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Front cover: Sun-god Papautl of the Mayas.

THE FIRST YEAR OF VOYAGER PLASMA WAVE OBSERVATIONS IN THE SOLAR WIND

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Abstract. The Voyager plasma wave instruments started to acquire data on August 20, 1977, and during the first year the instruments on the two spacecraft operated continuously as they traveled outward toward Jupiter, with Voyager 1 reaching a heliocentric distance of 4.0 A.U. on August 28, 1978. During the first year a large number of interplanetary shocks were detected in association with extended post-shock periods having high whistler and ion acoustic mode turbulence levels. Beyond 1 A.U., in many cases the passage of the interplanetary shock is preceeded by extensive ion acoustic wave precursor activity. Sporadic bursts of ion acoustic waves are also commonly detected on days that would otherwise be classifed as quiet; up to 70 percent of the days showed some evidence of this type of activity. In addition to these studies, we have been able to evaluate radial variations in the amplitudes of electron plasma oscillations associated with Type III solar bursts.

1. INTRODUCTION

The plasma wave system (PWS) was incorporated in the Voyager payload specifically to provide information on the important wave-particle interaction phenomena that develop in the magnetospheres of Jupiter and Saturn. However, since any planetary bow shock forms within the interplanetary plasma, and since magnetosheath flow represents shocked solar wind, these plasma wave instruments necessarily had to be designed to cover a range of anticipated interplanetary wave frequencies near 5 and 10 AU. The considerations naturally led to a system capable of measuring characteristics of interplanetary wave modes over a very wide heliocentric range. The Voyager wave instruments have been operating since the launches in August and September of 1977, and they have been analyzing interplanetary phenomena continuously during the initial cruise phase of the mission. This report contains a brief description of the observations for the initial year of operation, as the spacecraft traveled outbound from 1 AU to about 4 AU.

2. INSTRUMENTATION AND IN-FLIGHT SENSITIVITY

Each of the Voyager plasma wave instruments utilizes a balanced electric dipole with seven-meter effective length. The instrument electronics consists of a step-frequency-receiver and a waveform receiver. The step-frequency-receiver has 16 narrow-band filters logarithmically spaced from 10 Hz to 56.2 kHz. The field strength in each frequency channel is determined once during each frequency scan, which takes a minimum of 4 seconds (for the highest possible telemetry rates) to a maximum of 96 seconds. The Voyager spectrum analyzers do not sample continuously, however, since only two log compressors are used for the full spectral coverage, and there is no peak detection or sample and hold capability. The duty cycle for detecting short impulsive bursts in a given channel is approximately 1/80 at the highest telemetry rates and drops to about 1/1920 for the lowest cruise rate. The step-frequency-receiver is operated continuously throughout the cruise phase of the mission.

The waveform receiver utilizes a special high bit rate (115 kb/s) mode of the spacecraft telemetry system to provide high resolution waveform measurements over the frequency range extending from 50 Hz to more than 12 kHz. The waveform receiver consists of a bandpass filter to limit the bandwidth of the received signal and an automatic gain control circuit with a time constant of 0.5 sec to maintain the signal output at an approximately constant amplitude. The waveform output of the automatic gain control circuit is digitized into four bit words at a rate of 28,800 samples per second. The high rate waveform data are transmitted during selected times when pictures are not being transmitted by the imaging experiment. The waveform records are normally obtained in 48-second bursts. Further details on the instrumentation and a full description of the planetary science objectives are given in a recent report by Scarf and Gurnett [1977].

The overall Voyager PWS frequency coverage is roughly summarized on the left-hand side of Figure 1, but the lower eight channels actually have 30 percent band-

