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Observations of ELF Signatures Arising from Space Vehicle Disturbances of the Ionosphere

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ABSTRACT

We report on observations of Extremely Low Frequency (ELF) signatures during exit or reentry of space vehicles through the ionospere. The two modes regularly observed gave signals that peaked at 5.6 Hz and 11.2 Hz. The evidence points to the lower ionosphere, i.e., the D- and E-layers, as the generator of these signals. The measurements were performed using ground-based multi-turn coil sensors located in Reno and San Diego. The nature of these signals is unclear at present but it is surmised that we are detecting either the evanescent fields of hydromagnetic waves traveling in the ionosphere or the oscillating geomagnetic field associated with these hydromagnetic waves.

1. Introduction

Disturbances in the ionosphere can often be monitored on the ground. Examples include High Frequency (HF) fading (or enhancement), phase changes of Very Low Frequency (VLF) waves, and micropulsations. In general, disturbances in the ionosphere and magnetosphere arise from changes in solar activity. We report, perhaps for the first time in the open literature, observations of Extremely Low Frequency (ELF) signatures arising from space vehicle disturbances of the ionosphere. The sharply peaked signatures are observed in the lower ELF band (5 to 15 Hz) but are different from the broader Schumann resonances (1,2) that are also observed in this band. They are different from the Schumann resonances in both frequency and line shape (3).

According to discussions with Robert J. Dinger of Naval Weapons Center (NWC), China Lake, CA, and Mario Grossi of The Harvard-Smithsonian Centre for Astrophysics, Cambridge, MA, the Raytheon Research Laboratory and The Naval Research Laboratory (NRL) conducted a series of experiments in the early 1970s to look for Ultea Low Frequency (ULF) (.01 to 5 Hz) and ELF (5 to 3000 Hz) signals induced by rocket interaction with the ionosphere. It was suggested by Mario Grossi (then of Raytheon Research Laboratory) that the ionized rocket plumes could short-circuit the earth-ionosphere cavity plates and induce a large flow of current from the ionosphere to ground. This large transient flow of current will ring the ionosphere if any resonant modes exist. Another effect is the introduction of plume ions and water vapor directly into the ionosphere, thus changing its conductivity. The main effect comes from the water vapor which depletes ions and effectively punches a hole in the ionosphere (4). The ionosphere reacts to the change in conductivity in at least two ways: first, currents are induced to normalize the conductivity, and second, any existing natural upper atmospheric currents are diverted in direction. The associated magnetic effects should be observable on ground. Unfortunately, the data obtained were inconclusive and interest was diverted to ground-based stimulation of the ionosphere using high powered HF transmitters (5,6,7).

Acoustic excitation of the ionosphere arising from the eruption of Mount St. Helens, May 18, 1980, in Washington State induced detectable traveling ionospheric disturbances (8,9). Monitoring in Oregon by William Van Bise also revealed ULF signatures in the 3 to 4 Hz range (10). It was hypothesized that the passage of large spacecraft through the ionospere could also induce such ULF/ELF signatures. The first Space Shuttle mission (Columbia) began with the launch on April 12, 1981 and completed with the landing on April 14, 1981. ELF monitoring in Oregon by William Van Bise during the Columbia's landing period led to the discovery of strong signals peaking at 5.6 Hz and 11.2 Hz that corresponded with the spacecraft penetration of the ionosphere. Further observations of other Shuttle missions indicated possible connections between the ionospheric D-layer with the 5.6 Hz signals and the E-layer with the 11.2 Hz signals. The frequencies may vary somewhat, depending upon a variety of parameters. In 1989, an organized effort was launched at the Naval Ocean Systems Center (NAVOCEANSYSCEN) , San Diego, CA, to study the validity of this phenomenon. Shuttle missions starting from October 1989 were monitored and valid confirmation data were obtained for several missions. The description of the observations will be given in a later section.

2. Instrumentation

This initial study used three sites for the measurements. The sites are located in Reno, NV; in San Diego, CA; and in La Posta, CA. Fig. 1 shows the location of the three sites. The La Posta site is a remote site located 100 km east of San Diego and is linked to NAVOCEANSYSCEN, San Diego, via a commercial telephone link. All the sites use portable directional high turn coil sensors (search coil magnetometers) as the antenna elements. The San Diego and La Posta stations use identical magnetometer systems. Fig. 2 shows a schematic layout of these systems. Each sensor head consists of 90,000 turns of fine wire, wrapped on a mu-metal rod. A low noise instrumentation preamplifier is also located directly at the sensor head in order to avoid amplification of cable noise. The coil and electronics are electrostatically shielded with cylindrically shaped foil covers and are all housed inside a plastic cylinder. Each cylinder measures 10 cm in diameter by 34 cm in length. The three sensor heads are mounted inside a weather proof fiberglass enclosure. The fully loaded enclosure weighs approximately 30 pounds and is highly portable. In the field, the three orthogonally arrayed sensor heads are oriented with the x-sensor pointing east, the y-sensor pointing north, and the z-sensor pointing vertically. A 36 meter cable connects the sensor unit to the external amplifier unit which consists of an amplifier, a 40 Hz low-pass filter and a 60 Hz notch filter for each axis of operation. For general operations at the San Diego station, a spectrum analyzer (HP 3561A) is used for observations of real-time power spectra, and a magnetic tape data recorder (Honeywell 101) is used for data recording. The La Posta remote site uses a PC computer for data collection, processing, and recording. The collected data are stored on hard disk and are also processed with a Fast Fourier Transform (FFT) program. A telecommunications link using the telephone line, modems, and telecommunications software (PC Anywhere) connects the La Posta Station with the NAVOCEANSYSCEN Low Frequency Noise Lab at San Diego. Near real-time power spectrum displays and downloading of data can be performed remotely. Fig. 3 shows a sketch of the setup of this remote link.

The Reno sensor systems (11,12) are basically of the same design as those at San Diego and La Posta, with some differences. The Reno systems consist of single axis sensors; however, three of them together can serve as a three-axis system. The Reno sensors have the preamplifier located at the external amplifier unit rather than at the sensor heads making cable noise a problem if long cables are used. The Reno amplifier units, unlike those at San Diego and La Posta, contain correction elements for adjusting the non-linearity of the coil characteristics to provide a flat output response. This serves to assure uniform system response in the range of 0.1 to 50 Hz. A solid copper casing protects the coils and shields against electrostatic fields and completely excludes electric field components. Fig. 4 shows a schematic layout of the Reno sensor system.

The search coil magnetometer systems can measure minute changes in the ambient field. Fig. 5 shows the calibration chart of one axis of the three-axis magnetometer system used in San Diego and La Posta. The output response increases linearly with frequency because the coil sensors measure the derivative of the field and not the field itself. From this calibration chart, we can estimate the minimum field changes that we may expect to observe in the 0.1 to 40 Hz range. The self-noise of the system is approximately 2.5 mV(rms)/$\sqrt{Hz}$. At 10 Hz, the system outputs 10 volts per gamma (1 gamma = 1 nano-Tesla). An ambient signal to generate an output above the self-noise requires a signal of 0.00025 gamma/$\sqrt{Hz}$ or 0.25 milli-gamma/$\sqrt{Hz}$. This order of sensitivity is similar to the sensitivity of the US Geological Survey (USGS) and the University of California search coil magnetometer systems described in reference (13). This order of sensitivity is generally sufficient for all low frequency research because the ambient background noise levels are somewhat higher than the minimum levels that can be measured. The Reno search coil sensors are even more sensitive having a uniform sensitivity of approximately 0.05 milli-gamma/$\sqrt{Hz}$ in the range of 0.1 to 50 Hz. By contrast, fluxgate magnetometers have a sensitivity of only 100 milli-gamma/$\sqrt{Hz}$, and low frequency phenomena, such as observed by us, could be missed due to their lack of sensitivity.

3. Description of the Observations

Most of the observations of the ELF signatures were taken during Space Shuttle missions. Smaller spacecraft such as Delta rockets, have also been seen to generate similar signatures when traversing the ionosphere. Table 1 lists the recent Shuttle launches since October 1989.

