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Determining radiosonde maximum interference levels from link analysis and flight studies

RS Series

Remote sensing systems

International Telecommunication Union

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REPORT ITU-R RS.2187

Determining radiosonde maximum interference levels from link analysis and flight studies

(2010)

TABLE OF CONTENTS

Page

Page

1 Purpose

The objectives of this study are, through field testing and analytical analysis, to:

1. validate the use of the free-space path model in link budget calculations;
2. determine the actual link margin values that should be used in the link budget calculations;
3. determine the fading levels which must be accounted for in link budget calculations;
4. determine the maximum GPS radiosonde interference level that can be tolerated by a GPS radiosonde.

Once identified, these values can be used in future compatibility and interference studies.

Calculation of interference criteria is based on both the Metaids system link margin, and the link availability values of the system. There is a need to clearly define the term availability for Metaids systems, and to determine the appropriate link budget to be used with defining Metaids interference criteria.

In the ITU-R, Metaid's system interference criteria are typically based on the system link margin. A percentage of the link margin is given up to interference. The noise floor is raised slightly by the presence of the interference, resulting in a reduction in the link margin. The link availability objectives of the system must also be considered in order to determine the percentages of time that are applicable to the calculated interference criteria. This is the method used for the current values specified in Recommendation ITU-R RS.1263.

In past years, other radio services have noted that the Metaids performance objectives are set very high (link availability on the order of 99%) while the specified link margins are quite low (on the order of several dB or less). Such low link margins are not common radio link design practice and raised concern for the other radio services. However, for technical and safety reasons discussed in Recommendation ITU-R RS.1165, Metaids systems are designed to make the most efficient use of transmitter power and minimize the weight and density of the Metaids transmitter package.

2 Radiosonde link availability and data availability

For radiosonde systems, the value used for the availability performance objective should be link availability; the percentage of time that the receive signal strength is above the minimum receive threshold. When the receive level is above the minimum receive threshold, reliable reception of data should occur. Data availability is closely related to the percentage of time the link is available. Data availability is also affected by other factors as well. In addition to the path losses resulting in the receive signal level dropping below the minimum required level, radiosondes generate a small percentage of erroneous data due to sensor and processing errors. In the case of erroneous data, the link is sufficient to transmit the data to the receive station, but the receive station performs quality control and discards the bad data points during the data processing. Radiosonde users define their data availability performance objectives with consideration for loss of data due to sensor and processing errors as well as receive levels below the minimum receive threshold. Since radiosondes often use signals that are either partially or fully analogue, bit error rate values are also not applicable and data availability values are difficult to quantify. It is for these reasons that link availability should be used as the radiosonde performance objective. Link availability will be defined as the percentage of time that the received signal level is sufficient to produce at least the required signal-to-noise ratio (S/N). The required S/N is defined as the minimum value where no data loss occurs due to failure of the transmission link.

3 Procedure

Testing was conducted for both bands allocated to Metaids by conducting flights that approach or reach the maximum operational link range of the system. Both receiver systems used in the testing were capable of reporting the receive signal level detected at the output of the receive antenna so the receive level could be recorded by a computer.

3.1 400.15-406 MHz band

In order to assess the performance of the state-of-art radiosonde system in the 400.15-406 MHz band, and to justify the performance objectives, a small number of soundings were done using both low gain (omnidirectional antenna) and high gain (directional antenna). The system components used in this test are defined in Recommendation ITU-R RS.1165. Those components were System 2 for the Receiver, Type B radiosondes, Antenna B for the directional antenna, and Antenna C for the omnidirectional antenna. With Reed Solomon error correction and use of GMSK the receive sensitivity for the system was −120 dBm. The soundings were done at Jokioinen observatory in Southern Finland in expected high wind conditions to achieve maximum distance. All together three soundings were done using the omnidirectional antenna only, and three with both omnidirectional and directional antennas. The S/N, and received signal power were calculated from the software radio after the FFT conversion of the received signal. The use of advanced signal processing methods like Reed-Solomon provide processing gain of about 5 dB, suggesting that a minimum S/N ratio of 7.3 dB is the threshold for reliable reception of data. For existing analogue systems 12 dB is therefore a reasonable requirement. On the other hand the deviation in the received signal power suggests that even higher than 12 dB S/N as an average minimum would be needed.

3.2 1 668.4-1 700 MHz band

Testing was conducted using a new radiosonde system being deployed in the United States of America (System E in Recommendation ITU-R RS.1165). A series of flights were conducted, where the radiosonde signal strength at the output of the receive antenna connector was recorded at a one-second interval. The receive noise floor and the minimum receive signal threshold is known for the system, the percentage of time that the signal strength falls below the minimum receive signal threshold can be determined, revealing the flight link availability. In addition, the signal strength data can also be used to determine at what receive level above the minimum receive level the link availability equals the link availability performance requirement. The difference between the higher threshold and the minimum receive signal threshold can be assumed to be the link margin.

The data availability design requirement for the system used for this testing is 98% over the entire flight. As discussed in § 3, data loss occurs in radiosonde systems for reasons other than those related to the telemetry link. Therefore, one-half of the 2% allowable data loss will attributed to the signal strength falling below the minimum receive level while the remaining one-half will be attributed to other data loss factors not related to the radio link. The test results will show whether the system is meeting its design objective of 1% link unavailability. The link unavailability is determined by measuring the percentage of the time that the receive signal strength falls below the system minimum receive threshold relative to the time of the entire flight. The minimum receive threshold for the system under test is a level of −106.8 dBm, which provides for a 12 dB signal to noise ratio above the −118.6 dBm noise floor.

The system link margin for each flight is determined by determining the signal level that would correspond to a 1% data loss. This is the level that 1% of the data points fall below. The difference between this level and the minimum receive level is the link margin. In the case of this testing, the reported signal levels were at a 1 dB resolution, so it is not possible, in most cases, to determine the receive level exactly at where 1% data loss occurs. For this reason, the signal level closest to the 1% data loss point is used in calculating the margin.

4 Flight data results

The flight data is presented in two ways in this contribution. Annex 4 provides plots of the radiosonde to receive station link path loss over the entire time of the flight. Annex 5 provides plots of the radiosonde signal strength at the input of the receiver for the entire period of the flight. It should be noted that not all flights reached the maximum 250 km slant range limit.

4.1 Flight data results for 400.15-406 MHz

Table 1 provides the transmit power of the radiosonde and the distance at the end of each sounding.

TABLE 1

Soundings performed

Sounding	Frequency (MHz)	Transmit power (mW)	Transmit power (dBm)	Range (km)
1	402	20.3	13.07	194.4
2	402	22.2	13.46	143.4
3	402	21.4	13.30	108.4
4	402	20.9	13.20	131.5
5	402	22.6	13.54	365.8 (directional) 298.3 (omnidirectional)
6	405.5	19.4	12.88	272.5

As can be seen, sounding No. 5 was exceptionally long, over 360 km. At this distance, the radiosonde was received only with the directional antenna. With the omnidirectional antenna the signal started to be too weak at about 270 km, though some errors occurred earlier. The maximum range for good quality data transmission of each sounding is presented in Table 2.

TABLE 2

Maximum range for good data transmission

Sounding	Range of good data transmission (Omnidirectional) and rejected data frames (km)	Range of good data transmission (Directional) rejected data frames (km)
1	194.4 (N/A)	–
2	95.8 (1.67%)	–
3	108.4 (0.41%)	–
4	131.5 (0.71%)	131.5 (0.1%)
5	159 (1.05%)	354 (0.48%)
6	270 (0.48%)	272.5 (0.2%)

In all figures it should be noted, that the full transmission power is set on automatically only about 300 s after the beginning of the sounding. In Annex 1 the received radiosonde signal power with the omnidirectional antenna is presented. It is also compared with the theoretical receive level based on free-space attenuation (red curve). Annex 2 presents the received signal power with the directional antenna with same comparison to the theoretical receive level based on free-space path loss. In Annex 3 the signal level from the two antennas are compared. The data analysis for this band did not include the actual calculation of path loss as was done in the next section for the band 1 675-1 700 MHz.

Multipath fading can cause over 20 dB additional loss, which is seen as fading in the link. It is difficult to identify the exact reasons for signal level variations, but the multipath fading is the most important. The maximum negative and positive variations of the received signal strength from the free-space attenuation are listed in Table 3. The minimum fatal-error-free *S*/*N* value is also listed.

TABLE 3

Sounding statistics

Sounding	Maximum negative variation (dBm)		Maximum positive variation (dBm)		Minimum fatal-error-free *S*/*N* (dB)	
	Omnidirectional	Directional	Omnidirectional	Directional	Omnidirectional	Directional
1	28.1	–	6.1	–	7.3	–
2	27.5	–	2.0	–	7.3	–
3	26.3	–	4.0	–	7.7	–
4	19.5	7.5	1.3	2.2	6.9	11.8 (no errors)
5	15.9	12.4	6	1.6	7.3	7.3
6	10.8	7.7	1.8	0.8	7.5	7.3
Average	*21.4*	*9.2*	*3.6*	*1.5*	*7.3*	*7.3*

4.2 Flight data results for 1 675-1 700 MHz

4.2.1 Flight data for link path loss

The data for the plots in Annex 4 were derived from the receive signal strength reported by the radiosonde receiver. Using the reported signal strength, combined with transmitter, receiver, transmit antenna and receive antenna characteristics, the path loss of the radiosonde link can be calculated. Recommendation ITU-R RS.1165 provides the transmitter and receiver system characteristics used for the calculations and data analysis.

In addition to the characteristics provided in Table 1, the receive system has a systematic error in its signal reporting algorithm. The error varies slightly from system to system. Several receive systems were used in this testing. Each receiver was tested with a signal source to determine the reporting error at each signal level ranging from −30 dBm to −118 dBm. The known error could then be used to correct the path loss calculation for a more accurate result.

The formula for calculating the radiosonde link path loss, using the system parameters and the measured signal level is:

$$PL = P_{TX} - P_{RX} + G_{TX} + G_{RX} - E_{LEVEL}$$

where:

PL:	Radiosonde link path loss
P_{TX}:	Radiosonde transmit power
P_{RX}:	Receive signal level
G_{TX}:	Transmitter antenna gain
G_{RX}:	Receiver antenna gain
E_{LEVEL}:	Signal level reporting error.

The radiosonde link path loss was plotted for each flight. The plots are contained in Annex 4. Review of these plots reveals some propagation characteristics of the radiosonde link. The plots contain both a line that defines the median path loss from the measured data, and a curve showing the free-space path loss calculated solely from the slant range distance. The plots show that in nearly every case, the median path loss based on the measured data closely follows the curve of the calculated free-space path loss within approximately ±1 dB. Therefore, free-space path loss can be used to accurately define the radiosonde link budget. The second conclusion that can be drawn from the plots in Annex 4 is the level of fading that a radiosonde experiences during flight. The plots show that fading on the order of 2 to 3 dB short slant ranges that increases to on the order of 3 to 5 dB at the longer slant ranges. The plots also show that in addition the signal is enhanced by approximately the same amounts at both short slant ranges and longer slant ranges respectively. As would be expected, varying propagation conditions including multipath will cause signal fades and also cause increases in the signal level relative to free-space path loss. Therefore, fading on the order of 3 to 5 dB should be considered in the link budget calculations.

4.2.2 Link availability and link margin

The plots in Annex 5 are of the reported radiosonde signal strength over the entire period of the flight. The curve is the signal strength, corrected for the systematic reporting error of the receiver, plotted against the slant range between the receiver and the radiosonde (transmitter). The plots for flights that reach or approach the 250 km slant range limit also contain two other lines. The first (lower) line is the minimum receive level for which the receiver will see at least a 12 dB signal-to-noise ratio. For the systems used in these tests, this level is −106.8 dBm, which is 12 dB above the system noise floor of −118.6 dBm. As discussed in § 3 any point that falls below the

12 dB *S*/*N* level of −106.8 dBm is considered a point where link availability has failed. Above the 12 dB *S*/*N* line, a line is plotted where the data indicates that the system is approaching or is at the 1% unavailability level. The system used for testing only reported signal strength with a 1 dB resolution. In many cases the 1% unavailability point fell between two points 1 dB apart and could not be precisely determined. Therefore, the line is drawn using the signal level that fell closest to the 1% unavailability level.

These plots provide several important conclusions. Proponents of other radio services have argued that radiosonde systems operating with such small link margins should experience data loss at levels much higher than 1% to 2%. The plots show that the systems do operate with small link margins, but do not experience high levels of data loss. For the system type tested, a performance objective of 99% link availability is reasonable and attainable with a small link margin. The plots also provide an indication of the actual link margin that should be used in the link budget calculations. The results of the plots do vary somewhat for the systems type used in the tests, but in every case, the system is operating at a positive link margin.

5 Interference measurements based upon actual GPS radiosonde flight data

5.1 Background

This section of the document describes the test system and measurement methodologies, that were used to determine the maximum level of interference that can be tolerated by a GPS radiosondes which was operating at a frequency of 1 680 MHz. The results that are derived from these measurements and studies will be used to finalize the identification of radiosonde protection criteria levels as a part of an update to Recommendation ITU-R RS.1263.

From an operational perspective, a radiosonde is carried aloft by a weather balloon during which time measurement data is transmitted to a ground terminal. The flight ends when the balloon bursts at a pressure of approximately 4 hectopascals (hPa), and the balloon and the lightweight radiosonde descend to the Earth's surface. A flight typically lasts from 90 to 120 min. There are 103 launch sites in the United States of America and its possessions. Launches take place twice per day, at approximately 00:00 and 12:00 UTC. Data from upper air sites are combined with the radiosonde data and provide a profile of upper air conditions across the country.

Although interference to the radiosonde signal could occur at any time, multipath interference is more likely to occur for long flights where low antenna elevations are common. These flights generally occur at higher latitudes during the winter months. Flight data is difficult to obtain due to geographical and seasonal limitations. In order to overcome these limitations a series of flights were initiated during periods of time when strong upper air (Jet stream) winds were prevalent. Conducting the acquisition of flight data under these conditions maximized the probability of observing long flights.

The steps that are involved in determining the interference level that will result in the loss of PTU and or GPS data include:

Step 1: the acquisition and digitization of actual in-flight radiosonde RF signals.

Step 2: the reproductions of the digitized RF signal data.

Step 3: the combining of the reproduced RF data with and calibrated interfering signal.

Step 4: the application of the combined signals to the input of the radiosonde systems telemetry receiver.

Step 5: while varying the interference level (*I*/*N*), monitor the most sensitive data element until a data loss occurs.

5.2 Data acquisition data reproduction and interference level measurement hardware

The measurement system consists of two subsystems:

1. the radiosonde RF signal acquisition subsystem is used to acquire and digitize a live, in-flight radiosonde RF signal as received by the tracking station antenna;
2. the signal reproduction subsystem, which is used to reproduce the acquired radiosonde RF signal for interference analysis.

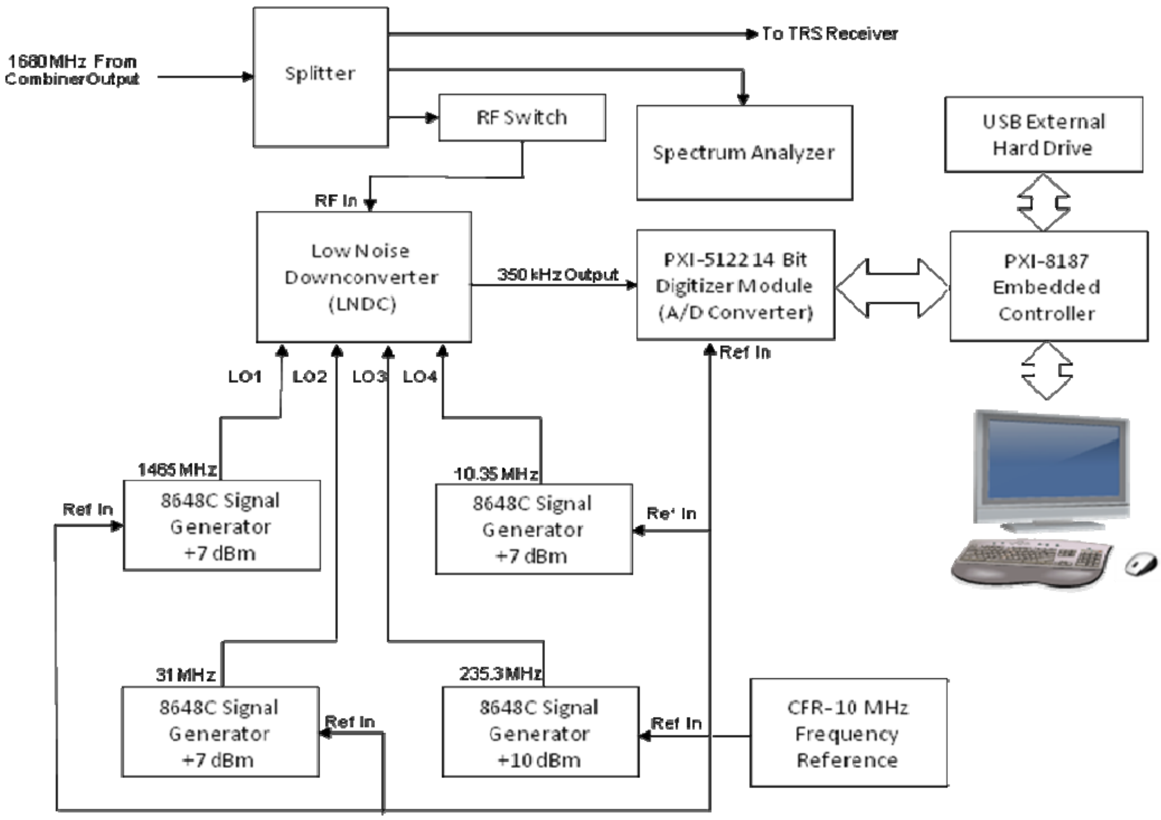
5.3 Radiosonde RF signal acquisition

To acquire the radiosonde flight RF signals, a radiosonde is deployed and then tracked by the receive antenna. The received 1 680 MHz radiosonde signal is split at the antenna, down converted to 350 kHz, digitized and stored on a hard drive by a data acquisition system, as shown in Fig. 1.