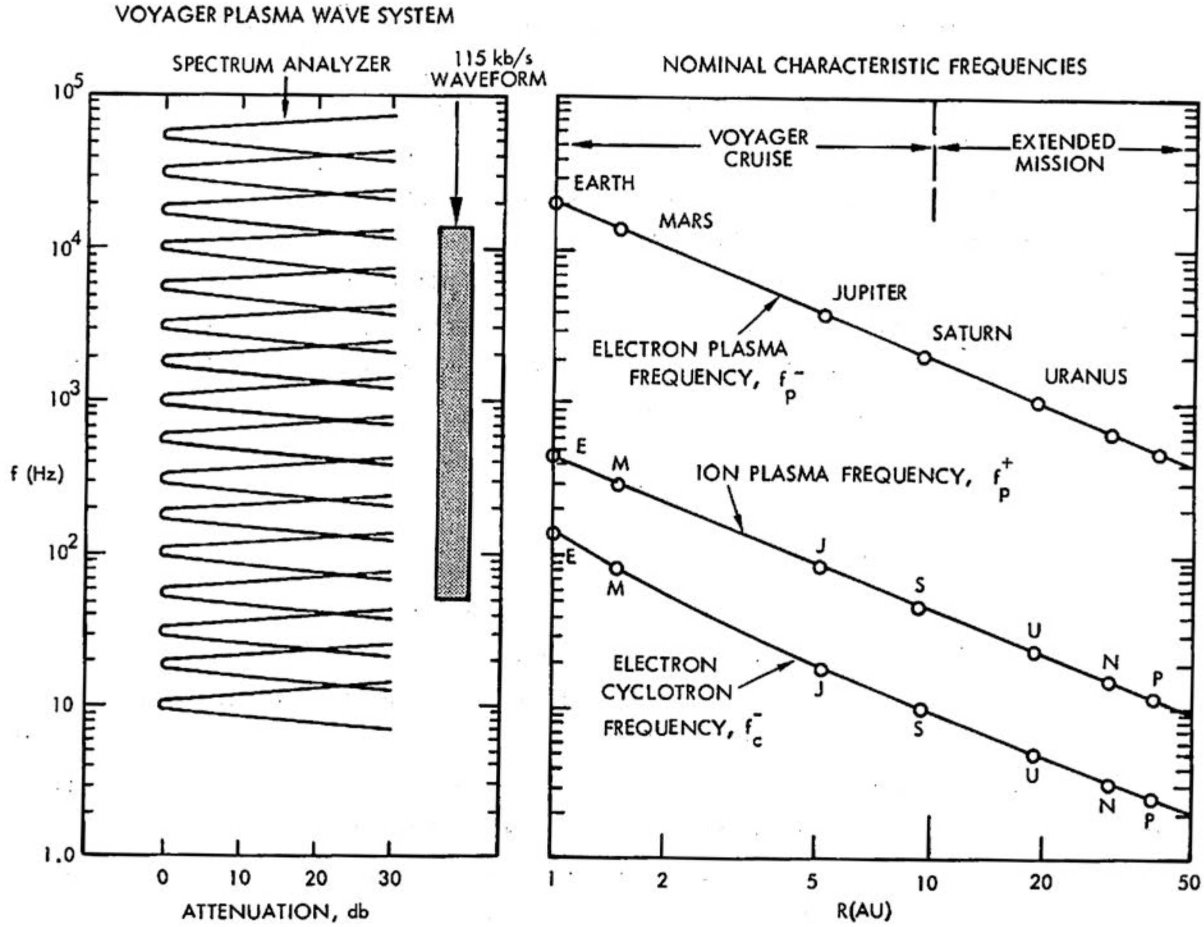
VOYAGER PLASMA WAVE SYSTEM

Figure 1. Spectral coverage of the Voyager plasma wave system (left side) and wave frequencies for nominal solar wind condition (right side).

pass filters with response curves that are broader than indicated here. The anticipated solar wind characteristic frequencies for nominal interplanetary conditions [N(1 AU) ≃ 5 cm^{-3}, B(1 AU) ≃ 5 gamma] are plotted on the right, and it can be seen that even out into the region of the extended mission [r > 10 AU], the Voyager wave instruments should be able to cover the important electron and ion wave modes.

The overall in-flight performance of the PWS can be evaluated by considering the response during the outbound passage through the earth's magnetosphere. Figure 2 shows all of the Voyager 1 wave observations in seven of the sixteen channels during a five and one-half hour period on September 5, 1977 when the spacecraft traveled out from 10 R_e to past 40 R_e (see the trajectory insert). The high telemetry rate gave one scan per four seconds throughout. The multiple magnetopause crossings are associated with the noise enhancements starting at about 1630 UT; a thick and diffuse bow shock crossing was centered about 1745 UT; and an extensive region with

