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Report ITU-R M.2233
(11/2011)

Examples of technical characteristics for unmanned aircraft control and non-payload communications links

M Series

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REPORT ITU-R M.2233

Examples of technical characteristics for unmanned aircraft control and non-payload communications links

(2011)

1 Introduction

There is significant growth forecast in the unmanned aircraft systems (UAS) sector of aviation. Though UAS have traditionally been used in segregated airspace where separation from other air traffic can be assured, administrations expect broad deployment of UAS in non-segregated airspace alongside manned aircraft. Current and future UAS operations include scientific research, search and rescue operations, hurricane and tornado tracking, volcanic activity monitoring and measurement, mapping, forest fire suppression, weather modification (e.g. cloud seeding), surveillance, communication relays, agricultural applications, environmental monitoring, emergency management, and law enforcement applications.

Based on Report ITU-R M.2171, it is predicted that a maximum of 34 MHz of terrestrial spectrum and 56 MHz of satellite spectrum, would be required to support control and non-payload communications (CNPC) links for the anticipated growth of UAS operations in non-segregated airspace.

It should be noted that the beyond line-of-sight (BLoS) maximum spectrum requirements of 56 MHz is derived from a regional beam architecture, which assumed three satellites to provide service in the same coverage area, as well as a UA antenna of a narrow enough beam-width to discriminate between the three satellites. Other architecture based on satellite spot beams and UA operating with omnidirectional antenna may lead to different spectrum requirements.

In this context, the purpose of this Report is to give examples of technical characteristics for terrestrial and satellite UAS CNPC links in certain frequency bands (960-1 164 MHz and 5 000-5 150 MHz frequency bands for line-of-sight (LoS), 1 545-1 555 MHz, 1 610-1 626.5 MHz, 1 646.5-1 656.5 MHz, 5 030-5 091 MHz, 12/14 GHz and 20/30 GHz frequency bands for BLoS). Although these characteristics could be used in compatibility studies, the compatibility studies are not the subject of this Report. It is noted that other frequency bands or systems may also be considered.

Frequency band and performance requirement will have to comply with the International Civil Aviation Organisations (ICAO) standards and recommended practices (SARPs), however in the absence of ICAO SARPs on UAS and of corresponding performance requirements, the examples provided in this report give useful information on achievable link performances.

2 List of Annexes

– **Annex 1:** Example of line-of-sight control and non-payload communication links characteristics for unmanned aircraft systems in the frequency bands 960-1 164 MHz and 5 000-5 150 MHz.

– **Annex 2:** Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency bands 1 545-1 555 MHz (space-to-Earth), 1 610-1 626.5 MHz (space-to-Earth and Earth-to-space) and 1 646.5-1 656.5 MHz (Earth-to-space).

– **Annex 3:** Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency band 5 030-5 091 MHz.

– **Annex 4:** Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency bands 12/14 GHz and 20/30 GHz.

– **Annex 5:** Glossary.

Annex 1

Example of line-of-sight control and non-payload communication links characteristics for unmanned aircraft systems in the frequency bands 960-1 164 MHz and 5 000-5 150 MHz

This Annex presents examples of link budgets for the terrestrial UAS control links used in the sharing studies in Report ITU-R M.2205 and Report ITU-R M.2237, respectively. With minor modifications, these budgets could be applied to a number of alternative architectures.

For the frequency band 5 000-5 150 MHz two sets of parameters are presented corresponding to the two architectures considered in Report ITU-R M.2237.

1 First set of parameters (960-977 MHz and 5 030-5 091 MHz frequency bands)

All UAS are grouped into two classes, medium/large UAS (M/LUAS) and small UAS (SUAS). Three kinds of links are considered:

– wideband M/LUAS links, which carry all classes of telemetry traffic (*including* pilot situational awareness enhancing video and downlinked weather-radar data) in 300 kHz channels;

– basic M/LUAS links, which operate in both telecommand and telemetry directions in 37.5 kHz channels and carry all traffic classes *except* pilot situational awareness enhancing video and downlinked weather-radar data;

– SUAS links that operate in both telecommand and telemetry directions in 12.5 kHz channels but carry only the telecommand and telemetry messages needed for pilot control of the UA.

Table 1-1 shows telecommand uplink (UL) and telemetry downlink (DL) budgets for five types of UAS links operating with 99.8% availability along 46 km paths between a ground-station antenna 30 m above the ground and a UA flying at 300 m above ground level (AGL):

– 960-977 MHz basic M/LUAS links;
– 960-977 MHz SUAS links;
– 5 030-5 091 MHz basic M/LUAS links;
– 5 030-5 091 MHz wideband M/LUAS links (DL only);
– 5 030-5 091 MHz SUAS links.

For the M/LUAS links operating in the frequency band 5 030-5 091 MHz in Table 1-1, two sets of telemetry DL budgets are provided. One set assumes a UA transmitter power of 40 dBm (10 W), unconstrained by the need to avoid interfering with nearby microwave landing system (MLS) receivers. The second set assumes the UA must transmit at lower power to protect an MLS receiver 300-1 000 m away (which could exist if the UA is within 43 km of an MLS transmitter, whose maximum operating range is 42 km). For a basic or wideband telemetry DL, the maximum MLS-constrained telemetry DL transmitter power is 31 dBm or 33 dBm, respectively. For a SUAS telemetry DL operating in the frequency band 5 030-5 091 MHz, the MLS-constrained power of 29 dBm (800 mW) is assumed in all cases, even when no MLS transmitter is in the vicinity. A positive link margin is shown to exist in all cases.

Table 1-2 shows the maximum ranges at which the M/LUAS links can operate when the UA flies 5.5 km AGL, and the link budgets for each of those cases. The basic 960-977 MHz link can work at 141 km, the basic 5 030-5 091 MHz link at 154 km, and the wideband 5 030-5 091 MHz telemetry DL at 109 km. The basic 5 030-5 091 MHz link has the longest range because it has a smaller bandwidth than the other 5 030-5 091 MHz link, and its postulated ground-antenna gain greatly exceeds that of the 960-977 MHz link.

TABLE 1-1

Example of link budgets for unmanned aircraft at 300 m above ground level and 46 km from ground station

Direction	**Frequency (MHz)**	**960-977**		**5 030-5 091**		
	UAS Type	**M/LUAS**	**SUAS**	**M/LUAS**		**SUAS**
	Link	**Basic**		**Basic**	**Wideband**	
	Bandwidth (kHz)	**37.5**	**12.5**	**37.5**	**300**	**12.5**
	Range (km)	**46**	**46**	**46**	**46**	**46**
UL	Transmitter power (dBm)	40	30	40	Not Applicable	29
	Transmitter antenna gain (1) (dBi)	8	8	28		28
	Transmitter cable loss (dB)	1	1	1		1
	Transmitter e.i.r.p. (dBm)	47	37	67		56
	Free-space loss (dB)	125	125	140		140
	Additional path loss (2) (dB)	11	11	12		12
	Receiving antenna gain (dBi)	−10	−10	−10		−10
	Receiver cable loss (dB)	1	1	2		2
	Received signal power (dBm)	−100	−110	−97		−108
	Noise SPD at 290 K (dBm/Hz)	−174	−174	−174		−174

Direction	Frequency (MHz)	960-977		5 030-5 091				
	UAS Type	M/LUAS	SUAS	M/LUAS				SUAS
	Link	Basic		Basic		Wideband		
	Bandwidth (kHz)	37.5	12.5	37.5		300		12.5
	Range (km)	46	46	46		46		46
	Receiver noise figure (dB)	2	2	2				2
	Receiver bandwidth (dB/Hz)	46	41	46				41
	Receiver noise power (dBm)	−126	−131	−126				−131
	SNR (dB)	26	21	29				23
	Theoretical SNR for BER=10^{-6} [3]	4	4	4				4
	Implementation margin	2	2	2				2
	Required SNR for BER = 10^{-6} [3] (dB)	6	6	6				6
	Aviation safety margin (dB)	6	6	6				6
	Excess margin (dB)	14	9	17				11
DL	Transmitter power (dBm)	40	30	40	31[4]	40	33[4]	29[4]
	Transmitter antenna gain[1] (dBi)	−10	−10	−10	−10	−10	−10	−10
	Transmitter cable loss (dB)	1	1	2	2	2	2	2
	Transmitter e.i.r.p. (dBm)	29	19	28	19	28	21	17
	Free-space loss (dB)	125	125	140	140	140	140	140
	Additional path loss[2] (dB)	11	11	12	12	12	12	12
	Receiving antenna gain (dBi)	8	8	28	28	28	28	28
	Receiver cable loss[3] (dB)	1	1	1	1	1	1	1
	Received signal power (dBm)	−100	−110	−97	−106[4]	−97	−104[4]	−108[4]
	Noise SPD at 290 K (dBm/Hz)	−174	−174	−174	−174	−174	−174	−174
	Receiver noise figure (dB)	2	2	2	2	2	2	2
	Receiver bandwidth (dB/Hz)	46	41	46	46	55	55	41
	Receiver noise power (dBm)	−126	−131	−126	−126	−117	−117	−131
	SNR (dB)	26	21	29	20[4]	20	13[4]	23[4]
	Theoretical SNR for BER=10^{-6} [3] (dB)	4	4	4	4	4	4	4
	Implementation margin (dB)	2	2	2	2	2	2	2
	Required SNR for BER = 10^{-6} [3] (dB)	6	6	6	6	6	6	6
	Aviation safety margin (dB)	6	6	6	6	6	6	6
	Excess margin (dB)	14	9	17	8[4]	8	1[4]	11[4]

(1) Airborne antenna diversity and/or ground-site diversity assumed.

(2) 99.8% availability; 30 m above ground-antenna height; 300 m UA altitude. Primarily multipath loss.

(3) QPSK with ½-rate concatenated Reed-Solomon and convolutional coding.

(4) Maximum feasible value when UA is within 43 km of MLS ground transmitter.

(5) Low-noise amplifier assumed to be near top of ground-antenna mast.

TABLE 1-2

Medium/large unmanned aircraft system

Example of link budgets for unmanned aircraft at 5.5 km above ground level and maximum link range

Direction	Frequency (MHz)	960-977	5 030-5 091	
	Link	Basic	Basic	Wideband
	Bandwidth (kHz)	37.5	37.5	300
	Range (km)	141	154	109
UL	Transmitter power (dBm)	40	40	Not Applicable
	Transmitter antenna gain(1) (dBi)	8	28	
	Transmitter cable loss (dB)	1	1	
	Transmitter e.i.r.p. (dBm)	47	67	
	Free-space loss (dB)	135	150	
	Additional path loss(2) (dB)	15	19	
	Receiving antenna gain (dBi)	−10	−10	
	Receiver cable loss (dB)	1	2	
	Received signal power (dBm)	−114	−114	
	Noise SPD at 290 K (dBm/Hz)	−174	−174	
	Receiver noise figure (dB)	2	2	
	Receiver bandwidth (dB/Hz)	46	46	
	Receiver noise power (dBm)	−126	−126	
	SNR (dB)	12	12	
	Theoretical SNR for BER = 10^{-6} (3) (dB)	4	4	
	Implementation margin (dB)	2	2	
	Required SNR for BER = 10^{-6} (3) (dB)	6	6	
	Aviation safety margin (dB)	6	6	
	Excess margin (dB)	0	0	
DL	Transmitter power (dBm)	40	40	40
	Transmitter antenna gain(1) (dBi)	−10	−10	−10
	Transmitter cable loss (dB)	1	2	2
	Transmitter e.i.r.p. (dBm)	29	28	28
	Free-space loss (dB)	135	150	147
	Additional path loss(2) (dB)	15	19	13
	Receiving antenna gain (dBi)	8	28	28
	Receiver cable loss(4) (dB)	1	1	1
	Received signal power (dBm)	−114	−114	−105
	Noise SPD at 290 K (dBm/Hz)	−174	−174	−174
	Receiver noise figure (dB)	2	2	2
	Receiver bandwidth (dB/Hz)	46	46	55
	Receiver noise power (dBm)	−126	−126	−117
	SNR (dB)	12	12	12
	Theoretical SNR for BER = 10^{-6} (3) (dB)	4	4	4
	Implementation margin (dB)	2	2	2
	Required SNR for BER = 10^{-6} (3) (dB)	6	6	6
	Aviation safety margin (dB)	6	6	6
	Excess margin (dB)	0	0	0

(1) Airborne antenna diversity and/or ground-site diversity assumed.

(2) 99.8% availability; 30 m above ground-antenna height; 5.5 km UA altitude. Primarily multipath loss.

(3) QPSK with ½-rate concatenated Reed-Solomon and convolutional coding.

(4) Low-noise amplifier assumed to be near top of ground-antenna mast.

2 Second set of parameters (5 000-5 150 MHz frequency band)

For the UA, it is considered to take an UA's antenna similar to the distance measurement equipment (DME)'s antenna referred to in Recommendation ITU-R M.1642-2 with a maximum antenna gain of 3 dBi.

For the UACS, two types of antenna are considered: tracking ones having 24 dBi gain and sectoral ones having 10 dBi gain.

Typical cell size is considered to be 200 km. Each link between the UA and the UACS would require bandwidth of 37.5 kHz. However, when considering approaches (distances up to 35 km), higher data rate might be needed and therefore, bandwidth of 300 kHz are considered (only the downlink case).

