

Direction-finding measurements of heliospheric 2-3 kHz radio emissions

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Abstract. Using data from the Voyager 1 plasma wave instrument, a series of direction-finding measurements is presented for the intense 1992-93 heliospheric 2- to 3-kHz radio emission event, and several weaker events extending into 1994. Direction-finding measurements can only be obtained during roll maneuvers, which are performed about once every three months. Two parameters can be determined from the roll-induced intensity modulation, the azimuthal direction of arrival (measured around the roll axis), and the modulation index (the peak-to-peak amplitude divided by the peak amplitude). Measurements were made at two frequencies, 1.78 and 3.11 kHz. No roll modulation was observed at 1.78 kHz, which is consistent with an isotropic source at this frequency. In most cases an easily measurable roll modulation was detectable at 3.11 kHz. Although the azimuth angles have considerable scatter, the directions of arrival at 3.11 kHz can be organized into three groups, each of which appears to be associated with a separate upward drifting feature in the radio emission spectrum. The first group, which is associated with the main 1992-93 event, is consistent with a source located near the nose of the heliosphere. The remaining two groups, which occur after the main 1992-93 event, have azimuth angles well away from the nose of the heliosphere. The modulation indexes vary over a large range, from 0.06 to 0.61, with no obvious trend. Although the variations in the directions of arrival and modulation indices appear to reflect changes in the position and angular size of the source, it is also possible that they could be caused by refraction or scattering due to density structures in the solar wind.

Introduction

For over fifteen years the Voyager 1 and 2 plasma wave instruments have been detecting an unusual radio emission in the frequency range from about 2 to 3 kHz that is believed to originate in the outer regions of the heliosphere. For a description of the Voyager plasma wave instrument see Scarf and Gurnett [1977], and for a review of the 2- to 3-kHz heliospheric radio emissions see Gurnett and Kurth [1996] and Kurth and Gurnett [1997]. Two particularly intense events have been detected, the first in 1983-84 [Kurth et al., 1984], and the second in 1992-93 [Gurnett et al., 1993]. In addition several weaker events have also been detected. These include five events between the strong 1983-84 and 1992-93 events [see Kurth et al., 1987, and Kurth and Gurnett, 1991], and several events immediately following the strong 1992-93 event [see Gurnett and Kurth, 1996]. The purpose of this paper is to analyze a series of roll maneuvers that occurred during and immediately following the 1992-93 event in order to determine the direction of arrival of the radiation.

Direction Finding With Voyager

Radio direction-finding measurements provide a very useful tool for determining the location of a remote radio source. Since the Voyager plasma wave antenna is essentially nondirectional (i.e., a simple dipole), and since the spacecraft is usually nonrotating (i.e., three-axis stabilized), normally no directional information can be obtained. However, every few months a spacecraft maneuver is performed that allows the direction of arrival to be determined from the rotationally induced modulation of the received signal strength. Two types of maneuvers are performed, roll turns and yaw turns. For a description of the in-flight operation of the Voyager spacecraft see Kohlhasse and Penzo [1977]. Roll turns are performed by rolling the spacecraft around the axis of the spacecraft high-gain communications antenna, which is normally pointed toward Earth, and yaw turns are performed by rolling the spacecraft around an axis that is perpendicular to the axis of the high-gain antenna. Since communication with the spacecraft is lost during a yaw turn, yaw turns are more risky than roll turns. Although both roll and yaw turns were performed during the planetary flyby phase of the Voyager mission (prior to the Neptune flyby, which occurred on August 25, 1989), because of the high risk associated with yaw turns and various other considerations, no yaw turns are being performed during the interstellar phase of the Voyager mission (i.e., after the Neptune flyby). During the planetary flyby phase of the mission only one spacecraft maneuver has been found for which the heliospheric radio emission had a detectable rotational modulation. This maneuver consisted of a yaw turn that was performed on November 2, 1983, shortly after the onset of the 1983-84 heliospheric radio emission event. This event has been analyzed in detail by Kurth [1988]. All of the remaining maneuvers for which a detectable rotational modulation has been observed involve roll-turn maneuvers performed during and immediately following the intense 1992-93 event. These roll turns are the subject of this study.

