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Radio Interference in the Near-Earth Environment

W. C. Erickson

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Jet Propulsion Laboratory
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ABSTRACT

Natural and man-made radio frequency interference (RFI) are potentially serious obstacles to the successful operation of an array of spacecraft used for low-frequency (1 to 30 MHz) radio interferometry in the near-Earth environment. Several satellites and planetary probes have carried radio astronomy experiments, and this report examines the moderate database that they provide to help understand the near-Earth RFI environment. The general conclusion is that the region of space within 100 Earth-radii of the Earth is quite a hostile environment for any radio astronomy experiment. If a low-frequency array in Earth orbit is to yield useful astronomical results, severe interference problems must be anticipated and overcome. A number of recommendations are made to further examine the feasibility of a such an array.

PREFACE

The work reported in this publication has been supported by the JPL Director's Discretionary Fund task entitled "Low Frequency Radio Astronomy Using GASCAN Satellites." Dr. Erickson of the University of Maryland is a co-investigator on the task with the following JPL staff: Michael A. Janssen (Principal Investigator), Dayton L. Jones, Thomas B. H. Kuiper, Michael J. Mahoney, Robert A. Preston, and Stephan P. Synnott. This survey of the low-frequency interference environment was undertaken because natural and man-made interference are recognized as potentially serious obstacles to the implementation of a low-frequency VLBI array of small satellites in Earth orbit.

One member of the JPL team (Mahoney) accepts responsibility for any aberrations that may have been added to Dr. Erickson's original document.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

If successful low-frequency (1 to 30 MHz) radio interferometry is to be achieved employing an array of spacecraft in Earth orbit, terrestrial interference presents an important problem that must be carefully studied. This interference is both natural and man-made. 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. A preliminary study has been made of this subject through discussions with the astronomers at Goddard Space Flight Center who have been involved with the relevant experiments, and through a perusal of the available literature. The general conclusion is that the region of space within 100 Earth radii (R_e) of the Earth is quite a hostile environment for any radio astronomy experiment. If a low-frequency radio array in Earth orbit is to yield useful astronomical results, severe interference problems must be anticipated and overcome.

II. TERRESTRIAL NOISE SOURCES AND EMISSION LEVELS

The most extensive measurements of terrestrial radio noise were made from Earth orbit aboard RAE-1 (Weber, Alexander, and Stone, 1971) and from lunar orbit aboard RAE-2 (Alexander et al., 1975). Probably the most spectacular evidence concerning the severity of terrestrial interference is shown in Figure 1, which is a "typical" record of RAE-2 radiometer outputs as the Earth is occulted by the Moon. At all of the frequencies observed, the noise levels are dominated by terrestrial sources except when the Earth is occulted by the Moon's limb. The immersion and emersion times in Figure 1 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.

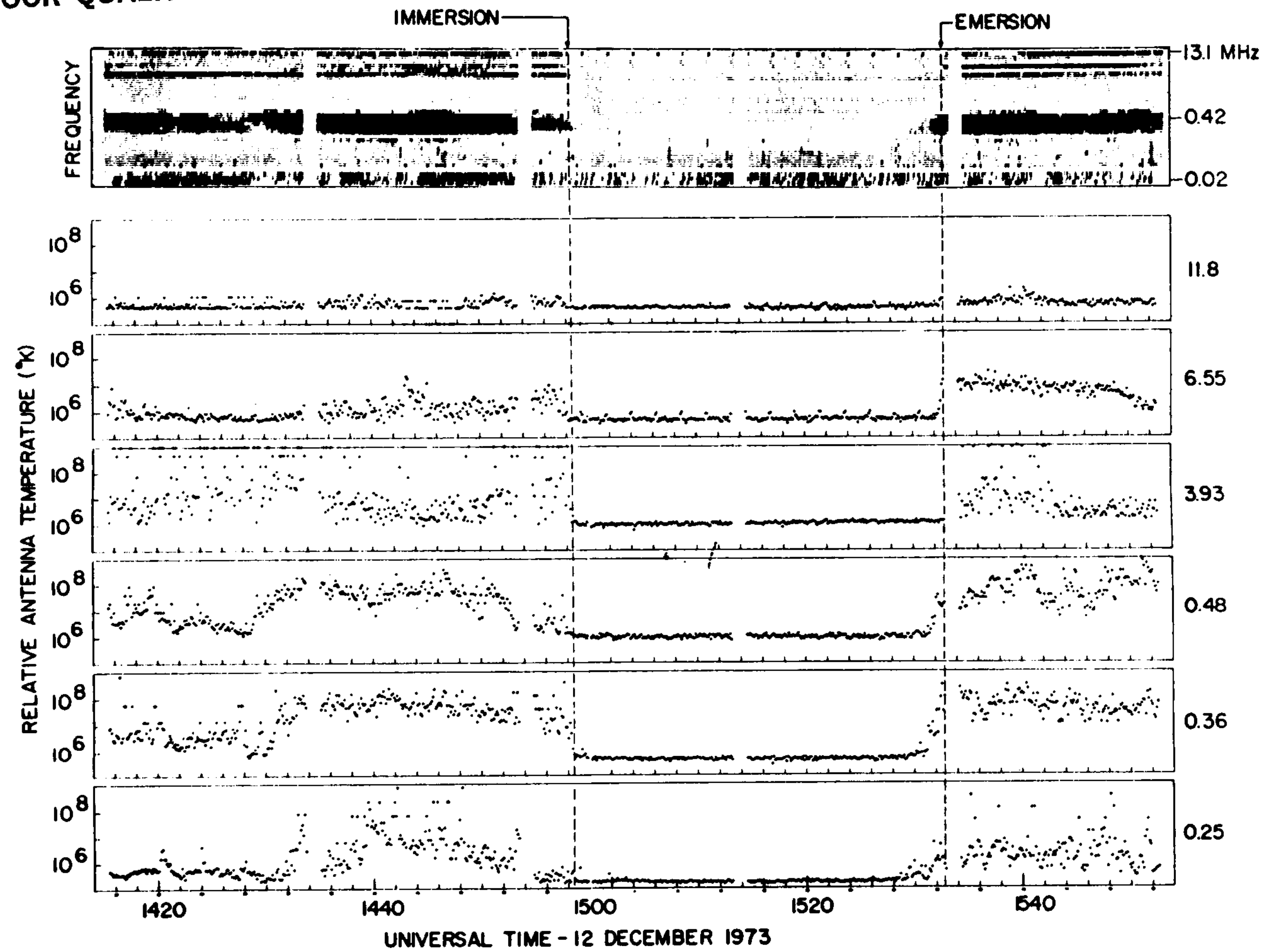

Figure 1. RAE-2 data taken from lunar orbit (from Alexander et al., 1975).

