The ISEE-1 and ISEE-2 Plasma Wave Investigation

D. A. GURNETT, F. L. SCARF, R. W. FREDRICKS, AND E. J. SMITH

Abstract—The ISEE-1 and ISEE-2 plasma wave investigation is designed to provide basic information on wave-particle interactions in the earth's magnetosphere and in the solar wind. The ISEE-1 plasma wave instrument uses three electric dipole antennas with lengths of 215, 73.5, and 0.61 m for electric-field measurements, and a triaxial search coil antenna for magnetic-field measurements. The ISEE-2 plasma wave instrument uses two electric dipoles with lengths of 30 and 0.61 m for electric-field measurements, and a single-axis search coil antenna for magnetic-field measurements. The ISEE-1 plasma wave instrumentation provides a comprehensive determination of wave characteristics over a broad frequency range, including high-frequency resolution spectrum scans, simultaneous high-time resolution electric- and magnetic-frequency-spectrum measurements, wave normal and Poynting flux measurements, and wide-band waveform measurements. The basic frequency range of the ISEE-1 measurements is 5.62 Hz-311 kHz, although wide-band waveform measurements can be made in selected frequency ranges up to 2.0 MHz using a special long baseline interferometer mode of operation. The ISEE-2 plasma wave instrumentation consists of a 16-channel spectrum analyzer covering the frequency range from 5.62 Hz to 31.1 kHz and a wide-band waveform receiver with the capability of making waveform measurements in selected frequency ranges up to 2.0 MHz.

I. INTRODUCTION

THE ISEE-1 AND ISEE-2 plasma wave instruments are designed to provide high sensitivity measurements of plasma waves in the earth's magnetosphere over the frequency range from about 5 Hz to 300 kHz. The electric- and magnetic-field components of plasma waves are detected using a combination of electric dipole antennas and search coil magnetic antennas. Signals from these antennas are analyzed by onboard spectrum analyzers to provide both high-frequency resolution and high-time resolution frequency spectrums. Electric- and magnetic-field waveforms are also transmitted to the ground to provide high-resolution frequency-time spectrograms and long baseline interferometry measurements between the two spacecrafts. On the ISEE-1 spacecraft, simultaneous amplitude and phase measurements are made between the various antennas to determine the wave normal direction and Poynting flux.

The primary scientific objectives of the ISEE-1 and ISEE-2 plasma wave investigation can be summarized as follows.

A. Resolve Space-Time Relationships

The ISEE-1 and ISEE-2 spacecrafts offer a unique opportunity to resolve spatial and temporal variations for a wide variety of magnetospheric and solar wind plasma wave phenomena. With simultaneous or nearly simultaneous measurements from both spacecrafts, it will be possible to determine the motion of magnetospheric boundaries such as the bow shock, the magnetopause, the plasma sheet, and the neutral sheet, and solar-wind boundaries such as interplanetary shock waves, tangential discontinuities, and rotational discontinuities. Because of the very short time scale of plasma wave phenomena and the very good time resolution provided by the wide-band telemetry, it will be possible to make very accurate determinations of boundary motions from the plasma wave measurements. Cross-correlation and time-delay measurements between the two spacecrafts will allow propagating waves to be distinguished from variations caused by the convective transport of irregularities past the spacecraft. For propagating waves, time-delay measurements will give the

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Manuscript received April 3, 1978.

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0018-9413/78/0700-225$00.75 © 1978 IEEE

group and phase velocity of the waves, thereby providing information essential for the proper identification of the mode of propagation of the waves.

B. Wave-Particle Interactions

One of the primary purposes of this investigation is the study of wave-particle interactions which occur in the magnetosphere and solar wind. Previous studies have shown that plasma waves play a fundamental role in determining the nonthermal plasma distributions in the magnetosphere and solar wind [1], [3]. In the earth's bow shock, intense electrostatic and whistler-mode turbulence act to heat the incoming solar wind at the shock boundary. Upstream of the bow shock, electron plasma oscillations are produced by suprathermal electrons streaming into the solar wind from the bow shock. Waves are also detected in the interplanetary medium in association with shocks and other discontinuities. Within the earth's magnetosphere, whistler-mode instabilities driven by the anisotropy in the electron pitch angle distribution are believed to control the trapped particle population by scattering the particles into the loss cone via resonant wave-particle interactions. In the auroral zone, intense low energy electron precipitation is known to be associated with intense whistler-mode "auroral hiss" emissions and with intense radio emissions escaping from the earth's magnetosphere at kilometer wavelengths.