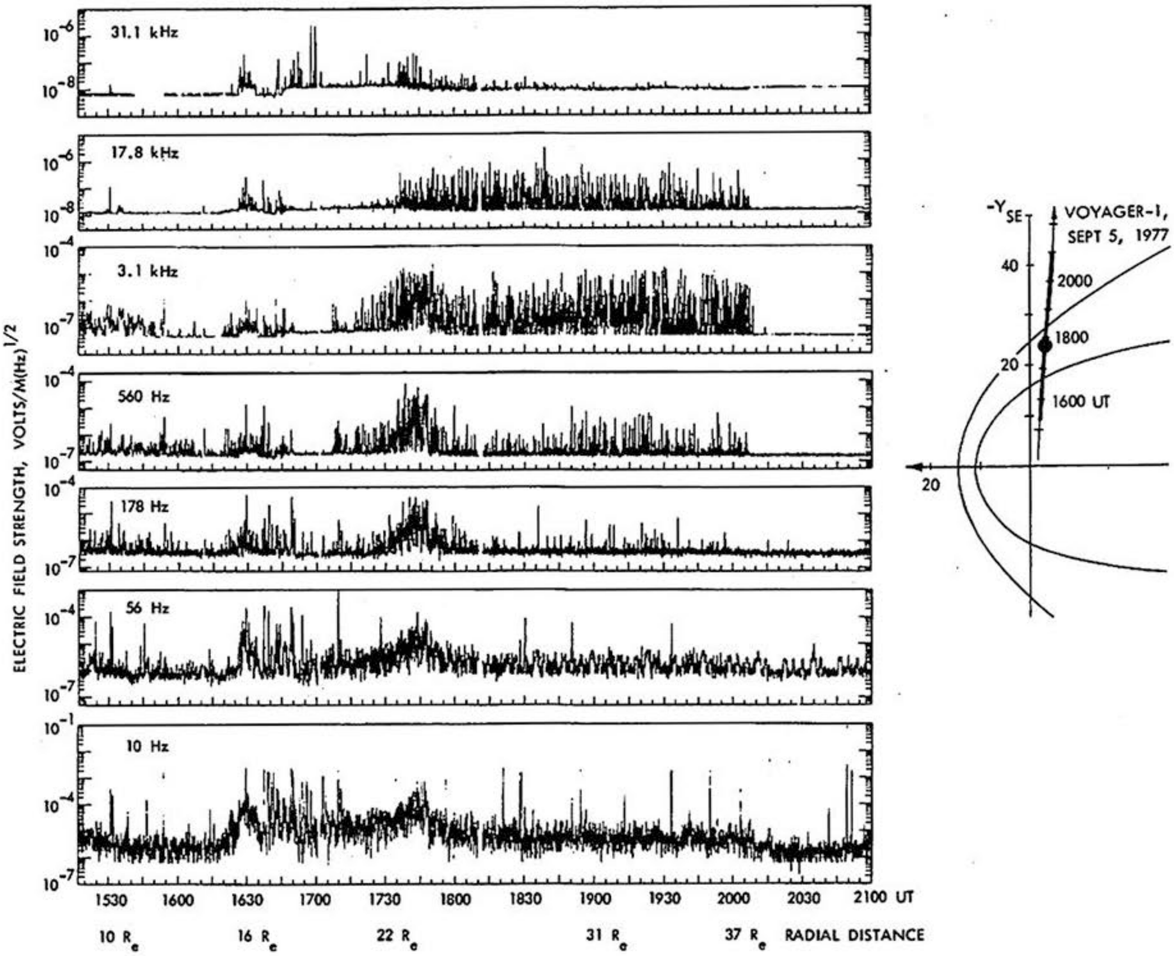

Figure 2. Voyager 1 measurements on September 5, 1977, during the outbound magnetosphere passage.

intense upstream ion acoustic wave turbulence (3.1 kHz), moderate electron plasma oscillations (17.8 kHz), and substantial mhd wave levels (10 Hz) ended abruptly near 2000 UT, as Voyager passed into very quiet solar wind. Figure 2 shows that the large PWS dynamic range is quite useful at shocks. It also shows the very low levels of spacecraft noise, although two mild in-flight interference effects are illustrated here: (a) the periodic low level 56 Hz enhancements evident after about 1800 UT are associated with operation of the Planetary Radio Astronomy receiver, which shares the 10-meter antennas; (b) the occasional intense and isolated bursts in the 10 Hz channel, such as the one at 1934 UT, are associated with bursts from the rocket thrusters of the spacecraft attitude control system. Other low level interference signals come from the modulation grid of the MIT plasma probe, and from the stepper motor of the APL/JHU low energy charged particle detector.

Six spacecraft with plasma wave instruments were launched between August of 1977 and August of 1978, and Figure 3 compares the in-flight thresholds. These background curves are computed assuming that in all cases the sensor effective length $\ell(\text{eff})$ is small compared to a half wavelength, so that $E(\text{min}) \simeq \phi(\text{min})/\ell(\text{eff})$, where $\phi(\text{min})$ is the measured minimum voltage amplitude on the sensor. Thus, the comparison of Figure 3 is valid as plotted only for those waves having $\lambda >> 200$ meters. Even for these longer wavelength oscillations it can be seen that the Voyager sensitivity is exceptional, especially for $f \lesssim 100$ Hz, since in general similar spacecraft potential noise amplitudes would yield $E(\text{min}) \times \ell(\text{eff}) \approx$ constant, rather than the near-equality that appears in the low frequency threshold levels for Voyager and ISEE-1. The low noise levels achieved on Voyager are undoubtedly associated with the imposition of an electrostatic cleanliness specification leading to a Faraday shield around the spacecraft, and to the absence of solar arrays which frequently couple noise to the plasma (see the prelaunch discussion by Scarf and Gurnett, 1977).

3. INTERPLANETARY SHOCKS

The Voyagers were launched in the midst of a period with great solar activity, and we have been able to study a large number of interplanetary shocks, starting with the intense storm events of September 1977. The left-hand side of Figure 4 shows the response in all sixteen channels for the initial event, detected on Voyager 2 at 0506 UT, on September 20. Acuna et al. [1978] identified this event as a fast forward shock with a jump in B from 3.6γ to 7.8γ. Thus after 506 UT the electron cyclotron frequency was 218 Hz, and we identify the enhanced post-shock noise in all channels up to and including the 178 Hz one as whistler mode turbulence. Very intense and impulsive higher frequency waves were also detected at the shock and in the immediate post shock region.

