The Stanford University VLF Wave Injection Experiment on the ISEE-A Spacecraft

T. F. BELL AND R. A. HELLIWELL

***Abstract*–A Stanford University VLF wave injection experiment will be carried out as part of the ISEE mission. This experiment consists essentially of three basic components; a broad-band VLF receiver on ISEE-A, a broad-band VLF transmitter located at Siple Station in the Antarctic, and a number of ground stations in the Antarctic and Canada. This experiment is an outgrowth of VLF wave injection experiments carried out over the past four years using the Stanford University transmitter at Siple Station, Antarctica. The purpose of this experiment is to study VLF-wave–particle interactions in the magnetosphere, with the goal of achieving a better understanding of this important portion of the earth's environment. In the present paper we sketch briefly the scientific background of the experiment and describe the functions of the ISEE-A instrument.**

I. INTRODUCTION

THE STANFORD University VLF wave injection experiment for the ISEE mission consists essentially of three separate components: 1) a broadband VLF receiver on ISEE-A, 2) a broad-band VLF transmitter located at Siple Station in the Antarctic, 3) ground stations in the Antarctic and Canada.

This experiment is an outgrowth of VLF wave injection experiments carried out over the past four years using the Stanford University broad-band (1-20-kHz) transmitter at Siple Station, Antarctica [2], [5].

The Siple Station wave-injection experiment is an active experiment designed to study VLF-wave-particle interactions in the magnetosphere. One goal of the experiment is to develop a sufficient understanding of the physics of wave–particle interactions to allow the control of the energetic particles by the injected waves.

Once control is established, the energetic particles can then be used as tools to study other important processes. For example, the control of energetic particle precipitation would allow interesting studies of X-ray, ionization and radiation emission processes in the ionosphere. Furthermore, modulation of precipitation flux might provide a means to produce Pc-1 ULF waves [1] on a controlled basis. Numerous other applications can be envisioned.

A second goal of the experiment is to determine the effects upon energetic particles in the magnetosphere of electrical power transmission line radiation.

Harmonics radiated by electrical power distribution systems are frequently observed to enter the magnetosphere where they are amplified to a level that is sufficient to stimulate VLF emissions, scatter energetic electrons and produce strong wave-wave interactions [3], [4]. In fact, the bulk of the data acquired at ground stations shows evidence of electrical power line radiation that propagates in the whistler mode within the magnetosphere and influences natural wave-particle interactions.

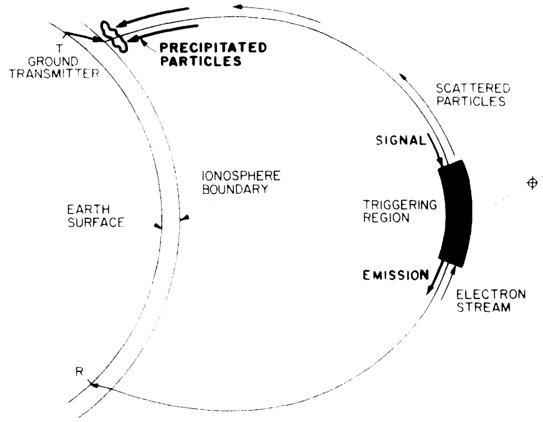

Fig. 1. Schematic representation of the ISEE VLF wave injection experiment (HEM).

In general, the power line radiation effects are studied through the injection into the magnetosphere by the Siple Station transmitter of wave structures similar in form to those typically generated by electrical power distribution systems. Since these injected waves produce effects similar to those produced by power line radiation, a controlled study of power line radiation effects is possible.

The basic mode of operation of the wave-injection experiment is depicted in Fig. 1. VLF signals from the Siple Station transmitter are radiated from the 21.2-km long antenna and propagate through the ionosphere above the antenna and into the magnetosphere. Once in the magnetosphere the signals follow the Earth's magnetic-field lines until they approach the magnetic equatorial plane, at which point they begin to interact strongly with energetic electrons through gyroresonance. During the interaction the injected wave amplitude may grow as much as 30 dB [6], VLF emissions may be produced, and significant numbers of resonant energetic electrons are pushed into the loss cone. After the interaction the injected waves, plus stimulated emissions, travel along the field lines until they reach the ionosphere above Roberval, the ground station conjugate to Siple Station. At the same time the loss cone particles travel down the magnetic-field lines and precipitate into the atmosphere over Siple Station.

