Performance of v.f. f.m. teleprinter circuits operating over a tropospheric-scatter link

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Synopsis

The paper describes an investigation undertaken to derive data on which to base estimates of the telegraph performance to be expected over tropospheric-scatter radio links. H. B. Law has shown how the telegraph error rate depends on the signal/noise ratio at the input to the telegraph equipment for the case of a steady signal, and also for the case of one subject to Rayleigh fading.

As the signal received over a tropospheric-scatter link has a short-term amplitude distribution following the Rayleigh law, it might be expected that Law's results could be applied directly. The problem is complicated, however, by the fact that most operational scatter links employ frequency modulation of the radio carrier, with the result that the receiver exhibits threshold effects. When the fading signal falls below the receiver threshold, which it may frequently do, the output signal/noise ratio is no longer linearly dependent on the input carrier/noise ratio. It is shown, however, that, if the output/input characteristic of the radio receiver is known, the telegraph error rate can still be calculated in terms of the mean carrier/noise ratio.

An empirical law for the output/input characteristic of an f.m. radio receiver is proposed, and, using this law, the telegraph performance of circuits carried by tropospheric-scatter links is then calculated for the cases of non-diversity and dual and quadruple selector-type diversity receiving systems. It was considered desirable to make experimental checks, and an analogue method was employed in which the effects of the radio path were recorded and used to operate a fading machine, so as to reproduce, in the laboratory, the conditions which had existed over an actual radio path.

A comparison is made of predicted values of telegraph error rate with experimental results obtained using the fading machine.

1 Introduction

The availability, in the last decade, of high-power u.h.f. and microwave transmitting valves has made the construction of tropospheric-scatter radio links a reasonable alternative to the use of the more conventional types of communication system, such as coaxial cable, submarine cable and line-of-sight microwave links etc., in situations where it is either undesirable or impracticable to install and maintain repeater stations.

As the signals received over a tropospheric-scatter path are usually very weak for a reasonable percentage of the year, it is necessary to employ both high-power transmitters and low-noise receivers, together with high-gain aerial systems, in order to provide the best possible service.

This inevitably means that the terminal equipment required for tropospheric-scatter radio paths is very expensive, both in capital expenditure and in operating costs. It is of paramount importance, therefore, to be able to predict the performance of such links with reasonable accuracy in order to plan an overall system which is capable of meeting a required specification.

Most tropospheric-scatter links are required to carry multichannel telephone and telegraph circuits simultaneously, using standard frequency-division-multiplex equipment; but, while the large amount of redundancy present in normal speech enables an intelligible speech signal to be received in a telephone channel which is subject to interference from an occasional burst of noise, in general, a noise level which is tolerable for speech transmission would result in errors in telegraph transmission.

Automatic error-detection (a.r.q.) equipment can be employed to improve the performance of the telegraph circuits; but this equipment is very expensive, and it would be uneconomic to use error-detection circuits when more than a few telegraph channels are required.

From the above arguments it would appear that, from the point of view of economy, tropospheric-scatter circuits should be engineered to meet a given telegraph performance. The purpose of the paper is to indicate a method of estimating the telegraph performance of such systems.

2 Performance of v.f. telegraph equipment

Law has investigated the performance of frequency-shift-keyed (f.s.k.) radiotelegraph systems, in which the telegraph signal was used to change the frequency of the carrier radiated by a radio transmitter by a few hundred cycles per second according to the state of the telegraph signal, i.e. mark or space, and the telegraph signal was recovered at the receiving terminal using a radio receiver incorporating a demodulator of the frequency-discriminator type.

The results obtained by Law indicate that a relationship exists between telegraph element error rate $E$ and the ratio $y$ of signal-power to noise-power density in the radiotelegraph receiver of the form

$$E = \frac{1}{2}e^{-yVb}$$

where $V$ is the transmission speed in bauds and $b$ is the characteristic signal/noise energy ratio required to produce an element error rate of $1/2e$.