The following table gives the main characteristics for UAS systems used in the studies contained in this document, as well as example link budgets for the different cases:

TABLE 1-3

Example of command and non-payload communication link budget

LINK BUDGET	Small UA		Medium/Large UA					
	UA --> UACS	UA (video) --> UACS	UACS (tracking antenna) --> UA	UACS (sectoral antenna) --> UA	UA --> UACS (tracking antenna)	UA --> UACS (sectoral antenna)	UA (video) --> UACS (tracking antenna)	UA (video) --> UACS (sectoral antenna)
Modulation	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK
Frequency (MHz)	5 091	5 091	5 091	5 091	5 091	5 091	5 091	5 091
Wavelength (m)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
UACS – UAV distance d (km)	26	26	200	200	200	200	35	35
UACS – UAV distance d (NM)	14	14	108	108	108	108	19	19
Free space losses (dB)	−134.88	−134.88	−152.6	−152.6	−152.6	−152.6	−137.5	−137.5
e.i.r.p. (dBm)	25.5	25.5	52	52	41	41	41	41
Transmitting antenna gain (dBi)	3	3	24	10	3	3	3	3
Transmitter cable losses (dB)	−2	−2	−1	−1	−2	−2	−2	−2
Received noise level (dBm)	−126.26	−117.23	−126.26	−126.26	−126.26	−126.26	−117.23	−117.23
Noise factor (dB)	2	2	2	2	2	2	2	2
kT (dBm/Hz)	−174	−174	−174	−174	−174	−174	−174	−174
Symbol rate (kHz)	37.5	300	37.5	37.5	37.5	37.5	300	300
Receiving antenna gain (dBi)	10	10	3	3	24	10	24	10
Receiver cable losses (dB)	−1	−1	−2	−2	−1	−1	−1	−1
Received power (dBm)	−100.38	−100.38	−99.6	−99.6	−88.6	−102.6	−73.5	−87.7
Received E_s/N_o (dB)	25.88	16.85	26.66	26.66	37.66	23.66	43.77	29.77
Required min E_s/N_o (dB)	6	6	6	6	6	6	6	6
CNPC link margin (dB)	19.88	10.85	20.66	20.66	31.66	17.66	37.77	23.77

Annex 2

Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency bands 1 545-1 555 MHz (space-to-Earth), 1 610-1 626.5 MHz (space-to-Earth and Earth-to-space) and 1 646.5-1 656.5 MHz (Earth-to-space)

1 Frequency bands 1 545-1 555 MHz (space-to-Earth) and 1 646.5-1 656.5 (Earth-to-space)

These frequency bands are already allocated for mobile-satellite use and are currently operational over a number of MSS networks worldwide.

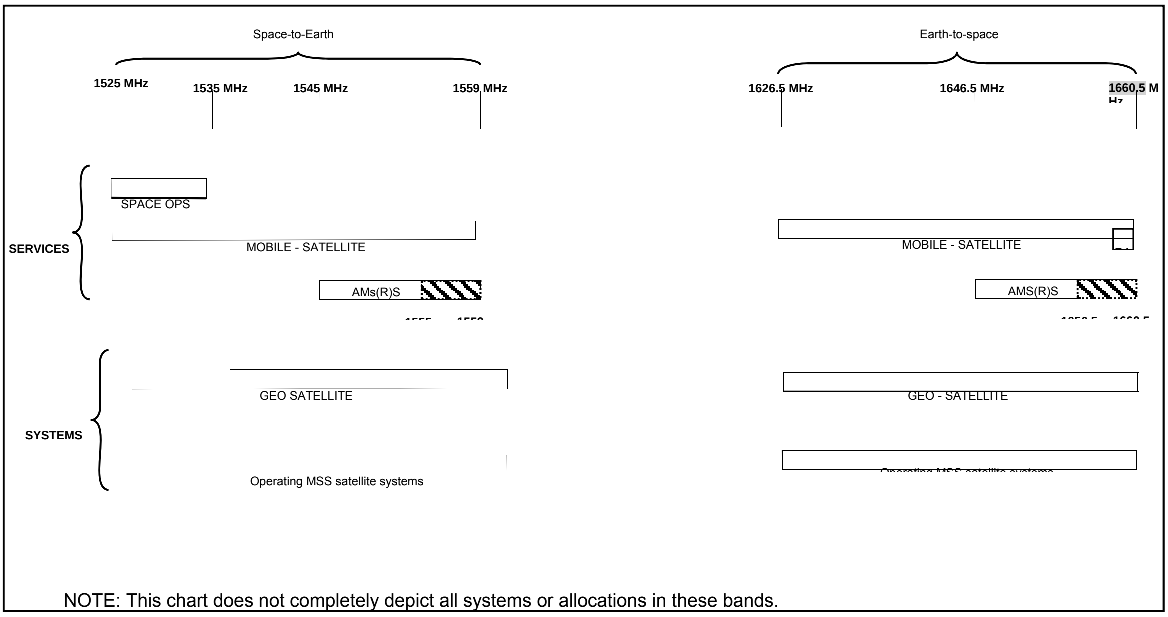
Geostationary MSS satellites currently operate worldwide in the frequency bands 1 545-1 555 MHz (space-to-Earth) and 1 646.5-1 656.5 MHz with provisions for AMS(R)S priority use for communication of messages within priority Categories 1 to 6 of Article 44.

A number of mobile satellite systems operate in these frequency bands, providing regional and global services subject to licensing and coordination agreements. It should be noted that the 10 + 10 MHz of AMS(R)S spectrum identified here would not be sufficient to address the 56 MHz of the required spectrum for UAS applications. These frequency bands are used extensively by various MSS systems worldwide providing many different types of satellite applications, and are intended to provide long-term spectrum availability for AMS(R)S communications satisfying ICAO CNS/ATM safety and regulatory of flights for civil air transportation.

Figure 2-1 depicts existing allocations and use in these frequency bands. The figure also shows the frequency ranges that are filed with the ITU for some operational MSS systems, although the operational frequency bands are subject to licensing and coordination agreements.

FIGURE 2-1

Aeronautical and satellite frequency use in the frequency bands 1 525-1 559 MHz and 1 626.5-1 660.5 MHz



2 Frequency band 1 610-1 626.5 MHz (space-to-Earth and Earth-to-space)

This frequency band is allocated for mobile-satellite use and is currently operational over two non-geostationary MSS networks worldwide. The footnote that applies to the frequency band 1 610-1 626.5 MHz, RR No. **5.367** indicates that it is allocated to the AMS(R)S on a primary basis subject to obtaining agreement under RR No. **9.21**. It should be noted that the 16.5 MHz of this frequency band will not be sufficient to respond to the spectrum requirement identified in the Report ITU-R M.2171.

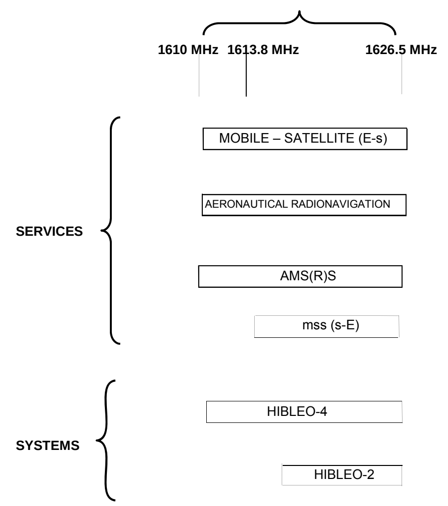
Two non-geostationary low Earth orbit (LEO) MSS satellites networks of HIBLEO-2 and HEBLEO-4 currently share and operate in the frequency band 1 610-1 626.5 MHz (Earth-to-space) that is also allocated on a primary basis to AMS(R)S.

One of these two non-geostationary satellite orbit (GSO) MSS systems, which uses part of the band for both uplink and downlink, currently provides low data rate service to unmanned aircraft. Higher data rate services to support UAS are possible with the current system and also will be introduced in next generation systems. The current system can support data rates up to 128 kbps with characteristics cited in section 3.2.

Figure 2-2 depicts existing frequency allocations and use in these frequency bands. The figure also shows the frequency ranges that are filed with the ITU for some operational MSS systems, although the operational frequency bands are subject to licensing and coordination agreements.

FIGURE 2-2

Aeronautical and satellite frequency use in the frequency band 1 610-1 626.5 MHz



NOTE: This chart does not completely depict all systems or allocations in these bands.

3 Examples of 1.5/1.6 GHz unmanned aircraft system link budgets

3.1 System 1

The parameters used in the example link budgets (Tables 2-1 and 2-2) are based on one system currently providing service for UAS:

Satellite parameters

Each satellite has

– one global beam;
– 19 regional beams;
– 228 high gain narrow spot beams;
– satellite high gain narrow spot beams are only used in the link budgets;
– G/T: 11 dB/K at the edge of coverage;
– e.i.r.p.: 25.7 dBW;
– it should be noted that all beams are shared by several 8 × 8 matrix power amplifiers (MPA) shown in Fig. 2-3. The system can allocated the power where and when needed. However, it may reduce the system capacity;
– UA transmit power: 10 W;
– UA antenna gain: 14 dBi;
– UACS antenna size: 10 m;
– Uplink data rate: 320 kbps;
– Downlink data rate: 10 kbps.

The telemetry and telecommand link budgets are presented in Tables 2-1 and 2-2.

FIGURE 2-3

8 × 8 Matrix power amplifier

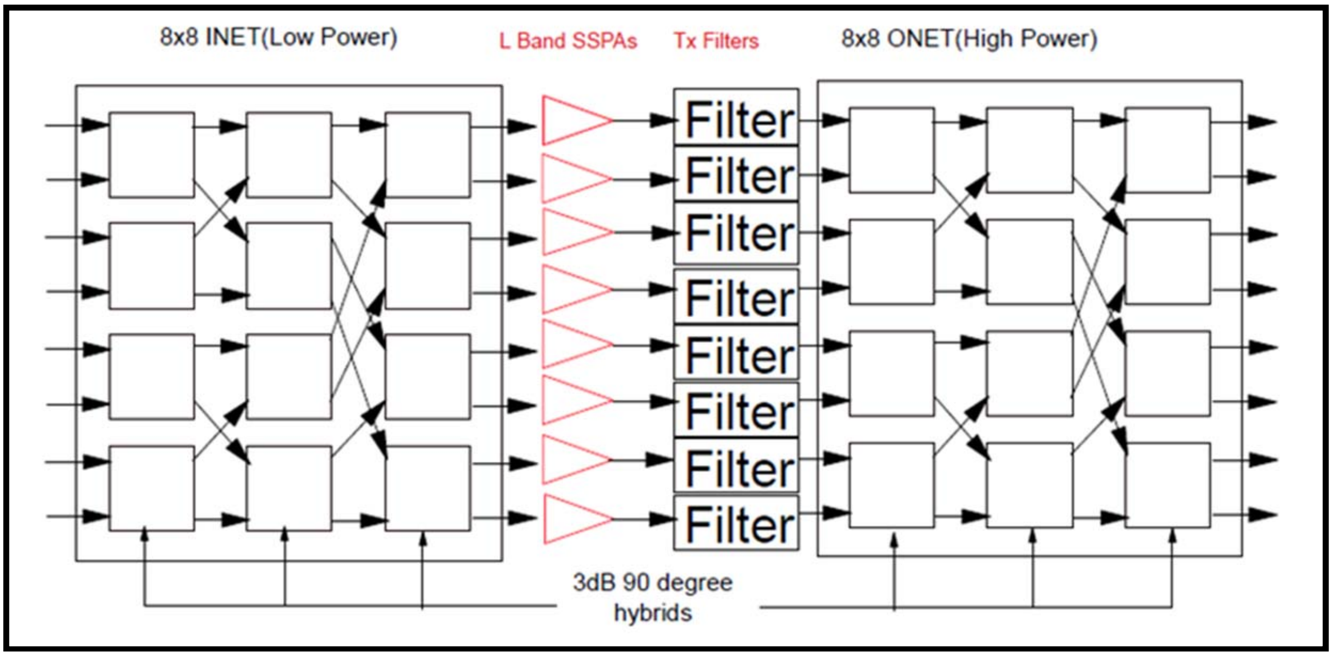


TABLE 2-1

Example of telemetry (unmanned aircraft-to-satellite and satellite-to-unmanned aircraft control station) link budgets

RETURN LINK		Clear Sky Conditions		Rain	
Link Parameter	**Units**	**UA Uplink**	**UA CS Downlink**	**UA Uplink**	**UA CS Downlink**
Earth station location			**Fucino, Italy**		**Fucino, Italy**
Frequency	GHz	1.60	3.60	1.60	3.60
Transmit EIRP	dBWi	22.3		22.3	
Number of carriers		1.0		1.0	
Output back off	dB	0.0		0.0	
EIRP per carrier	dBWi	22.3		22.3	
Transmit Power density	dBW/4 kHz	**-8.8**	**4.8**	**-8.8**	**4.8**
Edge of coverage (EOC)	dB	-	3	-	3
Total pointing loss (Tx & Rx)	dB	0.4	0.5	0.4	0.5
Space Loss	dB	188.5	195.5	188.5	195.5
Link availability	%	-	-	-	99.99
Atmospheric &Scintillation Loss	dB	0.18	0.16	-	-
Rain loss - ITU Combined Model		-	-	-	0.5
Maximum Rain Fade Margin - UA	**dB**	**-**	**-**	**6.0**	
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-167.0**	**-177.9**	**-172.8**	**-178.3**
Receive Antenna Gain	dB	42.0	49.4	0.0	49.4
Receiving System Temperature	°K	501.0	182.4	501.0	201.4
Edge of coverage (EOC)	dB	4.0	-	4.0	-
G/T at EOC	dB/°K	11.0	26.8	11.0	26.3
C/N	dB	19.9	24.6	13.6	23.7
C/I-Self interference due to freq re-use	dB	15.0	-	15.0	-
C/I2 -due to other satellites	dB	17.0	23.0	17.0	23.0
C/IM3	dB	-	17.0	-	17.0
C/(N+I)	dB	15.2	15.5	12.0	15.3
RX Eb/(No+Io)	dB	-	10.1	-	8.1
Required Eb/No	dB	-	6.9	-	6.9
Margin	**dB**	**-**	**3.1**	**-**	**1.1**

	Terminal Parameters		Satellite Comms Parameters	
Parameters	**Transmit (UA)**	**Receive (UA CS)**	**Receive**	**Transmit**
Earth Station location		**Fucino, Italy**		
* Latitude (N=" "; S ="-")		41.9		
* Longitude (E=" "; W= " "		13.6		
Transmit power (W)	10.0	-		
Circuit loss (dB)	2.0	-		
Antenna gain (dBi)	14.3	49.4		
* Antenna size (m)	0.40	9.00		
* Antenna efficiency	60%	75%		
* Beamwidth (deg)	31.5	0.6		
Pointing error (deg)	3.15	0.09		
Noise figure (dB)	-	2.0		
Axial ratio (dB)	2.0	2.0		

