SATELLITE OBSERVATIONS OF SOLAR RADIO BURSTS

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ABSTRACT

Space observations of solar radio bursts have provided the following information :

- From a single spacecraft :

Measurements within the burst source or close to it : fundamental and harmonic type III radio emission, the corresponding plasma waves and spectra of the exciting electrons.

- From a spacecraft and the earth or from two spacecrafts :

A better evaluation of the influence of the ionosphere on some ground-based observations.

Measurements of the beaming of the emission which yield constraints on the radiation mechanism and/or the role of coronal propagation in determining the source size and directivity (type I and III's).

Measurements of the differential time delay which yield for type III :

At short (m- and dam-) wavelengths, some evidence of group delays,

At long (hm- and km-) wavelengths one coordinate of the source.

Complete (3-dimensional) localization of the source at long wavelengths and therefore maps of the heliosphere magnetic field and electron density as well as the source size and, in the future, its polarization.

The results of these observations and their interpretation are reviewed and discussed.

In the past ten years or so,many observations of solar radio bursts have been obtained from spacecraft; they became more and more sophisticated with the progress of space technology, especially better control of electromagnetic interference from the vehicles themselves and better use of the directivity of short dipoles (Lecacheux, 1978).

The motivations for observing from far out in space are many :

- to escape the ionospheric or magnetospheric cut-off,although

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the ionosphere may be used in some instances to the scientist advantage. It is also of interest, for low frequency work, to reach rather large distances from the noisy terrestrial environment. Very low frequencies can be reached, down to 20 kHz or so, the limit being set by the local plasma frequency of the solar wind.

- to study type III sources in-situ at hm- and km-wavelengths.
- to detect and measure any beaming of the radio emission by simultaneous observations of the same events from widely different directions. This has now been done over a large range of wavelengths including some which are commonly observable from earth.
- to localize burst sources at low frequencies using several spacecrafts; this can be done by direction-finding techniques and by time delay measurements.

OBSERVATIONS FROM A SINGLE SPACECRAFT.

Identification of the type III radiation mode.

It is of course very important to know if the observed type III radiation is emitted at the plasma frequency or its first harmonic ; the radiation mechanism is not the same and people using type III sources as tracers of the local electron density want to know what they are measuring. Unfortunately, the situation is not yet completely clear or, maybe, there is no typical situation.

Haddock and Alvarez (1973) studied 32 type III events observed onboard OGO-5. They accepted the plasma hypothesis and assumed that the bursts were emitted at the different altitudes by constant velocity electrons travelling along Archimedes spirals in the ecliptic ; they neglected refraction and scattering of the em radiation. From these hypothesis they computed the arrival time of a burst at the spacecraft for their observing frequencies assuming radiation in the fundamental and harmonic mode. They fitted the data to this model (Fig.1). Their conclusion is that, below about 1MHz, the harmonic predominates. From these data and ground-based observations, Alvarez and Haddock (1973) derived an empirical expression of the frequency drift rate vs frequency valid from 75 kHz to 550 MHz (it is a power law to a high accuracy) and an electron density distribution which fits nicely the densities in coronal streamers and at the earth orbit.

More recently Kellogg (1979) used another technique with data from HELIOS-2. He plotted as a function of frequency the onset time of 3 type III's up to the point where the correlated plasma oscillations to be discussed later were observed ; on Fig.2, the rectangular box contains the plasma oscillations events. Kellogg's analysis shows convincingly that for days 326-1977 and 98-1978 radiation was in the fundamental mode ; on day 341-1977 it shifted from the harmonic to the fundamental as time went i.e. as frequency decreased. This conclusion is opposite to that of Alvarez and Haddock. Unfortunately only 3 events including plasma oscillations could be observed by Kellog.

Thus it appears that in most cases the first harmonic is observed

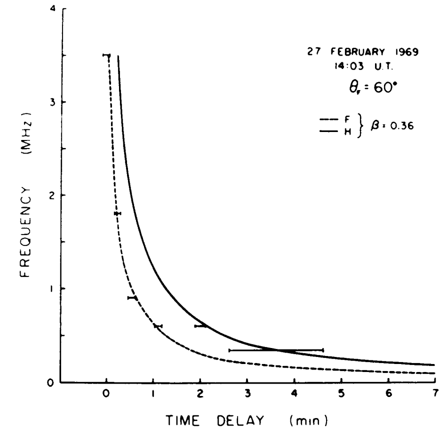

Figure 1 : Computed and measured time delay versus frequency (After Haddock and Alvarez, 1973)