Now, apart from the absolute differences in carrier frequency and frequency shift, the radiotelegraph receiving system examined by Law, with a carrier in the h.f. band, is identical to a single voice-frequency telegraph channel of the f.m. type, having a shift of $60c/s$ and a carrier in the v.f. band. Thus, the performance of a single channel of a multi-channel v.f. f.m. telegraph terminal may be determined by the methods applied by Law to his radiotelegraph system.
2.1 Element error rate of a v.f. f.m. telegraph channel carried by a radio circuit

The behaviour of the telegraph channels carried by a tropospheric-scatter radio circuit may then be estimated with the aid of eqn. 1, if the characteristics of the radio receiver employed on the scatter path can be determined in the form

\[ y = \phi(x) \]  

(2)

where \( y \) is the demodulated signal/noise power density ratio and \( x \) is the ratio of the mean carrier power to noise power in the i.f. amplifier of the radio receiver.

3 Characteristics of f.m. receivers above threshold

The theoretical treatment of the performance of an f.m. receiver for large values of carrier/noise ratio is simple, but becomes very complex for small values of this ratio. Thus, in the case of a multichannel system, if \( N \) is the noise power in the i.f. amplifier of bandwidth \( B \) of an f.m. receiver for which the carrier/noise ratio \( C/N \) exceeds 10 dB, the noise-power spectrum \( w \) at the output of the frequency discriminator is given by

\[ w = \frac{2AN}{BC^2} \]

where \( A \) is a constant of the discriminator.

The mean noise power \( N_0 \) in a telephone channel of bandwidth \( \delta f \) centred on a baseband frequency \( f \) is therefore

\[ N_0 = \int_{f-\frac{\delta f}{2}}^{f+\frac{\delta f}{2}} w \, df \]

For practical systems of the f.m. type \( \delta f \ll f \), and therefore

\[ N_0 \approx \frac{2AN}{BC} \delta f \]  

(3)

If the peak deviation of the carrier is \( D \) at a modulation frequency \( f \), the demodulated signal power output \( S_0 \) from the discriminator is given by

\[ S_0 = AD^2 \]

The demodulated signal/noise ratio in the output filter is therefore obtained by combining the above expression with eqn. 3 to give

\[ \frac{S_0}{N_0} = \frac{D^2 B C}{2f^2 \delta f N} \]  

(4)

3.1 Characteristics of f.m. receivers below threshold

When the carrier/noise ratio falls below 10 dB, however, the simple analysis outlined above fails, and the theoretical treatment of the subject is very complicated.

An analysis of the problem has been undertaken by Stumpers, in which the demodulated noise output from an f.m. receiver has been calculated for various carrier/noise ratios for the cases of rectangular and Gaussian i.f. passband characteristics and an unmodulated radio carrier. Stumpers states that the noise output would be expected to vary with the radio carrier. For constant carrier/noise ratio; consequently the demodulated noise power is substantially independent of carrier deviation for the values of deviation considered.

Now when the carrier/noise ratio is large, so that the simple theory of Section 3 applies, the demodulated signal/noise power density ratio is given by eqn. 4, which may be rewritten

\[ y = \frac{S_0}{N_0} \delta f = \frac{D^2}{B} \left( \frac{B^2 C}{2f^2 N} \right) \]

from which it may be seen that, if the channel frequency \( f \) is expressed as a fraction of the receiver bandwidth \( B \), the demodulated signal/noise power density ratio depends only on the terms outside the parentheses at constant carrier/noise ratio.

Now when the carrier/noise ratio is too small to produce an 'f.m. advantage', in the region commonly referred to as 'below f.m. threshold', the position of the channel within the baseband does not materially affect the demodulated signal/noise power density ratio; but it is reasonable to

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These results relate to the characteristics of the tropospheric equipment installed at the Nassau terminal of the Florida—Nassau link.

Whereas the carrier/noise ratio scale must continue down to \(-\infty\) dB, it is not unreasonable to extrapolate the curve down to carrier/noise ratios of zero. If we assume a relationship of the type given by eqn. 5, we may use it to determine \(U\) and \(F(x)\). This has been done in Fig. 2, in which the characteristics of receivers A and B have been normalised to \(D = 50\,\text{kc/s}\), \(B = 1\,\text{Mc/s}\) and \(\delta f = 1\,\text{c/s}\).

If we put
\[
\frac{x^2}{2} + B = \frac{1}{2B} y^2 \quad (10)
\]
we obtain
\[
y = \frac{U D^2}{B} F(x) \quad (5)
\]
where \(U\) is a constant.