The data acquisition system consists of an analogue to digital converter and embedded controller with hard drive. The digitized signal is stored as a binary file.

FIGURE 1

Equipment setup for acquiring radiosonde flight data



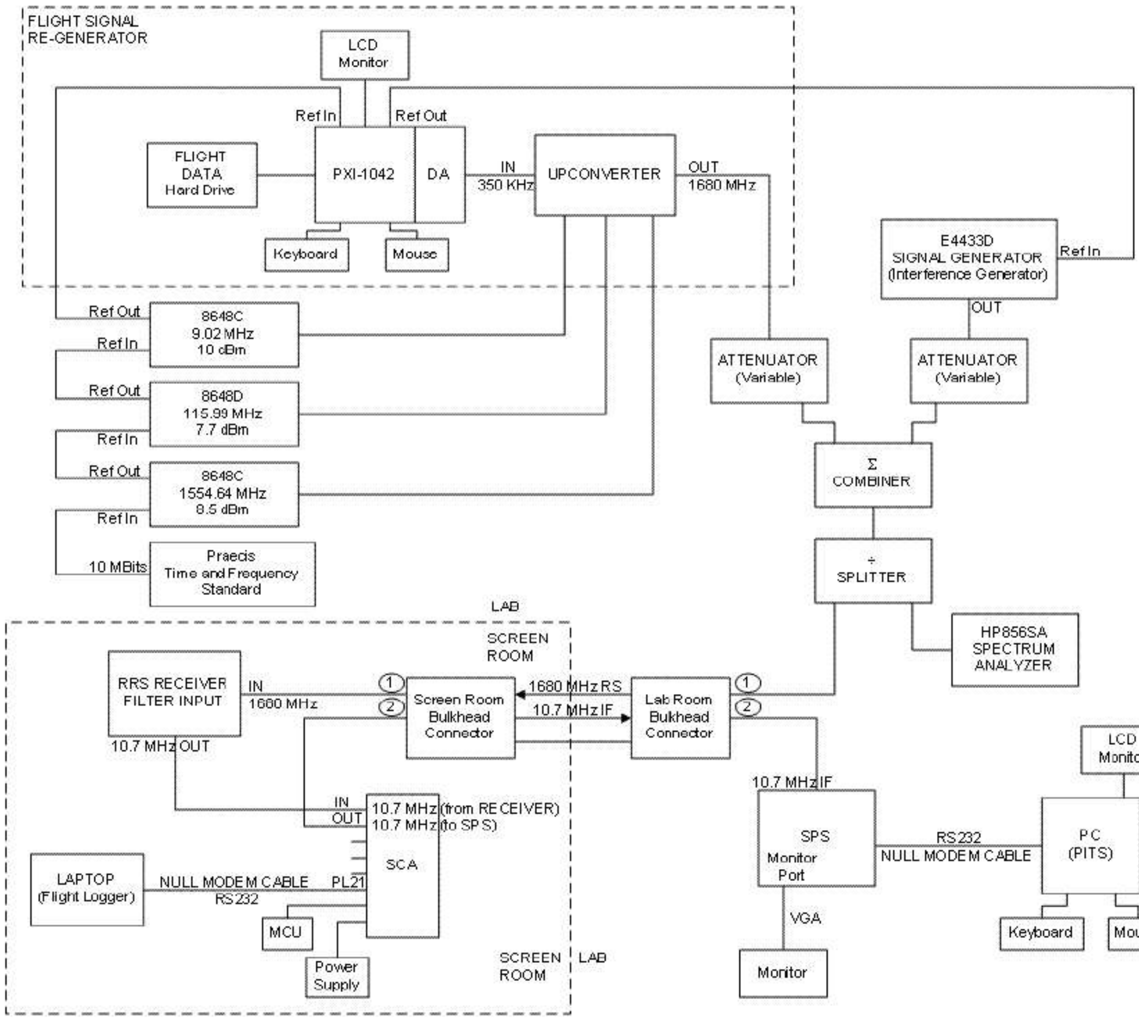
Operation is as follows: the signal from the radiosonde is tracked by a parabolic antenna and amplified 18 dB by a low noise amplifier. The low noise amplifier output is fed into a 3-way splitter. One of the splitter outputs is connected to the system receiver for normal signal processing and data storage. A second output is fed into a low noise down converter (LNDC) that amplifies and down converts the signal to 350 kHz. The 350 kHz signal is applied to an analogue to digital converter. The digitized RF signal is then stored by the embedded controller. A 10 MHz frequency reference is used to keep the signal generators and data acquisition system phase locked. The third output of the splitter is connected to a spectrum analyzer for RF monitoring purposes.

5.4 Radiosonde RF signal reproduction

The signal reproduction subsystem, Fig. 2, is used to reconstruct the radiosonde RF signal in a laboratory environment and allows interference signals at different levels to be combined with the 1 680 MHz radiosonde signal for analysis. The digitized down converted radiosonde signal that had been stored by the acquisition subsystem is applied to a digital to analogue converter in order to reconstruct an analogue version of captured RF radiosonde signal. The output of the digital to analogue converter is then up converted to 1 680 MHz. The reconstructed 1 680 MHz radiosonde RF signal is then applied to a combiner along with the interfering signal. The output of the combiner is applied to the RTS receiver which process, stores and displays the radiosonde data.

FIGURE 2

Setup for reproducing the radiosonde signal and injecting interference



The digital to analogue converter is a module in the PXI chassis. It reads the acquired binary data representing the digitized RF signal from the hard drive and reproduces the original 350 kHz down converted RF signal. The up converter consists of 3 mixers and filters to convert the reproduced 350 kHz signal from the digital to analogue converter to 1 680 MHz, the original radiosonde frequency.

The local oscillators, which are synchronized to the 10 MHz reference for phase coherence, provide the local oscillator signals used by the up converter. The variable attenuators, consisting of 1 dB and 10 dB step attenuators are used to compensate for level differences between the acquired and the reconstructed signals that occur due to cable, combiner and other losses. The receiver monitor and control PC (RTS-PC) sets the receive frequency, enables and disables the receiver automatic frequency control and provides the received signal strength. A separate computer running data processing software (DPS-PC) displays the pressure, temperature and relative humidity data as measured by the radiosonde and saves this data in a file.

5.5 Data acquisition, analysis and the determination of interference levels

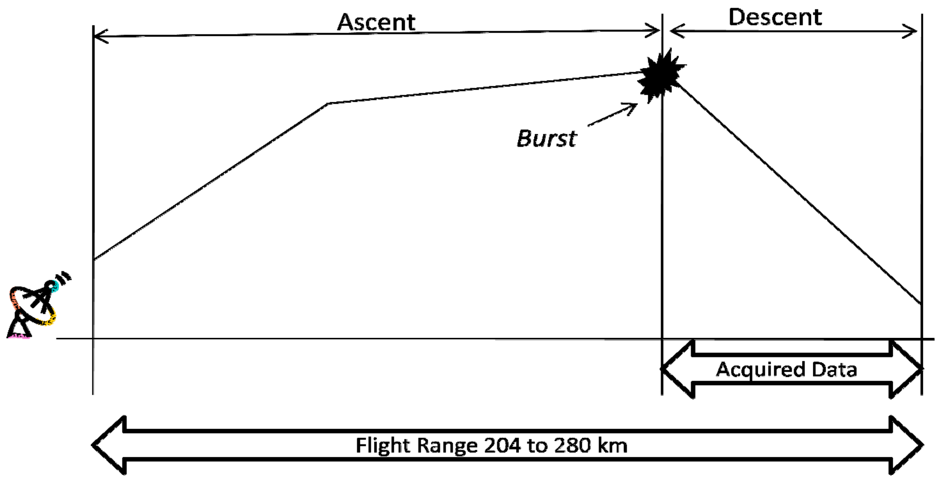
5.5.1 Data acquisition

Once activated, the radiosonde transmits continuously until the battery expires. The radiosonde system used for these measurements transmitted flight data (pressure, temperature, humidity (PTU) and Global Positioning System (GPS) data) to the ground terminal receiving station. The data was transmitted by a 0.25 W FM transmitter in the 1 680 MHz band. Communication between the radiosonde and the receiving system was from the radiosonde to the ground terminal.

The flight data was collected using the system that was described in § 5.3 and was comprised of post-burst (descent) flight segments (see Fig. 3). Data collection was terminated when radiosonde transmitter reached the ground level.

FIGURE 3

Acquired flight data and analyzed segments



Acquiring and storing the RF signal from the radiosonde during the descent phase resulted in the capturing data that incorporated both long slant range and low elevation angles (see Table 4). The data set consisted of 7 flights. The average range was equal to 248 km with an average final elevation angle of 0.9º.

TABLE 4

Flight range and final elevation data

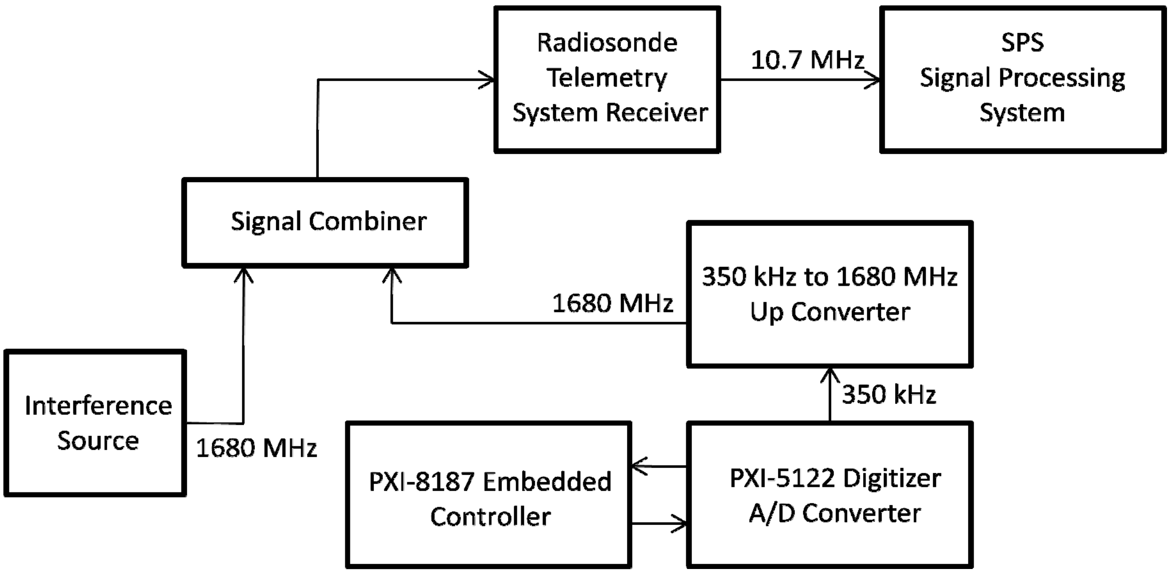
Flight number	Range (km)	Final elevation angle (degrees)
1	316	0.4
9	217	0.9
14	201	1
15	266	0.8
16	215	1
17	257	1
18	266	1

5.5.2 Data reconstruction

Figure 4 is a simplified block diagram of the signal reconstruction and interference injection subsystem. Interference is injected onto the reconstructed radiosonde RF signal through a combiner and fed into the telemetry receiver.

FIGURE 4

Radiosonde RF signal reconstruction and interference injection block diagram



The acquired flight data RF transmissions (in digital form), which were initially stored on an external hard drive, are accessed by the embedded controller and converted back into analogue form by the A/D converter. The analogue RF flight signal is up converted to 1 680 MHz. This up converted signal represents the actual RF signal that was seen by the receiving system antenna during the actual flight. This signal is fed to a combiner where it will be summed with the "interferer", a spread spectrum WCDMA signal with a center frequency of 1 680 MHz. The output of the combiner is fed to the radiosonde telemetry receiver system where it is processed and fed to the signal processing system.

The interference level is calibrated to an *I/N* of 0 dB at the IF output of the receiving system. This level is then used as the reference level for all subsequent interference measurements.

5.5.3 Interference calibration

To calibrate the signal reconstruction system for a known interference level at the radiosonde telemetry system receiver input, the receiver's noise floor was measured, without interference, at the 10.7 MHz IF output of the receiver. When the noise floor was recorded at the IF output, the interference signal was activated and its level was increased until the noise floor at the receivers IF output increased by 3 dB. This level corresponded to an interference level within the radiosonde telemetry receivers IF pass band which was equal to the receiver noise within the pass band, and an *I/N* ratio of 0 dB. The signal source output was recorded for the 0 dB *I/N* ratio. The actual level being injected into the radiosonde telemetry receivers was also measured and recorded. Knowing the signal source setting for the 0 dB *I/N*, the signal source could then be set for any other desired *I/N* by adjusting the signal source output level.

The technique for determining *I/N* levels was to first connect a spectrum analyzer with average detection to the radar IF output of the radiosonde telemetry system (RTS) receiver and observe the noise power level in a resolution bandwidth (RBW) that was matched as closely as possible to the receivers radar IF bandwidth (7 kHz). Then the interference generator output was fed into the radiosonde telemetry receiver's front end input and the interference power was adjusted until it caused an increase of 3 dB on the spectrum analyzer display. Since the spectrum analyzer display showed the quantity *I/(I+N)*, this meant that *I/(I+N)* = 3 dB, implying that *I* = *N* resulting in an *I/N* = 0 dB. With this method, all *I/N* levels were referenced to the indicated *I* = *N* level.

In terms of level calibration, the various levels of interference were subsequently adjusted by attenuating the input relative to the calibrated level. For example, suppose that the interference source generator power level that results in an *(I+N)/N* = 3 dB is −134 dBm. This becomes the 0 dB *I/N* point. Then a 2 dB reduction in the interference level relative to that point would be an *I/N* level of 2 dB, which would occur at −134 dBm output power from the interference source generator. Table 5 shows the interference levels that were used for this analysis as a function of *I/N*.

TABLE 5

Interference power levels as a function of *I/N* levels

***I/N* level (dB)**	**Interference power level (dBm)**
18	−116
16	−118
14	−120
12	−122
10	−124
8	−126
6	−128
4	−130
2	−132
0	−134

5.5.4 Theoretical maximum allowable interference level

The theoretical maximum allowable interference level can be calculated as follows. Given that the receivers noise floor is equal to −118 dBm, the maximum allowable increase in noise due to interference is 1 dB for a $I+N$ of −117 dBm. A 1 dB increase in the noise level corresponds to an I/N of −6 dB. Given an I/N of –6 dB and taking an additional 5 dB into account for fading results in a maximum allowable interference threshold level of –128 dBm (−158 dBW).

5.5.5 Interference power measurement methodology

Several iterations of measurements need to be taken in order to determine the level of the interference power as a function of percentage of time.

For each I/N value, the interfering signal is combined with the reconstructed radiosonde RF signal and applied to the radiosonde telemetry receiver. PTU data for each of the interference level values is collected from the radiosonde telemetry receiver and is stored for future analysis. This process is repeated for each of the 15 flights over which the RF signal was captured. (Table 5 illustrated the range over which, for each flight, the measurements were taken.)

Table 6 is an example of data that has been extracted from the telemetry data files which were generated during the interference injection process. (I/N values of 16 dB and 14 dB are shown here for illustrative purposes.)

TABLE 6

Typical telemetry data

File:	**Data_Met_KIAD_2009_001_2.txt**		
***I/N* = 16 dB**			
Timestamp	**Pressure**	**Temperature**	**Humidity**
26:01.5	38.81	–61.9	14.5
26:02.4	38.93	–61.91	14.6
26:03.5	39.1	–61.9	14.6
26:04.5	39.17	–61.81	14.6
26:05.5	39.29	–61.75	14.5
26:06.1	39.46	–61.69	14.5
26:07.1	39.51	–61.65	14.5
26:08.7	39.67	–61.52	14.5
26:09.1	39.77	–61.37	14.4
26:11.7	40.06	–61.16	14.3
26:12.8	40.19	–60.98	14.2
26:13.8	40.24	–60.86	14.1
26:14.8	40.38	–60.86	14.1
26:15.8	40.46	–60.72	14.1

File:	**Data_Met_KIAD_2009_001_3.txt**		
***I/N* = 14 dB**			
Timestamp	**Pressure**	**Temperature**	**Humidity**
14:38.6	38.8	–61.9	14.5
14:39.7	38.92	–61.91	14.6
14:40.6	39.09	–61.9	14.6
14:41.7	39.16	–61.81	14.6
14:42.7	39.28	–61.75	14.5
14:43.8	39.45	–61.69	14.5
14:44.8	39.49	–61.65	14.5
14:45.8	39.65	–61.52	14.5
14:46.8	39.75	–61.37	14.4
14:47.3	39.9	–61.26	14.3
14:48.9	40.04	–61.16	14.3
14:49.9	40.17	–60.98	14.2
14:51.0	40.22	–60.86	14.1
14:52.0	40.36	–60.86	14.1

In order to determine the signal power level to be exceeded no more than 20% of the time, the overall duration of the flight along with the period of time during which the radiosonde data has been corrupted needs to be quantified. The percentage of time that the data has been corrupted can be computed once these values have been determined.