Although many of the general features of these wave-particle interactions are known, in most cases a complete verification and identification of the plasma instability mechanisms involved has not been possible because of incomplete information on the relevant plasma parameters. The excellent plasma- and energetic particle instrumentation on ISEE-1 and ISEE-2, with the ability to provide full three-dimensional velocity distribution functions together with the complete wave diagnostic measurements available from the plasma wave instrumentation, are expected to provide a major advance in the detailed analysis and understanding of wave-particle interactions.

C. Long Baseline Interferometry

Because essentially identical receivers are being flown on ISEE-1 and ISEE-2, it will be possible to perform a variety of long baseline interferometry experiments on both terrestrial and extraterrestrial radio sources at selected frequencies up to 2 MHz. Together with identical receivers which will be flown on the DE-A spacecraft, these measurements will provide low-frequency radio-interferometry measurements over baseline distances of several earth radii, much longer than has ever been attempted previously. It is expected that these measurements will provide important new information on the angular size and location of radio emissions from the earth, from the sun, and from other planetary radio sources such as Jupiter and Saturn.

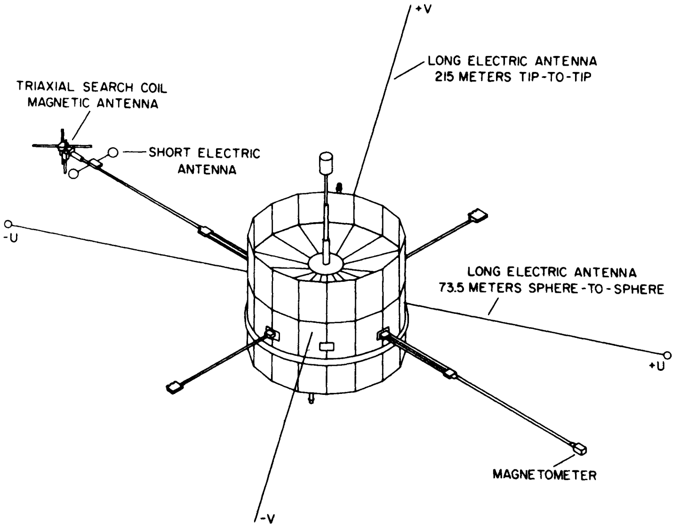

Fig. 1. The configuration of the plasma wave electric- and magnetic-field antennas on ISEE-1. The u-axis antenna consists of two 8-cm diameter spheres mounted on the ends of a multiconductor cable which provides power and signal returns for preamplifiers inside of each sphere. The v-axis antenna consists of a fine wire with the preamplifiers mounted inside the spacecraft at the base of each antenna element. The triaxial search coil magnetic antenna consists of three high permeability cores each wound with 10 000 turns of fine wire and three preamplifiers to provide signals to the main electronics package in the spacecraft.