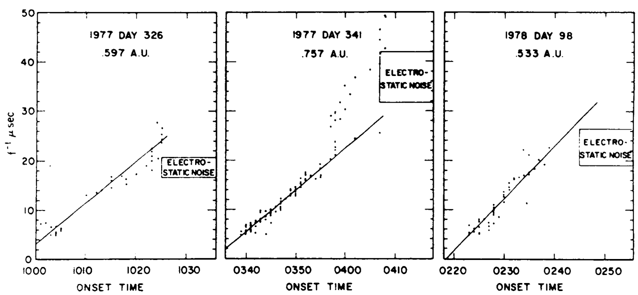

Figure 2 : Onset time of 3 type III bursts versus the inverse of the observing frequency (after Kellogg, 1979).

at the lower frequencies but that,in some instances,the fundamental can be recorded as well. The identification of the mode of radiation of type III bursts in interplanetary space is not a settled question; but we may hope that many more observations will be available in the next few years for instance from ISEE-3,HELIOS-2 and VOYAGER-1 and -2. There are reasons to believe that the fundamental radiation should be seldom observed at low frequencies: it should be very directional in the absence of scattering ; but since electron density inhomogeneities are present, they should act as very effective scatterers for radiation near the plasma frequency ; and this effect is all the more important that the gradient of the scattering power is smaller as it is probably the case when the electron density becomes smaller or the distance to the sun larger. The final, observed intensity of the fundamental also depends upon the distance of the source to the observer so that a good knowledge of the geometry is required which can only be obtained by triangulation from several satellites. On the other hand, there are theoretical reasons (Smith and Davis, 1975) for expecting that the generation should change to predominantly fundamental emission at large distances from the sun.

Polarization of type III fundamentals.

As far as we know the radiometers on VOYAGER-1 and -2 did not measure any polarization of solar radio bursts. Hanacz, Schreiber and Aksenov (1979) report observations of type III and III-b polarization between 2.3 and 4.9 MHz on-board INTERCOSMOS 500-COPERNICUS, a joint Polish -Soviet project. These authors used the cut-off of the ordinary and extraordinary modes by the ionosphere to deduce the circular polarization ratio of the incoming radiation. Three bursts have been analyzed (Fig.3)

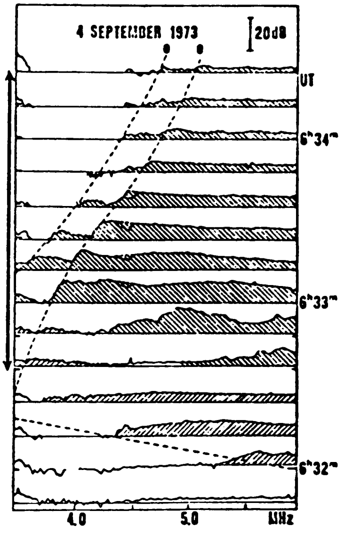

Figure 3 : Ionospheric cut-off on successive frequency scans of a type III. Left dotted line : ordinary mode cut-off, right one extraordinary cut-off. The cut-off frequency variation is due to the variation of the satellite altitude ; its orbit is 202-1551 km. (After Hanacz, Schreiber and Aksenov, 1979).

For only one of them, the orientation of the antenna with respect to the local magnetic field was known. For the others, only upper and lower limits of the polarization ratio could be obtained. Anyhow it appears that between 2 and 5 MHz, the polarization of type III, III-b and spike bursts is just about the same as in the decameter wavelength range. Polarization ratios of 50 - 100% are measured. Highly polarized spikes are probably fundamental emission. A lower limit of about .001 G is deduced for coronal magnetic field near the sources at an altitude of about 8 solar radii.

Type III bursts and the associated electrons and plasma waves.

One of the great successes of space radioastronomy in recent years has been the observation in-situ of the plasma waves which produce, via scattering, the type III radio emission.Earth orbiting satellites observe many emissions of plasma waves which are not always connected to type III bursts. And it was first concluded that no plasma waves associated with type III's were detected from IMP-6 and IMP-8 at levels high enough to account for the radio radiation (Gurnett and Franck,1975). But plasma waves electric field measurements on board HELIOS-1 and -2, closer to the sun, provided clear evidence of high level bursty plasma wave emissions associated with type III's (Gurnett and Anderson, 1976, see Fig.4).