There were many unexpected schedule changes made during these missions, and opportunities for observations have been lost due to these changes.

Typically, recordings are initiated one hour prior to launch time or one hour prior to touchdown. The April 24, 1990 launch of the discovery was recorded on magnetic tape at the Reno station and provided a good example of the signal characteristics. In this particular mission, the Shuttle Discovery was launched at 0531 PST (1331 UT) from Cape Kennedy. Four minutes later, signals peaking at 5.7 Hz became prominent. Another two minutes later, signals peaking at 12 Hz also appeared. During the following five minutes the two signals became the two most prominent peaks in the DC (0.1 Hz) to 20 Hz band.

Fig. 6 shows a four-minute average of the DC (0.1 Hz) to 20 Hz background spectrum at 0520, eleven minutes before launch. The averages were performed on an HP3561A Signal Analyzer. No particularly strong signals were observed except for the 15 Hz peak (which most likely was a local artifact). Fig. 7 shows a spectrum observed at 0536, five minutes after launch. The 5.7 Hz peak is clearly visible. Fig. 8 shows a three-minute average spectrum taken from 0538 to 0541. Here the 12 Hz peak dominates the 5.7 Hz peak. The 12 Hz peak is also broader than the 5.7 Hz peak, indicating a lower Q phenomenon. The twin peaks at 1.0 and 4.0 Hz are background noise signals probably not associated with this phenomenon. Fig. 9 shows a time history of the phenomenon showing a one minute average power spectrum every two minutes. The display of the time history clearly shows the appearance and disappearance of the twin peaks. The Shuttle Discovery touched down five days later on 29 April 1990 at 0649 (1449 UT). The overall background noise was high that day and the resonant peaks can best be seen through a long time average. Fig. 10 shows a half hour average taken from 0610 to 0640. The peaks have shifted in frequency to 5.3 Hz and

10.55 Hz. The observed peaks at 6.75 Hz and 9.25 Hz do not always appear, and are as yet unexplained.

This series of observations can be correlated with a typical trajectory given by NASA. In launches, the Shuttle reaches 60 km in about five minutes (D-layer) and 100 km in 8.5 minutes (E layer). Then it coasts into orbit at about 240 km traveling at Mach 25. The landing manoeuvers can take up to an hour and involve more inclined angles (with respect to the ionosphere) than during launch. Hence during landings the signals generally last longer than during launches. The correlations fit the hypothesis that the 5.6 Hz signals originate from the D-layer and the 11.2 Hz signals originate from the E-layer.

The October 18 to October 23, 1989 mission of the Shuttle Atlantis gave another good example of this phenomenon. Fig. 11 shows a strong 5.16 Hz peak appearing 23 minutes after launch. The low frequency and the long duration of the signal, and the absence of the 10-12 Hz peak, probably indicated changed ionospheric conditions arising from the large October 17 Loma Prieta quake which occurred on the previous day (14). Fig. 12 shows a strong 11.08 Hz peak at 0910 (1810 UT) on 23 October and Fig. 13 shows a strong 5.64 Hz peak at 0925. Touchdown was seven minutes later at 0932. Apparently, the ionospheric conditions had normalized and the peaks had reverted back to the more typical frequencies.

4. Interpretation of Results

As discussed in the previous section, the evidence points to the D-layer as the generator of the 5.6 Hz signals and the E-layer as the generator of the 11.2 Hz signals. The signals, observed in Reno and San Diego simultaneously, indicated a large scale phenomenon. It should be noted that the signatures were observed clearly in Reno but very poorly in San Diego and La Posta. The reason for this difference is yet to be determined. The energy of the phenomenon probably derives from both mechanical contact between the spacecraft and the ionosphere and a shock excitation following the spacecraft. The shock excitation from the reentering Shuttle is strong enough to excite seismic waves (15). In general, the turbulent wake of the spacecraft excites many excitation modes in the plasma fluid. Most modes will be damped out. The undamped modes will be the resonant modes and will propagate for long distances. In the ELF frequency range, two types of plasma waves are seen to be candidates for the signatures observed by us. These candidates are the Alfven waves and the magnetosonic waves (16). The Alfven waves are also known as slow hydromagnetic waves and the magnetosonic waves are also known as fast hydromagnetic waves. Hydromagnetic waves are low frequency (less than several hundred Hertz) ion acoustic waves traveling in a region with a magnetic field. Ion acoustic waves are compressional waves formed from the ion background. Slow hydromagnetic waves propagate parallel to the ambient magnetic field while fast hydromagnetic waves propagate perpendicular to the ambient magnetic field. In hydromagnetic wave propagation, the magnetic field lines and the plasma fluid oscillate together as if the particles were stuck to the lines. The field lines act as if they were mass-loaded strings under tension and a hydromagnetic wave can be regarded as the propagating disturbance occurring when the strings are plucked. A theory that models this phenomenon is called the field line resonance model (18,19).

A simple formula exists for the velocity of propagation of slow hydromagnetic waves (Alfven velocity) but unfortunately it is accurate only for fully ionized plasmas. However, a chart of the distribution of the Alfven velocity with respect to height in the ionosphere has been produced from more detailed calculations (20). The chart shows that the Alfven wave velocities in the D-layer and E-layer are approximately 600 km/sec and 500 km/sec, respectively. These velocities are much faster than pure ion-acoustic wave velocities which are of the order of several hundred meters/sec. At hydromagnetic speeds East coast to West coast travel time will be less than 10 seconds. This short delay is consistent with observations.

It is surmised that large amplitude hydromagnetic waves are induced by the action of the spacecraft. The waves travel both parallel and perpendicular to the earth's magnetic field. Those waves traveling along the field lines are guided to the bottom of the ionosphere in one direction and guided to the magnetosphere in the other direction. Thus, immediately below the disturbed ionosphere, the disturbance will be seen as evanescent fields. The waves traveling up to the magnetosphere will be seen as evanescent fields at the conjugate location of the planet. The waves traveling East-West will be traveling perpendicular to the earth's field and hence will be fast hydromagnetic waves. Fast hydromagnetic waves travel somewhat faster than Alfven waves. What is observed on the West coast during an East coast Shuttle launch is either the evanescent field of the traveling fast hydromagnetic waves or the oscillating magnetic field lines of the earth associated with the passage of the hydromagnetic waves. The exact nature of the observed signals is being explored both experimentally and theoretically.

The question of the resonant nature of the observed peaks is a more difficult question to answer. One approach is to treat the earth, the geomagnetic field, and the lower ionosphere as one giant RLC circuit. The resonant frequency is

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

where L and C are the effective inductance and the effective capacitance, respectively. To our knowledge, there are no estimated values of L and C that can be used for this situation. However, there have been rough estimates given for the R, L, and C values for the upper ionospheric/magnetospheric circuit (21,22). The estimates given by Rostoker and Lau (22) gave a resonant frequency for that circuit in the millihertz range which is consistent with only the Pc5 micropulsation frequencies. Fig. 14 depicts a schematic of the equivalent circuit. The existence of the Pc1 micropulsations (up to 5 Hz) give hope that R, L, and C values exist to explain the 5 - 12 Hz oscillations of the type observed by us. At present there is insufficient knowledge to even estimate R, L, and C values for the earth/geomagnetic field/lower ionospheric circuit. More in-depth studies need to be performed to determine the values of geophysical parameters. Because of the large amount of geophysical aeronomic research conducted in Canada and the large number of ULF/ELF recording stations located in the pertinent sub-auroral regions of Quebec, Ontario, Manitoba, Saskatchewan, Alberta, and British Columbia, we invite our Canadian colleagues to join us in this endeavor.