The first step in accomplishing these tasks involves the establishment of an interference free baseline representation of the reconstructed signal. This baseline representation is used to determine the flight duration. In addition, corrupted data elements within the baseline representation are noted and then removed from subsequent interference level data segment analysis in order to avoid duplicate counting of corrupted data elements.

The second step involves the identification of corrupted data elements and the determination of the period of time over the duration of the flight during which the radiosonde data has been corrupted. Corrupted data at a given interference level setting is easily identified as the radiosonde telemetry unit identifies corrupted data by inserting 9s into the data element field. Table 7 is an illustrative example which shows both uncorrupted sensor data and corrupted (i.e., **999** in the data element field of the Table) sensor data.

TABLE 7

Illustrative example of uncorrupted and corrupted data elements

File:	**Data_Met_KIAD_2009_001_2.txt**		
***I/N* = 16 dB**			
Timestamp	**Pressure**	**Temperature**	**Humidity**
26:01.5	38.81	–61.9	14.5
26:02.4	38.93	–61.91	14.6
26:03.5	**999**	**999**	**999**
26:04.5	**999**	**999**	**999**
26:05.5	39.29	–61.75	14.5
26:06.1	**999**	**999**	**999**
26:07.1	**999**	**999**	**999**
26:08.7	**999**	**999**	**999**
26:09.1	39.77	–61.37	14.4
26:11.7	**999**	**999**	**999**
26:12.8	**999**	**999**	**999**
26:13.8	40.24	–60.86	14.1
26:14.8	**999**	**999**	**999**
26:15.8	40.46	–60.72	14.1

File:	**Data_Met_KIAD_2009_001_3.txt**		
***I/N* = 14 dB**			
Timestamp	**Pressure**	**Temperature**	**Humidity**
14:38.6	38.8	–61.9	14.5
14:39.7	38.92	–61.91	14.6
14:40.6	**999**	**999**	**999**
14:41.7	39.16	–61.81	14.6
14:42.7	39.28	–61.75	14.5
14:43.8	39.45	–61.69	14.5
14:44.8	**999**	**999**	**999**
14:45.8	**999**	**999**	**999**
14:46.8	39.75	–61.37	14.4
14:47.3	**999**	**999**	**999**
14:48.9	40.04	–61.16	14.3
14:49.9	40.17	–60.98	14.2
14:51.0	999	999	999
14:52.0	40.36	–60.86	14.1

The third step in this process is to compute the percentage of time that the flight data had been interfered with by dividing the period of time during which data elements were corrupted (second) by the flight duration time (second).

$$\%Tdc = (Tdc\text{-}Tdcb)/Ft)*100$$

where:

- %Tdc: % time (data corruption)
- Tdc: period of time that data was corrupted
- Tdcb: period of time that baseline data was corrupted
- Ft: flight time.

Table 8 illustrates the results of this process. The data represents a summary of the per cent of data corruption as a function interference signal level in dBm, dBW and the calibrated *I/N* values.

TABLE 8

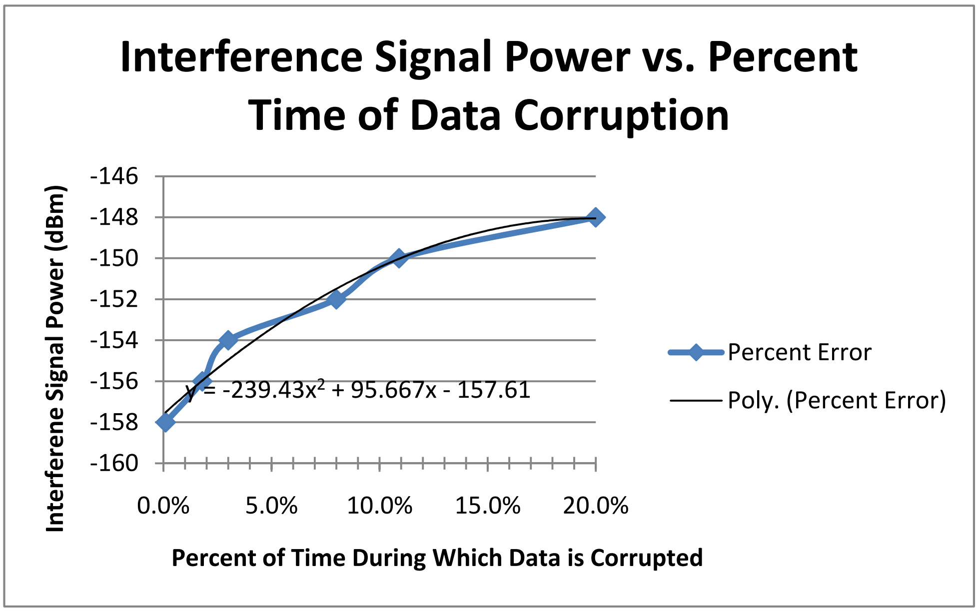
Flight 1 data summary

I/N	16	14	12	10	8	6
Level (dBm)	−118	−120	−122	−124	−126	−128
Level (dBW)	−148	−150	−152	−154	−156	−158
(%) data corrupted	20.0	10.9	8.0	3.0	1.8	0.1

Plotting the data from Table 8 as a function of interference signal power versus per cent of time during which the radiosonde data is corrupted results in the graph which is displayed in Fig. 5.

FIGURE 5

Interference signal power vs. per cent time of data corruption



Performing a regression analysis results in the derivation of an equation which can be used to calculate the interference levels as a function of percentage of time during which data is corrupted.

The next step in the process is to use that equation to compute the interference level that is associated with data corruption that occurs 20% of the time.

$$y = -239.4x^2 + 95.66x - 157.6$$

Table 9 shows the results of that calculation.

TABLE 9

Interference criteria for GPS radiosondes

Per cent of time	**Interference power (dBW)**
20	−148

The final step in the analysis is to compute the interference power levels that result in data corruption that occurs for 0.5 and 0.025% of the time. These values can be calculated by using the interference power level that is associated with data corruption levels that occur for 20% of the time along with the ratios between equations (1), (2) and (3) in Recommendation ITU-R RS.1263. Table 10 lists the results of those calculations.

TABLE 10

Interference power as a percentage of time

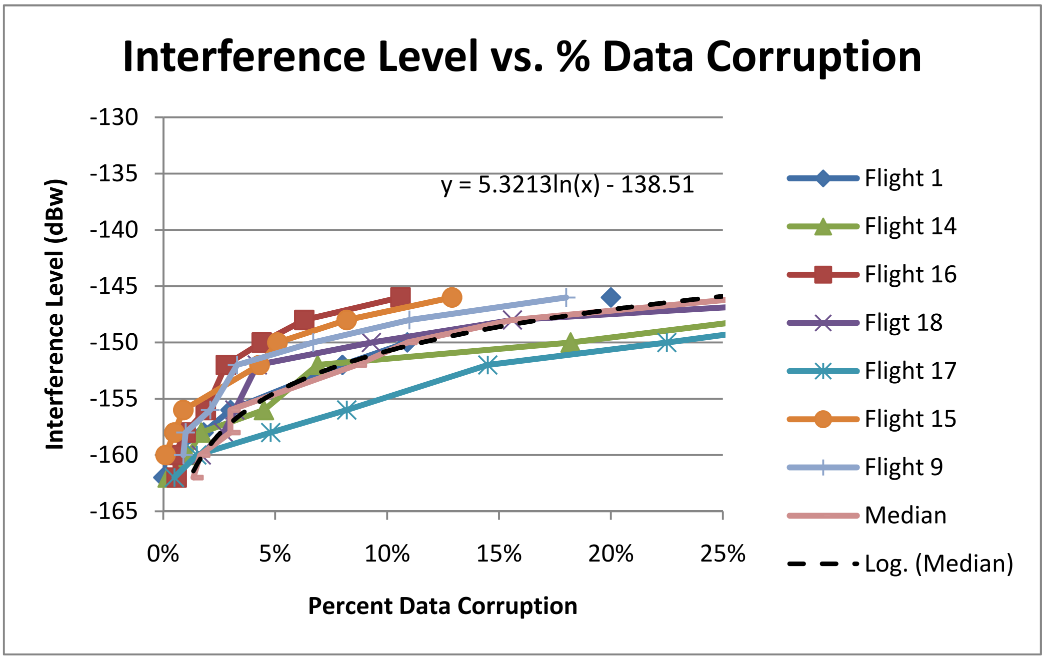
Per cent of time	Interference criteria ratios	Interference power (dBW)
20	1	−148
0.5	0.95	−141
0.025	0.89	−132

6 Measurement results

A total of 7 flights were analysed. The per cent of data corruption and the associated interference levels were plotted for each flight. Figure 6 also contains a plot of the median value of the data from each of the flights. A regression analysis was performed on the median value and an equation was derived from which the interference level that is associated with data corruption that occurs 20% of the time.

FIGURE 6

Interference level vs. % of time during which data is corrupted



Using the equation which was derived from the regression analysis of the complete data set:

$$y = 5.321 \ln(x) - 138.5$$

results in a interference signal power level to be exceeded no more than 20% of the time of –147 dBW.

Table 11 lists the interference signal power levels[1] to be exceeded no more than 20% of the time for each flight[2].

TABLE 11

Per flight interference signal power levels to be exceeded no more than 20% of the time

Flight number	Interference signal power level (dBW)
1	–147.9
9	–145.6
14	–149.6
15	–143.5
16	–142.4
17	–150.3
18	–147.4
Median	–147.4
Standard deviation	0.27

Interference power levels that result in data corruption that occurs for 0.5 and 0.025% of the time have been derived using the methodology which was outlined in § 5.5.5 and are listed in Table 12.

[1] Variations in the received signal level for each flight (as seen in Fig. 5) account for the differences in the measured interference signal power level.

[2] The difference between the calculated interference power level as derived from equation (1) (–147 dBW) and the mean value as derived from the individual flight calculation (–147.4 dBW) represents a 0.3%. The standard deviation of 0.27 gives a measure of the consistency of the measurements and provides an indication that the data are tightly clustered lending credibility and a high degree of confidence to the results and the measurement process.

TABLE 12

Interference power levels as a percentage of time

Per cent of time not to be exceeded	Interference criteria ratios (Based upon formulas 1, 2 and 3 from Rec. ITU-R RS.1263)	Measured interference power (dBW)	Additional compensation for fading and anomalous propagation (dB)	Resultant interference criteria power levels (dBW)	Calculated interference criteria power levels (dBW) (Based upon formulas 1, 2 and 3 from Rec. ITU-R RS.1263)
20	1	–147.4	5	–152	—152
0.125	0.95	–140	5	–145	—145.6
0.025	0.90	–132.7	5	–137	—132.2

7 Conclusions

Radiosondes are intentionally designed to use the lowest transmitter power necessary to maintain the required radio link. This design objective keeps the battery to a minimum size and reduces weight and density of the radiosonde. In the original version of Recommendation ITU-R RS.1263, link budgets were calculated using free-space path loss, and included consideration for fading and other propagation anomalies. Based upon the results which have been outlined in this report several important conclusions regarding the use of free-space loss and the incorporation of considerations for fading and other propagation anomalies can be drawn from the test results in § 5 and the test data which is included in Annexes 1 through 5.

Measurements based upon reconstructed radiosonde RF signals and soundings which were acquired during actual flights have been used to validate the use of free-space path loss and considerations for fading and other propagation anomalies in calculating link budgets. In addition, data from reconstructed radiosonde flights has been used to determine the interference signal power levels that are associated with the percentages of time during which GPS radiosonde data is corrupted by an interfering signal. The data support the approach taken in Recommendation ITU-R RS.1263 that use of free-space path loss combined with consideration for fading, is adequate for calculating the system interference criteria[3].

7.1 Conclusions specific to 400.15-406 MHz

The transmitted signal is affected in several ways during the transmission. It is bent, scattered and reflected in the atmosphere. At 400 MHz and within the distances in the radiosonde soundings these phenomena are not very significant. The most important propagation mechanisms of the radiosonde signal are the line-of-sight propagation and multipath fading. The latter is problematic, because it can cause erosion of the link margin that degrades the performance of the telemetry link. Buildings, hills, forest and other obstacles can cause diffraction and therefore fading through multipath propagation.

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[3] The propagation model defined in Recommendation ITU-R P.528 may yield more accurate results.

According to the results, the telemetry link worked very well with the directional antenna supporting the claim for 250 km performance with high data availability. With the omnidirectional antenna the performance was rather variable, but the claim for reasonable performance up to 150 km is feasible. One sounding was very well received out to a range of 270 km, but on the other hand some soundings had several telemetry failures at much shorter distances. Thus, it seems that the good telemetry range cannot be guaranteed for the distances of over 150 km with the omnidirectional antenna. The variations caused primarily by multipath, relative to free-space loss, were between +6.1 to −28.1 dB with the omnidirectional antenna and +2.2 to −12.4 dB with the directional antenna.

In two long soundings the telemetry performance is much better in the sounding No. 6 than it is in sounding No. 5. In both soundings the flying direction at the end was rather similar; 9.3° from South to East in sounding 5 and respectively 5.6° in sounding 6. The probable reason for worse performance in the other sounding is the different multipath characteristics in these directions.

In conclusion, fading on the order of 20 dB for the omnidirectional antenna and 10 dB for the directional antenna must be accounted for in link budget calculations. The use of the free-space path model was confirmed to be appropriate. The use of the ITU-R free-space path model Recommendation ITU-R P.528 may provide even more accurate results.

7.2 Conclusions specific to the band 1 675-1 700 MHz

Data from reconstructed radiosonde flights has been used to determine the interference signal power levels that are associated with the percentages of time during which GPS radiosonde data is corrupted by an interfering signal.

Injection of various interference power levels into the reconstructed radiosonde flight signals and the subsequent measurement and analysis of interference power levels which are associated with the percentages of time during which GPS radiosonde data is corrupted by an interfering signal provided results which showed a strong correlation between the measured interference power levels and those which were calculated using formulas 1, 2 and 3 of Recommendation ITU-R RS.1263. The resultant measurements support the calculations of GPS radiosonde interference levels as outlined in Recommendation ITU-R RS.1263.

Analysis of the soundings in Annex 4 shows that fading levels on the order of 3 to 5 dB should be used for GPS systems in the band 1 675-1 700 MHz. The data also shows that the system tested met the performance objectives, even with a small link margin. Other antenna systems with different designs may be more or less susceptible to multipath fading if the antenna pattern is significantly different. Other flight tests would be required to verify the values for those systems.

Annex 1

Flight signal level and *S/N* plots for 400.15-406 MHz with omnidirectional antenna

