Troposcatter Link Design Using Air-borne Microwave Refractometer Observations over Kanpur

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Received 14 September 1987; revised received 20 January 1988

In a troposcatter system, the received power is determined by the intensity and scale of the refractive index fluctuations in the path, especially the "common volume" of the transmitting and receiving antenna beams. Fine structure of the radio refractivity information was collected over Kanpur for winter conditions, using the air-borne microwave refractometer developed by the author. This information was used to design an optimum troposcatter link and the results are compared with the empirical relationships obtained by making use of radiosonde observations. Refractometer observations resulted in a gain of 35 dB in path loss which has reduced the power requirement of the transmitter considerably and hence the cost reduction. Use of radio refractive fine structure information collected by air-borne microwave refractometer in the design of a troposcatter communication link has resulted in optimization of the link and reduced the long distance electromagnetic interference on other circuits.

1 Introduction

Spatial and temporal structure of the atmosphere is of interest in the studies of atmospheric processes and their effects on electromagnetic wave propagation. Communication system coverage is critically dependent on the radio refractive index fine structure information of the troposphere. The turbulent fluctuations in atmospheric refractive index can produce scattering of energy beyond the geometrical horizon that can greatly extend the coverage of any microwave communication system. An accurate assessment of the severity of turbulence effects on communication system, which is adequate for the projected needs but not overdesigned and hence more expensive, is necessary. This will also reduce the electromagnetic interference (EMI) problems on other circuits.

The actual scatter power available in any troposcatter circuit is a function of power spectral intensity as well as the scale size of the irregularities averaged over the common volume. While the intensity is essentially controlled by the energy in the larger scale lengths, the microwave scatter power depends on the abundance of lower scale sizes comparable to the operating wavelengths. In general, communication engineers depend upon the empirical relationships derived from the local meteorological measurements based on radiosonde measurements of pressure, temperature and relative humidity supplemented with surface measurements of wind speed. The detailed information of the refractivity structure in the first 1500 m above the ground could not be collected by the radiosonde measurements as these observations are not representative of the true atmospheric conditions even though such information is widely used in the assessment of propagation and system performance. The poor spectral resolution and extremely slow response of the sensors in a radiosonde system do not permit its data to be used for any reliable circuit design. Further, the radiosonde data are subjected to errors arising from instrumental and observational shortcomings thereby seriously compromising their validity. In order to overcome this situation, for the first time in India, a highly sophisticated air-borne solid state digital microwave refractometer was designed, fabricated and flight tested aboard an aircraft over Kanpur. The height resolution of the radio refractivity gradients obtained from the above air-borne microwave refractometer is far superior to the currently available information in India. This fine structure of the radio refractivity gradient information is also useful in estimating the magnitude of the propagation anomalies on systems like earth-space, line-of-sight, radar and troposcatter links, guidance systems, missile tracking systems, aircraft warning systems and many more applications in remote sensing. Using this air-borne microwave refractometer data were collected over Kanpur and this information was used to design an optimum troposcatter link, with its common volume over Kanpur, and the results are compared with empirical relationships obtained using radiosonde observations over Lucknow, a meteorological station nearby to Kanpur. Horizontal homogeneity of radio refractive index was assumed between Kanpur and Lucknow as the aerial distance...
between the two stations is about 60 km and both the stations are in the northern plains of India. Many workers\(^2\)\(^3\) have assumed the above homogeneity over regions of some hundreds of kilometres in extent over a flat terrain. This assumption may be correct provided the two stations are at least 80 km from a major landmass and there exists no land/sea interface and no significant change in airmass boundaries. These conditions are completely satisfied in the present analysis. As we have taken observations only on two consecutive days in January 1985 (during daytime only) we did not observe any day-to-day changes in the above period in the refractivity data except that there are some minor changes which are attributed to turbulence behaviour which is always present in the lower atmosphere. Radiosonde observations are taken twice a day from Lucknow which is the nearest station from Kanpur for comparison of the results.