5. Conclusion

We have presented evidence for at least two resonant modes of the lower ionosphere that have not been reported before to the best of the authors' knowledge. These modes occur in the lower ionosphere (D- and E-layers) because they are not usually seen in the evening sectors when sunlight is absent. The nature of the modes are not clearly known at present. It is surmised that the sensors are detecting the evanescent fields of hydromagnetic waves or the oscillating geomagnetic field associated with these waves. The frequencies of these waves are most likely related to the resonant conditions that exist in the earth/geomagnetic field/lower ionospheric cavity. In fact, the observed signatures may indicate the natural oscillations of the lower ionosphere. Intensive investigation is under way to clarify these issues.

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Table 1. Space Shuttle Missions (October 1989 to pesent).

Shuttle	Launch (UT)	Touch Down (UT)
Atlantis	1989, Oct 18, 1753	1989, Oct 23, 1732
Discovery	1989, Nov 23, 0638	1989, Nov 28, 0029
Columbia	1990, Jan 09, 1335	1990, Jan 20, 0935
Atlantis	1990, Feb 29, 0750	1990, Mar 04, 1808
Discovery	1990, Apr 24, 1331	1990, Apr 29, 1449
Atlantis	1990, Oct 06, 1035	1990, Oct 10, 1357
Atlantis	1990, Nov 15, 2247	1990, Nov 20, 2043

FIGURE CAPTIONS

Fig 1. Map showing location of ELF monitoring sites at Reno, San Diego, and La Posta.

Fig 2. Diagram of one axis of the NAVOCEANSYSCEN three-axis search coil magnetometer system. Insert shows coil orientations.

Fig 3. Diagram of the NAVOCEANSYSCEN remote site set-up. The search coil magnetometer system is the same as that shown in Fig 2.

Fig 4. Diagram of the Reno single axis search coil magnetometer system.

Fig 5. Calibration curve of the NAVOCEANSYSCEN search coil magnetometer system in volts/gamma versus frequency. Dark line indicates measured values; dashed line indicates extrapolated values. Low pass cutoff at 40 Hz and notch filtering at 60 Hz are clearly seen.

Fig 6. Four minute average power spectrum of background noise. Artifact at 15 Hz. Recorded in Reno eleven minutes before the April 24, 1990 Shuttle launch.

Fig 7. "Snapshot" spectrum taken 5 minutes after the April 24, 1990 Shuttle launch. Peak at 5.7 Hz is clearly visible.

Fig 8. Three minute average spectrum taken 7 minutes after the April 24, 1990 launch. Peaks at 5.7 and 12 Hz predominate.

Fig 9. Time history display of the Shuttle launch episode on April 24, 1990. Each curve represents a 1 minute average spectrum. Launch time was 0531 PST. The 5.7 Hz signal begin appearing at 0535 PST, and the 12 Hz signal begin appearing at 0537 PST.

Fig 10. One half hour average spectrum taken during the April 29, 1990, Shuttle landing episode. Strong peaks at 5.3 and 10.55 Hz are present.

Fig 11. "Snapshot" spectrum taken 23 minutes after the Oct. 18, 1989, Shuttle launch. Recorded in Reno. Strong 5.16 Hz peak is present.

Fig 12. "Snapshot" of spectrum taken 22 minutes before Shuttle touchdown on Oct. 23, 1989. Strong 11.08 Hz peak is present.

Fig 13. "Snapshot" of spectrum taken 7 minutes before Shuttle touchdown on Oct. 23, 1989. Strong 5.64 Hz peak is present.

Fig 14. Equivalent circuit explanation of 2 mHz Pc5 micropulsations. E represents energy source in the magnetosphere. Subscripts M and I refer to magnetosphere and ionosphere, respectively (after Rostoker and Lau. Space Sci. 26, 493, 1978).


