The Wideband Plasma Wave Investigation

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Abstract

The Cluster Wideband (WBD) Plasma Wave investigation is designed to provide high-resolution frequency/time spectra of plasma waves in the Earth's magnetosphere. Wideband measurements are important for identifying and studying plasma emissions that have very complex frequency/time characteristics. As part of the Wave Experiment Consortium (WEC), the WBD instrument provides measurements of both electric and magnetic fields in selected frequency bands from 25 Hz to 577 kHz. Continuous waveforms are digitised, formatted, and transferred to the spacecraft telemetry system using either a 220 kbit/s real-time mode or a 73 kbit/s burst mode. The real-time data require direct acquisition by a NASA Deep Space Network (DSN) receiving station, and the burst-mode data are stored on the spacecraft tape recorder for later playback. On the ground the waveforms are Fourier transformed to provide high-resolution frequency/time spectrograms. The WBD measurements complement those of the other WEC instruments and also provide unique new capabilities such as very-long-baseline interferometry (VLBI).

Keywords: Wideband, WBD, Plasma Waves, Magnetosphere, Waveform

1. Introduction

The Cluster Wideband (WBD) Plasma Wave investigation is designed to provide very high-resolution frequency/time measurements of plasma waves in the Earth's magnetosphere. The WBD instrumentation is part of the Wave Experiment Consortium (WEC) and consists of a digital wideband receiver which can provide electric- or magnetic-field waveforms over a wide range of frequencies.

The importance of wideband measurements for the study of space plasma waves was recognized over three decades ago, when the technique was first introduced on the Alouette 1 [1] and Injun [2] satellites. Since then, wideband measurements have become a standard technique for the study of space plasma waves. Wideband receivers have been carried by many spacecraft, including OGO 1 through 6, IMP 6 and 8, S(3), Geos-1 and -2, S3-3, ISEE-1 and -2, Prognoz 8, Voyager 1 and 2, DE 1, and Galileo. The Cluster wideband receiver is similar to that being flown on the Polar spacecraft.

The wideband technique involves transmitting band-limited waveforms directly to the ground using a high-rate data link. The primary advantage of this approach is that continuous waveforms are available for detailed high-resolution frequency/time analysis. The frequency/time resolution is limited only by the uncertainty principle, $\Delta\omega\Delta t \sim 1$. Since the frequency resolution ($\Delta\omega$) and time resolution (Δt) can be selected on the ground, the wideband technique has the advantage that the resolution can be adjusted during the processing to provide optimum analysis of the plasma-wave phenomena of interest.

The high-resolution nature of wideband measurements is of particular importance for the study of plasma emissions that have very complex frequency/time characteristics. The distinctive fine structures of chorus and auroral kilometric radiation, for example, were first identified by means of wideband measurements. To illustrate the flexibility and extremely high resolution available from wideband data, Figure 1 shows representative spectrograms of several types of plasma-wave emissions observed in the Earth's magnetosphere. In the processing of the spectrogram in panel (a), for example, use has been made of a very expanded time scale in order to permit resolution of the fine structure of whistler-mode chorus emissions. In the processing of the spectrogram in panel (b), a greatly expanded frequency resolution at low frequencies was used to enable the narrowband structure of electrostatic ion cyclotron waves to be resolved. The spectra in panels (c) and (d) were obtained in a frequency conversion mode of operation and show the extremely complicated fine structure of $(n+½)f_{ce}$ electron cyclotron waves near the upper hybrid resonance (UHR) and the complex narrowband structure of auroral kilometric radiation. Finally, to illustrate

Table 1. Investigators

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the use of wideband data as a means of obtaining very high-resolution measurements of basic plasma parameters, panel (e) shows a spectrum of auroral hiss which has a sharp upper frequency cutoff at the electron plasma frequency, f_{pe}. The cutoff at f_{pe} provides very accurate (few percent), high-resolution (0.1 s) measurements of the electron density in the auroral zone and over the polar cap.

2. Scientific objectives

The eccentric, highly inclined orbit of the Cluster mission carries the spacecraft through most of the important regions of the magnetosphere, including the polar cusp, the plasma mantel, the magnetopause boundary layer, the polar cap, the auroral zones, the plasma sheet, and the plasma sheet boundary layer. Many diverse types of plasma waves occur in these regions. Some of the more important include electrostatic ion cyclotron waves, broadband electrostatic noise, whistler-mode chorus, auroral hiss, auroral kilometric radiation, continuum radiation, electrostatic electron cyclotron waves, upper hybrid emissions, and lower hybrid waves.

