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Integration Losses and Clutter-Doppler Spread for a Space Based Radar Caused by Ionospheric Scintillation During a Solar Maximum

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Estimates are obtained of the effect of worst-case, ionospheric scintillation on the combined, coherent-noncoherent, integration process and on the clutter-Doppler spread for a specific waveform and a space based radar in a 1030-km orbit. These estimates are generated from data taken during the Defense Nuclear Agency's Wideband experiment. The experiments are representative of worst-case scintillation conditions. The results of these data, which correspond to a period of solar maximum, are compared to earlier results for a period of severe scintillation but minimal solar activity. The frequency-diverse waveform consists of bursts (coherent pulse trains) of 0.256-s duration at four distinct frequencies per look and six looks per dwell. The space based radar will suffer a combined integration loss not exceeding 2.54 dB, 0.70 dB, and 0.06 dB at VHF, UHF, and L-band, respectively, for 95% of the time in worst-case conditions. In addition, the clutter-Doppler spread that is induced by ionospheric scintillation is less than 4.90 Hz, 1.58 Hz, and 0.26 Hz at the same frequencies and under the same conditions as for 95% of the time.

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CONTENTS

INTEGRATION LOSSES AND CLUTTER-DOPPLER SPREAD FOR A SPACE-BASED RADAR CAUSED BY IONOSPHERIC SCINTILLATION DURING A SOLAR MAXIMUM

1. INTRODUCTION

Recent work (Mokole 1991; Mokole and Knepp 1991) analyzed the effect of ionospheric scintillation on the total integration loss and clutter-Doppler spread for a space-based radar (SBR) system in a 1030-km orbit with a carrier frequency between 130 and 1500 MHz. These efforts used data that were taken at the end of a period of solar minimum (1977). Although a fair portion of the 1977 data experienced severe scintillation, it is not representative of worst-case scintillation effects. Consequently, results are obtained from additional data corresponding to a period approaching solar maximum (1979). These results are compared to those derived from the 1977 data to determine how much worse the system impact is.

Although a solar cycle lasts an average of eleven years, the time between a solar minimum and a solar maximum is not necessarily 5.5 years. In fact, for this particular cycle, the minimum occurred in the middle of 1976, and the maximum occurred at the beginning of 1980. The average sun spot number, which is one parameter that characterizes solar activity, had a fairly flat valley about the minimum until the end of 1977. At this point, it steeply rose to a maximum in two years (Allnutt 1989). The 1979 data were taken very near the peak, while the 1977 data were measured very near the solar minimum.

The 1977 and 1979 data come from the same experiment, the Defense Nuclear Agency's Wideband, satellite, experiment of 1976–1979 (Fremouw et al. 1978). The 1979 data were measured at Kwajalein. Table 1 summarizes the information on the eleven individual satellite passes that are selected for this work. These passes occurred on a range of days from mid-June through the end of July. The designation, KWAJN 16212, means that the ground site at Kwajalein received signals from the Wideband satellite on day 162 of 1979 between 12:00 and 13:00 universal time (UT). According to (National Geophysical Data Center), this time frame corresponds to daily smoothed sunspot numbers between 135 and 218, with monthly averages of 149.5 (June) and 159.4 (July). These values are associated with maximal and nearly maximal solar activity. Therefore, these data are more representative of the most severe scintillation conditions.

Since the analytical foundation for processing the data has been discussed previously (Mokole and Knepp 1991; Knepp and Mokole 1991; Mokole 1991), only the results from earlier work based on the 1977 data and from processing the 1979 data are presented. The complex decorrelation time (τ_0), the total integration loss (TIL), and the clutter-Doppler spread caused by scintillation (σ_{SC}) are addressed in that order.

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Table 1 — Summary of Wideband Passes at Kwajalein in 1979

Pass Designator	Day	UT Start	UT End	Local Time Start	Local Time End
KWAJN 16212	162	12:34	12:51	00:34	00:51
KWAJN 17012	170	12:36	12:53	00:36	00:53
KWAJN 17312	173	12:50	13:07	00:50	01:07
KWAJN 17812	178	12:38	12:56	00:38	00:56
KWAJN 18112	181	12:52	13:09	00:52	01:09
KWAJN 18312	183	12:27	12:44	00:27	00:44
KWAJN 18413	184	13:06	13:23	01:06	01:23
KWAJN 20212	202	12:45	13:02	00:45	01:02
KWAJN 21111	211	11:43	11:59	23:43	23:59
KWAJN 21113	211	13:27	13:42	01:27	01:42
KWAJN 21212	212	12:21	12:39	00:21	00:39

