RADIO NOISE NEAR THE EARTH IN THE 1-30 MHz FREQUENCY RANGE

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Abstract

Terrestrial radio interference presents a serious problem for sensitive low-frequency radio observations from space near the Earth. The interference is both narrow band and broad band. Several satellites and planetary probes have carried radio astronomy experiments so a moderate amount of information is available concerning the noise radiation from the Earth. The region of space within 100 R_E of the Earth is quite a hostile environment for any radio astronomy experiment. Observations up to 10 MHz employing ionospheric shielding may be possible from satellite altitudes on the sunlit side of the Earth near solar maximum. Observations above 10 MHz should be made from the surface of the Earth or from the Moon.

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Terrestrial Noise Sources and Emission Levels

Extensive measurements of terrestrial radio noise up to 13.1 MHz were made from Earth orbit aboard RAE-1 (Weber, Alexander, and Stone, 1971) and from lunar orbit aboard RAE-2 (Alexander et al., 1975). LaBelle, Treumann, Boehm, and Gewecke (1989) discuss more recent measurements up to about 5 MHz made from various spacecraft.

Spectacular evidence concerning the severity of terrestrial interference is shown in Figure 1. It is a "typical" record from RAE-2 as the Earth is occulted by the Moon. One sees that even from the distance of the Moon, the radio noise in the 1 to 10 MHz range is dominated by terrestrial interference. The interference levels that would be encountered by a satellite 10,000 km above the Earth's surface (24 times closer to Earth than the Moon) would be some 28 db higher than those shown in Figure 1.

Radiometer noise levels are normally dominated by the Galactic backgroung and this background level is used as a reference noise level. Near the Galactic Poles the background has a brightness of about 10^{-20} w m^{-2} Hz^{-1} $ster^{-1}$ in the 2 to 10 MHz range. The brightness temperature varies approximately as $(wavelength)^2$, from about $2x10^7$ K at 1 MHz to $2x10^5$ K at 10 MHz. Near the Galactic Plane the background temperatures are lower due to free-free absorption, but the above values would be typical antenna temperatures for low-gain dipolar antennas.

Herman, Caruso, and Stone (1973) made a specific study of terrestrial radio noise in the 4 to 10 MHz range with RAE-1. Their study employed the downward-pointing "V" antenna which had a typical beamwidth of ≈30° and their data refer to the radio noise emanating from the sub-satellite region of the Earth. They found that terrestrial noise levels were lowest when RAE-1 was over the oceans and the highest intensities were recorded over major northern and southern land masses. From the noise characteristics they surmised that over the United States the principal source is man-made noise from populated areas (ignition noise, electrical machinery, etc.), while over South America it is lightening. Ground-based transmitters apparently dominated the noise levels over Asia and Eastern Europe.

A typical global noise distribution at 9.18 MHz is shown in Figure 2. It appears that natural and man-made noise emissions are more-or-less comparable in level. This means that operation of a satellite system in an allocated radio-quiet band, even if effective policing of the band were possible, will not solve the interference problems because much of the noise is broad band static from unlicensed sources. Antenna temperatures observed by RAE-1 at nighttime over central United States agree well with Horner's (1965) estimates of the interference levels to be expected from lightening; these levels are about 35 db above the Galactic background. On control nights (without thunderstorms) the observed levels were about 25 db above background and agreed with those predicted for man-made noise levels from electrical machinery.

LaBelle et al. (1989) have made a more recent study employing the AMPTE/IRM spacecraft in the 1.0-5.6 MHz range at a distance of 10 to 18 R_E. They suggest that terrestrial radiation levels may now be approximately 20 db higher than those measured by Herman et al. in 1968.

Terrestrial interference has prevented scientific investigations of natural sources from satellite altitudes in the 10-30 MHz range but there is not much information available about these interference levels. Spacecraft receivers in this band are often saturated until the spacecraft are well away from the Earth. However, most of the sources of terrestrial noise below 10 MHz, such as transmitters, electrical machinery, and lightening, are not significantly weaker in the 10-30 MHz range. Cosmic sources, having non-thermal spectra, are considerably weaker relative to the interference.

