RECOMMENDATION ITU-R S.1427-1

Methodology and criterion to assess interference from terrestrial wireless access system/radio local area network[*] transmitters to non-geostationary-satellite orbit mobile-satellite service feeder links in the band 5 150-5 250 MHz[**]

(Question ITU-R 248/4)

(2000-2006)

Scope

This Recommendation provides a methodology and criterion that allow assessment of interference from terrestrial WAS/RLAN transmitters into non-GSO MSS feeder links (Earth-to-space) in the band 5 150-5 250 MHz, reflecting also results of WRC-03 as regards this issue.

The ITU Radiocommunication Assembly,

considering

a) that the potential large-scale deployment of wireless access system/radio local area network WAS/RLAN transmitters in the band 5 150-5 250 MHz could cause interference to non-geostationary-satellite orbit mobile-satellite service GSO MSS satellite systems operating their feeder uplinks in this band;

b) that the potential large-scale deployment of WAS/RLAN transmitters in the band 5 150-5 250 MHz could cause significant reduction in MSS satellite transponder capacity;

c) that WAS/RLAN transmitters in the band 5 150-5 250 MHz are operating on a license-exempt or class-licensed basis in many countries;

d) that the non-GSO MSS feeder-link beam coverage is of a regional and/or global nature;

e) that WAS/RLAN interference can only be accounted for in terms of an aggregate and constant increase in the non-GSO MSS feeder-link noise floor and its consequences to reduction in satellite capacity;

f) that *resolves* 3 of Resolution 229 (WRC-03) states that administrations may monitor whether the aggregate pfd levels given in Recommendation ITU-R S.1426 have been, or will be, exceeded in the future, in order to enable a future competent conference to take appropriate action;

g) that a method of assessing the interference from WAS/RLAN emissions to non-GSO MSS satellite feeder-link receivers, as well as, a method of processing the measurements, is required;

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[*] In this Recommendation WAS/RLAN is to mean wireless access system/radio local area network, or any other transportable or fixed devices offering local network connectivity (e.g. high performance RLANs (HIPERLANs), U-NII, wireless local area network (WLAN), or others; see also Recommendations ITU-R F.1244 and ITU-R M.1450).

[**] This Recommendation should be brought to the attention of Radiocommunication Study Groups 8 and 9 for information.

h) that the evolution of WAS/RLANs in the marketplace will occur independently on a national or regional basis;

j) that there is a need to protect the non-GSO MSS feeder links from WAS/RLAN interference,

noting

a) that the 5 150-5 250 MHz band is subject to other sources of interference (including unwanted emissions from transmitters in nearby bands) to non-GSO MSS feeder links, in addition to that from WAS/RLAN transmitters;

b) that the methodologies given in Annexes 1, 2 and 3 are only applicable to non-GSO constellations with a large number of satellites which are sufficiently spaced,

recognizing

a) that the band 5 150-5 250 MHz is allocated worldwide to FSS (Earth-to-space) for use by non-GSO MSS feeder links on a co-primary basis without restriction in time as per No. 5.447A of the Radio Regulations (RR);

b) that the band 5 150-5 250 MHz is also allocated on a worldwide primary basis to the aeronautical radionavigation service (ARNS);

c) that the band 5 150-5 216 MHz is also allocated to feeder links of the radiodetermination-satellite service (space-to-Earth) subject to RR No. 5.446;

d) that the band 5 150-5 216 MHz, under RR No. 5.447B and the provisions of RR No. 9.11A, is also allocated to the fixed-satellite service (FSS) (space-to-Earth) for use by non-GSO MSS feeder links on a worldwide primary basis;

e) that the band 5 150-5 250 MHz has been allocated to the mobile service in accordance with RR No. 5.446A, RR No. 5.446B, and Resolution 229 (WRC-03);

f) that the band 5 150-5 250 MHz is allocated via RR No. 5.447 to the mobile service in a number of countries subject to coordination under RR No. 9.21;

g) that Resolution 229 (WRC-03) limits the WAS/RLAN transmission to indoor transmissions,

recommends

1 that the assessment of interference from WAS/RLAN emissions to non-GSO MSS satellite feeder-link receivers, operating in the band 5 150-5 250 MHz, should be based on the increase ($\Delta T_{satellite}$) in satellite noise temperature ($T_{satellite}$);

2 that in order to ensure the adequate protection for the non-GSO MSS feeder links in the band 5 150-5 250 MHz the aggregate $\Delta T_{satellite}/T_{satellite}$ from WAS/RLAN emissions should be no more than 3%;

3 that if the measurement of interference from WAS/RLAN emissions to a non-GSO MSS satellite feeder-link receiver is made, the methodology described in either Annex 2 or 3 to this Recommendation could be used for that purpose by the interfered-with non-GSO feeder-link system. Background information regarding such methodologies can be found in Annex 1;

4 that the following Notes are considered as part of the Recommendation.

NOTE 1 – The impact of the aggregate long-term interference due to WAS/RLANs into non-GSO MSS feeder links, in terms of the reduction in non-GSO MSS satellite capacity, should also be considered in conjunction with the methodology proposed in the above *recommends*. This is to ensure that the interference power captured by the non-GSO MSS satellites should account for a reduction in available satellite capacity less than or equal to 1%. This value may require further study.

NOTE 2 – By the term “aggregate” it is meant that the interference to the satellite receiving beam is to be calculated from all of the WAS/RLAN devices within the field of view of the non-GSO satellite feeder-link receiving beam.

NOTE 3 – Annexes 2 and 3 to this Recommendation describe two alternative implementations of a measurement payload on board a satellite to determine the aggregate noise and interference that would be received at an operational satellite of the same type as the rest of the satellites in the constellation. Furthermore, the Annexes also describe the respective methods to process, on the ground, the measurements made at the satellite.

NOTE 4 – The methodologies described in Annexes 2 and 3 may be used to measure the aggregate interference into the space station receiver of the feeder link of any non-GSO MSS satellite system. To provide explicit results, the technical parameters of the LEO-D constellation as described in Recommendation ITU-R M.1184 are used. Further study may be required to determine what portion of that aggregate interference comes from WAS/RLAN transmitters. That study can best be carried out when the results of the measurements obtained using one of the methodologies described in Annexes 2 and 3 are available.