2. COMPLEX-SIGNAL DECORRELATION TIME (τ_0)

Figures 1 and 2 show histograms of the values of τ_0 for the 1979 Kwajalein and 1977 Ancon data at 137.6748, 413.0244, and 1239.0730 MHz. At both locations, as the frequency increases, the percentage of τ_0 decreases at the smaller values and increases at the larger values. In particular, 58.86% (26.32%), 17.44% (3.40%), and 0.05% (0.10%) of the τ_0 are less than 0.256 s at VHF, UHF, and L-band, respectively, for the Kwajalein (Ancon) datasets; and 17.45% (4.89%), 44.81% (34.11%), and 70.76% (84.40%) of the τ_0 are greater than 4.5 s at the same frequencies. At VHF and UHF, the percentages of small τ_0 are greater for 1979, which confirms that scintillation was worse in 1979. The reverse is true at L-band, where the percentages are less than 0.1%. These trends are confirmed in Fig. 3, where the distribution of τ_0 is plotted for both years. For both sets of data and for each frequency, the minimum value of τ_0 is 24 ms.

3. TOTAL INTEGRATION LOSS (TIL)

The TIL is a combination of coherent and noncoherent summation and is considered for a coherent integration time of 0.256 s and for a specific, frequency-diverse waveform (Mokole and Knepp 1991). The waveform consists of bursts of pulses at each of four distinct frequencies (one look) that are repeated six times with random time separations between looks. Thus the target dwell has 24 bursts, and each burst consists of 128 pulses. Because the data occur every 2 ms, the 128 pulses per burst correspond to the coherent integration time of 0.256 s.

In the hypothesized radar system, the returned pulses within each burst are coherently added, yielding a power for each burst. These outputs are summed noncoherently to obtain the combined output of both integrators (total integration). The intent of using such a waveform is (1) to select a coherent integration time so that the samples within a burst are essentially coherent, (2) to separate frequencies so that the bursts comprising each look are statistically independent, and (3) to choose a minimum separation between looks that insures the statistical independence of bursts from different looks. Satisfying (1) minimizes the loss of noncoherently integrating the outputs of all bursts. The applicability of assumptions (1) and (2) depends respectively on whether the coherent integration time is less than τ_0 and on whether the frequency separation is greater than the coherence bandwidth of the ionospheric channel (Knepp 1983).

To relate the processing of this waveform to the data, the following procedure is followed. The τ_0 statistics and the coherent integration time are used to generate a cumulative distribution of the coherent integration loss (CIL) per frequency burst. In turn, a distribution of the TIL (Figs. 4 and 5) is generated from the distribution of the CIL. Three special cases provide insight in determining bounds on the actual TIL:

A. all bursts from all looks are completely coherent;
B. the bursts in each look are completely coherent, but the looks are statistically independent; and
C. the bursts from all looks are statistically independent.

The numbers 1 (Case A), 6 (Case B), and 24 (Case C) represent the number of statistically independent (noncoherent) bursts in the processed return.

In practice, it is believed that separating the looks, so that they are statistically independent, is practicable. Consequently, the system response to the waveform lies somewhere between Cases B and C, that is, between the curves labeled 6 and 24 in Figs. 4 and 5. Each set of three curves qualitatively has the same form. However, quantatively, for each location, the distribution approaches unity sooner as the frequency increases. As one expects for the more severe ionospheric conditions of the Kwajalein data, the TILs are greater, except for L-band at the 0.999-level, which corresponds to the reversal in trend of τ_0 that is mentioned earlier (Fig. 3). Table 2 summarizes this. For example, for 95% of the data at Kwajalein, the bounds for the TIL at VHF, UHF, and L-band are 2.54, 0.70, and 0.06 dB, respectively; whereas, the TILs at Ancon are 1.30, 0.30, 0.02 dB, respectively.

Table 2 — TIL for Selected Percentages at Kwajalein/Ancon

Percent	TIL @ VHF (dB)	TIL @ UHF (dB)	TIL @ L-band (dB)
95.0	2.54/1.21	0.70/0.29	0.06/0.03
99.0	3.13/1.64	0.92/0.46	0.10/0.05
99.9	3.97/2.21	1.24/0.70	0.20/0.59