The primary purpose of a roll-turn maneuver is to calibrate the zero offset of the magnetometer [Burlaga and Ness, 1994]. Each roll-turn maneuver consists of ten complete rotations of the spacecraft around the axis of the high-gain antenna (the spacecraft z axis) at a rate of one rotation every 33 minutes. A roll-turn maneuver is performed approximately once every two to three months. In this study all of the available roll-turn maneuvers have been analyzed over a 24-month interval from August 7, 1992, to August 5, 1994. This interval includes the intense 1992-93 event and several subsequent weaker events. The locations of the maneuvers analyzed are indicated by the circles numbered 1 to 12 in Figure 1, which shows a three-year frequency-time spectrogram of the electric field intensities from the wideband waveform receiver on Voyager 1. See Kurth et al. [1987] for a description of the processing required to convert the electric field waveforms to spectrograms of this type. The intense 1992-1993 radio emission event and several subsequent weaker events are clearly evident in the spectrogram. The strong narrowband emission line at 2.4 kHz is interference from the spacecraft power system. Although the data from the wideband waveform receiver provides very good

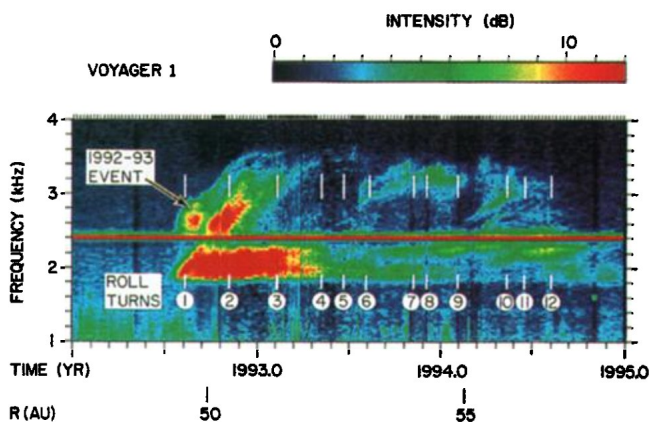


Figure 1. A three-year frequency-time spectrogram of the Voyager 1 wideband plasma wave data showing the strong 1992-93 heliospheric radio emission event and several subsequent weaker events extending into 1994. The intensity is indicated by color, with red being the most intense and blue being the least intense. An intensity scale is shown at the top of the spectrogram. The circles labeled 1 through 12 indicate the times of a series of roll-turn maneuvers that have been analyzed to determine the direction of arrival of the radio emission. The vertical white bars in the spectrogram indicate the approximate frequency range sampled by the 1.78- and 3.11-kHz channels during the roll maneuvers.

frequency resolution, the wideband data does not have adequate time resolution to resolve the roll modulation itself. Usually only one 48-s wideband recording is obtained per week. The exact times of the wideband waveform samples used to compute the spectrums in Figure 1 are shown by the short vertical bars at the top of the spectrogram.

To detect roll modulation, data from the on-board 16-channel spectrum analyzer must be used. In the telemetry mode currently being used on Voyager 1, this analyzer provides an average of four scans of the spectrum every 16 seconds. Only two of the sixteen channels, 1.78 and 3.11 kHz, are suitable for detecting the