It is clear that there are a number of important questions which cannot be answered using ground data alone.

Manuscript received April 3, 1978.

The authors are with the Radioscience Laboratory, Stanford University, Stanford, CA 94305

0018-9413/78/0700-0248$00.75 © 1978 IEEE

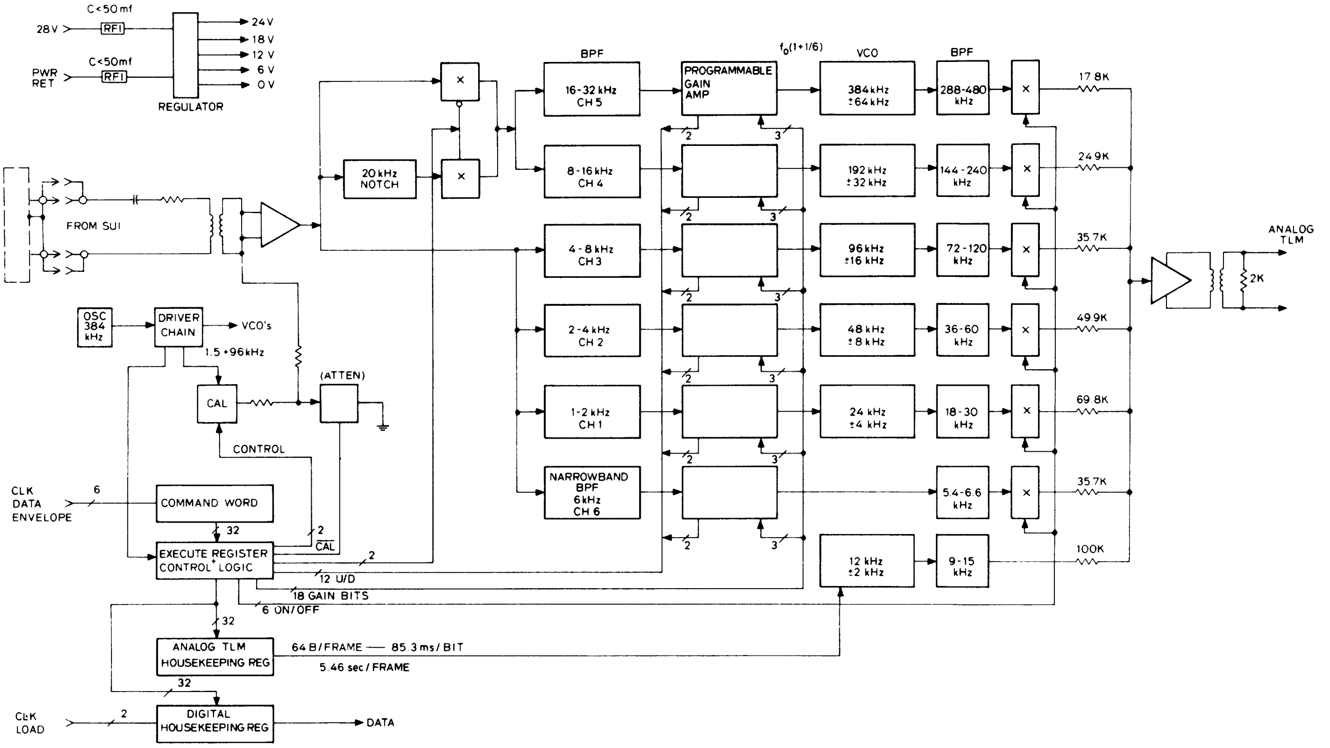

Fig. 2. Block diagram of HEM VLF receiver.

1) Where is the exact location of the interaction region in which VLF emissions are produced and what is the distribution of wave amplitude within this region?

2) What is the magnitude of the energetic particle scattering due to the injected waves and stimulated emissions?

3) What is the relative efficiency of nonducted waves in producing emissions?

All of these questions involve quantities which at our present state of knowledge can only be measured *in situ*, by satellites. Thus an important component of the wave-injection experiment is the measurement by the ISEE satellites of the characteristics of waves and particles in the magnetosphere during the wave-injection process.

