Table 1. Correlation of Faraday rotation transients and radio bursts in the dekametric range.

Dekametric noise burst* (U.T.)	Intensity†	Velocity ($10^3 \times$km/sec)
4 November 1968 (1700 U.T.) (10.9 solar radii from solar center)		
1244		0.45
1305		.49
1457	2	.93
1502	2	.97
1522	2	1.17
8 November 1968 (1730 U.T.) (8.6 solar radii from solar center)		
1631	3	1.49
12 November 1968 (1900 U.T.) (6.2 solar radii from solar center)		
1643	3	0.44
1647	2	.43
1726	3	.64
1746	1	.82

* All bursts in the dekametric range were of type III. † Intensity scale: 3 > 2 > 1.

a change in the sign of the particles in the ionosphere or a large concentration of electrons in a region where the longitudinal component of the magnetic field is in the opposite direction to the magnetic field of the earth. These considerations demonstrate that the phenomena were produced by plasma near the sun.

In the third event, the base line was approximately 87°. The reason for the change in base line appears to be an increase in the steady-state plasma density and magnetic field as the line of sight approached the sun. At the same time that these polarization measurements were being made, Goldstein (*4*) was using the same antenna to measure spectral broadening. Enhanced spectral broadening was observed during all three of the Faraday rotation transients. Enhancement of spectral broadening is consistent with an increase in the turbulence and density of the coronal portion of the line of sight.

Two possible explanations for the observed transient polarization effects are (i) a quasi-stationary structure which is probed as the line of sight is swept through, or (ii) a moving plasma concentration which is ejected by the sun. If we assume that we are seeing fairly stationary objects, then we can determine one dimension of these objects in terms of the time it took to sweep through them. Since the duration of each event was approximately 2 hours and the velocity of the line of sight relative to the plane containing the sun was approximately half a solar radius per day, the dimensions of these objects are of the order of 0.04 solar radius. If, on the other hand, we were observing a high-velocity concentration of plasma ejected from the sun, we would expect to find correlation with surface effects. On the 3 days that these transients were observed, there were active areas observed near the west limb where the observations were made. These areas were observed (*5*) by means of several mapping surveys at different radio frequencies. The events were poorly correlated with optical flares. However, in each case it appears that noise-burst events in the dekametric wavelength region preceded these transient Faraday rotation phenomena. On 8 November, the only events in the dekametric range that were reported prior to the Faraday rotation transient occurred between 1631 and 1632 and were classified, respectively, as intensity 1 and 3. On both 4 and 12 November there were many bursts. All bursts with wavelengths in the dekametric range which occurred within 11 hours before the Faraday rotation transient are listed in Table 1 along with the reported intensity (where available). Furthermore, we have calculated the velocity that the plasma clouds must have had if they were produced by the same mechanism that produced the noise bursts in the dekameteric range (Table 1).

Unfortunately, the locations of the origins of these noise bursts in the dekametric range on the photosphere were not known. Only three transients were observed in a period of high solar activity; thus the significance of the correlation with noise bursts is not known at this time. An effort is being made to see if other solar and interplanetary phenomena can be correlated with the Faraday rotation transients.

G. S. Levy, T. Sato
B. L. Seidel, C. T. Stelzried
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103
J. E. Ohlson, W. V. T. Rusch
Department of Electric Engineering, University of Southern California, Los Angeles 90007

References and Notes

1. A. J. Siegmeth, *Space Program Summary 37–50* (Jet Propulsion Laboratory, Pasadena, Calif., 31 March 1968), vol. 2, pp. 17–27; Pioneer Project Office, *Pioneer 6 Mission* (Ames Research Center, National Aeronautics and Space Administration, Moffett Field, Calif., May 1967).
2. D. Bathker, T. Sato, C. T. Stelzried, in preparation; J. E. Ohlson, G. S. Levy, C. T. Stelzried, in preparation.
3. I. C. Browne, J. V. Evans, J. K. Hargreaves, W. A. S. Murray, *Proc. Phys. Soc. (London)* **69B**, 901 (1956); G. J. Aitchison and K. Weekes, *J. Atmos. Terrest. Phys.* **14**, 236 (1959); F. B. Daniels and S. J. Bauer, *J. Franklin Inst.* **267**, No. 3, 187 (1959).
4. R. M. Goldstein, *Science*, this issue.
5. *Solar Geophysical Data No. 293* (Environmental Science Services Administration, Washington, D.C., January 1969).
6. We acknowledge the cooperation and support of the personnel at the Pioneer Project Office and the Deep Space Network, and particularly of D. Girdner and the operational personnel at the Jet Propulsion Laboratory Mars site. We also thank D. Bathker, F. McCrea, and R. Cormack for their work in developing the microwave portion of the system. W. Peterschmidt supplied the servo electronics, and B. Parham assisted with the digital instrumentation. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory under NASA contract NAS 7-100.