FIGURE 1-1

Sounding 1. Received signal power, omnidirectional antenna

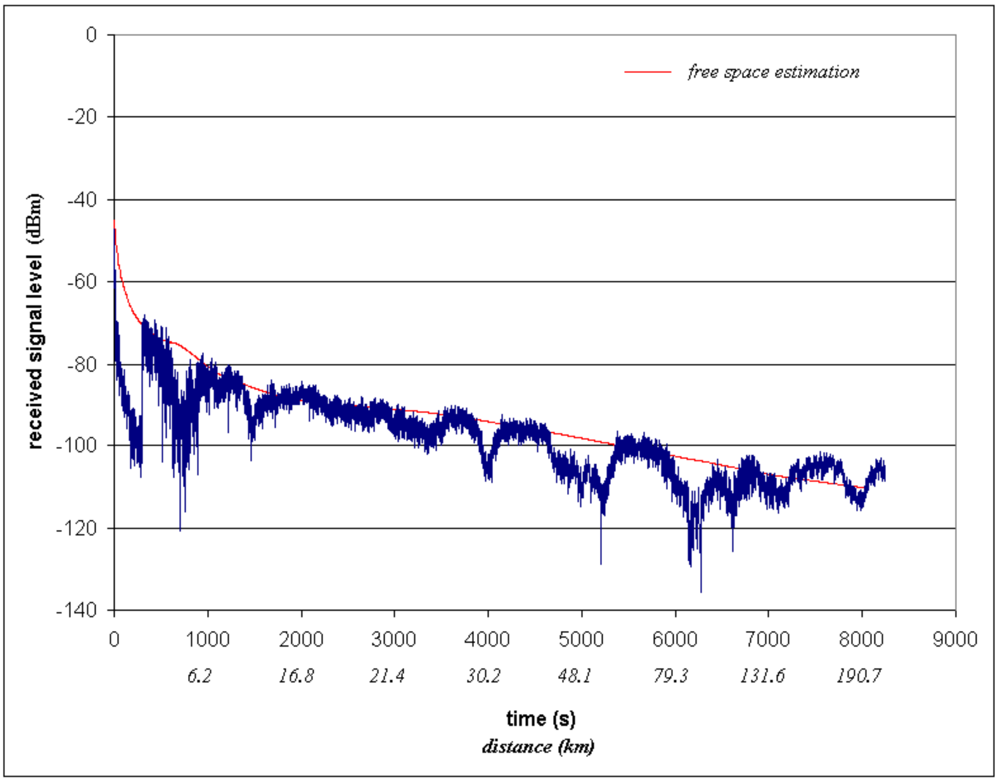


FIGURE 1-2

Sounding 1. *S*/*N*, omnidirectional antenna

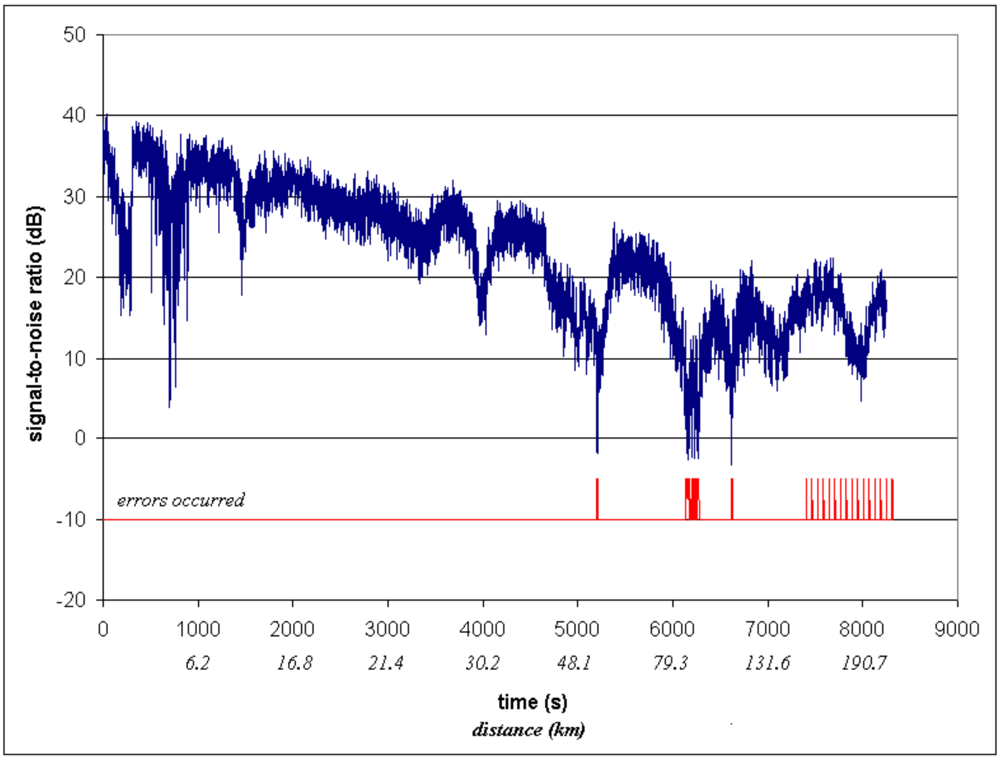


FIGURE 1-3

Sounding 2. Received signal power, omnidirectional antenna

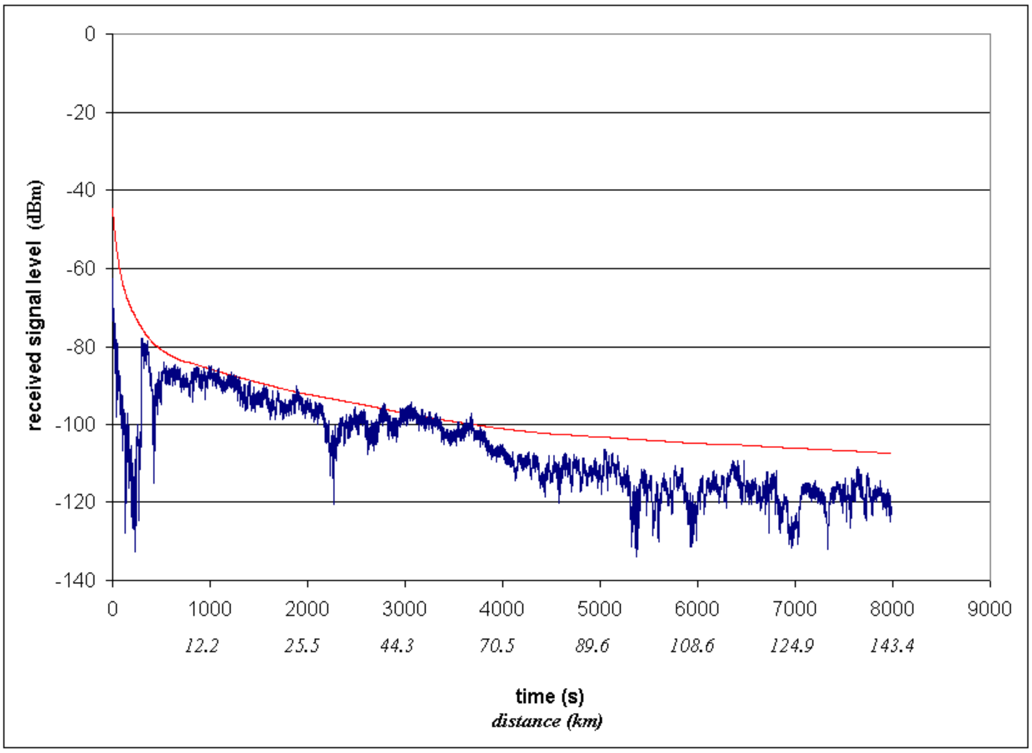


FIGURE 1-4

Sounding 2. *S*/*N*, omnidirectional antenna

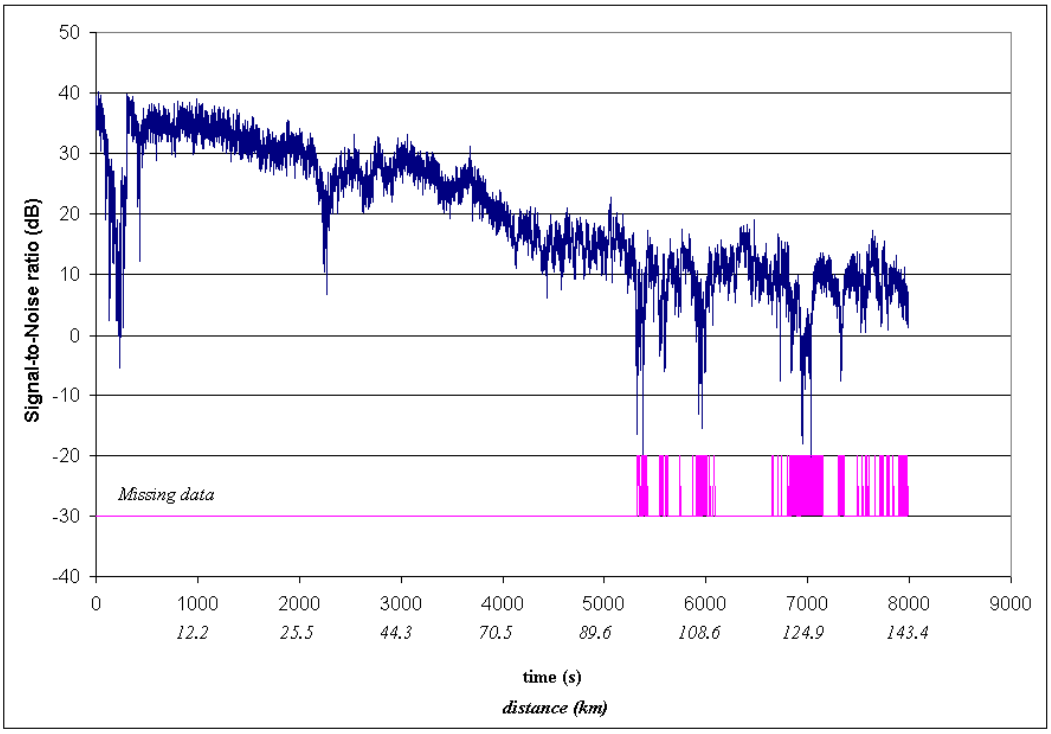


FIGURE 1-5

Sounding 3. Received signal power, omnidirectional antenna

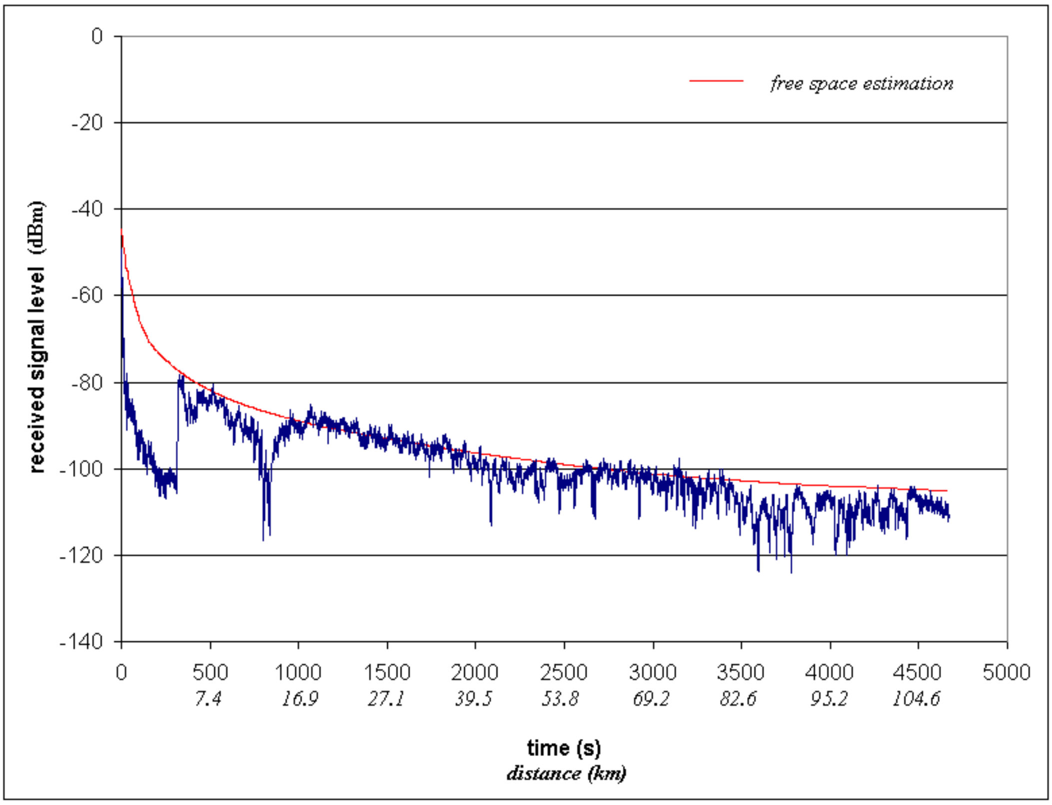


FIGURE 1-6

Sounding 3. *S*/*N*, omnidirectional antenna

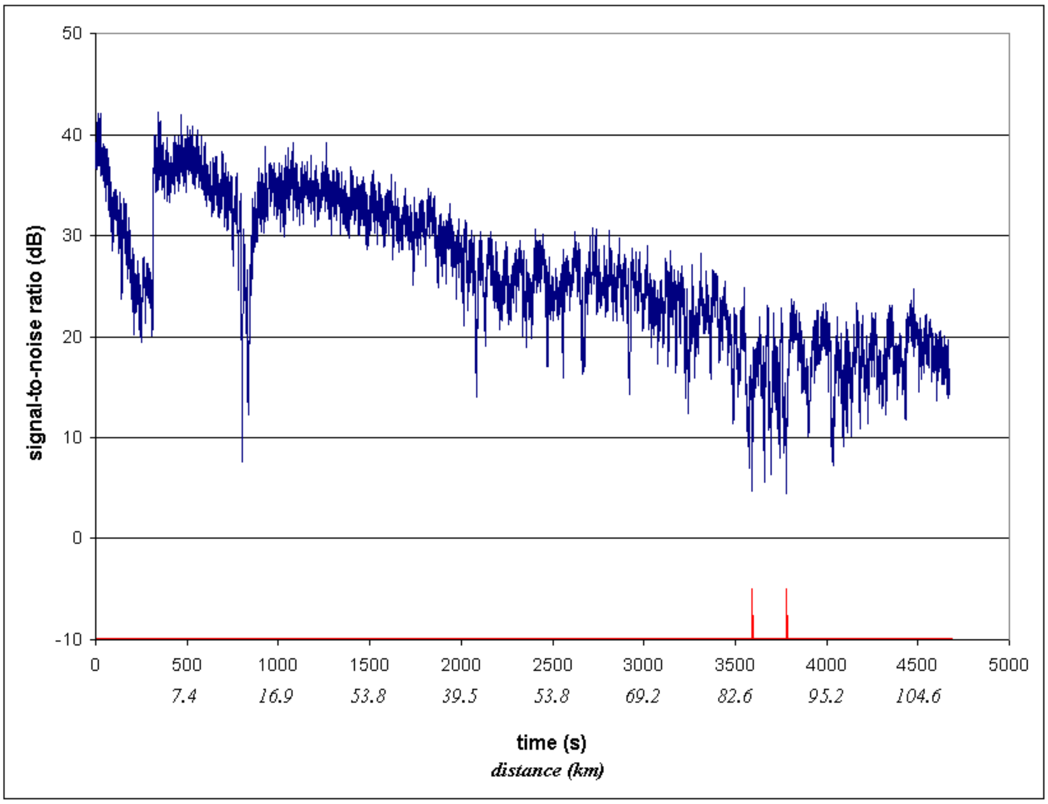


FIGURE 1-7

Sounding 4. Received signal power, omnidirectional antenna