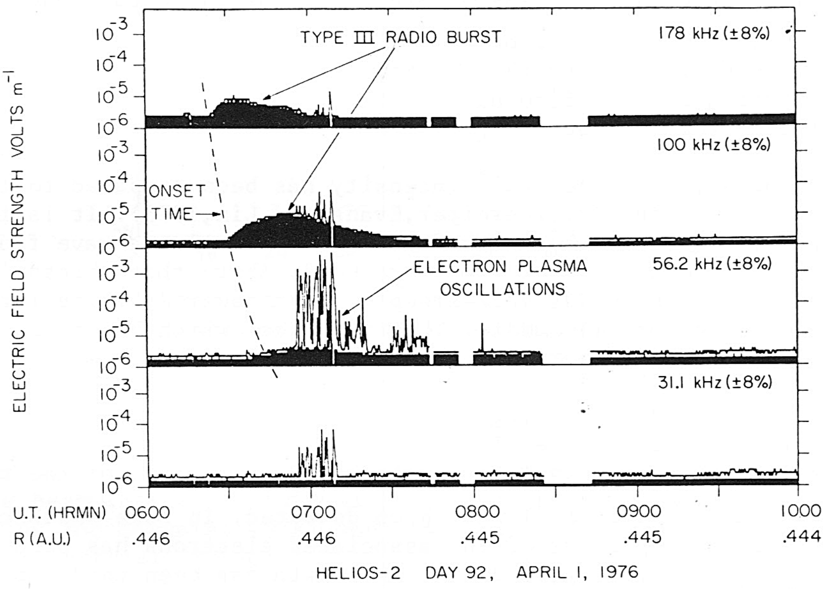

Figure 4 : Example of the intense electron plasma waves detected by HELIOS in association with a type III radio burst. The electron plasma frequency determined by the solar-wind plasma experiment on HELIOS is 54 kHZ which is very close to the observed frequency of the electron plasma oscillations. (After Gurnett and Anderson, 1976).

These observations directly confirm the prediction of Ginzburg and Zeleznyakov (1958) although the detailed theory of type III fundamental and harmonic emission is still not fully developed.

The type III plasma waves do not propagate so that the spacecraft must be inside the source to detect them ; this is rarely the case since plasma waves are detected for only a few percent of the recorded type III radio bursts; so that it appears that the plasma wave source is small in extent (or multiple) while the radio source is often very large (see for example Baumback,Kurth and Grunett,1976;Kellogg,1976;Fitzenreiter et al.1977). How small is the plasma wave source is an interesting question ; the full bandwidth of the plasma wave emission recorded by Kellogg (1979) is about 20% which can be fairly well explained by the known fluctuations of the electron density in the solar wind which are swept past the spacecraft over the duration of the event.

In many instances it is difficult from simultaneous observations of type III plasma and radio waves to identify the mode of radiation, fundamental or harmonic ; one of the reasons is that various bursty plasma waves emissions are quite commonly observed beyond .5 AU from the sun. It is therefore not surprising that there is no general agreement yet about the mode identification.

The association of plasma waves with type III bursts is striking when observations are made closer to the sun than about .5 AU (Gurnett et al. 1978) because the plasma wave amplitude is much higher there than at the earth orbit (variation as $R^{-3.5}$).This is mostly due to the electron beam dynamics and to the radiation mechanism itself : a complete interpretation of this finding will require a very thorough understanding of the overall type III phenomenon.

The variation of the radio intensity has been compared to that of the plasma wave flux (Fitzenreiter,Evans and Lin,1976). It is found that the radio intensity is a linear function of the plasma wave flux as long as the latter remains below some threshold. Above that threshold, the radio intensity increases more steeply, as a power 2.5. The threshold is not the same for all bursts. This is a fact which has to be accounted for by any type III theory.

Let us conclude that single spacecraft observations have demonstrated convincingly that type III radio emission is due to electron plasma oscillations triggered by fast electrons. Plasma waves of the required amplitude (about 10 mV m^{-1}) have been detected. In some instances, the evolution of the spectrum of the associated electrons has been followed (Lin, Evans and Fainberg,1973) and this data has been used (Harvey,1976) and will be used by theoreticians to refine their model of the beam plasma interaction and of the beam stabilization mechanism ; these mechanisms are also studied by artificial injection of electrons in the ionosphere.