Modulation - Clear sky	8PSK 3/4 - DVB	rameters	
Data rate (Mbps)	0.32	Type of satellite	GSO
Required Bandwidth (MHz)	0.190	Orbital location	64
Required Eb/No (dB)	6.9	Satellite Altitude (km)	35,878
Pfd (dB(W/m2/MHz)	-134.2331	Orbital Period (minute:	1440.8
Total rq. Bandwidth (MHz)	114.0	Or (hours)	24.0
Modulation - Rain	8PSK 3/4 - DVB		
Data rate (Mbps)	0.32	U/L Elevation angle (d	20
Required Bandwidth (MHz)	0.2	U/L Slant range (km)	39647
Required Eb/No (dB)	6.9	D/L Elevation Angle	20
Pfd (dB(W/m2/MHz)	-134.2331	D/L Slant range (km)	39630

TABLE 2-2

Example of telecommand (UACS–to-satellite and satellite-to-UA)

Forward Link		Clear Sky Conditions		Rain	
Link Parameter	Units	UA Control Uplink	UA Downlink	UA Control Uplink	UA Downlink
Earth station location		Fucino, Italy		Fucino, Italy	
Frequency	GHz	6.60	1.50	6.60	1.50
Transmit EIRP	dBWi				
Number of carriers					
Output back off	dB				
EIRP per carrier	dBWi	39.8	25.7	39.8	25.7
Transmit power density	dBW/4kHz	-18.0	22.2	-18.0	22.2
Edge of coverage (EOC)	dB	-	4	-	4
Total pointing loss (Tx & Rx)	dB	0.4	0.4	0.4	0.4
Space Loss	dB	200.8	187.9	200.8	187.9
Link availability	%	-	-	99.99	
Atmospheric &Scintillation Loss	dB	0.15	0.14	-	-
Rain loss - ITU Combined Model		-	-	1.5	-
Maximum Rain Fade Margin - UA	**dB**				**5.0**
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-161.7**	**-167.0**	**-163.1**	**-171.9**
Receiver Antenna Gain	dB	-	14.1	-	14.1
Receiving System Temperature	°K	-	181.4	-	355.2
Edge of coverage (EOC)	dB	3.0	-	3.0	-
G/T at EOC	dB/°K	-8.0	-8.5	1.4	-11.4
C/N	dB	19.4	13.6	27.3	5.6
C/I-Self interference due to freq re-use	dB	-	15.0	-	-
C/I1 - due to other satellite systems	dB	26.0	17.0	26.0	17.0
C/IM3	dB	18.0	18.0	18.0	18.0
C/(N+I)	dB	15.3	12.1	17.1	5.3
RX Eb/(No+Io)	dB	-	9.8	-	4.5
Required Eb/No	dB	-	3.8	-	3.8
Margin	**dB**	**-**	**6.0**	**-**	**0.7**

	Terminal Parameters		Satellite Comms Parameters	
Parameters	Transmit (UA CS)	Receive (UA)	Receive	Transmit
Earth Station location	Fucino, Italy			
* Latitude (N=" "; S ="-")	41.9			
* Longitude (E=" "; W= " "	13.6			
Transmit power (W)	500.0	-		
Circuit loss (dB)	2.0	-		
Antenna gain (dBi)	54.3	14.1		
* Antenna size (m)	9.0	0.40		
* Antenna efficiency	70%	65%		
* Beamwidth (deg)	1.4	14.0		
Pointing error (deg)	0.21	1.40		
Noise figure (dB)	-	2.0		
Axial ratio (dB)	2.0	2.0		

Modulation - Clear sky	3/4 QPSK- DOCSIS	**rameters**	
Data rate (Mbps)	0.010	Type of satellite	GSO
Required Bandwidth (MHz)	0.01	Orbital location	64
Required Eb/No (dB)	3.8	Satellite Altitude (km)	35,878
Pfd (dB(W/m2/MHz)	-116.7863	Orbital Period (minute	1440.8
Total rq. Bandwidth (MHz)		Or (hours)	24.0
Modulation - Rain	3/4 QPSK- DOCSIS		
Data rate (Mbps)	0.010	U/L Elevation angle (d	20
Required Bandwidth (MHz)	0.009	U/L Slant range (km)	39630
Required Eb/No (dB)	3.8	D/L Elevation Angle	20
Pfd (dB(W/m2/MHz)	-116.7863	D/L Slant range (km)	39647

3.2 System 2

A non-GSO system in the 1 610-1 626.5 MHz band currently provides aeronautical services that could support UAS. This system has the following characteristics:

– constellation of 66 satellites providing full earth coverage including polar and oceanic regions;

– each satellite in the constellation provides a footprint approximately 3 460 km (2 150 miles) wide, consisting of 48 spot beams that are nominally 483 km (300 miles) wide. The spot beam antennas provide a near-isoflux gain level across the satellite footprint;

– the satellites in the constellation are cross-linked together and therefore don’t require ground stations within the satellite footprint to support services in that region. Therefore, the UAS platform would only need to transmit and receive communications between itself and the nearest satellite;

– user link channels are part of an FDMA/TDMA/TDD access and channelization scheme, with channel spacing of 41.7 kHz in the frequency domain and multiple timeslots per frame in the time domain;
– each individual channel supports a user data rate of 2.4 kbps; however, multi-channel mode allows up to 16 frequency channels and 4 timeslots may be combined to support user data rates up to 128 kbps;
– multi-channel mode employs 12 dB link margin on uplink and downlink.

Annex 3

Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency band 5 030-5 091 MHz

1 Introduction

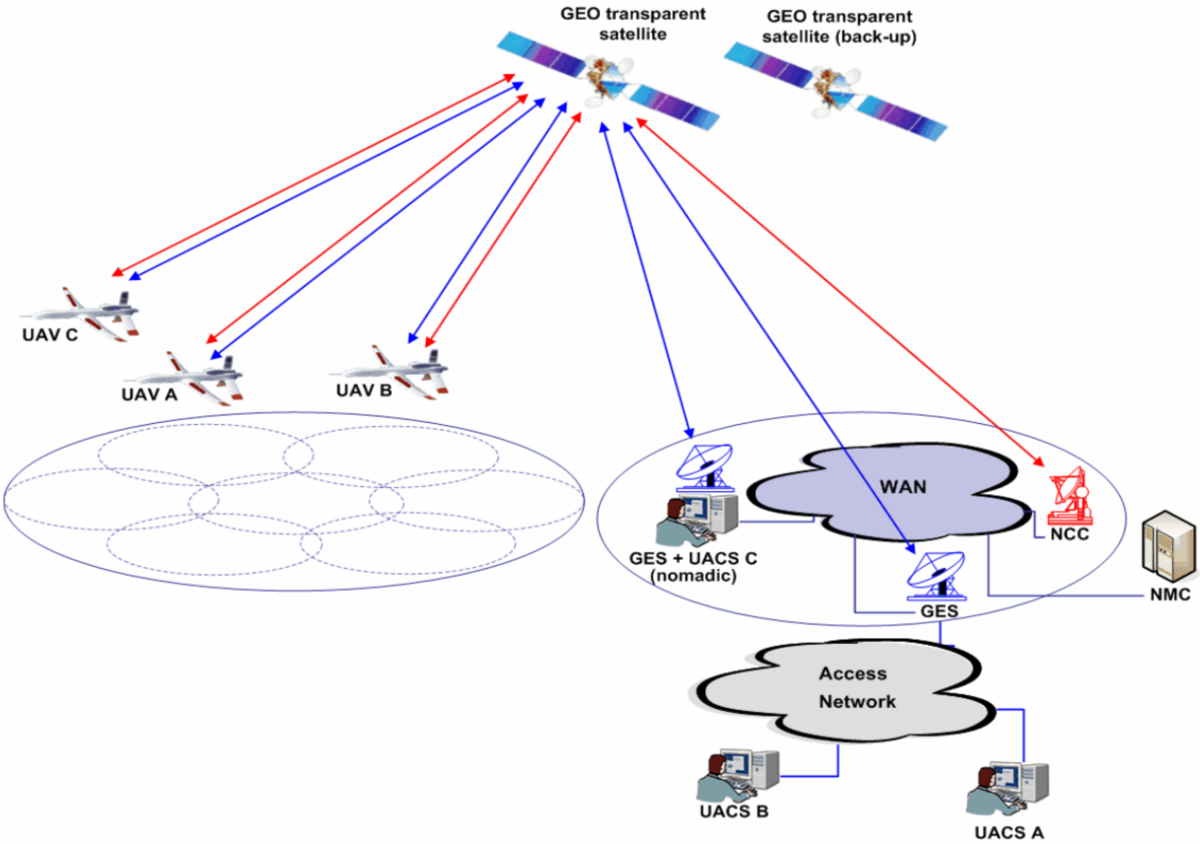
Example of characteristics of a satellite communication infrastructure operating in the frequency band 5 030-5 091 MHz and tailored to the integration of UAS in civil airspace is presented in this Annex. They are used in sharing studies contained in Annex 2 of Report ITU-R M.2205.

2 General architecture

The following figure presents the high-level architecture of a possible AMS(R)S system in the frequency band 5 030-5 091 MHz. UACS can be collocated with a dedicated ground earth station (GES) or connected to a centralized GES through a terrestrial network. As a baseline, the link between the GES and the satellite, i.e. the feeder link, also uses the frequency band 5 030-5 091 MHz.

FIGURE 3-1

AMS(R)S architecture



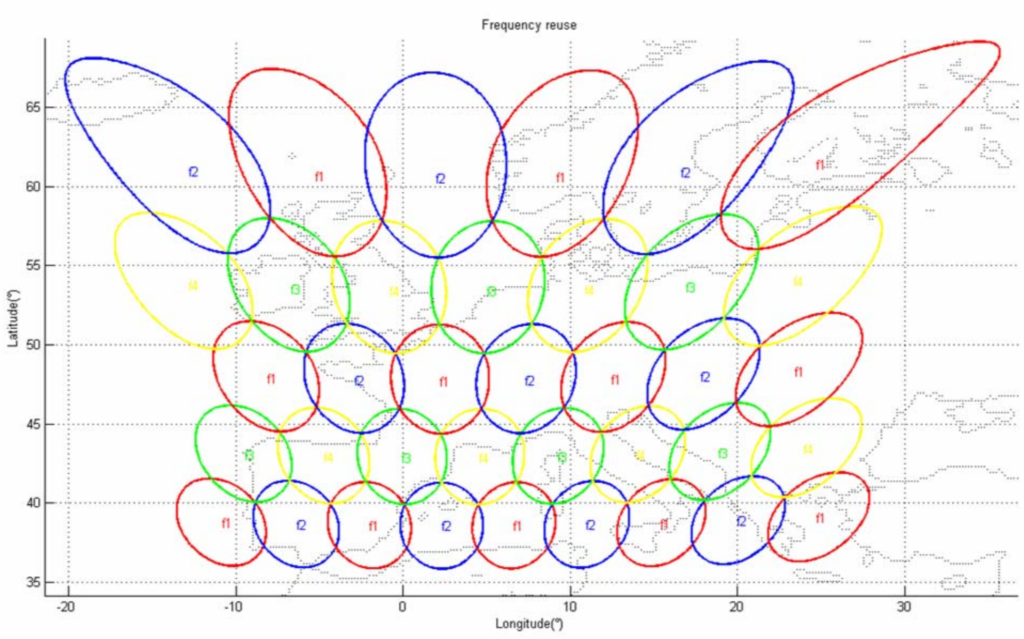
3 Space segment

The satellite segment is composed of several geostationary satellites in order to offer a global coverage of the part of the Earth visible from the geostationary orbit.

Frequencies are reused through the creation of narrow spots. For each satellite, spot beams can be activated dynamically within the satellite coverage. As a baseline, a frequency reuse factor of 4 is considered. An example of pattern is illustrated on the following figure for a 6-metre satellite antenna.

FIGURE 3-2

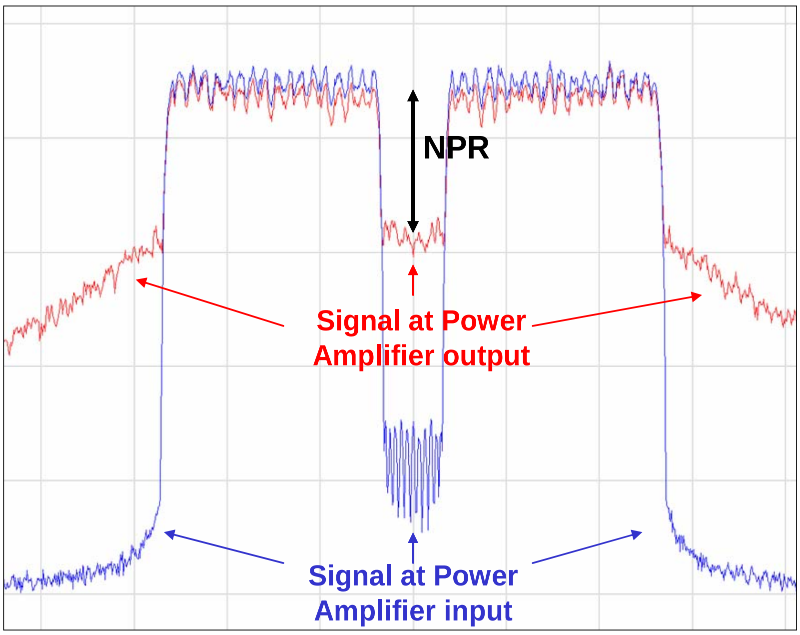
Illustrative state-of-the-art spot beam satellite antenna and frequency reuse pattern



Satellite out-of-band emissions are driven by its noise power ratio (NPR) performance. As depicted below, the NPR is the ratio between the carrier signal power and the noise level brought by multi carrier amplifier nonlinearities. A NPR equal to 17 dB is considered for the analysis (typical value for a state-of-the-art satellite) as well as a 3-4 dB output back-off (OBO), difference between the effective amplifier output power and the maximum amplifier output power.

FIGURE 3-3

Satellite noise power ratio



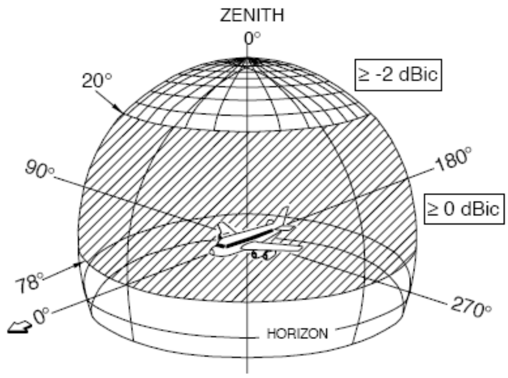
4 Unmanned aircraft terminal segment

As far as the UA terminal segment is concerned, a low-gain omnidirectional terminal is considered. Possibly, several antennas, e.g. above and below the UAV, may be used to ensure the availability of the link whatever the attitude of the UA is.