One sees that even from the distance of the Moon, the background radio noise in the 1 to 10 MHz range is dominated by terrestrial interference. Also of interest is a similar plot shown in Figure 2; it is RAE-2 data which show the variation of interference levels with the position of the Moon (and spacecraft). At new Moon, i.e., on the sunlit side of the Earth, the ionosphere effectively shields almost all of the interference in the 1 to 4 MHz band; strong interference is found near full Moon.

In the discussion that follows, interference levels will be referred to those that would be encountered by a satellite at an altitude of 10,000 km above the Earth's surface, that is, twenty-four times closer to Earth than the Moon. At this altitude,

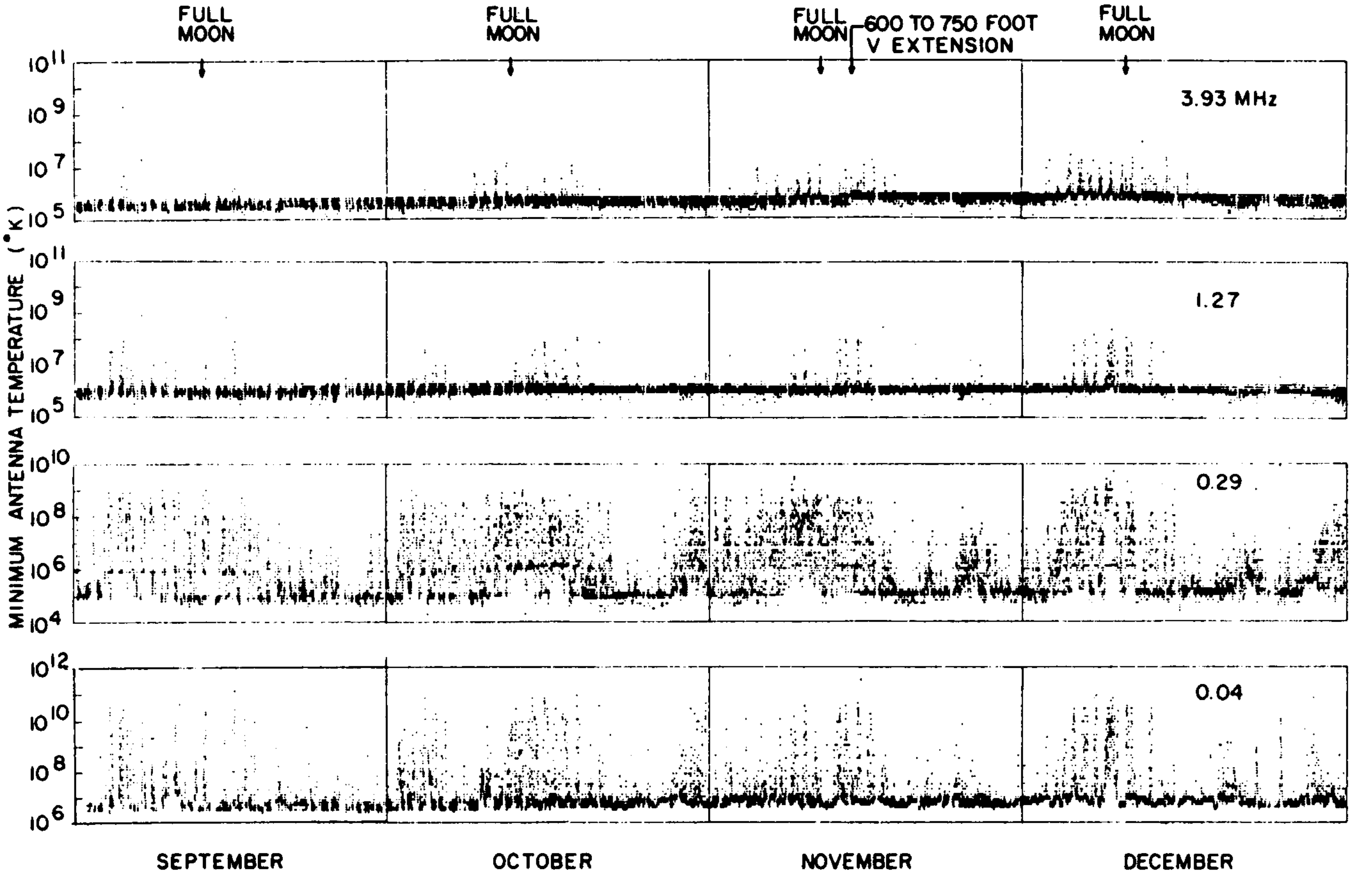

Figure 2. The time distribution of terrestrial noise observed from lunar orbit for four months near solar minimum in 1973 (from Alexander et al., 1975).