Another natural source of intense low frequency noise is auroral kilometric radiation (AKR) (Gurnett, 1974; Kaiser and Alexander, 1977; Benson,1985). This radiation can be 90 to 100 db above the Galactic background. It occurs primarily below 1 MHz on the nighttime side of the Earth. First harmonic emissions of AKR were observed up to 1 MHz by LaBelle et al (1989) but they do not find evidence for higher harmonics. Therefore, it appears that AKR is not a particularly grave problem above 1 MHz.

It should be noted that ISEE-3 carried a radio receiving system that operated in the 30 kHz to 2 MHz band. This satellite was located at the inner libration point, ≈240 R_E from Earth towards the Sun where it was shielded by the ionosphere. It made excellent solar observations for several years without any particular problems caused by terrestrial interference. Although ISEE-3 was much less sensitive than any proposed low frequency space array, its highly successful operation suggests that sensitive observations up to a few MHz should be possible in regions of space shielded by the ionosphere.

Ionospheric Shielding

The ionosphere should effectively block all ground-level emissions at frequencies below f_oF_2. Electromagnetic waves below this ionospheric plasma frequency become evanescent and die away with skin depths of only tens of meters. The ionosphere should become extremely opaque and attenuate such waves by thousands of decibels.

Typical global distributions of f_oF_2 suggest that ionospheric shielding should be effective up to at least 10 MHz on the sunlit side of the Earth near solar maximum and up to at least 3 MHz near solar minimum. At frequencies somewhat above f_oF_2 the ionosphere strongly refracts and reflects the waves, usually allowing them to reach a satellite only if the source is located near the sub-satellite point. However, terrestrial radiation escaping through the ionosphere at some distant point can sometimes be ducted to the vicinity of a satellite that would otherwise be shielded. The RAE-1 and AMPTE/IRM data both show cases where terrestrial noise broke through the ionosphere at frequencies where it would not be predicted. Nevertheless, both these data sets also show long periods when the satellite was shielded and the Galactic background level was recorded. Figures 3 and 4 illustrate these situations.

Solar and Jovian Emission

Ionospheric shielding will be effective only on the sunlit side of the earth, where solar emission may interfere with observations. Type III solar bursts are the most common. These bursts have average durations at ≈1 MHz of about ten minutes; at ≈10 MHz their durations are a few minutes or less. They occur at a typical rate of several per hour at solar maximum and at average intervals of many hours at solar minimum. Weak bursts are a few decibels above the Galactic background on low gain antennas; strong bursts are 30-50 db above background. Statistics concerning solar bursts are available from ISEE-3 and I am in the process using these data to make quantitative estimates of the proportion of time when bursts of various intensities occur.

Jovian bursts can be intense but they are short-lived, they occur during predictable periods, and come from a definite direction. They may be a nuisance but it should be possible to cope with any problems that they present.

Interference Levels Harmful to a Low Frequency Interferometer in Space

The CCIR definitions of harmful interference have proven to be highly appropriate for radio astronomy observations. The CCIR definition of the interference level which is harmful to radio astronomy observations is 10% of the RMS noise limit of a simple, filled-aperture radio telescope. The harmful interference levels for interferometers were analyzed by Thompson (1982) who calculated the interference level that would add 10% to the noise fluctuations in a map produced by a synthesis telescope. Thompson also conducted an experiment with an artificial interfering source located on a mountain overlooking the VLA in order to verify his calculations. He found that the VLA at 1400 MHz, in its most compact configuration, is about 14 db less sensitive to interference than a filled-aperture system. In its most extended configuration, it is about 22 db less sensitive. This results primarily from the reduction of the system's response to an interference source at zero fringe frequency when the system is introducing fringe rotation to follow the sidereal motion of an astronomical source. The interfering signal is rotated in phase over many cycles and its effects are greatly diminished. The reduction factor for each interferometer baseline is given by

$$F_i = \mathrm{sinc}(\tau f_i)$$

where f_i is the fringe frequency on the i'th baseline and τ is the averaging period for the data on this baseline. The total reduction factor is found by averaging F_i over all baselines.