Type II bursts have been first reported in 1973 (Malitson,Fainberg and Stone,1973) but no more observations obtained in space are available yet. We have to wait for the data from VOYAGER and ISEE-3 to be analyzed. Many type II's have been recorded on these spacecrafts.

OBSERVATIONS WITH TWO LINES OF SIGHT - TYPE I BURSTS.

Simultaneous observations of type I (and type III) bursts have been obtained at 169 MHz from the Soviet probe MARS-3 in a cooperative program between France and the USSR. The interpretation of these measurements has been severely hampered by the destruction, at the beginning of the mission, of the Nançay Mark 1 radioheliograph ; only one-dimensional positions and sizes were available for some of the bursts.

On Fig.5 is a summary of all type I observations available; percentage of recognizable corresponding events versus angle between the lines of sight. Although this kind of data is essentially of a statistical nature, it produces clear-cut evidence of the high directivity of type I radiation at 169 MHz (Bougeret, 1978).

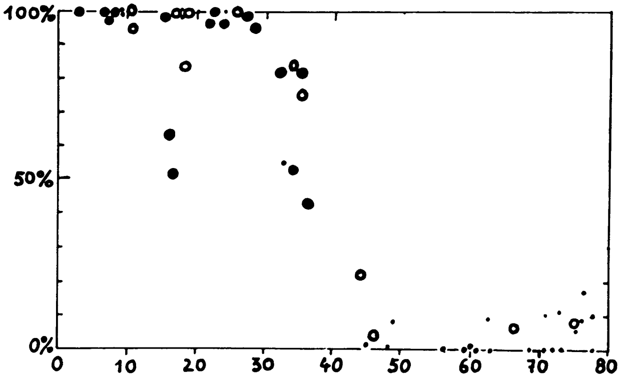

Figure 5 : Percentage of the type I bursts observed on MARS-3 which are also seen from the Earth as a function of the angle between the two directions of observation. The large full circles correspond to N>100 bursts observed in both directions, the open circles to 100>N>15 and the dots to N<15. (After Bougeret, 1978).

Observations of individual events occurring on given storm centers show that the beamwidth of individual events is smaller than 25° (Steinberg, Caroubalos and Bougeret,1974) and sometimes tilted 60° away from the local solar vertical (Bougeret,1978).This finding is a striking confirmation of the analysis made by Steinberg and Caroubalos (1970) who showed that the directivity derived from E-W histograms of occurrence might have little to do with the actual beaming of individual events.
An implication of these observations is the following : an upper limit of the beamwidth yields an upper limit to the total angular scattering suffered by a ray issued from the type I source ; this cannot be larger than the half-beamwidth (12°). Simple considerations show that the total amount of scattering is then too small to produce any important broadening of the source ; this conclusion is based on the assumption that one is dealing with scattering by weak and non-reflecting inhomogeneities (with small relative deviations of electron density, a few percent at most). If one considers as necessary to keep some scattering in the type I theory,another mechanism will have to be invoked : for instance multiple reflection and refraction in fiber bundles;in such a medium, directivity can be preserved in a plane containing the fibers (Bougeret and Steinberg,1977) and the apparent source can be broadened and displaced.

Another likely consequence is that type I radiation is beamed more or less along the fibers and,therefore,the magnetic field. This might have some implications on the radiation mechanism; it is known that type I are observed at altitudes much higher than the average plasma level in the low corona ; but there is little doubt that the corona is highly inhomogeneous in the vicinity of active regions where type I are observed. Moreover, type I sources are found at discrete positions (type I sources in storm centers, see Bougeret, 1973) above loopy regions as observed in X-rays (Stewart and Vorpahl,1977). It is therefore probable that they take place in overdense arches ; but, then, if they radiated by the plasma mechanism in the fundamental mode, the beam would be about perpendicular to the arches so that it would not be expected that their apparent altitude increases with their longitude. This discussion favours a gyromagnetic emission mechanism rather than the plasma one.

Measurements of type I time delays between the space probe MARS-3 and Nançay have confirmed the existence of discrete sources of type I bursts within noise storm centers (Bougeret, 1978).

OBSERVATIONS WITH SEVERAL LINES OF SIGHT - TYPE III BURSTS.