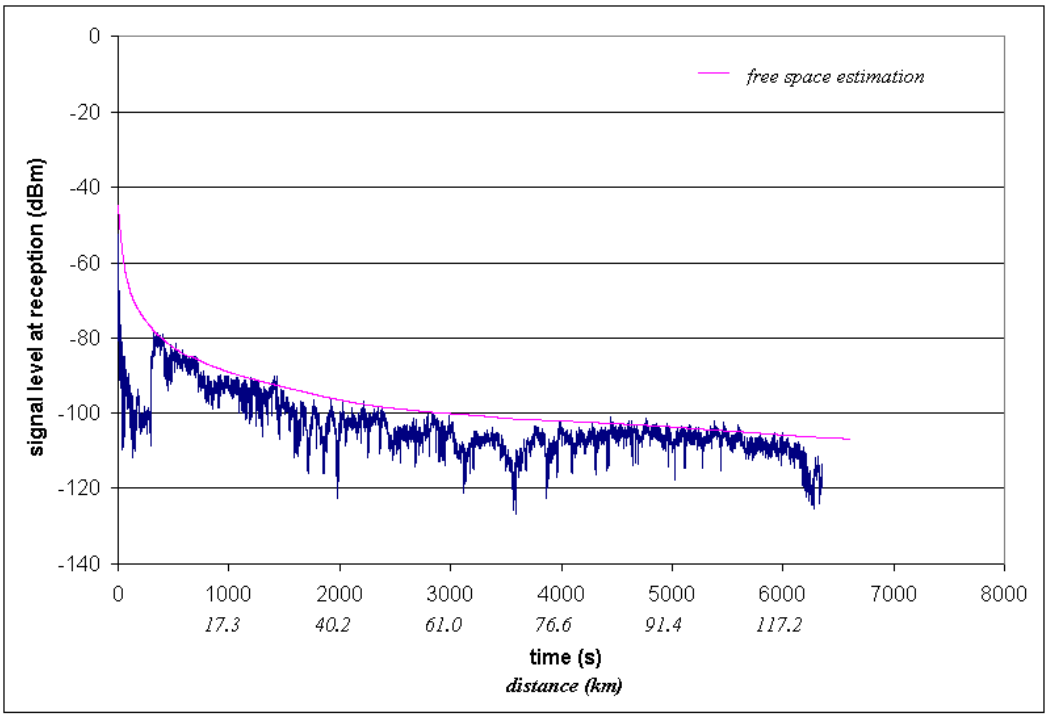


FIGURE 1-8

Sounding 4. S/N, omnidirectional antenna

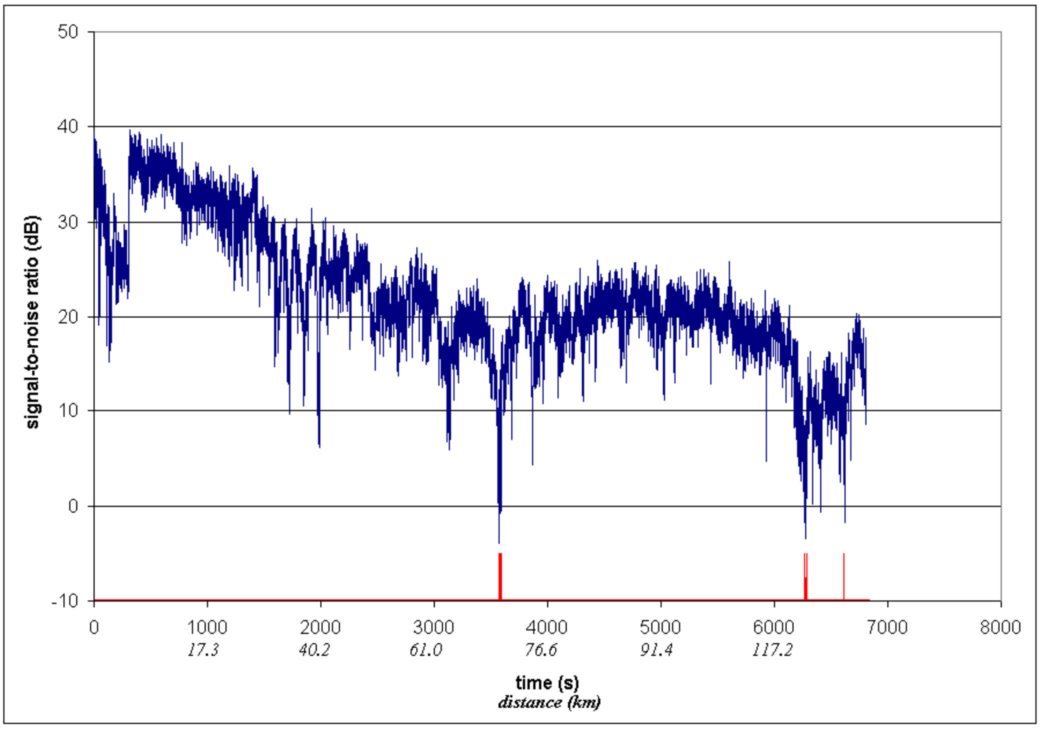


FIGURE 1-9

Sounding 5. Received signal level omnidirectional antenna

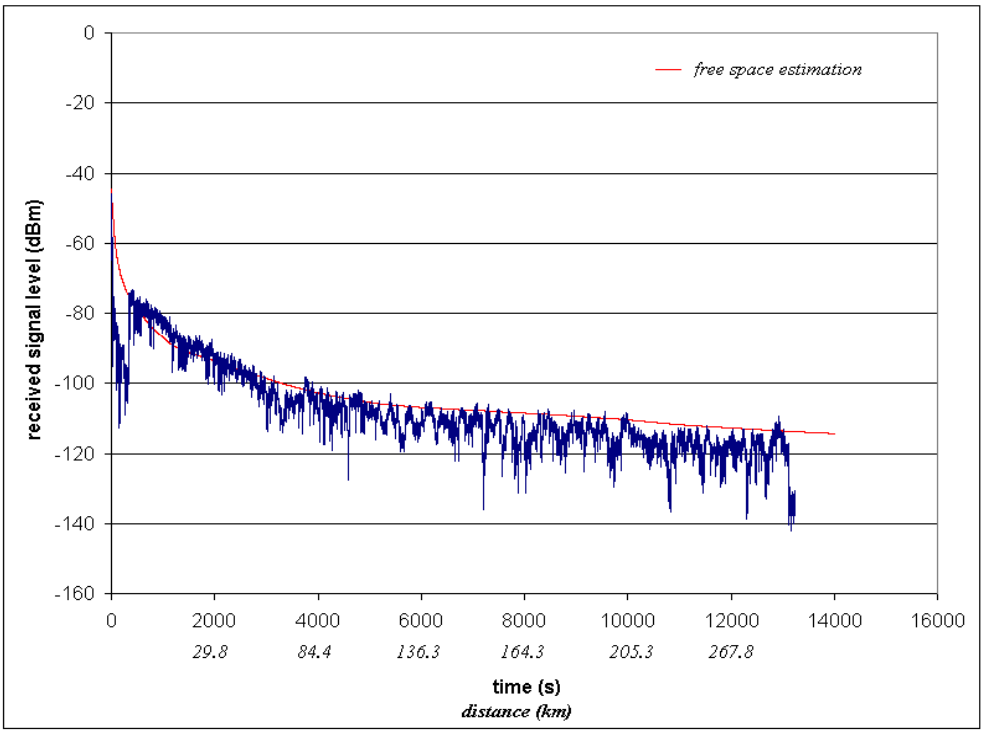


FIGURE 1-10

Sounding 5. *S*/*N*, omnidirectional antenna

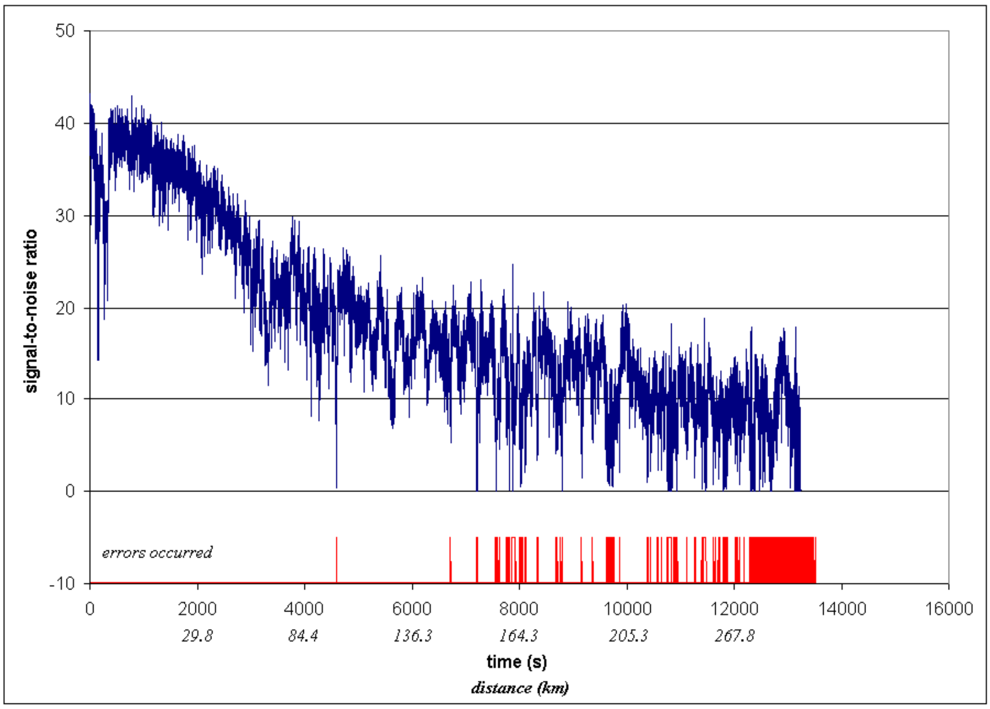


FIGURE 1-11

Sounding 6. Received signal power, omnidirectional antenna

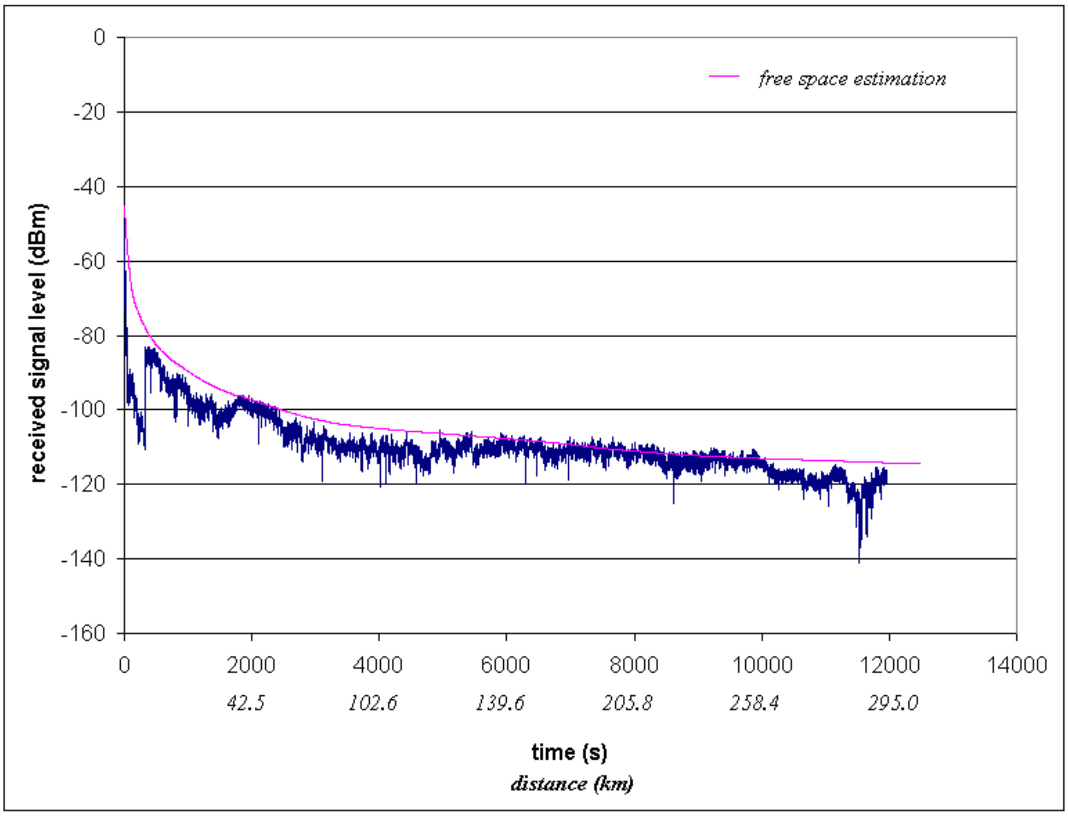
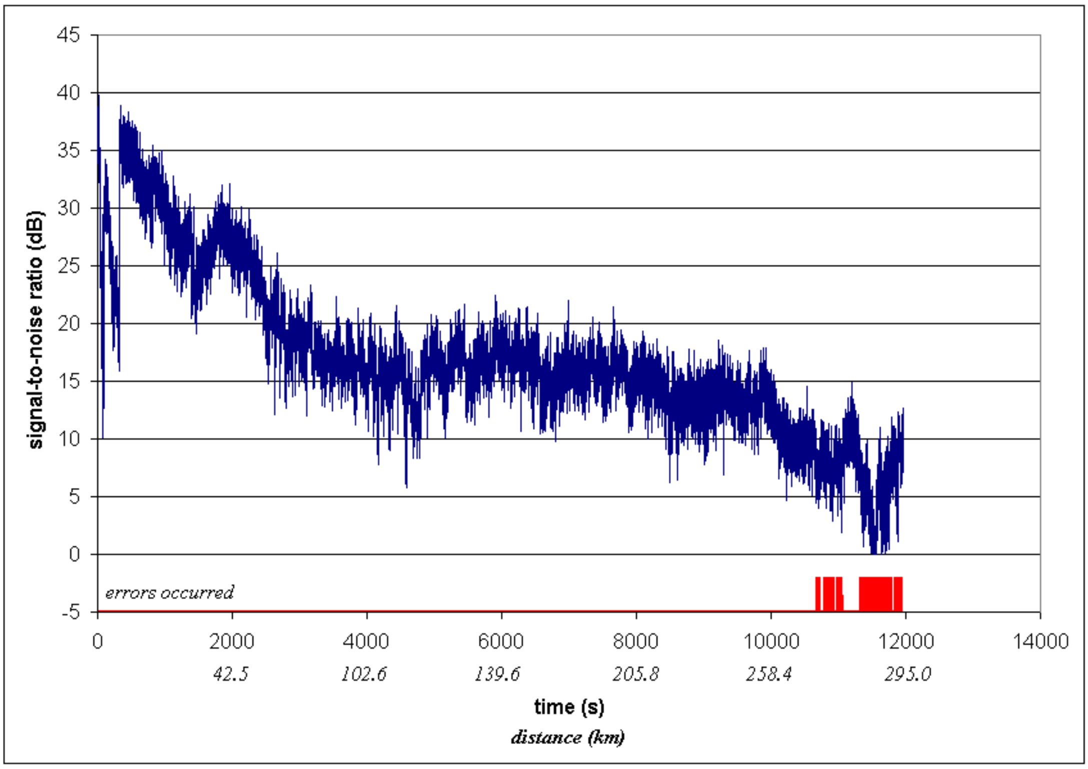


FIGURE 1-12

Sounding 6. *S*/*N*, omnidirectional antenna



Annex 2

Flight signal level and *S*/*N* plots for 400.15-406 MHz with directional antennas

