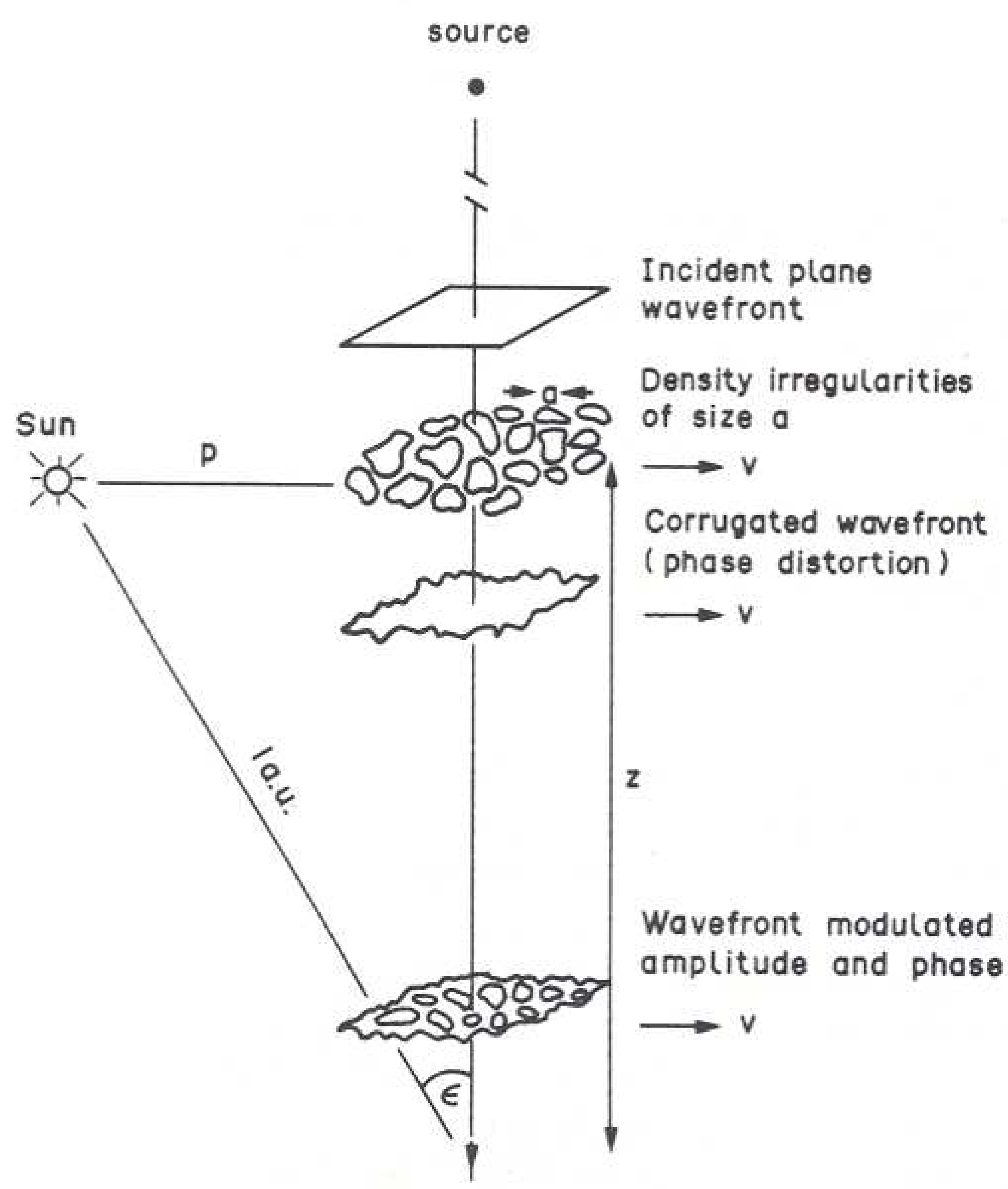

Fig. 1. IPS geometry.

permits determination of strength of plasma turbulence in three dimensions around the sun and its day-to-day changes as shown by Cambridge astronomers in Fig. 3.

2. MEASUREMENT OF SOLAR WIND VELOCITY BY IPS TECHNIQUE

In 3-site IPS observations, the telescopes are simultaneously operated with good relative time accuracy (better than few millisecond) to record scintillations at each of the 3 sites. The scintillations are then cross-correlated to determine the time delays between the three pairs of sites. Knowing the delays and separation of sites, it is possible to calculate the "pattern velocity", from which one can calculate the radial solar wind velocity at different radial distances from the sun as well as at different helio-latitudes and -longitudes. Such observations were first made by Hewish and Symonds[2].

Such 3-site IPS observations were made regularly up to the end of 1987 in U.S.A. At present Japan and India are the only countries where solar wind velocity measurements using the IPS technique are being regularly carried out[3]. IPS observations are useful in the studies of high-speed co-rotating streams which were detected at + 50° helio-latitude, interplanetary travelling disturbances and tracking of large scale turbulent regions in the interplanetary space[1,4–15].

3. SCINTILLATION MAPS OR "g-MAPS"

IPS observations from a single station with a large antenna array can be used to produce scintillation maps, or g-maps, of the interplanetary medium and can be used to track IP disturbances from about 0.3 AU to the Earth's orbit. This can be carried out by using at least 1 year's observations to determine the trend of variation in scintillation with elongation for each of the scintillation sources. The lines of sight to these sources are well distributed around the sun and, therefore, it is possible to calculate the scintillation index or scintillating flux of radio sources at different distances and direction around the sun in the main scattering zone for heliospheric work on a day-to-day basis. Comparison of the scintillation index maps were made on daily basis for the study of interplanetary plasma turbulence[16]. But systematic variation of scintillation index has been removed by Cambridge workers[12,17,18] thereby making it easy to interpret these maps. A scintillation enhancement factor g is defined as:

$$\frac{\text{Observed scintillating flux}}{\text{Mean scintillating flux}}.$$

As shown in Fig. 3 it is possible to plot the distribution of g over the sky in ecliptic coordinates with the sun at the center of the map and the Earth being at 90° circle. On such maps large regions over which g is well correlated can be clearly marked. Typically, a region of enhanced scintillation signifies an IP disturbance followed by a region of reduced scintillation. The leading edge of a transient