WA
MT
OR
ID
WY
PACIFIC OCEAN
Reno
NV
UT
CO
CA
La Posta
San Diego
AZ
NM

Fig 1

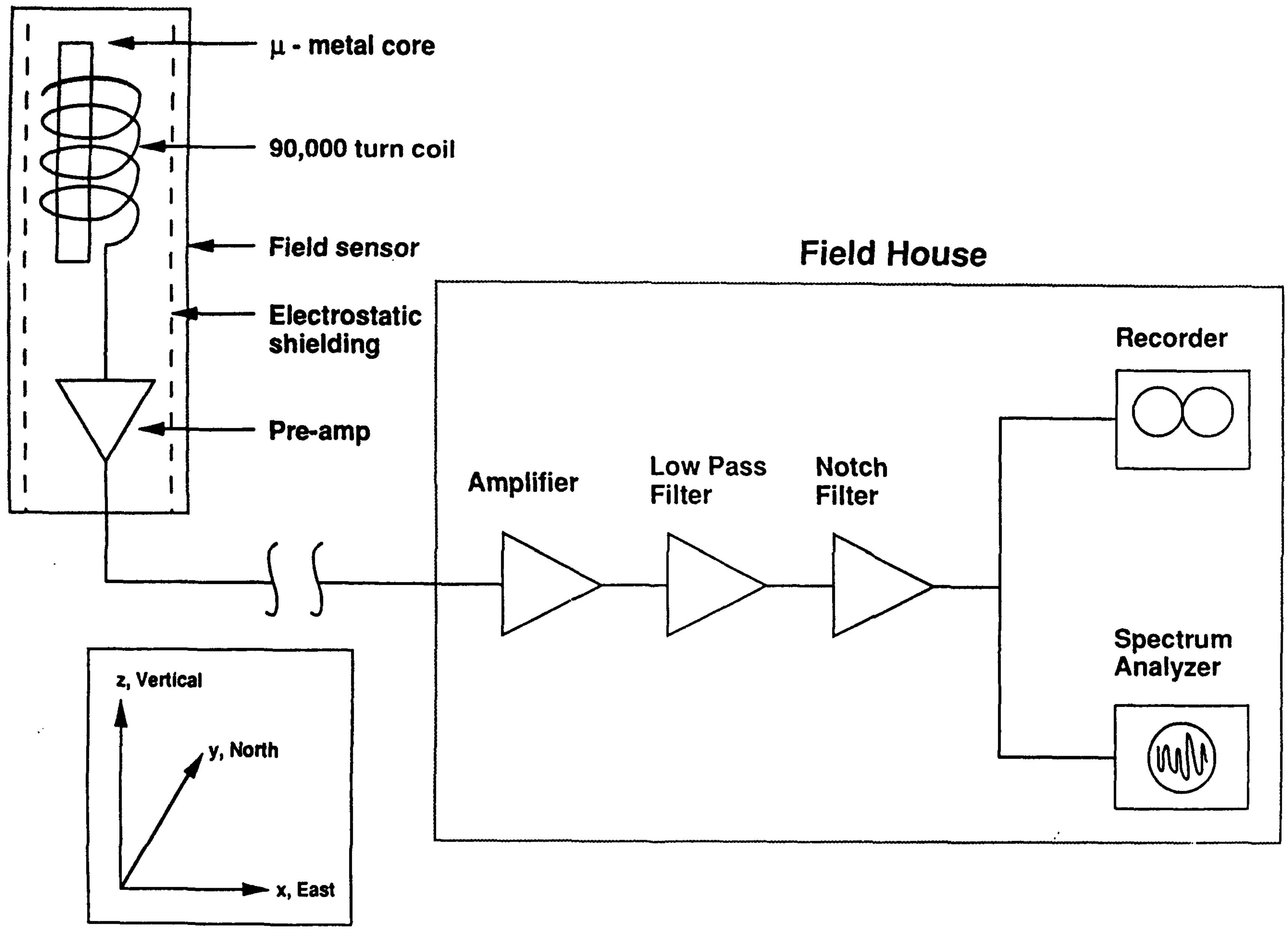
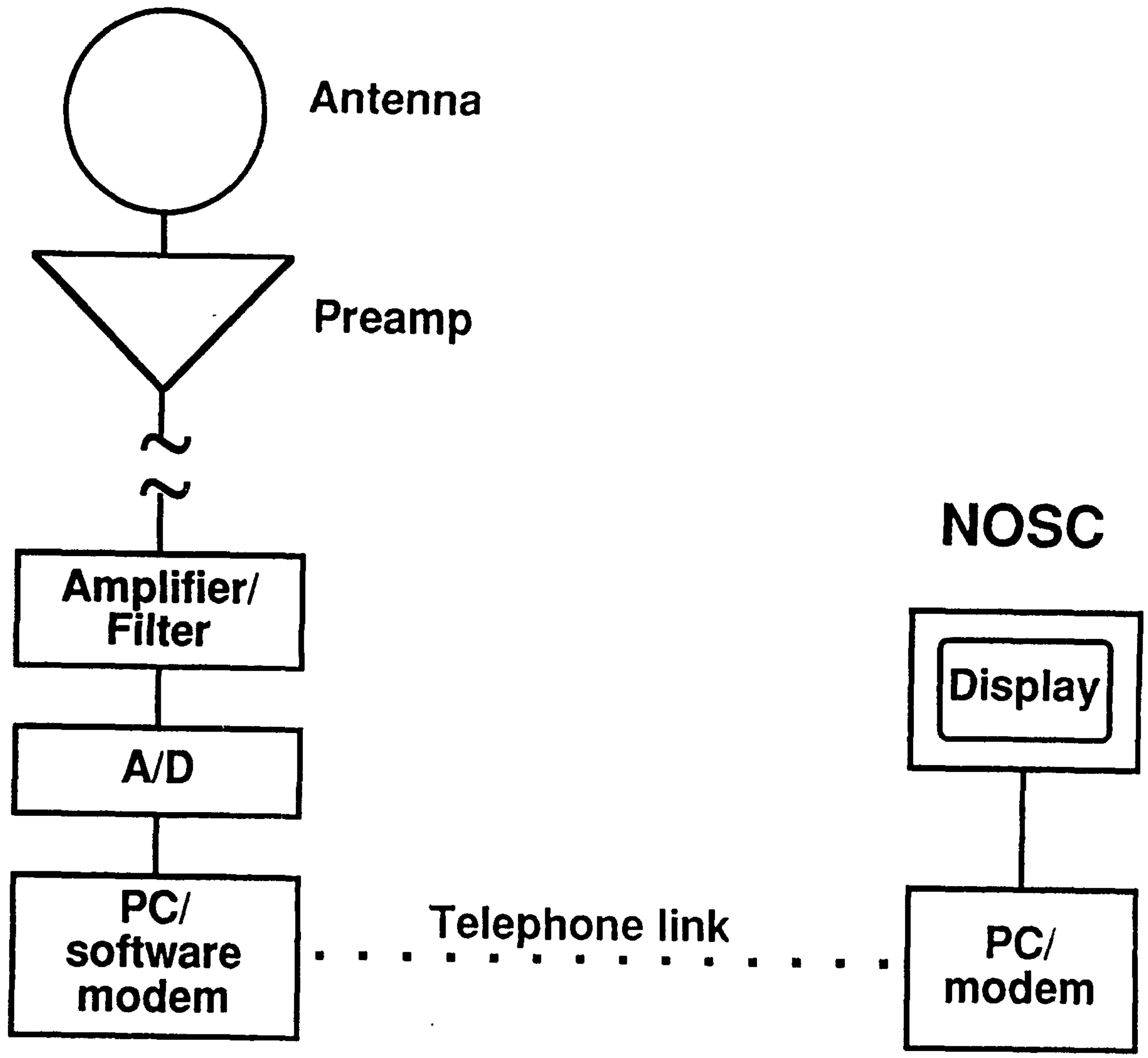
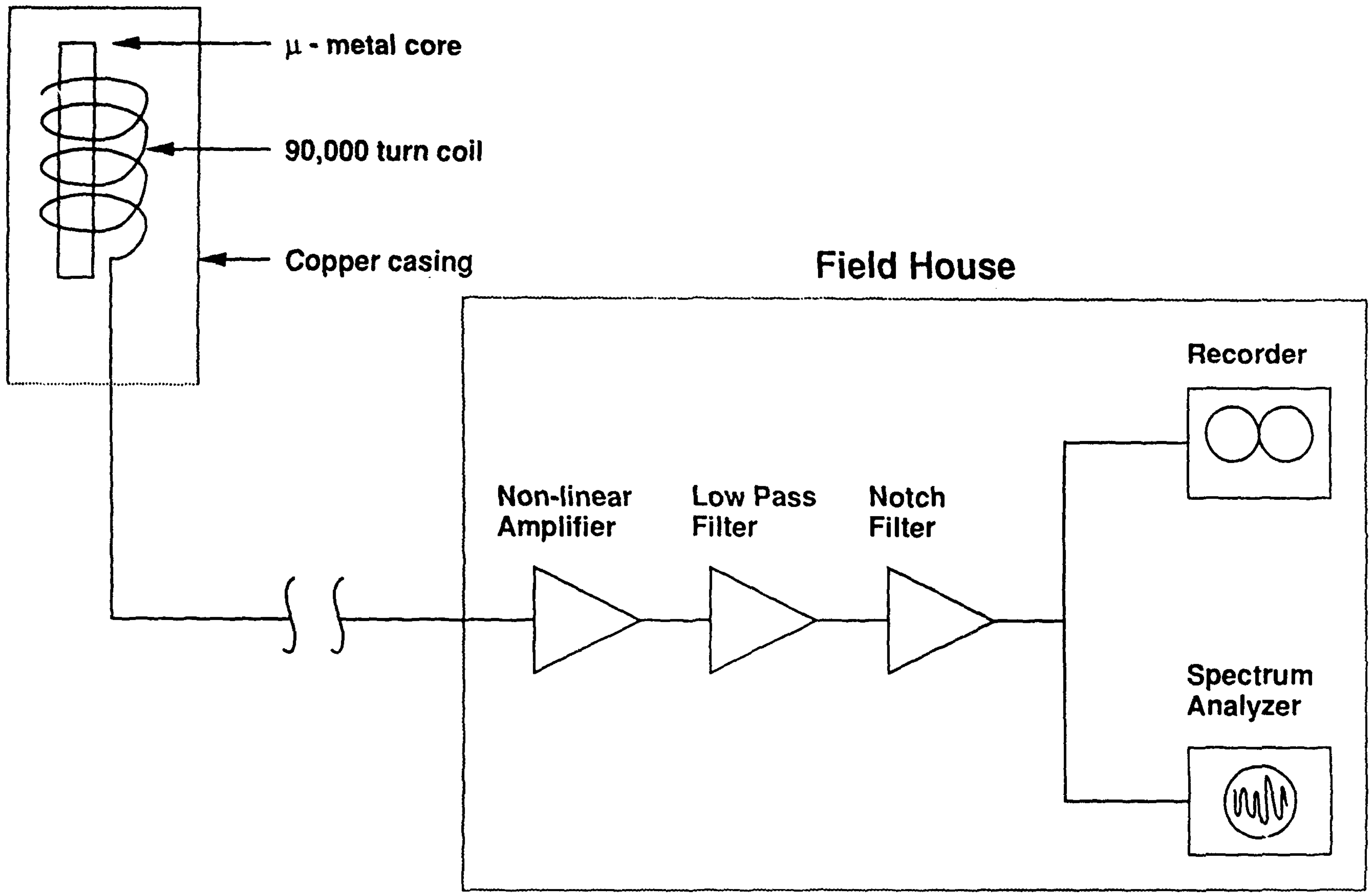

μ - metal core
90,000 turn coil
Field sensor
Electrostatic shielding
Pre-amp
Field House
Amplifier
Low Pass Filter
Notch Filter
Recorder
Spectrum Analyzer
z, Vertical
y, North
x, East

Fig 2



Antenna
Preamp
Amplifier/ Filter
A/D
PC/ software modem
Telephone link
NOSC
Display
PC/ modem

Fig 3



μ - metal core
90,000 turn coil
Copper casing
Field House
Non-linear Amplifier
Low Pass Filter
Notch Filter
Recorder
Spectrum Analyzer