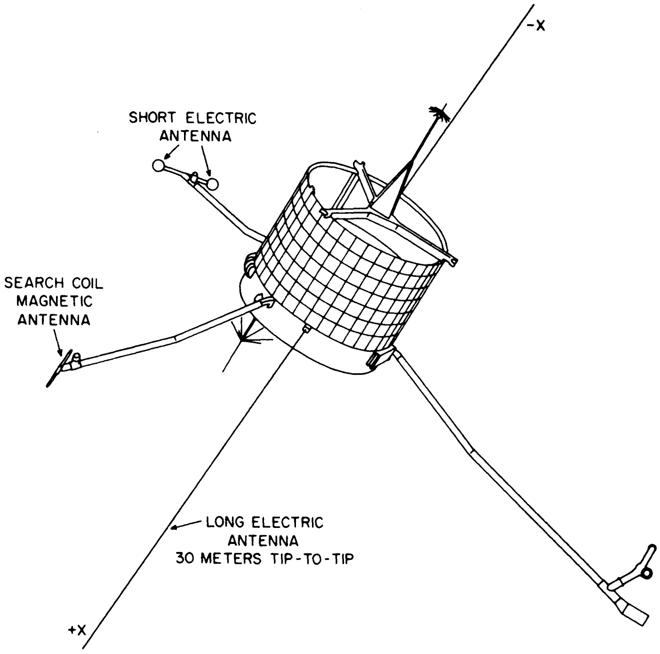

Fig. 2. The configuration of the plasma wave electric- and magnetic-field antennas on ISEE-2. The x-axis antenna consists of a fine wire which is extended by centrifugal force from a drum inside the spacecraft. The short electric antenna and the search coil antenna are identical to ISEE-1.

II. INSTRUMENT DESCRIPTION

A. Antennas

The location and orientation of the various plasma wave antennas on ISEE-1 and ISEE-2 are shown in Figs. 1 and 2. On ISEE-1, the plasma wave antennas consist of: 1) a two-sphere electric antenna (u axis) with a sphere-to-sphere separation of 73.5 m which is shared with the Mozer quasi-static electric-field experiment, 2) a fine wire electric dipole antenna (v axis) with a tip-to-tip length of 215 m which is shared with the Heppner dc electric-field experiment, 3) a short two-sphere electric antenna with a sphere-to-sphere separation of 0.61 m