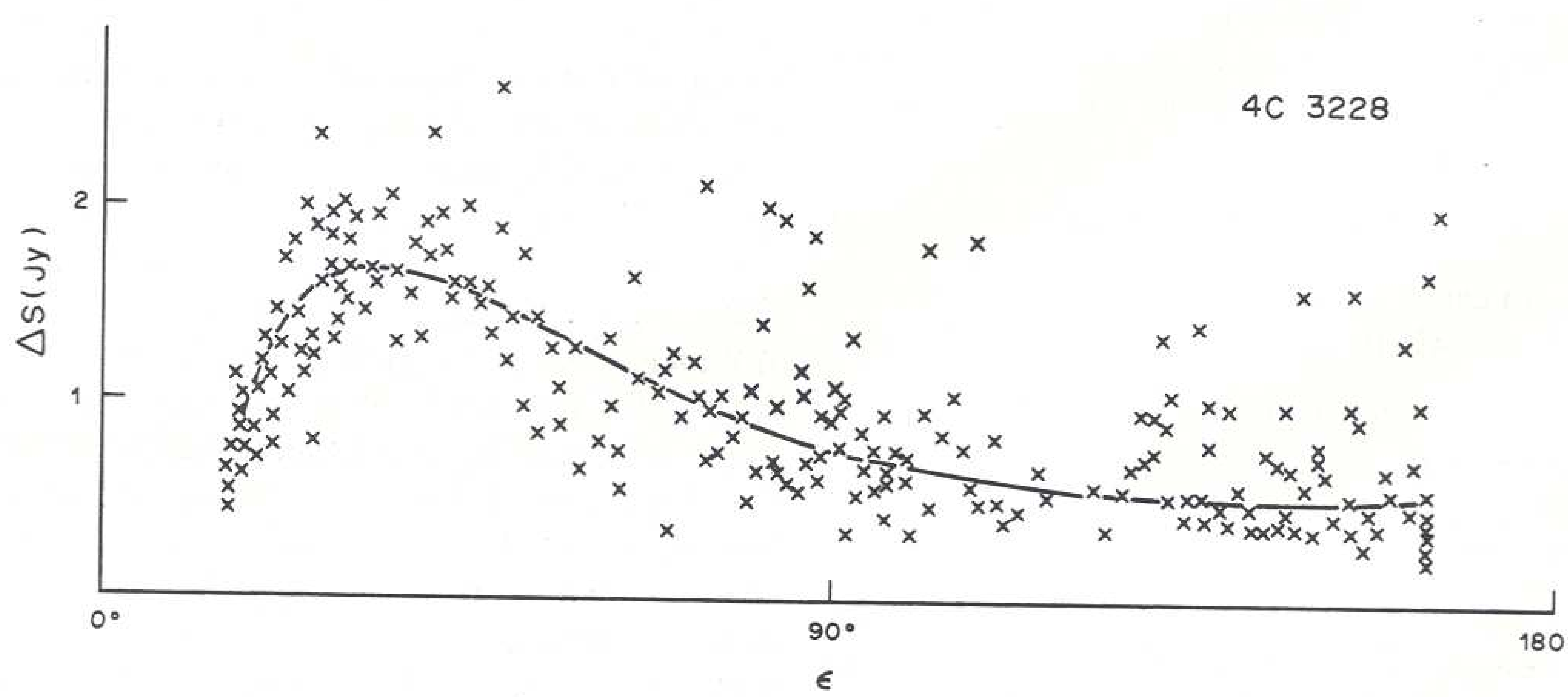

Fig. 2. Scintillation as a function of elongation.

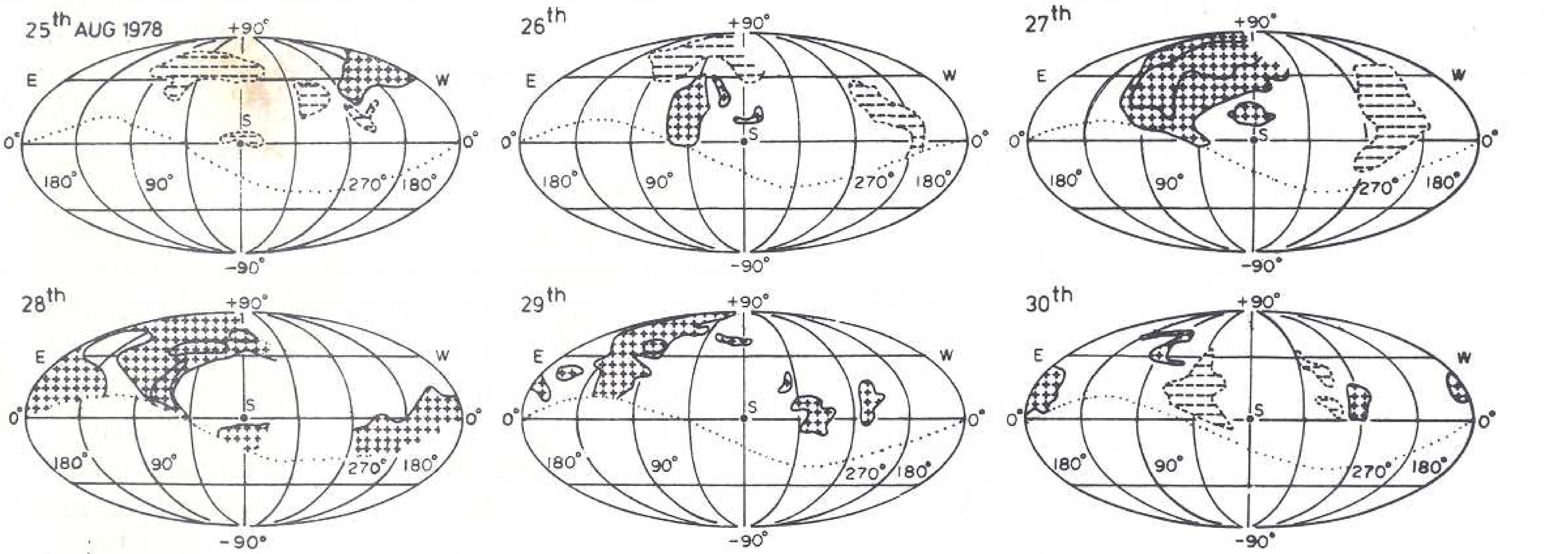

Fig. 3. Typical g-map.

disturbance is usually seen about 1 day before it reaches the Earth. Such single station IPS observations of a large number of sources have established that the arrival of IP disturbances at Earth correlates well with geomagnetic activity[8,15,17–21].

4. PROPOSED MODIFICATION OF IPS TELESCOPE AT THALTEJ FOR MAKING g-MAPS

The present collecting area of the antenna array at Thaltej is $10{,}000\ \text{m}^2$. This will not be sufficient to make g-maps with a closely knit grid of radio sources. Hence, expansion work of the antenna array from 10,000 to $20{,}000\ \text{m}^2$ has already been undertaken. This would enable us to detect about 1500 sources each day and determine the changes in their scintillating flux on a regular basis. The receiving system would consist of 32 dual- channel receivers with in-phase and out-of-phase simple radio interferometer outputs as well as 32 scintillometer outputs, which will be recorded on a PC/AT-based data acquisition system feeding the data in a Micro Vax Computer for producing g-maps.