Fig 4

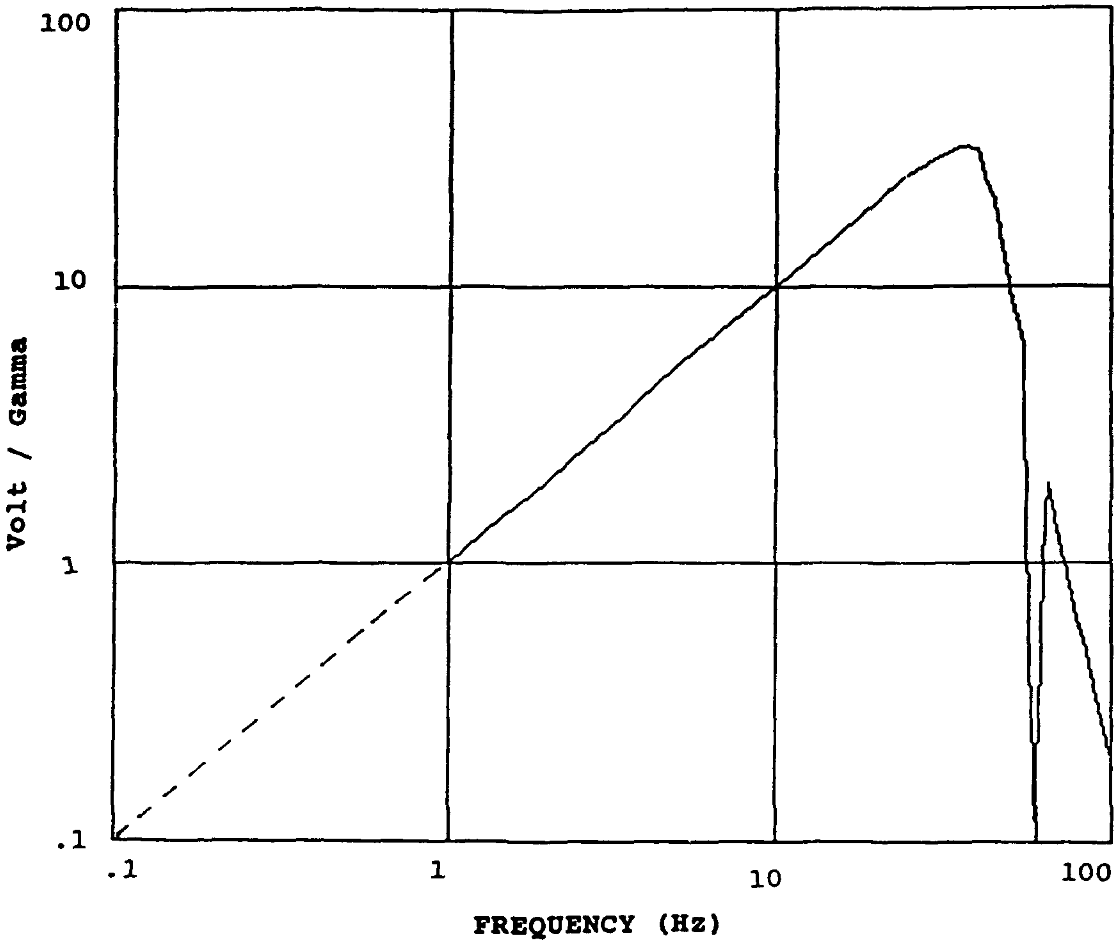
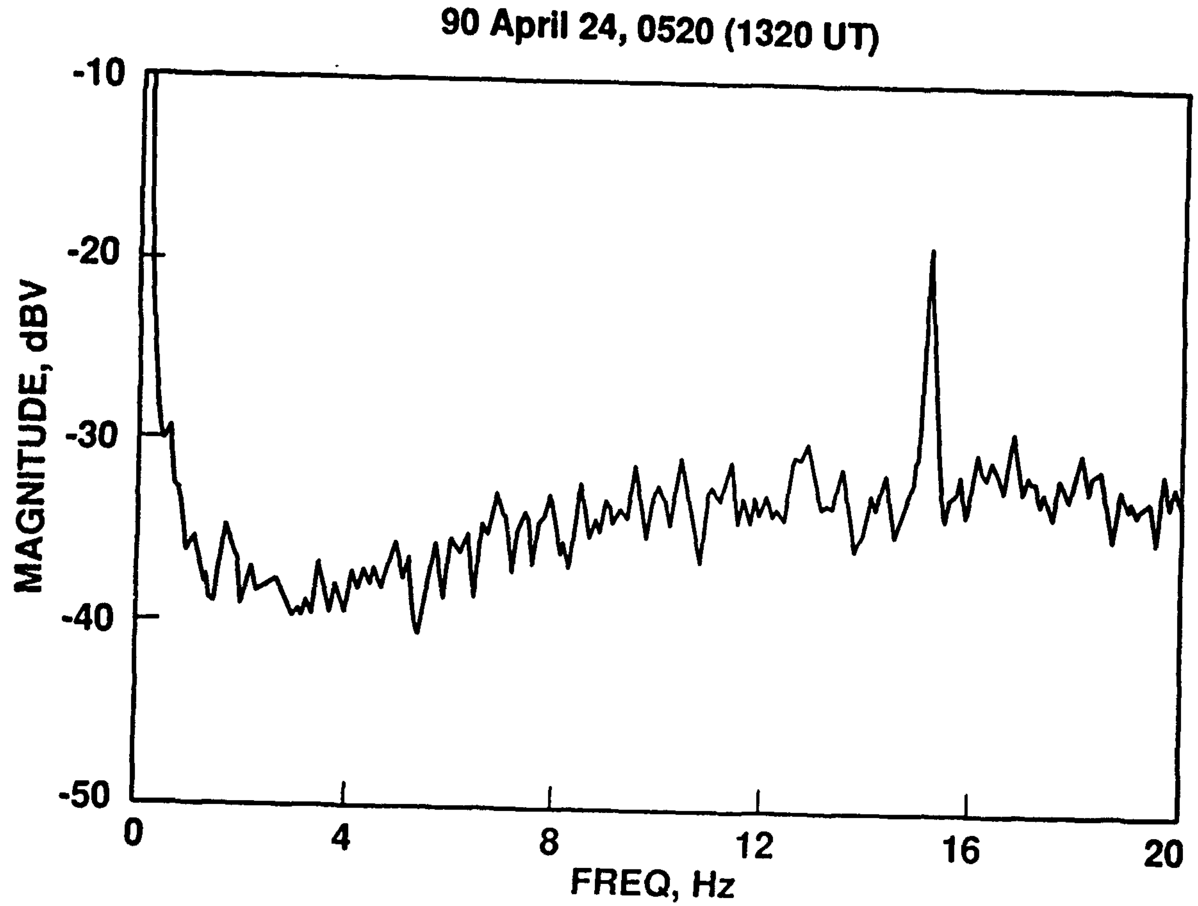