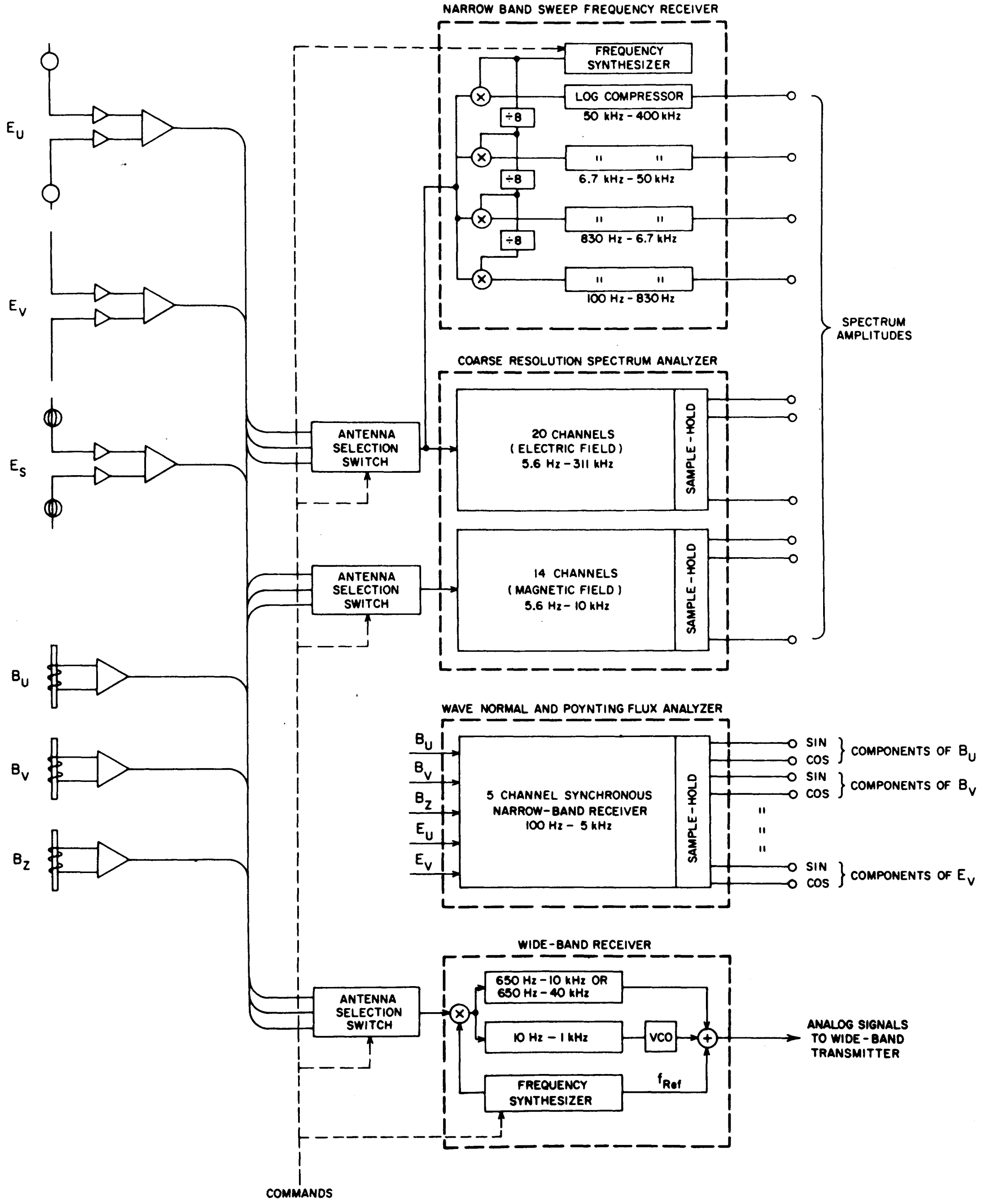

Fig. 3. A block diagram of the plasma wave instrument electronics on ISEE-1.

mounted on a boom approximately 3 m from the spacecraft, and 4) a triaxial search coil magnetic antenna mounted on the same boom as the short electric antenna approximately 3.25 m from the spacecraft. The spheres on the u axis antenna have a diameter of 8.0 cm and each contains a high-impedance preamplifier which provides signals to the main electronics box. The search coil magnetic antennas each contain a high permeability μ-metal core 16 in long, wound with 10 000 turns of wire and a preamplifier. The coil sensitivity constant is 35 $\mu V/\gamma Hz$ and the upper cutoff frequency is 10 kHz. On ISEE-2, the plasma wave antennas consist of: 1) a fine-wire electric dipole antenna (x axis) with a tip-to-tip length of 30 m, 2) a short electric antenna identical to ISEE-1, and 3) a single-axis search coil magnetic antenna identical to the search coil antenna used on ISEE-1.

B. Electronics Instrumentation

The basic philosophy in the design of the ISEE plasma wave electronics instrumentation is to provide a very comprehensive set of wave measurements on ISEE-1 and only those measurements on ISEE-2 which are essential to resolve space-time differences. Block diagrams of the electronics instrumentation are shown in Figs. 3 and 4.

1) ISEE-1: The ISEE-1 plasma wave instrumentation consists of four main elements: 1) a narrow-band sweep frequency receiver, 2) a high time resolution spectrum analyzer, 3) a wave normal analyzer, and 4) a wide-band receiver. These elements can be connected to the six plasma wave antennas in various combinations by antenna selection switches as shown in Fig. 3.