The primary wave measurement device during the ISEE wave-injection experiments is the Stanford University multichannel broad-band (1-32 kHz) VLF receiver. This receiver is designed to make rapid and accurate frequency and amplitude measurements of the injected signals as a function of time. Rapid measurements are necessary since the injected waves may grow as much as 30 dB during the initial 100 ms of interaction. A multichannel receiver is necessary since strong natural background noise (10-30 dB above injected signal levels) is a common feature of the wave spectrum in the 1-10 kHz range and this noise will cause suppression of the injected signal in single channel receivers employing automatic gain control (AGC). Energetic particle measurements during the wave-injection experiments will be carried out by the FRM and WIM experiments.

Wave and particle measurements from the ISEE spacecraft should serve to answer the questions posed above and increase our understanding of VLF wave-particle interactions in the magnetosphere.

II. Instrument Description

A. *Theory of Instrument Operation*

The receiver package contains signal filtering, amplification, gain control, switching, calibration, and other functions necessary to transfer the 1- to 32-kHz signal from the preamplifier to the analog telemetry system. The system block diagram in Fig. 2 shows the major receiver functions.

Signals in the 1- to 32-kHz band from the preamplifer (supplied by the University of Iowa) are fed to a parallel bank of six filters. Five of the filters are broad-band octave width filters and one filter is a narrow-band filter centered at 6 kHz, an operating frequency of the Siple transmitter. A 20-kHz notch filter is incorporated into the 8- to 16-kHz and 16- to 32-kHz bandpass filters to minimize interference arising from the spacecraft power converter which operates at 20 kHz.

The outputs of the filters are fed into six programmable gain amplifiers (PGA). The purpose of the variable gain for each band is to maintain output signal levels within the range required by the spacecraft telemetry. The signal level is maintained below telemetry saturation and above telemetry system noise levels. The gain of each channel is adjustable in 10-dB steps over a 0- to 70-dB range by ground command or by automatic signal level sensing. When a ground command for automatic gain is received, the amplitude envelope of signals in each channel is monitored and the gain adjusted to maintain a prescribed level. This adjustment is made in 10-dB increments at intervals of about 5.4 s.

Each signal channel, except for the 6-kHz channel, drives a voltage controlled oscillator (VCO). Normally the output of each VCO and a housekeeping VCO are summed, and the resultant signal used to modulate the analog telemetry trans-

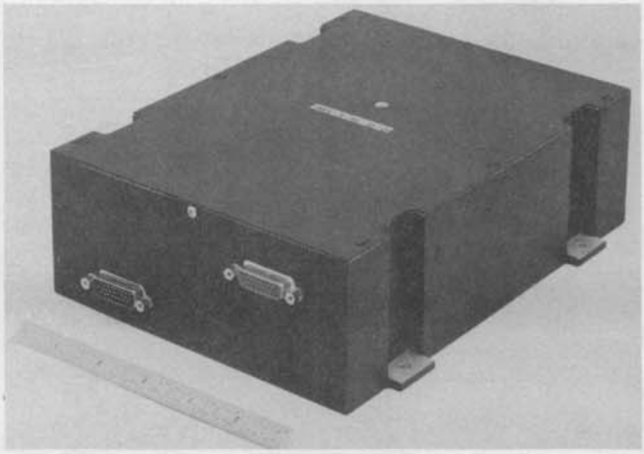

Fig. 3. External physical characteristics of HEM instrument.

mitter. When all channels are summed, the transmission of the VLF data requires a 500-kHz bandwidth analog telemetry link. However, the output of any signal channel can be turned off by ground command. This allows the telemetry power to be concentrated on a desired channel for maximum signal-to-noise ratio.

A relatively narrow-band VCO is provided to generate an FSK signal for housekeeping functions. The PGA gain levels, channel ON/OFF, and AUTO/MAN mode for each channel, and notch filter ON/OFF and CAL ON/OFF data are transmitted over this VCO.

System calibration signals are generated in the receiver package. The amplitude and duration of the CAL signal is sufficient to cause each channel to step from 70- to 0-dB gain over a period of approximately 45 s. Provision to inhibit its operation after a preset length of time is also incorporated into the source as a safety precaution against intermittent operation.

The spacecraft can verify that the experiment has received the proper command word through the digital telemetry link between the experiment and spacecraft controller. Upon request from the spacecraft, a 32-bit telemetry word will be serial shifted from the experiment under spacecraft control.