Annex 1

The measurement of the aggregate noise and interference into the space-station receiver of the 5 GHz Earth-to-space feeder link of a LEO-D MSS satellite system

1 Introduction

This Annex describes how the aggregate interference into the receiving antenna of the space-station receiver of a 5 GHz Earth-to-space feeder link of a non-GSO MSS satellite system is measured. Given that the overall objective of Annex 2 or 3 is to be able to estimate the magnitude of the aggregate RLAN interference with high accuracy, this Annex describes in general terms how the measurement of the total power received at the satellite antenna may be made with an r.m.s. error of about 0.03% of the thermal and background noise in the uplink.

2 The Dicke radiometer receiver

The Dicke radiometer receiver has been used for decades by the radio astronomy community and others to measure very low levels of Gaussian noise in an environment of much higher levels of Gaussian noise in the receiver itself. The application considered here is almost identical, in that the aggregate interference signal from a very large number of transmitting RLAN devices would have Gaussian stochastic characteristics, independent of the detailed characteristics of an individual transmission. Similarly, the stochastic characteristics of the background receiver noise would be Gaussian in Earth exploration-satellite (passive) applications, space research (passive) applications, radio astronomy applications, and the interference measurement of WAS/RLAN interference application described in this Recommendation.

A block diagram of a generic Dicke radiometer is shown in Fig. 1. In general, the Dicke radiometer is built around the "receiver system" block, which is the actual 5 GHz MSS feeder-link receiver before the addition of Dicke radiometer blocks. The additional blocks are added to enable the receiver to:

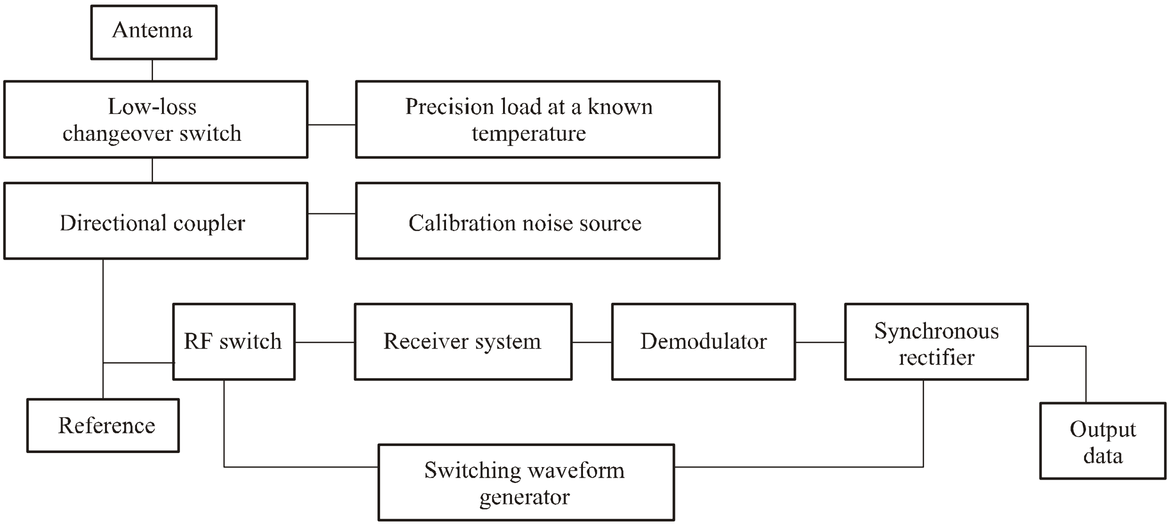
– integrate the detected envelope of the wideband Gaussian signal in the RF and IF stages of the satellite receiver itself for a measurement time τ;

– calibrate its measurements so that gain variations of the receiver over time do not affect the accuracy of the measurement, and so that the estimates of the noise level being measured do not include the receiver internal noise.

To do these tasks two reference noise sources are used, and compared with the incoming Gaussian signal to be measured. One of these reference signals is comparable with the noise in the receiver; the other is comparable with the external signal being measured.

FIGURE 1

A generic Dicke radiometer



3 Performance of the Dicke radiometer

A Dicke radiometer is designed to switch rapidly between the antenna and a reference load or noise source, at a rate faster than the most rapid gain variations. Typically, gain fluctuations have a spectrum extending out to at least 5 Hz, so the RF switch should switch between the antenna and reference at a rate of at least 30 Hz or so. The gain variations then only act upon the difference between the inputs. Ideally, therefore, the reference temperature should be as close to the antenna temperature as possible. An antenna looking at the ground will always have an antenna temperature of at least 150 K or so (if the antenna beam is not filled by the ground – if it is something like 250 K is more likely). A matched load or noise source would therefore be a practical reference. Indeed, a PIN diode attenuator could be driven to match the inputs to the receiver so that the receiver is always balanced.

A calibration noise source adds a known amount of noise to the receiver, increasing the input by a known amount. Switching to a matched load is a useful adjunct to the calibration process, so that the basic noise level can be calibrated. However, when the matched load is connected, the antenna is not, so the baseline noise level will change.

The Dicke radiometer output is an unbiased measurement of the power level of the signal received by the 5 GHz satellite antenna over the bandwidth B of the receiver. The r.m.s. error of that measurement is:

$$\Delta T_{error} = T_{sys}/(B\tau)^{0.5} \tag{1}$$

where:

ΔT_{error}: r.m.s. error in the measurement of the noise temperature of the random signal at the antenna output

T_{sys}: noise temperature of the total noise in the receiver, the sum of the satellite receiver noise temperature and the noise temperature of the received signal, as described in Recommendation ITU-R RS.515

B: bandwidth (Hz) of the receiver

τ: integration time of the receiver (s).

If the noise level being measured is 3% of the total noise in the receiver, and the r.m.s. error in the measurement of that quantity is required to be in the order of 1% of the measurement, the quantity $(B\tau)^{-0.5}$ must be in the order of 3×10^{-4}.