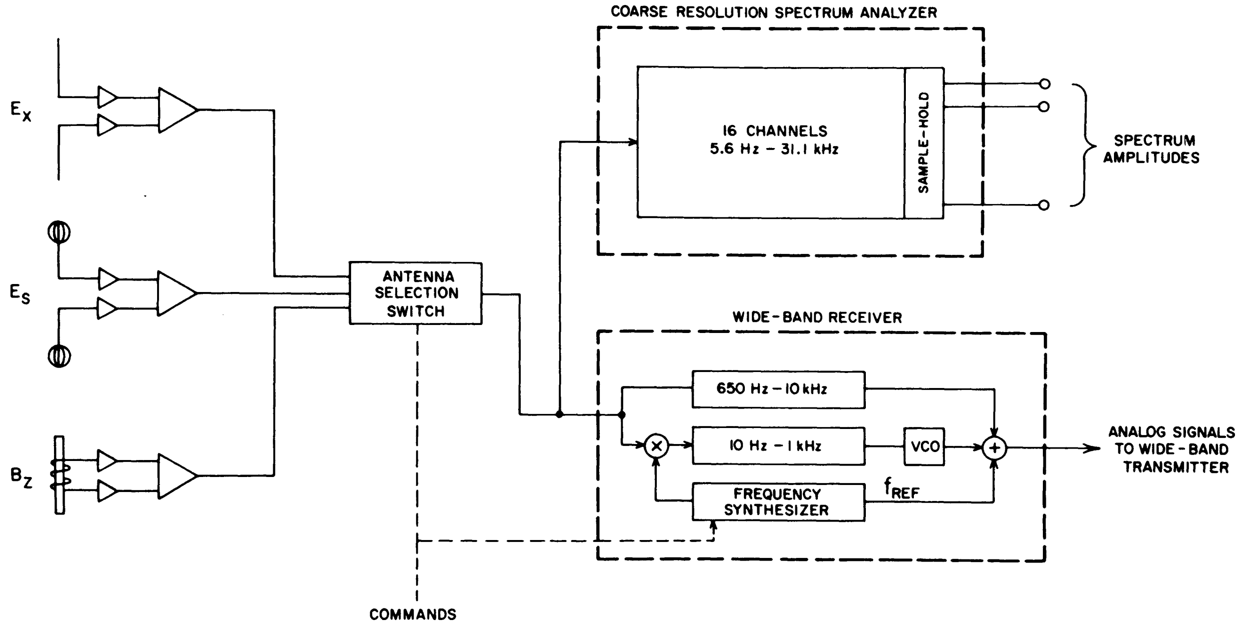

Fig. 4. A block diagram of the plasma wave instrument electronics on ISEE-2. The center frequencies and bandwidths of the 16-channel spectrum analyzer and wide-band receiver are the same as for ISEE-1.

The narrow-band sweep frequency receiver is intended to provide very high-resolution frequency spectrums with low-time resolution for analyzing relatively steady narrow-band emissions such as upper hybrid resonance noise, electron plasma oscillations, and electron cyclotron harmonics. The sweep frequency receiver has 32 frequency steps in each of four bands covering the frequency range from approximately 100 Hz to 400 kHz. The frequency steps are logarithmically spaced with a frequency resolution of about 6.5 percent. The time for a complete sweep is 32 s. The output of the receiver is a voltage proportional to the logarithm of the signal strength. The dynamic range of the receiver is 100 dB in the lowest three frequency bands, and 80 dB in the highest frequency band. Because the time resolution of this receiver (32 s) is greater than the typical delay times for waves propagating between the two spacecrafts, this receiver is only included on ISEE-1.

High time resolution spectrum measurements are obtained from the coarse resolution spectrum analyzer shown in Fig. 3. This spectrum analyzer consists of a 20-channel analyzer covering the range from 5.62 Hz to 311 kHz, and a 14-channel analyzer covering the range from 5.62 Hz to 10 kHz. These analyzers have relatively coarse frequency resolution, with four frequency channels per decade and bandwidths of ±15 percent up to 10 kHz, and ±7.5 percent for 10 kHz and above. The center frequencies and bandwidths of the 20- and 14-channel analyzers are identical. The 20-channel analyzer is nominally intended for electric field measurements (which extend up to higher frequencies than the magnetic measurements), and the 14-channel analyzer is nominally intended for magnetic-field measurements. All channels are sampled simultaneously so that electric-to-magnetic-field ratios can be accurately determined. The outputs from the spectrum analyzers are voltages proportional to the logarithm of the field strength with a dynamic range of 110 dB. The analyzer outputs are converted to an 8-bit binary number for transmission by the spacecraft data system. The sampling rate is 1 sample/s for each channel in the low data rate and 4 sample/s in the high data rate.

The wave normal analyzer is intended to provide detailed phase and amplitude measurements between the various electric- and magnetic-field components for purposes of computing the wave normal direction and Poynting flux. The wave normal analyzer consists of five narrow-band frequency conversion receivers all tuned to the same frequency. These receivers are connected to the E_u, E_v, B_u, B_v, and B_z antennas. The relative phase of the signals in all five receivers is preserved by using the same frequency conversion signal to each receiver. Each receiver produces two outputs which correspond to the cosine and sine components (or real and imaginary parts) of the signal being detected by that channel. The sine output is obtained by shifting the phase of the frequency conversion signal by 90°, relative to the frequency conversion signal for the cosine output. The ten sine and cosine outputs are all sampled simultaneously and held for transmission by sample-and-hold circuits. The bandwidth of the wave normal analyzer is 10 Hz and the center frequency can be tuned to any one of 32 frequencies from 100 Hz to 5 kHz, or can be commanded to step through all 32 frequencies at a rate of one step every 32 s. The receivers have a digital automatic gain control which maintains the output amplitudes within the proper dynamic range. The automatic gain control has 16 discrete gain steps and is updated once every second.