The antenna pattern is supposed to be omnidirectional for the azimuth and partially omnidirectional above the horizon for the elevation. The antenna gain is expected to vary between 1 dBi and 7 dBi depending on the antenna type and on the number of antennas. As a baseline, a 3 dBi antenna gain is assumed. For information, an example of an airborne antenna pattern is presented below. Let us note that the antenna gain decreases when reaching the zenith.

FIGURE 3-4

Example of an airborne antenna pattern

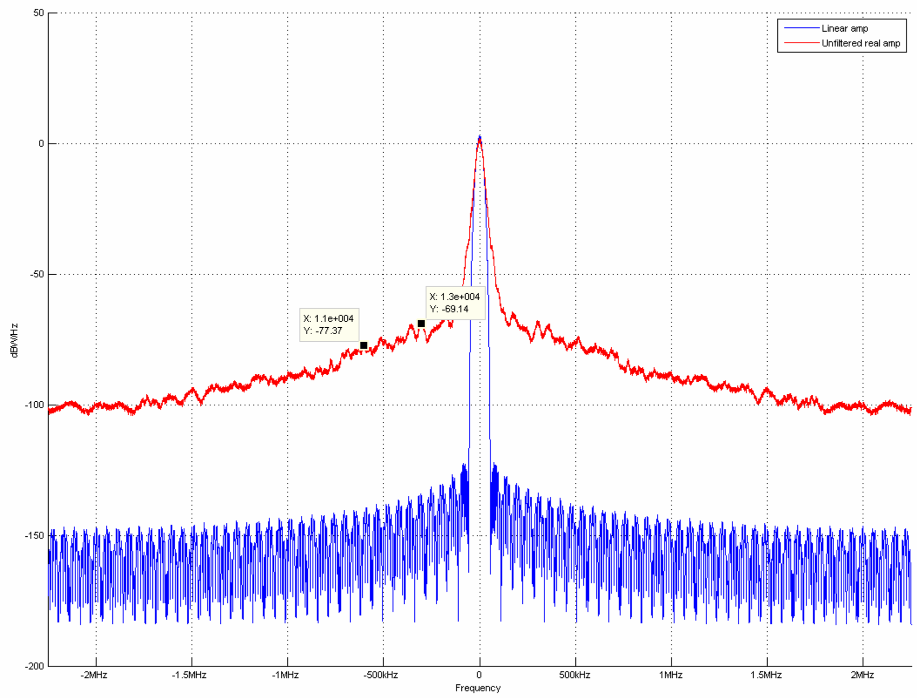


A circular polarization is used, either right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP).

A power amplifier providing at maximum a 20 W radio output power is considered. The emission spectrum has been modelled though simulations and is depicted on the following figure. The blue curve represents the ideal amplifier while the red curve represents the real amplifier.

FIGURE 3-5

Unmanned aircraft emission spectrum



5 Carrier bandwidth and frequency plan

Considering the frequency plan (a single 60 MHz continuous band), several duplex schemes can be envisaged:

– Frequency Division Duplex (FDD): forward and return channels are implemented in separated frequency bands and forward and return transmissions are performed simultaneously.

– Half Frequency Division Duplex (HFDD): forward and return channels are implemented in separated frequency bands but, on AES side, forward and return transmissions are performed sequentially.

– Time Division Duplex (TDD): forward and return transmissions are performed sequentially.

A HFDD system was considered in Report ITU-R M.2205 and is presented here as an example. Given that the UA terminal doesn't transmit and receive at the same time, it must thus transmit or receive twice as faster. That's why the required bandwidth is twice as wider. Note that such a design doesn't impact the overall system capacity given that two users can be multiplexed in time on a single carrier.

The resulting frequency plan is thus as follows:

– 5 030-5 050 MHz: satellite to UA (forward) and satellite to UACS (return) paths;

– 5 071-5 091 MHz: UA to satellite (return) and UACS to satellite (forward) paths.

Finally, the following table presents the computation leading to the carrier bandwidth. In the return link, 2 carriers, i.e. 4 UA, are multiplexed on a 300 kHz channel. In the forward link, 8 carriers, i.e. 16 UA, are multiplexed on a 300 kHz channel.

Data rates values considered below (i.e. 44 kbps for the return link and 7kbps for the forward link) are the satellite estimated non-payload throughput requirements of a single UA as per methodology 1 in Report ITU-R M.2171.

TABLE 3-1

Carrier bandwidth

	Forward	**Return**
Data rates (incl. upper layers overheads) (kbps)	7.0	44.0
Multiplexing ratio	2	2
Modulation	QPSK 1/2	QPSK 1/2
Physical layer headers (%)	15%	15%
Physical layer efficiency (bps/Hz)	0.85	0.85
Roll-off factor	1.35	1.35

6 Link budgets

Link budgets for the return link and the forward link are presented hereafter.

It is to be noted that:

– links between the UACS and the satellite are assumed to be in the frequency band 5 030-5 091 MHz, but may also be accommodated in other frequency bands;

– a QPSK 1/2 DVB-RCS type waveform is considered;

– the availability (link availability from the ground earth station to the UA and from the UA to the ground earth station) considered in this example is 99.99%. Depending on the final availability requirement and on the possible redundancy scheme (an AMS(R)S system described in Annex 2 could be used as a back-up), this value may be updated;

– the link budgets are performed for UA and UACS located in Western Europe, corresponding to the worst case in terms of sharing with MLS (according to ICAO database used in Report ITU-R M.2205). On other areas more favourable from a sharing point of view, additional margin is available;

– the path loss includes the degradation due to atmospheric effects. The multipath and scintillation effects are included in the 3 dB link budget margin. Such a value is consistent with the margins needed for multipath and scintillation in the propagation channel of the 1.5/1.6 GHz aeronautical band;

– the link budget is carried out considering rain loss on the satellite – UA link, this representing the worst case compared to the UACS – Satellite link.

The feeder link is assumed to be in the frequency band 5 030-5 091 MHz, this case being the most restrictive one. A QPSK 1/2 DVB-RCS type waveform is considered. The availability (link availability from the ground earth station to the UA and from the UA to the ground earth station) that is considered is 99.99%.

TABLE 3-2

AMS(R)S return link budget

System			**Repeater**	
Availability (%)	99.99%		Repeater gain (dB)	110.5
Satellite longitude (degrees)	–2.8		Tx feeder loss (dB)	1.0
Conditions	Rain UL		Amplifier BO (OBO) (dB)	3.5
Modulation	QPSK 1/2		Amplifier NPR (dB)	17.0
Useful bit rate per carrier (kbps)	44.0		$C/IM0$ degradation (dB/Hz)	67.2
Duplex ratio	0.5			
Symbol rate per carrier (kbauds)	103.5		**Satellite Tx antenna**	
Minimum bandwidth per carrier (kHz)	139.8		Tx antenna diameter (m)	6.0
			Tx e.i.r.p. per carrier (dBW)	14.1
AES			Max Tx e.i.r.p. per carrier (dBW)	17.1
Frequency (MHz)	5 000		Downlink C/I inter-spots (dB)	17.0
Elevation (degrees)	39.5		Downlink $C/I0$ inter-spots (dB/Hz)	67.2
Carrier HPA power (W)	20.0			
Antenna gain (dBi)	3.0		**Downlink propagation**	
Tx loss (dB)	2.0		Total path loss (dB)	198.0
Power control uncertainty (dB)	0.5			
Tx e.i.r.p. per carrier (dBW)	13.5		**GES**	
			Downlink frequency (MHz)	5 000
Uplink propagation			Elevation (deg)	39.5
Total path loss (dB)	198.5		Antenna diameter (m)	3.8
			G/T (dB/K)	18.8
Satellite Rx antenna			Downlink $C/N0$ (dB/Hz)	63.5
Rx antenna diameter (m)	6.0			
Rx antenna gain (dBi)	45.1		**Demodulation**	
Rx feeder loss (dB)	0.5		MLS degradation (dB)	1.0
Satellite G/T (dB/°K)	18.7		Total $C/(N0+IM0+I0)$ (dB/Hz)	57.0
Uplink $C/N0$ (dB/Hz)	62.4		Total $C/(N+IM+I)$ (dB)	6.8
Uplink $C/I0$ inter-spots (dB/Hz)	67.2		Required $C/(N0+IM0+I0)$ (dB/Hz)	54.0
Uplink C/I inter-spots (dB)	17.0		Required $C/(N+IM+I)$ (dB)	3.8
			Margin (dB)	3.0

TABLE 3-3

AMS(R)S forward link budget

System			Repeater	
Availability (%)	99.99%		Repeater gain (dB)	104.5
Satellite longitude (degrees)	–2.8		Tx feeder loss (dB)	1.0
Conditions	Rain DL		Amplifier BO (OBO) (dB)	4.0
Modulation	QPSK ½		Amplifier NPR (dB)	17.0
Useful bit rate per carrier (kbps)	7.0		*C*/*IM*0 degradation (dB/Hz)	59.2
Duplex ratio	0.5			
Symbol rate per carrier (kbauds)	16.5		**Satellite Tx antenna**	
Minimum bandwidth per carrier (kHz)	22.2		Tx antenna diameter (m)	6.0
			Tx e.i.r.p. per carrier (dBW)	44.7
GES			Max Tx e.i.r.p. per carrier (dBW)	47.7
Frequency (MHz)	5.000		Downlink *C*/*I* inter-spots (dB)	17.0
Elevation (degrees)	39.5		Downlink *C*/*I*0 inter-spots (dB/Hz)	59.2
Number of carriers	20			
HPA power (W)	100.0		**Downlink propagation**	
Antenna diameter (m)	3.8		Total path loss (dB)	198.5
Antenna gain (dBi)	44.1			
Tx loss (dB)	1.0		**AES**	
Power control uncertainty (dB)	0.5		Downlink frequency (MHz)	5.000
Tx e.i.r.p. per carrier (dBW)	49.6		Elevation (deg)	39.5
			G/*T* (dB/K0	–23.0
Uplink propagation			Downlink *C*/*N*0 (dB/Hz)	51.9
Total path loss (dB)	198.0		Downlink *C*/*N* (dB)	9.7
Satellite Rx antenna			**Demodulation**	
Rx antenna diameter (m)	6.0		MLS degradation (dB)	1.0
Rx antenna gain (dBi)	45.1		Total *C*/(*N*0+*IM*0+*I*0) (dB/Hz)	49.0
Rx feeder loss (dB)	0.5		Total *C*/(*N*+*IM*+*I*) (dB)	6.8
Satellite *G*/*T* (dB/K)	18.7		Required *C*/(*N*0+*IM*0+*I*0) (dB/Hz)	46.0
Uplink *C*/*N*0 (dB/Hz)	98.9		Required *C*/(*N*+*IM*+*I*) (dB)	3.8
Uplink *C*/*I*0 inter-spots (dB/Hz)	59.2		Margin (dB)	3.0
Uplink *C*/*I* inter-spots (dB)	17.0			

Annex 4

Example of beyond line-of-sight control and non-payload communication link characteristics for unmanned aircraft systems in the frequency bands 12/14 GHz and 20/30 GHz

1 Unmanned aircraft system and geostationary orbit analysis methodology

This Annex's technical evaluation is performed in two steps. Step one (Sections 3.3 and 4.3) develops link budgets for 12/14 GHz and 20/30 GHz GSO links based on the assumption that the UA operating in both the 12/14 GHz and 20/30 GHz frequency bands meets all of the uplink power density, off-axis e.i.r.p. density, downlink power flux-density (pfd) and antenna pattern requirements of a typical GSO FSS operating in the same frequency band. The objective of the link budgets shown in Sections 3.3 and 4.3 is to compute the maximum available rain fade margin for the satellite-to-UA and UA-to-satellite links.

1.1 Rain fade investigation

Step two of the technical evaluation (Sections 3.4 and 4.4) uses the maximum rain fade margins for the 12/14 GHz and 20/30 GHz UA links determined in step one and evaluates the minimum operational altitude that the UA can fly, with a wide range of $R_{0.01}$ rain rates, while still achieving the desired UA link availability determined in Section 2.2.

1.2 Provision for adjacent satellites

Off-axis e.i.r.p limits are specified in order to keep emissions from the UA to adjacent satellites within acceptable levels. The example link budgets include the adjacent satellite interference levels of a coordinated GSO FSS *C*/*I* environment.

2 Unmanned aircraft system control and communications system characteristics

2.1 Information data rate

Previous analysis performed in methodology 2 of Report ITU-R M.2171 estimated the maximum data rate required to be sent from the pilot in the UACS to the UA (telecommand) and from the UA to the pilot in the UACS (telemetry). These maximum rates were:

– Telecommand, UACS-to-Satellite and satellite-to UA: 10 kbps;

– Telemetry, UA-to-satellite and satellite -to UA Control Station: 320 kbps.