Figure 4 shows that very intense and impulsive higher frequency waves were also detected in association with all three discontinuities. These waves are thought to be short wavelength ($\lambda \gtrsim 2\pi\lambda_D$, where λ_D is the Debye length) Doppler shifted ion

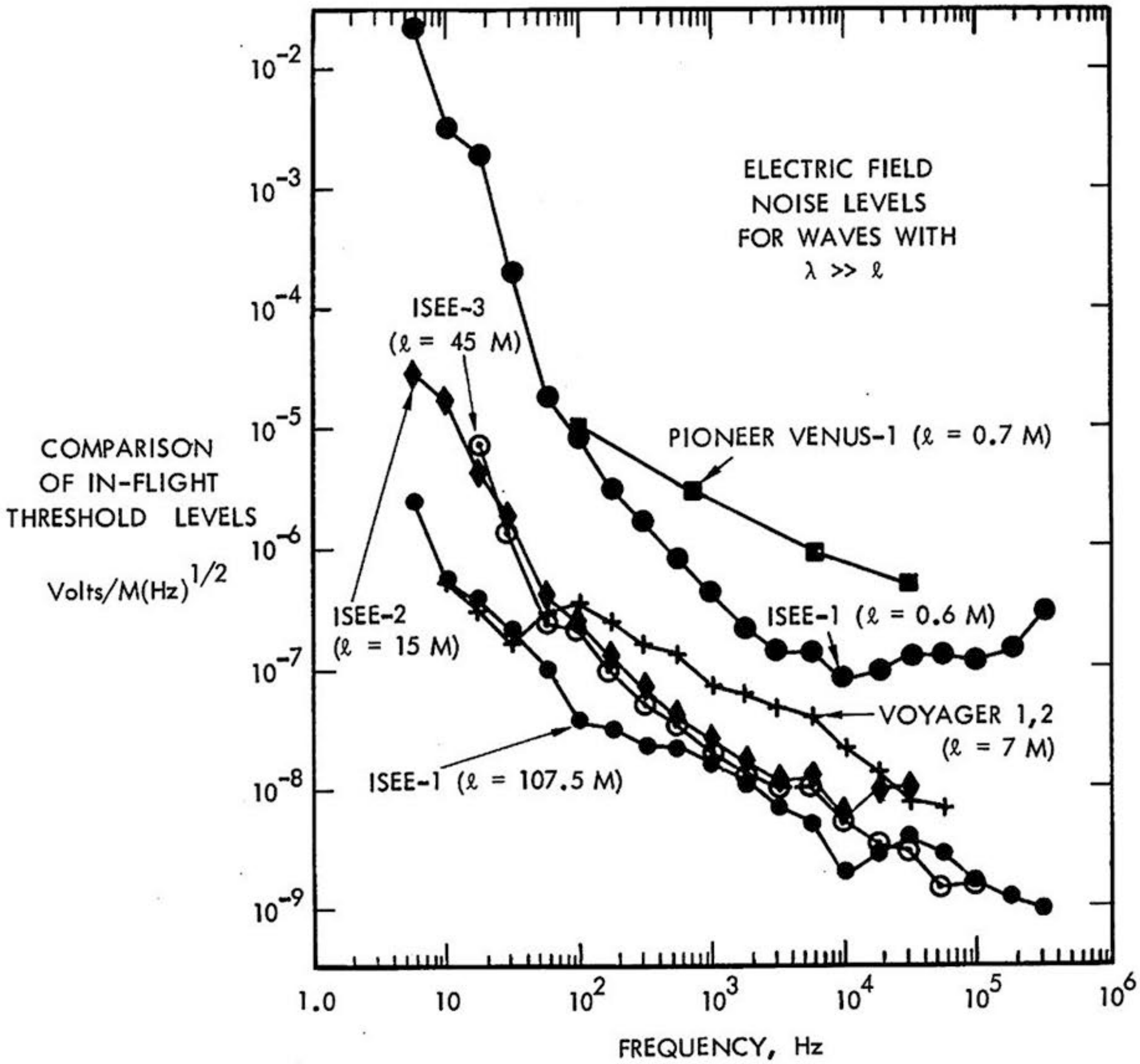

Figure 3. In-flight background levels for wave instruments on six new spacecraft, assuming $\lambda >> 200$ meters.

sound waves (of the type discussed by Gurnett and Anderson [1977], Kurth et al. [1978] and others), and a preliminary analysis supports this interpretation. For instance, just after 0506 UT on September 20, the MIT plasma probe data yielded $V \approx 380$ km/sec, $N \approx 20$ cm^{-3}, $T_+ \approx 2.5 \times 10^4$°K (J. Sullivan and H. Bridge, private communication) so that f_p^+ (the rest frame ion plasma frequency) was 935 Hz and the proton Debye length was 2.5 meters. However, for $T_- \approx 10^5$°K, the electron Debye length is near 5 meters and in this case the Doppler shift, $\Delta f = kV \cos (k,V)$, has a peak value [Δf(max)] of $V/(2\pi\lambda_D) \simeq 12$ kHz; thus it is easy to explain the observed signals in all the channels up to and including the 17.8 kHz one, in terms of ion sound wave detection. A more detailed account of the Voyager 1 and 2 wave observations for the entire September 1977 storm period is published elsewhere [Scarf, Gurnett, Kurth and Shaw, 1978].