The data are gridded in the u,v plane before Fourier transformation and τ is determined by the length of time required for the i'th baseline to rotate across each cell in this grid. The grid size is equal to the reciprocal width of the synthesized field. For large x, $\mathrm{sinc}(x) \approx 1/x$ so F_i is small if (τf_i) is large. The interference perturbs most strongly those interferometer baselines having small (τf_i). In the case of the VLA this product is >>100 for most baselines. The contributions from those baselines having low fringe rates results in "noise" which is mostly in the form of low frequency ripples across the synthesized map.

If low gain dipolar antennas are used in a space array it will be necessary to synthesize about 2π steradians of the sky in order to deconvolve the sidelobe effects of numerous strong sources within the primary patterns of the antennas. This means that very small cell sizes are required. The data must be gridded into cells no more that one wavelength across if a 180° field of view is to be synthesized. Thus, only a few radians of fringe phase would occur within each integration period. (τf_i) will be ≈ 1 and fringe rotation will not be very effective in reducing the system's response to harmful interference.

It may be possible to use coherence effects and fringe-rate smearing to reduce the effective field-of-view to a steradian or less. This would allow a somewhat larger cell size and somewhat longer integrations. I would estimate that the harmful interference limit will be only 3 to 10 db above that of a filled-aperture system. A more exact estimation would be difficult without a detailed system design. (Note that coherence effects will not reduce the system's responses to narrow band signals; these responses can only be reduced by fringe rotation.)

VLBI experience with interference is not applicable to a low frequency interferometer in space. VLBI systems are especially insensitive to interference because the interfering signal does not correlate at the two ends of the interferometer. Unfortunately, terrestrial interference will be fully correlated on all interferometer baselines of a space array. Thus, a low frequency interferometer in space will be highly susceptible to harmful interference.

In order to be really useful, the low frequency array must be capable of observing sources at the 1 to 10 Jy level and the harmful interference level would be 0.1 to 1 Jy. For example, if one assumes a harmful interference limit of 0.5 Jy and a frequency of 3 MHz, then on a single satellite's dipole this signal will produce an antenna temperature of 0.23 K and if the array has 10 satellites this gives an equivalent filled-aperture antenna temperature of 2.3 K. Assuming that the interferometer provides 10 db protection compared to a filled aperture, the harmful interference limit would correspond to an antenna temperature of 23 K. This is some 50 db below the Galactic background temperature. All of the previous estimates of interference levels were a few decibels to 70 db above the Galactic background. Thus, shielding or interference rejection at the level of 50 to 120 db would be required for successful operation. The development of interference rejection techniques to this level is not feasible so ionospheric shielding must be employed. Any small leakage of interference through the ionosphere would destroy the data unless sophisticated interference rejection techniques are used as well.

Conclusions

In the 1 to 10 MHz range ionospheric effects make high-angular resolution (≈arc-minute) observations from the Earth's surface virtually impossible and it is necessary to go to space. At satellite altitudes near the Earth, terrestrial sources generate noise levels millions of times above the level of interference harmful to observations with a low-frequency space array. This interference is both narrow band and broad band noise. It is essentially impossible to filter or excise interference to such levels.

Near solar minimum, sensitive observations up to a few MHz may be possible from Earth orbit on the sunlit side of the Earth where the ionosphere should provide sufficient shielding from terrestrial interference. Near solar maximum it may be possible to work up to 10 MHz from the sunlit side, at least during selected periods.