Observations at 169, 60 and 30 MHz have been made from the MARS-3 and MARS-7 Soviet probes (STEREO-1 and -5 experiments). One of the results was the necessity to reevaluate the role of the ionosphere in determining the time profile and intensity measured on the ground (Steinberg and Poquérusse,1979) especially at the lower frequencies. This has led to a new analysis of scattering by the daytime ionosphere where periodic electron density inhomogeneities due to gravity waves are often present. These inhomogeneities shift back and forth the apparent positions of type I bursts at 169 MHz (Bougeret,1978) washing out the discrete type I sources positions. They can also produce apparent halos around 30 MHz bursts (Meyer-Vernet, 1979).

At 169 MHz, the STEREO-1 experiment provided observations of 6 type III pairs on a given day for which the directivity was systematically larger for the first, fundamental, component as compared to the second which is believed to be an harmonic. This can be taken as another strong argument for the plasma hypothesis and the existence of the fundamental and harmonic pairs (Caroubalos, Poquérusse and Steinberg, 1974).

Time delays have been measured for type III pairs ; the time delay between the two components is not the same as seen from two different directions ; moreover that time delay does not vary with the longitude of the source in the same way for fundamentals and harmonics (Fig.6. Bougeret and Poquérusse, 1979) ; the time delay for fundamentals does not vary much with the longitude while that of harmonics decreases with increasing longitude : propagation effects will most probably have to be invoked to interpret these observations but the classical approach (larger group delay for the fundamental) does not seem to work; in any case, this remarkable observation shows that the coincidence in the positions of the two components is due to a propagation effect since the time delay between the two components of a pair is a function of the longitude of observation.

For at least one large longitude center, large intensity ratios were observed on harmonics thus suggesting that occultation could occur on some coronal structure with rather large density gradients. This is a very direct indication of strong deviations of the corona from spherical symmetry (Hoang, Poquérusse and Steinberg, 1977).

More recently, results came out of the STEREO-5 experiment which operated at 30 and 60 MHz : drift pairs or type III-b (short bursts) are much more directive than type III harmonics (Poquérusse, 1979) as seen on Fig.7. Even if this is known from the statistical analysis of ground based observations, it is extremely useful to confirm it by direct stereoscopic observations of the same events.

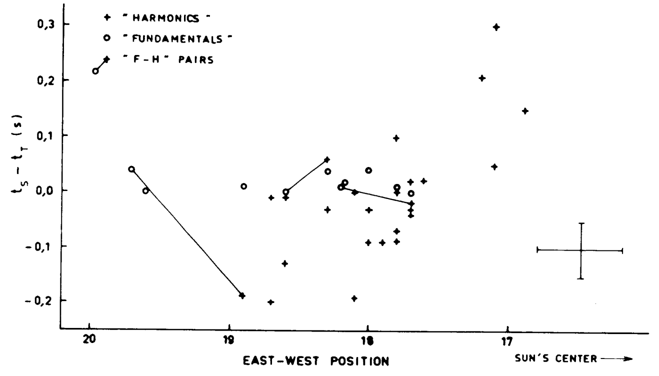

Figure 6 : Time delay vs E-W position for type III F-H pairs. (After Bougeret and Poquérusse, 1979).

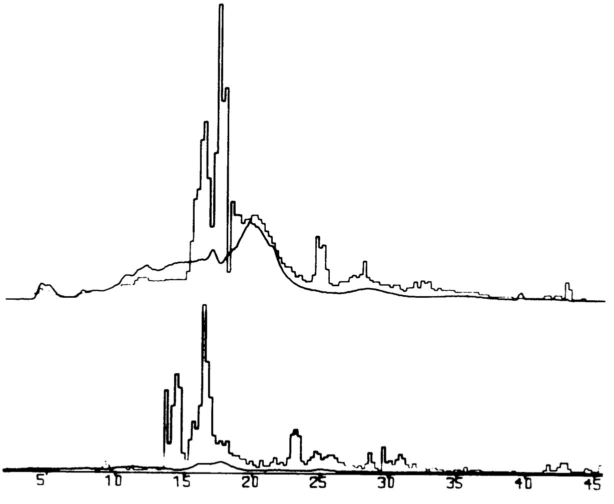

Figure 7 : Different directivities of short and long bursts at 30 and 60 MHz. The space data are quantized. (After Poquérusse, 1979).

Type III bursts in interplanetary space can be used as tracers of the magnetic lines of force which guide the electrons which produce them. If one can track type III's at several frequencies using properly instrumented spacecraft, one can plot the field lines.