The wide-band receiver is intended to condition electric and magnetic-field waveforms for transmission to the ground via the special-purpose analog transmitter. This receiver also provides the signals for long baseline interferometer measurements between the two spacecrafts. Because of the large dynamic range of the received signals and the low signal-to-noise ratio of the analog telemetry link, an automatic gain control is used to maintain a nearly constant signal amplitude into the wide-band transmitter, independent of the amplitude of the re-

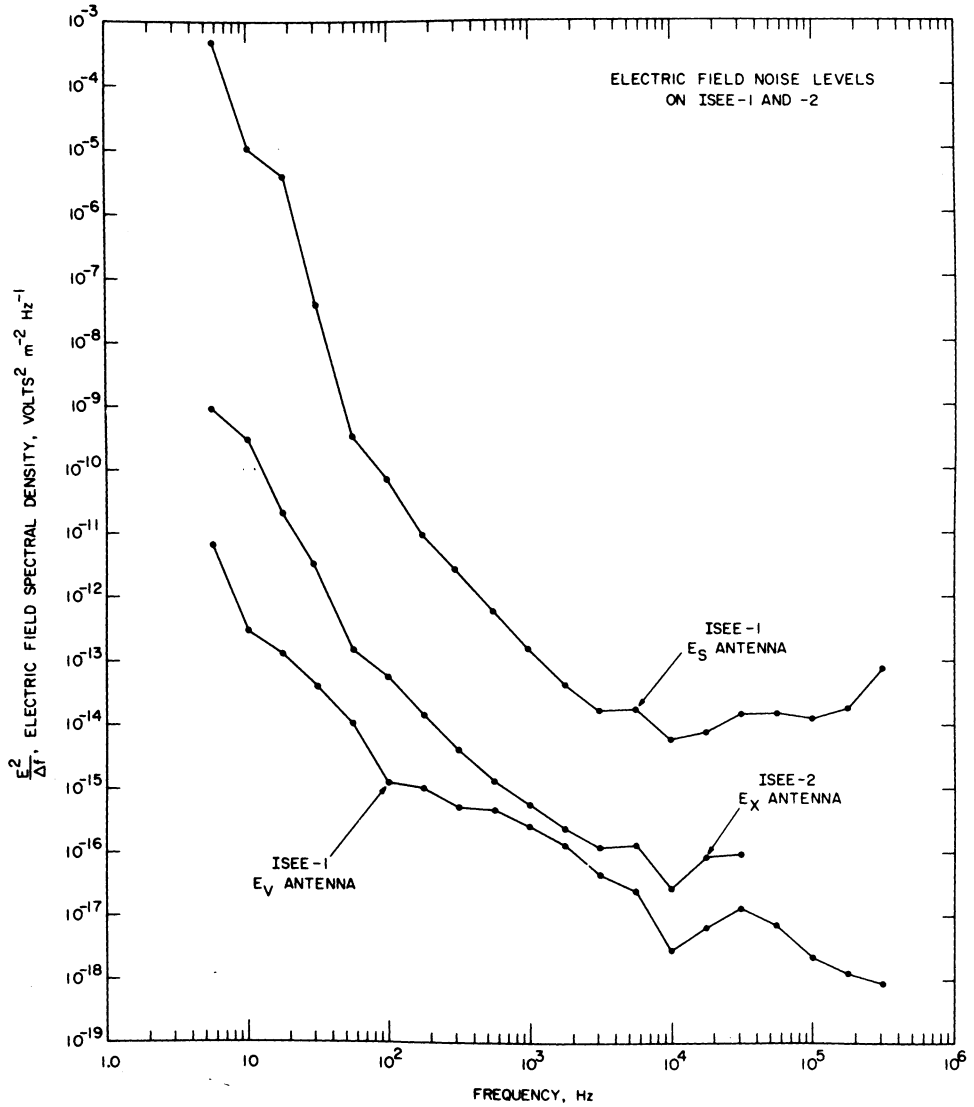

Fig. 5. Representative noise levels for the plasma wave electric-field measurements on ISEE-1 and ISEE-2. The rapid increase in the noise level with decreasing frequency below about 100 Hz is due to interference from the spacecraft solar array.