The primary goal of the Wideband Plasma Wave investigation is to support WEC science objectives by providing high-resolution spectral analysis. At boundaries and other regions with steep spatial gradients, WBD will provide high-time-resolution, single-spacecraft measurements for comparison with data from other instruments with high temporal resolution, such as the magnetometer and plasma instruments. From these data, waves produced by current-driven instabilities and other mechanisms involving spatial inhomogeneities can be clearly identified. In addition to single-point measurements, wideband data from two or more spacecraft can also be used to resolve space/time ambiguities as the spacecraft pass through these complex spatial structures. The study of such structures is one of the primary objectives of the Cluster mission. In cases where the upper hybrid or electron plasma frequency can be identified, WBD will provide very-high-resolution passive measurements of the electron density. Also,

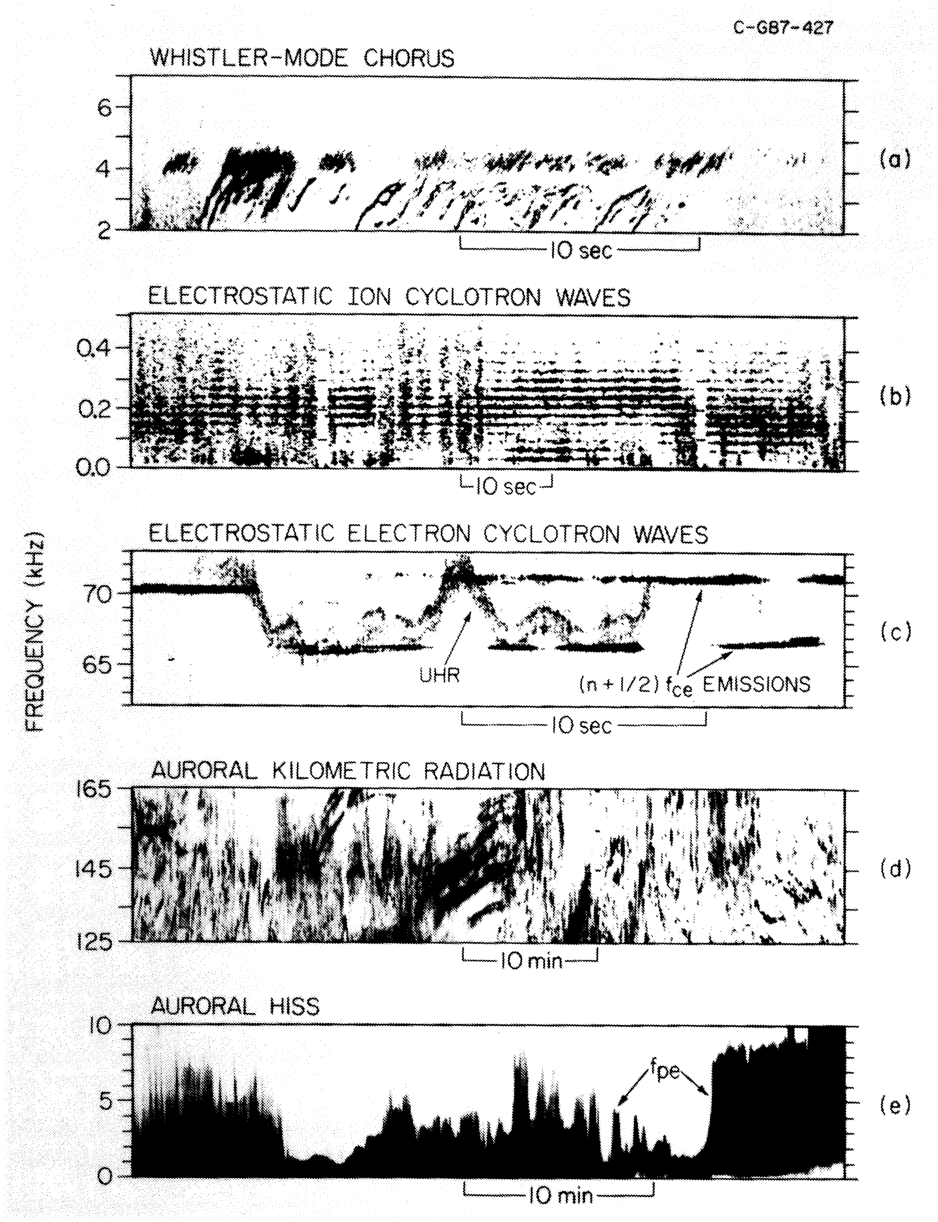

Figure 1. Frequency/time spectrograms of plasma emissions observed in the Earth's magnetosphere using wideband instrumentation.

multiple-point comparisons of electron densities can be used to analyse the motion and evolution of plasma structures in the auroral zone and polar cap.