Troposcatter circuit design should take care of the required performance in terms of signal-to-noise ratio per channel for voice transmission and bit-error rate for digital transmission. The former is related to the carrier-to-noise ratio of the system and this relationship depends on the number of channels and the modulation technique. In case of digital transmission, in addition to the above relationship the signal fading and the receiving diversity also play an important role. The signal fading margin determines the reliability of the circuit. Thus, in the troposcatter circuit design the following are some of the important factors: signal fading and multipath effects, path loss and correction factors due to terrain and meteorological effects, aperture-to-medium coupling loss, etc. For frequency modulation system the circuit performance depends on both the carrier-to-thermal noise ratio and the minimum usable signal-to-noise ratio per voice channel at the threshold and the latter is generally taken as 15-20 dB.

For the sake of continuity a short description of the refractometer design and the retrieval of \(C_n^2\), the atmospheric structure constant, from the refractometer data are given below.

### 2 Air-borne Microwave Refractometer

The major refractometer system elements are: (i) microwave source, (ii) a pair of high \(Q\) transmission type resonant cavities (one for use as a reference cavity and the other for use as a sensor (sampling cavity) through which the atmosphere under investigation can pass through freely, and (iii) the electronic circuitry including the data acquisition system. Refractometer makes use of a microwave cavity having a resonant frequency (adjustable) as determined by its dimensions, and the refractive index of the contained atmosphere (normally vacuum or filled with inert gases and hence refractive index can be approximately taken as unity). By comparing the resonant frequency of the sampling cavity with that of a sealed reference cavity, a direct measure of the variation of the refractive index of the atmosphere is obtained from the frequency difference. This, in turn, will be converted to refractivity and fed to data acquisition system. In the present system data are printed at a rate of 3 samples per second to an accuracy of 1 Nunit. The height resolution in the present system can be about 3 to 4 cm (since the refractometer operates in the X-band) and is mainly dependent on the climb rate of the aircraft in addition to its sensor dimension. This refractometer was mounted in the CESSNA 182 H SKYLANE aircraft of the Indian Institute of Technology (IIT), Kanpur, with its sensor's location under the wing of the aircraft where the aircraft's slip stream effects are minimum. The flight pattern of the aircraft was in the form of a spiral and a constant climb rate is maintained to get the vertical profile of the refractivity of the atmosphere up to an altitude of about 10,000 ft above the ground level.

### 3 Atmospheric Turbulence

Atmospheric turbulence parameters (\(C_n^2\), the structure constant) were deduced from the vertical profiles of radio refractive index measured with the air-borne microwave refractometer. With the hypothesis of frozen-in turbulence, the temporal variations in refractive index have been analyzed to compute the structure constant, \(C_n^2\), and the scale sizes of the atmospheric turbulence. From theoretical considerations the scale size in the atmosphere should increase with altitude and hence the lowest altitudes are preferred for the higher operational frequencies. The measured variations in refractive index are treated as spatial variations. The variance of the refractive index \(\langle \Delta n^2 \rangle\) was computed for different heights. The mean height profiles of \(C_n^2\) are computed from the observed \(\langle \Delta n^2 \rangle\) values. Radiosonde observations underestimate the observed \(C_n^2\) values and hence refractometer data were used in the design of the present troposcatter circuit.