It has been shown by Cambridge workers that

$g = (N/9)^{0.52 \pm 0.05}$ over the range $3 < N < 40\ \text{cm}^{-3}$

where N is electron density measured by a spacecraft near the Earth's orbit.

The method of g-maps and their interpretation has proved very successful in elucidating large-scale structure of transient disturbances. The capability to track IP disturbances in the range 0.3–1.0 AU should be extremely useful in the field of solar-terrestrial physics and as a technique for prediction of geomagnetic storms. Hewish *et al.*[15] suggested that the primary source of energy for large-scale interplanetary transients may be identified with the mechanisms that accelerate high speed streams (from coronal holes) and not with the impulsive release of magnetic field energy in the chromosphere (flares) and corona.

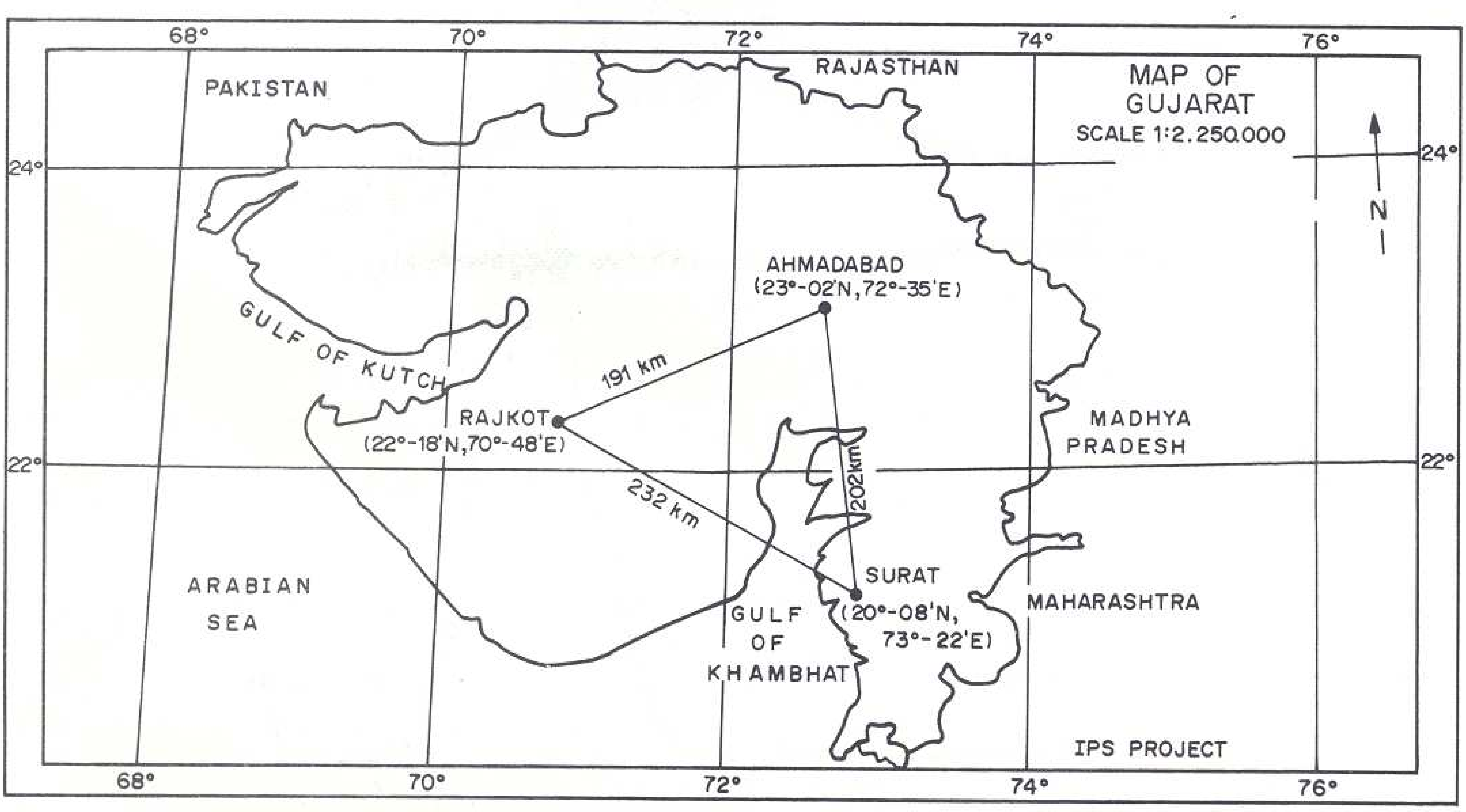

Fig. 4. Geometery of the 3-IPS stations.