FIGURE 2-1

Sounding 4. Received signal power, directional antenna

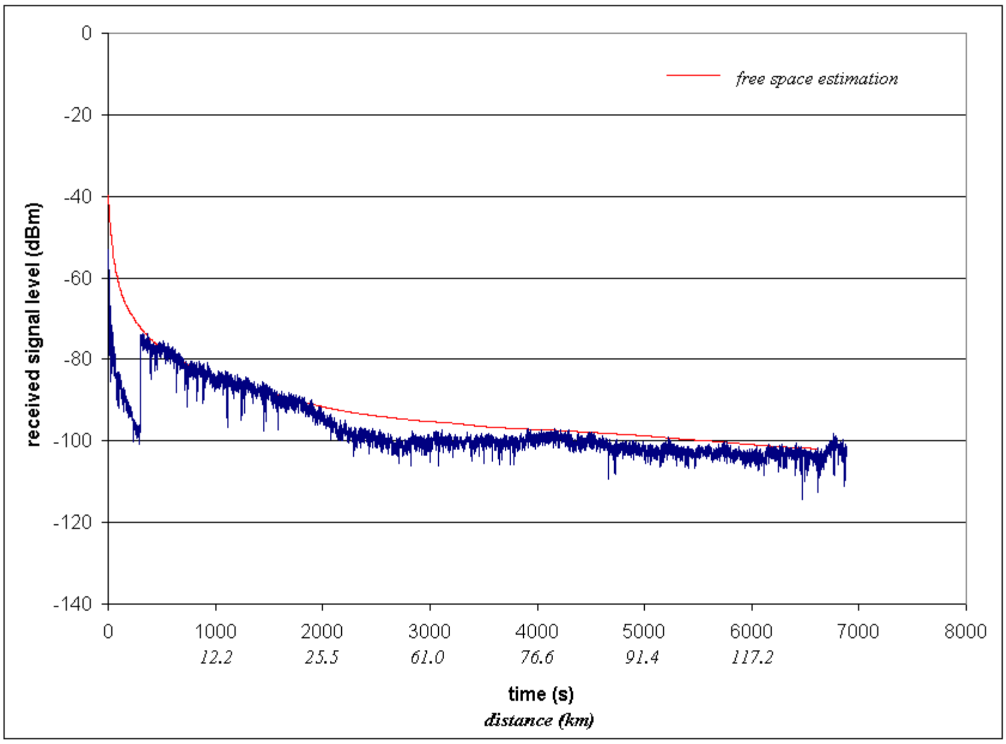


FIGURE 2-2

Sounding 4. *S*/*N*, directional antenna

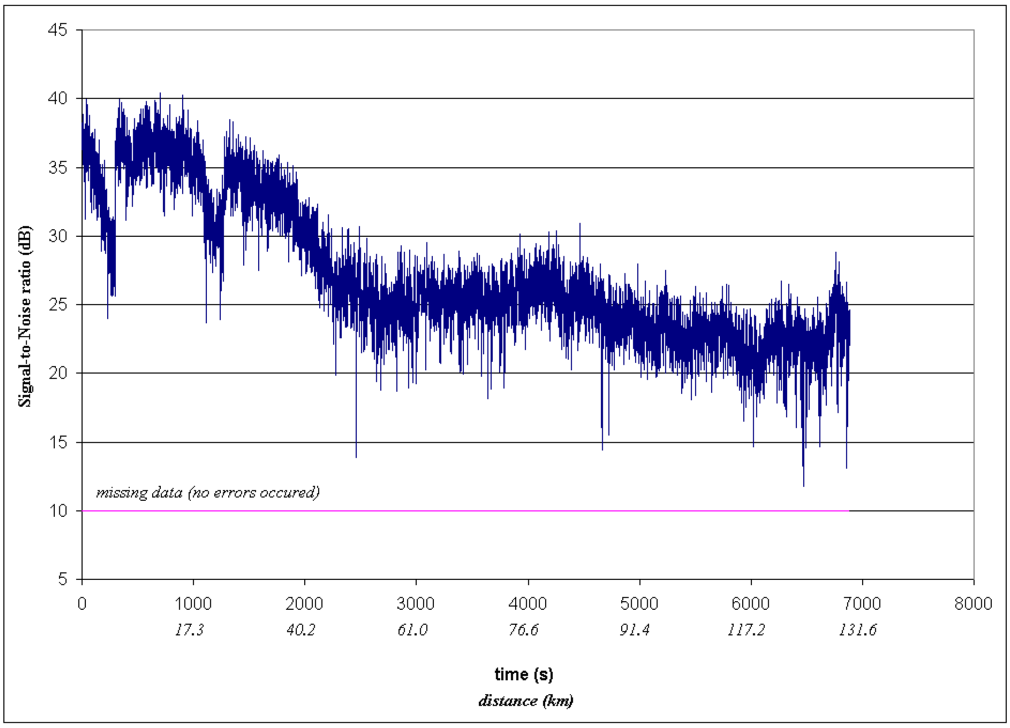


FIGURE 2-3

Sounding 5. Received signal with directional antenna

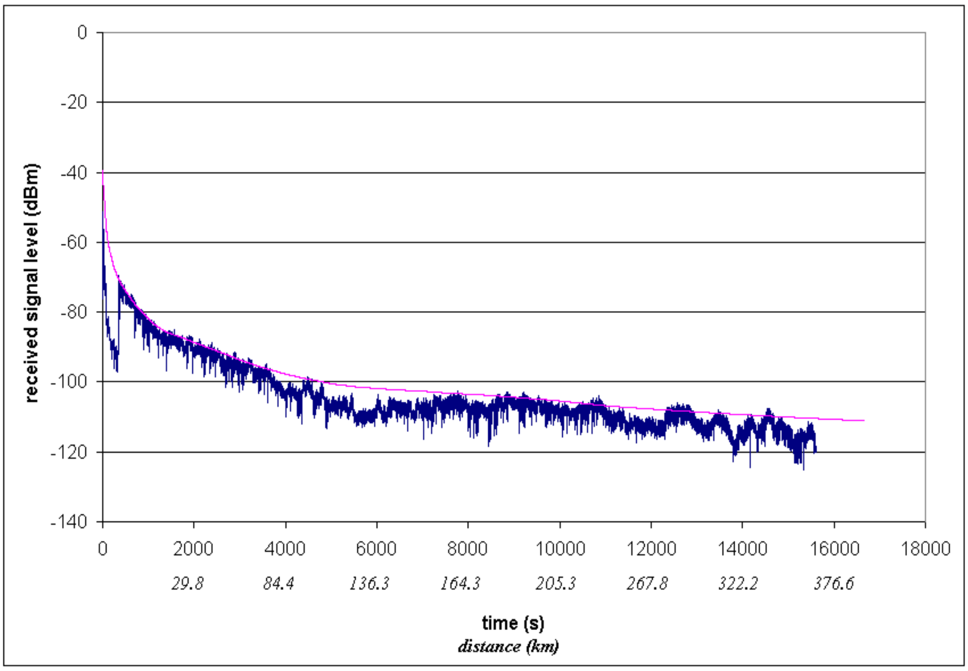


FIGURE 2-4

Sounding 5. *S*/*N*, directional antenna

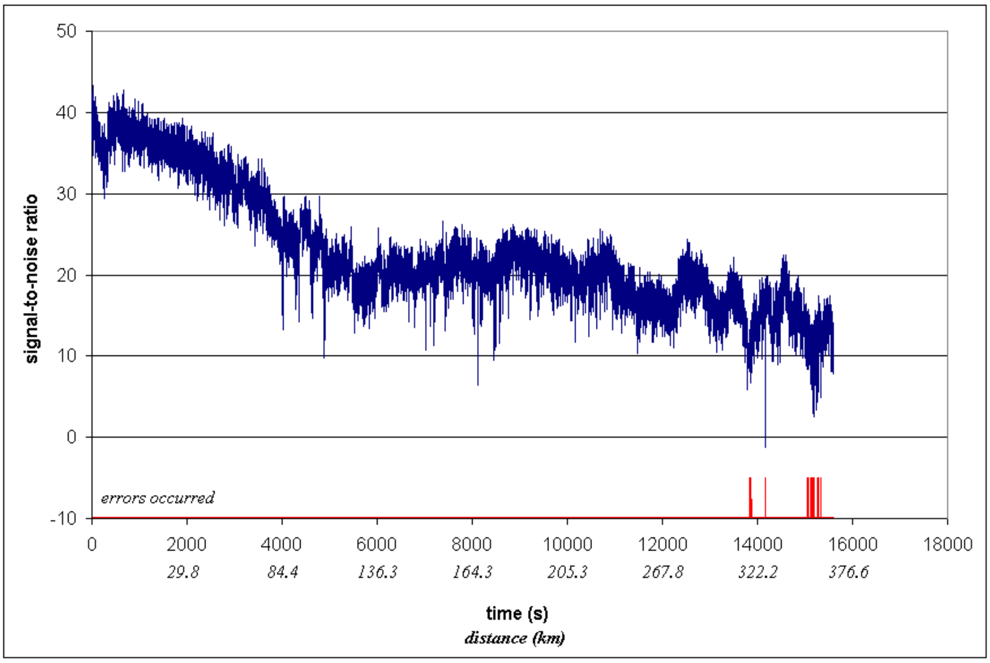


FIGURE 2-5

Sounding 6. Received signal power, directional antenna

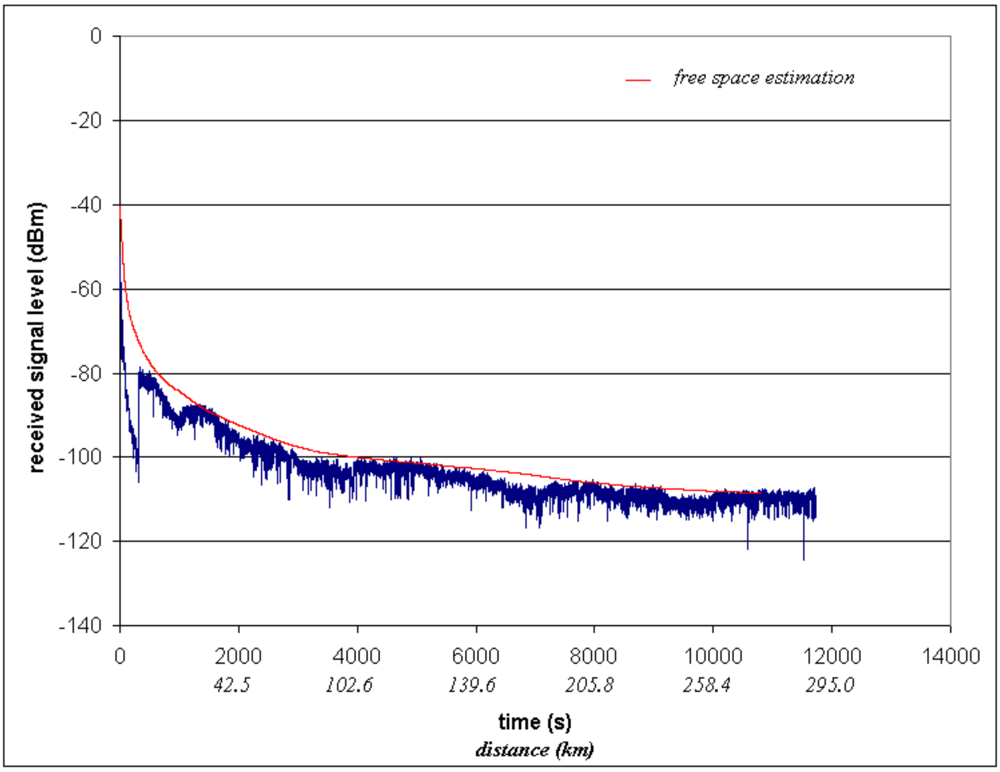
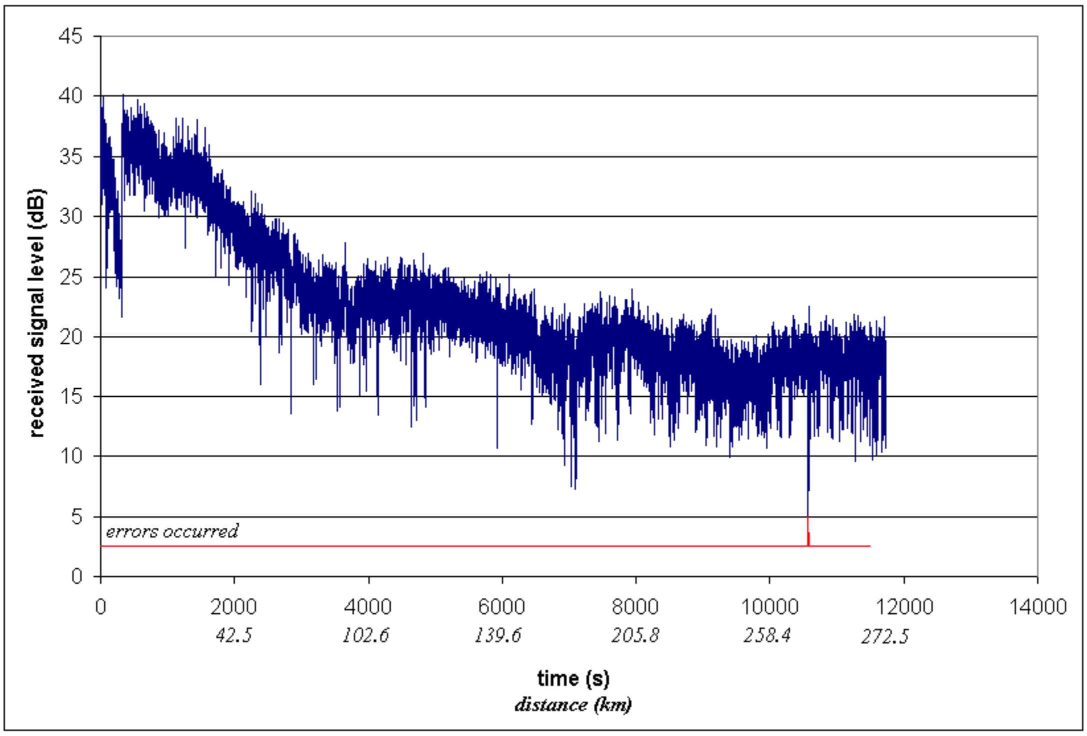


FIGURE 2-6

Sounding 6. *S*/*N*, directional antenna



Annex 3

Flight signal level plots for 400.15-406 MHz, comparison of directional and omnidirectional antennas