B. Power, Weight, and Dimensions

The instrument requires the following power source:

Voltage: 28-V dc ± 5 percent
Current: 25 mA average, 30 mA peak, 250 mA surge (power up)
Average Power: 0.7 W.

The +28-V dc source is regulated to supply +24, +18, +12, and +6 V.

In order to minimize power consumption, the supply is a totem-pole configuration.

The weight and dimensions of the instrument are as follows:

Weight: 1303 g
Height: 2.75 in
Length: 9.02 in (does not include connector protrusions)
Width: 7.25 in (including mounting feet).

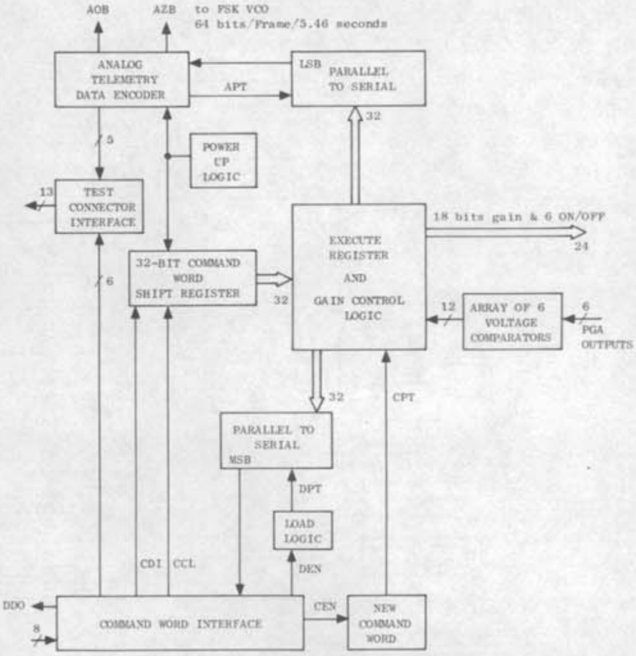

Fig. 4. Block diagram of digital command link circuitry.

TABLE I
GLOSSARY

AOB	Analog Telemetry One Bit
APT	Analog Telemetry Parallel Transfer
AZB	Analog Telemetry Zero Bit
CCL	Command Word Clock
CDI	Command Word Data In
CEN	Command Word Envelope
CPT	Command Word Parallel Transfer
DDO	Digital Telemetry Data Out
DEN	Digital Envelope
DPT	Digital Telemetry Parallel Transfer
LSB	Least Significant Bit
MSB	Most Significant Bit

The external characteristics of the instrument are depicted in Fig. 3.

C. Circuit Description

1) Digital Command Link: The digital section of the HEM experiment provides gain control settings to 6 channels of VLF amplifiers, output summing control for 6 VLF amplifier outputs, digital telemetry information to the spacecraft computer, analog telemetry information to the ground, known "power up" status, calibration function, and interfacing for digital signals between the spacecraft and experiment. A block diagram of the digital command link circuitry is shown in Fig. 4. A list of abbreviations used in Fig. 4 is contained in Table I.

The digital electronics operates on a synchronous 5.4-s cycle with the exception of command word and digital telemetry transfers which are under control of the spacecraft computer.

The HEM experiment interfacing circuit translates up lower level experiment input signals to the experiment 12-V dc level and translates down the experiment output signals to the required levels. The input interfacing elements are implemented by 2N5116 J-FETS and 2N2484 transistors, while the DDO output line is stepped down by two 6.2-kΩ resistors. A zener diode clamping circuit is used for the signal return. Six translators are used for the 3 pairs of redundant signals: namely, CDE, CCL, and CEN. An additional two translate DEN and the digital telemetry clock.

The 32-bit command word, CDI, is clocked by CCL into a 32-bit serial to parallel register implemented with four CD4034 integrated circuits. At the end of the CEN gate, the new command word is parallel loaded to the execute registers made up by CD4042 and CD4029 integrated circuits. This loaded command word can be read back to the spacecraft computer through line DDO by activating line DEN along with the digital telemetry clock.

The line DEN parallel loads the command word into four CD4021 integrated circuits. These ICS are 8-bit parallel in, serial out, devices. The NRZ output data is interfaced to the computer.