Fig 5

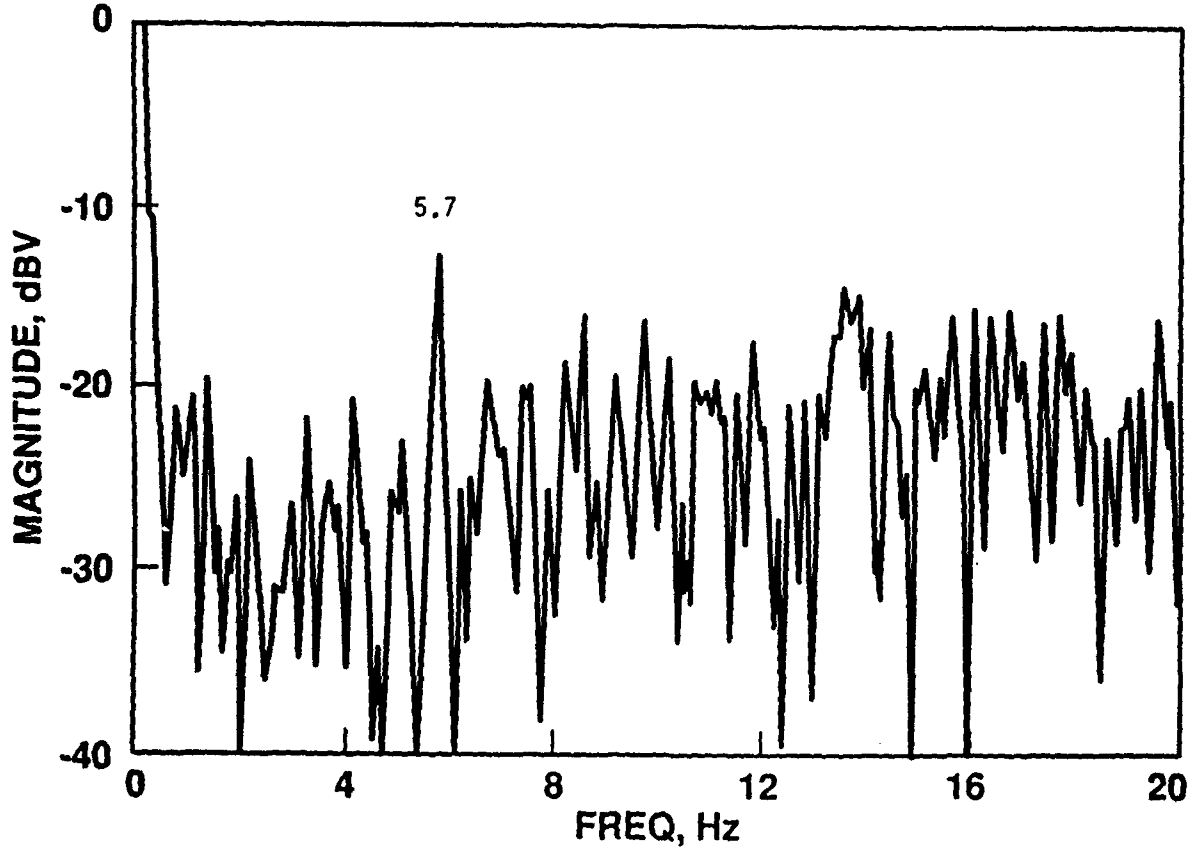


90 April 24, 0520 (1320 UT)
MAGNITUDE, dBV
-10
-20
-30
-40
-50
0
4
8
12
16
20
FREQ, Hz

845-1.83

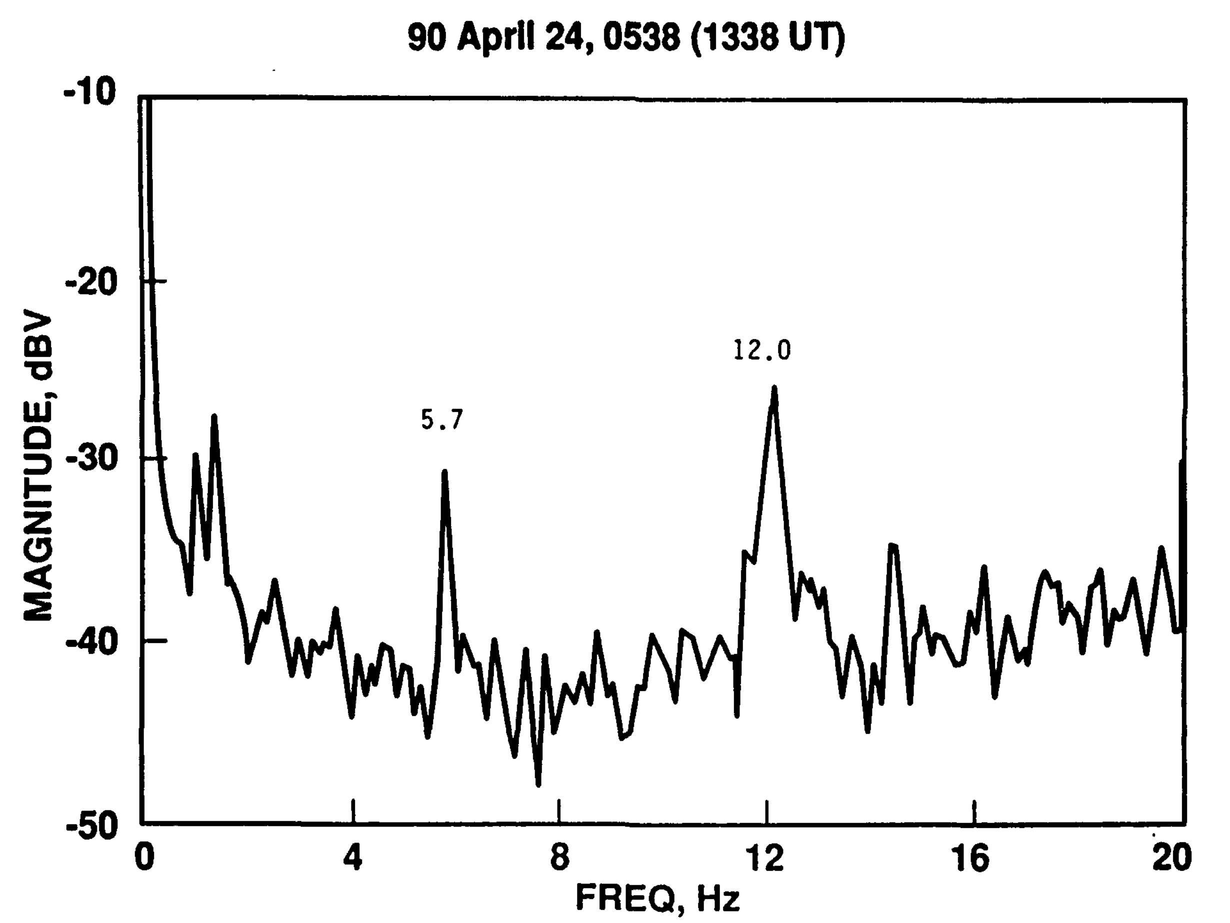
Fig 6

90 April 24, 0536 (1336 UT)



845-2.83

Fig 7


90 April 24, 0538 (1338 UT)
MAGNITUDE, dBV