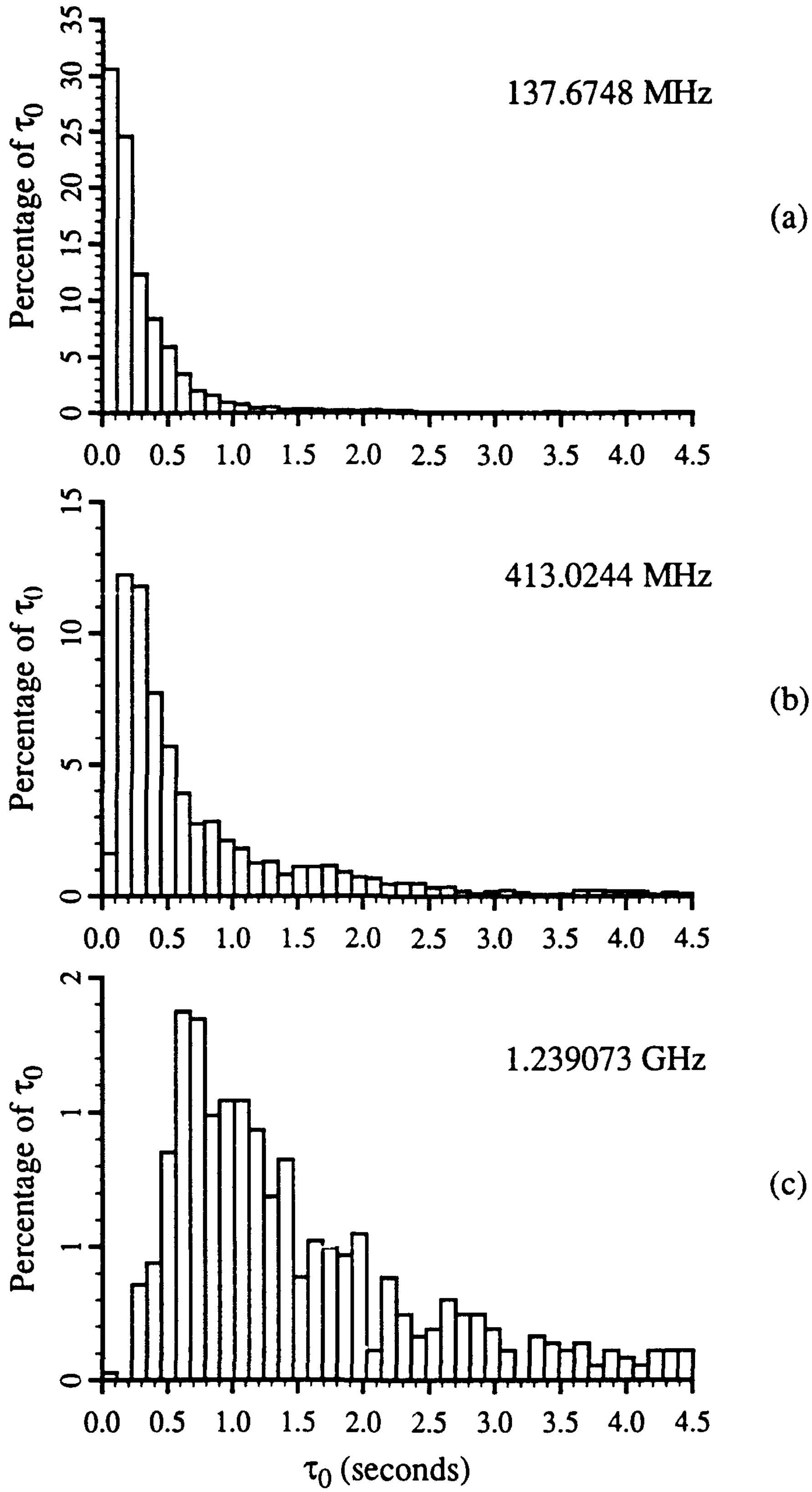

Fig. 1 — Occurence percentage of τ_0 at VHF, UHF, and L-band for 1979 Kwajalein satellite passes. Although not pictured, 4.81%, 34.03%, and 84.29% of the τ_0 are > 4.5 sec at VHF, UHF, L-band, respectively.