2.2 End-to-end link availability

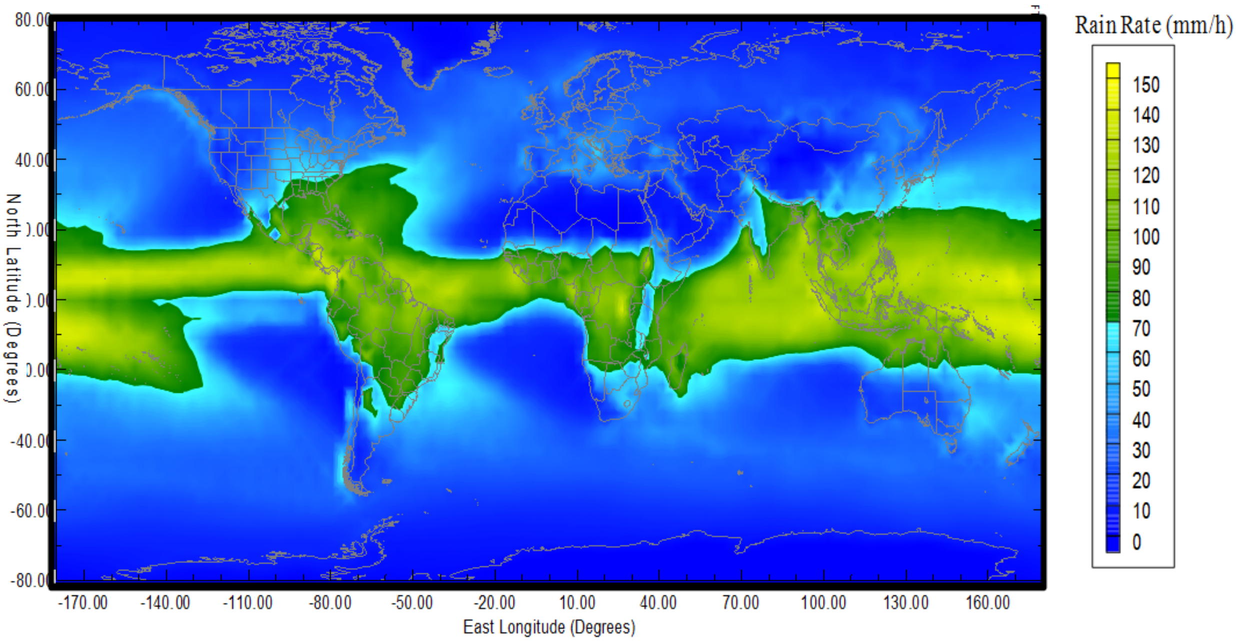
In this example, the assumed end-to-end link availability of the BLoS CNPC link subsystem is 99.8%. This availability is defined in a similar manner to the availability described in Recommendation ITU-R S.1806 except that the period defined in recommends 5 and in subsequent notes is reduced from 10 seconds to 1 second. Because of the critical nature of the UAS CNPC link an interruption longer than 1 second could give rise to an unsafe condition. In order to achieve this link availability, the UA and UACS link availability need to be derived. The UACS can operate with larger antennas and/or use rain mitigation techniques, such as site diversity, etc., to achieve higher than 99.8% link availability. In order to meet this overall link availability, a 99.95% link availability for the UA control station to/from satellite link and a 99.85% link availability for the UA to/from satellite were assumed in this example.

The required rain fade margin to achieve the desired link availability depends on the location, elevation angle, rain rate and operational altitude, particularly of the UA. The rain rate (mm/h) exceeded for 0.01% of the average year is shown in Figures 1-8 of Recommendation ITU-R P.837-5.

The rain fall rate around the globe is summarized in Fig. 4-1.

FIGURE 4-1

Rain rate (mm/h) exceeded for 0.01% of the average year



2.3 Unmanned aircraft terminal parameters

Most UA operate with size, weight and power constraints, particularly for antenna size. In general, the UA is designed to operate with as small an antenna as possible. However, it may not be able to close the link, or to meet the overall design objectives, such as link availability and in addition, it may cause and/or receive unacceptable interference levels to and from other systems operating in the same frequency bands if the antenna is too small. The systems parameters shown below are used in this example:

- 12/14 GHz frequency bands
  - UA antenna size: 0.8 m
  - UA transmit power: 10 W
- 20/30 GHz frequency bands
  - UA antenna size: 0.5 m
  - UA transmit power: 10 W.

2.4 Unmanned aircraft control station parameters

The UACS parameters, such as terminal antenna size, number of antennas, transmit RF power, etc. will depend on such factors as the actual earth station location and rain climate, etc. For the purpose of this Annex, the terminal antenna size and transmit power are assumed to be less than 7.0 m and

500 W, respectively. It should be noted that in this Annex the UA links to and from the satellite have the greatest influence on the overall UA to UACS link performance because the UA has limited antenna size and transmit power compared to the UACS.

3 Using geostationary orbit satellites in the 12/14 GHz frequency bands for unmanned aircraft system control

3.1 12/14 geostationary orbit satellite characteristics

The satellite receive G/T and transmit e.i.r.p. density used in this Annex are:

– Satellite receive *G/T* @ 3 dB edge of coverage (EOC): 1.4 dB;

– Satellite transmit e.i.r.p. density: 10 dBW/4 kHz;

– Transponder bandwidth: 36 MHz.

3.2 Uplink off-axis e.i.r.p. density and downlink power flux density

3.2.1 Uplink off-axis e.i.r.p. density limits

Based on Recommendation ITU-R S.524-9 Section 3, an example of an earth station uplink off-axis e.i.r.p. density for the 14 GHz frequency band can be summarized below:

Angle off-axis	*Maximum e.i.r.p. per 40 kHz*
$2.5° \leq \varphi \leq 7°$	$(39 - 25 \log \varphi)$ dBW/40 kHz
$7° < \varphi \leq 9.2°$	18 dBW/40 kHz
$9.2° < \varphi \leq 48°$	$(42 - 25 \log \varphi)$ dBW/40 kHz
$48° < \varphi \leq 180°$	0 dBW/40 kHz.

In this example, a maximum input power density into the antenna of −14 dBW/4 kHz level was used for both the UA and the UACS. In addition, the UA and UACS antennas are assumed to meet the antenna patterns shown below:

Angle off-axis	*Antenna pattern*
$1.5° \leq \theta \leq 7°$	$29 - 25 \log \theta$ dBi
$7° < \theta \leq 9.2°$	8 dBi
$9.2° < \theta \leq 48°$	$32 - 25 \log \theta$ dBi
$48° < \theta \leq 180°$	–10 dBi.

It should be noted that the uplink off-axis e.i.r.p. density used in this example is significantly lower than the values shown in Recommendation ITU-R S.524-9.

3.2.2 Downlink power flux density limits

The pfd limits of GSO satellites operating in the 12 GHz frequency band used in this example are below the maximum values indicated in ITU Radio Regulations Table 21-4. However this example may not reflect the situation of satellite currently in operation or those to be operated in the future.

3.3 12/14 GHz link budget calculation – assumptions

In this example, the link budget calculations use the following assumptions:

– Satellite transmit downlink e.i.r.p. density: 10 dBW/4 kHz

– Satellite receive *G/T* @ 3 dB EOC: 1.4 dB/K

– UA transmit power density input to antenna: −14 dBW/4 kHz

– UA antenna patterns – See Section 3.2.1

– In the context of performance– Receive interference from 2 satellites ± 2 degrees

  – Receive interference from 2 satellites ± 4 degrees

  – Earth station off-axis e.i.r.p. from interfering systems: same as the transmit UA off-axis e.i.r.p. density

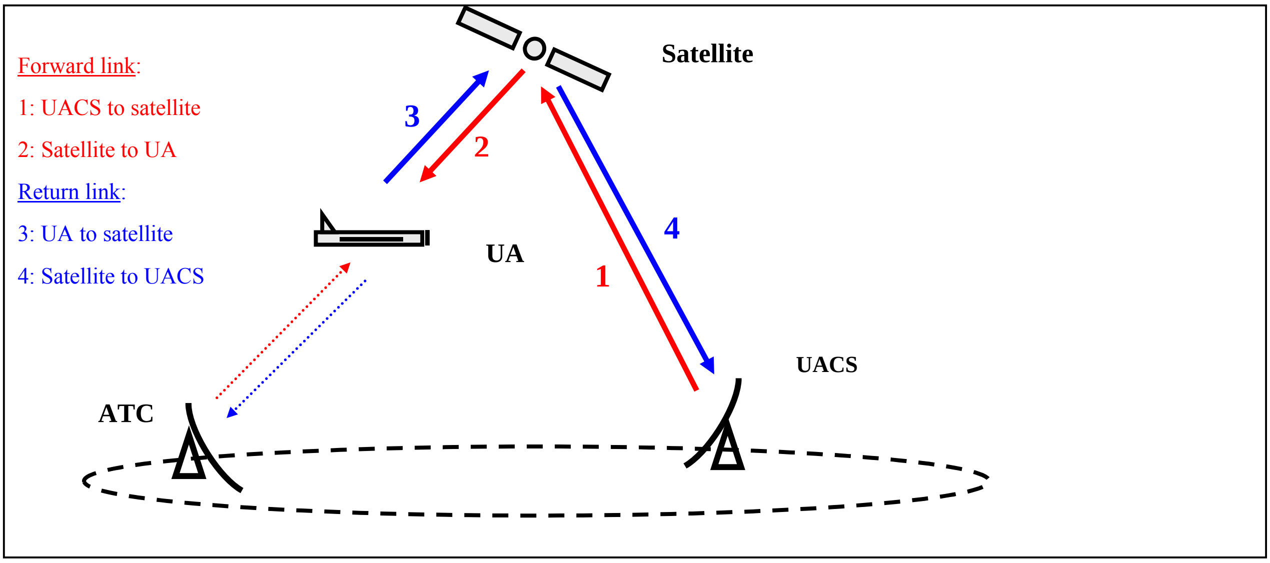
  – Satellite transmit e.i.r.p. density – from interfering systems: 10 dBW/4 kHz.

  The potential degradation due to the adjacent satellites interference, four satellites located ±2°and ±4° away from a satellite associated with UAS was taken into account as shown in Tables 4-1 and 4-2 link budgets. In order to achieve the availability performance, a combination of satellites operating in the same frequency band or satellites operating in different frequency bands are needed. However the potential interference from other adjacent satellites located at ±6°, ±8° and ±10° away was not taken into account because the impact to the link budget was less than 0.1 dB. It should be noted that interference environment presented here is only an example of possible constituent parts of overall interference margin within the link budgets.

3.3.1 Telecommand link budgets (unmanned aircraft control station-to-satellite and satellite-to-unmanned aircraft) (Links 1 and 2 of Fig. 4-2 below)

FIGURE 4-2

Links involved in beyond line-of-sight (BLoS) communications via satellite



The 12 GHz telecommand and 14 GHz telemetry link budgets are summarized in Tables 4-1 and 4-2. The purpose of these link budgets is to compute the maximum available rain fade margin. Based on the available rain fade margin and the assumed link availability (99.85% for UA links), the maximum rain fall rate and the operational altitude of the UA are presented in Section 3.4. The 12/14 GHz link budgets and rain fade mitigation techniques, if any, are discussed in Section 3.5.

An example of a telecommand link budget, UACS-to-satellite and satellite-to-UA is shown in Table 4-1.

TABLE 4-1

Example of telecommand link budgets unmanned aircraft control station-to-satellite and satellite to-unmanned aircraft

Forward Link		Clear Sky Conditions		Rain	
Link Parameter	**Units**	**UA Control Uplink**	**UA Downlink**	**UA Control Uplink**	**UA Downlink**
Earth station location		**Orlando AP**		**Orlando AP**	
Frequency	GHz	14.25	**11.95**	14.25	11.95
Transmit EIRP	dBWi			81.1	
Number of carriers				100.0	
Output back off	dB			12.5	
EIRP per carrier	dBWi	48.6	13.5	48.6	13.5
Transmit power density	dBW/4kHz	-14.0	10.0	-14.0	10.0
Edge of coverage (EOC)	dB	-	3	-	3
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5
Space Loss	dB	207.0	206.0	207.0	206.0
Link availability	%	-	-	99.95	
Atmospheric &Scintillation Loss	dB	0.25	0.16	-	-
Rain loss - ITU Combined Model		-	-	9.8	-
Maximum Rain Fade Margin -	**dB**				**1.0**
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-159.4**	**-196.4**	**-168.9**	**-197.2**
Receiver Antenna Gain	dB	-	38.1	-	38.1
Receiving System Temperature	dB-°K	-	238.3	-	281.2
Edge of coverage (EOC)	dB	3.0	-	3.0	-
G/T at EOC	dB-°K	1.4	14.4	1.4	13.6
C/N	dB	31.1	7.1	21.5	5.4
C/I-Self interference due to freq re-use	dB	99.0	99.0	99.0	99.0
C/I1 - two interference satellites +/- 2de	dB	35.4	14.4	35.4	14.4
C/I2 - Two interference satellites +/- 4 d	dB	43.1	22.1	43.1	22.1
C/IM3	dB	18.0	18.0	18.0	18.0
C/(N+I)	dB	17.7	5.9	16.3	4.6
RX Eb/(No+Io)	dB	-	5.4	-	3.8
Required Eb/No	dB	-	3.8	-	3.8
Margin	**dB**	**-**	**1.6**	**-**	**0.0**

Parameters	**Transmit (UA CS)**	**Receive (UA)**	**Receive**	**Transmit**
Earth Station location	**Orlando AP**			
* Latitude (N=" "; S ="-")	28.6			
* Longitude (E=" "; W= " "	-81.4			
Transmit power (W)	250.0	-		
Circuit loss (dB)	2.0	-		
Antenna gain (dBi)	59.1	38.1		
* Antenna size (m)	7.0	0.80		
* Antenna efficiency	75%	65%		
* Beamwidth (deg)	0.2	2.1		
Pointing error (deg)	0.03	0.32		
Noise figure (dB)	-	2.5		
Axial ratio (dB)	2.0	2.0		
Modulation - Clear sky	3/4 QPSK- DOCSIS	**rameters**		
Data rate (Mbps)	0.010	Type of satellite		GSO
Required Bandwidth (MHz)	0.01	Orbital location		-105
Required Eb/No (dB)	3.8	Satellite Altitude (km)		35,878
Pfd (dB(W/m2/MHz)	-128.4389	Orbital Period (minute		1440.8
Total rq. Bandwidth (MHz)		Or (hours)		24.0
Modulation - Rain	3/4 QPSK- DOCSIS			
Data rate (Mbps)	0.010	U/L Elevation angle (d		48
Required Bandwidth (MHz)	0.009	U/L Slant range (km)		37315
Required Eb/No (dB)	3.8	D/L Elevation Angle		20
Pfd (dB(W/m2/MHz)	-128.4389	D/L Slant range (km)		39647

Table 4-1 shows that:

– the downlink transmit data rate shown in the link budget is 10 kbps and the downlink transmit e.i.r.p. density is 10 dBW/4 kHz. In reality, the downlink transmit data rate of commercial 12/14 GHz frequency band satellites is significantly higher. The downlink power is assumed to be adjusted for different data rates; however, the downlink e.i.r.p. density, 10 dBW/4 kHz level would be kept constant;

– the maximum satellite–to-UA link fade margin is 1.0 dB. The purpose of the link budget shown in Table 4-1 is to compute the maximum rain fade margin, from satellite-to-UA. An elevation angle, from satellite-to-UA, of 20º was used in this example. The UA link availability, depending on rain rate and operational altitude, is shown in Fig. 4-3;

– the UACS link availability, from control station to satellite is 99.95% as shown in Table 4-1. The actual UACS earth terminal antenna size and transmit power will depend on the UACS earth station location (e.g. elevation angle, rain rate etc.).