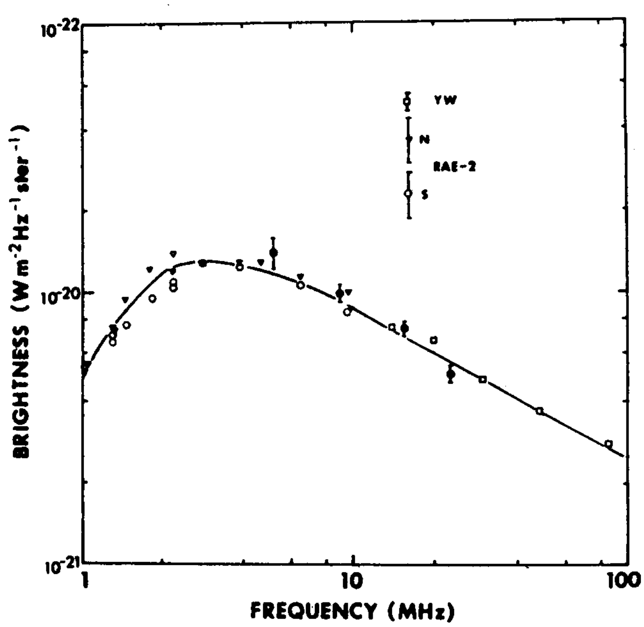

Figure 3. The brightness of the galactic background polar regions (from Cane, 1979).

terrestrial interference levels would be approximately 28 decibels (dB) higher than those shown in Figures 1 and 2. Since most authors give the observed levels relative to the galactic background, this reference level is also adopted here. Figure 3 shows that the brightness, B, of the background near the galactic poles has a broad maximum of about 10^{-20} $W \cdot m^{-2} \cdot Hz^{-1} \cdot ster^{-1}$ in the 2 to 10 MHz range. The brightness temperature varies approximately as $(wavelength)^2$ from a value of $\approx 2 \cdot 10^7$ K at 1 MHz to $\approx 2 \cdot 10^5$ K at 10 MHz. Near the galactic plane the background temperatures are lower due to free-free absorption, but the above values are typical of what can be expected for antenna temperatures of low-gain dipolar antennas.

Since preamplifier noise temperatures of ≈ 100 K are easily achievable in this frequency range, antenna noise will dominate the system noise level even if the antenna is coupled rather inefficiently into the first-stage amplifier, or if the preamplifier noise level is traded off for linearity.

The total galactic background power to be expected from an antenna in the 1 to 10 MHz range is:

$$P = \int B\ A\ \Omega\ df = 3.5 \cdot 10^{-10}\ W = -65\ dBm$$

where B is the galactic background brightness, A is the antenna collecting area (taken as $[wavelength]^2/8$), and Ω is the beam solid angle (taken as 2π steradians).

Figure 1 shows that terrestrial interference levels 30 to 40 dB above background are common at the lunar distance. These correspond to levels of 58 to 68 dB above background at a height of 10,000 km, or -7 to +3 dBm. These are very high levels to be accommodated linearly by any broad-band preamplifier; tuned narrow-band amplifiers may be necessary. This calculation agrees with the RAE experience. The RAE system had fixed-frequency, narrow-band amplifiers on 229-meter "V" antennas and broad-band amplifiers on 37-meter dipoles. The broad-band amplifiers were frequently saturated on the night-side of the Earth.

Herman, Caruso, and Stone (1973) made a specific study of terrestrial radio noise with RAE-1. Their study primarily employed the downward-pointing "V" antenna which had a typical beamwidth of ≈30°. Since RAE-1 was at an altitude of 6000 km, the Earth subtended a much larger angle than the beam, and their data refer to the radio noise emanating from the sub-satellite region. They used 200 kHz bandwidths centered on 3.93, 4.70, 6.55, and 9.18 MHz. Within each of these bands there are numerous (≈30 to 100) low power (<1 kW) transmitters widely distributed throughout the world. Herman et al. found that terrestrial noise levels were lowest when RAE-1 was over the oceans and highest when it was over major northern and southern land masses. Over the United States the principal source is probably man-made noise from populated areas (ignition noise, machinery noise, etc.), while over South America it is likely to be thunderstorm noise. Ground-based transmitters apparently dominated the noise levels over Asia and Eastern Europe.

A typical global noise distribution is shown in Figure 4. It appears that natural and man-made noise emissions are more-or-less comparable in level so that operation of a satellite system in an allocated radio-quiet band, even if effective policing of the band were possible, will not solve all interference problems. This is reinforced by the data shown in Figure 5. Antenna temperatures observed by RAE-1 at nighttime over the central United States agree well with Horner's (1965) estimates of the interference levels to be expected from thunderstorms at satellite altitudes; 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 by the Joint Technical Advisory Committee of IEEE (Herman, 1970) for man-made noise levels.

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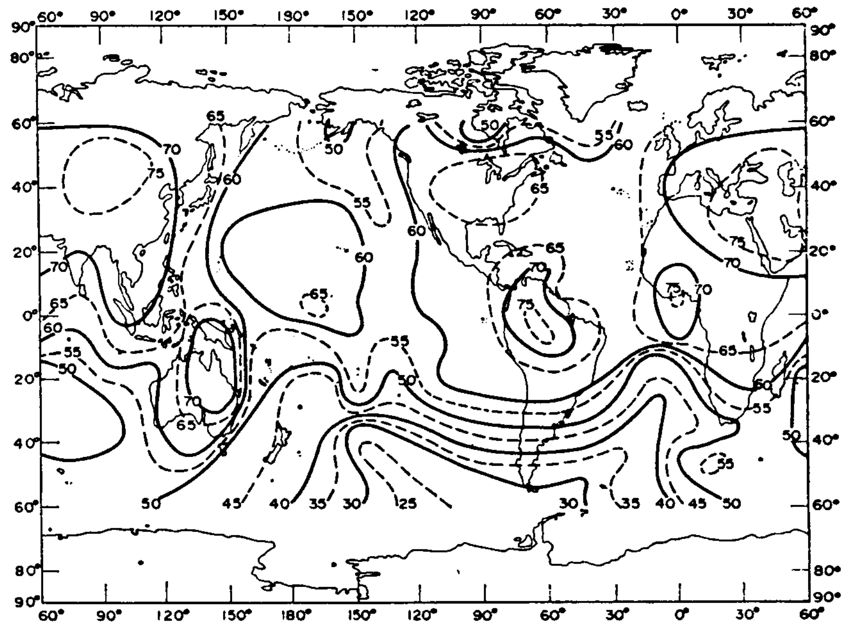

Figure 4. The terrestrial radio noise distribution derived from the RAE-1 (height 6000 km) lower "V" antenna data at 9.18 MHz for December 2-6, 1968. The secondary peaks in activity over the mid-Pacific and northern Australia are believed to be correlated with local thunderstorm activity. Contour levels are dB above 288 K. The galactic background on this scale would be ≈31 dB and the receiver saturated at 75 dB (from Herman et al., 1973).