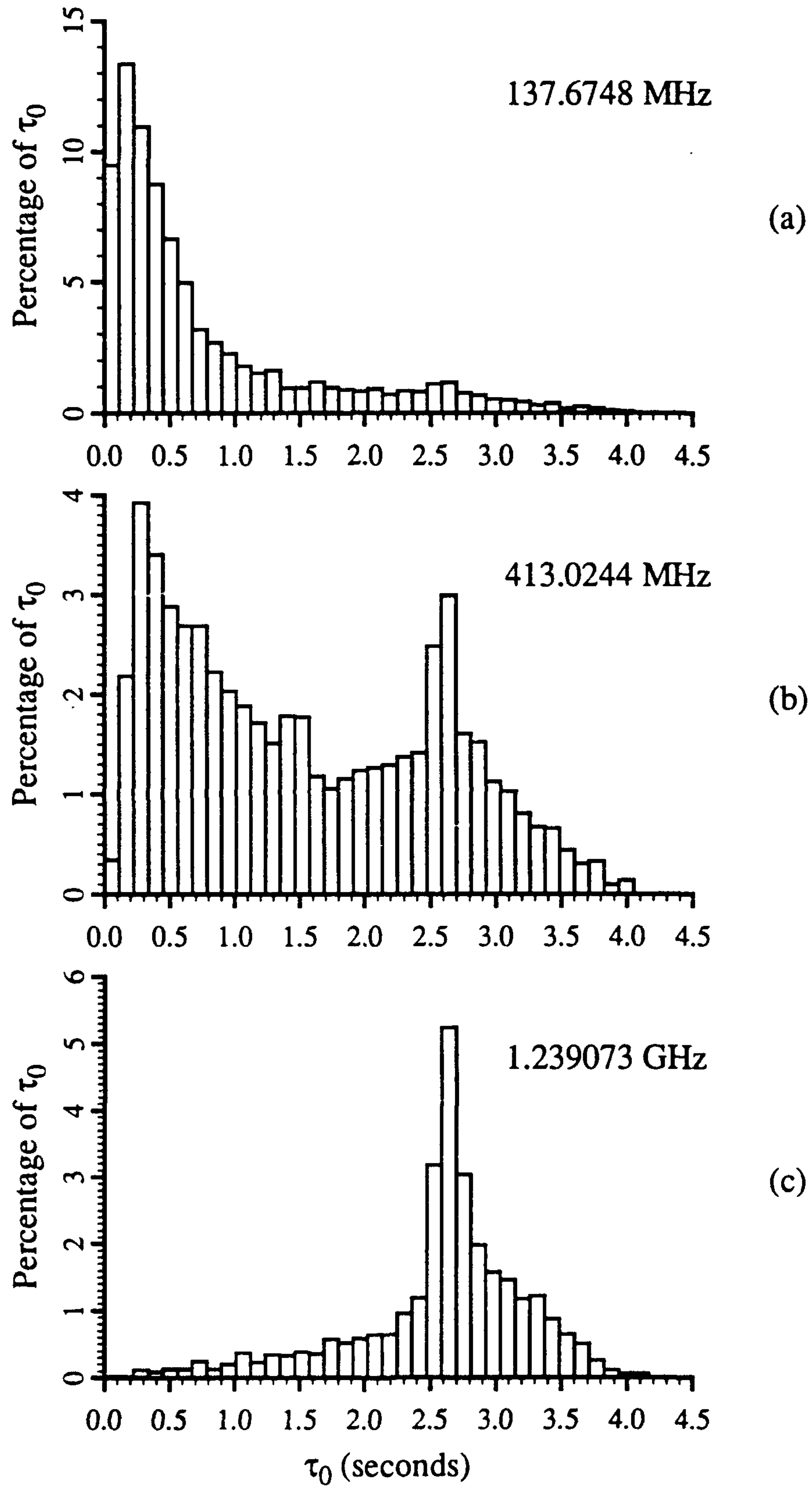

Fig. 2 — Occurence percentage of τ_0 at VHF, UHF, and L-band for 1977 Ancon satellite passes Although not pictured, 17.45%, 44.81%, and 70.45% of the τ_0 are > 4.5 sec at VHF, UHF, L-band, respectively.