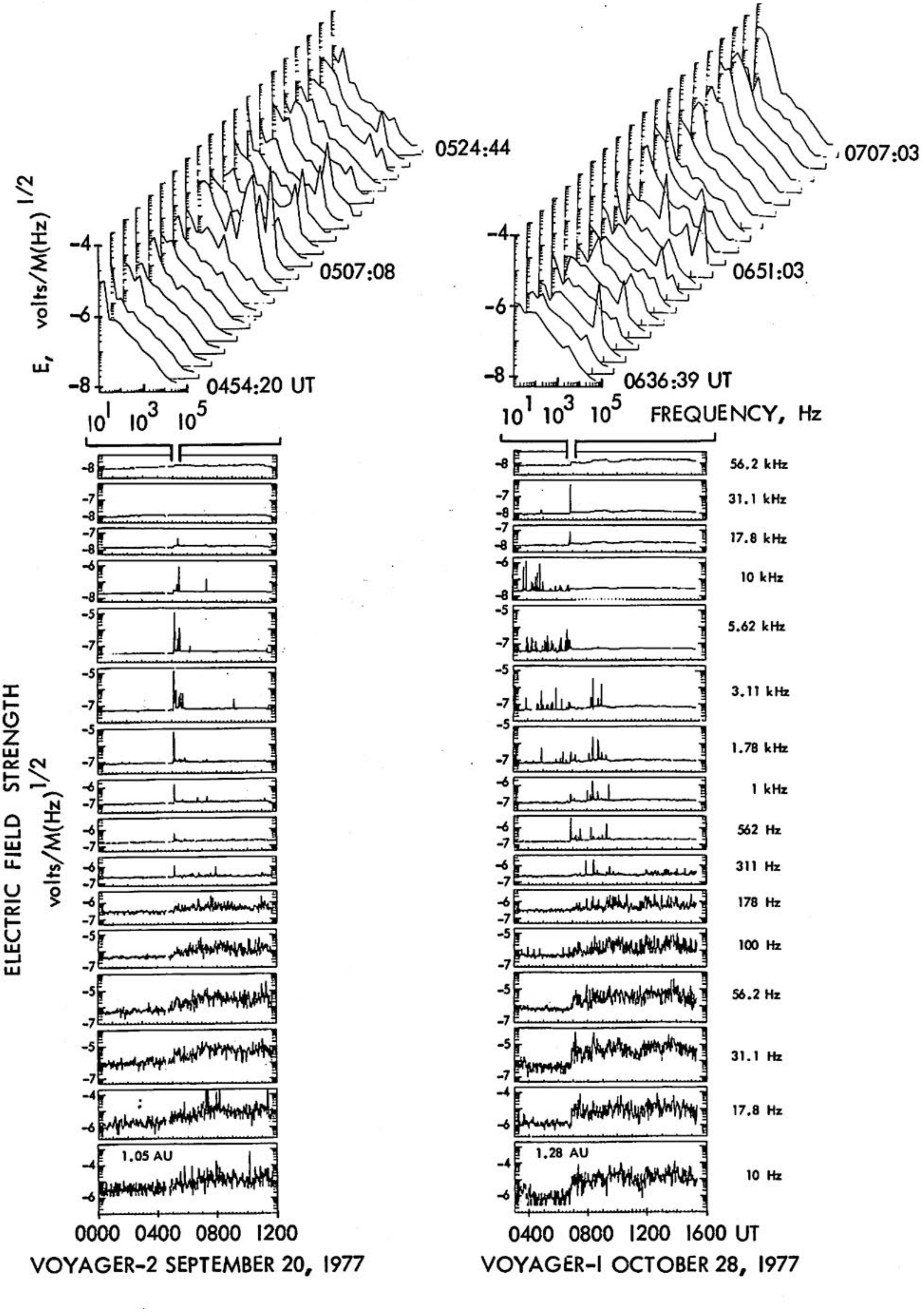

Figure 4. Detection of wave level changes at interplanetary shocks.

The left side of Figure 4 shows variations in wave characteristics that are typical of those commonly detected near interplanetary shock fronts for $r \lesssim 1$ AU, but the Voyager PWS has discovered that shocks detected farther from the sun generally have significantly different variations in plasma wave turbulence. These changes are illustrated on the right side of Figure 4, which contains plots of PWS data for the interplanetary shock of 0651 UT, October 28, 1977 (encountered when Voyager 1 was at 1.28 AU). It can be seen here that sporadic large amplitude ion acoustic wave precursors were clearly detected for several hours before this shock arrived. In terms of upstream precursors, this effect is similar to the one illustrated in Figure 2. For quasi-parallel bow shocks such as this one, reflected and locally accelerated protons generate intense ion acoustic wave turbulence in the upstream region. However, it has certainly not yet been established that this analogy explains the upstream ion wave turbulence for an interplanetary shock. In fact, Russell and Greenstadt [1979] have shown that the October 28 Voyager shock had a distinctly laminar appearance when it was apparently detected at 1 AU by the ISEE 1 and 2 magnetometers (at 2328 UT, October 26, 1977). Further multi-spacecraft studies of the variations in shock turbulence characteristics with increasing heliocentric range will be performed after detailed determination of the changes in shock geometry, Mach number, etc. have been completed.