In addition to supporting WEC objectives, the Wideband Plasma Wave investigation will also perform a variety of measurements unique to the WBD instrumentation. The extremely high (microsecond) time resolution provided by the WBD measurements, for example, makes it possible to utilise the signals from two or more spacecraft to perform very-long-baseline-interferometer (VLBI) measurements. Figure 2 shows simultaneous observations of auroral kilometric radiation (AKR) obtained from the ISEE-1 and -2 spacecraft over the northern auroral zone at a geocentric radial distance of about 14 R_E, and a baseline separation distance (between ISEE-1 and -2) of 3 260 km. The top two panels show the AKR spectrum received at the two spacecraft, and the bottom panel shows the cross-correlation between the waveforms over a time interval of about 1.3 seconds. The sinusoidal waveform in the cross-correlation is the characteristic 'fringe pattern' produced by interference between the two received signals. Analysing the fringe amplitude enables the angular size of the source to be determined. For a more detailed discussion of this and other ISEE-1 and -2 interferometer measurements, see Baumback et al., 1986 [3]. Similar interferometer measurements using three or more spacecraft can be made with Cluster. Multispacecraft interfero-

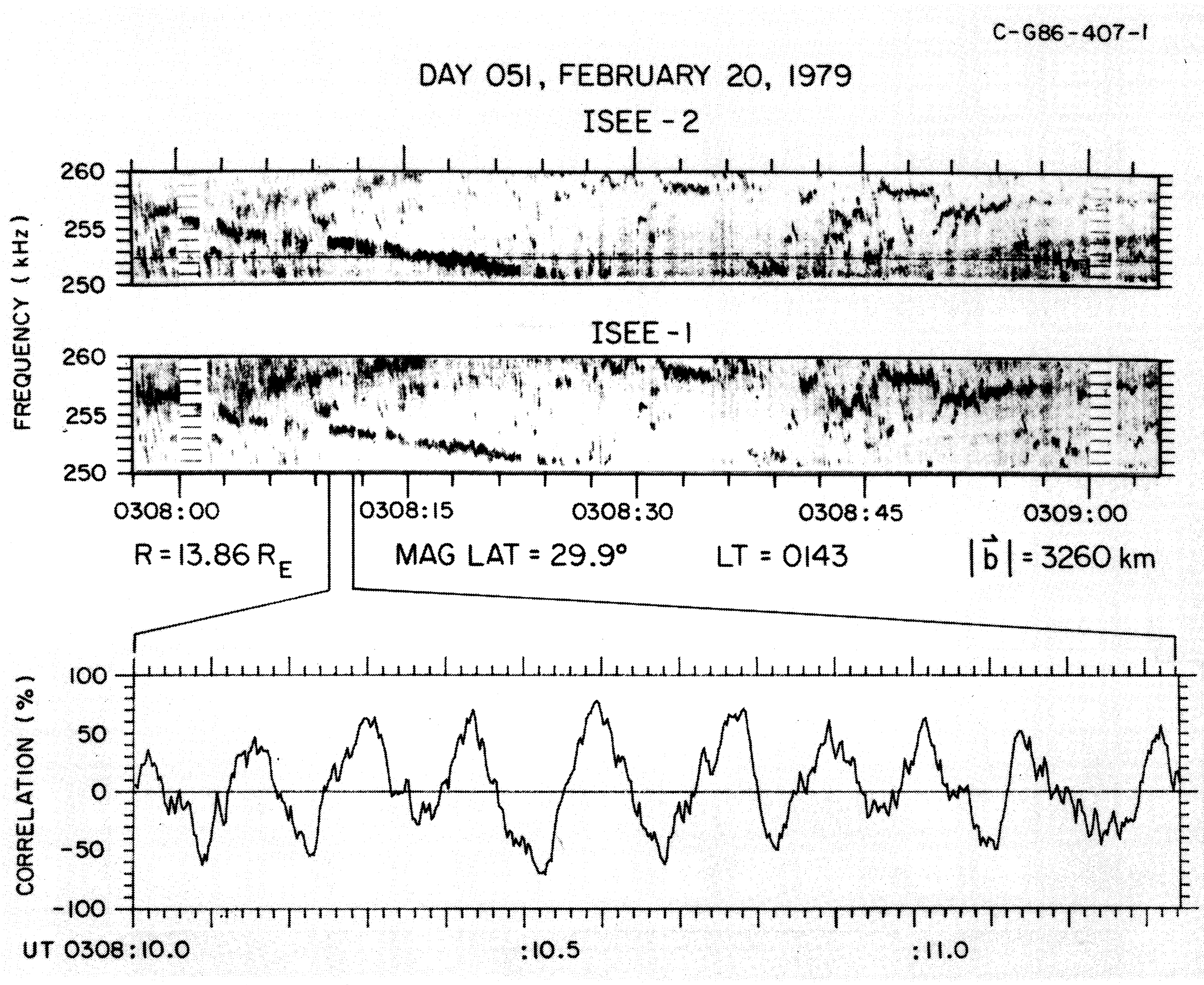

Figure 2. Simultaneous frequency/time spectrograms of an auroral kilometric radiation event detected by ISEE-1 and -2. The bottom panel shows an interference fringe pattern in the cross-correlation between the two signals.

meter measurements have the potential of giving important new information on the angular size and motion of the sources of various types of terrestrial radio emissions, such as auroral kilometric radiation.

3. Description of the wideband receiver system

A simplified block diagram of the WBD design is provided in Figure 3. The instrument processes signals from one of four sensors which can be chosen via an antenna selection switch located at the receiver input. The four selectable inputs consist of two electric-field signals, and two magnetic-field signals. These inputs are provided by the electric-field (EFW) and magnetic-field (STAFF) experiments.

In the WBD design, input bandpass filters limit the incoming signal to one of four possible frequency bands ranging from baseband to 500 kHz. The band-limited signal then goes to a single-sideband frequency-conversion stage, which determines the range of frequencies to be received. Under this scheme, the filtered input signal is mixed with conversion frequencies f and $f \angle 90°$. The input signals are thereby converted to baseband with upper and lower sidebands superposed and with a phase difference of 180 degrees. A quadrature phase shift network shifts one converted signal by an additional 90 degrees so that when the converted signals are summed, the upper sideband components add and lower sideband components cancel. The output of the conversion stage then goes to one of a set of three bandpass filters, which determines the bandwidth of the output waveform.

Because of the large dynamic range of the input signal, and in order to maintain a high