3.3.2 Telemetry link budgets (Unmanned aircraft-to-satellite and satellite-to-unmanned aircraft control station) (Links 3 and 4 of Fig. 4-2)

The telemetry link budget, UA-to-satellite and satellite-to-UACS is shown in Table 4-2.

TABLE 4-2

Example of telemetry link budgets (unmanned aircraft-to-satellite and satellite-to-unmanned aircraft control station)

RETURN LINK		Clear Sky Conditions		Rain	
Link Parameter	Units	UA Uplink	UA CS Downlink	UA Uplink	UA CS Downlink
Earth station location			Orlando AP		Orlando AP
Frequency	GHz	14.25	11.95	14.25	11.95
Transmit EIRP	dBWi	47.7		47.7	
Number of carriers		1.0		1.0	
Output back off	dB	3.5		3.5	
EIRP per carrier	dBWi	44.2	28.6	44.2	28.6
Transmit Power density	dBW/4 kHz	-14.0	10.0	-14.0	10.0
Edge of coverage (EOC)	dB	-	3	-	3
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5
Space Loss	dB	207.5	205.4	207.5	205.4
Link availability	%	-	-	-	99.97
Atmospheric &Scintillation Loss	dB	0.44	0.47	-	-
Rain loss - ITU Combined Model		-	-	-	15.1
Maximum Rain Fade Margin -	**dB**	**-**	**-**	**3.8**	
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-164.5**	**-181.1**	**-167.9**	**-195.7**
Receive Antenna Gain	dB	-	57.6	-	57.6
Receiving System Temperature	dB-°K	-	256.2	-	487.4
Edge of coverage (EOC)	dB	3.0	-	3.0	-
G/T at EOC	dB-°K	1.4	33.5	1.4	30.7
C/N	dB	10.9	26.4	7.2	8.9
C/I-Self interference due to freq re-use	dB	99.0	99.0	99.0	99.0
C/I1 -2 interference satellites +/- 2deg	dB	15.9	33.9	15.9	33.9
C/I2 - 2 interference satellites +/- 4 deg	dB	23.6	41.5	23.6	41.5
C/IM3	dB	99.0	18.0	99.0	18.0
C/(N+I)	dB	9.6	17.3	6.53	8.3
RX Eb/(No+Io)	dB	-	8.4	-	3.8
Required Eb/No	dB	-	3.8	-	3.8
Margin	**dB**	**-**	**4.6**	**-**	**0.0**

	Terminal Parameters		Satellite Comms Parameters	
Parameters	Transmit (UA)	Receive (UA CS)	Receive	Transmit
Earth Station location		Orlando AP		
* Latitude (N=" "; S ="-")		28.6		
* Longitude (E=" "; W= " "		-81.4		
Transmit power (W)	10.0	-	-	120.0
Circuit loss (dB)	2.0	-	-	2.5
Antenna gain (dBi)	39.7	57.6	36.7	39.0
* Antenna size (m)	0.80	7.00	0.8	1.2
* Antenna efficiency	65%	75%	33%	35%
* Beamwidth (deg)	1.8	0.2	1.77	1.41
Pointing error (deg)	0.27	0.04	0.27	0.21
Noise figure (dB)	-	2.5	3.4	-
Axial ratio (dB)	2.0	2.0	2.0	2.0

Modulation - Clear sky	3/4 QPSK- DOCSIS	rameters	
Data rate (Mbps)	0.32	Type of satellite	GSO
Required Bandwidth (MHz)	0.3	Orbital location	-105
Required Eb/No (dB)	3.8	Satellite Altitude (km)	35,878
Pfd (dB(W/m2/MHz)	-128.9552	Orbital Period (minutes	1440.8
Total rq. Bandwidth (MHz)	15.1	Or (hours)	24.0
Modulation - Rain	3/4 QPSK- DOCSIS		
Data rate (Mbps)	0.32	U/L Elevation angle (de	20
Required Bandwidth (MHz)	0.3	U/L Slant range (km)	39647
Required Eb/No (dB)	3.8	D/L Elevation Angle	48
Pfd (dB(W/m2/MHz)	-128.9552	D/L Slant range (km)	37315

Table 4-2 shows that:

– in order to maintain the –14 dBW/4 kHz transmit power density level requirement, with the telemetry data rate of 320 kbps, the nominal 10 W transmitter has been backed off by 3.5 dB to approximately 5 W. The purpose of the 14 GHz link budget shown in Table 4-2 is to compute the maximum rain fade margin, from UA-to-satellite;

– the maximum UA-to-satellite link fade margin is 3.8 dB based on a 20º elevation angle;

– the UA link availability, depending on rain rate and operational altitude, is shown in Fig. 4-4.

3.4 12/14 GHz link availability

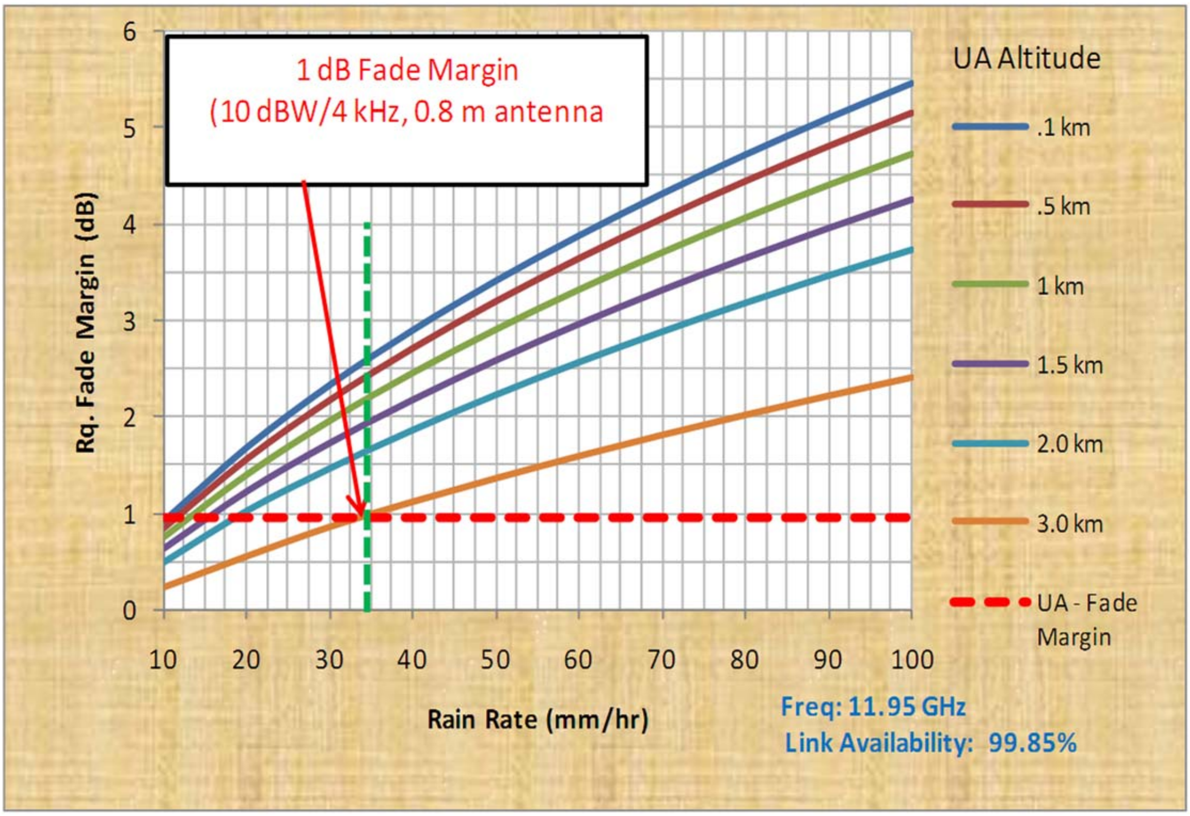
In order to achieve the assumed 99.8% overall end-to-end link availability, the UA to and from satellite links must have 99.85% link availability and the UACS to and from satellite links must have 99.95% link availability as discussed in Section 2 of this example. The following sections examine the impact of rain on the UA/satellite link availability based on the parameters used in the link budgets in Section 3.3.

3.4.1 Telecommand link (satellite-to-unmanned aircraft) rain fade margin

The satellite-to-UA link rain fade margin versus rain fall rate, which is based on Recommendation ITU-R P.618-9, is shown in Fig. 4-3.

FIGURE 4-3

Example of telecommand link (satellite-to-unmanned aircraft) rain fade margin versus rain fall rate (99.85% link availability and 20 degrees unmanned aircraft antenna elevation angle; at 11.95 GHz)



If the UA operates in the 12 GHz frequency band with a 0.8 m antenna, the system can only achieve a 1.0 dB rain fade margin. The UA telecommand link, from satellite-to-UA can achieve 99.85% if:

– UA Operational altitude ≥ 3 km and rain rate ≤ 35 mm/hour;

– UA Operational altitude ≥ 2 km and rain rate ≤ 20 mm/hour;

– UA Operational altitude ≥ 1.5 km and rain rate ≤ 15 mm/hour.

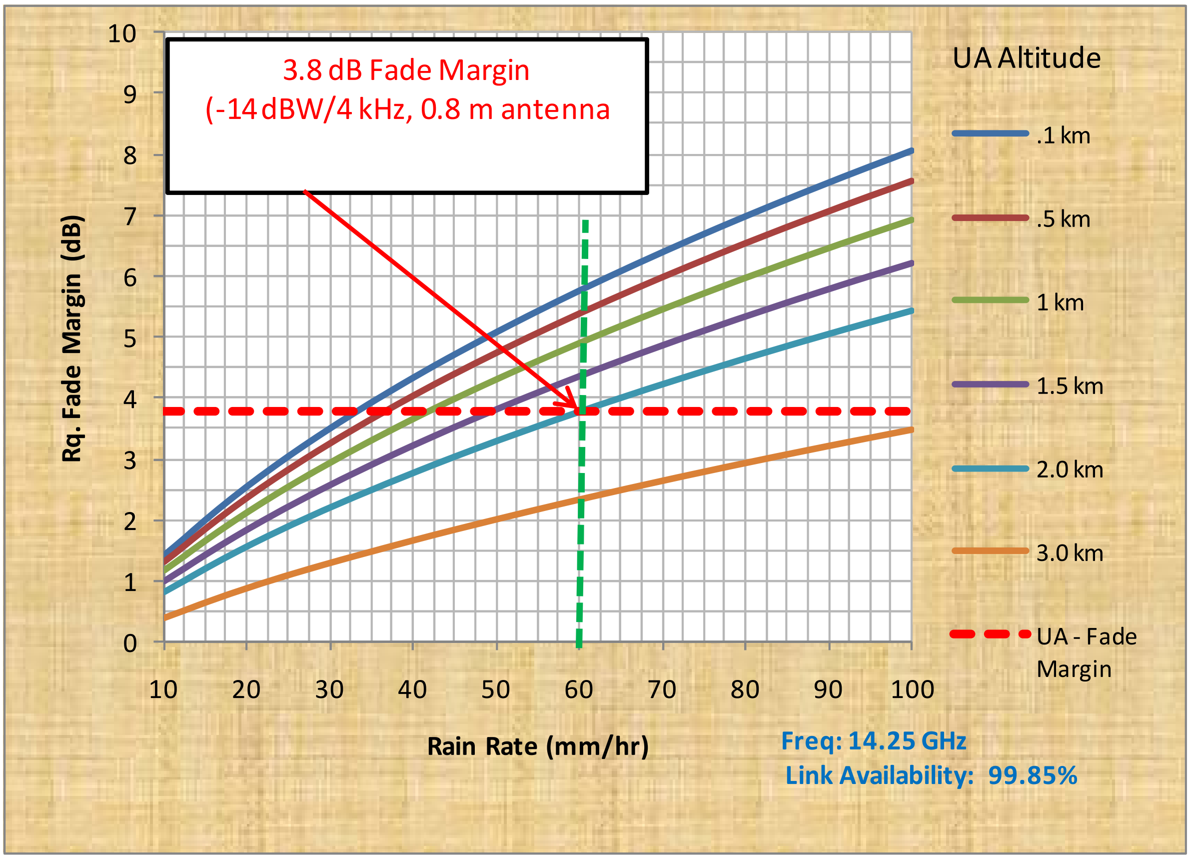
In general this low rain fade margin may not be adequate to achieve the assumed link availability for most locations around the world. In order to achieve the assumed link availability the UA may need to operate with a larger antenna size and/or utilize spread-spectrum and other rain fade mitigation techniques such as satellite diversity, etc. If a 1.0 m antenna was used, a 2.9 dB rain fade margin may be achieved (see Fig. 4-3).

3.4.2 Telemetry link availability (unmanned aircraft-to-satellite) rain fade margin

The UA-to-satellite link rain fade margin versus rain fall rate, which is based on Recommendation ITU-R P.618-9, is shown in Fig. 4-4.

FIGURE 4-4

Example of telemetry link (unmanned aircraft-to-satellite) rain fade margin versus rain fall rate (99.85% link availability and 20 degrees unmanned aircraft antenna elevation angle, 14.25 GHz)



If the UA operates in the 14 GHz frequency band with a 0.8 m antenna, the system can only achieve a 3.8 dB rain fade margin. Depending on the UA operational altitude, the 3.8 dB rain fade margin may be adequate to achieve the 99.85% link availability assumed, particularly when it operates at high altitude.

The UA telemetry link, from UA-to-satellite can achieve 99.85% if:

– UA Operational altitude ≥ 3 km and rain rate ~ 100 mm/hour;

– UA Operational altitude ≥ 2 km and rain rate ≤ 60 mm/hour;

– UA Operational altitude ≥ 1.5 km and rain rate ≤ 50 mm/hour.