4 Radiometers appropriate for use in the LEO-D system

The design of the radiometers used in the LEO-D system can be simplified if the measurement can use as reference-channel measurement of the noise in nearby reference-band spectrum immediately below 5 150 MHz, and use of those measurements in estimating the interference above 5 150 MHz. Application of this possibility allows a simplification of the in-orbit radiometer required to accurately measure the aggregate interference into the satellite receiver in the 5 150-5 250 MHz band, compared to the general-purpose Dicke radiometer in Fig. 1. Further, this modification in the measurements made by the radiometer modifies what on-ground data-processing of in-orbit measurements are necessary to make those aggregate-interference measurements.

This simplification of the radiometer used in the LEO-D satellite is based on the following five observations:

- Recommendation ITU-R S.1427 does not place a limit on the aggregate interference I from WAS/RLAN devices as such. Rather, it rather limits the ratio of that interference to the baseline noise level N, or the ratio I/N, equivalent to the ratio $\Delta T/T$ at the satellite receiver, which should not exceed 3%.
- In the LEO-D system that operates from 5 091 MHz to 5 250 MHz there are eight RF channels, each 16.5 MHz wide. Channels 1 and 2 operate completely below 5 150 MHz, the lowest frequency at which WAS/RLAN devices operate. Channel 3 operates at the 5 150 MHz boundary, and Channels 4 to 8 inclusive operate above 5 150 MHz in an environment in which there may be WAS/RLAN interference.
- The background noise N does not change appreciably over the frequency range from 5 091 MHz to 5 250 MHz, although there may be a slight variation.
- All of the slowly time-varying variations in N are common between the background noise N in the lower two RF channels and the upper five channels. The reasons for this time-variation of N may not be known, but the variations are embedded in variations in the noise in the lower two RF channels.
- There may be more rapid variations in the gains of satellite components at rates up to about 10 Hz, which must be taken into account in making observations that would lead to estimates of the interference I.

In determining how to effectively use the reference signals in Channels 1 and 2 to estimate the *I*/*N* ratio in Channels 4, 5, 6, 7, and 8, it is observed that the "calibration" of the radiometer could be done through making measurements in Channels 1 and 2. An additional advantage of this approach is that all of the time variations in the background noise levels in different 16.5 MHz wide channels due to the varying location of the satellite, and time that the measurements are taken, are embedded in the simultaneous measurements of the noise level in Channels 1 and 2, subject to the minor variations in the background noise level over the frequency band 5 091 MHz to 5 250 MHz.

The two radiometers described in Annexes 2 and 3 respectively take into consideration the above mentioned observations. In both of those radiometers the "calibration" signals can be the noise levels in Channels 1 and 2, because the variations in the noise levels in Channels 4 to 8 inclusive is fully embedded in the noise levels in Channels 1 and 2. Because of this, the 550 K calibration noise source and the 16.5 K precision load of Fig. 1 are redundant, and so can be and are deleted from the block diagrams of both of the two satellite radiometers described in Annexes 2 and 3.

Annex 2

A radiometer with an in-line switch to measure aggregate noise and interference into the space-station receiver of the 5 GHz Earth-to-space feeder link of a LEO-D MSS satellite system

1 Introduction

In this Annex one of two implementations of a radiometer to be used in the LEO-D space station to measure aggregate noise and interference in its Channels 4 to 8 inclusive is described. Further, the on-ground processing of those measurements to estimate the *I*/*N* ratio due to RLAN interference is described.

2 The spaceborne radiometer with an in-line switch

The radiometer described here uses measurements of thermal noise in Channels 1 and 2, rather than measurements of the two internal calibration noise sources that are used in the generic Dicke radiometer shown in Fig. 1. This is possible because Channels 1 and 2 of the LEO-D L network operate below 5 150 MHz and so do not suffer interference from RLAN transmissions in the 5 150-5 250 MHz band.

This radiometer is different from that shown in Fig. 1 in that it:

- does not have the calibration noise source, the precision load, nor the directional coupler or low-loss changeover switch shown in Fig. 1;
- includes a demodulator and a synchronous detector in each of the eight 16.5 MHz wide channels at 5 GHz. The output of the eight synchronous detectors is converted to a digital representation of the synchronous-detector outputs, to be transmitted to an earth station every ξ milliseconds. The nominal value of ξ is 25 ms, but this might be shortened to reduce the effect of random variations in the measured results due to conversion of the analogue measurements in the satellite to a digital format before transmission to the ground.

A diagram of this radiometer is shown in Fig. 2. In addition to the 5 GHz receiver of the operational LEO-D network, the 5 GHz satellite payload includes:

– An in-line high-speed repetitive switch, switching between the satellite antenna and a reference noise source every ξ ms.

– A stable 200 K reference noise source.

– A demodulator and synchronous rectifier on each of the eight 16.5 MHz wide channels of one polarization of the LEO-D system.

– An *A*/*D* converter of the output of each of the eight outputs of the synchronous detectors to a η-bit digital representation of each measurement. The nominal value of η is 12, but this may be varied during the detailed design of the radiometer.

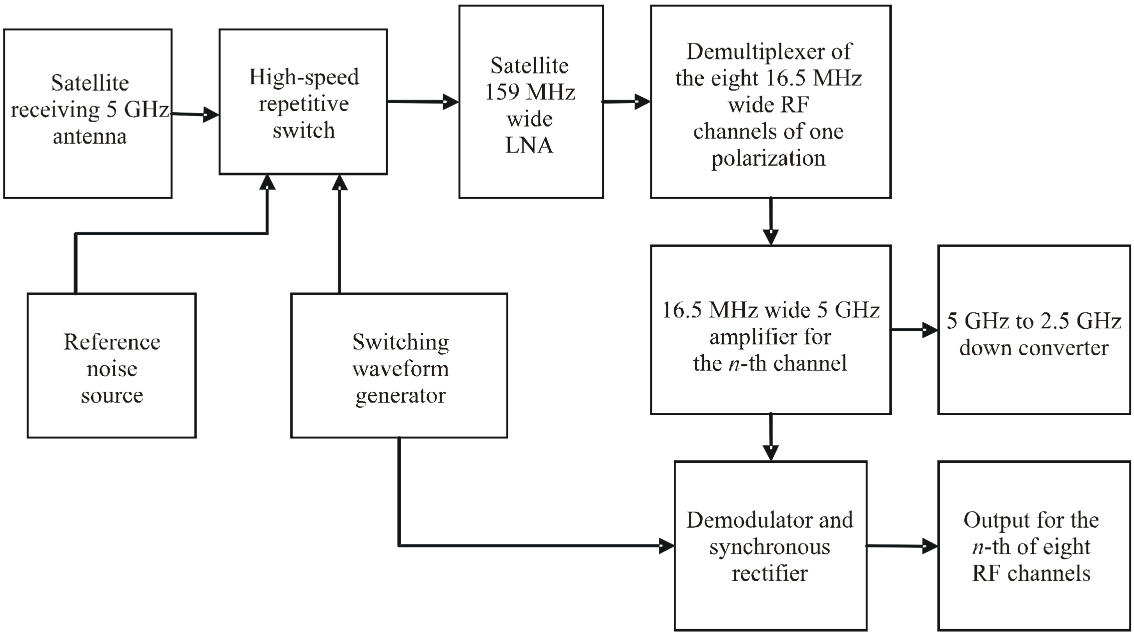
– A switching waveform generator to control the timing of the synchronous detectors and the repetitive switch.