21 April 1969; revised 9 July 1969

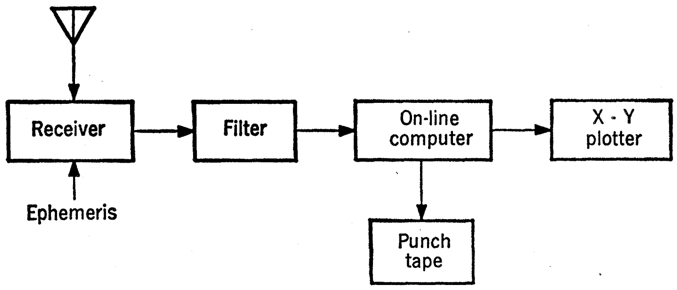
Superior Conjunction of Pioneer 6

Abstract. *Spectrograms of the radio signals from Pioneer 6 were taken as the spacecraft was occulted by the sun. The spectral bandwidths increased slowly at first, then very rapidly at 1 degree from the sun. In addition, six solar "events" produced marked increases of bandwidth lasting for several hours. The received signal power seemed unaffected by the solar corona.*

The remarkable lifetime of the Pioneer 6 spacecraft, still operating 3.5 years after launch, has provided us with a rare opportunity to examine the solar corona. Pioneer 6 was injected into solar orbit 16 December 1965 and ever since has reliably transmitted to earth by S-band telemetry the results of its scientific experiments. Last November Pioneer 6 traveled directly behind the sun so that the telemetry signals passed through the interesting regions of the corona.

The corona is a very difficult object to study. The best data have been obtained only during the rare event of a total solar eclipse. Recently, radio astronomers have observed the scintillation of radio stars as they pass behind the sun, in order to draw conclusions about the corona. Radio stars are wide-band sources of radiation, and scintillation can be thought of as a manifestation of multipath phenomena. The Pioneer 6 signals, on the other hand, were extremely narrow-band (monochromatic) and give information of an entirely different kind about the corona.

During the superior conjunction of



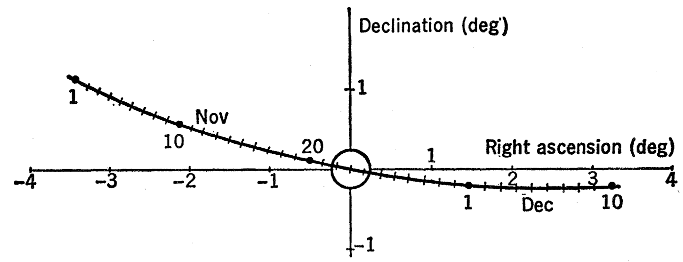


Fig. 1 (left). Block diagram of the experimental system. Fig. 2 (right). Angles made by Pioneer 6, the earth, and the sun as a function of date.

Pioneer 6 we observed the spectrum of the signal and its broadening as the rays passed close to the sun. We observed also a short-term (several hours) broadening of the spectra induced by certain solar events. During our measurements of the spectra of the signals, the direction of the polarization of the waves was monitored by Levy and his group (*1*). They observed Faraday rotation of the polarization which correlated strongly with the same events.

Pioneer 6 normally transmits telemetry composed of a spectrally pure carrier wave plus a set of modulation side bands. In our experiment, only the carrier wave (nominally at 2295 Mhz) was observed. The side bands, separated from the carrier wave by multiples of 2 khz, were removed by filtering.