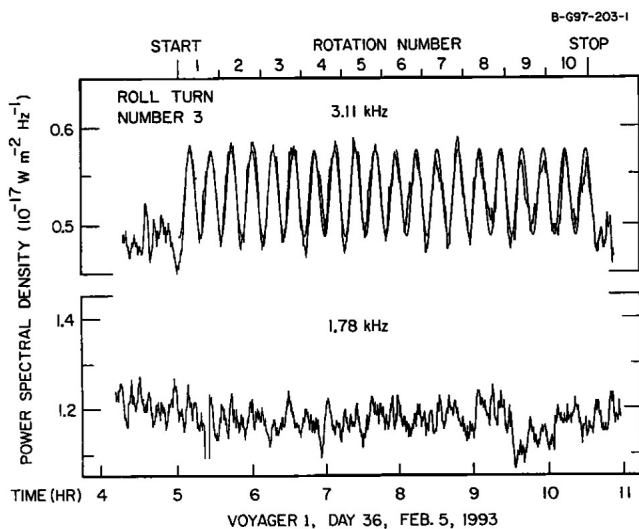


Figure 2. The radio emission intensity in the 1.78- and 3.11-kHz channels of the 16-channel plasma wave spectrum analyzer on Voyager 1 during roll-turn maneuver number 3 (see Figure 1). No roll modulation is present in the 1.78-kHz channel. However, a very clear roll modulation can be seen in the 3.11-kHz channel. The solid sinusoidal line is the least-mean-square fit of Equation 1 to the observed intensities.

heliospheric radio emission. The vertical white lines in Figure 1 indicate the approximate frequency range sampled by these channels, which have bandwidths of approximately ± 7.5 percent. Because of a data system failure on Voyager 2, intensity measurements at 1.78 and 3.11 kHz cannot be obtained from Voyager 2 with adequate resolution to detect the heliospheric radio emission. Therefore, direction-of-arrival measurements can only be obtained from Voyager 1. As can be seen from Figure 1, the 1.78-kHz channel responds to the smooth continuum-like band at about 2 kHz, and the 3.11-kHz channel responds to the discrete bands that drift upward in frequency to about 3.6 kHz.

An example of a roll-turn maneuver with detectable roll modulation is illustrated in Figure 2, which shows the radio emission intensities in the 1.78- and 3.11-kHz channels for a ten turn roll maneuver performed on February 5, 1993 (roll turn number 3 in Figure 1). The start and stop times of the maneuver and the corresponding spacecraft rotation numbers are shown at the top of the plot. To correct for the receiver noise level, background power spectral densities of 2.4×10^{-17} and $1.52 \times 10^{-17} \text{ W m}^{-2} \text{ Hz}^{-1}$ have been subtracted from the measured power levels in the 1.78- and 3.11-kHz channels. Although no roll modulation can be detected in the 1.78-kHz channel, a very clearly defined roll modulation is present in the 3.11-kHz channel. This event is typical of the events analyzed. No roll modulation has ever been detected in the 1.78-kHz channel, whereas a clearly defined roll modulation is usually present in the 3.11-kHz channel.