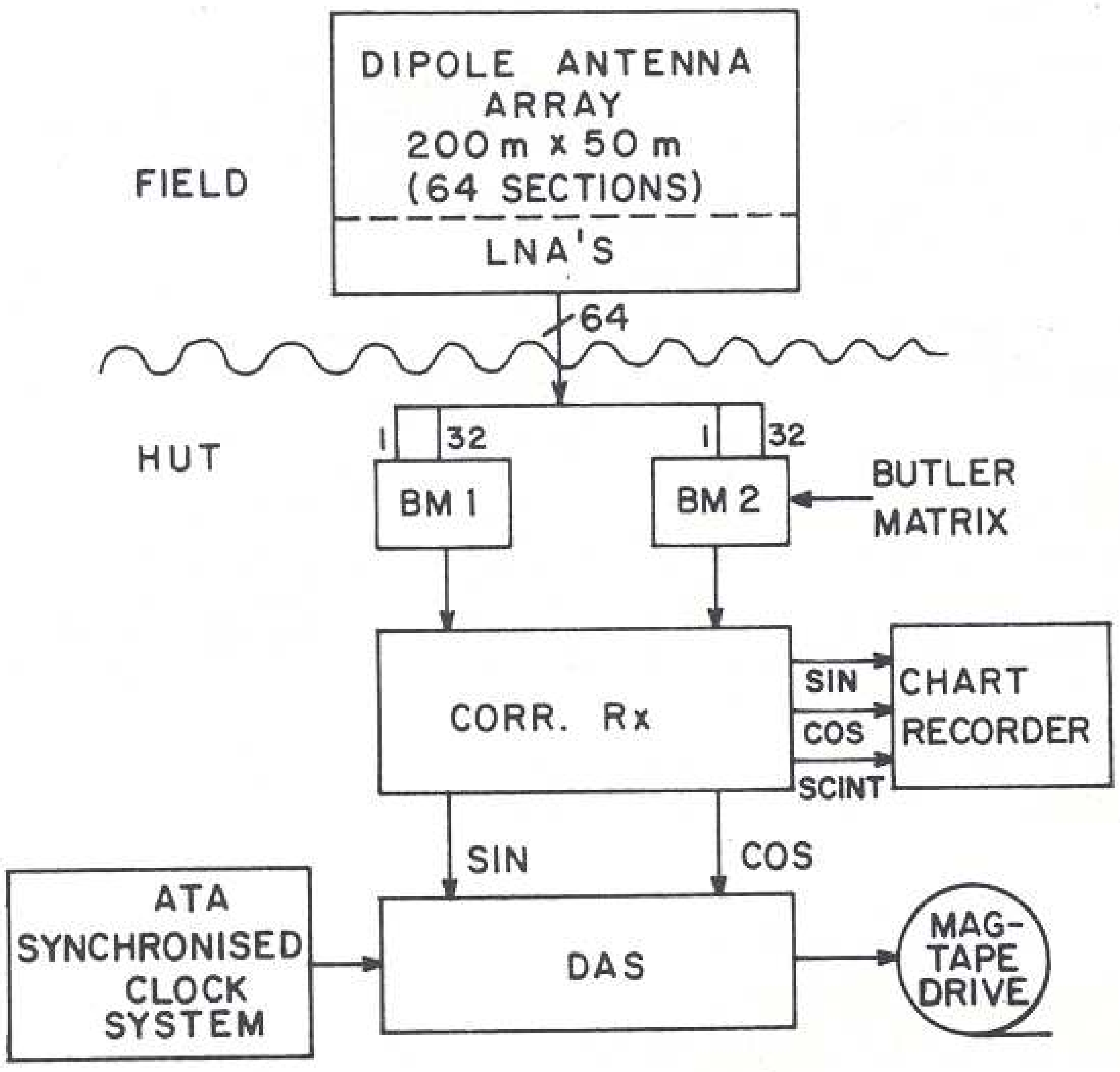

Fig. 5. General schematic: IPS set-up.

5. DESCRIPTION OF 3-SITE IPS NETWORK IN INDIA

The three IPS telescopes are located at Thaltej, Rajkot and Surat as shown in Fig. 4. At each of the 3 sites we have a dipole antenna array, low noise amplifiers, Butler matrices, correlation receiver, a data acquisition system (DAS) and a clock system. Figure 5 shows a general schematic of such a set up. Each antenna section has 16 full wave dipole antenna elements connected to a transmission line. The output of the transmission line is connected to a low noise amplifier. This is to amplify the signal so, as to compensate for the transmission loss due to cable used to carry the LNA output signals to the Butler matrix (BM) which is a beam forming network. There are two BMs each giving 32 beams. The individual beams are 2° wide in declination centered around zenith and about 3.5° in right ascension. The selected beams from BM outputs are then connected to a correlation receiver. The advantage of using the correlation receiver is that it eliminates uncorrelated noise signals. The receiver provides three outputs, viz. sin, cos and scintillometer. The three outputs are recorded on the chart recorder for monitoring as shown in Fig. 6. The sin and cos outputs are also connected to DAS for processing and recording. The total system is controlled by a clock synchronized to Indian Standard Time, transmitted by ATA New Delhi.

The existing DAS has been designed with the following specifications. The analog input range; ± 5 V, ADC of 12 bits and sampling rate of 20 Hz. The system status to be recorded includes time upto ms, source code, beam code and gain. The time keeping system should have relative accuracy of ± 5 ms. The recording medium is a digital magnetic tape.

An oven controlled crystal oscillator at a frequency of 10 MHz with stability of 5×10^{-10} is used as a basic oscillator for the clock. The signal, after amplification and processing, is used to generate various timing pulses required for the clock. We use ATA time signals to synchronize the clocks at the 3 stations, to have relative time accuracy (within a few ms). ATA time signals are transmitted at a frequency of 5, 10, and 15 MHz. A very simple method, for