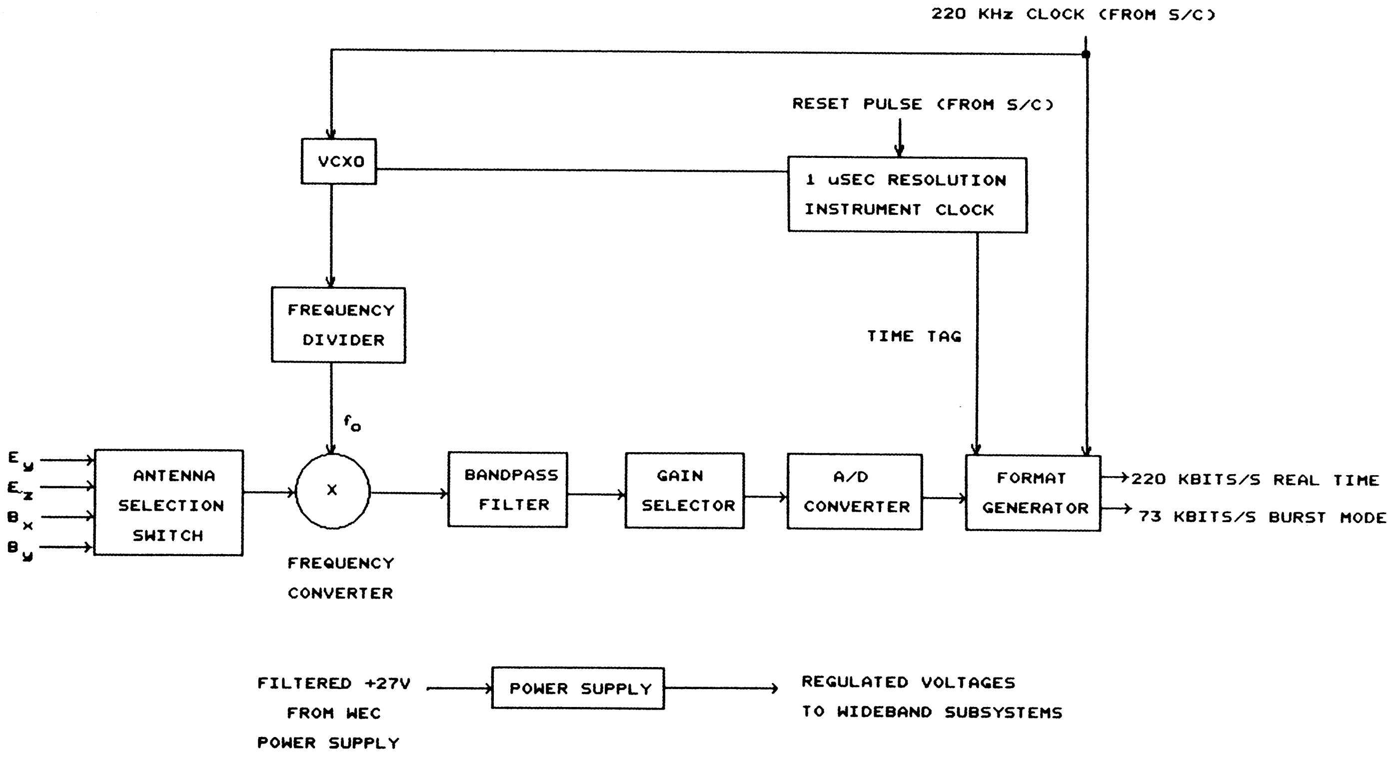

Figure 3. Block diagram of the Cluster wideband receiver.

signal-to-noise ratio for the processed signal, an incremental automatic gain control (AGC) amplifies the signal to the proper level in steps of 5 dB over a range of 0 dB to 75 dB. The output from the gain select then goes to an analog-to-digital converter which provides 1-bit, 4-bit, or 8-bit resolution for a selection of sample rates.

Finally, a format generator organises the digitised waveform data into a data frame suitable for the spacecraft telemetry system. The digitised wideband data are transferred to the spacecraft data system in either a real-time data mode at 220 kbit/s which requires direct acquisition by a NASA DSN ground station, or a burst-data mode, which provides data to the spacecraft tape recorder via the WEC data processing unit (DWP). This latter mode provides the capability for acquiring data when the spacecraft cannot be tracked by a DSN station, and also provides capability for collecting data from more than one spacecraft at a time.

Commanding of the WBD instrument is managed by the DWP.

A summary of WBD instrument parameters is given in Table 2. Individual aspects of the wideband receiver system are discussed in detail in the following sections.

3.1 Sensors and sensor interfaces

The Cluster plasma wave sensors consist of two orthogonal spherical electric antennas located in the spin plane of the spacecraft, and a triaxial search-coil magnetometer oriented with two measurement axes in the spin plane and the third measurement axis oriented parallel to the spacecraft spin axis. The electric antennas, designated E_y and E_z, are provided by the EFW investigation and, after full deployment, have sphere-to-sphere separations of about 100 m. The spheres each contain a