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The solid curve has an empirical law
\[
y = \frac{1}{2B} x^2(1 + 0.24x^2) \quad (6)
\]
which will be used throughout the remainder of the paper as representing the characteristics of a frequency-modulated radio receiver for the purpose of determining telegraph performance.

4 Prediction of telegraph error rate

4.1 Constant radio carrier

If a constant carrier level is applied to the input of the radio receiver, producing a constant carrier/noise ratio at the radio-frequency discriminator, both the signal and the mean noise power density obtained at the output of the receiver will also be constant.

Hence, from eqns. 1 and 2, the element error rate of the system is
\[
E = \frac{1}{2} \exp \left[ -\frac{\phi(x)}{Vb} \right] \quad (7)
\]
Combining eqns. 6 and 7 gives
\[
E = \frac{1}{2} \exp \left[ -\frac{1}{2B} x^2 B(1 + 24x^2) \right] \quad (8)
\]
and the element error rate is therefore
\[
E = \frac{1}{2} \exp \left[ -\frac{K}{2B} x^2 \right] \quad (9)
\]

4.2 Radio carrier subject to flat (non-selective) fading

Eqn. 9 expresses the telegraph error rate of a system in terms of the carrier/noise ratio existing at the input of the discriminator for the case of a constant-amplitude carrier. In practice, however, the amplitude of the carrier received over a tropospheric-scatter path is not constant, but is subject to large and rapid fluctuations.

A considerable amount of data have been collected on the short-term distribution of amplitude of carriers received over tropospheric-scatter systems; analysis generally indicates that, when deep fading occurs, the Rayleigh formula provides the most satisfactory description of the observations.

The Rayleigh distribution, for the case of a carrier having a mean power \(C\), is defined by
\[
p = 1 - e^{-x/C} \quad (10)
\]
where \(p\) is the probability that the carrier power received over a short period of time will be less than a specified value \(x\); it follows, therefore, that the probability that the carrier power is within the range \(c\) and \(c + dc\) is
\[
dp = \frac{1}{C} e^{-x/C} dc \quad (10)
\]
If we put \(x = C/N\) and \(X = C/N\), eqn. 10 may be rewritten
\[
dp = \frac{1}{X} e^{-x/X} dx \quad (11)
\]
It should be noted that \(X\) is the mean carrier/noise power ratio, and that eqn. 11 expresses the probability of obtaining a carrier/noise power ratio within the range \(x\) and \(x + dx\).

Now the element error rate of a telegraph circuit operating over a link in which the carrier/noise ratio is \(x\) is given by eqn. 7; consequently, the contribution to the average error rate of the circuit under these conditions is
\[
E dp = \frac{1}{X} \exp \left[ -\frac{\phi(x)}{Vb} \right] \frac{1}{X} \exp (-x/X) dx
\]
The average error rate is given by considering the contributions for all possible values of \( x \), i.e.

\[
E = \int_0^1 Edp = \int_0^\infty \frac{1}{2} \exp \left( - \frac{\phi(x)}{Vb} \right) \frac{1}{X} \exp \left( - \frac{x}{X} \right) dx . 
\] (12)

From eqns. 8 and 12, the element error rate for a Rayleigh fading carrier is

\[
E = \frac{1}{2X} \int_0^\infty \exp \left( - Kx^2(1 + 0.24x^2) \right) \exp \left( - \frac{x}{X} \right) dx . 
\] (13)

It will be noted that the upper limit of integration has been changed from infinity in eqn. 12 to 3 in eqn. 13. This is because the empirical law for the radio receiver applies only for the range \( 0 < x < 3 \). A second integral would be required for the range \( 3 < x < \infty \), with another expression for the receiver characteristic, but in practice the integral is sensibly zero for \( x > 3 \).

A general solution to eqn. 13 has not been obtained, but it has been evaluated for the range \( 0.2 < K < 100 \), which is thought to be adequate for all practical systems; the results are plotted in Fig. 3.

All the curves are approximately straight lines for the region in which the mean carrier/noise ratio exceeds 10 dB, the slope of the curves being 10 dB per decade of error rate in all cases. For carrier/noise ratios less than 10 dB the error-rate characteristics are curved, all being asymptotic to an error rate of 0.5.