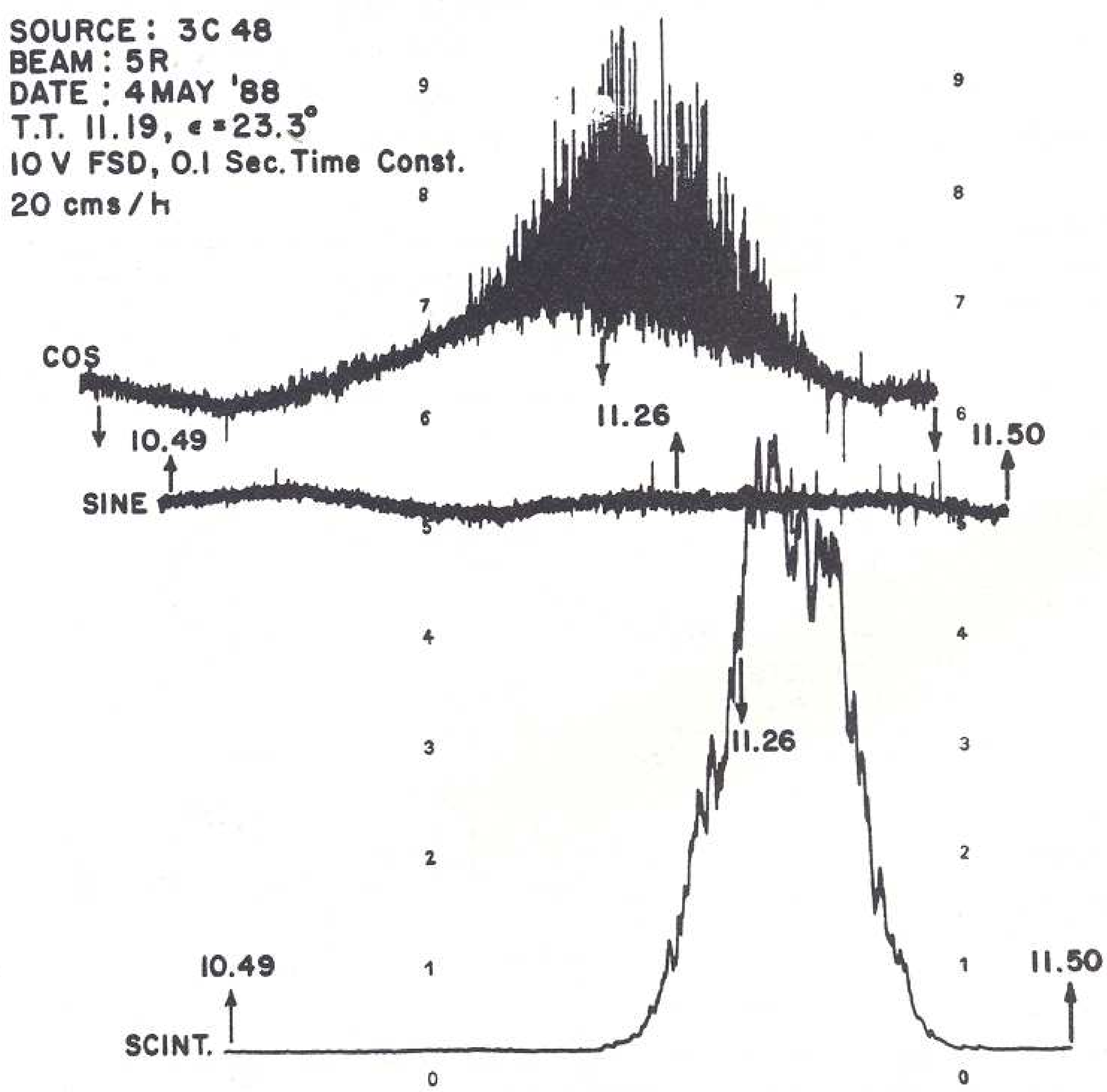

Fig. 6. Sample IPS recordings.

Table 1. List of the strongly scintillating sources observed by Thaltej IPS telescope

Source	Code	Beam	Declination (deg.)	Flux (Jy)
3C2	01	12L	+1	28
48	12	5B	+33	61
67	19	2R	+28	22
74	1D	33L	+19	23
119	2C	9C	+41	21
123	2E	3R	+29	289
125	30	8R	+39	25
144	37	1L	+22	1623
147	38	13R	+50	52
161	3E	14L	−06	76
186	46	7R	+37	29
196	4B	12R	+48	115
237	64	8L	+08	36
254	6C	9R	+41	48
263.1	6F	1L	+22	29
265	71	4R	+31	32
267	73	5L	+12	25
270.1	77	6R	+34	27
273	79	11L	+2	142
274	7A	6L	+12	1552
286	82	4R	+31	29
298	8C	9L	+07	81
318	96	2L	+20	21
324	99	2L	+21	23
368	AC	7L	+11	32
380	AE	12R	+48	112
409	B1	1R/1L	+23	144
454	CO	3L	+18	20
459	C4	10L	+04	44

synchronization, using a dual beam oscilloscope, with external trigger facility, along with a Racal communication receiver is used.

The data acquisition system(DAS) is divided into the following sub-systems:

(a) hex encoder,
(b) source library,
(c) A/D converter,
(d) multiplex controller,
(e) data multiplexer and
(f) PERTEC controller/interface.

In order to have high reliability of the system and to reduce the number of interconnections of these sub-systems, a mother board concept of interconnection is adopted[22]. This has been running at each of the 3 stations for last couple of years. A list of strongly scintillating sources observed is shown in Table 1 and a few sample results of solar wind measurements are shown in Table 2.

In order to have greater operational flexibility and ease of operation a PC/XT-based DAS has been designed. The system is designed on the same concept as that of the earlier DAS, the difference being that the control circuits are now replaced by a Z-80 microprocessor and the magnetic tape transport is eliminated. It has a Z-80 microprocessor board with 16K RAM and 12K PROM as shown in Fig. 7. The DAS card has S&H, ADC, and other circuits. The PC/XT having 8088 cpu, 640K RAM, 10 MB hard disk, floppy disk, key board and a monitor. The Z-80 and PC/XT are connected by RS-232 serial interface. The IST clock (with no change) is connected to Z-80 cpu board, which in turn synchronizes the internal clock of Z-80.

The system is MENU DRIVEN as shown in Fig. 8. The first operation after putting on the system is to synchronize the time and the START does exactly that. It takes 1 min and 50 kHz pulses from the clock and synchronizes its own clock. By selecting TERMINAL from the menu the system is used to debug the Z-80 microprocessor software. For observation there are two modes: the first is OBS. Schedule, by which the day's observations are made one after another, and the other mode is SOURCE by which a single selected source is observed. The SAVE stores the observed data on the hard disk, while the LOAD reads the selected hard disk file to RAM which then could be displayed on the monitor using DISPLAY. The CLOCK menu if selected will

Table 2. 3-Station IPS solar wind velocities (Specimen values)

Source	Date	Velocity (km/s)	Elongation (deg.)	Error %
3C48	11.3.87	$V_{pk} = 472.362 \pm 10.683$ $V_{md} = 486.842 \pm 21.905$	49.12	2.26 4.50
3C48	16.4.87	$V_{pk} = 371.49 \pm 24.314$ $V_{md} = 378.479 \pm 26.711$	23.39	6.5 7
3C48	21.4.87	$V_{pk} = 518.906 \pm 24$ $V_{md} = 523.532 \pm 1.916$	21.88	4.62 0.364
3C48	1.5.87	$V_{pk} = 447.357 \pm 113.753$ $V_{md} = 441.555 \pm 100.498$	21.88	25.42 22.76
3C48	15.5.87	$V_{pk} = 428.624 \pm 78.831$ $V_{md} = 421.180 \pm 74.994$	27.92	18.39 17.80
3C48	17.5.87	$V_{pk} = 483.900 \pm 93.332$ $V_{md} = 470.982 \pm 86.704$	29.19	19.28 18.41
3C48	19.5.87	$V_{pk} = 561.301 \pm 153.542$ $V_{md} = 504.253 \pm 147.455$	30.48	27.35 29.24
3C48	26.5.87	$V_{pk} = 434.253 \pm 96.825$ $V_{md} = 402.660 \pm 93.576$	35.46	22.29 23.23
3C48	29.5.87	$V_{pk} = 308.911 \pm 90.374$ $V_{md} = 281.708 \pm 75.561$	37.74	29.25 26.82
3C48	30.5.87	$V_{pk} = 274.872 \pm 70.547$ $V_{md} = 252.577 \pm 72.136$	38.51	25.66 28.56