– The means to transmit the eight digital signals to the ground through either the 2.5 GHz or the 7 GHz space-to-Earth links of the LEO-D satellite network.

The radiometer simultaneously measures the eight rectifier outputs $\{S_1, S_2, ... S_7, S_8\}$ in a ξ millisecond interval, during which the in-line switch connects the 5 GHz satellite receiver to either its RHCP receiving antenna or its LHCP receiving antenna. In the next ξ ms the radiometer simultaneously measures the eight rectifier outputs $\{R_1, R_2, ... R_7, R_8\}$ while the in-line switch connects the 5 GHz satellite receiver to the reference noise source. The 16 measurement results are converted to digital format and transmitted to the ground for further processing. This process is repeated every 2ξ ms. The timing and action of each of the radiometer components is under the control of the switching control generator.

FIGURE 2

Radiometer with a repetitively switched reference noise source



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3 On-ground processing of the output of the radiometer with an in-line switch

The on-ground real-time calculations to convert the measurement sets $\{S_1, S_2, ...S_7, S_8\}$ and $\{R_1, R_2, ...R_7, R_8\}$ that are transmitted from the satellite every ξ ms to interference-to-thermal noise ratios I/N of Channels 4, 5, 6, 7, and 8 are described here. Note that the terms $\{\mathrm{S}i\}$, $\{\mathrm{R}i\}$, and $\{(I/N)i\}$ are power levels and ratios; dB measures are not included in the following equations. The 16 values $\{\mathrm{S}i\}$ and $\{\mathrm{R}i\}$, and the five results $\{(I/N)i\}$ that are generated every 2ξ ms can also be stored for further data processing. This processing is likely to include averaging in a digital filter of the $\{\mathrm{S}i\}$ and $\{\mathrm{R}i\}$ results for an extended period of a minute or more, limited only by the change in the actual observed interference as the satellite service area changes. This averaging would reduce the random errors in the $\{\mathrm{S}i\}$ and $\{\mathrm{R}i\}$ results, including quantization noise generated by the A/D converter in the satellite by the square root of the number of 2ξ intervals that the averaging takes place.

The first step in this on-ground computation is to determine the "normalized" signal samples $\{\mathrm{S}i\}$ by dividing the signals by the corresponding reference signal of the set $\{\mathrm{R}i\}$ to produce the set $\{\mathrm{X}i\}$, where

$$\mathrm{X}i = \mathrm{S}i / \mathrm{R}i \qquad (2)$$

The processing of the radiometer measurements includes dividing the magnitude of the received signal by the reference signal, rather than subtracting the magnitude of the reference signal from the magnitude of the received signal. However, the gain variations in the satellite receiver, and the differences in gain between one channel and another have been removed in equation (2). The radiometer produces unbiased estimates of the correct values of $\{\mathrm{S}i\}$ and $\{\mathrm{R}i\}$ The random component or the variance of Xi is equal to the sum of the variance of Si and that of Ri, because as before the random components of the two are statistically independent.

The next data-processing task is to estimate the thermal noise, or more accurately the "normalized" thermal noise, in each of the eight channels. It is assumed that $X1$ and $X2$ are normalized estimates of thermal noise only, but it must also be assumed that there may be a frequency-dependence in the thermal noise levels in the different channels. That variation is expected to be small, and so can be modelled as a linear variation with carrier frequency as the varying parameter. In that case define the varying thermal noise component Δ as:

$$\Delta = X_2 - X_1 \qquad (3)$$

This real-time noise frequency-dependent rate of change of the thermal noise in different channels can be used to estimate the normalized thermal noise components of $\{X4, X5, X6, X7, X8\}$ as:

$$\mathrm{N}i = X_1 + (i - 1)\,\Delta \qquad (4)$$

Equation (4) assumes that the rate of change Δ in the thermal noise component is the same for all adjacent channels for Channels 4 through 8. Once the noise Ni in Channels 4 to 8 are estimated, the interference Ii in the i-th channel can be estimated to be:

$$\mathrm{I}i = Xi - \mathrm{N}i, \qquad \text{for } i = 4, 5, 6, 7, \text{ or } 8 \qquad (5)$$

The "normalized" tag on the estimates $\{\mathrm{X}i\}$ and $\{\mathrm{N}i\}$ can be removed in estimating the interference-to-noise ratios $\{(I/N)i;\ i = 4, 5, 6, 7, \text{and } 8\}$because the same normalization is present in both $\{\mathrm{X}i\}$ and $\{\mathrm{N}i\}$. With this clarification:

$$(I/N)\mathrm{i} = \mathrm{I}i \;/\; \mathrm{N}i, \qquad \text{for i} = 4, 5, 6, 7, \text{ or } 8 \qquad (6)$$

Note again that the terms $\{(I/N)i;\ i = 4, 5, 6, 7, \text{and } 8\}$ are power ratios, not in dBs.