4.3 Selector-type diversity receiving systems

The effect of the rapid fluctuations in amplitude of the carrier received over a tropospheric-scatter link may be alleviated by the use of some form of diversity receiving system. A system which, although not the most efficient, has the merit of simplicity is the switched or selector arrangement, in which the carrier is received by a number of diversity paths, the receiver being designed to select the output from the diversity path which produces the largest instantaneous signal.

Thus, in the case of a diversity system having \( \lambda \) diversity paths, the probability that the received carrier level selected by the receiver is within the range \( c \) and \( c + dc \) is

\[
dp = \frac{\lambda}{C} e^{-\alpha C} \left( 1 - e^{-\alpha C} \right) \lambda^{-1} dc
\]

where \( C \) is the mean carrier power received by each of the \( \lambda \) diversity paths.

As the mean receiver noise power is constant and independent of the path providing the received carrier, the substitutions \( x = c/N \) and \( X = C/N \) may be made as before.

Fig. 3
Error-rate curves for Rayleigh fading carrier. Non-diversity

Fig. 4
Error-rate curves for Rayleigh fading carrier. Dual selector-type diversity

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Hence the probability of obtaining a carrier/noise ratio within the range \( x \) and \( x + dx \) is
\[
dp = \frac{\lambda}{x} e^{-x/\lambda} (1 - e^{-x/\lambda})^{-1} dx
\]
Consequently, the error rate resulting from the use of the \( \lambda \)-order selector-type diversity system is given by
\[
E = \frac{\lambda}{2X_y} \exp \left( -Kx^2 (1 + 0.24x^2) \right) \exp \left( -\frac{x}{\lambda} \right)
\]
\[\left[ 1 - \exp \left( -\frac{x}{\lambda} \right) \right]^{-1} dx
\]
As before, the integral has been evaluated graphically for the cases \( \lambda = 2 \) and \( 4 \), and the results are plotted in Figs. 4 and 5, respectively. From Fig. 4 it is seen that, for error rates less than about one in 100, the curves are essentially straight lines having a slope of 5 dB per decade of error rate, while the slope of the linear portion of the characteristics in Fig. 5 is 2.5 dB per decade of error rate; it may be inferred from this and the results for dual and non-diversity, that the slope of the curves for \( \lambda \) diversity paths would be \( 10/\lambda \) decibels per decade of error rate.

5 Measurement of telegraph error rate

In order to verify the results obtained in Figs. 3, 4 and 5, for the error rate of a telegraph circuit operating over a tropospheric-scatter link, it was decided to perform some actual error-rate tests.

In view of the difficulties of accurately determining the conditions of test at the terminals of a radio link 100 or so miles long, together with difficulties of allowing for the effects of the slow variations in the mean power of the short-term (Rayleigh) amplitude distribution during the period of a test, it was considered desirable to construct an artificial tropospheric-scatter link which could be used in the laboratory.

The artificial tropospheric-scatter path comprised an amplitude modulator in which the output of an r.f. signal generator could be modulated by the envelope of an audio-frequency signal which was recorded on magnetic tape.

The a.f. signals recorded on the magnetic tape were obtained by heterodyning the unmodulated carrier of an actual tropospheric-scatter signal with a local oscillator in order to produce an audio beat frequency, the carrier level being adjusted during the period of the recording in an attempt to maintain a constant mean power.

The fading machine, or artificial scatter link, is therefore capable of impressing the amplitude distribution of the original u.h.f. tropospheric-scatter signal on a locally generated carrier of any frequency.

The experimental arrangement for the measurement of telegraph error rate is shown in Fig. 6, from which it is seen that a telegraph test signal generated by a 50-baud automatic tape transmitter was used to control a channel oscillator of an f.m. voice-frequency telegraph terminal.

The output of the telegraph terminal, which was a tone of 630 or 690 c/s, corresponding, respectively, to the spacing and marking condition of the telegraph signal, was used to frequency-modulate the carrier generated by a signal generator.

The carrier frequency of the signal generator was adjusted to correspond to that of the midband of the lowest i.f. amplifier in the receiver under test, and the f.m. carrier was then passed to the fading machine, where it was amplitude-modulated by the Rayleigh distributed signals previously recorded over a tropospheric-scatter link.