There is not much information available about terrestrial noise levels in the 10-30 MHz range. However, most of the interference sources below 10 MHz also emit at similar levels in the 10-30 MHz range. Transmitters, man-made noise, and thunderstorm noise are not markedly weaker. On the other hand, cosmic sources are considerably weaker relative to the interference, and ionospheric shielding will be ineffective. Therefore, it is to be expected that interference will make successful observations from near-Earth orbit impossible between about 10 and 30 MHz.

Another natural source of intense low-frequency noise is auroral kilometric radiation (AKR) (Gurnett, 1974; Kaiser and Alexander, 1977; Benson,1985). As can be seen from Figure 6, this radiation can also be 60 to 70 dB above the galactic background at 25 R_e. It occurs primarily below 1 MHz on the nighttime side of the Earth and it is closely associated with discrete auroral arcs and inverted-V electron precipitation

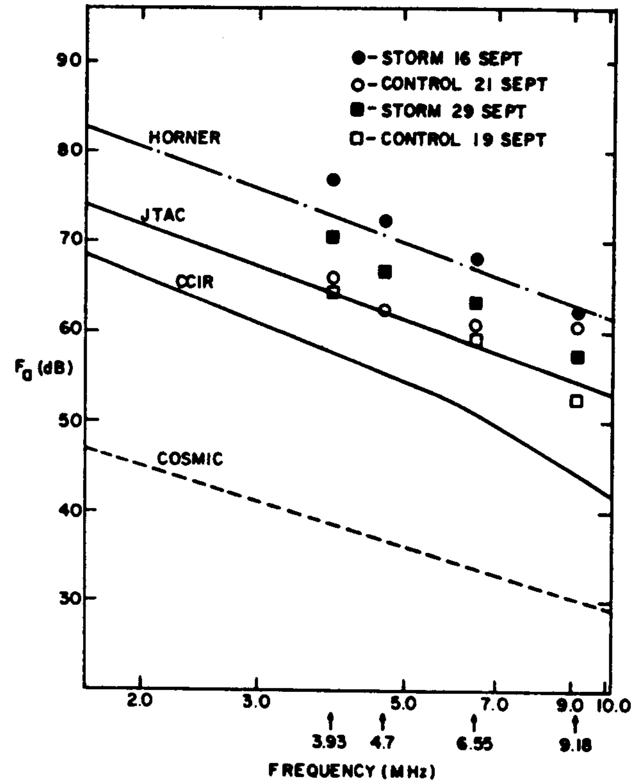

Figure 5. Radio noise levels observed by RAE-1 over the central United States at nighttime between September 16 and 29, 1969. The predicted levels for thunderstorm noise are from Horner (1965) and those for the control nights with little thunderstorm activity (labeled JTAC) are from Herman (1970). (This figure is from Herman, 1975.) Figure copyrighted by the American Geophysical Union.

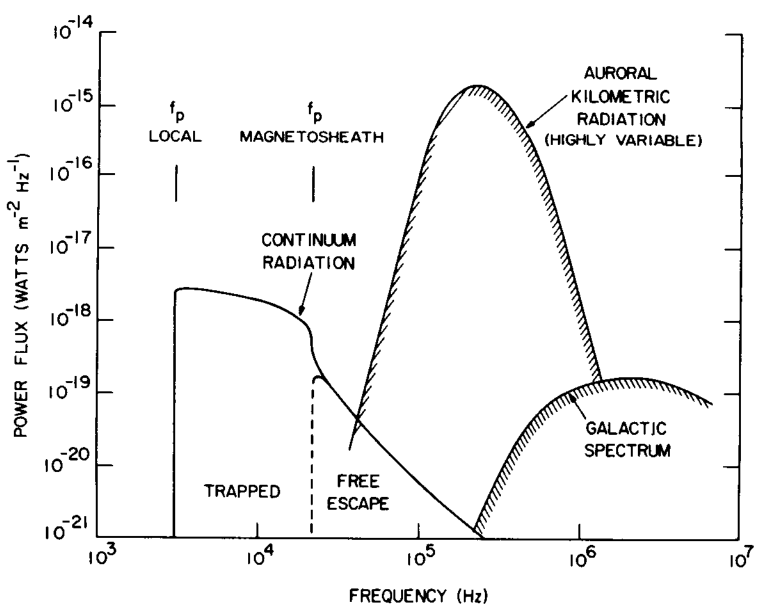

Figure 6. The spectrum of AKR as observed by IMP-8 (from Gurnett, 1974). Figure copyrighted by the American Geophysical Union.

(Benson and Wong, 1987; James et al., 1974). However, emissions near 2 and 4 MHz have been observed (James et al., 1974) and emissions in the 2.6 to 6 MHz region have also been reported (Kellogg and Monson, 1979). Harmonics of the fundamental AKR are definitely observed (Benson, 1985). A satellite system in an equatorial orbit will probably be well-shielded by the ionosphere from the higher frequency (>1 MHz) AKR because this radiation is emitted from relatively low altitudes in the polar regions. This shielding will be particularly effective on the daytime side of the Earth. Independent of the AKR, sensitive observations are probably impossible from the nighttime side because of other terrestrial sources. Therefore, it appears that while AKR is not a particularly grave problem, it certainly should be investigated more fully before any system is built.