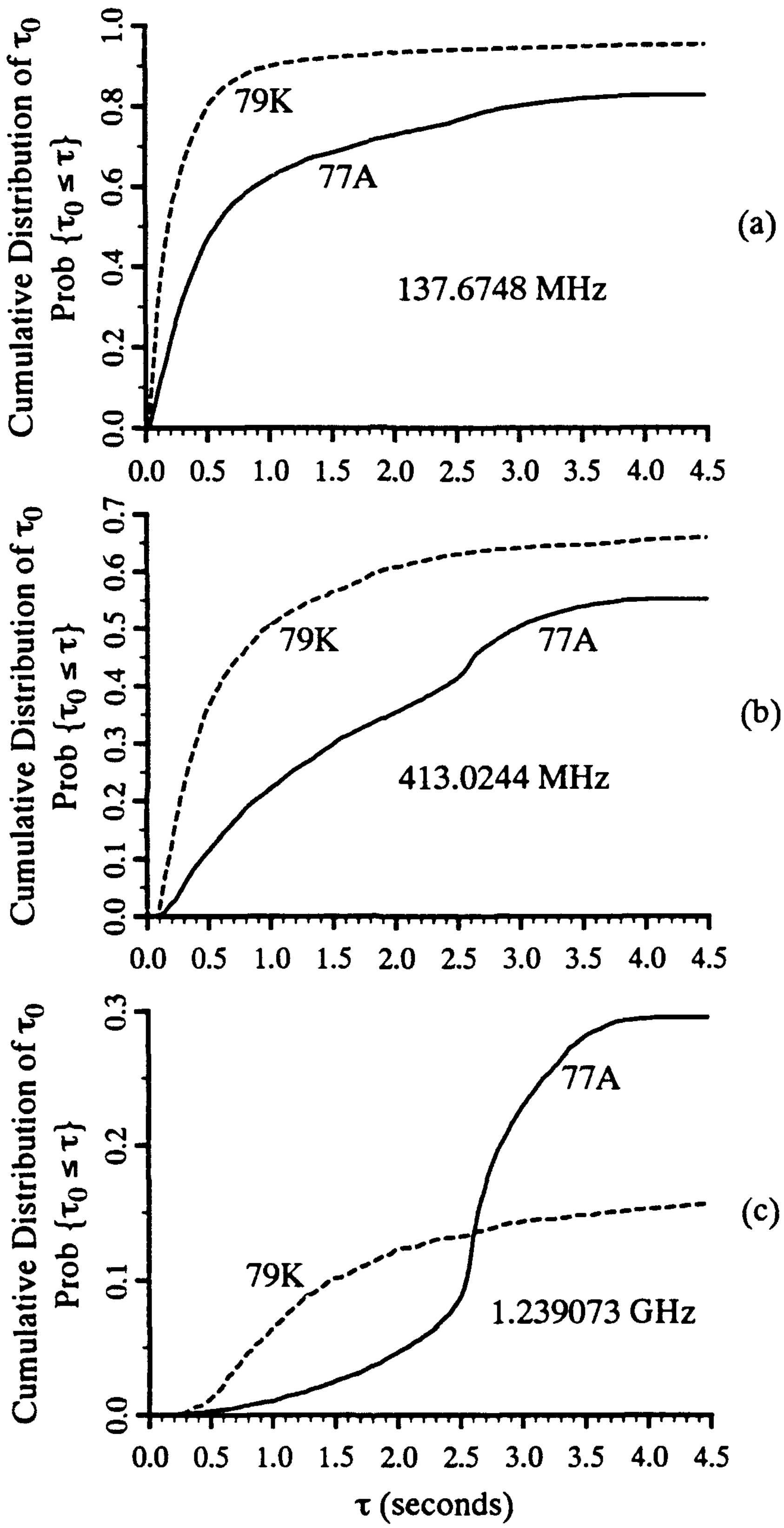

Fig. 3 — Cumulative distribution of complex decorrelation time for Kwajalein in 1979 (79K) and Ancon in 1977 (77A) at VHF, UHF, and L-band