### 4 Troposcatter System Design

In a troposcatter link the secondary waves only carry the signals towards the receiver. Refractive index inhomogeneities existing in the common volume of the antenna beams scatter part of the energy towards the receiving antenna and the received level undergoes rapid fading since the relative phases of each wave vary with atmospheric movements. Thus, the greater the vertical gradient in refractive index over the common volume the higher will be the received signal level.
4.1 Total System Loss

The ratio between the transmitted and received power is the total system loss, $L_t$, and is expressed as

$$L_t = L_p - G_t - G_r + L_c + L_a + L_f \quad \text{(in dB)} \quad \ldots (1)$$

where

- $L_p$: Yearly median path loss in dB
- $G_t$: Transmitted antenna gain in dB
- $G_r$: Received antenna gain in dB
- $L_c$: Aperture-medium coupling loss in dB
- $L_a$: Total feeder and junction losses in dB
- $L_f$: Fading margin in dB for a specific reliability

4.2 Medium Path Loss

The medium path loss, $L_p$, depends on carrier frequency, distance, terrain and climatological effects and can be expressed as

$$L_p = L_{th} + L_s + L_w - 0.2 \left( N_s - 310 \right) \quad \text{(in dB)} \quad \ldots (2)$$

where

- $L_{th}$: Transmission loss, in dB, between isotropic antennas (which is otherwise called as the basic transmission loss or the free space loss)
- $L_s$: Yearly median scatter loss in dB
- $L_w$: Frequency correction for the scatter loss in dB
- $N_s$: Surface refractivity in $N$ units

4.3 Basic Transmission Loss

The transmission loss (free space loss) can be expressed as (which is purely an empirical relation)

$$L_{th} = 102 + 30 \log_{10} f + 30 \log_{10} D + 1.5 G_c \quad \text{(in dB)} \quad \ldots (3)$$

where

- $D$: Distance in km
- $f$: Frequency in MHz
- $G_c$: Equivalent gradient between the ground and the common volume, i.e., the average path curvature (assuming the field to have a log-normal distribution), in dB.

4.4 Median Scatter Loss

The median scatter loss can be expressed as

$$L_s = 57 + 10(\theta - 1) + 10 \log_{10} \left( \frac{f}{400} \right) \quad \text{(in dB for } \theta > 1^\circ) \quad \ldots (4)$$

where $\theta$ is the scattering angle in degrees (This scattering angle is expressed in degrees in order to take care of the terrain effect.).

4.5 Gain Degradation

In a troposcatter circuit the apparent gain of the receiving antenna is less than the free-space gain. This reduction in gain is the aperture-to-medium coupling loss and can be determined to a reasonably fair accuracy from the earlier experimental data\(^6\) - \(^9\). This aperture-to-medium coupling loss estimate from theories seems to be optimistic at small $\theta/\alpha$ ratios and pessimistic at large $\theta/\alpha$ ratios where $\alpha$ is the antenna beam width. However, these theories led to contradictory conclusions with respect to distance or antenna gain. This aperture-to-medium coupling loss in the present case is estimated from an empirical equation

$$L_c = G_t + G_r - G_{eff} \quad \text{(in dB)} \quad \ldots (5)$$

where

$$G_{eff} = \text{effective path antenna gain in dB}$$

$$G_{eff} = (G_t + G_r) \times \exp \left\{ - \left( \frac{G_t + G_r}{148} \right)^4 \right\} \left[ 1 + \left( \frac{G_t + G_r}{148} \right)^4 \right] \quad \text{(in dB)} \quad \ldots (6)$$

This above equation is valid for values of $(G_t + G_r) < 120$ dB only.

However, this loss, $L_c$, can be reduced by utilizing antennas whose beams feature different angular apertures in both vertical and horizontal planes to accommodate the structure inhomogeneities which is highly complicated compared to the results expected. In the present case this loss comes out to be 20 dB.

4.6 Scatter Loss (Fading)

Conceptually, the simplest way of overcoming attenuation is to provide so much signal at the receiver that the fade does not matter. However, this may cause EMI problems on other circuits, which is an extremely undesirable feature. This scatter loss is statistical in nature and depends on fast fading due to multipath effects and slow fading due to changes in refractive index of the atmosphere. Thus the instantaneous signal is a combination of the above two factors which had been discussed widely\(^10\) and for voice communication this instantaneous signal fading depends on scatter angle and order of diversity. In the case of analog systems, multipath fading effects can be eliminated by providing a clear weather margin sufficient to overcome the fades that are anticipated for a stated percentage of time. However, the terrestrial links designed according to the established procedures for analog systems have failed to provide the desired reliability\(^11\). Thus proper fading margin is to be taken for a specific reliability. Further, a basic necessity is there...
to apply a frequency correction (in dB) for the scatter loss and in the present case it is assumed as 7 dB.