FIGURE 3-1

Sounding 4. Comparison of omnidirectional and directional antennas

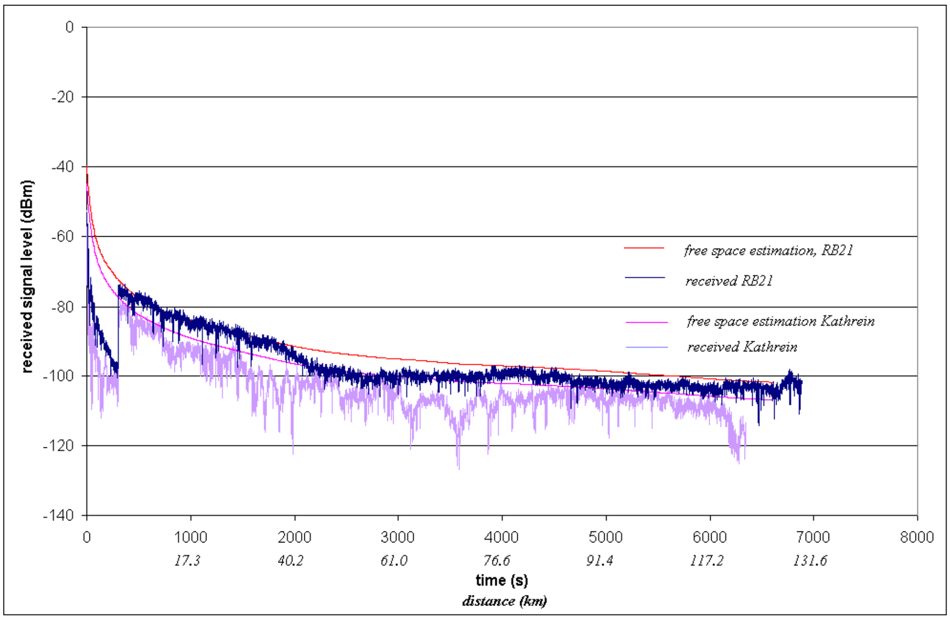


FIGURE 3-2

Sounding 4. Comparison of omnidirectional and directional antennas

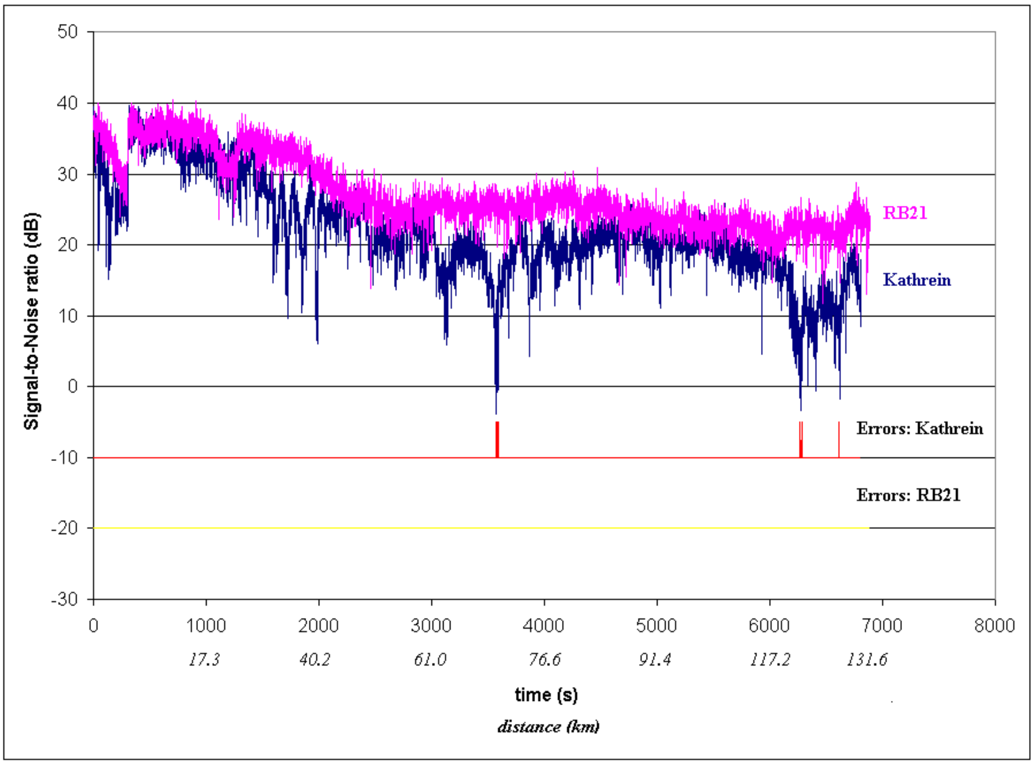


FIGURE 3-3

Sounding 5. Comparison of omnidirectional and directional antennas

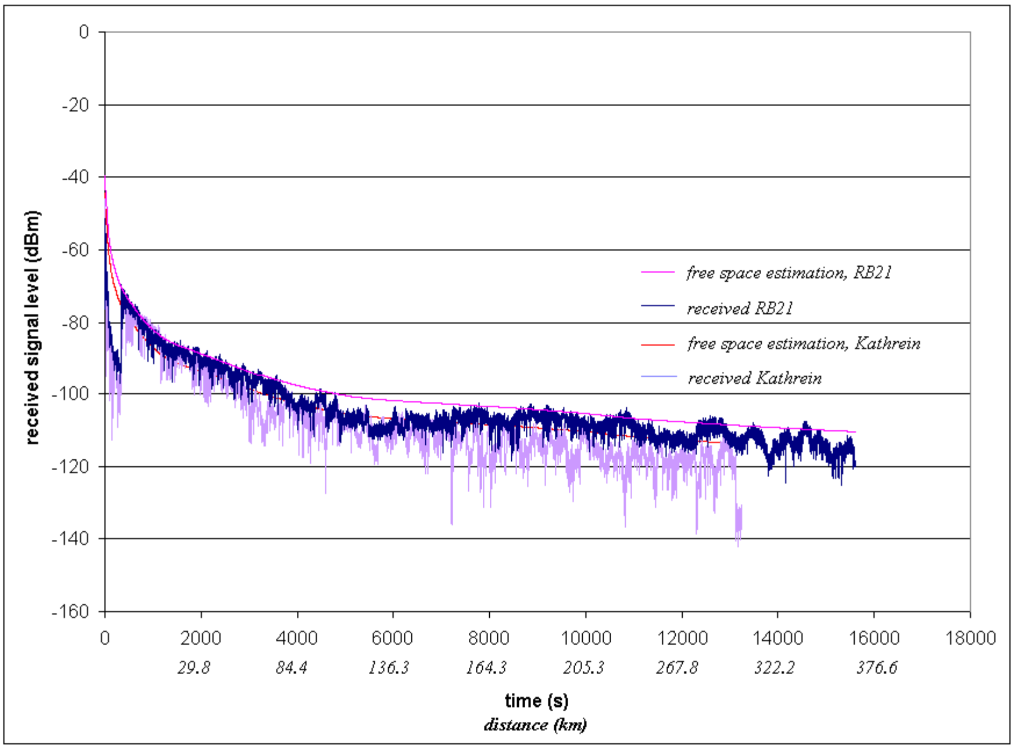


FIGURE 3-4

Sounding 5. Comparison of omnidirectional and directional antennas

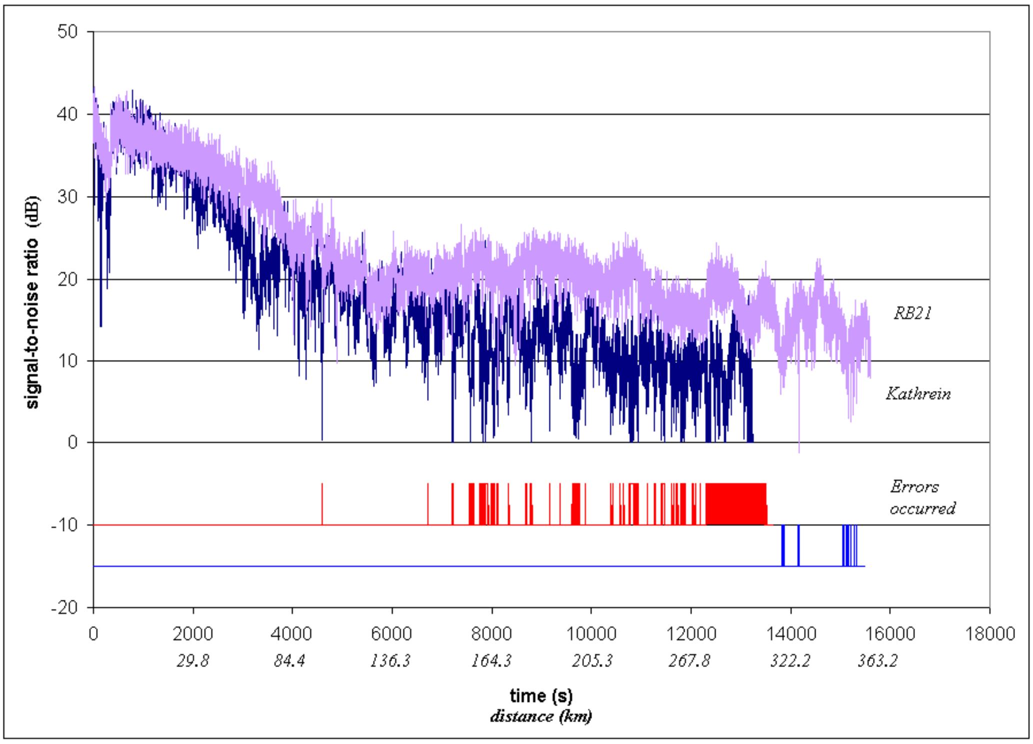


FIGURE 3-5

Sounding 6. Comparison of omnidirectional and directional antennas

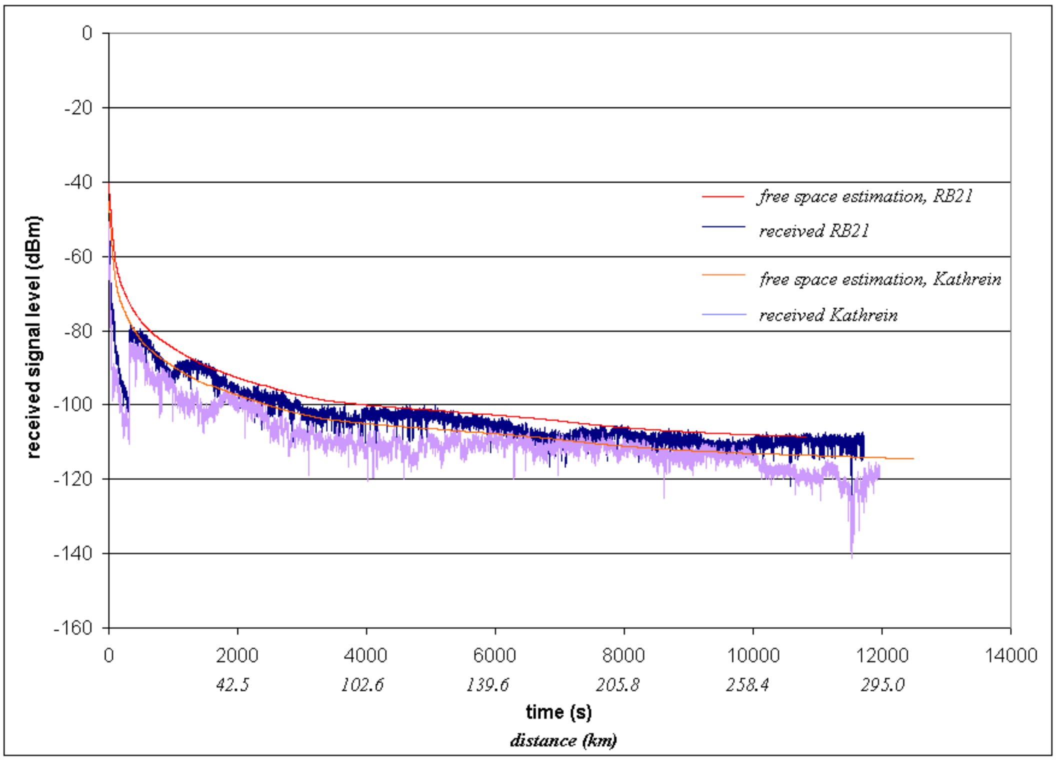
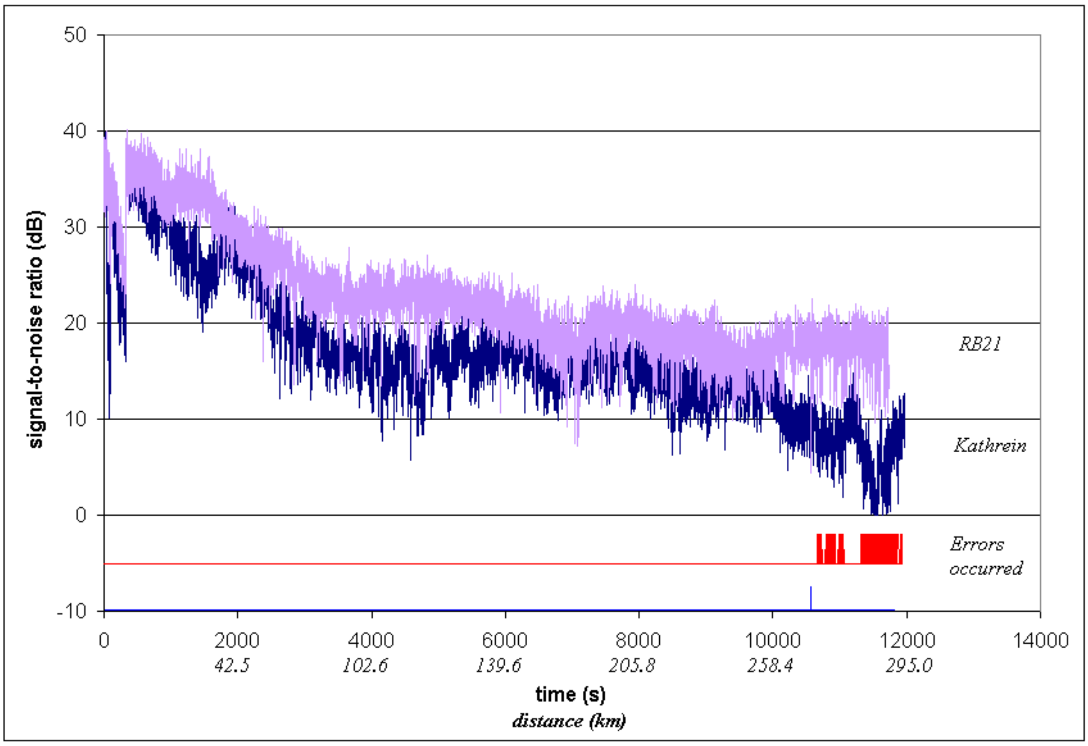


FIGURE 3-6

Sounding 6. Comparison of omnidirectional and directional antennas



Annex 4

Flight path loss plots for 1 675-1 700 MHz

FIGURE 4-1

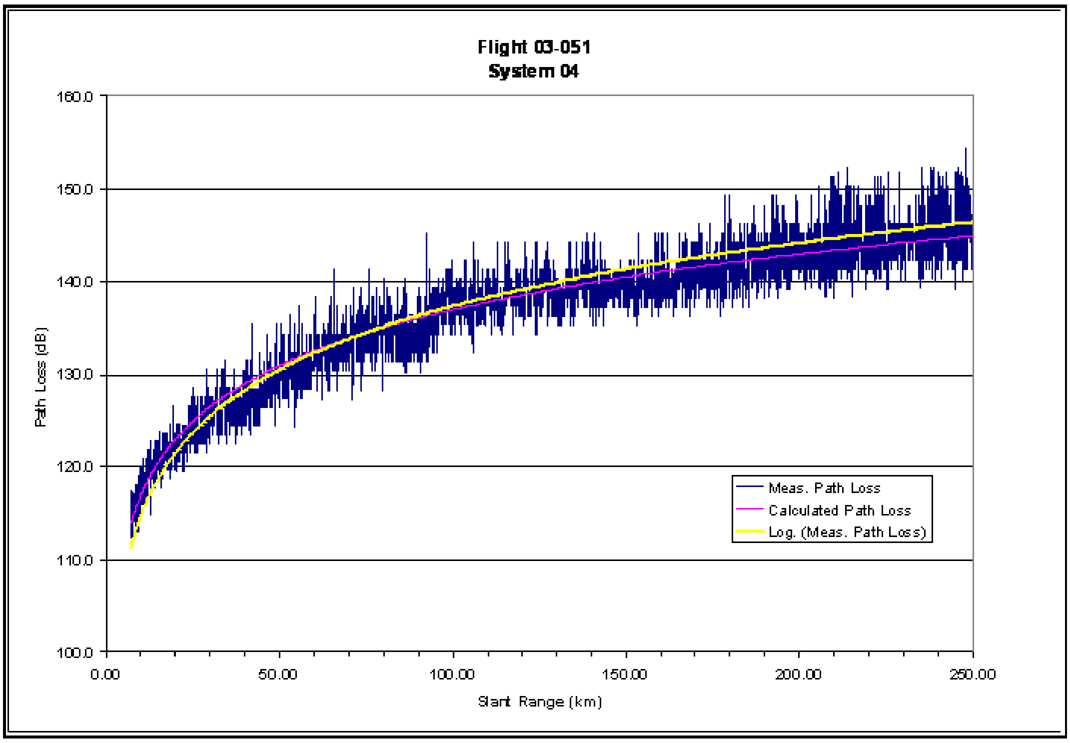


FIGURE 4-2

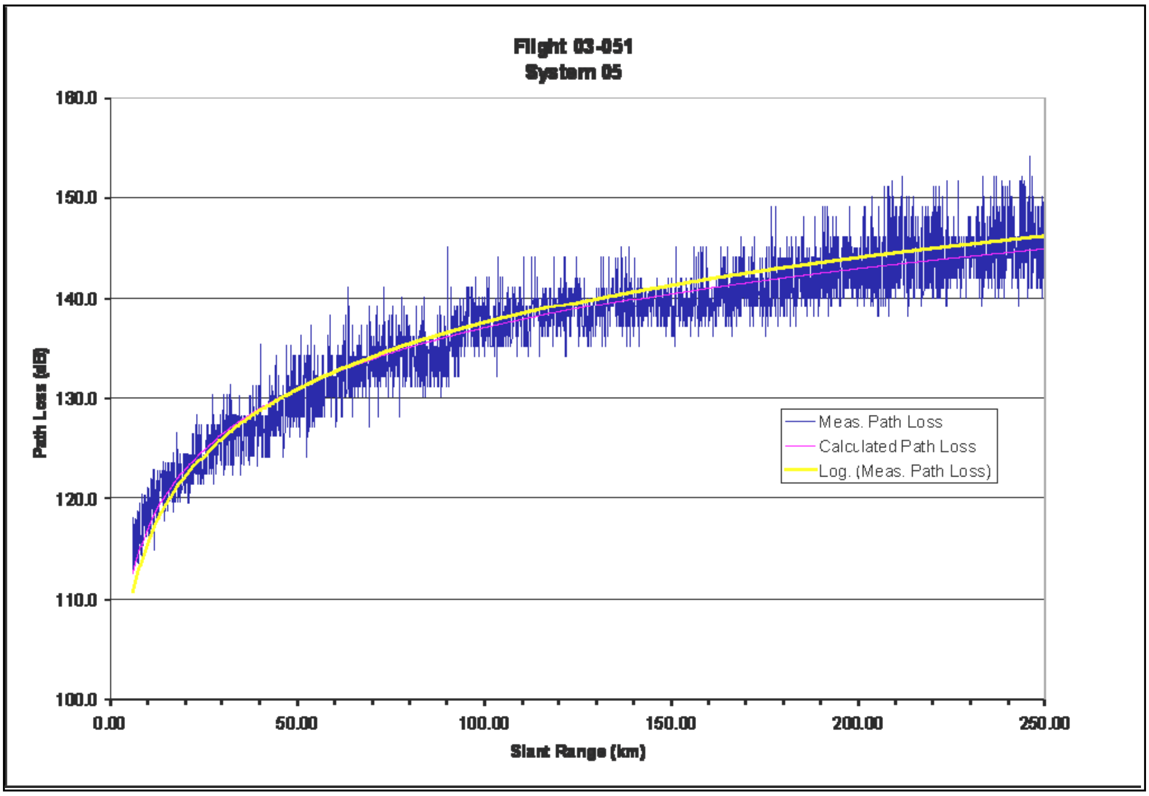


FIGURE 4-3

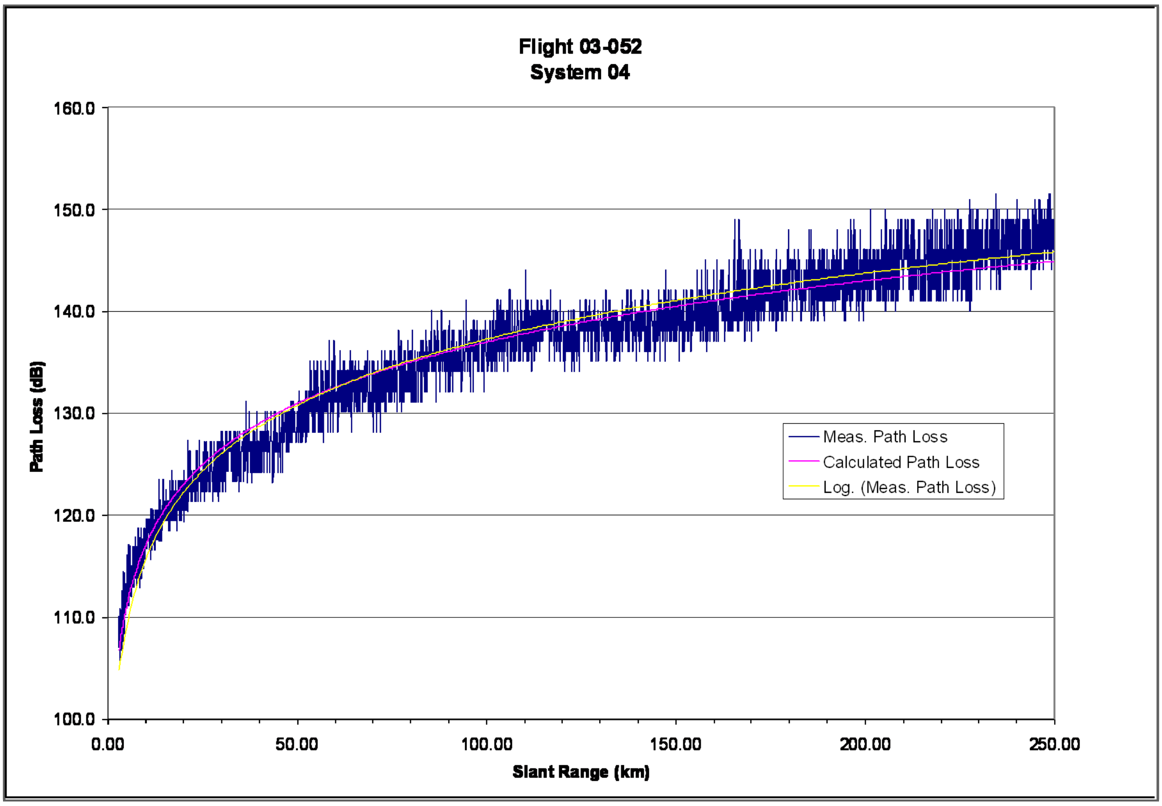


FIGURE 4-4

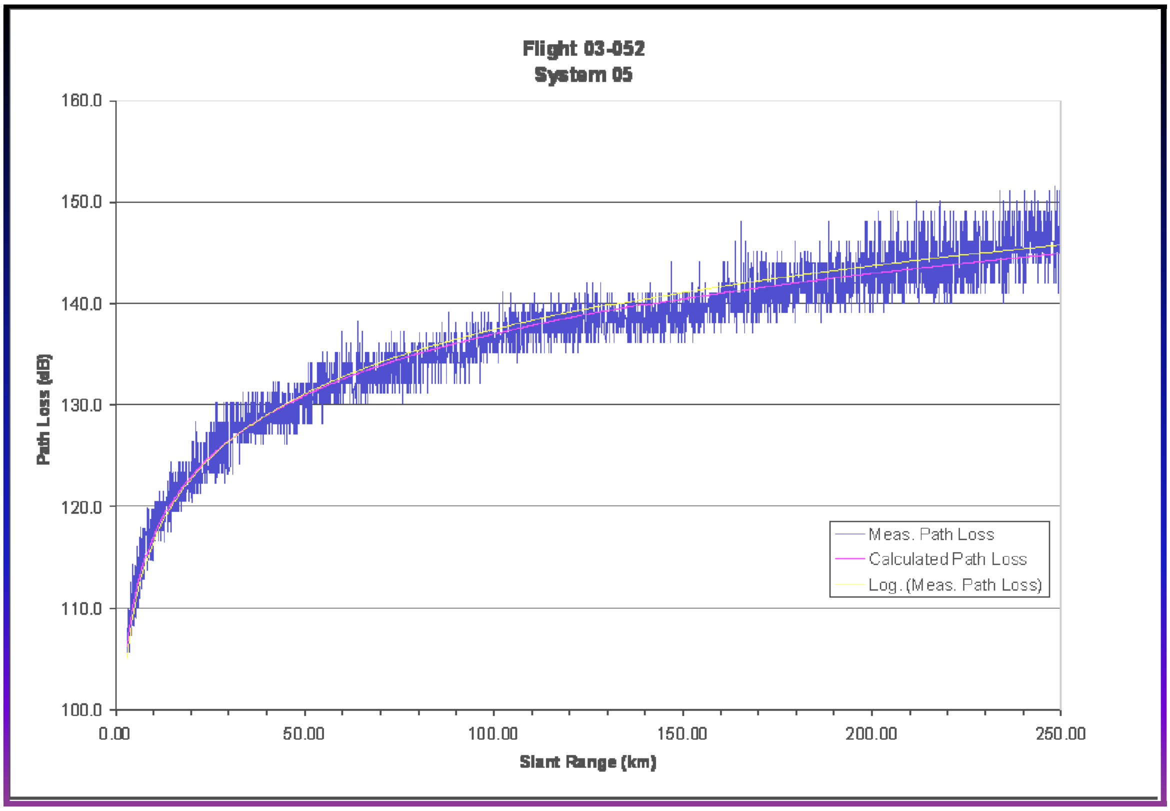
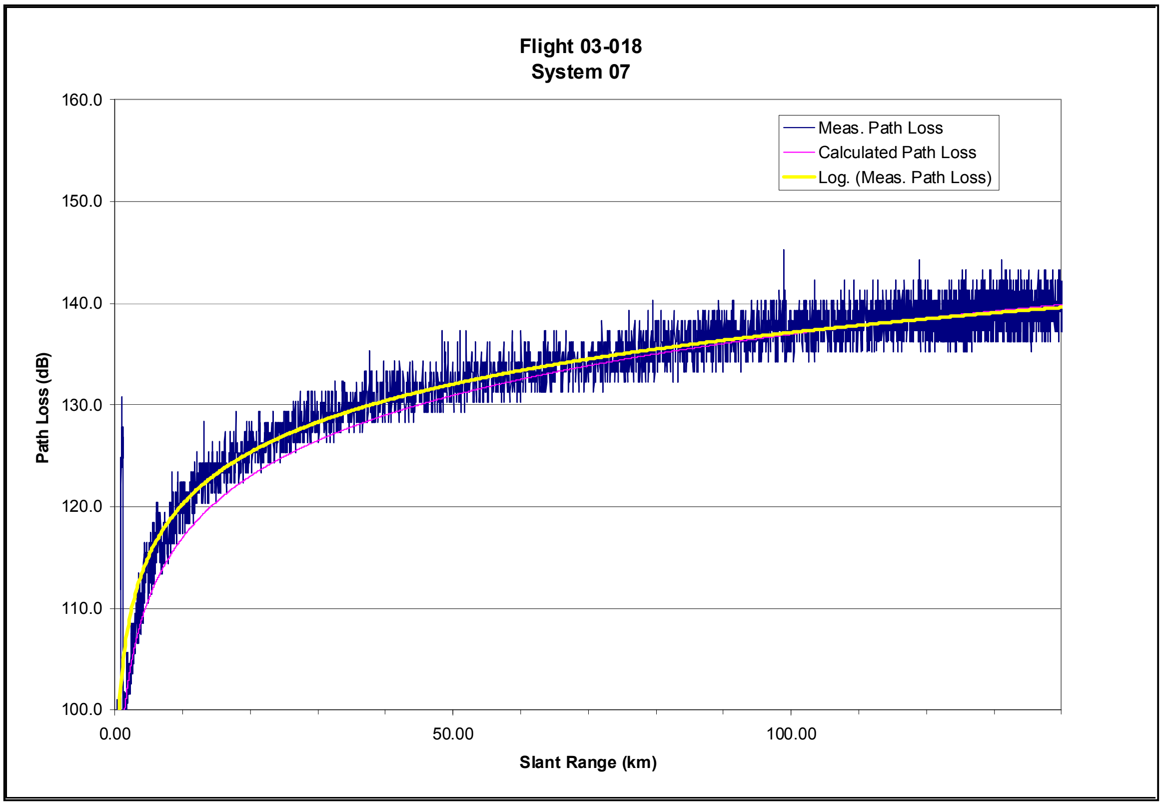