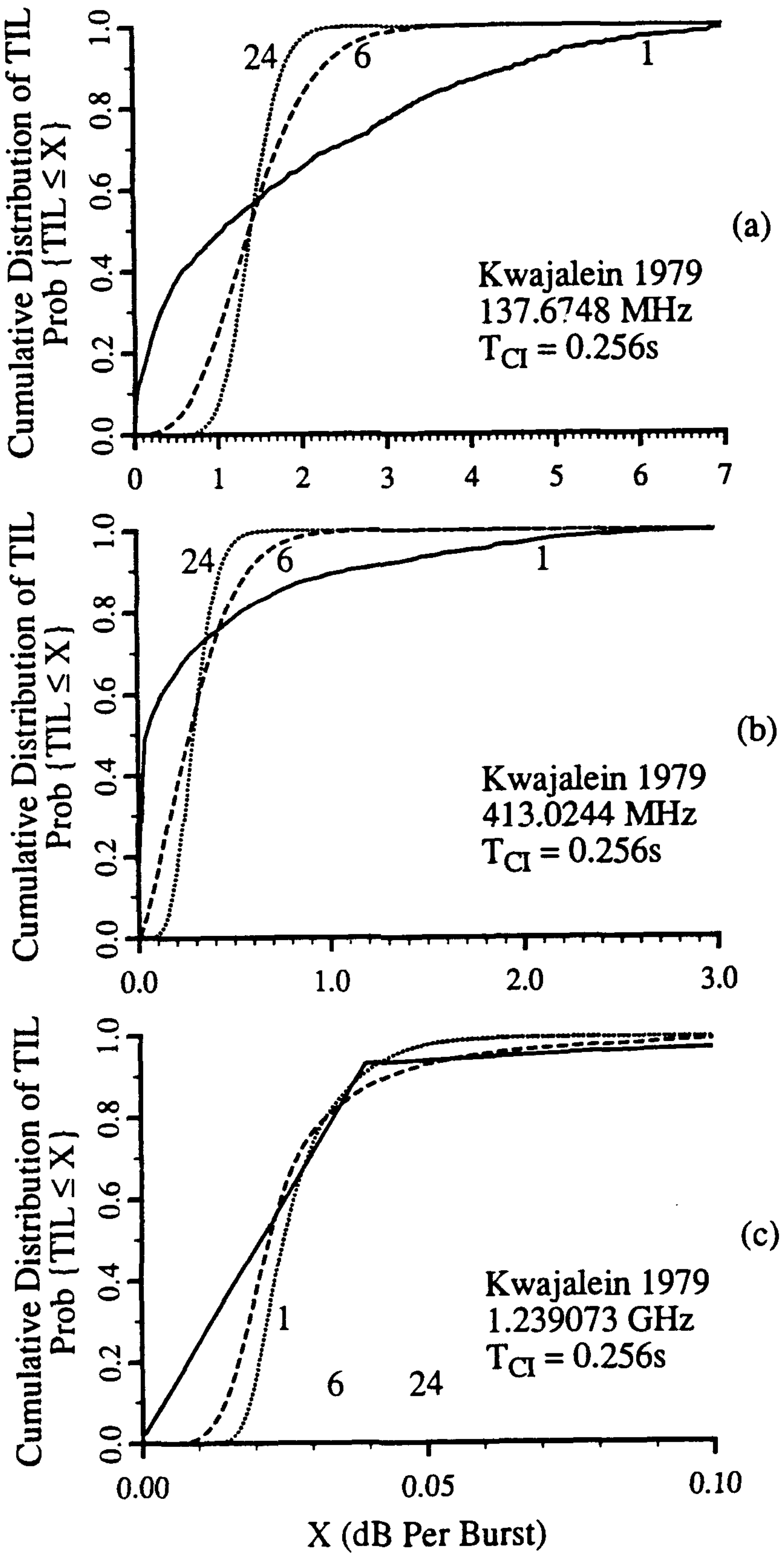

Fig. 4 — Cumulative distribution of the total integration loss (TIL) for Kwajalein with a coherent integration time T_{CI} of 0.256s at VHF, UHF, and L-band. The numerical designations are defined in the text.