Figure 4 contains wave observations made at the low 96-second per scan rate, and this sampling clearly gives an inadequate representation of the very impulsive upstream wave phenomena. A much better characterization of the effect is shown in Figure 5, which contains data from a high rate (4 seconds/scan) shock event at 1.6 AU. It can be seen that sporadic large amplitude ion acoustic wave enhancements were again clearly evident in the upstream region, but in fact we know from related observations on ISEE, Helios, IMP, etc., that even the four-second/scan rate is inadequate without some form of storage. We will show below that the high time resolution capability of the waveform channel is needed to process these impulsive signals in the absence of peak detection or sample and hold capability.

Finally, the left side of Figure 6 shows wave turbulence associated with another shock detected early in 1978, when Voyager 2 was well beyond 2 AU. Once again, this shows extensive upstream ion acoustic wave precursors in the 1.0 and 1.78 kHz channels. This upstream turbulence appears to be an intrinsic feature of the shock in the distant solar system.

4. ION ACOUSTIC WAVES

Gurnett and Anderson [1977] used data from Helios 1 and 2 to show that sporadic bursts of electrostatic turbulence commonly occur in the inner solar wind [$0.3 \text{ AU} < r \leq 1$ AU] at frequencies between the electron and ion plasma frequencies. Further analysis (by Gurnett and Frank [1978], for instance) supported the suggestion that this noise represents short wavelength ion acoustic turbulence with rest frame wave

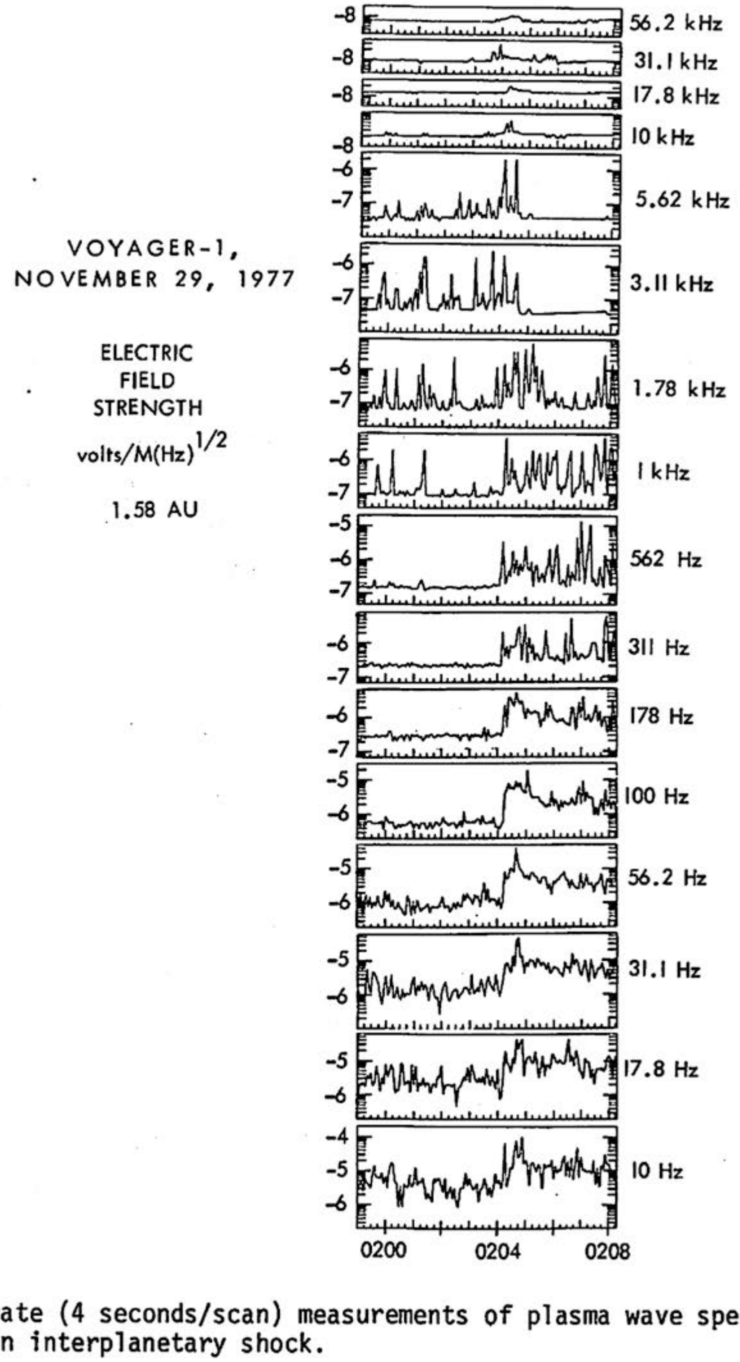

Figure 5. High rate (4 seconds/scan) measurements of plasma wave spectral variations near an interplanetary shock.

frequencies below the ion plasma frequency. As solar wind moves rapdily past the spacecraft, these oscillations experience Doppler shifts to higher frequencies. Gurnett and Frank also demonstrated that these waves have characteristics similar to the ion sound waves associated with suprathermal protons streaming into the solar wind from the bow shock, and they therefore used the same designation to refer to these deep space observations.