Finally, it should also 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, $\approx 240\ R_e$ from Earth towards the Sun. 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 interferometer system, its highly successful operation suggests that sensitive observations may be possible on the daytime side of the Earth.

III. IONOSPHERIC SHIELDING

The ionosphere effectively blocks all ground-level emissions at frequencies below f_oF2, the critical frequency for vertical incidence reflection. f_oF2 is the maximum plasma frequency in the ionospheric F2 layer. Electromagnetic waves at frequencies below this plasma frequency become evanescent and die away with a skin (or e-folding) depth of

$$\delta = c/(2\pi\sqrt{\nu_o^2 - \nu^2})$$

$$= 47.75/(\sqrt{f_o^2 - f^2}) \text{ meters}$$

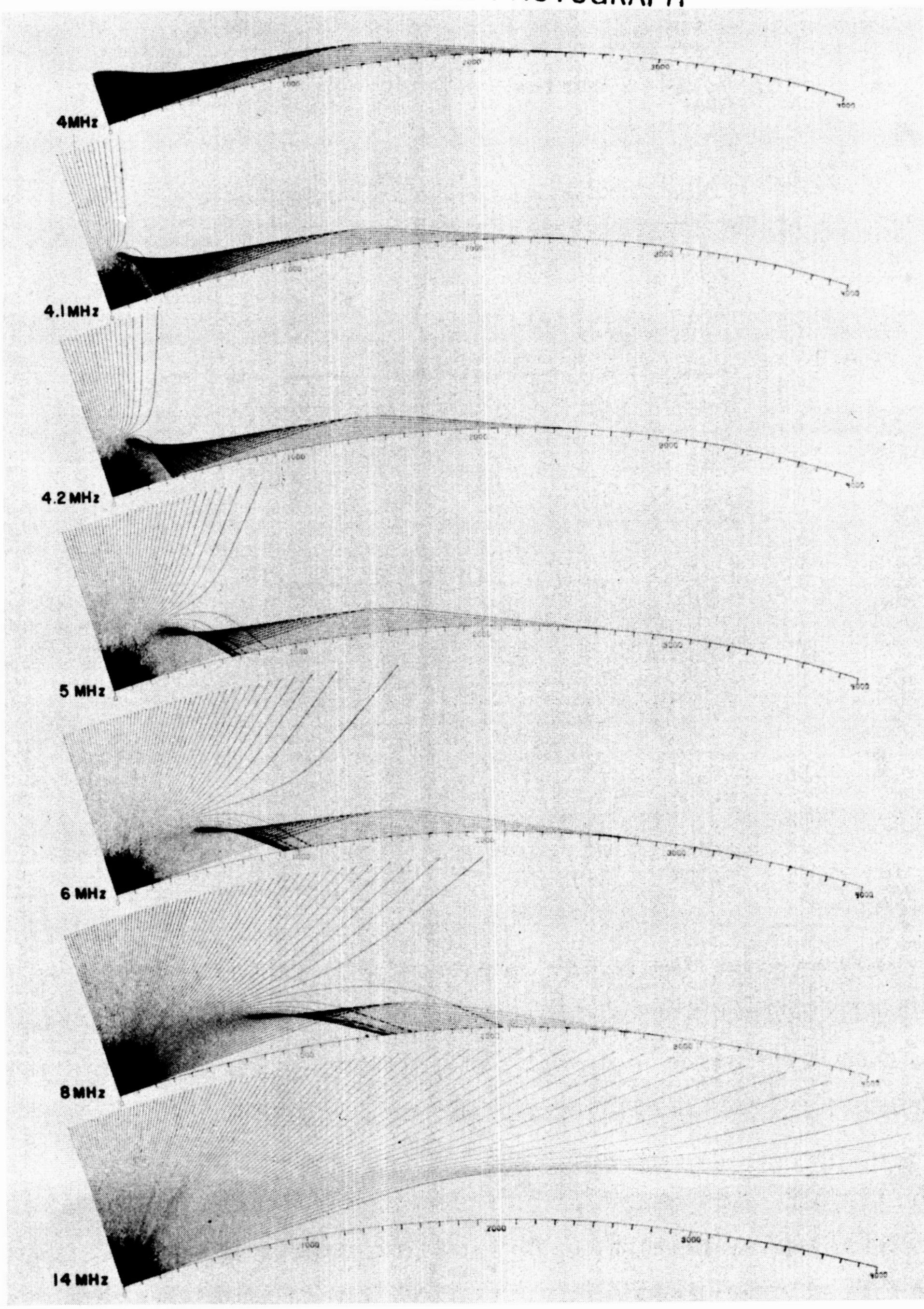

Figure 7. Families of rays at seven frequencies computed for a single-layer ionosphere with f_oF2 equal to 4.0 MHz and without tilts or irregularities (from Croft, 1972).

where ν_o and ν are the plasma and wave frequencies in Hz, while f_o and f are the same frequencies in MHz. At frequencies below f_o the ionosphere becomes extremely opaque. For example, if f_o is 4.0 MHz and f is 3.9 MHz, δ becomes only 53.7 m. An F2 layer of 200 km thickness would attenuate waves of this frequency by exp(-3723) or some 16,000 dB!