The output of the fading machine was therefore similar to a tropospheric-scatter carrier, frequency-modulated by a telegraph signal and frequency-changed to a suitable intermediate frequency. The r.f. stages of the receiver were operated under normal conditions in order to provide a convenient means of generating white noise at an appropriate level in the final i.f. amplifier. A thermal instrument was connected to the i.f. amplifier output in order to facilitate measurements of carrier/noise ratio, and the demodulated carrier plus noise was filtered by a bandpass filter having a passband centred on 600 c/s.

The filtered signal was attenuated to a standard level of \(-20 \text{dBm}\), and then passed to the receive leg of the v.f. telegraph terminal. The telegraph signal recovered from the
telegraph terminal was used to operate a teleprinter and also a synchronous bit-error detector.

The bit-error detector compares a delayed version of the transmitted telegraph signal with a sample taken from the nominal centre of each element in the received signal; the delay being equal to the transmission time through the system. If the polarities of the signals differed, an error was indicated on a gas-tube counter, and the total number of bits transmitted was indicated on a second counter. Thus, the element error rate was indicated by the ratio of the counts indicated by the two counters.

5.1 Constant-carrier telegraph tests

Error-rate measurements were made on receivers A and B for the case of constant-amplitude radio carrier inputs to the receivers; the results are indicated in Figs. 7 and 8, respectively. The solid curves were calculated by means of eqn. 9, and the experimental results are shown by the points plotted in the Figures.

The value of the constant \( k(=1.7) \) had been measured in a previous error-rate test on the telegraph equipment employing various values of v.f. tone/noise ratio.

5.2 Fading-carrier telegraph tests

Error-rate measurements were made on receivers A and B for the case of Rayleigh-fading carrier, using the arrangements of Fig. 6. The results are indicated in Figs. 9 and 10, respectively. The solid curves were calculated using the empirical receiver characteristic by interpolation from Figs. 3 and 4; the experimental points are plotted for comparison.

6 Character error rates

6.1 Synchronous systems

The telegraph performance quoted above is in terms of the element error rate, as this is a fundamental quantity which is relatively easy to measure and is also independent of the type of transmission, i.e. synchronous or start/stop.

The telegraph user is, however, primarily interested in the printed character rather than the elements which go to make up the character; thus his requirement is usually for a given character error rate.

For a synchronous transmission this does not involve any great difficulty, for, as practical bit error rates will normally be better than \( 1 \times 10^{-4} \), it is reasonable to suppose that there will be only one bit error corresponding to each character error.

The character error rate \( W \) is then given by \( m \) times the bit error rate if there are \( m \) code elements per character. Thus, an element error rate \( E \leq 1 \times 10^{-4} \) will result in a basic character error rate \( W = mE \) for a synchronous system. This result ignores a number of multiple errors which may be caused by a single element error.

Thus, a single bit error may cause the following types of multiple error:

(a) an incorrect 'carriage return' signal may cause loss of the subsequent line of characters.

Fig. 8
Error-rate curves for constant radio carrier for receiver B

Fig. 7
Constant-carrier test for receiver A
(b) an incorrect 'line feed' may cause overprinting, and result in the loss of both the previous and subsequent line of characters.

As the two shift signals differ by only one element, the probability of this occurring is simply \( E(1 - W) \approx E \). Errors of the type noted under (d) are difficult to avoid by operating technique, and consequently they must be accepted. Errors due to (a) and (b) can, of course, only occur with page printers, but few commercial users consider using tape printers.

6.2 Loss of carriage-return signal
The loss of a carriage-return signal will result in the loss of the following line of characters. If an average line comprises \( h \) characters, then a block of \( M \) characters will contain an average of \( M/h \) carriage-return signals; consequently, the mean number of incorrectly received carriage return signals in a block of this size is \( P = WM/h \).

As each incorrect carriage-return signal will result in the loss of \( h \) characters, the mean number of characters lost from this cause, out of a block of \( M \) characters, will be \( v = hP \). The basic characters error rate is increased, therefore, by an amount \( W_1 = hP/M = W \) on this account.

6.3 Loss of line-feed signal
The loss of a line-feed signal will result in the loss of two lines owing to overprinting. Using an analysis similar to that in Section 6.2, and noting that in this case \( v = 2hP \), it is found that the basic character error rate must be increased by \( W_2 = 2hE \) owing to the loss of line-feed signals.