high-impedance preamplifier which provides signals to the EFW main electronics, and to WBD and other wave instruments via buffer amplifiers. The EFW/WBD buffer amplifier is a low-noise, low-power design which meets WBD frequency/amplitude response requirements, particularly the need to maintain a flat response up to about 600 kHz. The three orthogonal search coils (B_x, B_y, and B_z) are part of the STAFF instrumentation, and provide magnetic field signals up to 4 kHz.

Table 2. WBD Instrument Parameters

Sensors	Two electric dipole antennas; two search coil magnetometers
Conversion Frequencies	0, 125 kHz, 250 kHz, 500 kHz
Bandpass Filter Ranges	1 kHz to 77 kHz 50 Hz to 19 kHz 25 Hz to 9.5 kHz
Frequency Resolution	Determined by FFT
Time Resolution	10-20 msec (per FFT spectrum)
Gain Select	5 dB steps, 16 levels, dynamic range 75 dB, automatic ranging or set by command
A/D Converter	1-bit, 4-bit, or 8-bit resolution for a selection of sample rates
Mass (EM, measured)	1.67 kg
Power (EM, measured)	1.57 W

The WBD instrument has the capability of processing signals from one of four sensors which may be selected by spacecraft command. Under the control of DWP, WBD can be switched to either the E_y or the E_z sensor, to a spin-plane search coil (B_y), or to the spin-axis search coil (B_x).

3.2 Frequency bands

The input frequency range of the wideband receiver can be shifted by a frequency converter to any one of four frequency ranges, where the conversion frequency f determines the lower edge of the frequency range to be received. The conversion frequency is obtained by dividing a 14-MHz reference oscillator. To maintain phase stability in the entire system, this internal oscillator is synchronised to a 220.752 kHz high-frequency clock, which is the spacecraft's Ultra Stable Oscillator (USO) divided by 38.