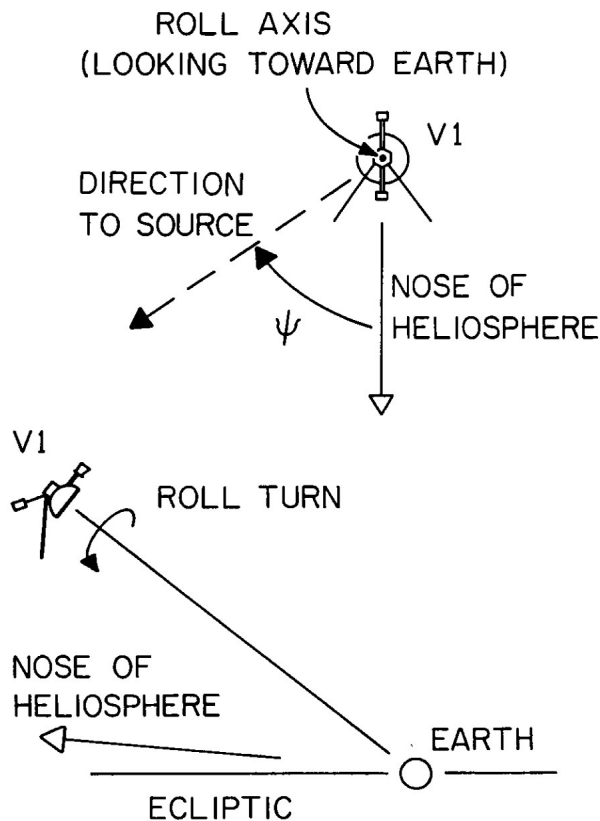


Figure 3. A sketch showing the basic geometry of a roll turn. All roll turns are performed around the axis of the spacecraft high-gain antenna, which is always pointed toward Earth. At the time of these observations, Voyager was at a latitude of about 33° above the ecliptic plane and a heliospheric radial distance of about 51.2 AU. The least-mean-square fit of Equation 1 to the observed radio emission intensities gives the azimuthal angle of arrival, Ψ , relative to a reference direction, which is taken to be a vector towards the nose of the heliosphere.

Table 1. Data Summary

Roll Turn Number	Day, Date, Year	Spacecraft Location			Roll Axis Direction		Ψ	m
		R(A.U.)	β	λ	β	λ		
1	220, Aug. 7, 1992	49.4	33.5	245.0	-33.7	63.7	$-10.4^\circ \pm 3.0^\circ$	0.29
2	311, Nov. 6, 1992	50.3	33.5	245.3	-33.0	64.8	$33.4^\circ \pm 1.6^\circ$	0.08
3	36, Feb. 5, 1993	51.2	33.6	245.6	-33.4	66.8	$21.8^\circ \pm 1.6^\circ$	0.15
4	126, May 6, 1993	52.1	33.6	245.8	-34.2	66.3	---	---
5	174, June 23, 1993	52.6	33.7	245.9	-34.2	65.4	---	---
6	218, Aug. 6, 1993	53.0	33.7	246.0	-33.9	64.8	$-43.1^\circ \pm 8.5^\circ$	0.06
7	309, Nov. 5, 1993	53.9	33.7	246.3	-33.2	65.8	$-52.4^\circ \pm 3.5^\circ$	0.13
8	336, Dec. 6, 1993	54.2	33.7	246.4	-33.2	66.4	$-63.1^\circ \pm 0.6^\circ$	0.52
9	35, Feb. 4, 1994	54.8	33.8	246.5	-33.5	67.7	$-85.1^\circ \pm 3.4^\circ$	0.15
10	125, May 5, 1994	55.7	33.8	246.7	-34.3	67.2	$31.9^\circ \pm 1.3^\circ$	0.28
11	166, June 15, 1994	56.1	33.8	246.8	-34.4	66.5	---	---
12	217, Aug. 5, 1994	56.6	33.8	247.0	-34.1	65.8	$58.9^\circ \pm 10.7^\circ$	0.61

For a rotating electric dipole antenna it can be shown that the azimuthal direction to the source is perpendicular to the antenna axis at the time of maximum signal strength. This result is exact for a circular or random polarization, but has an error if the polarization is elliptical. The error for an elliptical polarization is negligible if the source is located in the rotational plane of the antenna, but becomes increasingly large as the elevation angle of the source increases relative to the rotational plane of the antenna. Unfortunately, for the simple antenna configuration used on Voyager, it is not possible to determine the elevation angle of the source. The constraint on possible source locations is best visualized by constructing a diagram looking down on the spin plane of the antenna (i.e., along the spacecraft roll axis). Such a diagram is shown in the top panel of Figure 3. The approximate geometry viewed along the ecliptic plane is shown in the bottom panel of Figure 3. From the phase of the roll modulation the azimuthal direction to the source, Ψ , can be computed. The reference direction for the azimuth angle is taken to be the direction of the Sun's velocity relative to the local interstellar medium (ecliptic latitude and longitude of $\beta = 5.0^\circ$ and $\lambda = 254^\circ$), as given by Ajello et al. [1987]. This definition is convenient, since the nose of the heliosphere is then located at $\Psi = 0$ [see Axford, 1990].