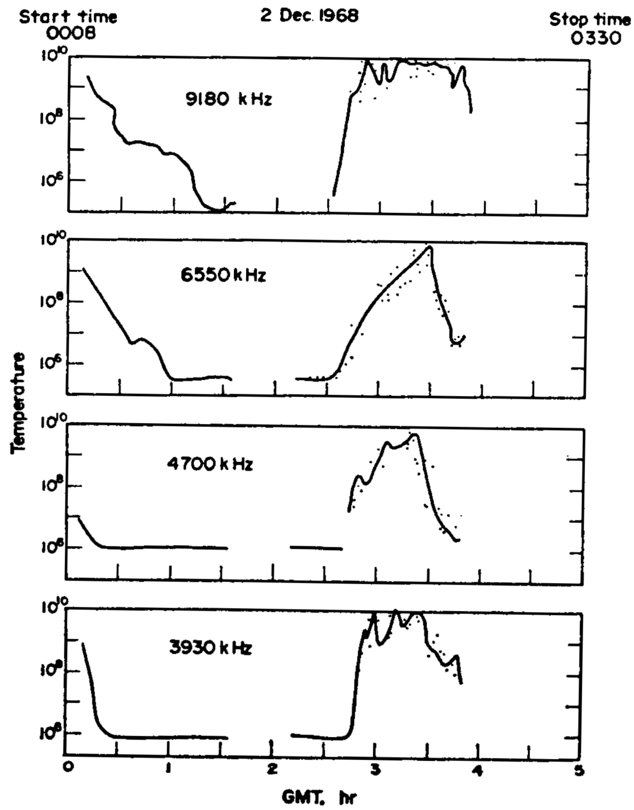

Figure 8(a). Temperature variations measured by the RAE-1 lower "V" antenna at several frequencies (from Herman et al., 1973).

At frequencies somewhat above f_oF2 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. This effect is illustrated in Figure 7.

Both theory and experience indicate that if a satellite is over a region of maximum f_oF2 and if the sub-satellite f_oF2 is above the observing frequency, radiation from a distant source of interference will almost certainly be deflected away from the satellite even if the f_oF2 in the vicinity of the source is well below the frequency being observed. The strong correlation between "ground-breakthrough" frequencies and sub-satellite f_oF2 is shown in Figures 8(a) and 8(b). The opposite condition has, of course, also been observed; when the satellite is on the night-time side of the Earth, radiation from transmitters on the daytime side can be refracted around the Earth to reach the satellite.

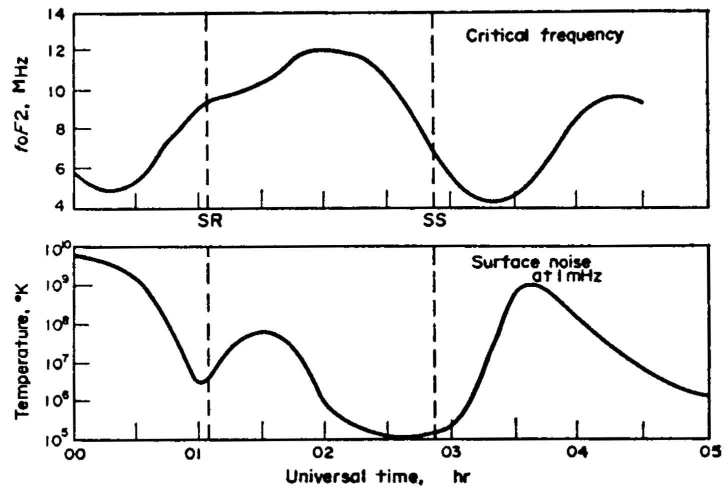

Figure 8(b). Predicted sub-satellite f_oF2 and predicted surface radio noise corresponding to the data shown in Figure 7 (CCIR and CRPL predictions reproduced from Herman et al., 1973).

If ionospheric shielding is to be used to protect a satellite system from terrestrial interference, it is necessary to consider the global and temporal variations in f_oF2. If one examines typical global distributions of f_oF2 near solar maximum, one sees that ionospheric shielding should be effective up to at least 10 MHz on the sunlit side of the Earth. It is possible, however, that ionospheric shielding may not be as effective as one might expect from the calculation given above. Figure 9 shows RAE-1 data from 26 consecutive orbits near solar maximum. Data from the nighttime side of the Earth are dominated by strong interference, but even on the daytime side there are occasional strong "spikes." Some or all of these spikes may be due to the solar emission. This solar radio emission may prove to be a problem in the solar maximum period. Type-III solar bursts are the most common. These bursts occur at a typical rate of several per hour at solar maximum and their average durations at ≈1 MHz are tens of minutes. Weak bursts are a few dB above the galactic background on broadbeam antennas; strong bursts are 30-50 dB above background. Statistics concerning these bursts are available and would have to be examined before planning a mission.

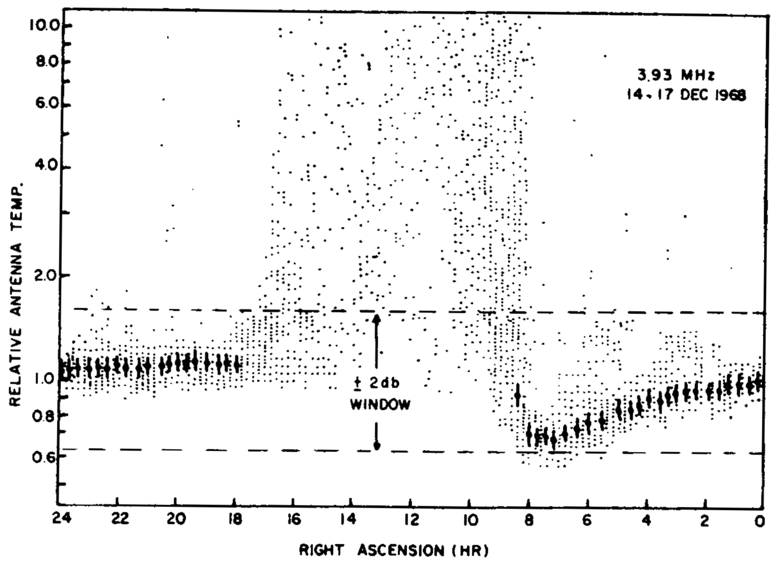

Figure 9. Raw data from 26 consecutive orbital scans of RAE-1 (solid dots) and final averages after removal of interference spikes (open circles) (from Alexander and Novaco, 1974).