A spacecraft command to select a particular frequency band causes DWP to switch the wideband receiver to the appropriate input bandpass filter and to select conversion frequencies of 0, 125, 250, or 500 kHz. If baseband ($f=0$) is selected, the mixing stage is bypassed so that the signal is routed directly to the output bandpass stage with no frequency conversion.

The bandwidth of the WBD instrument's output waveform is determined by one of three bandpass filters selected in combination with a given output mode. Conversion frequencies and bandpass filter ranges are summarised in Table 2.

3.3 Gain control

The gain select of the wideband receiver employs a set of dual-gain amplifiers which may be selected to provide gain control in increments of 5 dB. This programmable amplifier stage consists of amplifiers having gains of 0/5 dB, 0/10 dB, 0/20 dB and 0/40 dB.

In manual gain select mode, the total receiver gain can be set to one of the sixteen levels (from 0 dB to 75 dB) by the appropriate spacecraft command.

Additionally, WBD has the capability of auto-ranging through the gain steps. The auto-ranging mode is enabled by command and allows the instrument to automatically manage large changes in signal intensity. In this operational mode, the output from the programmable amplifier is compared with a pair of reference amplitudes. If the criteria for changing the gain are met, the gain state is either increased by one step

Table 3. WBD Output Modes

Mode	Bandwidth	Sample Rate	Bits/ Sample	Duty Cycle	Comments
0	25 Hz - 9.5 kHz	27.4 kHz	8	100%	Default Mode
1	25 Hz - 9.5 kHz	27.4 kHz	8	100%	
2	50 Hz - 19 kHz	54.9 kHz	4	100%	
3	50 Hz - 19 kHz	54.9 kHz	8	50%	
4	1 kHz - 77 kHz	219.5 kHz	8	12.5%	
5	1 kHz - 77 kHz	219.5 kHz	1	100%	
6	1 kHz - 77 kHz	219.5 kHz	4	25%	
7	1 kHz - 77 kHz	219.5 kHz	8	12.5%	*Note 1

*Note 1. This mode is a repeat of output Mode 4, but also toggles the primary and redundant OBDH interfaces

(5 dB) or decreased by one step, accordingly. In order to avoid excessive toggling between gain steps, a commandable threshold must be exceeded, thereby introducing hysteresis in the AGC control loop. The gain is updated (if required) at a rate determined by the gain update clock, which is a DWP function selected by spacecraft command. The period of the clock is programmable from 0.1 to 10 seconds in increments of 0.1 second. The actual gain change takes place at the beginning of the next WBD major frame.

3.4 A/D converter and format generator

The output analog waveform is sampled by an 8-bit analog-to-digital converter which provides the sampling resolution and data output rates listed in Table 3.

For sample rates where the bit rate exceeds the spacecraft telemetry data rate (220 kbit/s), the digitised wideband data are buffered by the format generator and read out at a reduced average bit rate of 220 kbit/s. The format generator organises the digitised waveform data into a 1096-byte output frame, which includes appropriate timing and status information.

3.5 WBD data interfaces

The WBD instrument utilises two separate paths for transferring frames of digitised data to the spacecraft data handling system. The primary path supports real-time acquisition of WBD data by the NASA DSN. The second data path supports burst data acquisition via an on-board tape recorder.

3.5.1 Real-time data acquisition

A special serial data interface between the WEC (originating at WBD) and the spacecraft's Central Data Management Unit (CDMU) supplies the primary path for data from the WBD instrument. Interface functions consisting of 220 kHz sampling clock, timing pulse, and data output are redundantly implemented. Data are present on this interface (at 220 kbit/s) whenever WBD is powered. During real-time data acquisition, the WBD data appears on a dedicated virtual telemetry channel (VC5), embedded in the 1096-byte data field of the standard 1279-byte transfer frame. The WBD transfer frames are acquired by a DSN receiving station.

3.5.2 Burst data acquisition

A second path for WBD data is provided by a serial interface between WBD and DWP. This interface supports a special burst mode (BM2) dedicated to WBD. When the BM2 operational mode is enabled, WBD data are transferred to DWP at 220 kbit/s, and the DWP, in turn, reduces the wideband data by a factor of three