-10
-20
-30
-40
-50
FREQ, Hz
0
4
8
12
16
20
5.7
12.0

845-3.83

Fig 8

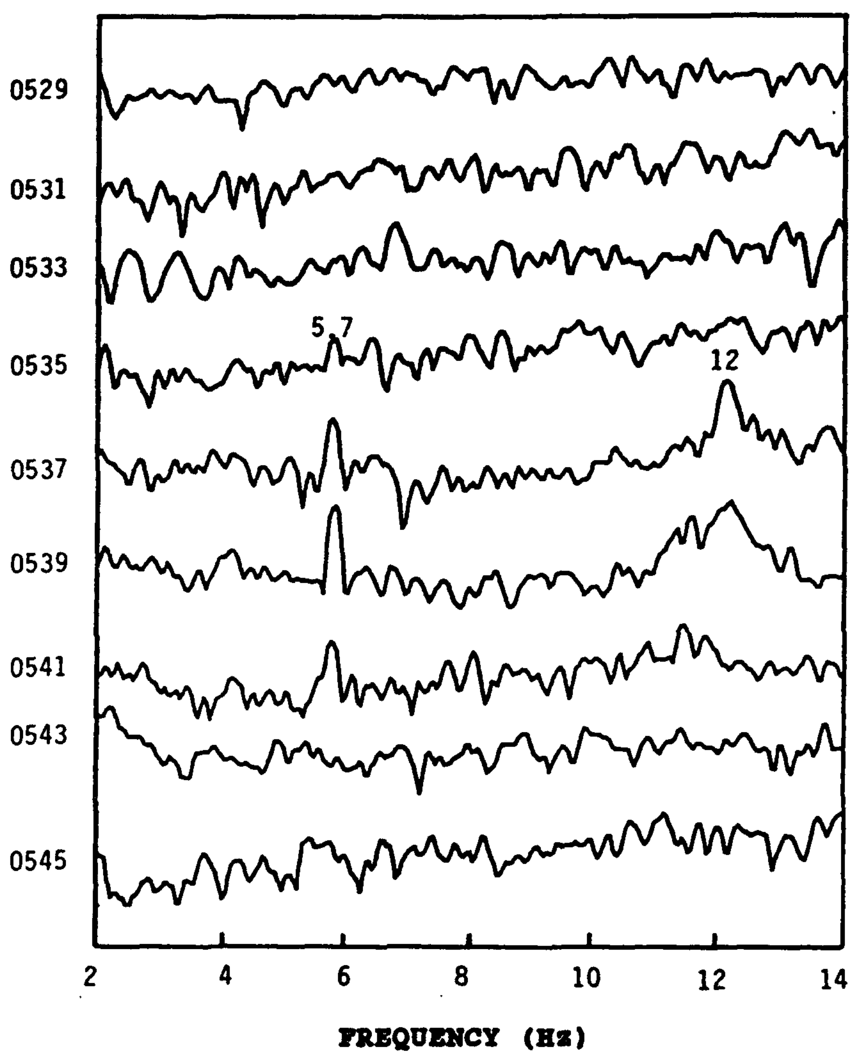
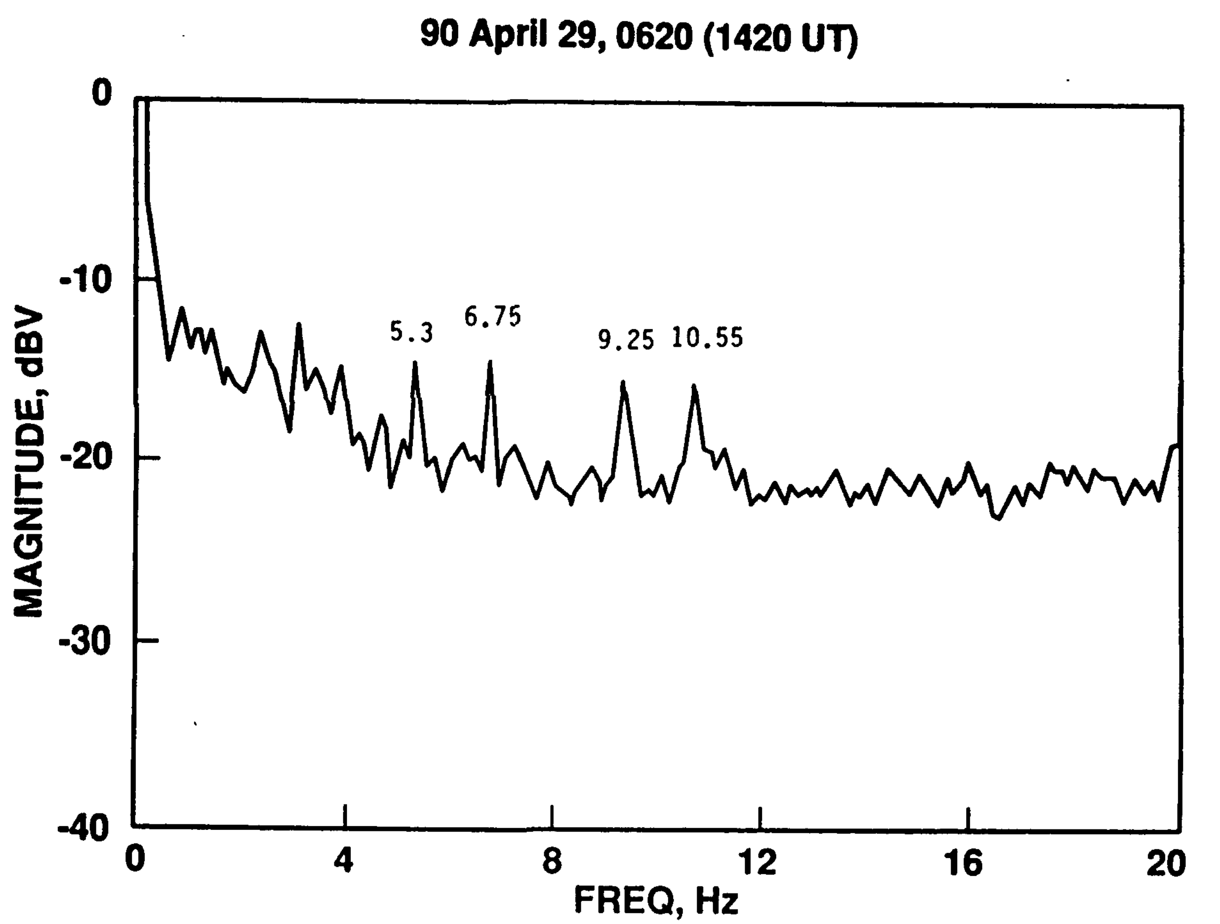
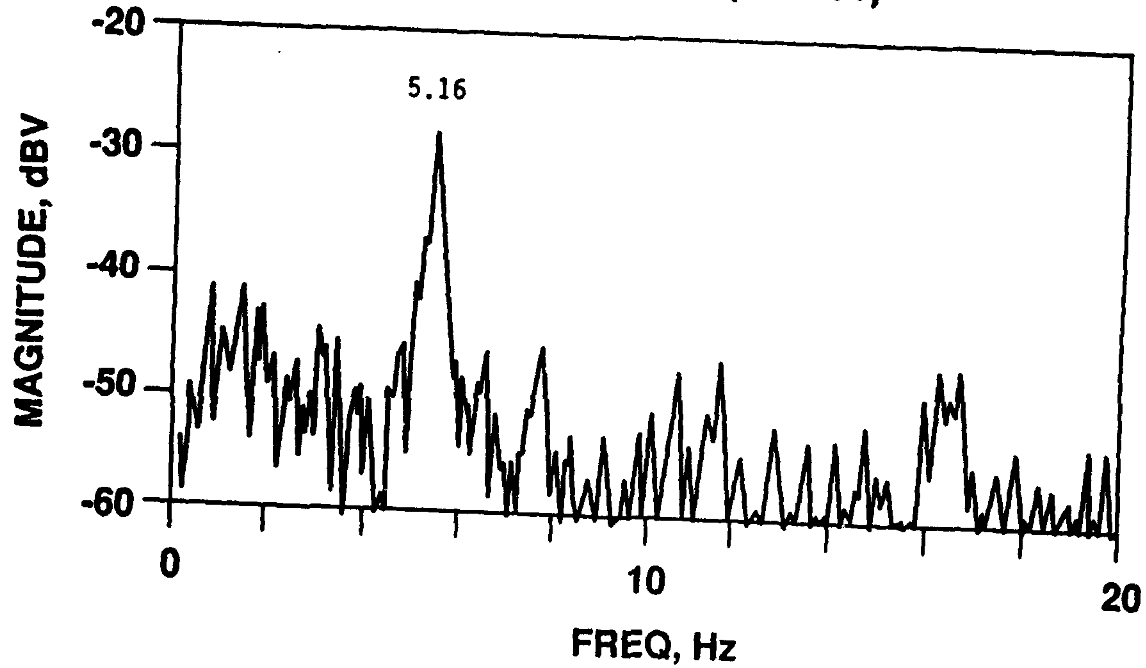

0529
0531
0533
0535
0537
0539
0541
0543
0545
5.7
12
2
4
6
8
10
12
14
FREQUENCY (Hz)