The best fit azimuth angle, Ψ , is determined by performing a least mean square fit of the received electric field amplitude, E , to a function of the form

$$E^2 = E_0^2 \left\{ \left(1 - \frac{m}{2}\right) - \frac{m}{2} \cos [2(\Psi_A - \Psi)] \right\} \quad (1)$$

where E_0 is the maximum electric field strength, m is the modulation index, and Ψ_A is the instantaneous roll angle of the antenna axis. Since the dipole antenna pattern has two peaks per rotation the azimuth angle has two solutions, Ψ , and $\Psi + 180^\circ$. The direction of arrival is constrained to lie in a plane defined by the roll axis (i.e., the direction to the Earth) and the azimuth direction Ψ . The modulation index, m , gives the ratio of the peak-to-peak intensity of the roll modulation to the maximum intensity. The modulation index is controlled by three factors, the elevation angle of the source relative to the rotational plane of the antenna, the source size, and whatever scattering may exist between the source and the spacecraft. Unfortunately, without independent knowledge of two of these three parameters it is not possible to resolve these dependencies. The sinusoidal line in the 3.11-kHz channel of Figure 2 shows the least mean square fit of the above

equation to the measured intensities. The best fit values for this event are $\Psi = -21.8^\circ \pm 1.6^\circ$ and $m = 0.15$. Because of the 180° ambiguity, a second solution also exists, $\Psi = 158.2^\circ \pm 1.6^\circ$.

Results

The results of the direction-finding analyses at 3.1 kHz are given in Table 1 for the twelve roll maneuvers analyzed. The modulation indexes for roll turns number 3, 4, and 11 were too low to give meaningful results, so no Ψ or m values are listed for these roll turns. The remaining nine roll turns all provided good fits, with uncertainties in the azimuth angle ranging from a few tenths of a degree to about ten degrees. Plots of the radio emission intensity in the 3.11-kHz channel, the azimuth angle, and the modulation index, are shown as a function of time in Figure 4. The azimuth angles

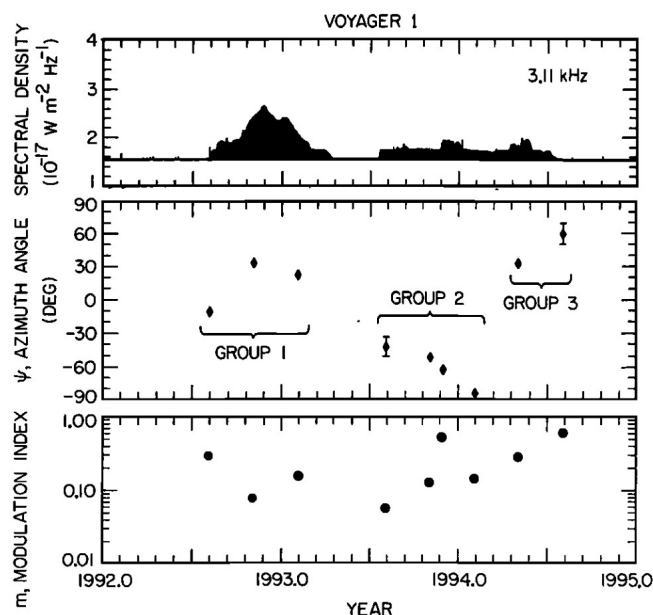


Figure 4. A three-panel plot showing the radio emission intensities in the 3.11-kHz channel and the corresponding best fit azimuth angle, Ψ , and modulation index, m . No roll modulation was observed in any of the 1.78-kHz data.