Observations have first been carried out from spinning satellites fitted with short electric antennas mounted perpendicular to the spin axis and in the ecliptic (Fainberg,Evans and Stone,1972). But such a device can only provide the azimuth of the source, not its elevation, as soon as the source has a finite diameter ; an electron density model has to be used from which the position of the source as projected onto the ecliptic can be obtained. By using a second spacecraft whose spin axis is not parallel to the first one, one can get two angles and determine a direction (Baumback, Kurth and Gurnett,1976) ; an electron density model or the parameters of the Archimedes spiral are again necessary to reach a 3-D position (Fig.8). If one of the spacecrafts is orbiting the Moon, occultation can be measured and directions obtained (Fitzenreiter, Fainberg and Bundy, 1976,Fig.9). More recently, Weber et al (1977) used data from 3 spacecrafts, HELIOS-1 and -2 plus RAE-2 none of which could measure elevation angles with the ecliptic ; but it has been possible in this way to completely determine positions in the ecliptic, independently of any model. (Fig.10).

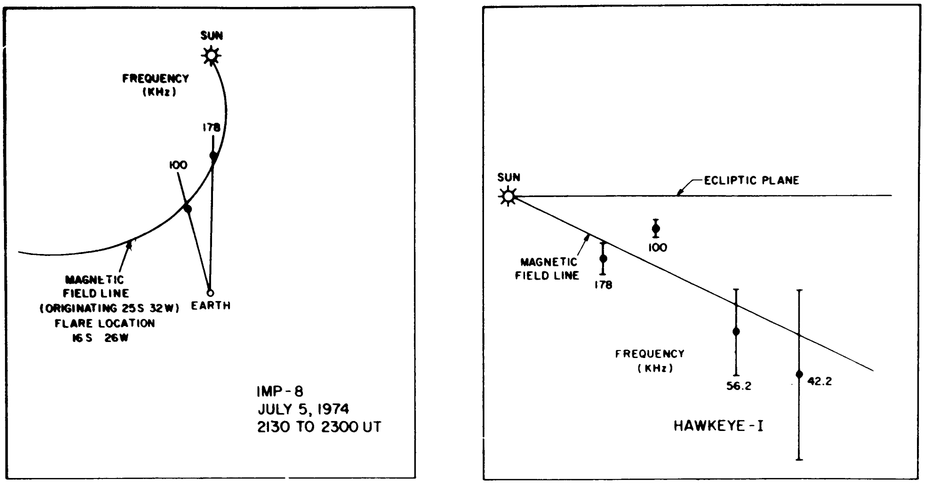

Figure 8 : Source location of a type III event on July 5, 1974, left as projected onto the ecliptic, right solar latitude as a function of the heliocentric distance ; the magnetic field line appears close to a constant latitude model (After Baumback, Kurth and Gurnett, 1976).

As far as solar radioastronomy is concerned, these increasingly sophisticated observations have produced the following results :

- They have clearly confirmed that type III bursts are produced by electrons travelling in interplanetary space at a nearly constant

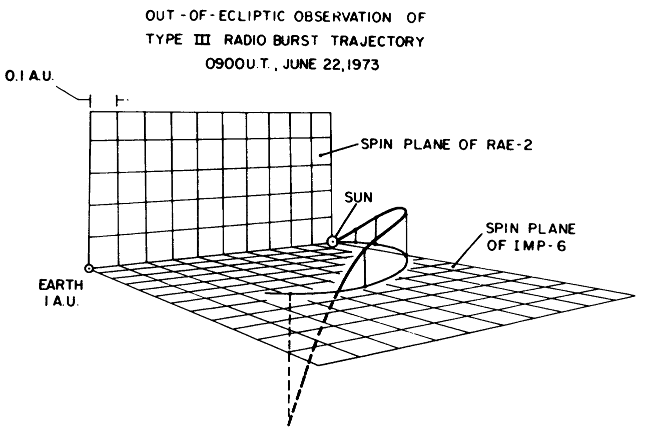

Figure 9 : Out of ecliptic observation of a type III trajectory on June 1973 (After Fitzenreiter et al. 1977).