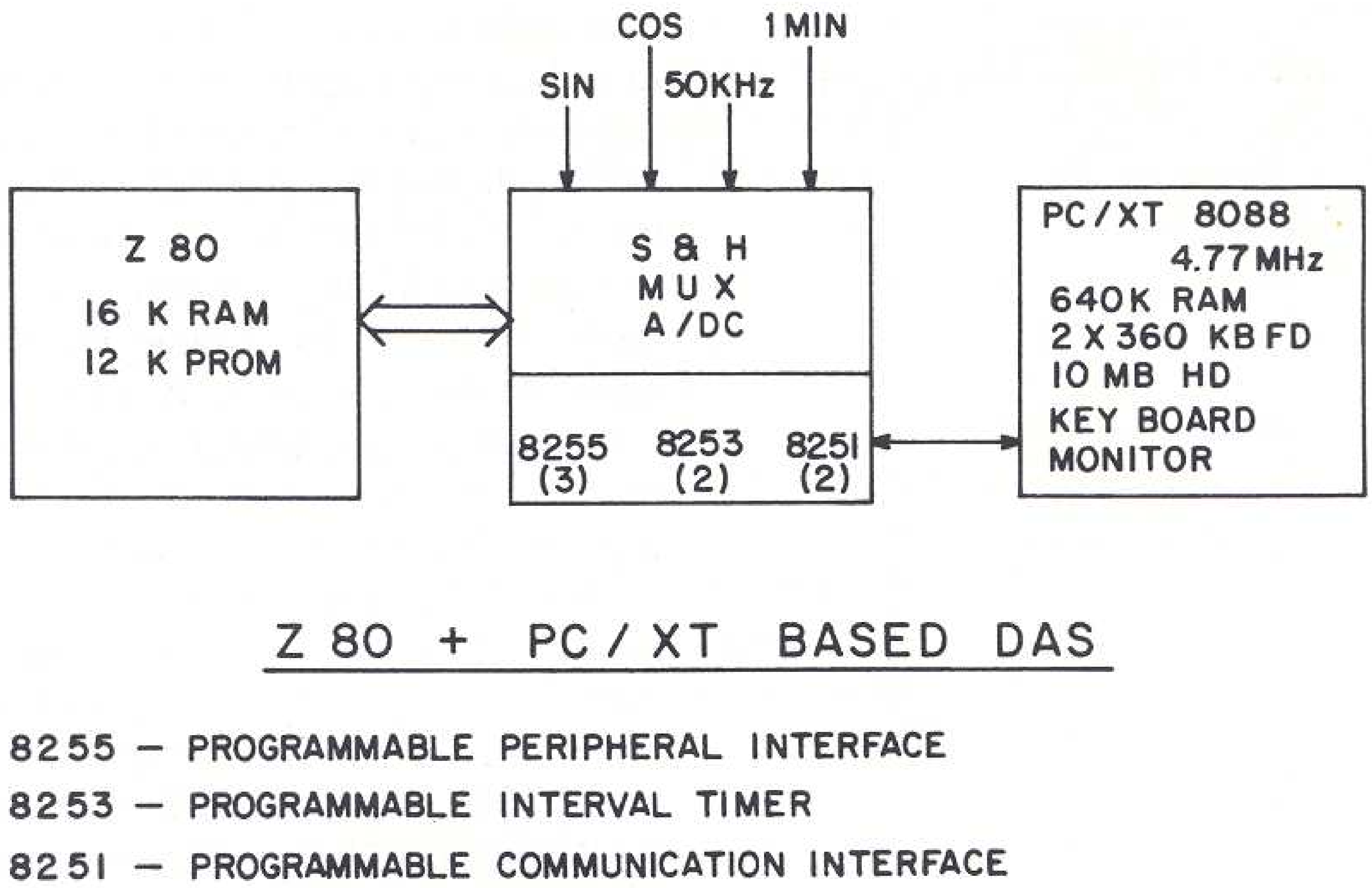

Fig. 7. Z-80 + PC/XT-based DAS.

display the time after synchronization. EXIT is used to shut the IPS observation programme. The computer can then be used for other experiments such as near real-time data transmission.

A prototype Z-80 PC/XT-based DAS as described above has been developed with all the required hardware and software. It has undergone field tests satisfactorily at Thaltej. Three identical DAS have been developed for installation at the three IPS field stations.

It is planned to provide near real time data communication system (DCS) and to transmit data from the two remote stations to Thaltej at the end of each day. As shown in Fig. 9, the dedicated telephone lines from Rajkot and Surat are connected to a data modem at Thaltej. The two data modems then can be connected to two PC/XTs using serial port COM1. The DCS will be established serially and the data would be received simultaneously from the two remote stations. The two PC/XTs work in parallel. One of the PC/XTs is dedicated to receive data from Rajkot and the other from Surat. This improves the reliability and makes all 3 station data available for processing simultaneously.

MENU

1. Start:	Sync. time
2. Terminal:	Debugging Z80
3. Observation schedule:	Source data + obs.
4. Save:	Save to disk from RAM
5. Load:	Load from Disk to RAM
6. Source:	Obs. single source
7. Clock:	Synchronization and display time
8. Display:	*X–Y* plot
9. Exit:	Quit

Fig. 8. Z80 + PC/XT-based DAS menu.

The overall system at the Thaltej field station for communication and data processing is shown in Fig. 10. A Micro Vax II computer system is the heart of the total system; consisting of 9 MB memory, floating point processing, 3 × 71 MB hard disk drive, terminals a tape drive and a printer/plotter. The 3 PC/XTs (two receiving PC/XT and Thaltej DAS PC/XT) are connected to Micro Vax on asynchronous communication port. It is also connected to PRL DEC-10 system using synchronous modem at 2400/4800 baud rate.

The observations would be made during the day at all the 3 field stations. The data from the remote IPS stations would be transmitted during the night when the telephone traffic is expected to be low to have low level of noise and interference. The Thaltej data and that received from the remote stations would then be edited using a software (e.g. EDIT), to eliminate interference, man-made noise and spikes. This editing would be done by respective PC/XTs. In the morning when the Micro Vax is switched on, this edited data would then be fed to it for processing to calculate the solar wind velocities. We have planned to have a colour plotter and a graphics terminal to this Micro Vax.