In the 10 to 30 MHz range sensitive observations from space near the Earth are probably impossible because ionospheric shielding will be ineffective. In this case, Earth-based observations utilizing terrain shielding are far more practical. The problems associated with ionospheric refraction in Earth-based observations can be attacked with modern self-calibration techniques that have proven to be highly effective at higher frequencies. This approach is far more feasible than an attempt to cope with the interference levels at satellite altitudes.

The interference levels at the near side of the Moon will be about a thousand times lower than those at typical satellite altitudes. This reduction in levels may make relatively sensitive observations possible if effective interference rejection techniques are developed.

The far side of the Moon appears to be the only location near the Earth that is sufficiently shielded from terrestrial interference to permit observations without interference rejection systems. In the distant future, when the severe communication and logistical problems associated with the lunar far side are solved, it is the most promising site for low-frequency radio astronomy.

Acknowledgements

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Figure Captions

Figure 1. RAE-2 data taken from lunar orbit. At all of the frequencies observed the noise levels are dominated by terrestrial noise except when the Earth is occulted by the Moon's limb. When the Earth is occulted, the noise levels are dominated by the Galactic background. Immersion and emersion are calculated for the center of the Earth. Some of the terrestrial noise sources, such as auroral kilometric radiation (AKR) below 1 MHz, are located 1 to 2 R_e from the Earth on the nighttime side and radiate past the calculated position of the limb. (from Alexander et al, 1975)

Figure 2. The terrestrial radio noise distribution derived from the RAE-1 (height 6000 km) lower "V" data at 9.18 MHz for December 2-6, 1968. The secondary peaks in activity over the mid-Pacific and northern Australia are believed to be correlated with local thunderstorm activity. Contour levels are db above 288 K. The Galactic background on this scale would be about 31 db and the receiver saturated at 75 db. (from Herman et al, 1973)

Figure 3. AMPTE/IRM data showing two-minute averages of the rms spectral intensity versus time for seven frequency bins (3.2-5.6 MHz), each 10 kHz broad, for 0215-0915 UT on January 3, 1986, a typical time interval away from the noon local sector. The satellite was at distances from 11.60 to 16.48 R_E. Values of rms spectral intensity 10-30 db above the noise level occur in bursts lasting from a few minutes to a few hours. The absolute intensity of these bursts is in general higher at distances nearer to the Earth. (from LaBelle et al, 1989)

Figure 4. AMPTE/IRM data showing two-minute averages of the rms spectral intensity for seven frequency bins (3.2-5.6 MHz) on a linear scale for a 12-hour interval on September 5, 1984, when the satellite was near noon local time and moved outwards from 11.3 to 18.6 R_E. The bottom panel presents an expanded view showing 2-second resolution data (at 4.4 MHz only) from a 12-minute interval on the same day. The noise level observed near noon local times is constant except for fluctuations of about 10% at time scales of a few seconds and much less over longer time scales. No radial dependence of the noise level is observed. (from LaBelle et al, 1989)