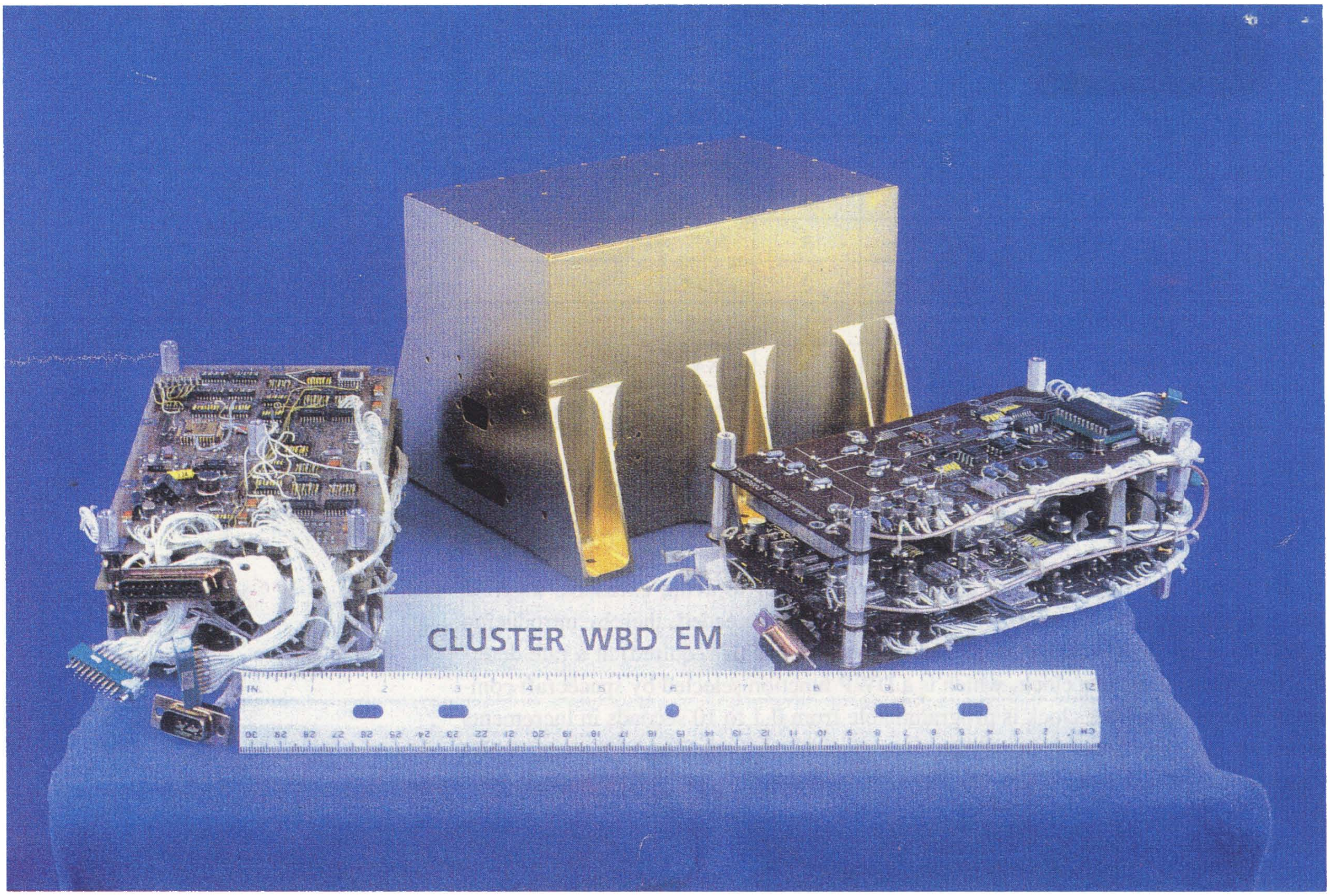

Figure 4. WBD Engineering Model.

either by digital filtering or by duty cycling (accepting only one out of three frames). At the new average bit rate of 73 kbit/s, the WBD data are transferred to the OBDH system for recording and subsequent playback.

4. Hardware development

4.1 WBD Engineering Model

Electrical and mechanical designs have been completed and are represented in the WBD Engineering Model (EM). The WBD EM (shown in Figure 4) has undergone extensive testing at the unit level and has successfully participated in all activities required to verify the integrated WEC Engineering Model. After the WEC EM is integrated into the EM spacecraft, and system-level verification commences, the results from WEC-specific automatic test sequences will be used to verify that the WBD EM is operating correctly.

4.2 WBD Electrical Ground Support Equipment (EGSE)

During the unit level, WEC level, and spacecraft level testing, the WBD EM and flight models are supported as needed by the WBD EGSE, which is a 386-based PC fitted with specialised hardware. At the unit level of test, the WBD EGSE emulates all command and data interfaces. During WEC-level integration and test, the WBD EGSE augments the WEC EGSE by emulating the WBD/CDMU 220 kbit/s data path.