When a command word is received, the gain control bits will be loaded into the CD4029 UP/DOWN counters, and the remaining bits into the CD4042 latches; in turn, the command word is loaded into the analog telemetry shift registers (four CD4021). The command word stored in the CD4029 and CD4042 set up the state of the experiment.

During each frame, the data loaded in the analog telemetry register is formatted and encoded to a 2-line tristate code by the encoder implemented by one CD4040, two CD4017, and two CD4013. The 2 tristate lines named AOB and AZB drive the 12-kHz HK VCO, and they are organized as a 48-bit word instead of 32 for purposes of decoding and data verification.

At the beginning of each frame cycle, a double clock pulse is provided to the gain control logic for the purposes of updating the gain setting. Whether the CD4029 UP/DOWN counter will retain, increase, or decrease its 3-gain bits depends on the state of the AUTO/MAN bit and the UP/DOWN lines from the PGA threshold detectors.

Immediately after the gain bits double clock pulse, new commands will be loaded into the execute registers whenever there is a new command stored. If not, the information in the latches stays, and will be transmitted via the analog telemetry registers.

2) *Input Amplifier and Bandpass Filter Board:* The input amplifier and bandpass filter board contains the input signal conditioning amplifier, 20-kHz notch filter and associated switching circuitry, calibrate signal injection switching, and 6 bandpass filters. The bandpass filters divide the 1- to 32-kHz spectrum into five octave bands, and one 6-kHz narrow-band segment.

The input amplifier incorporates four transistors and provides a voltage gain of approximately 3. (Overall gain including transformer loss is about 1.5.) Feedback is established by a combination of resistors. The calibration signal is injected into the emitter of the primary transistor and may be switched on or off by a CD4016 CMOS quad-analog gate. Low output impedance, a requirement for driving the bandpass filter array properly, is obtained by a complimentary emitter-follower output stage.

The 6-kHz narrow-band filter and the three lowest octave frequency band filters (covering 1 through 8 kHz) are driven directly by the input amplifier. The two higher octave band filters covering the frequency range 8 through 32 kHz are driven via the 20-kHz notch filter and filter switch, two sections of a CD4016 analog gate, and by an emitter-follower. The emitter-follower exhibits high input impedance to minimize loading of the 20-kHz notch filter, while providing a low output impedance required to drive the two bandpass filters. The notch filter is a second order Chebyshev bandstop filter with a maximum attenuation of 30 dB at 20 kHz.

The 1- to 2-kHz, 2- to 4-kHz, 8- to 16-kHz, and 16- to 32-kHz bandpass filters are third order Chebyshev octave band filters with 1-dB passband ripple. These filters provide approximately 38 dB of attenuation an octave above or below the band edges. The 4- to 8-kHz bandpass filter is a fourth order Cauer parameter filter with 0.28-dB passband ripple. This filter provides about 40-dB attenuation below 2.9 kHz and above 10.9 kHz. The 6-kHz narrow bandpass filter is a second order Chebyshev, 1-dB passband ripple filter. The measured 1-dB bandwidth is 226 Hz, and the 3-dB bandwidth 377 Hz. All filters have transformer-coupled outputs.

3) *Programmable Gain Amplifier:* The programmable gain amplifier is a 5 stage switched gain amplifier having a maximum voltage gain of 96 dB. Gain may be varied in 10-dB steps over a 70-dB range by means of gain control lines in a 4-2-1 binary coded sequence.

Each stage is comprised of a dual-transistor differential pair with emitter-follower output. This type of configuration provides symmetrical limiting and rapid recovery range from signal overloading.

The first stage is a fixed-gain signal conditioning stage providing a gain of approximately 26 dB. Accounting for the filter voltage loss due to impedance transformation ratio, the actual gain is 10-dB gain referring to the filter input.

Stages two through five are gain programmed by switching the resistors between the emitters of the differential pair by means of a CD4066 analog gate. Stages two, three, and four each have a switched gain of either 0 or 20 dB. Stages two and three are switched simultaneously by a control line to provide an overall gain of either 0 or 40 dB. Stage four is switched to provide a gain of 0 or 20 dB. The fifth stage is switched to provide a gain of 0 or 10 dB.