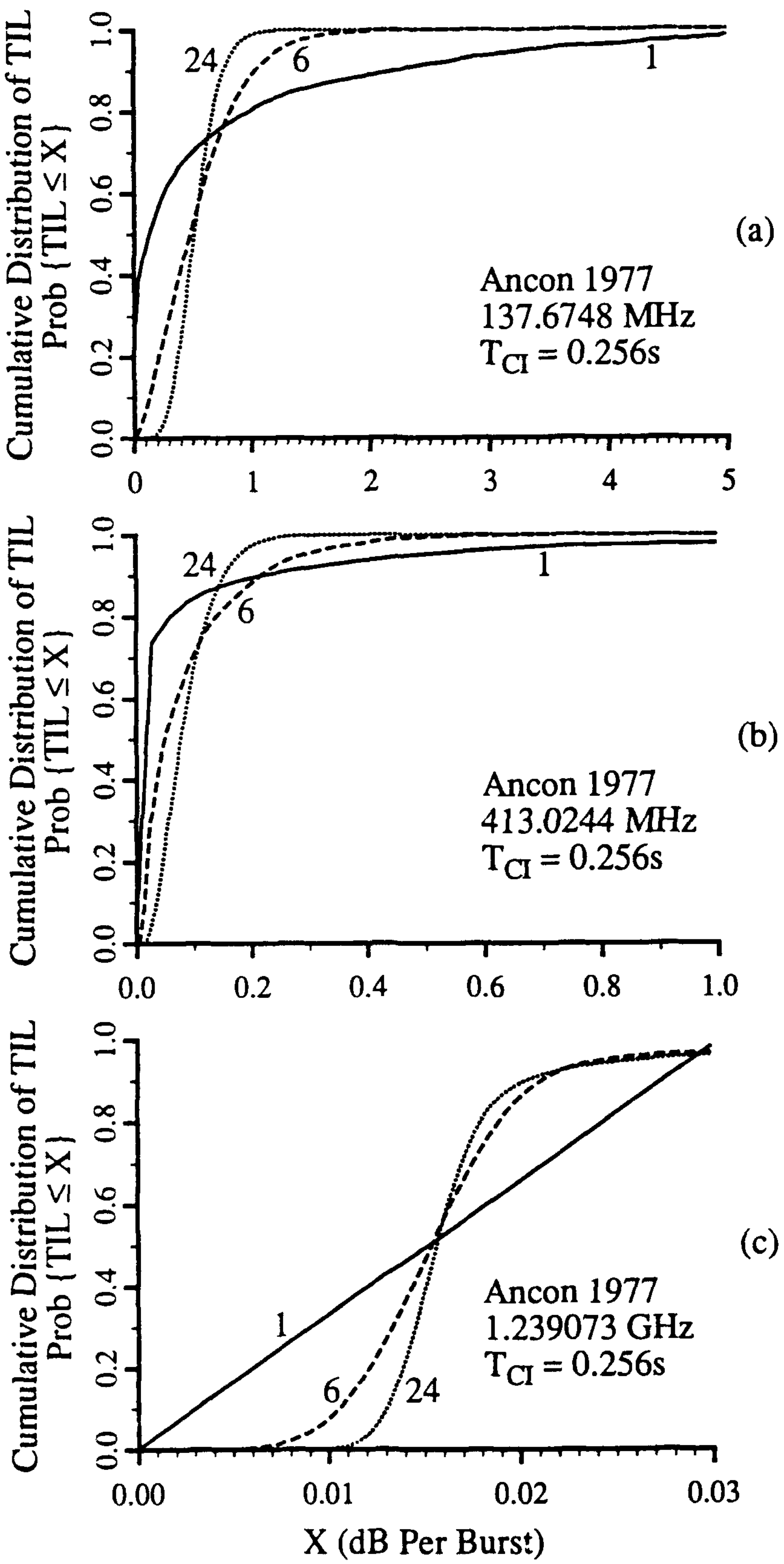

Fig. 5 – Cumulative distribution of the total integration loss (TIL) for Ancon with a coherent integration time T_{CI} of 0.256 s at VHF, UHF, and L-band. The numerical designations are defined in the text.

4. CLUTTER-DOPPLER SPREAD CAUSED BY SCINTILLATION (σ_{SC})

The autocorrelation R_{SC} of the envelope fluctuation A_{SC} of the received clutter voltage, incurred by severe scintillation, is modeled analytically as a Gaussian function (Knepp 1983; Mokole 1991)

$$R_{SC}(\tau) = \langle A_{SC}(t+\tau)A^*_{SC}(\tau)\rangle = \exp\left(-\frac{\tau^2}{\tau_0^2}\right). \qquad (1)$$

Equation (1) implies that the spectrum of A_{SC} (the Fourier transform of R_{SC}) is

$$S_{SC}(f) = \frac{1}{\sqrt{2\pi}\sigma_{SC}} \exp\left(-\frac{f^2}{2\sigma_{SC}^2}\right), \qquad (2)$$

where the clutter-Doppler spread is

$$\sigma_{SC} = \frac{1}{\pi\tau_0\sqrt{2}}. \qquad (3)$$

Analytically, S_{SC} spreads and σ_{SC} increases as τ_0 decreases. Since a greater number of small values of τ_0 are measured for the 1979 Kwajalein data, one expects the cumulative distribution of the clutter spread for Kwajalein to lie below that of the 1977 Ancon data for the smallest frequency. Figure 6 confirms this expectation. Further, the Kwajalein curve is always below the Ancon curve at VHF and UHF. For 99% of the data at Kwajalein/Ancon, σ_{SC} is less than 7.46 Hz/4.66 Hz, 2.14 Hz/1.38 Hz, and 0.46 Hz/0.22 Hz at VHF, UHF, and L-band, respectively. Table 3 provides spreads at chosen percentage levels. Also, note that the spectral spread decreases with increasing frequency, which is expected since the decorrelation increases with increasing frequency. Lastly, because the minimum value of τ_0 for both the Kwajalein and Ancon data at each frequency is 24 ms, the maximum clutter spread for each dataset and each frequency is 9.38 Hz.

Table 3 — σ_{SC} for Selected Percentages at Kwajalein/Ancon

Percent	σ_{SC} @ VHF (Hz)	σ_{SC} @ UHF (Hz)	σ_{SC} @ L-band (Hz)
95.0	4.90/2.74	1.58/0.74	0.26/0.10
99.0	7.46/4.66	2.14/1.38	0.46/0.22
99.9	7.98/5.94	2.50/2.66	0.78/0.86