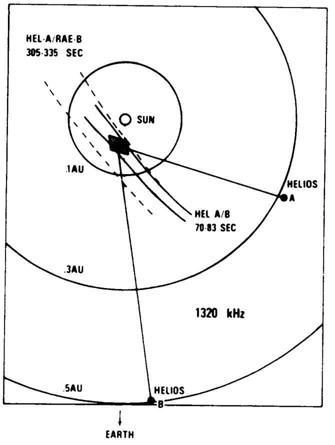

Figure 10 : Location of a burst source region given by intersections of the directions measured by HELIOS-1 and -2 and by arrival time differences at HELIOS-1 and -2 as well as HELIOS-1 and RAE-2. Direction finding and arrival time results are in agreement. (After Weber et al. 1977).

velocity along spiral magnetic field lines (Fainberg, Evans and Stone, 1976)

- They have given the size of the sources as a function of frequency : when the frequency decreases, the size increases enormously (Baumback, Kurth and Gurnett, 1976 ; Fitzenreiter et al. 1977 ; Kellogg, 1976). However it is not yet known how much of the apparent diameter is due to scattering by interplanetary electron density inhomogeneities (Steinberg, 1972) and how much to the actual extent of the primary source or sources or the electron beam. Computed propagation effects had to be taken into account to reconcile accurately the source locus obtained from triangulation techniques and from time delay measurements (Fig.10).

- Directivity has been measured directly (Weber et al. 1977) and statistically (Kaiser, 1975 ; Fitzenreiter, Fainberg and Bundy, 1976). The figures are just about the same as those measured at 169 MHz by STEREO-1 but, here again, the respective roles of the emission mechanism and the propagation cannot yet be identified. In particular, it appears that the beam axis is not oriented along the radial electron density gradient but closer to the magnetic field direction. More observations and computations are required to know precisely how the beam is oriented, how wide it is for the fundamental and the harmonic and which phenomena control it. More data are being acquired by ISEE-3 and HELIOS-2.

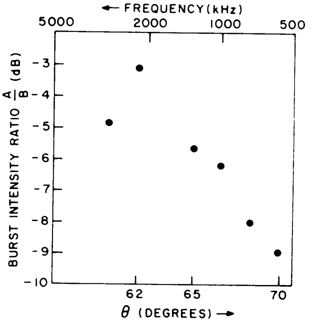

Figure 11 : Burst intensity observed at HELIOS-1 compared to HELIOS-2 for different frequencies. θ is the angle between the directions of HELIOS-1 and HELIOS-2 as seen from the source location. Consequently, these data are a measure of the radiation pattern of the burst in the interplanetary medium under the assumption that it is frequency-independent. (After Weber et al. 1977).

For the time being, few type III's have been found more than 20° from the ecliptic. The interpretation of this fact is not yet clear because of the small number of 3-dimensions positions available. It might be due to the directivity of the radiation (high latitude sources could not be seen from a spacecraft in the ecliptic) or to the topology of the interplanetary magnetic field (open lines of force rooted in active regions would bend toward the ecliptic).

The main results of all these space observations and of future ones (such as those to be obtained during the Out of Ecliptic mission) do not only belong to solar radioastronomy ; they do pertain also to the study of the heliosphere at large, its electron density distribution and magnetic field topology in three dimensions.

There is no doubt that space observations have already provided and will provide information which are essential to our understanding of the physics of solar radio bursts. Of course these observations must be compared with and added to those obtained with Earth-based instruments ;

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but in some instances, it seems that there are differences between the radio phenomena observed in the coronal and the interplanetary medium.

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DISCUSSION

Benz: One may get the general impression that type III bursts travel always from high frequencies to the plasma frequency near earth. R. Treumann, however, pointed out that data taken by the IKARUS spectrometer in Zürich often show type III's ending before they reach 200 MHz. Do you see bursts which end somewhere between here and the sun? Is there an explanation for it?

Steinberg: Some of them do escape into interplanetary space and we see the type III's ending at the local plasma frequencies in many cases. Some other times they stop at much higher frequencies for the time being we don't really know why.

Stewart: What propagation effects were considered for the 2 space-craft observations of kilometric type III source positions?

Steinberg: Refraction and scattering were included in the propagation computations. This was necessary to make triangulation and time of flight positions to coincide. (see Weber et al. Solar Phys. 56, 631-639.)

Sheeley: You said that you have seen dozens of type II bursts from ISEE-3. The NRL coronagraph on the P78-1 satellite observed a large coronal transient on May 8, 1979. Did you see a type II burst on that day?

Steinberg: I do not know, but we can look into the dynamic spectra at Goddard (J. Fainberg added that probably data was not processed yet).

Elgaröy: Is there any reason to consider space observations of moving type IV's?

Steinberg: There are no reasons not to consider moving type IV radiation; except that as far as I know nobody has ever reported any yet.