ceived signals. Because of the automatic gain control, only relative amplitudes can be determined from the wide-band data. Although absolute amplitudes cannot be determined, these measurements have the advantage of providing extremely high time resolution, since waveforms with bandwidths of up to 40 kHz can be transmitted to the ground for detailed analysis.

As shown in Fig. 3, the wide-band receiver has two basic frequency channels, one from 10 Hz to 1 kHz which is transmitted as an FM subcarrier, and another from 650 Hz to 10 kHz (or 40 kHz) which directly modulates the wide-band transmitter. The choice of the 10 or 40 kHz is determined by command. Because of signal-to-noise ratio limitations, the 40-kHz bandwidth cannot be used at radial distances greater than about 15 R_e. The 10-kHz bandwidth can be used over the entire orbit. In addition to the bandwidth selection, the frequency range of the wide-band receiver can also be shifted by a frequency conversion scheme to any one of eight frequency ranges, one of which consists of the baseband range (with no frequency conversion). The low-frequency limit of these bands are at 0.0 kHz (baseband), 31.25 kHz, 62.5 kHz, 125.0 kHz, 500.0 kHz, 1.0 MHz, and 2.0 MHz. The higher frequency ranges are intended mainly for long baseline interferometer measurements. Since precise measurements of the frequency and phase of the received signal are needed for interferometer measurements a reference frequency f_{Ref} which is phase locked to the signal used to perform the frequency conversion, is transmitted to the ground. The frequency conversion signals are obtained from a crystal oscillator which is stable to within about 1 part in 10^6. The wide-band receiver can be connected to either the E_u, E_v, E_s, or B_z antenna, as determined by command.

2) ISEE-2: The ISEE-2 plasma wave instrument is simpler than the ISEE-1 and consists of only two elements, a high time resolution spectrum analyzer and a wide-band receiver. These two elements can be connected to any one of the three antennas as shown in Fig. 4. The high time resolution spectrum analyzer has 16 frequency channels extending from 5.62 Hz to 31.1 kHz. The bandwidths and center frequencies of these channels are identical to ISEE-1. The upper frequency limit of this analyzer extends up to the typical electron plasma

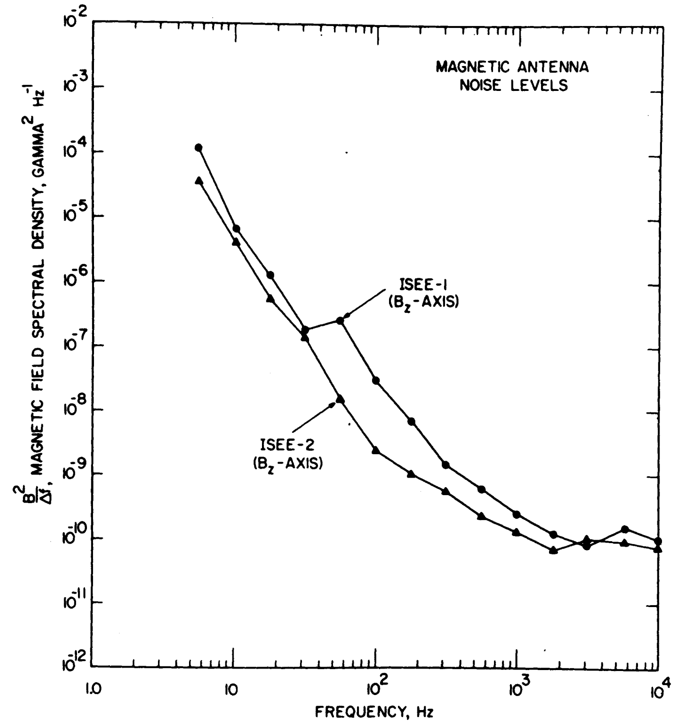

Fig. 6. Representative noise levels for the plasma wave magnetic field measurements on ISEE-1 and ISEE-2.