A functional block diagram of the experiment is shown in Fig. 1. The 210-foot (64-m) antenna of the Jet Propulsion Laboratory was used. This remarkable antenna has a beam width of only 0.14 degree at 2300 Mhz (S-band). Such a narrow beam width was necessary for this experiment in order that we might be able to discriminate between the signal and the powerful radio noise emitted by the sun. Normally, the antenna-receiver system is extremely sensitive, having an equivalent noise temperature of only 25° K. As the angle made by Pioneer 6, the earth, and the sun diminished, the system temperature rose, until at 1 degree the temperature was between 200° and 300°K. The signal disappeared when this angle was less than 1 degree, apparently an effect of the corona. The signal-to-noise ratio would still have been adequate for detection at smaller angles.

Because of the orbital velocities of Pioneer 6 and the earth, the Doppler frequency of the signal shifted on the order of several hundred kilohertz. In addition, the earth's spin imparted an additional Doppler shift of 15 khz per day. In order to compensate for these effects, the receiver was tuned continuously according to an ephemeris. This automatic tuning was accurate to 0.05 hz.

A slight frequency instability remained, due to the spacecraft oscillator. A slow drift of 14 hz/day, presumably of thermal origin, was observed. In addition, a more erratic drift of up to 1 or 2 hz per 15 minutes was observed.

The frequency band which was observed, 100 hz, was the same for each spectrogram taken. This bandwidth was defined by a filter at the last stage of the receiver. A small computer (Scientific Data Systems model 920), programmed with a version of the fast Fourier transform, produced all of the spectrograms on-line. Each group of 1024 samples of the signal wave form was transformed to produce 512 points on the spectrum; this resulted in a frequency resolution of 0.2 hz over the 100-hz bandwidth. Averaged spectra were displayed on an *x-y* plotter and stored on punched tape for further processing.

Data were taken almost daily from 31 October to 8 December 1968. During that time, Pioneer 6 passed from an angular distance from the sun of 3.5 degrees, through geometric occultation, to a position 2.5 degrees on the other side of the sun. Figure 2 shows the angle made by Pioneer 6, the earth, and the sun during the time of interest.

All of the data were collected in the form of spectrograms. Each spectrogram is the result of about 15 minutes of