Fig. 1

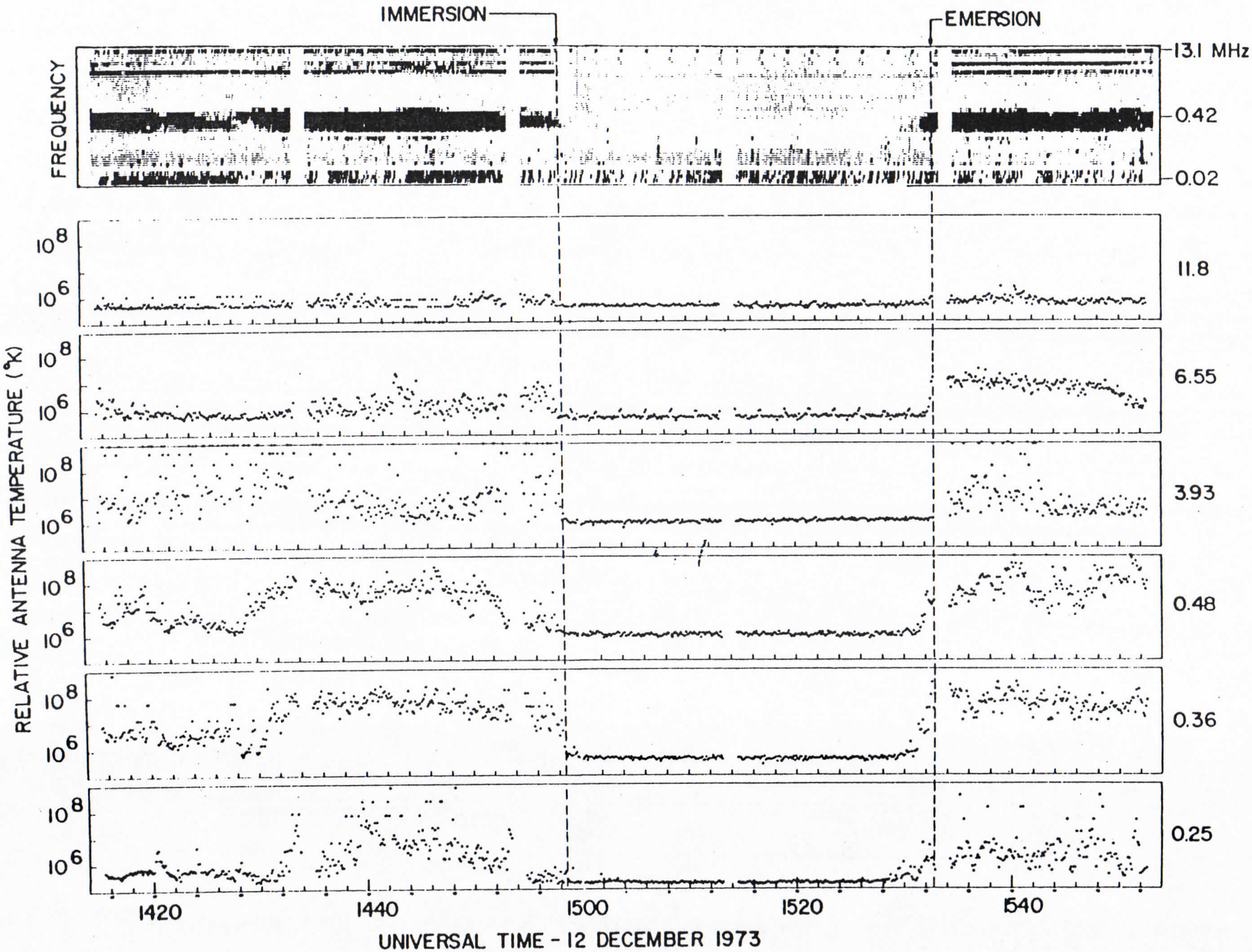

IMMERSION
EMERSION
FREQUENCY
13.1 MHz
0.42
0.02
RELATIVE ANTENNA TEMPERATURE (°K)
10^8
10^6
11.8
6.55
3.93
0.48
0.36
0.25
1420
1440
1500
1520
1540
UNIVERSAL TIME - 12 DECEMBER 1973