In order to achieve higher rain fade margins and still meet the uplink transmit power density, the UA may need to operate with a larger antenna size and/or utilize spread-spectrum and other rain fade mitigation techniques such as satellite diversity, etc. If a 1.0 m antenna was used, a 5.74 dB (3.8 dBW/0.8 m antenna +1.94 dB – additional gain, from 0.8 m to 1.0 m antenna), rain fade margin could be achieved.

3.5 Unmanned aircraft link budget summary for the frequency bands 12/14 GHz

This example has shown that, under some conditions, a UA CNPC link operating in the frequency bands 12/14 GHz can achieve an overall end-to-end 99.8% link availability assumed (in both telecommand and telemetry directions) using antennas and transmitters that can be accommodated within the UA described in Report ITU-R M.2171 and the UACS while operating within the constraints of the transmit power density and off-axis power spectral density values mentioned in Radio Regulations.

Results shown in Section 3.4 indicate that if the UA operates with a 0.8 m antenna, the system can only achieve 1.0 dB telecommand link rain fade margin with 10 dBW/4 kHz satellite power density and 3.8 dB telemetry link rain fade margin with a UA transmit power density at −14 dBW/4 kHz.

This low rain fade margin for the telecommand link may not be adequate to meet the desired link availability. In order to achieve higher rain fade margins, several techniques may be considered:

– Operate with a larger antenna size as mentioned in Report ITU-R M.2171.
– Operate with higher satellite transmit power densities without exceeding the values mentioned in the RR however, this may cause interference to the receiving earth stations of other satellite systems and may require further coordination with the adjacent satellite operators.
– In order to use higher transmitter powers while maintaining pfd, the utilization of alternative modulation schemes may be appropriate (e.g. spread spectrum techniques).

In so doing, there is a need to ensure that the coordination requirements already established are maintained unchanged. However, the telemetry link with 3.8 dB of rain fade margin in this example may be adequate, particularly when the UA operational altitude is higher than 2 km in order to reduce the rain effect. As mentioned in Section 3.4, if the UA in the 12/14 GHz frequency bands operates with a 1.0 m antenna, the system can achieve the assumed link 99.85% availability.

4 Using geostationary orbit satellites in the 20/30 GHz frequency bands for unmanned aircraft system control

4.1 20/30 GHz geostationary orbit satellite characteristics

The characteristics of the GSO satellites currently on orbit operating in the frequency band 20/30 GHz can be summarized below:

– Satellite receive *G*/*T*: ~ 12 dB/K to 16 dB/K @ 3 dB EOC
– Satellite transmit e.i.r.p.: ~57 dBW to 64 dBW @ 3 dB EOC depending on the transmit bandwidth. However, in general, they all operate at almost the same downlink power flux density level, –118 dB W/m^2/MHz. This power flux density used in this example is below the maximum values indicated in Table 21.4 of Article 21 of the Radio Regulations.

4.2 Uplink off-axis e.i.r.p. density and downlink power flux density

4.2.1 Uplink off-axis e.i.r.p. density

Based on Recommendation ITU-R S.524-9, an example of an off-axis e.i.r.p. density of an earth station operating in the GSO networks in the FSS transmitting in the frequency band 27.5-30 GHz is summarized below:

Angle off-axis	*Maximum e.i.r.p. per 40 kHz*
$2.0° \leq \Theta \leq 7°$	$((18.5 – 25 \log \Theta) – 10\log(N))$ dBW/40 kHz
$7° < \Theta \leq 9.23°$	$(–2.63 - 10\log(N))$ dBW/40 kHz
$9.23° < \Theta \leq 48°$	$((21.5 – 25 \log \Theta) – 10\log(N))$ dBW/40 kHz
$48° < \Theta \leq 180°$	$(–10.5 – 10\log(N))$ dBW/40 kHz).

where:

– Θ is the angle in degrees from the axis of the main lobe;
– N is the likely maximum number of simultaneously transmitting co-frequency earth stations in the receive beam of the satellite; N = 1 for TDMA and FDMA systems;

– earth stations operating with uplink power control can increase their uplink power to overcome rain fade.

4.2.2 Downlink power flux density levels

The pfd limits for GSO FSS satellite networks operating in the 20 GHz frequency band used in this example are below the maximum values indicated in Table 21-4 of Article 21 of the Radio Regulations.

4.3 20/30 GHz Link budgets calculation – Assumptions

In this example, the link budget calculations use the following assumptions:

- UA e.i.r.p. and G/T
  - e.i.r.p.: 50.1 dBW
  - Antenna size: 0.5 m
  - Transmit power: 10 W
  - G/T : 14.1 dB/K
- UA uplink power control: Uplink power was used in this example.
- Satellite receive G/T @ −3 dB EOC: 12.2 dB/K.
- Downlink pfd: ≤ −118 dBW/m^2/MHz.
- Data rate
  - Telecommand: 10 kbps. It should be noted that the required data rate is only 10 kbps; however, the downlink "burst" rate is significantly higher. The downlink transmit data rate of 20/30 GHz satellites currently on orbit is in a range from 18 Mbps to 450 Mbps. The objective of the link budget shown in Table 4-3 is to determine the downlink fade margin so the downlink transmit data rate is not important because the satellite power is assumed to be adjusted to meet the −118 dB(W/m^2/MHz) requirement.
  - Telemetry: 320 kbps.
- UA uplink transmit power density level: The values shown in Section 4.1 were used.
- UA antenna patterns: Antenna patterns specified in Section 4.2 were used in this example.
- In the context of performance: In the 20/30 GHz band satellites are assumed to be spaced every 2 degrees and utilize small spot beam architectures. Most 20/30 GHz band satellites utilize a four times frequency reuse scheme and operate with narrow spot beams. The probability that all adjacent satellites will operate the same frequency and polarization in the spot being used by the satellite providing service to the UAS at the same time is less than 50%. In the link budget, only one of the two possible satellites spaced 2 degrees and 4 degrees either side needs to be taken into account However, the worst case adjacent satellite interference (receiving interference from 2 satellites at ± 2 degrees plus 2 satellites at ± 4 degrees) are used in the link budgets shown in Tables 4-3 and 4-4. It should be noted that interference environment presented here is only an example of possible constituent parts of overall interference margin within the link budgets. In so doing, there is a need to ensure that the coordination requirements already established are maintained unchanged.

4.3.1 Telecommand link budgets (unmanned aircraft control station-to-satellite and satellite-to-unmanned aircraft) (links 1 and 2 of Fig. 4-2)

The 20 GHz telecommand and 30 GHz telemetry link budgets are summarized in Tables 4-3 and 4-4. The purpose of these link budgets is to compute the maximum available rain fade margin.

Based on the available rain fade margin and the assumed link availability (99.85% for UA links), the maximum rain fall rate and the operational altitude of the UA are presented in Section 4.4.

An example of a telecommand link budget, UACS-to-satellite and satellite-to-UA is shown in Table 4-3.

TABLE 4-3

Example of telecommand link budgets (unmanned aircraft control station-to-satellite and satellite-to-unmanned aircraft)

Forward Link		Clear Sky Conditions		Rain	
Link Parameter	Units	UA Control Uplink	UA Downlink	UA Control Uplink	UA Downlink
Earth station location		Orlando AP		Orlando AP	
Frequency	GHz	30.00	20.00	30.00	20.00
Transmit EIRP	dBWi		61.5		61.5
Number of carriers			1550.0		1550.0
Output back off	dB		5.2		5.2
EIRP per carrier	dBWi	47.8	24.4	67.8	24.4
Edge of coverage (EOC)	dB	-	3	-	3
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5
Space Loss	dB	213.4	210.4	213.4	210.4
Link availability	%	-	-	99.9	-
Atmospheric &Scintillation Loss	dB	0.76	0.65	-	-
Rain loss - ITU Combined Model		-	-	30.1	-
Maximum Rain Fade Margin - UA	**dB**				**6.4**
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-167.1**	**-190.5**	**-176.5**	**-196.2**
Receiver Antenna Gain	dB	43.2	38.5	43.2	38.5
Receiving System Temperature	dB-°K	634.5	265.8	634.5	367.9
Edge of coverage (EOC)	dB	3.0	-	2.0	-
G/T at EOC	dB-°K	12.2	14.3	13.2	12.9
C/N	dB	34.1	12.9	25.8	5.7
C/I-Self interference due to freq re-use	dB	18.0	18.0	18.0	18.0
C/I1 -2 interference satellites +/- 2deg	dB	43	15.0	43.3	15.0
C/I2 - 2 interference satellites +/- 4 deg	dB	51	22.5	50.9	22.5
C/IM3	dB	18.0	18.0	18.0	18.0
C/(N+I)	dB	14.9	9.2	14.6	4.8
RX Eb/(No+Io)	dB	-	7.7	-	3.8
Required Eb/No	dB	-	3.8	-	3.8
Margin	**dB**	**-**	**3.9**	**-**	**0.0**

	Terminal Parameters		Satellite Comms Parameters	
Parameters	**Transmit (UA CS)**	**Receive (UA)**	**Receive**	**Transmit**
Earth Station location	Orlando AP	Augusta AP		
* Latitude (N=" "; S ="-")	28.6	44.3		
* Longitude (E=" "; W= " "	-81.4	-69.8		
Transmit power (W)	500.0	-	-	120.0
Circuit loss (dB)	2.0	-	-	2.5
Antenna gain (dBi)	65.6	38.5	43.2	43.2
* Antenna size (m)	7.0	0.50	0.8	**1.2**
* Antenna efficiency	75%	65%	33%	33%
* Beamwidth (deg)	0.1	2.0	0.84	0.84
Pointing error (deg)	0.01	0.30	0.13	0.13
Noise figure (dB)	-	2.5	3.4	-
Axial ratio (dB)	2.0	2.0	2.0	2.0
Modulation - Clear sky	3/4 QPSK- DOCSI	**ital parameters**		
Data rate (Mbps)	0.01	Type of satellite		GSO
Required Bandwidth (MHz)	0.0089	Orbital location		-105
Required Eb/No (dB)	3.8	Satellite Altitude (km)		35,878
Pfd (dB(W/m2/MHz)	-118.0831	Orbital Period (minutes)		1440.8
Total rq. Bandwidth (MHz)	13.8	Or (hours)		24.0
Modulation - Rain	3/4 QPSK- DOCSI			
Data rate (Mbps)	0.0100	U/L Elevation angle (deg		48
Required Bandwidth (MHz)	0.0089	U/L Slant range (km)		37315
Required Eb/No (dB)	3.8	D/L Elevation Angle		20
Pfd (dB(W/m2/MHz)	-118.0831	D/L Slant range (km)		39647

Table 4-3 shows that:

– the data rate is 10 kbps; however, the downlink burst rate of the satellite is significantly higher. The downlink transmit data rate of a typical 20/30 GHz frequency band satellite, currently on orbit, is in the range from 18 Mbps to 450 Mbps. The downlink power is assumed to be adjusted for different data rates; however, the downlink power flux-density level, −118 dBW/m^2/MHz, will be kept constant. Therefore, the downlink fade margin would remain the same;

– it should be noted that in the link budgets, the location of UACS is in a high rain zone with an $R_{0.01}$ rain rate of 90 mm/hour. With a 7 m earth terminal antenna, the UACS link with 30.1 dB of rain fade margin can only achieve 99.9% instead of the assumed 99.95% link availability. However, the UACS could operate with larger antenna size (e.g. 8 m instead of 7 m), or use site diversity to achieve the assumed link availability, 99.95%;

– the maximum link fade margin, from satellite-to-UA is 6.4 dB. The purpose of the link budget shown in Table 4- 3 is to compute the maximum rain fade margin, from satellite to

UA. An elevation angle, from satellite-to-UA, of 20º was used in this example. The UA link availability, depending on rain rate and operational altitude, is shown in Fig. 4-5.

4.3.2 Telemetry link budgets (unmanned aircraft-to-satellite and satellite-to-unmanned aircraft control station) (Links 3 and 4 of Fig. 4-2)

An example of a telemetry link budget, UA-to-satellite and satellite-to-UACS is shown in Table 4-4.

TABLE 4-4

Example of telemetry link budgets (unmanned aircraft-to-satellite and satellite -to-unmanned aircraft control station)

RETURN LINK		Clear Sky Conditions		Rain	
Link Parameter	**Units**	**UA Uplink**	**UA CS Downlink**	**UA Uplink**	**UA CS Downlink**
Earth station location			**Orlando AP**		**Orlando AP**
Frequency	GHz	30.00	20.00	30.00	20.00
Transmit EIRP	dBWi	50.1		50.1	
Number of carriers		1.0		1.0	
Output back off	dB	10.0		0.0	
EIRP per carrier	dBWi	40.1	39.4	50.1	39.4
Edge of coverage (EOC)	dB	-	2	-	2
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5
Space Loss	dB	214.0	209.9	214.0	209.9
Link availability	%	-	-	-	99.9
Atmospheric &Scintillation Loss	dB	1.23	2.13	-	-
Rain loss - ITU Combined Model		-	-	-	26.6
Maximum Rain Fade Margin - UA	**dB**	**-**	**-**	**14.3**	
Polarization loss	dB	0.2	0.2	0.2	0.2
Rcvd Incident Pwr (RIP)(dBw)	**dBW**	**-175.9**	**-175.4**	**-179.0**	**-199.8**
Receiver Antenna Gain	dB		62.1		62.1
Receiving System Temperature	dB-°K		332.1		495.1
Edge of coverage (EOC)	dB	3.0	-	3.0	-
G/T at EOC	dB-°K	12.2	36.9	12.2	35.1
C/N	dB	10.3	35.6	7.2	9.4
C/I-Self interference due to freq re-use	dB	18.0	18.0	18.0	18.0
C/I1 -2 interference satellites +/- 2deg	dB	17.5	40.5	17.5	40.5
C/I2 - 2 interference satellites +/- 4 deg	dB	22.1	48.1	22.1	48.1
C/IM3	dB	99.0	18.0	99.0	18.0
C/(N+I)	dB	8.8	14.9	6.4	8.3
RX Eb/(No+Io)	dB	-	7.3	-	3.8
Required Eb/No	dB	-	3.8	-	3.8
Margin	**dB**	**-**	**3.5**	**-**	**0.0**