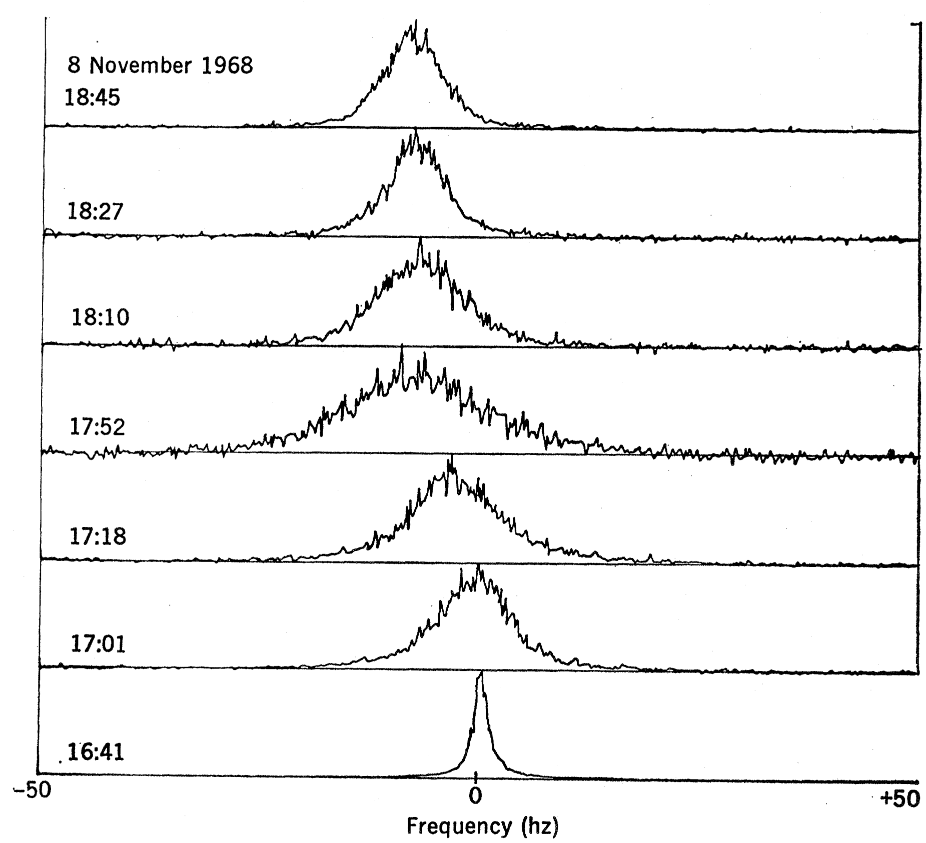


Fig. 3. Sample spectrograms taken on 8 November 1968, showing the effects of a solar event. Each spectrogram is the result of 15 minutes of averaging time.

Table 1. Times of observation.

Date (1968)	Time	Event
10/31	1800–2300	None
11/2	2211–2300	Event 2244
11/3	1622–1815, 1900–1950	None
11/4	1540–1645, 1840–1927	Event 1555–1645
11/5	1606–1720, 2104–2248	None
11/6	1635–1913	None
11/7	2110–2145	None
11/8	1641–2100	Event peak 1800
11/9	1653–1708, 1741–1940	None
11/10	1557–1817	None
11/11	1624–1915	Event peak 1707; gradual reduction to 1915
11/12	1613–2105	Events 1804–2105; peak at 1900
11/13	1640–2236	None
11/14	1648–1900, 1930–2050	None
11/15	1717–1915, 2022–2354	None
11/16	1538–1731	None, but no signal found 1923–2232
11/17	1539–1635	None
11/29	1747–1850, 1920–2100	None
11/30	1539–2005, 2130–2350	None
12/1	1533–1922, 2054–2204	None
12/2	1536–1753	None
12/3	1534–1860	Event peak 1700; gradual taper-off
12/4	1619–1800	Minor peak 1630; gradual taper-off
12/5	1555–1745	Minor peak 1710
12/6	1633–1800	None
12/7	1547–1800	None
12/8	1600–1800	None

observation. The actual schedule of observations each day was variable, depending on conflicting demands for the antenna as well as the results of the spectral measurements. During the occasions of unusual spectral activity, more observing time was made available. No data were taken when Pioneer 6 was closer than 1 degree from the sun as the signals there were not detectable. All together, over 450 spectrograms were taken during the experiment.

Each spectrogram was processed to provide three parameters of interest: signal power, center frequency, and bandwidth. The actual quantity measured $P(f)$ is the sum of the signal spectrum $S(f)$ and the noise spectrum N (assumed to be flat), both having passed through the system filter $H(f)$

$$P(f) = [S(f) + N]\, H(f)$$

Thus the first task in the data reduction was the subtraction of the noise spectrum and the removal of the effects of the system filter. To accomplish this, a calibration spectrum $Q(f)$ was measured, in which only system noise was measured with the receiver offset from the signal

$$Q(f) = aN\, H(f)$$

where a accounts for a possible change in system gain.

It can be seen from the equations above that

$$S(f)/N = P(f) \int_C P(f)df / Q(f) \int_C P(f)df - 1$$

where C is an interval which contains no signal. We used the first quarter plus the last quarter of the spectrum for this interval.

Signal power P_s was obtained by integration of the spectrum over the bandwidth and removal of the normalization N

$$P_s = \left(\int_0^{100} \frac{S(f)}{N}\, df \right) kT$$

where k is the Boltzmann constant and T is the system temperature, was measured separately by reference to a standard noise source. The measurement of P_s produced considerable scatter (± 2 db) caused primarily by the widely fluctuating system temperature. Minor side lobes of the antenna would rotate across the disk of the sun and cause tempera-