FIG. 2

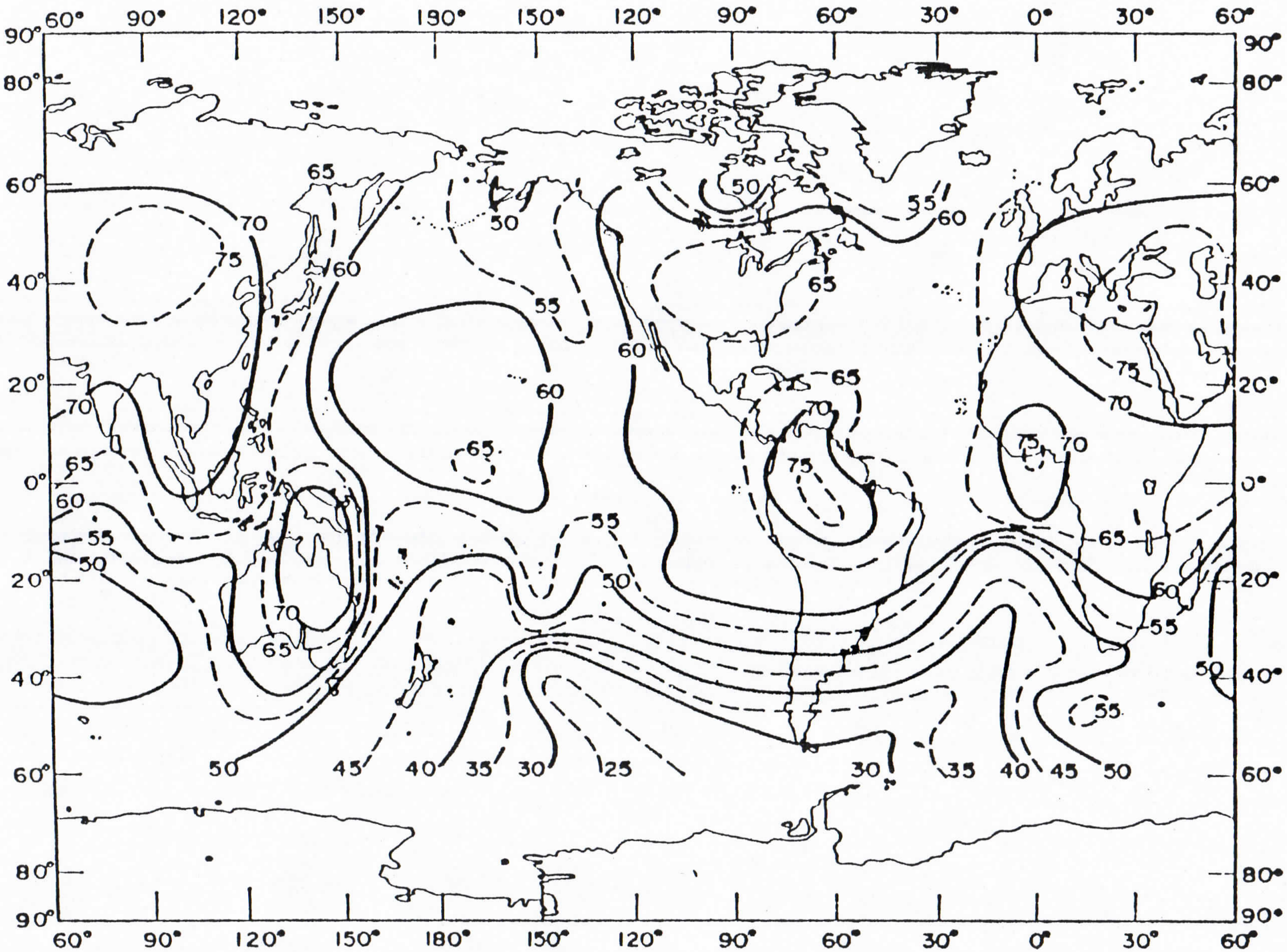
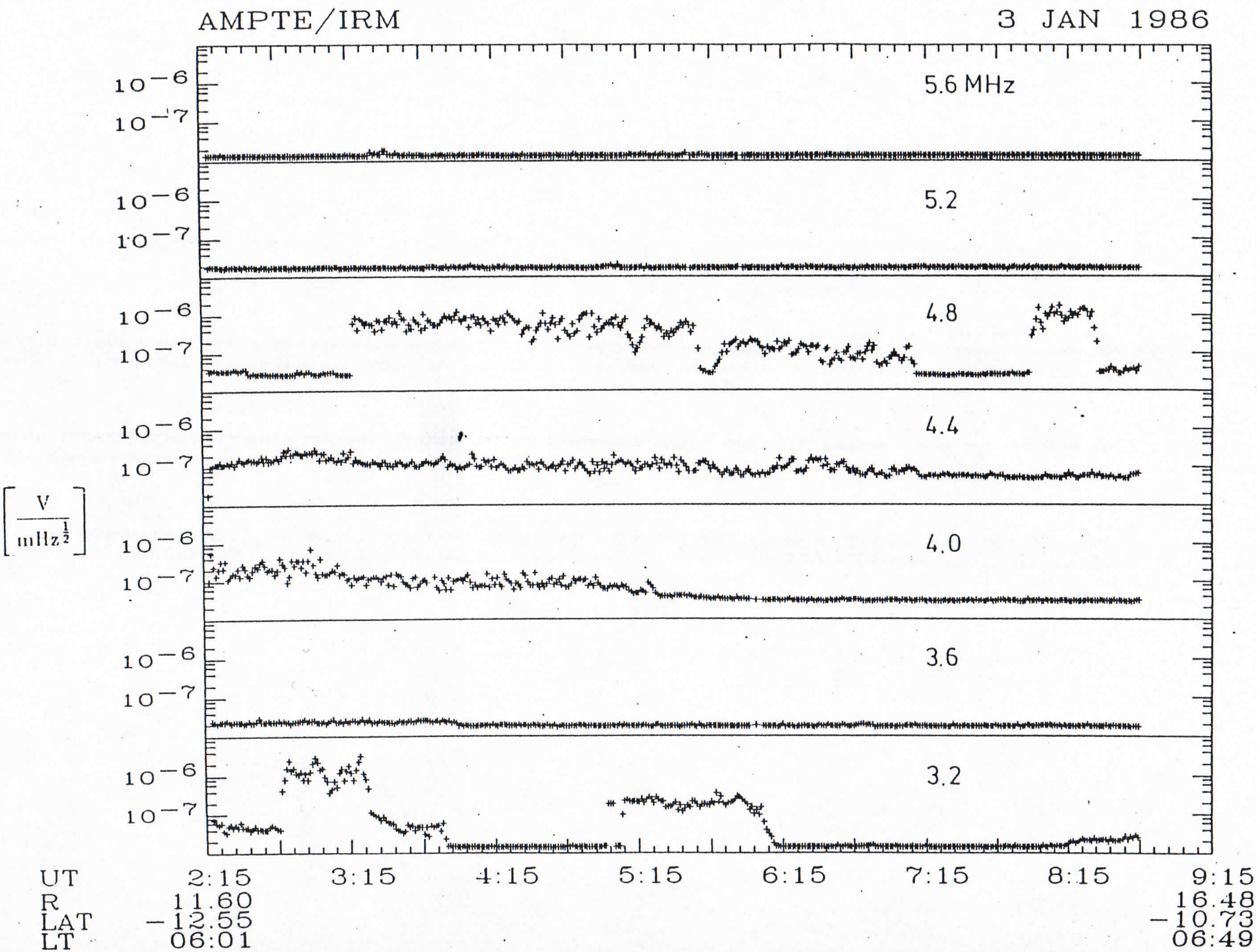
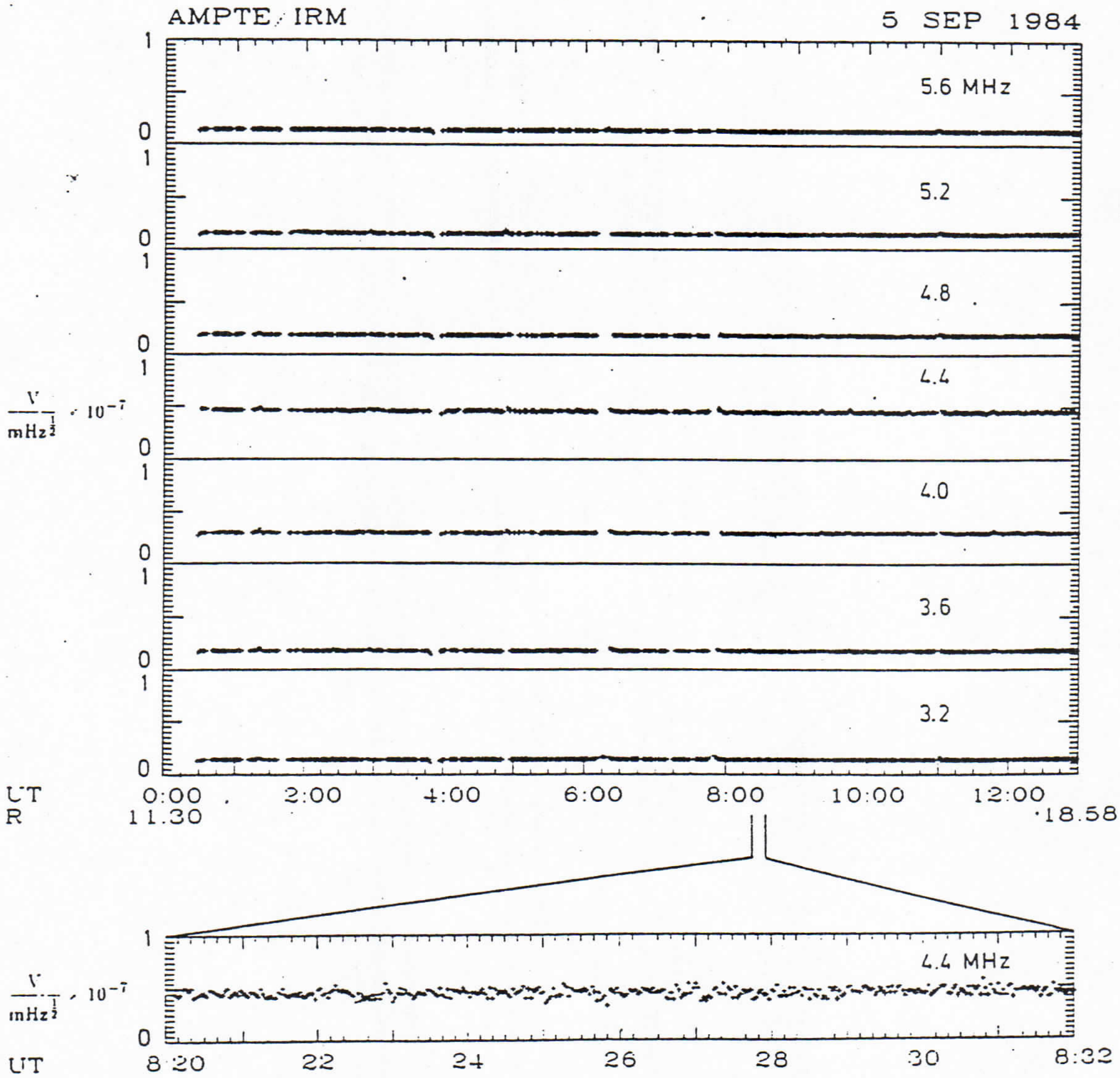

60° 90° 120° 150° 180° 150° 120° 90° 60° 30° 0° 30° 60°
90° 80° 60° 40° 20° 0° 20° 40° 60° 80° 90°
75
70
65
60
55
50
45
40
35
30
25

Fig. 3



AMPTE/IRM
3 JAN 1986
5.6 MHz
5.2
4.8
4.4
4.0
3.6
3.2
10^-6
10^-7
V / mHz^1/2
UT
R
LAT
LT
2:15
11.60
-12.55
06:01
3:15
4:15
5:15
6:15
7:15
8:15
9:15
16.48
-10.73
06:49

Fig. 4


AMPTE / IRM
5 SEP 1984
5.6 MHz
5.2
4.8
4.4
4.0
3.6
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1
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R
0:00
2:00
4:00
6:00
8:00
10:00
12:00
11.30
18.58
4.4 MHz
8:20
22
24
26
28
30
8:32