These five equations can be combined into a single equation that expresses the interference-to-noise ration $(I/N)i$ in terms of the terms $\{Si\}$ and $\{Ri\}$ through the equation:

$$(I/N)i = \{(Si/Ri)/\{(i-1)S_2 / R_2 - (i-2)S_1/R_1\}\} -1$$
$$= \{Xi / \{(i-1)X_2 - (i-2)\, X_1\}\} -1 \qquad (7)$$

It is these six equations that are solved on the ground every 2ξ ms to estimate the aggregate interference levels in Channels 4 to 8 of the LEO-D 5 GHz satellite receiver.

4 Error in the {S*i*} and {R*i*} measurements

The radiometer makes unbiased estimates of the power levels {Si} and {Ri} of the Gaussian noise at the eight receiver outputs. These power levels are proportional to, and can be expressed in terms of, their respective noise temperatures Tx. As indicated in equation (1), the r.m.s. error ΔT_{error} in these measurements of Tx, due to finite integration time of the random output of the radiometer is:

$$\Delta T_{error} = \text{Tx} / (B\ \xi)^{0.5} \qquad (8)$$

As well, the unbiased estimate of Tx suffers a multiplicative error due to its quantization in an *A*/*D* converter to a digital format that can be transmitted to the ground for further processing. If the *A*/*D* converter expresses the analogue quantity Tx by a binary number with η digits, the r.m.s. error in the digital representation of the quantity Tx is:

$$\text{Tx} / 2^{(\eta - 0.5)} \qquad (9)$$

where the expected value of Tx is half of the maximum input value to the *A*/*D* converter, and the r.m.s. error of the quantization is 0.707 of the smallest quantization level of the *A*/*D* converter.

In estimating the r.m.s. error in the results $\{(I/N)i,\ i = 4, 5, 6, 7, 8\}$ as expressed in equation (7), there are places where two random quantities are added together, there are places where two random quantities are multiplied together, and there are places where one random quantity is divided by another. If the two terms are statistically independent, and if the variances of the random component of the terms are small with respect to its expected value, the variance of the result is approximately equal to the sum of the variances of the two input quantities. The variance of the term $A*X$, where A is a constant and X is a random variable, is A^2 times the variance of X.

The expressions for the terms $\{(I/N)i,\ i = 4, 5, 6, 7, 8\}$ would be very complex if the parameter values ξ and η remained as parametric variables in the analysis. To avoid that complexity the default values of 25 ms for ξ and 12 for η is used in the following analysis of r.m.s. errors in the terms $\{(I/N)i,\ i = 4, 5, 6, 7, 8\}$. Further, it is assumed here *only for this estimation of r.m.s. errors* that the background Gaussian noise from a warm Earth is about 200 K, the same temperature as the reference noise source, so the noise temperature at the satellite receiver input is about 550 K both when the antenna is connected to the receiver and when the reference noise source is so-connected.

On that basis, the r.m.s. error of either the terms $\{Si\}$or $\{Ri\}$, according to equation (8), is the expected value of the term, divided by $(B\ \xi)^{0.5}$, or $(16.5 \times 10^6 \times 25 \times 10^{-3})^{0.5}$, or 642. The quantization r.m.s. error of either the terms $\{Si\}$or $\{Ri\}$, according to equation (8), is the expected value of the term, divided by $2^{(12-0.5)}$ or 2 896. The r.m.s. error is the root of the sum of the squares of these two terms, the expected values times 0.00159. Since the expected values of the terms $\{Si\}$and $\{Ri\}$ are about 550 K, the r.m.s. error in these terms when a 25 ms integration time and a 12-bit *A*/*D* converter is used is 0.87 K, 5.8% of the 15 K 3% of the thermal noise at the receiver input.

These r.m.s. errors are increased by carrying out the computations specified by equation (7). The r.m.s. error in {X*i*}is 2 ^{½} of the errors in {S*i*}or {R*i*}, or their expected value times 0.00226. The r.m.s. errors in {(*I*/*N*)*i*, *i* = 4, 5, 6, 7, 8} depend on the value of "*i*", as indicated in equation (7). Those r.m.s. error values, as fractions of the expected values of the terms {(*I*/*N*)*i*}, can be determined based on the relationship:

$$\begin{aligned} \text{Var}\ \{(I/N)i\} &= \text{Var}\ (Xi) + (i\text{-}1)^2 * \text{Var}\ (X_2) + (i-2)^2 * \text{Var}\ (X_1) \\ &= \text{Var}\ (Xi) * \{1 + (i\text{-}1)^2 + (i-2)^2\} \qquad (10) \end{aligned}$$

because the variances of all {*Xi*, *i* = 1 to 8} are equal to $(0.00226)^2$ times their expected values, where Var (*Z*) is "the variance of" a random quantity *Z*. The variances and r.m.s. errors of {(*I*/*N*)*i*} based on (10) are indicated in Table 1.

TABLE 1

r.m.s. values of estimates of *I*/*N* values in Channels 4 to 8

Channel	**Weighting**	**Variance of (*I*/*N*)*i***	**r.m.s. error of (*I*/*N*)*i***	**Percentage r.m.s. error of (*I*/*N*)*i* (%)**
4	14	0.0000715	0.008456	0.8456
5	26	0.000133	0.011524	1.1523
6	42	0.000215	0.014646	1.46647
7	62	0.000317	0.017795	1.7795
8	86	0.000439	0.020958	2.0958

These r.m.s. errors in {(*I*/*N*)*i*, *i* = 4,...8}are significant portions of the 3% maximum percentage interference specified by the Recommendation. However, it is noted that the estimates determined through application of equations (1) to (6) above provide unbiased estimates of the actual {(*I*/*N*)*i*, I = 4,...8}. The r.m.s. errors in Table 1 are a result of integration of the signals for only 50 ms, double the integration time used in the evaluation of equation (8). Further integration on the ground of either the (*I*/*N*)i estimates after application of equations (2) to (7) or of the observations {S*i*}and {R*i*}will reduce the r.m.s. errors indicated in Table 1 by the square root of the number of the samples that go into the averaging. For example, if the initial estimate sequences are averaged for 10 s, producing an average of 200 samples, the r.m.s. errors in Table 1 would be reduced by a factor of 14. The result of this on-ground averaging is indicated in Table 2