The Voyagers provided the first opportunity to search for isolated ion acoustic

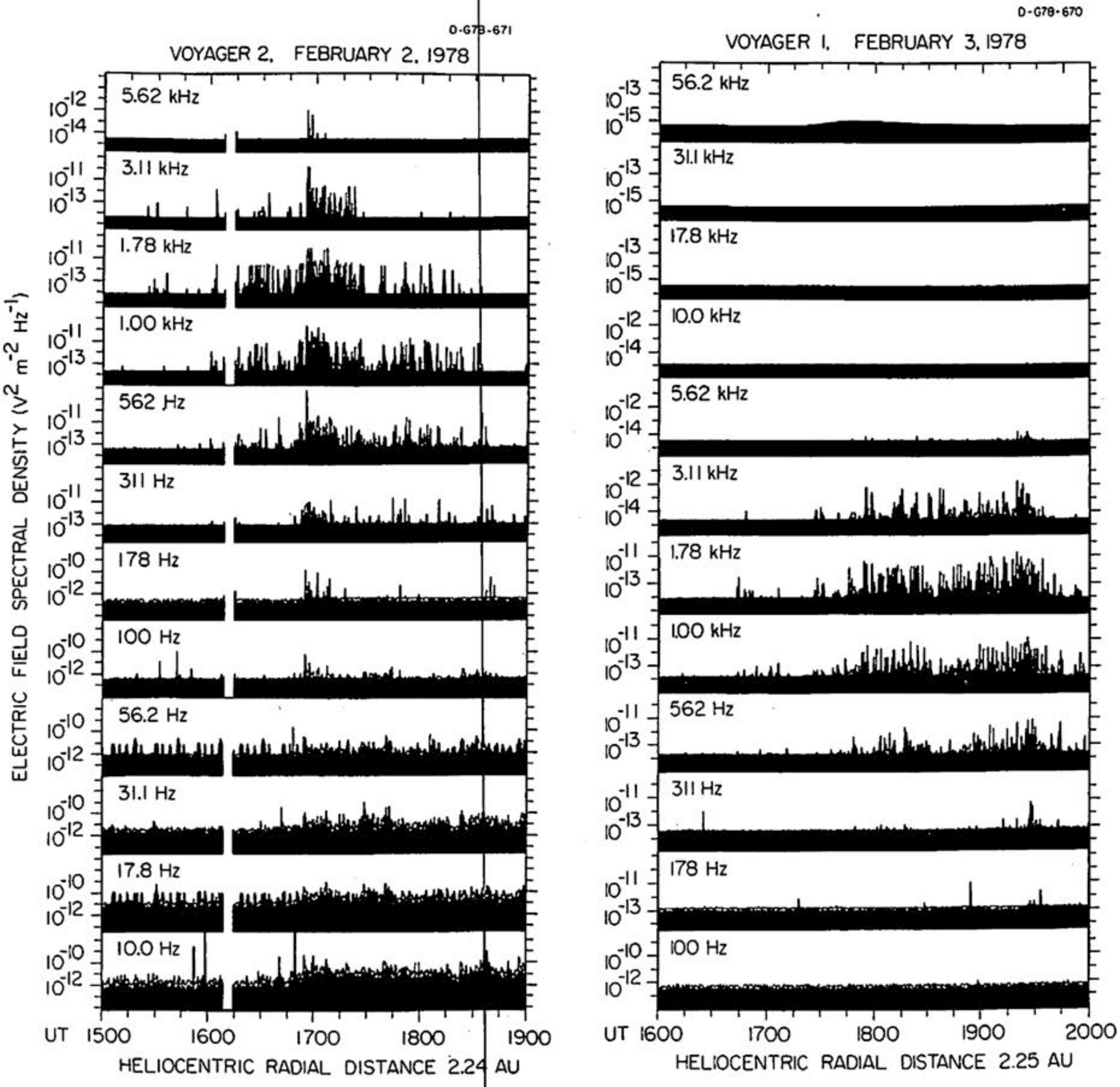

Figure 6. Left side: an interplanetary shock detected past 2.2 AU; right side: interplanetary ion acoustic waves.

wave bursts (independent of shocks) in the solar wind beyond 1 AU, and the right side of Figure 6 shows a fairly typical example of this sporadic electrostatic turbulence, as it appears in the Voyager spectrum analyzer output. Usually the ion acoustic waves detected with the Voyager PWS tend to occur in "storms" that last from a few hours to a few days, and activity similar to that shown in Figure 6 is observable to some extent during 50-70 percent of the days when the PWS 16-channel analyzer operates at its highest sampling rate.

In the inner solar system the Helios observations of extremely high peak-to-average ratios for ion acoustic wave turbulence clearly showed that a spectrum analyzer with no peak detection or sample and hold capability (such as the Voyager ones) would give inadequate information on wave amplitudes, frequency of occurrence, etc. Fortunately, the Voyager PWS has the broadband channel that allows the full waveform to be recorded at selected times, and we have been able to use this channel to study full details of the ion acoustic wave turbulence. Kurth, Gurnett and Scarf [1978] discussed the first high resolution frequency-time spectrograms for these waves, and they showed that out to about 1.7 AU the ion acoustic wave turbulence consists of narrowband bursts that last from a fraction of a second to a few seconds. Figure 7 shows a more recent example of ion sound wave detection with the waveform channel, and once again it can be seen that the bursts have very short durations, with rapid changes in frequency. It is evident that these characteristic oscillations persist out past 4 AU, and they undoubtedly arise from one or more interplanetary plasma instabilities of the type recently discussed by Gurnett et al. [1978].