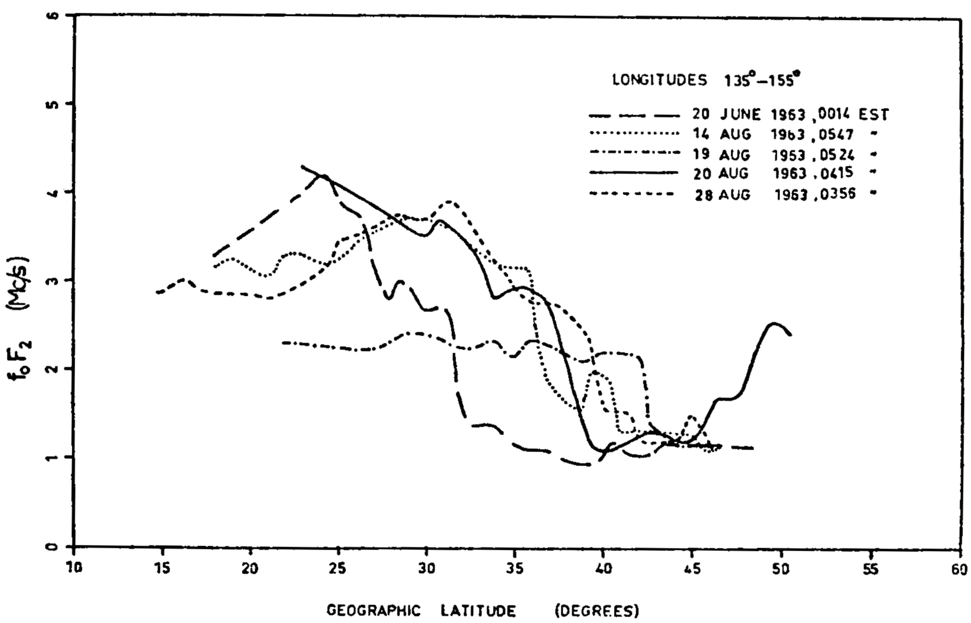

Figure 10(a). The variation of f_oF2 with geographical latitude as observed by Alouette (from Ellis and Hamilton, 1966).

On the other hand, at solar minimum Type-III bursts occur only at average intervals of many hours. They might prove to be a nuisance but they would not seriously disturb the system. Ground-based observers have collected some statistics concerning

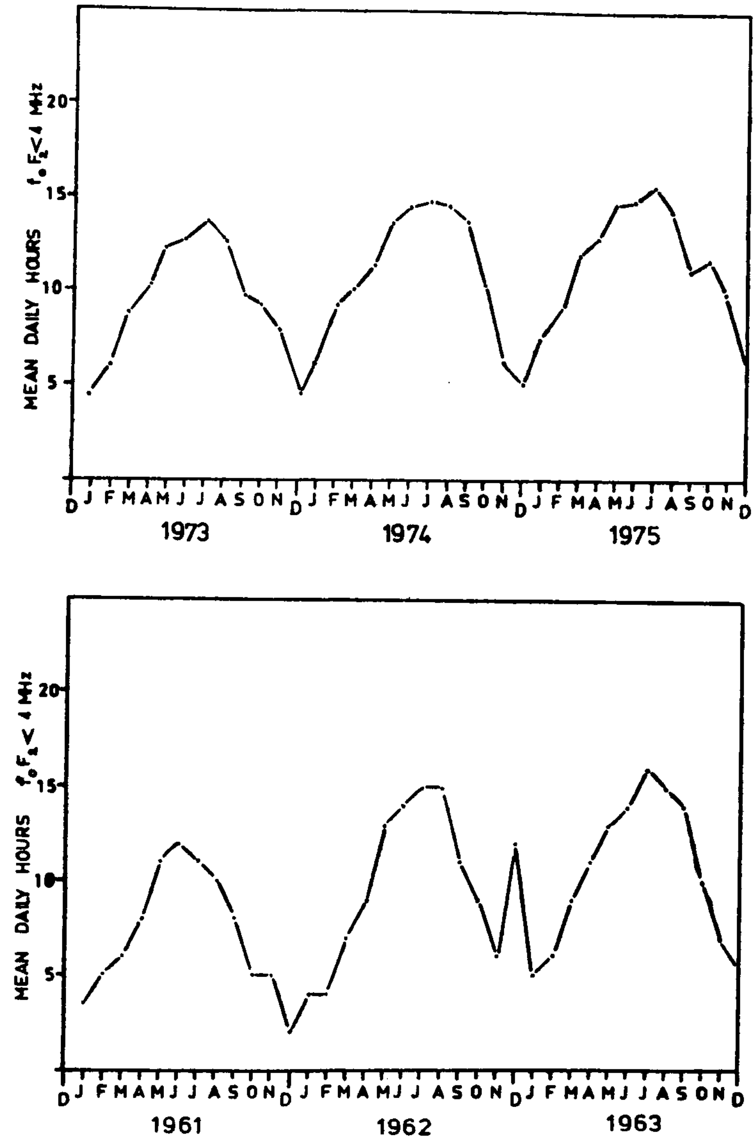

Figure 10(b). Variations of f_oF2 at Hobart, latitude 40°S, during two solar minima (from Cane, 1978).

the distribution and occurrence of various f_oF2 values during solar minimum. These data are illustrated in Figures 10(a) and 10(b) and show that even at a latitude of 40°, near the minimum in the global distribution of f_oF2, the critical frequency is generally above 4 MHz for about 14 hours per day.