TABLE 2

The effect of averaging initial estimates of (*I*/*N*)*i* for 10 s

Channel	**Percentage r.m.s. error in (*I*/*N*)*i* before on-ground averaging (%)**	**Percentage r.m.s. error in (*I*/*N*)*i* after on-ground averaging (%)**
4	0.8456	0.060
5	1.1523	0.082
6	1.46647	0.1047
7	1.7795	0.1271
8	2.0958	0.1497

The further averaging on the ground for 10 s the initial $(I/N)i$ estimates that are based on 50 ms of averaging in the satellite reduces the r.m.s. errors in the estimates in all channels to levels that are considerably smaller than the 3% value of aggregate $\Delta T_{satellite}/T_{satellite}$ that is specified in *recommends* 2 of this Recommendation. There is a limit in the amount of on-ground averaging that can be done, however, because the satellite is moving appreciably during the 10 s interval over which the averaging is done in the above example. In a 10 s interval the satellite, at a 1 414 km circular altitude and a period of about 114 min will travel approximately 72 km. Taking into account the total amount of WAS/RLAN interference visible from the satellite, the interference environment will not change appreciably as the satellite travels this 72 km distance, but significantly larger on-ground integration times should be used with caution.

Annex 3

A radiometer with an in-line directional coupler to measure aggregate noise and interference into space-station receiver of the 5 GHz Earth-to-space feeder link of a the LEO-D MSS satellite system

1 Introduction

In this Annex the second of two implementations of a radiometer to be used in the LEO-D space station to measure aggregate noise and interference in its Channels 4 to 8 inclusive is described. Further, the on-ground processing of those measurements to estimate the I/N ratio due to RLAN interference is described.

2 The spaceborne radiometer

The radiometer considered here is similar to that described in Annex 2 above, except that it does not have an in-line switch, so does not have the single-point failure point of the 5 GHz satellite FSS feeder-link payload. Instead, the reference noise signal is fed into the 5 GHz receiver chain of LEO-D through a passive directional coupler. This increases the reliability of the FSS feeder-link payload.

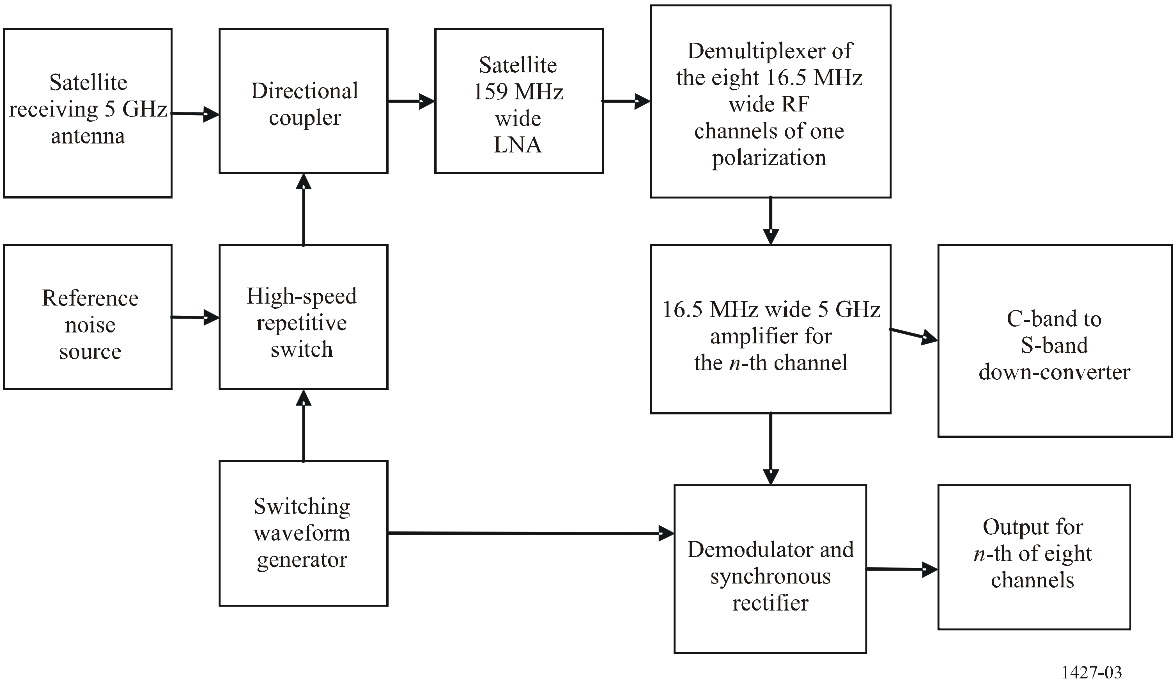
This radiometer is shown in Fig. 3. The only additions to the FSS feeder-link 5 GHz receiver of the LEO-D network in this case are:

- a directional coupler immediately after the satellite 5 GHz antenna and before the 5 GHz receiver of one or the other of the two circularly polarized signals;
- a calibrating 200 K noise source, switched every 2ξ ms for a ξ ms duration into the 159 MHz wide 5 GHz receiver through the directional coupler. The signal from the noise source has an effective 200 K noise temperature after passing through the directional coupler into the 5 GHz receiver;
- a demodulator and synchronous rectifier of each of the eight frequency-multiplexed 16.5 MHz wide channels in the 159 MHz wide receiver. Each of the eight demodulated, rectified, and integrated signals is sampled every ξ ms;
- the switching waveform generator to control both the 5 GHz RF switch and the eight demodulator/integrators.

In summary, the magnitude of sixteen signals, each 16.5 MHz wide, is measured each 2ξ ms and transported to an earth station through either of the 7 GHz or the 2.5 GHz existing space-to-Earth links of the LEO-D satellite network.

FIGURE 3

Radiometer with a coupled calibrating noise source



The radiometer considered here is similar to that considered in Annex 2 in that the switching waveform generator, the eight demodulator/rectifier/integrators, and the path to transport the sixteen digital measurements to the ground every 2ξ ms is the same in both receivers. The difference between the two radiometers is the method by which the reference noise source is introduced: in this case it is through an in-line directional coupler, whereas in the radiometer described in Annex 2 it is introduced through an in-line switch that switches between the input signal and the reference source every ξ ms.