vary over a wide range, from -85.1° to 58.9° . Although the azimuth angles have considerable scatter, they are clearly not randomly distributed. Comparison with Figure 1 suggests that the directions of arrival can be arranged into three groups. Group 1 consists of the first three points, which have azimuth angles of -10.4° , 33.4° and 21.8° . These directions of arrival are from the upward-drifting bands associated with the main 1992-93 event, at times ranging from about 1992.6 to 1993.2 (see Figure 1). These bands are generally consistent with a source near the nose of the heliopause (i.e., $\Psi = 0$). Group 2 consists of the next four points, which have azimuth angles of -43.1° , -52.4° , -63.1° , and -85.1° . These directions of arrival come from a pair of considerably weaker bands drifting upward in frequency at times ranging from about 1993.6 to 1994.1 (see Figure 1). These bands appear to originate from a source at relatively large angles to the left of the nose of the heliosphere (as viewed looking along the roll axis toward the Earth, see Figure 3). Group 3 consists of the last two points, which have azimuth angles of 31.9° and 58.9° . These directions of arrival come from a weak band drifting upward in frequency at times from about 1994.2 to 1994.6 (see Figure 1). This band appears to originate from a source at a relatively large angle to the right of the nose of the heliosphere (on the opposite side relative to Group 2). The modulation indexes for all three groups vary over a large range, from as low as 0.06 to as high as 0.61, with no obvious overall trend. Note that the modulation index near the time of highest intensity (roll-turn maneuver number 2) is among the lowest ($m = 0.08$), whereas the highest modulation index ($m = 0.61$) occurs near the time of lowest intensity (roll-turn maneuver number 12). The high modulation index for roll turn number 12 is possibly due to the fact that when the intensity is very low, the modulation index becomes extremely sensitive to the exact choice for the background receiver noise level, and therefore may not be very accurate.

Discussion

The most striking aspect of the direction-of-arrival measurements is the large amount of scatter in the azimuth angle. Based on the early direction-finding measurements of Gurnett et al. [1993], which involved only the first three roll maneuvers (i.e., Group 1 in Figure 4), it appeared that the heliospheric radio emission originated from near the nose of the heliosphere. However, our subsequent measurements now show that the radio emission can also originate from regions well away from the nose of the heliosphere. If the discrete upward drifting bands are indicative of individual interplanetary shocks interacting with the heliopause, as suggested by the model of Gurnett et al. [1993], it is possible that the variations in the azimuth directions might simply reflect the azimuthal directions of the coronal mass ejections responsible for the individual shocks. We have investigated this possibility, but without much success. The problem is that because of the long travel time and the uncertainty in the shock propagation speed it is very difficult to uniquely associate a coronal mass ejection with an upward drifting band. For a discussion of the candidate coronal mass ejections that can be plausibly associated with these radio emission events see Gurnett and Kurth [1995]. Also, because of the complicated geometry, the measured azimuth angle cannot be simply related to the solar latitude and longitude of the coronal mass ejection without making additional unsupported assumptions about the radial distance to the source.

The large spread in the arrival directions could also suggest another alternate explanation, namely refraction by large-scale density fluctuations in the solar wind. Recently, Cairns [1995, 1996] has analyzed the scattering of radio waves in the outer heliosphere, and has concluded that scattering by solar wind density fluctuations is quite significant. For example, Cairns estimates that radiation approaching the Sun from a distant point source at 3 kHz

scatters through an average angle of 1.0 radians (57°) by the time it reaches 50 AU, and that the angular size of a point source broadens to the point that the modulation index measured by a rotating antenna could be as large as 0.2 to 0.5. His estimates of the modulation index are comparable to those reported in this study. Thus, it appears that scattering by density fluctuations in the solar wind could be a very important factor. Finally, we comment on the possibility that the radiation could be trapped in the heliospheric density cavity, as has been suggested by Czechowski and Grzedzielski [1990]. Since radiation trapped in a cavity should be isotropic, the persistent occurrence of detectable roll modulation at 3.11 kHz appears to rule out the possibility that the rising bands observed at this frequency are trapped in a cavity. However, the absence of roll modulation at 1.78 kHz would be consistent with trapping in a cavity. On the other hand, the absence of roll modulation at 1.78 kHz could also be due to scattering, which is expected to increase rapidly at lower frequencies [see Cairns, 1995, 1996].

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