frequencies encountered in the solar wind and in the earth's magnetosphere beyond the plasmapause. All channels of the spectrum analyzer are sampled once per second in the low data rate mode and 4 times per second in the high data rate mode. The wide-band receiver on ISEE-2 is essentially the same as on ISEE-1, with the exception of the bandwidth of the 650-Hz to 10-kHz channel, which has no 40-kHz mode. This mode was eliminated on ISEE-2 because of limitations on the bandwidth of the analog data channel.

III. INFLIGHT OPERATION

The ISEE-1 and ISEE-2 plasma wave instruments were both turned on shortly after launch and comparisons with the prelaunch calibrations indicated that the instruments are operating perfectly. During the first few days after launch, the long electric antennas were extended in various stages, with pauses to evaluate their performance at different lengths. The only anomaly occurred with the E_u antenna, which stopped approximately 5 m short of full extension. The final sphere-to-sphere separation for the E_u antenna is 73.5 m. Proper operation of the wide-band transmission link was confirmed for both ISEE-1 and ISEE-2 by recording and listening to various types of plasma waves (whistlers, chorus, and VLF emissions) which were received by the spacecraft and transmitted to the ground over the wide-band telemetry system. Preliminary indications are that wide-band data can be obtained in the 10-kHz mode at apogee from both spacecrafts, although the ISEE-2 signal-to-noise ratio is somewhat degraded from ISEE-1 because of the lower transmission power of the ISEE-2 wide-band telemetry link.

Representative noise levels for selected antennas on the two spacecrafts are shown in Figs. 5 and 6. The noise levels of the ISEE-2 magnetic antenna is in close agreement with levels measured at low noise sites on the ground prior to launch, indicating that the magnetic interference from the spacecraft is below the noise level of the instrument. The noise level of the ISEE-1 magnetic antennas shows a slight increase (about 10 dB) above the expected noise level from about 50 to 200 Hz, probably due to spacecraft-generated interference. The noise levels of the electric antennas are generally in good agreement with the preflight noise levels at frequencies above about 100 Hz. Below 100 Hz, the inflight noise levels rapidly increase above the preflight noise levels with decreasing frequency. Observations when the spacecraft enters the earth's shadow show that this low-frequency noise disappears when the spacecraft is not in the sunlight. Low-frequency electric-field interference of this type has been commonly observed on spinning spacecraft with solar cells, and is attributed to the voltage transients produced as the solar panels rotate into and out of the sunlight. Since many separate solar panels are used, this interference extends up to high harmonics of the spin rate. Because of the conductive coating used over the solar cells on ISEE-1 and ISEE-2, it was expected that the interference from the solar cells would be substantially reduced. Comparisons with noise levels on previous spacecraft experiments of this type [2] confirm that the ISEE-1 and ISEE-2 electric-field interference levels are lower than on IMP-6, IMP-8, Helios-1, or Helios-2. The largest improvement is for the 215-m antenna. The 0.61-m short electric antenna on the other hand still has an unusually high noise level at low frequencies, much higher than can be accounted for by the ratio of the antenna lengths. These comparisons suggest that the interference produced by the solar array is confined to the plasma sheath relatively close to the spacecraft, and has a larger effect on the short electric antenna which is located within the sheath region than on the long electric antennas which extend well beyond the sheath region.

ACKNOWLEDGMENT

The authors are very thankful to Project Manager, D. Odem and his team at the University of Iowa, consisting of R. D. Anderson, W. Walker, and K. Baker, who carried out the design and construction of these large and complex instruments, and to R. R. Anderson who was responsible for the scientific calibration and testing. Special thanks are also given to R. Shaw of the University of Iowa, who helped direct this project for one year while D. Gurnett was on sabbatical leave. The authors are also indebted to A. Frandsen of JPL and P. Virobik of TRW for their contribution to the design and construction of the search coil and short electric antennas. The authors are also very grateful for the fine support and cooperation of the many members of the ISEE Project at GSFC and ESTEC who made this mission a success.

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