IV. INTERFERENCE LEVELS HARMFUL TO A LOW-FREQUENCY INTERFEROMETER IN SPACE

The CCIR normally defines interference as being harmful to radio astronomy observations if it is at a level of 10 percent of the rms noise limit of a simple, filled-aperture radio telescope. The harmful interference levels for interferometers were analyzed more carefully by Thompson (1982) who calculated the interference level that would add 10 percent to the noise fluctuations in a map produced by a synthesis telescope such as the VLA. 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, in its most compact configuration, is about 14 dB less sensitive to interference at 1400 MHz 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 thus rotated in phase over many cycles and its effects are greatly diminished. The reduction factor for each interferometer baseline is given by

$$F_i = \text{sinc}(f_i \cdot \tau)$$

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 to form a map 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 example, a field 0.5° in diameter implies a grid size about 100 wavelengths.

For large x, $\text{sinc}(x) \approx 1/x$, so F_i is small if $(f_i \cdot \tau)$ is large. The interference perturbs most strongly those interferometer baselines having small ($f_i \cdot \tau$). 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.

It should specifically be noted that although a low-frequency interferometer in space would employ VLBI techniques, VLBI experience with regard to interference is not applicable to this case. VLB interferometers are usually insensitive to interference because the interfering signal does not correlate at the two ends of the interferometer. These considerations lead to the conclusion that a VLBI system is some 40 dB less sensitive to harmful interference than a filled-aperture system (Thompson, Moran, and Swenson, 1986). Unfortunately, terrestrial interference affecting a low-frequency interferometer in space will be fully correlated on all interferometer baselines. Also, there may be only a small amount (a few radians) of fringe rotation introduced during each integration. The field-of-view will be large and the grid size will be correspondingly small. Thus, a low-frequency interferometer in space will be highly susceptible to harmful interference.

If low-gain dipolar antennas are used, it may be necessary to synthesize about 2π steradians of the sky simultaneously in order to deconvolve the sidelobe effects of numerous strong sources within the primary patterns of the antennas. This would mean that very small cell sizes would be 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. ($f_i \cdot \tau$) will be ≈ 1 and fringe rotation will not be very effective in reducing the system's response to harmful interference. An exact estimation would be rather difficult to make because of the complex geometry involved; both the astronomical sources and the interference sources move in the frame of reference of the array.

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. (Note that coherence effects will not reduce the system's responses to narrow-band signals; these responses can only be reduced by fringe rotation.) An educated guess is that the harmful interference limit will be only 3 to 10 dB above that of a filled-aperture system.

In order to be really useful, the low-frequency array must be capable of observing sources at the 1 to 10 Jy level. Let us assume a harmful interference limit of 0.5 Jy. On a single 3-MHz dipole this will produce an antenna temperature of 0.23 K. If the system has ten satellites, this gives an equivalent filled-aperture antenna temperature of 2.3 K. If we make the assumption 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 of $2.6 \cdot 10^6$ K at this frequency. All of the previous estimates of interference levels were a few dB to 70 dB above the galactic background. Thus, ionospheric shielding at the level of 50 to 120 dB will be required for successful operation. Perhaps this is achievable on the daytime side of the Earth, but any small "leakage" of interference from the nighttime side will destroy the data.

V. CONCLUSIONS

Sensitive radio astronomy observations will be impossible at satellite altitudes on the nighttime side of the Earth due to terrestrial interference. The interference is not only due to licensed transmitters; ignition noise, machinery noise, and thunderstorms probably cause interference levels similar to those of transmitters. Thus, operation in a radio-quiet band allocated exclusively to radio astronomy would not solve the problem. Observations may be possible on the sunlit side of the Earth at frequencies where ionospheric shielding is effective in blocking ground-based emissions. Even this is not certain because shielding on the order of 50 to 120 dB is required. Sensitive observations are probably impossible in the 10 to 30 MHz range where ionospheric shielding is ineffective. The far side of the Moon appears to be the only location near the Earth that is definitely shielded from terrestrial interference to the required levels.

VI. RECOMMENDATIONS

Several studies should be carried out to examine the feasibility of a low-frequency interferometer in Earth orbit.

1. ISEE-3 data should be carefully examined for any traces of terrestrial interference. This will help to determine the feasibility of sensitive observations from spacecraft at low latitudes on the daytime side of the Earth. At the same time, the statistics of solar radio bursts should be compiled. ISEE-3 was at the inner libration point from August, 1978 to October 1982, a period that spanned solar maximum. A study of these data would serve to determine the level of solar interference to be expected near solar maximum and the feasibility of a mission during solar maximum when ionospheric shielding would be the most effective.

2. It appears likely that sensitive observations will be limited to the daytime side of the Earth. This restriction would have many ramifications on the profile of the mission. These ramifications need to be considered in detail.

3. A more careful study of AKR should be made in order to determine whether or not it will be a serious problem.

4. If possible, a low-frequency spectrum analyzer should be flown on some spacecraft to experimentally determine the effectiveness of ionospheric shielding. Perhaps the French

radio astronomy experiment on SOHO (scheduled for launch in 1994) will provide the required information. This satellite will be situated at the inner libration point and the French receiver operates from 30 kHz to 30 MHz.

5. A computer model should be constructed of the data which would be obtained from a low-frequency interferometer in space. We know enough about the distributions and spectra of radio sources and of the galactic background to construct a valid model of the sky in the 1 to 10 MHz range. The model of the sky could be scanned with a simulated interferometer array to determine the feasibility of synthesis with low-gain, dipolar elements. Terrestrial interference could also be simulated and the effective sensitivity of the system to terrestrial interference could be studied under varying array configurations. The effectiveness of bandwidth and fringe-frequency smearing to limit the field-of-view could be assessed. Perley (1989) has recently developed 3-dimensional algorithms that promise to solve the field curvature problems that will inevitably arise in attempting to construct images with this wide-field instrument. These algorithms could also be tested on simulated data.

6. A ground-based synthesis array employing low-gain dipoles should be constructed and successfully operated in some convenient frequency band, such as the 73.8 MHz radio astronomy band. This would prove empirically that synthesis is possible with such receiving elements and would allow us to anticipate many of the problems which may arise with a similar array in space.

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