For the present troposcatter circuit design a 99.9% reliability is assumed at 2 GHz carrier frequency and 300 km great circle distance. Minimum usable signal-to-thermal noise ratio of 15 dB is assumed with carrier-to-noise ratio of 10 dB. A 100 channel voice communication with frequency modulation was desired. The IF bandwidth comes to be about 2 MHz for a deviation ratio of one. The scattering angle can be calculated if the scatter geometry/path profile is known. In the present case the path profile is smooth earth. Zero antenna height is assumed. Hence, the scattering angle, \( \theta \), is given by the following equation

\[
\theta = \frac{180 D}{\pi R} \text{ (in deg)}
\]  

where \( R \) is the effective earth's radius in km, and \( D \) the great circle distance in km; and the height of the scattering volume is given by

\[
h = \frac{D^2}{8R} \quad \ldots \ldots (8)
\]

Using Eqs (7) and (8) the scatter angle comes out to be 2° and the height of the common volume is 1250 m above the ground. Antenna gains are assumed as 53 dB and the beamwidth of the antenna comes to 0.5°. Normally the feeder and junction losses at 2 GHz comes out to be of the order of 2 dB.

Fade margin is the decibel difference between the link carrier-to-noise ratio that is achieved in clear weather and the minimum value of link carrier-to-noise ratio that is necessary for a satisfactory operation and stated reliability. This fading margin for zero diversity at 2° scatter angle and 99.9% reliability comes to about 38 dB. For the refractometer data \( G_c \) comes to about \(-66 N\) per km, as evident from Fig. 1 and for the radiosonde data it is about \(-3 N\) per km as evident from Fig. 2. Thus the refractometer usage gives a gain of 34.5 dB in the tropocircuit design for a typical winter condition over northern plains in India. The surface refractivity is 266 \( N \) units over Kanpur during that period. Using Eqs (1)-(5) the total system loss is found out to be about 206.8 dB using refractometer data and it is about 240.3 dB using the radiosonde data.

Normally the receiver noise figure \( F \), in a troposcatter circuit at 2 GHz is of the order 3 dB. The carrier-to-thermal noise ratio, \( C/N \), is taken as 10 dB.

\[
C/N \text{ (in dB)} = 10\log_{10} \frac{P_t}{N} - 10\log_{10} N \quad \ldots \ldots (9)
\]

where

\( P_t \) Transmitted RF power in watts (average power for FM)

\( N \) Total IF thermal noise power in watts

The total IF thermal noise power can be expressed as
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\[ N = FKTB_{\text{if}} \] \hspace{1cm} \text{(10)}

where

- \( F \) Receiver noise figure
- \( K \) Boltzmann's constant
- \( T \) 300 K
- \( B_{\text{if}} \) Receiver's IF bandwidth in Hz

Using Eqs (9) and (10) the transmitter power required can be calculated. Refractometer data have reduced the power requirement of the transmitter considerably for a troposcatter circuit design.

5 Conclusion

A 300 km troposcatter link at 2 GHz was designed, with the common volume of the antenna beams located over Kanpur, making use of the realistic refractive index fine structure information derived from airborne microwave refractometer for winter conditions. The path loss determined by using the refractometer observations is about 35 dB less than that obtained by normal practice (by making use of radiosonde observations). This reduction in path loss is really significant as the power requirement of the transmitter is reduced considerably and hence the cost reduction of the system. Further, use of refractometer in a troposcatter circuit design has resulted in optimization of the links thereby reducing the long distance interference on the other circuits.

References