4) *Power Supply and Threshold Detector:* The power regulator accepts unregulated 28 V and provides four regulated voltages at +6, +12, +18, and +24 V. The + 6, +12, and +18 V supplies are obtained from voltage followers, which provide a low output impedance for driving the experiment circuitry. Increased current drive capability for the +12-V buss is provided by a complimentary emitter follower.

The threshold detectors provide digital output signals used to initiate an increase or decrease in gain of the PGA. The circuit consists of a signal amplitude detector and two comparators.

The detector output is applied to two comparators. The output of the upper threshold comparator is the compliment of the command to change amplifier gain downward, and is normally at a +12-V logic level, going to 0 V when the input signal level exceeds the upper threshold. The output of the lower threshold comparator is the compliment of the command to change amplifier gain upward. It is normally at a +12-V logic level, changing to 0 V when signal amplitude is below the lower threshold.

The upper threshold and lower threshold are established by a voltage divider network. A small amount of hysteresis is provided in each comparator.

5) Voltage-Controlled Oscillator: An array of six VCO's is implemented by the integrated circuit CD4046. The center frequency of each VCO is spaced octavely starting at 12 kHz, and the highest center frequency is 384 kHz. With the exception of the 12-kHz VCO (HK VCO), each VCO is driven by its corresponding PGA; the frequency deviation is ±16.7 percent of center frequency for ±5 V referring to the input.

The output of all six VCO's are filtered by their respective two-pole Cheyshev bandpass filters. Harmonic suppression for these filters is about 30 dB.

With the exception of the HK VCO, the outputs of all VCO's can be switched in or out from the output amplifier by five transmission gates (CD4016). The HK VCO stays on at all times. Another transmission gate couples the 6-kHz NB channel to the output amplifier. The lines feeding to the output amplifier are voltage summed by weighted resistors to scale the subcarrier power distribution.

The output amplifier, implemented by two 2N2605 and two 2N2484 transistors, provides 14-dB voltage gain. It has an output impedance of 100 Ω, and it is transformer coupled to its load.

An *L-C* type oscillator is chosen for power and stability tradeoff. A CMOS Device CD4007 is used for the gain element for the *L-C* oscillator. A CD4040 device generates all the reference frequencies for the VCO's and the 187.5-Hz clock. A CD4013 device is used to generate to 1.5-kHz calibrate pulse. Zener diodes are used to translate the signals from the binary divider to the pulse generator.

III. SUMMARY

The Stanford University broad-band VLF receiver on ISEE-A is an integral part of the Stanford University VLF wave injection experiment being carried out as part of the ISEE mission. Data acquired with this instrument will help achieve a better understanding of dynamical processes in the magnetosphere, an important portion of the earth's environment.

ACKNOWLEDGMENT

We wish to acknowledge the many valuable discussions we have held with our colleagues at the Radioscience Laboratory. We also wish to acknowledge the efforts and dedication of the engineering staff of Develco, Inc., Mountain View, CA, in developing and building our ISEE-A VLF wave-injection receiver.

REFERENCES

[1] T. F. Bell, "VLF wave generation through particle precipitation induced by VLF transmitters," *J. Geophys. Res.*, vol. 81, p. 3316, 1976.

[2] R. A. Helliwell and J. P. Katsufrakis, "VLF wave injection into the magnetosphere from Siple Station, Antarctica," *J. Geophys. Res.*, vol. 79, p. 2511, 1974.

[3] R. A. Helliwell, J. P. Katsufrakis, T. F. Bell, and R. Raghuram, "VLF line radiation in the earth's magnetosphere and its association with power system radiation," *J. Geophys. Res.*, vol. 80, p. 4249, 1975.

[4] C. G. Park, "The role of manmade VLF signals and noise in wave-particle interactions in the magnetosphere," in *Proc. Int. Symp. Solar-Terrestrial Physics* (Boulder, CO), D. Williams, Ed., June 1976.

[5] R. Raghuram, R. L. Smith, and T. F. Bell, "VLF Antarctic antenna: Impedance and efficiency," *IEEE Trans. Antennas Propagat.*, vol. AP-22, pp. 334–338, 1974.

[6] G. S. Stiles and R. A. Helliwell, "Frequency-time behavior of artificially stimulated VLF emissions," *J. Geophys. Res.*, vol. 80, p. 608, 1975.