	Earth Terminal Parameters		Satellite Comms Parameters	
Parameters	**Transmit (User)**	**Receive (Feeder)**	**Receive**	**Transmit**
Earth Station location		**Orlando AP**		
* Latitude (N=" "; S ="-")		28.6		
* Longitude (E=" "; W= " "		-81.4		
Transmit power (W)	10.0	-		
Circuit loss (dB)	2.0	-		
Antenna gain (dBi)	42.1	62.1		
* Antenna size (m)	0.50	7.00		
* Antenna efficiency	65%	75%		
* Beamwidth (deg)	1.3	0.1		
Pointing error (deg)	0.20	0.02		
Noise figure (dB)	-	2.5		
Axial ratio (dB)	2.0	2.0		

Modulation - Clear sky	3/4 QPSK- DOCSI	**tal parameters**	
Data rate (Mbps)	0.320	Type of satellite	GSO
Required Bandwidth (MHz)	0.3	Orbital location	-105
Required Eb/No (dB)	3.8	Satellite Altitude (km)	35,878
Pfd (dB(W/m2/MHz)	-118.06544	Orbital Period (minutes)	1440.8
Total rq. Bandwidth (MHz)	14.2	Or (hours)	24.0
Modulation - Rain	3/4 QPSK- DOCS		
Data rate (Mbps)	0.320	U/L Elevation angle (deg	20
Required Bandwidth (MHz)	0.3	U/L Slant range (km)	39647
Required Eb/No (dB)	3.8	D/L Elevation Angle	48
Pfd (dB(W/m2/MHz)	-118.06544	D/L Slant range (km)	37315

Table 4-4 shows that:

– it should be noted that in the link budgets, the location of UACS is in a high rain zone with an $R_{0.01}$ rain rate of 90 mm/hour. With a 7 m earth terminal antenna, the UACS link with 26.6 dB of rain fade margin can only achieve 99.9% instead of the assumed 99.95% link availability. The UACS could operate with a larger antenna size (e.g. 8 m instead of 7 m), or use site diversity to achieve higher link availability;

– again the objective of the link budget shown in Table 4-4 is to determine the maximum UA-to-satellite rain fade margin, The UA-to-satellite link fade margin is 14.3 dB using 10 W and a 0.5 m antenna on the UA;

– the UA link availability, depending on rain rate and operational altitude, is shown in Fig. 4-6.

4.4 20/30 GHz link availability

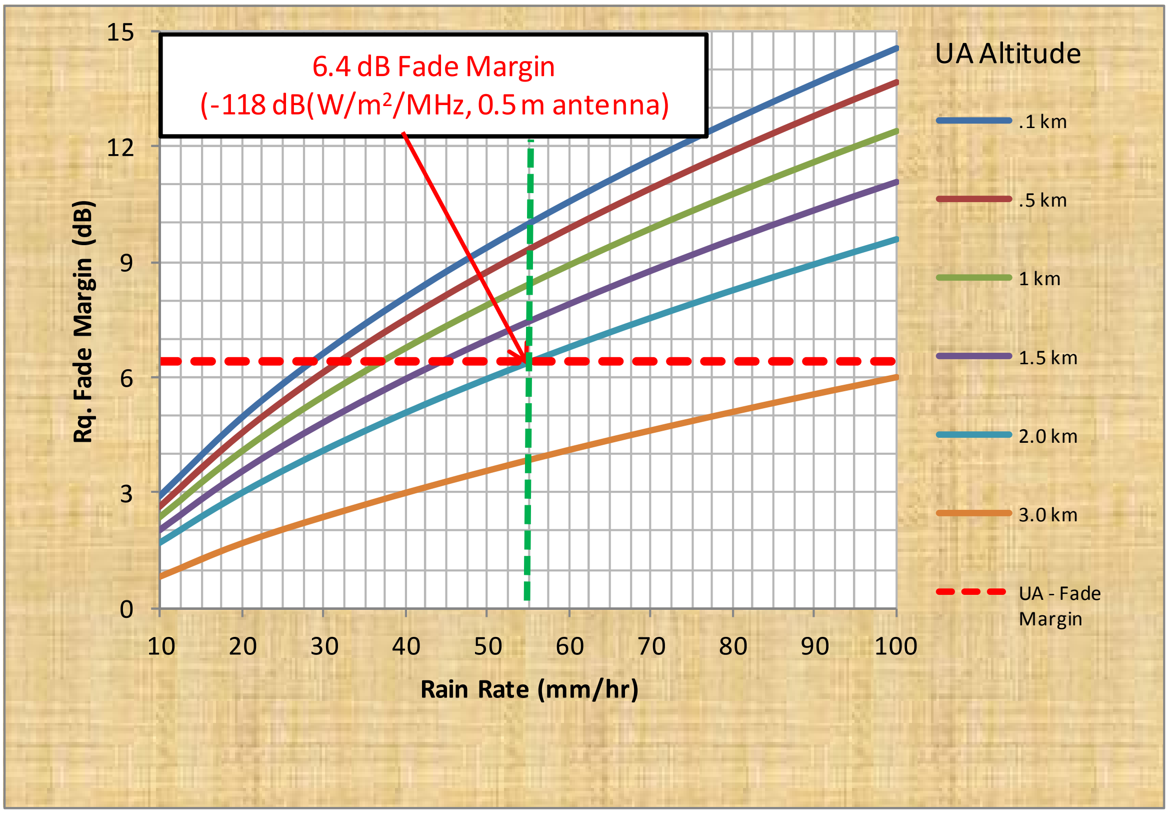
In order to achieve the assumed 99.8% overall end-to-end link availability, the UA/satellite link must have 99.85% link availability (in both directions) as discussed in Section 2.2 of this example. The following sections examine the impact of rain on the UA/satellite link availability based on the parameters used in the link budgets in Section 4.3.

4.4.1 Telecommand link (satellite-to-unmanned aircraft) rain fade margin

The satellite-to-UA link rain fade margin versus rain fall rate, which is based on Recommendation ITU-R P.618-9, is shown in Fig. 4-5.

FIGURE 4-5

Example of a telecommand link (satellite-to-unmanned aircraft) rain fade margin versus rain fall rate (99.85% link availability and 20 degree unmanned aircraft antenna elevation angle; at 20 GHz)



If the UA operates in the 20 GHz frequency band with a 0.5 m antenna the system can achieve a 6.4 dB rain fade margin. Results shown in Fig. 4-5 indicate that the UA telecommand link, from satellite-to-UA can achieve 99.85% link availability assumed, if:

– UA operational altitude ≥ 3 km and rain rate > 100 mm/hour;

– UA operational altitude ≥ 2 km and rain rate ≤ 55 mm/hour;

– UA operational altitude ≥ 1.5 km and rain rate ≤ 45 mm/hour.

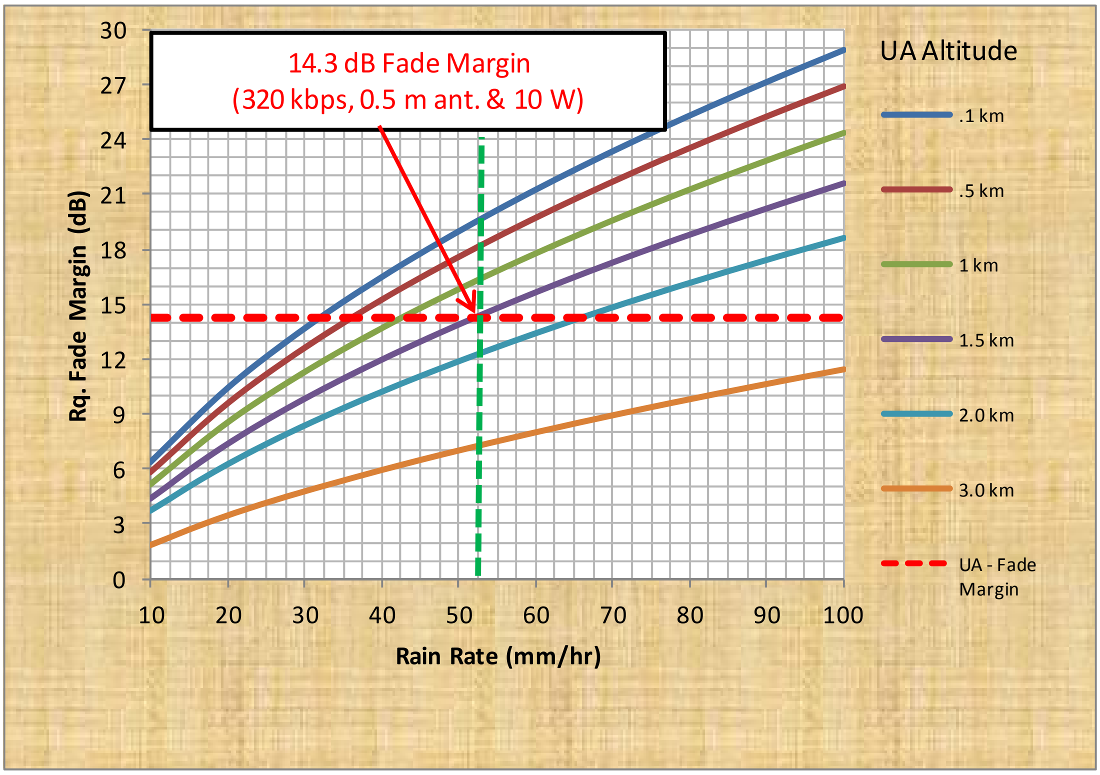
The telecommand link with 6.4 dB of rain fade margin in this example, may be adequate if the UA operational altitude is greater than 1.5 km in order to reduce the rain effect.

4.4.2 Telemetry link availability (unmanned aircraft-to-satellite) rain fade margin

The UA-to-satellite link rain fade margin versus rain fall rate, which is based on Recommendation ITU-R P.618-9, is shown in Fig. 4-6.

FIGURE 4-6

Example of a telemetry link (unmanned aircraft-to-satellite) rain fade margin versus rain fall rate (99.85% link availability and 20 degree unmanned aircraft antenna elevation angle, 30 GHz)



The UA operating with a 0.5 m antenna and 10 W can achieve a 14.3 dB uplink, telemetry link, from UA-to-satellite rain fade margin. Results shown in Fig. 4-6 indicate that the satellite-to-UA link can achieve 99.85% link availability assumed, if:

– UA operational altitude ≥ 3 km and rain rate >100 mm/hour;

– UA operational altitude ≥ 2 km and rain rate ≤ 65 mm/hour;

– UA operational altitude ≥ 1.5 km and rain rate ≤ 52 mm/hour.

The telemetry link with 14.3 dB of rain fade margin in this example, may be adequate if the UA operational altitude is approximately 1.5 km or higher in order to reduce the rain effect.

4.5 20/30 GHz frequency bands unmanned aircraft link budget summary

This example has shown that, in the 20/30 GHz frequency bands a UAS CNPC link operating in the 20/30 GHz frequency bands can achieve an overall end-to-end 99.8% link availability assumed (in both telecommand and telemetry directions) using antennas and transmitters that can be accommodated within the UA described in Report ITU-R M.2171 and the UACS while operating within the constraints of the transmit power density and off-axis power spectral density values mentioned in Radio Regulations.

Results shown in Section 4.4 indicate that if the UA operates with a 0.5 m antenna and a 10 W transmitter, the system can achieve 6.4 dB of telecommand link rain fade margin and 14.3 dB of telemetry link rain fade margin. These rain fade margins would be adequate to achieve the assumed link availability particularly when the UA is operating at altitudes higher than 1.5 km in order to reduce the rain effect.

5 Potential interference to/from other satellite systems operating in the same frequency bands

In this example, the UA in both the 12/14 GHz and 20/30 GHz frequency bands meets both the designated uplink transmit power density and downlink transmit density or pfd limits. Therefore, the UA operating like a GSO FSS user would not cause harmful interference to other systems operating in the same frequency bands.

If the UA operates like a GSO FSS user in an environment where the transmission of other adjacent satellites are subject to the same limits (e.g. uplink power density, downlink pfd, etc.) as the UA to/from satellite links, it would not pose any potentially operational constraints on the other systems operating in the same frequency band.

Annex 5

Glossary

ACP	Aeronautical Communications Panel
AES	Airborne earth station
AGL	Above ground level
AM(R)S	Aeronautical-mobile (route) service
AMS	Aeronautical-mobile service
AMS(R)S	Aeronautical-mobile satellite (route) service
AMSS	Aeronautical-mobile satellite service
ARNS	Aeronautical radionavigation service
ATC	Air traffic control
BER	Bit error ratio
BLoS	Beyond line-of-sight
CNPC	Control and non-payload communications
DL	Downlink
DME	Distance measuring equipment
DME/N	Narrow-spectrum distance measuring equipment
DME/P	Precision distance measuring equipment
DQPSK	Differential Quadrature Phase-Shift Keying
e.i.r.p.	Equivalent isotropically radiated power

E/S	Earth-to-space
EUROCAE	European Organization for Civil Aviation Equipment
FDD	Frequency-division duplex
FDR	Frequency-dependent rejection
FL	Forward link
FSS	Fixed-satellite service
GES	Ground earth station (for SATCOM CNPC system)
GPS	Global Positioning System
GS	Ground station (for terrestrial CNPC system)
GSO	Geostationary satellite orbit
G/T	Ratio of receiving-antenna gain to receiver thermal noise temperature in kelvins
HIBLEO-4	A non-geostationary-orbit satellite network
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.16e	IEEE standard for mobile broadband wireless access systems)
ILS	Instrument Landing System
INR	Interference-to-noise ratio
LAN	Local area network
LEO	Low Earth orbit (or a satellite in that orbit)
LoS	Line-of-sight
MLS	Microwave landing system
MS	Mobile service
MSS	Mobile-satellite service
NPR	Noise power ratio
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
pfd	Power flux density
QPSK	Quadrature phase-shift keying
RL	Return link
RNSS	Radionavigation-satellite service
RR	Radio Regulations
Rx	Receiver
S&A	Sense and avoid
SATCOM	Satellite communications
SNR	Signal-to-noise ratio
TDD	Time-division duplex

Tx	Transmitter
UA	Unmanned aircraft
UACS	UA control station
UAS	UA system(s)
UL	Uplink