Fig 9


90 April 29, 0620 (1420 UT)
0
-10
-20
-30
-40
MAGNITUDE, dBV
5.3
6.75
9.25
10.55
0
4
8
12
16
20
FREQ, Hz

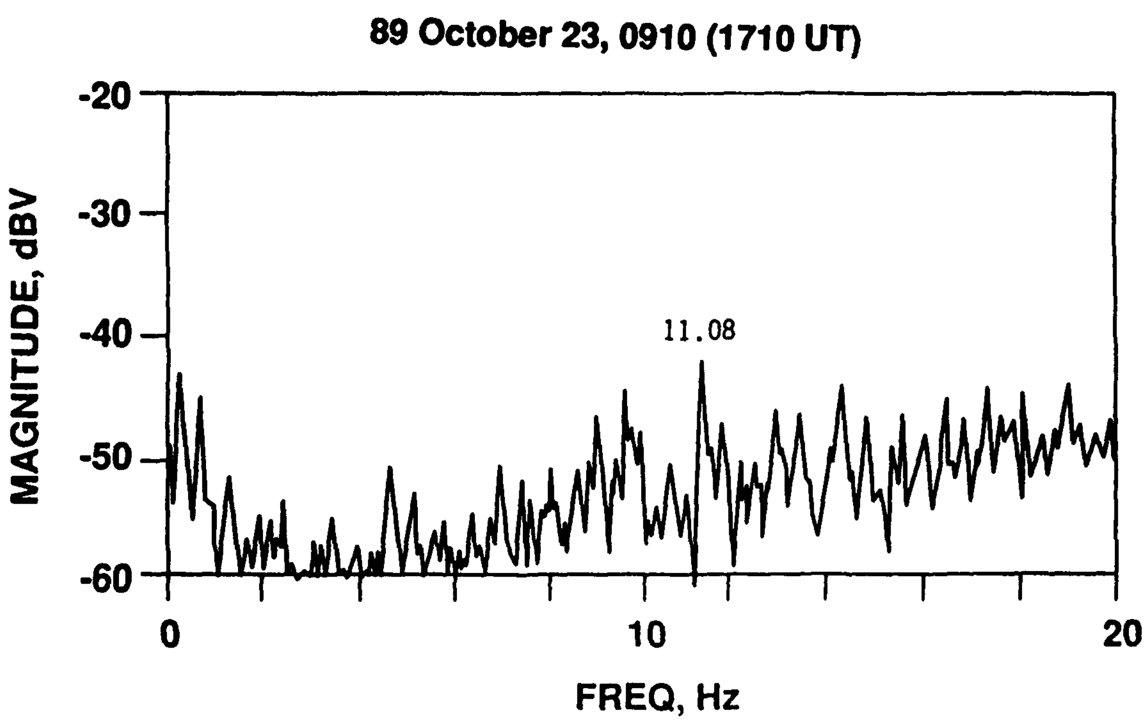
845-4.83

89 October 18, 1015 (1815 UT)



845-8.83

Fig 11



845-9.83

Fig 12

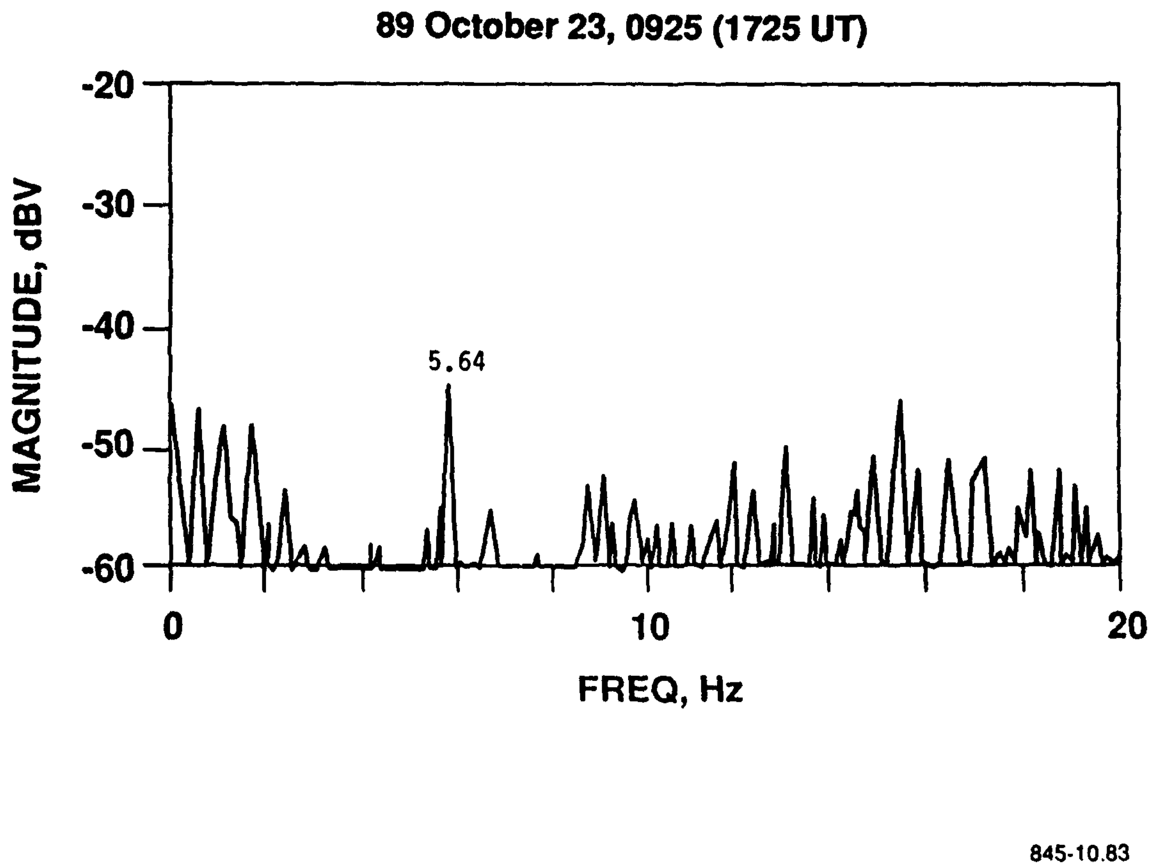
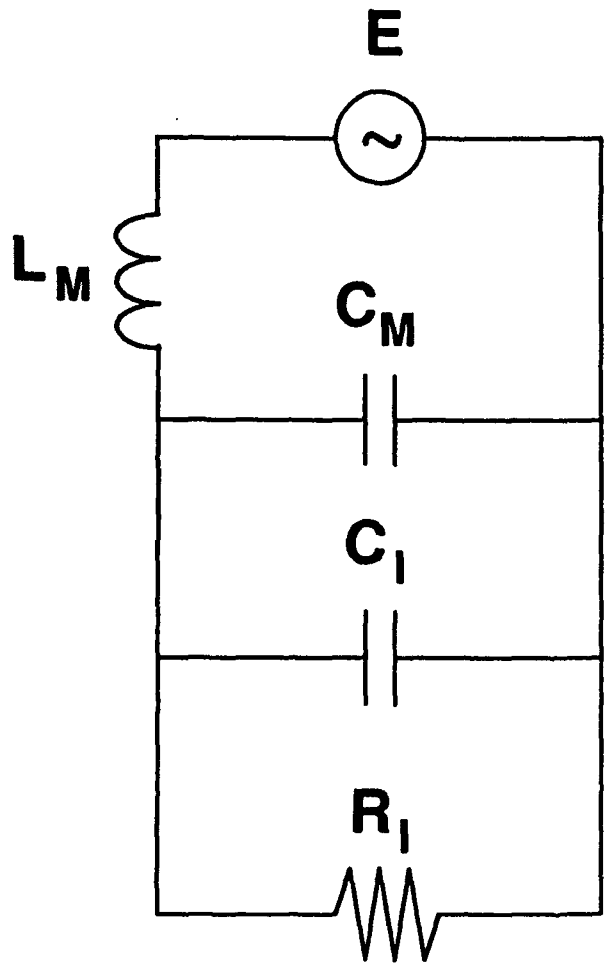

89 October 23, 0925 (1725 UT)
MAGNITUDE, dBV
-20
-30
-40
-50
-60
5.64
0
10
20
FREQ, Hz
845-10.83

Fig 13

Example of Equivalent Circuit for the Ionosphere/Magnetosphere



$L_M \approx 7H$

$C_M \approx 8 \times 10^2 F$

$C_I \approx 20 F$

$R_I \approx 0.5 \Omega$

→ f = 2 mHz (Pc5 micropulsation frequency)