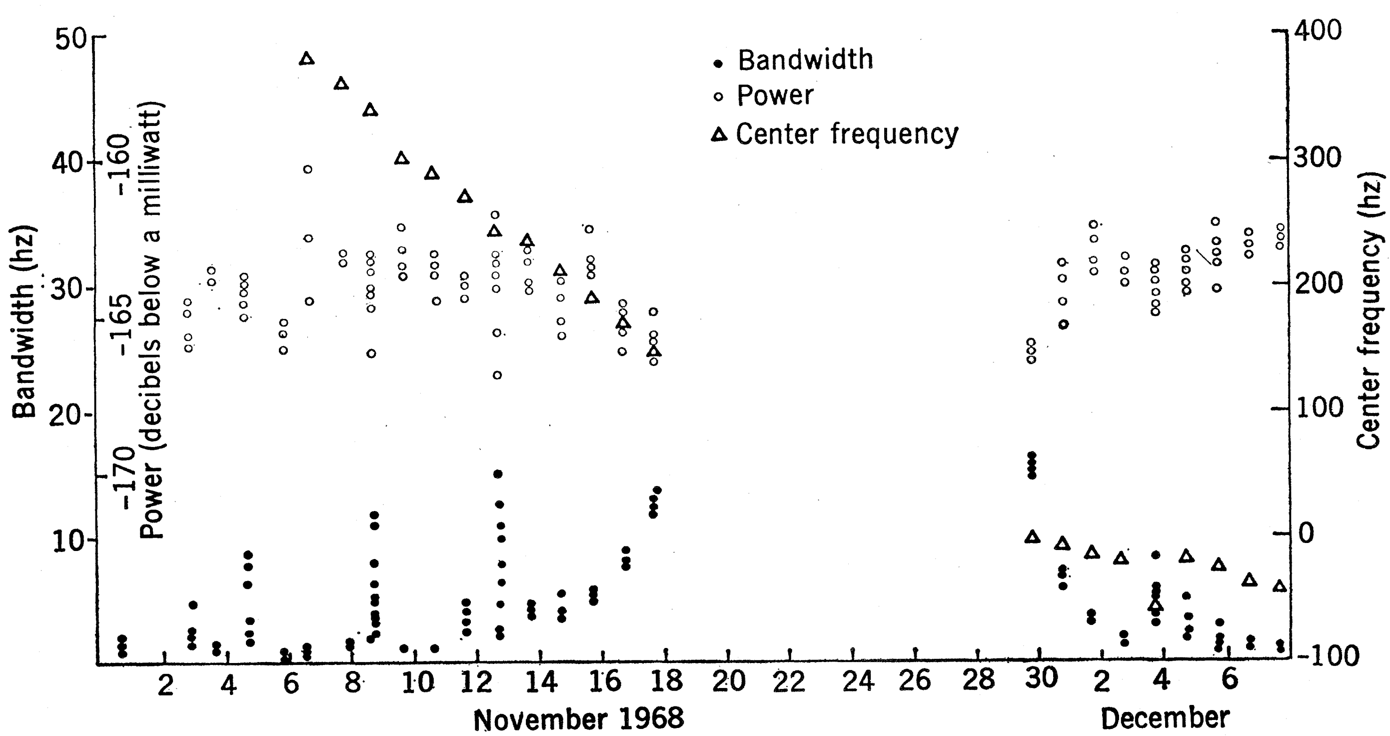


Fig. 4. Bandwidth, center frequency, and power of the Pioneer 6 signals as a function of date.

ture variations of up to several hundred degrees.

The center frequency f_c of each spectrum was estimated as that frequency which splits the received power into equal halves; that is

$$\int_0^{f_c} S(f)df = \int_{f_c}^{100} S(f)df$$

The bandwidth B of each spectrum was estimated, similarly, as that band which contains the central half of the signal power

$$\int_0^{f_1} S(f)df = 1/4\, P_s$$

$$\int_{f_2}^{100} S(f)df = 3/4\, P_s$$

$$B = f_2 - f_1$$

Figure 3 is a sequence of spectrograms taken on 8 November when Pioneer 6 was 2.4 degrees away from the sun and approaching the sun. This figure shows the effect of increased turbulence in the corona, presumably caused by some solar "event." The effects lasted several hours, the decay being much slower than the onset. Only six such events were observed. Most of the spectra were constant, showing only a slow thermal drift of the spacecraft frequency.

The results of the experiment are summarized in Fig. 4, where the bandwidth and power of each spectrum are plotted against the date. The average center frequency for each day is also plotted.