6. RELEVANCE OF THE IPS PROGRAM TO THE SATELLITE MISSION "ULYSSES" AND THE INTERNATIONAL HELIOSPHERIC STUDY (IHS)

According to the report to COSPAR (July 1988) by the chairman of IHS, "The scientific topics to be addressed by the IHS are the three-dimensional structure of the solar wind and the interplanetary magnetic field carried by it and their relation to features in the

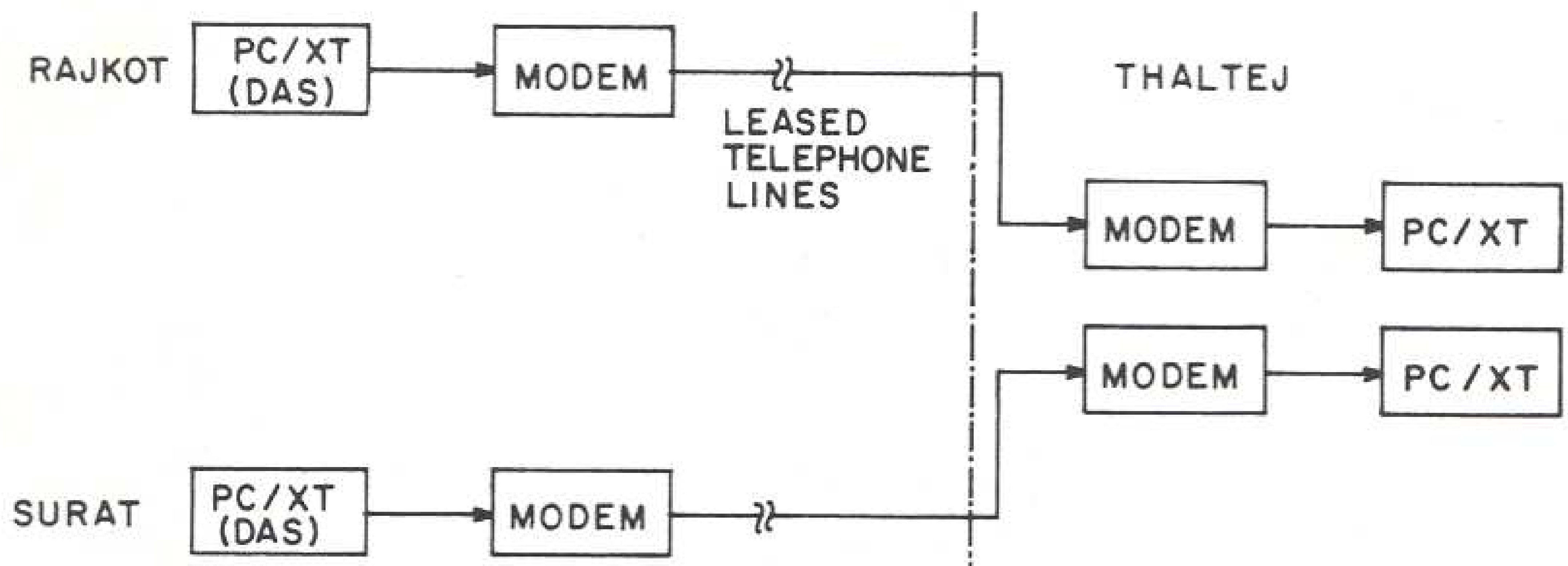

Fig. 9. Near realtime data transmission.

solar corona etc.". The IHS was first approved by COSPAR Council in 1982. "At that time it was expected that study would center on the Ulysses spacecraft. Unfortunately the start of the mission has been delayed till October 1990".

"Ulysses" is an International Solar Polar Mission (ISPM) to be carried out jointly by the European Space Agency (ESA) and NASA. The primary objective of the Ulysses mission is to investigate, for the first time, the properties of the solar wind, the structure of sun/wind interface, the heliospheric magnetic field etc. The heliosphere is a vast region of space in which radial outflow of solar wind dominates. It is an extended plasmasphere of the sun. It is expected that the physical properties of the heliosphere to be drastically different as one moves away from the ecliptic plane to the higher heliolatitudes. So far, the knowledge regarding the physical processes occurring in the heliosphere has been gained from observations made in the narrow belt of helioatitudes ($+7.25^\circ$ to -7.25°) accessible to the spacecraft in the ecliptic. The Ulysses spacecraft will be placed in a high-inclination, heliocentric orbit by means of a Jupiter gravity-assist maneuver, as shown in Fig. 11. The spacecraft will be launched in October 1990. It will reach Jupiter's orbit in February 1992 and pass over the southern solar pole at a distance of 2.3 AU above the ecliptic some 3.5 years (May–September 1994) after launch. The second pole-to-pole segment of the trajectory is traversed relatively quickly, and the second (northern) polar passage occurs approx. 12 months after the first. In total, the spacecraft will spend more than 200 days at heliographic latitudes in excess of 70°.

The relevance of IPS program to Ulysses and IHS arises from the fact that as of today, IPS is the only available technique to obtain 3-dimensional structure of solar wind velocity and plasma density irregularities over a range of distances from 0.3 to 1.0 AU from the sun. These IPS measurements will serve as baseline measurements which can later be compared with *in situ* particle and field measurements made with Ulysses. In addition, the "*g*-maps" and "Velocity maps" of interplanetary medium using IPS scintillation index and velocity measurements can be used to study travelling interplanetary disturbances such as corotating high speed particle streams coming from coronal holes, interplanetary shock waves from coronal holes and/or solar flares which on arrival at the Earth's orbit may cause geomagnetic storms and aurorae. It has been established by Cambridge radio astronomers that using "*g*-maps" (prepared using high sensitivity IPS observations of large number of scintillating sources) it is possible to predict the onset of geomagnetic storms with longer lead times.