The radiometer simultaneously measures the eight rectifier outputs $\{S_1, S_2, ..., S_7, S_8\}$ in a ξ ms interval, during which the reference noise source is not introduced through the switch and the directional coupler. In the next ξ ms the output of the reference noise source is added to the 5 GHz receiver input through the closed switch and the in-link directional coupler. In this interval radiometer measures the eight rectifier outputs $\{Y_1, Y_2, ..., Y_7, Y_8\}$. The 16 measurement results are converted to digital format and transmitted to the ground for further processing. This process is repeated every 2ξ ms. The timing and action of each of the radiometer components is under the control of the switching control generator.

3 Processing of the output of the radiometer with an in-line directional coupler

With this radiometer the set of eight simultaneous measurements $\{S_1, S_2, ...S_7, S_8\}$ are made for the same ξ ms that the same measurements are made in the radiometer with an in-line switch (see Annex 2). In the next ξ ms the switch is closed and the calibrating noise is added to the uplink thermal noise and the RLAN interference. In this second interval the set of eight simultaneous measurements $\{Y_1, Y_2, ..., Y_7, Y_8\}$ are made. Every 50 ms these sixteen measurements are converted to digital format and transported to the ground, as was the $\{S_1, S_2, ...S_7, S_8\}$ and $\{R_1, R_2, ...R_7, R_8\}$measurements as described in Annex 2. However, the sixteen numbers $\{S_1, S_2, ...S_7, S_8\}$ and $\{Y_1, Y_2, ..., Y_7, Y_8\}$ are processed differently.

Again, the measurement time for the set of sixteen measurements is kept small enough, at about 2ξ ms, that the amplifier gains in the satellite, do not vary appreciably. The first step in the **on-ground data-processing** is to determine the magnitude of the calibration signals in each of the eight channels, with the simple calculation:

$$C_i = Y_i - S_i, \qquad \text{for } i = 4, 5, 6, 7, \text{ or } 8 \tag{11}$$

These $\{C_i\}$ are the levels of the calibrating signal at the location where the measurements are taken. We can determine the level of the calibration signal C_0 at the point where it is inserted at the directional coupler (see Fig. 3), from previous measurements before the satellite is launched, so can determine the gains G_i in each of the eight channels during the 2ξ ms period. Those gains are:

$$G_i = C_i / C_0, \qquad \text{for } i = 4, 5, 6, 7, \text{ or } 8 \tag{12}$$

The values of the thermal noise for Channels 1 and 2, or thermal noise plus interference in Channels 4, 5, 6, 7, and 8 can then be referred back to the output of the satellite 5 GHz antenna with the simple calculations:

$$Q_i = S_i \;/\; G_i, \qquad \text{for } i = 1, 2, 4, 5, 6, 7, \text{ and } 8 \tag{13}$$

As in the calculations for the radiometer that is described in Annex 2, the thermal noise levels $\{M_i\}$ alone in Channels 1 and 2 is specified by Q1 and Q2 of equation (13). Again it is assumed that the noise levels alone in Channels 4 to 8 are:

$$M_i = Q_1 + (i - 1) * \Delta \tag{14}$$

where in this case:

$$\Delta = Q_2 - Q_1 \tag{15}$$

The aggregate interference I_i into Channels 4 to 8 can now be determined by the simple calculations:

$$I_i = Q_i - M_i, \qquad \text{for } i = 4, 5, 6, 7, \text{ and } 8 \tag{16}$$

These values are the interference levels referred to in *resolves* 3 of Resolution 229 (WRC-03). The interference to noise ratios referred to in Recommendation ITU-R S.1427 can be determined easily from the calculations:

$$(I/N)_i = I_i \;/\; M_i, \qquad \text{for } i = 4, 5, 6, 7, \text{ and } 8 \tag{17}$$

The $\{(I/N)_i, i = 4, 5, 6, 7, 8\}$ can be expressed in terms of the measurements $\{S_i\}$ and $\{Y_i\}$ by the equation:

$$(I/N)_i = \{(S_i/C_i)/\{(i - 1)(S_2 / C_2) - (i - 2)(S_1/C_1)\}\} - 1 \tag{18}$$

where the terms$\{C_i\}$are specified by equation (11) in terms of the measured values $\{S_i\}$ and $\{Y_i\}$. It is noted that the term C_0 of Equation (12) does not appear in the overall Equation (18) or in equation (11), indicating that the estimates of $\{(I/N)_i, i = 4, 5, 6, 7, 8\}$ are independent of the value of C_0.

Again, these simple calculations in equations (11) to (18) inclusive could be done in real time on the ground with a fast computer at the location where the 2.5 GHz or 7 GHz downlink signal is received. Alternatively, the measurements could be stored for subsequent averaging and possibly further processing. The advantage of stored measurements is that comparative calculations could be done subsequently on repeated observations.

The ξ ms observation intervals are too short to acquire enough $(B\tau)^{0.5}$ processing gain to make accurate estimates of the interference-to-noise ratios specified by equation (17) or by equation (18). However, the values obtained by the above algorithm are unbiased estimates of the required values, so further averaging on the ground can be done to achieve a large enough $(B\tau)^{0.5}$, and so provide estimates with a small enough random component. Again, the only limit to this integration is that the parameters being measured will change as the satellite moves in its trajectory and so both the noise coming from the ground and the RLAN aggregate interference will change.

4 Error in the {S*i*} and {Y*i*} measurements

Determination of the r.m.s. error in the estimates follows a process very similar to that described in § 4 of Annex 2. Because of that, background details that are common to both analyses are not repeated here. It is noted that:

- the measurement approach provides unbiased estimates of $\{\mathrm{S}i\}$, $\{\mathrm{Y}i\}$, and $\{(I/N)i\}$, so averaging reduces any random or systematic errors in $\{(I/N)i\}$;
- the noise temperatures of $\{\mathrm{S}i\}$are about 550 K, but when the reference noise source is added at the receiver input the noise temperatures of $\{\mathrm{Y}i\}$ are about 750 K. This fact is taken into account in the determining the estimates of $\{(I/N)i\}$through equation (11), but has to be taken into account here in the determination of the r.m.s. errors in $\{(I/N)i\}$.