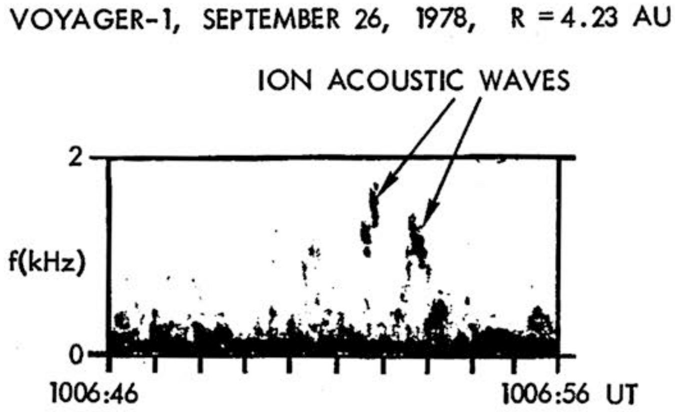

Figure 7. Frequency-time spectrogram showing characteristics of ion sound bursts.

5. ELECTRON PLASMA OSCILLATIONS AND TYPE III BURSTS

Although Type III solar radio bursts are commonly detected in space, only a small number of such bursts have had electron plasma oscillations clearly associated with them. Gurnett, Anderson, Scarf and Kurth [1978] discussed eighteen such events derived from nine years of observations (IMP 6,8; Helios 1,2; Voyager 1,2) and they showed that the intensity and the frequency of occurrence of the electron plasma oscillation events decrease significantly with increasing radial distance. The left side of Figure 8 shows the Voyager-1 data from November 22, 1977, which represents the most distant event discussed by Gurnett et al. As expected, the associated electron plasma oscillations at $r \simeq 1.5$ AU are relatively weak, but they were clearly detectable. Farther from the sun, Type III bursts are still frequently observed for example, see the 56 kHz panel in the February 3, 1978 data of Figure 6), but these are not accompanied by measureable electron plasma oscillations. However, past 2 AU, we have occasionally observed very intense bursts of electron plasma oscillations <u>without</u> evidence for Type III bursts. An example is shown on the right side of Figure 8. To date we have not been able to determine the origin of these bursts,

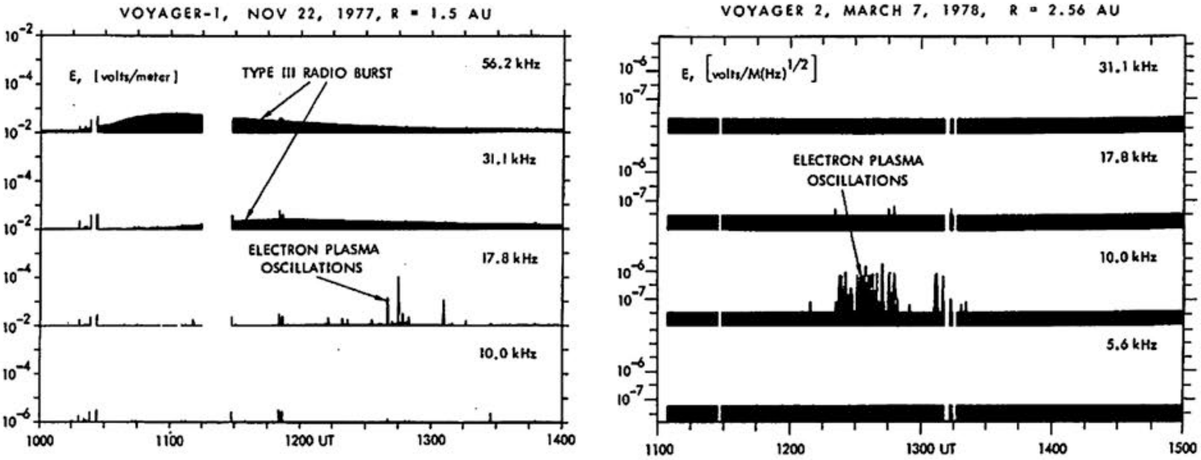

Figure 8. Left side: Type III solar radio burst and associated electron plasma oscillations; right side: a burst of electron plasma oscillations without accompanying solar radio noise.

but as Voyager closes in on Jupiter, we do expect to find electron plasma oscillations associated with emission of electrons from Jupiter.

6. CONCLUDING REMARKS

This report includes a brief description of the in-flight PWS response and illustrations of most kinds of wave turbulence measured between 1 and 4.3 AU, as the two spacecraft complete the earth-to-Jupiter phase of the mission. In addition to the more detailed studies indicated by the above discussions, plans are underway for analysis of the variations in whistler mode turbulence as a function of time and changing solar activity; the high sensitivity of the Voyager PWS at low frequencies provides a unique opportunity to study the electric field component of whistler turbulence in deep space.

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