Two separate phenomena are manifested in Fig. 4. The first is the occasional marked increase in bandwidth caused by the solar events mentioned above. The second is a background bandwidth of about 1 hz, due to frequency instabilities of the system, which appeared when Pioneer 6 was far from the sun. This component increased slowly as the rays penetrated more deeply into the corona. Finally, the bandwidth increased very rapidly at about 1 degree from the sun, just before the signal disappeared. The effect is as though the solar radius were 1 degree at S-band.

The measurements of power do not seem to correlate with those of bandwidth. In particular, the power fluctuations do not correspond to the sudden increases in bandwidth induced by the solar events. Although there is considerable scatter associated with the power estimates, they are on the whole relatively constant throughout the experiment. The only exception would be the 2 days at 1 degree when the power appears to be somewhat smaller.

The nature of the solar events is not known. They do not appear to correlate well with solar flares or with the apparition of sunspots on the solar limb or with the S-band solar flux. They may be the result of streamers sweeping across the line of sight.

In the hope of establishing a correlation of the spectral broadening with other solar phenomena, I present in Table 1 the times and durations of the observed events. Table 1 also gives the times when spectrograms were taken but no events were observed. A full set of spectrograms will soon be available (*2*).

R. M. GOLDSTEIN
Jet Propulsion Laboratory, California Institute of Technology, Pasadena

References and Notes

1. G. S. Levy, T. Sato, B. L. Seidel, C. T. Stelzried, J. E. Ohlson, W. V. T. Rusch, *Science*, this issue.
2. R. M. Goldstein, *Jet Propulsion Lab. Tech. Rep. TR 32-1435* (1969).
3. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract No. NAS 7-100.

24 June 1969

Seismic Activity and Faulting Associated with a Large Underground Nuclear Explosion

Abstract. *The 1.1-megaton nuclear test Benham caused movement on previously mapped faults and was followed by a sequence of small earthquakes. These effects were confined to a zone extending not more than 13 kilometers from ground zero; they are apparently related to the release of natural tectonic strain.*

On 19 December 1968, a 1.1-megaton nuclear explosion was detonated 1.4 km beneath Pahute Mesa at the Nevada Test Site. This explosion, code named Benham, caused movement on nearby faults and was followed by a sequence of earthquakes lasting several months. Such phenomena have been observed for earlier explosions, but this was the first test that was monitored by a dense network of seismograph stations capable of locating the aftershocks with high accuracy and defining the *P*-wave first-motion pattern in sufficient detail to determine the earthquake mechanism.

Movements along faults or fractures are observed near most underground tests. When these effects were first observed, it was thought that they were probably related either to deformations caused by the formation of the underground cavity or to compaction of the rocks in the vicinity of the test. As the number and size of tests increased, however, it became apparent that these explanations were inadequate. Displacements as great as 1 m along virtually continuous fractures extending for distances of as much as 8.5 km were observed at both Yucca Flat and Pahute Mesa in southern Nevada, and Hot Creek Valley in central Nevada. Such movement was not entirely unexpected; it was in fact anticipated for the Aardvark event and reported (*1*). Many subsequent occurrences of fault movement have been reported (*2, 3*). Since 1966, a number of nuclear tests have caused fault movement in bedrock that could not be explained by differential compaction of poorly consolidated alluvium. On those faults where the direction of previous vertical movement could be determined, the movement caused by the explosion was always in the same direction as the last recognizable tectonic movement.

The first reports of seismic activity following underground nuclear explosions were made by Westphal (*4*), who described the intense seismicity near the detonation point and concluded that most of the earthquakes were associated with the collapse of the cavity formed by the explosion. A few earthquakes, however, were located too far from the cavity to be associated with the collapse phenomena.

A number of investigators studying the radiation pattern of seismic waves have reported that their observations could not be explained by a simple explosive source in a homogeneous medium. Press and Archambeau (*5*) reported a strong excitation of horizontally polarized shear waves (*SH* waves) and examined the possibility that these waves might result from insertion of a spherical cavity in a strained medium. They concluded that a cavity the size of the crushed zone would not release sufficient tectonic energy to produce the observed amplitudes. Brune and Pomeroy (*6*), on the basis of observation of a surface-wave radiation pattern with a double-couple symmetry, reported that the Hardhat explosion had triggered release of tectonic strain. They concluded that movement along fault planes extending beyond the