As in § 4 of Annex 2, the determination of the r.m.s. error in the terms $\{(I/N)i\}$is done for the case where the integration time ξ in the satellite is 25 ms, and the number of bits η in the output of the *A*/*D* converter is 12. The r.m.s. errors due to rectification and integration of the random variables $\{\mathrm{S}i\}$ and $\{\mathrm{Y}i\}$ are given by equation (8) above, and the r.m.s. errors due to quantization are specified by equation (9).

As in the derivation of the r.m.s. error of the terms $\{\mathrm{S}i\}$or $\{\mathrm{R}i\}$ in Annex 2, the r.m.s. errors of $\{\mathrm{S}i\}$ and $\{\mathrm{Y}i\}$ here are specified by equations (8) and (9). The r.m.s. errors due to rectification and integration are the expected value of the terms, divided by $(\mathrm{B}\ \xi)^{0.5}$, or $(16.5 \times 10^6 \times 25 \times 10^{-3})^{0.5}$, or 642. The quantization r.m.s. error of either the terms $\{\mathrm{S}i\}$ or $\{\mathrm{Y}i\}$ is the expected value of the term, divided by $2^{(12-0.5)}$ or 2 896. The r.m.s. error in either $\{\mathrm{S}i\}$ or $\{\mathrm{Y}i\}$ is the root of the sum of the squares of these two terms, the expected values times 0.00159. The expected values of the terms $\{\mathrm{S}i\}$ are about 550 K, so the r.m.s. error in these terms when a 25 ms integration time and a 12-bit *A*/*D* converter is used is 0.87K. The expected values of the terms $\{\mathrm{Y}i\}$ are about 750 K, so the r.m.s. error in these terms is 1.19K.

The r.m.s. errors of the terms {Ci} are the root of the sum of the squares of the r.m.s. errors of the appropriate Si and Yi, as specified by equation (11). These r.m.s. errors of the terms $\{\mathrm{C}i\}$ after integration and quantization in the satellite are 1.474 K or 0.00737 of their expected value of about 200 K. The r.m.s. errors of the terms $\{\mathrm{S}i/\mathrm{C}i\}$ or $\{1/\{(\mathrm{Y}i/\mathrm{S}i)\text{-}1\}\}^{-1}$ of equation (18) are the same 0.00737 of their expected values.

The r.m.s. errors in $\{(I/N)i,\ i = 4, 5, 6, 7, 8\}$ depend on the value of "i", as indicated in equation (18). Those r.m.s. error values, as fractions of the expected values of the terms $\{(I/N)i\}$, can be determined based on the relationship:

$$\begin{aligned}\mathrm{Var}\ \{(I/N)i\} &= \mathrm{Var}\ (\mathrm{Z}i) + (i-1)^2 * \mathrm{Var}\ (\mathrm{Z}_2) + (i-2)^2 * \mathrm{Var}\ (\mathrm{Z}_1)\\ &= \mathrm{Var}\ (\mathrm{Z}i) * \{1 + (i-1)^2 + (i-2)^2\} \qquad (19)\end{aligned}$$

where Z*i* is defined to be identical to (S*i*/C*i*) of equation (18). (The terms Z_1 and Z_2 are Zi with *i* equal to 1 and 2 respectively.) Note that equation (19) has the same form as (10), although the 0.00737 r.m.s. errors in the terms {Z*i*} in equation (19) are somewhat larger than the 0.00226 r.m.s. errors in the terms {X*i*} of equation (10). This increase is because the noise from the reference noise source is added in the design of this radiometer rather than replacing the noise from the input antenna in the radiometer described in Annex 2, and the ensuing calculations necessary for this implementation of the radiometer.

As discussed in Annex 2, the variance of (*I*/*N*)*i* is a function of the channel number *i*, a result of estimating N*i* by equations (14) and (15).

TABLE 3

r.m.s. values of estimates of *I*/*N* values in Channels 4 to 8

Channel	**Weighting**	**Variance of (*I*/*N*)*i***	**r.m.s. error of (*I*/*N*)*i***	**Percentage r.m.s. error of (*I*/*N*)*i* (%)**
4	14	0.00076	0.02758	2.75
5	26	0.00141	0.03758	3.75
6	42	0.00228	0.04776	4.78
7	62	0.00337	0.05803	5.80
8	86	0.00467	0.06835	6.83

These r.m.s. errors in the estimates of {(*I*/*N*)*i*, *i* = 4, ..8} using the radiometer described in this Annex are of the same order as the 3% limit in *I*/*N*, so further averaging on the ground is necessary. As discussed in § 4 of Annex 2, averaging of the results on the ground reduces the r.m.s. error of the results by the square root of the number of samples averaged. If the initial estimate sequences are averaged for 10 s as discussed in Annex 2, producing an average of 200 samples, the r.m.s. errors in Table 3 would be reduced by a factor of 14. The result of this on-ground averaging is indicated in Table 4. Averaging for 30 s, using 600 samples to reduce the r.m.s. error by a factor of 25 is also shown in Table 4.

TABLE 4

The effect of averaging initial estimates of (*I*/*N*)*i* for 10 s and for 30 s

Channel	**Percentage r.m.s. error In (*I*/*N*)*i* before on-ground averaging (%)**	**Percentage r.m.s. error in (*I*/*N*)*i* after 10 s of on-ground averaging (%)**	**Percentage r.m.s. error in (*I*/*N*)*i* after 30 s of on-ground averaging (%)**
4	2.75	0.197	0.110
5	3.75	0.268	0.150
6	4.78	0.341	0.191
7	5.80	0.414	0.232
8	6.83	0.488	0.273

As indicated in Table 4, the r.m.s. errors in the unbiased measurements of the values of $\{(I/N)i, i = 4, ...8\}$ can be reduced significantly by averaging on the ground the initial estimates that are based on averaging the measurements in the satellite for 25 ms. It is noted that in 10 s the satellite travels 72 km, and in 30 s it travels 216 km; there is a limit on the extent of averaging the results over time, because the actual interference seen by the satellite will vary as the satellite moves appreciably. Given the omni-gain characteristics of the LEO-D antenna, averaging on the ground over 30 s is viable, producing results with r.m.s. errors that are considerably smaller than the 3% value of the aggregate $\Delta T_{satellite}/T_{satellite}$ that is specified in *recommends* 2 of this Recommendation.