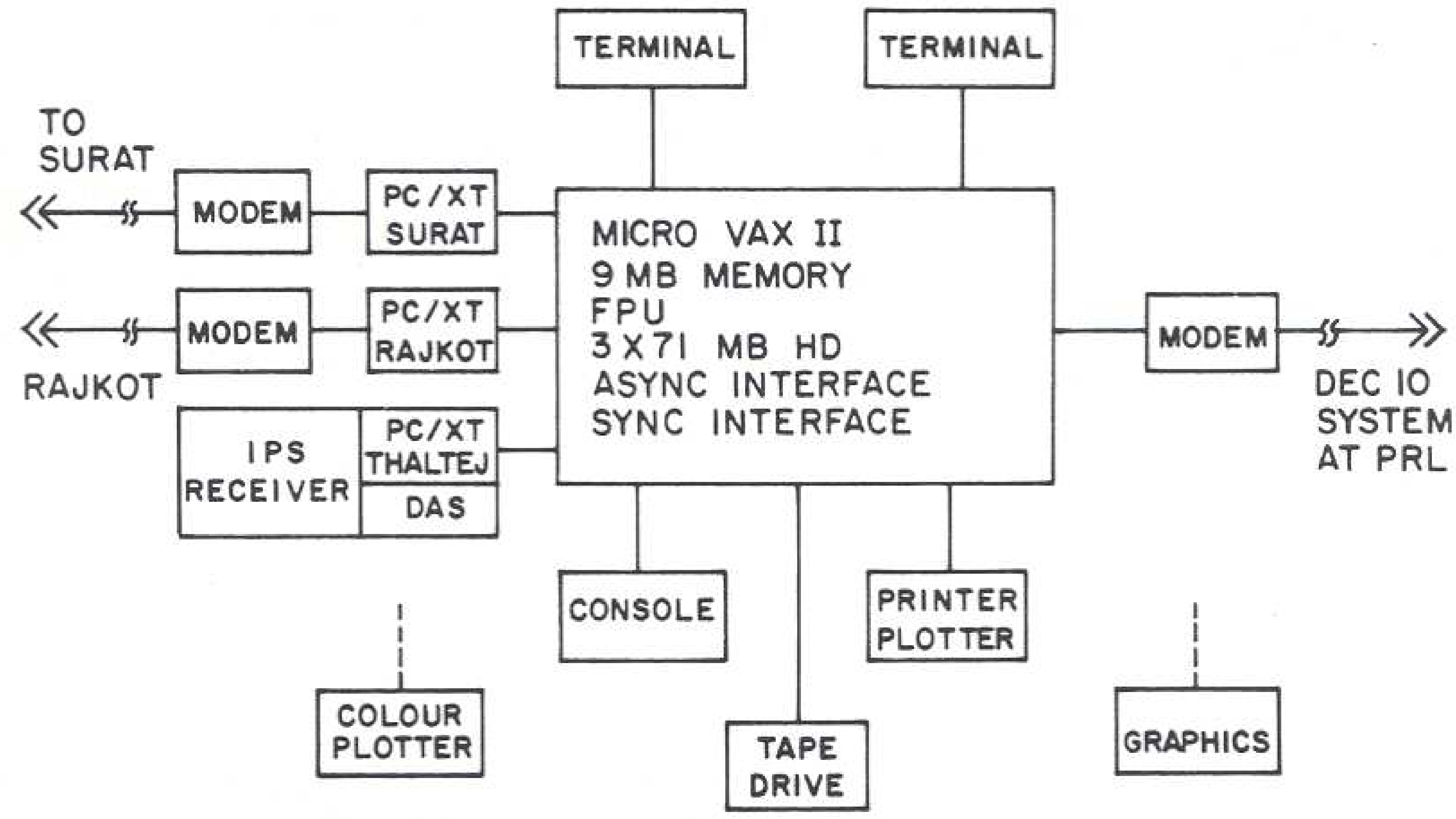

Fig. 10. Overall system.

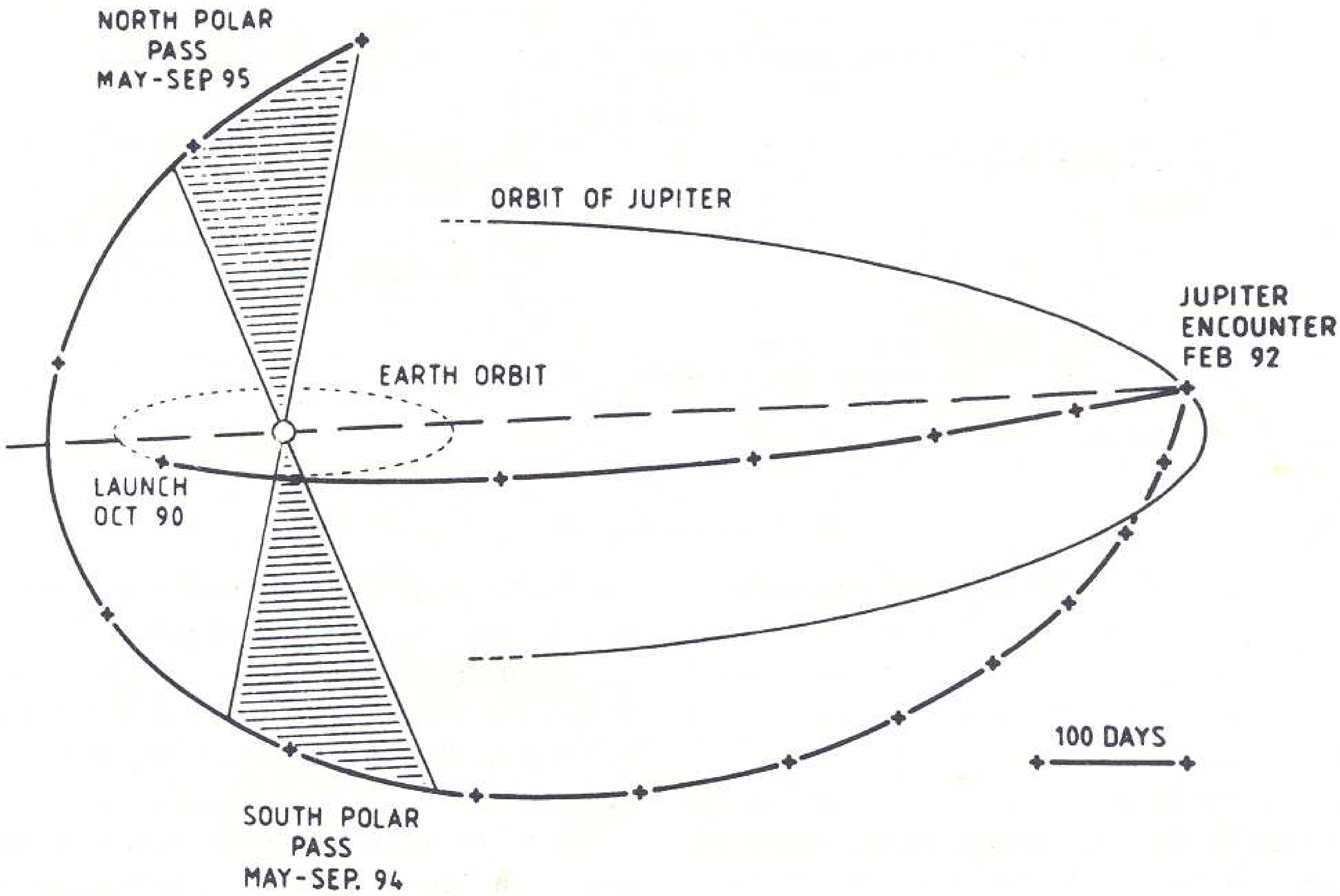

Fig. 11. Typical Ulysses trajectory viewed from 15° above the elliptic plane. Crosses are shown at 100-day intervals.

Acknowledgements—The authors thank Professor R. K. Varma, Director, and Professor S. P. Pandya for their enthusiastic support of IPS programme at the Physical Research Laboratory. Cooperation of South Gujarat and Saurashtra Universities by providing sites for radio telescopes on their campuses is gratefully acknowledged. Financial support came form the Departments of Space and Science and Technology in establishing a 3-site IPS Network in India. The expansion of the IPS facility for near real time solar wind velocity and "*g*-maps" is being carried out with a generous grant NA 87 AA-D-ER046 under the programme of Indo–U.S. Cooperation in Science and Technology.

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