6.4 Overall synchronous character error rate
It is difficult to estimate the effect of incorrect shift signals, as these depend on the nature of the message. If a shift is known to be incorrectly received, it is, of course, possible to 'translate' short passages received in the wrong shift position.
It is evident, however, that the mean character error rate encountered in a synchronous system will exceed the contributions due to causes listed in Sections 6.1, 6.2 and 6.3 if a page printer is used without any special operating techniques designed to reduce the incidence of multiple errors. Thus, the unprotected character error rate will exceed

\[ W + W_1 + W_2 = 4W = 4mE \]

### 6.5 Start/stop systems

In addition to the types of error which can occur in a synchronous system, the start/stop arrangement is subject to errors in the start and stop elements, which can result in yet another type of multiple error.

As the start/stop code involves \( m + 2 \) elements per character, the proportion of characters involving an element error will be \( q = E(m + 2) \), where \( E \) is the element error rate. Now an error in any one of the code elements cannot cause loss of synchronism; consequently, the proportion of character errors in which only code errors occur is \( 2qz(m + 2) \). The proportion of character errors in which start or stop elements are mutilated is therefore \( 2qz(m + 2) \), and, in general, each such character error will result in the loss of a total of \( z \) characters owing to loss of synchronism.

The net proportion of characters printed in error due to errors in the start or stop elements is therefore \( 2qz(m + 2) \). The basic start/stop character error rate is therefore

\[ R = \frac{m}{m + 2} q + \frac{2}{m + 2} qz = E(m + 2z) \]

The analysis of a number of teleprinter records for which \( m = 5 \) indicates that a reasonable value for \( z \) is about 3.5; consequently, the basic character error rate of a start/stop system of this type would be approximately \( R = 12E \), ignoring multiple errors due to loss of line-feed, carriage-return, shift signals etc.

### 6.6 Overall start/stop character error rate

If the basic character error rate of a start/stop system is \( R \), the contributions due to loss of carriage-return and line-feed signals will be \( R_1 = R \) and \( R_2 = 2R \), respectively. The overall start/stop character error rate will therefore normally exceed \( R + R_1 + R_2 = 4R \), unless special operating precautions are taken to reduce the incidence of ‘avoidable’ multiple errors.

For normal start/stop telegraph systems employing five code elements plus start and stop elements, it has been shown that \( R = 12E \). The overall character error rate for such a system will therefore normally exceed \( 48E \).

### 6.7 Experimental measurement of overall start/stop character error rate

Teleprinter records obtained during the fading-carrier error-rate tests carried out with the artificial tropospheric-scatter link were examined in order to determine the overall start/stop character error rate.

The analysis of the records, which involved 1-2 million elements for which the element error rates were better than 1 in 10^3, indicated that the ratio between the overall character error and the element error rate was 38, compared with 48 calculated in Section 6.6.

The 20% discrepancy is thought to be caused by a number of multiple element errors producing single character errors. It is possible that an analysis involving very much better element error rates may reduce the discrepancy, but suitable records were unfortunately not available.

### 7 Conclusions

The results of the error-rate tests are in reasonable agreement with the predictions based on the empirical receiver characteristic for the constant-carrier and the non-diversity tests on receiver B, but the experimental results of the non-diversity and dual-diversity tests on receiver A depart from the predicted curves by about 1.0 and 1.5dB, respectively.

Most of this discrepancy is due partly to the fact that the empirical receiver law is not identical with the actual characteristic of the receiver, and partly to the experimental difficulties associated with the dual-diversity radio tests.

It is clear, however, that the slopes of the error-rate curves for receiver A agree with prediction, and also that the relative positions of the non-diversity and dual-diversity experimental error-rate curves are also in substantial agreement with the predictions from Figs. 3 and 4.

As the tests covered a large range of the parameter \( K \), from 0.6 to 34, it is concluded that the empirical receiver characteristic provides a satisfactory basis for the calculation of telegraph error rates.

The results of the analysis of the relationship between element and character error rates emphasise the desirability of employing special teleprinter operating techniques, i.e. repetition of carriage-return, line-feed and shift signals, when the radio circuit includes a tropospheric-scatter path.

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### 9 References