FIGURE 4-5


Flight 03-018
System 07
160.0
150.0
140.0
130.0
120.0
110.0
100.0
Path Loss (dB)
0.00
50.00
100.00
Slant Range (km)
Meas. Path Loss
Calculated Path Loss
Log. (Meas. Path Loss)

Annex 5

Flight signal strength plots for 1 675-1 700 MHz

FIGURE 5-1

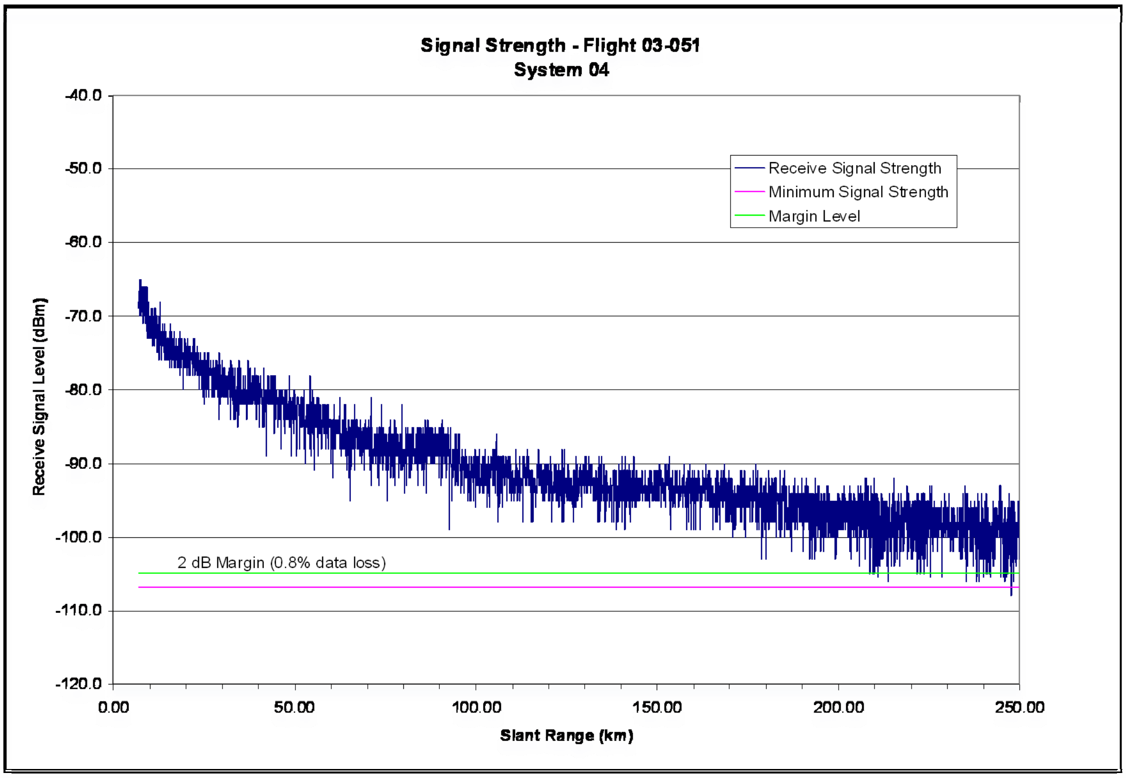


FIGURE 5-2

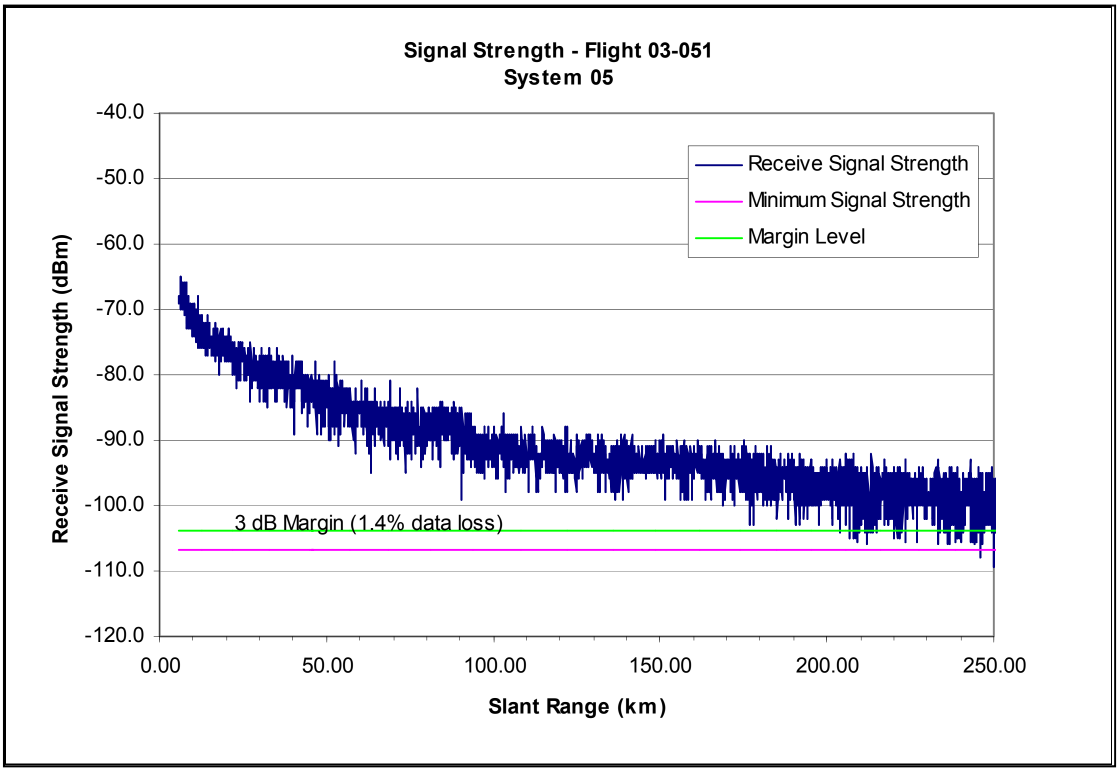


FIGURE 5-3

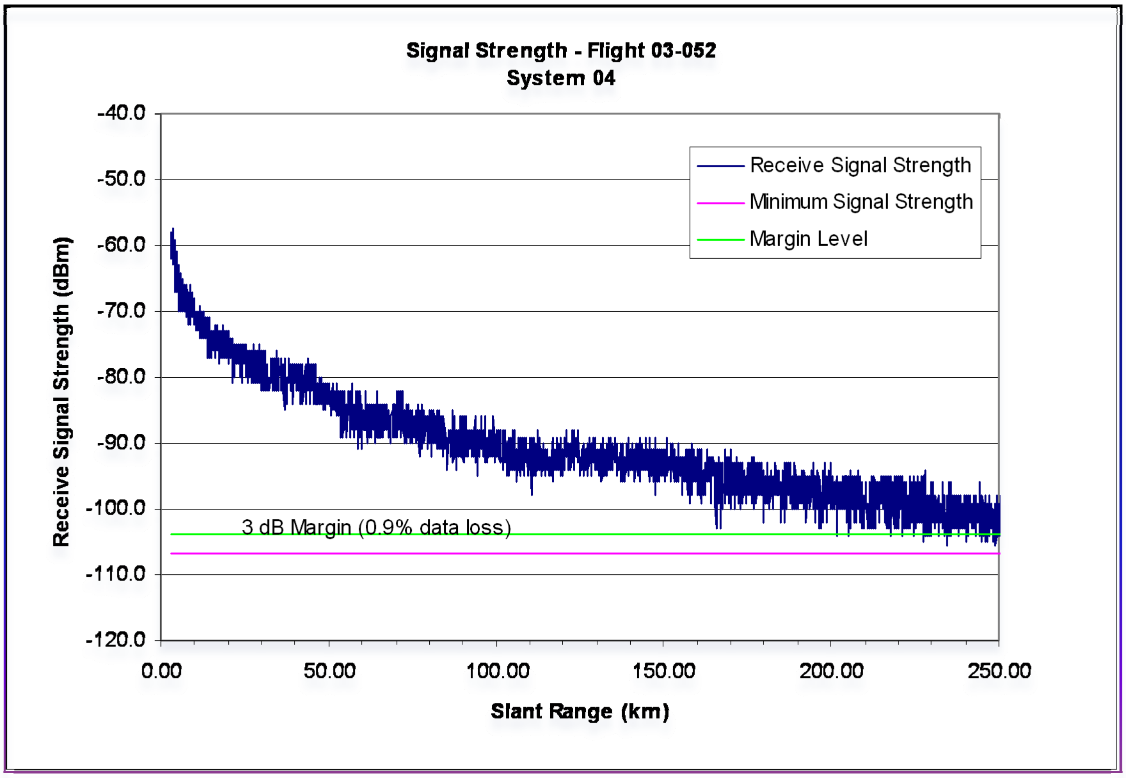


FIGURE 5-4

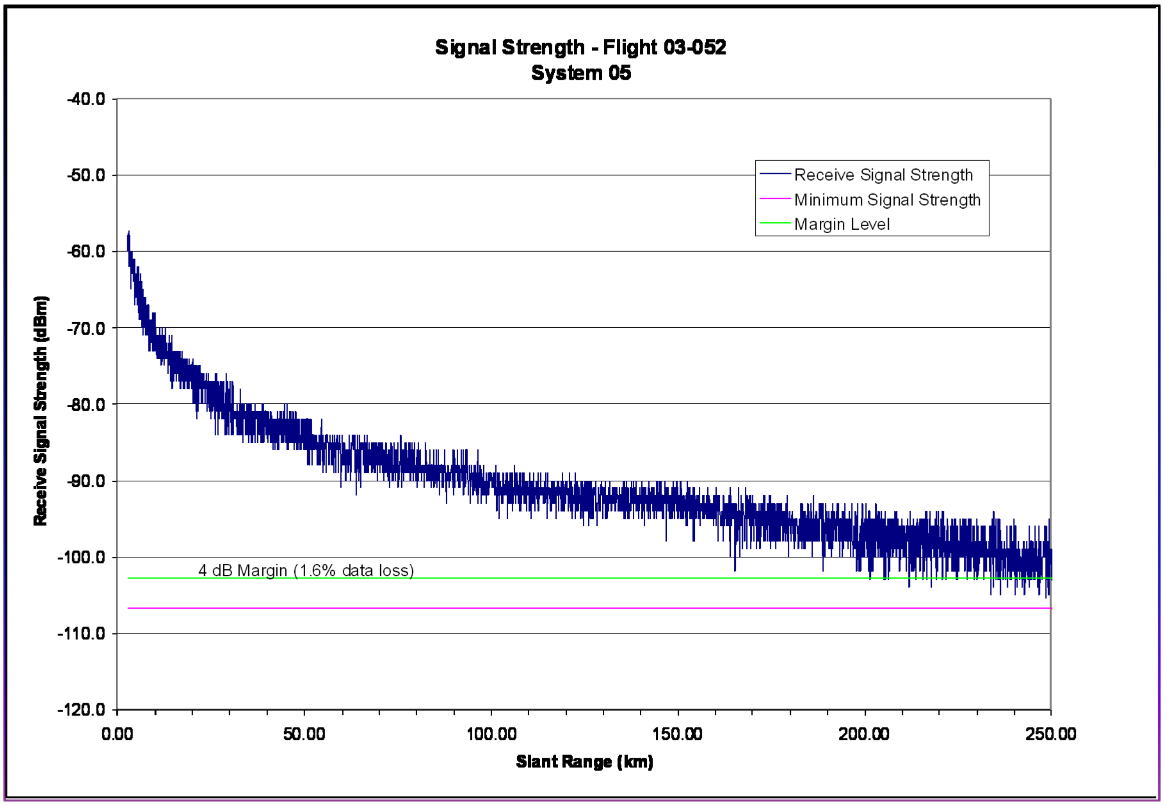
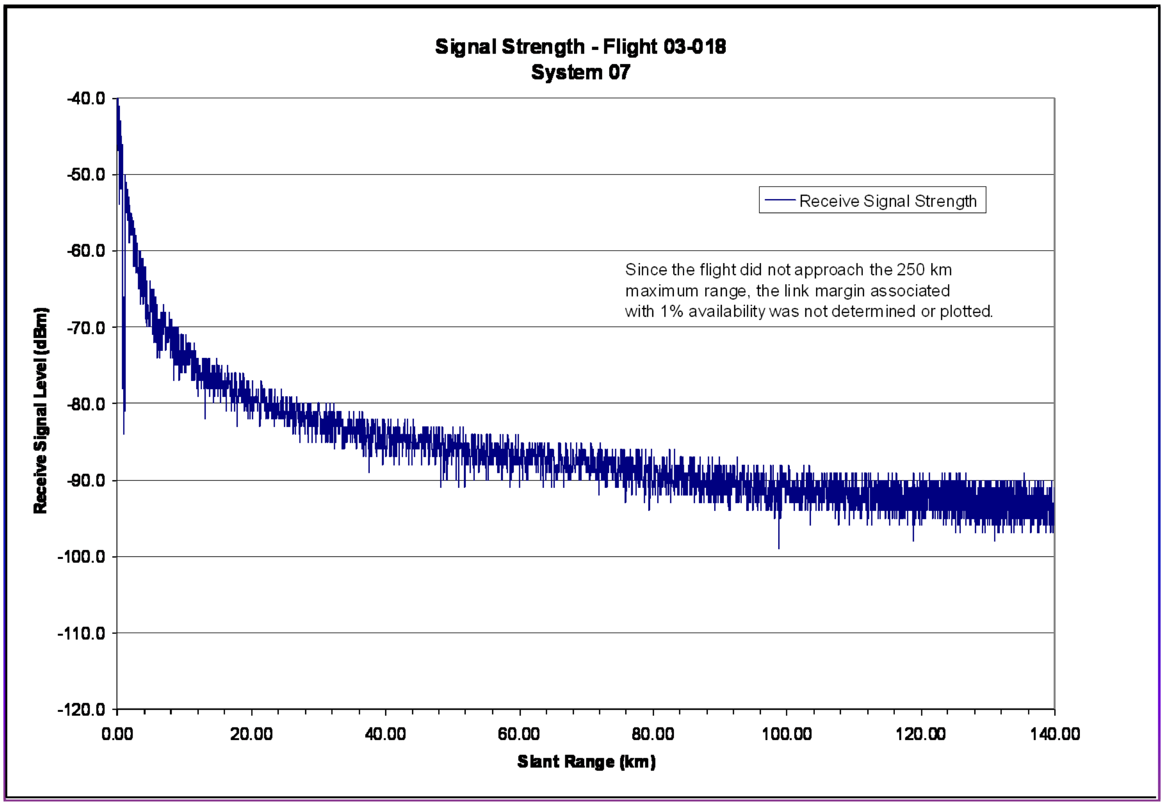


FIGURE 5-5


Signal Strength - Flight 03-018
System 07
Receive Signal Strength
Since the flight did not approach the 250 km maximum range, the link margin associated with 1% availability was not determined or plotted.
Receive Signal Level (dBm)
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-120.0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Slant Range (km)