The WBD EGSE provides both real-time and offline data processing and display capability. An example of one of several available WBD display pages is shown in Figure 5. The upper two panels give snapshot information about instrument configuration (left panel) and digitised waveform (right panel). The upper right-hand panel shows both time series and FFT spectrum. A history of the test sequence is preserved in the frequency/time spectrogram given in the bottom panel. The spectrogram covers

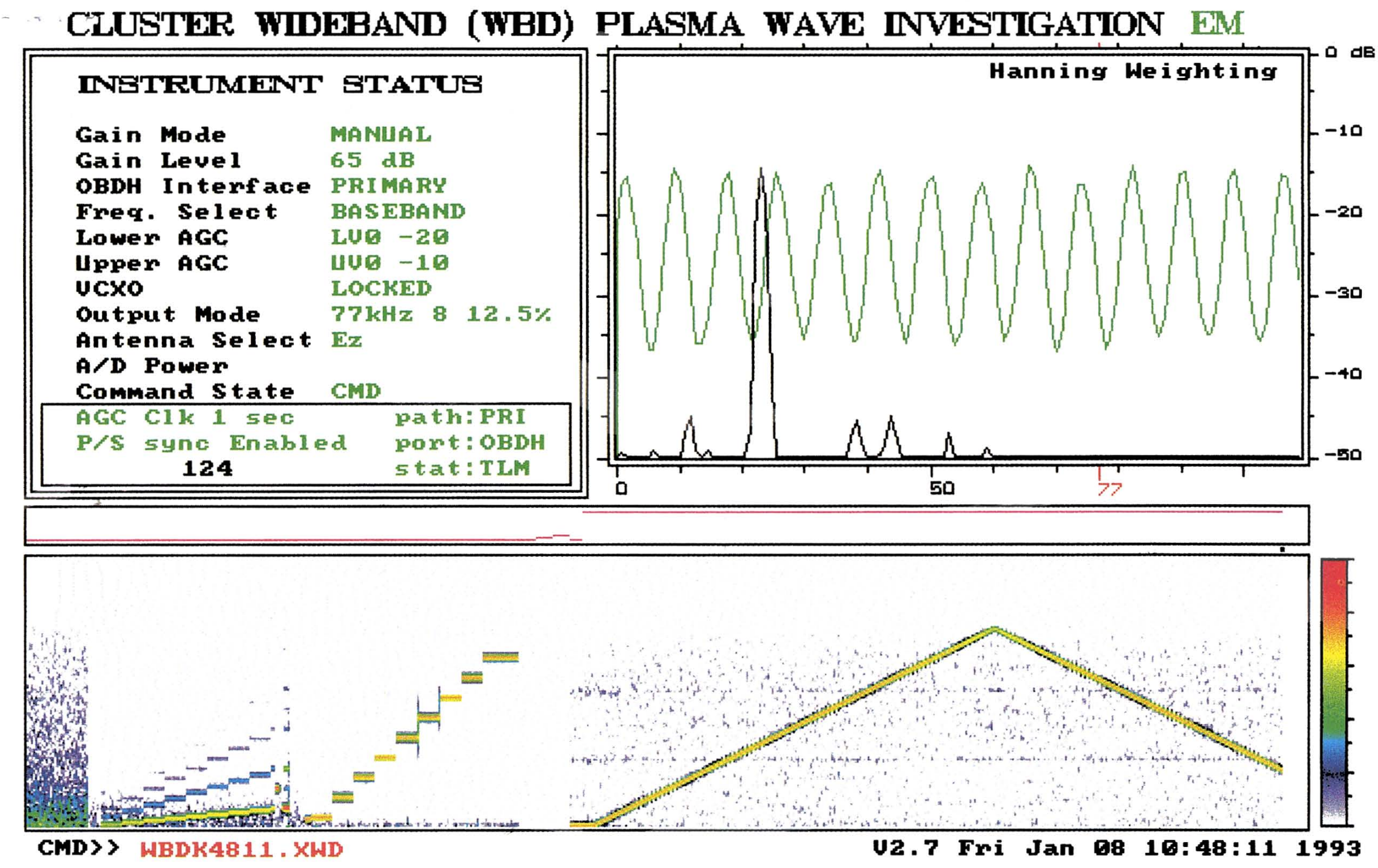

Figure 5. WBD EGSE display.

approximately two minutes in time, and shows a test sequence where the input signal is stepped over frequency in several instrument modes. The sequence terminates as the stimulus sweeps down to 23 kHz, which can also be seen in the snapshot spectrum in the panel above.

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