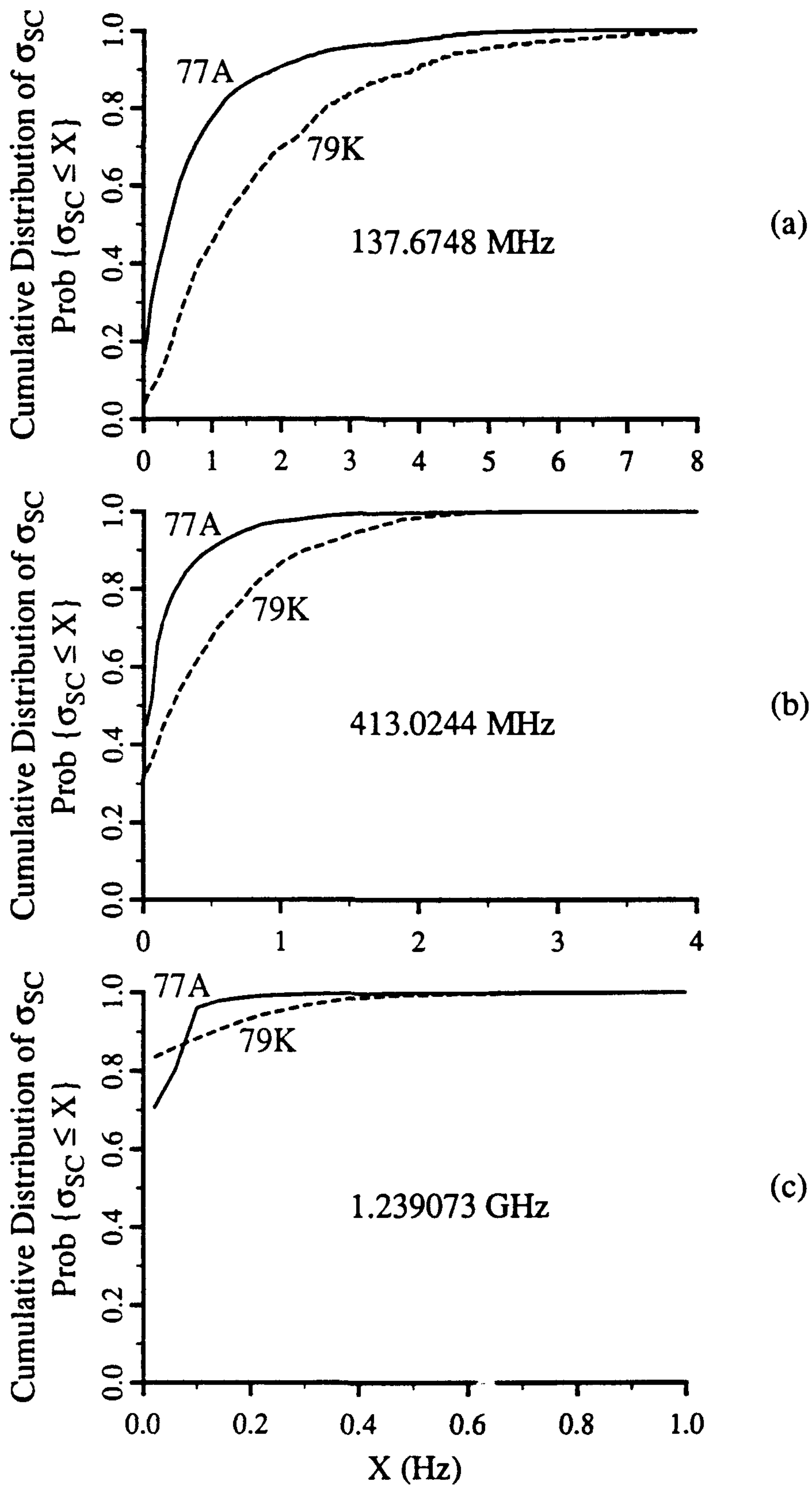

Fig. 6 — Cumulative distribution of the clutter-Doppler spread σ_{SC} caused by ionospheric scintillation for Kwajalein in 1979 (79K) and Ancon in 1977 (77A) at VHF, UHF, and L-band

5. SUMMMARY

The data received from two equatorial ground stations, Kwajalein in 1979 and Ancon in 1977, are processed and analyzed. The Kwajalein data were taken at the beginning of a period of maximal solar activity, while the Ancon data correspond to a solar minimum. As expected, the Kwajalein data, which typify worst-case ionospheric conditions, experienced more severe scintillation than the Ancon data. This is manifested by a weighting of the distribution of the complex decorrelation time (τ_0) for the Kwajalein dataset toward smaller values. However, the minimum value of τ_0 for both locations and each frequency is the same (24 ms).

A bound on the combined coherent-noncoherent integration loss (TIL), resulting from worst-case scintillation, is obtained for a waveform tha. consists of four bursts per look and six looks per dwell and for a coherent integration time of 0.256 s. The bound is generated from a cumulative distribution of the TIL, which is created from τ_0 statistics and a distribution of the coherent integration loss per burst. The bounds for the Kwajalein data are larger than those for the Ancon data, and both sets of bounds decrease with increasing frequency. In particular, a space-based radar in a 1030-km orbit will suffer a TIL not exceeding 2.54, 0.70, and 0.06 dB at VHF (138 MHz), UHF (413 MHz), and L-band (1239 MHz), respectively, for 95% of the time in worst-case conditions.

For severe scintillation, the clutter-Doppler spreads (σ_{SC}) for the data are calculated with a simple analytical expression from the τ_0-statistics. Since the Kwajalein data experienced more severe scintillation, its clutter spreads are larger than those of Ancon. In particular, for 95% of the time during worst-case conditions, σ_{SC} is less than 4.90, 1.58, and 0.26 Hz at VHF, UHF, and L-band, respectively. However, because the minimum τ_0 is the same for each location and frequency, the maximum σ_{SC} are equal. Hence this maximum (9.38 Hz) is a conservative bound on how much the total clutter spread can be reduced ovrr this frequency range (130–1240 MHz) for worst-case ionospheric conditions.

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