International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Frequency sharing between unmanned aircraft systems for beyond line of sight control and non-payload communications links and other existing and planned services in the frequency bands 13.25-13.40 GHz, 15.4-15.7 GHz, 22.5-22.55 GHz and 23.55-23.60 GHz

M Series

Mobile, radiodetermination, amateur and related satellite services

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Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

REPORT ITU-R M.2230

Frequency sharing between unmanned aircraft systems for beyond line of sight control and non-payload communications links and other existing and planned services in the frequency bands 13.25-13.40 GHz, 15.4-15.7 GHz, 22.5-22.55 GHz and 23.55-23.60 GHz

(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, communications relays, agricultural applications, environmental monitoring, emergency management, and law enforcement applications.

Based on Report ITU-R M.2171, it is predicted that 56 MHz of satellite spectrum and an additional 34 MHz of terrestrial spectrum would be required to support the anticipated growth of UAS operations in non-segregated airspace. It should be noted that for a regional coverage, in order to meet the BLOS spectrum requirements to support unmanned aircraft (UA) control links, three or more satellites were assumed to provide service in the same coverage area.

Several frequency bands above 10 GHz (12/14 GHz, 13/15 GHz, 20/30 GHz and 22/23 GHz) have been identified as potential frequency bands to support beyond line-of-sight (BLOS) UAS control links in non-segregated airspace.

The purpose of this Report is to:

–   present the potential system characteristics of a UAS control link operating in the 13.25-13.40 GHz, 15.4-15.7 GHz, 22.5-22.55 GHz and 23.55-23.60 GHz frequency bands; and

–   examine whether UAS control links operating in these frequency bands can:

   –   support adequate levels of link availability for safe UA operation;

   –   successfully share the frequency bands with other existing and planned services;

   –   protect the passive services in the nearby frequency bands;

   –   be implemented (e.g. passive inter-modulation also known as PIM, filters, etc.).

In addition, the advantages and disadvantages of using these potential frequency bands (13/15 GHz and 22/23 GHz) and the geostationary orbit (GSO) satellites in 12/14 GHz, 20/30 GHz frequency bands are also presented.

The intent of this Report is to consider technical feasibility and advantages or disadvantages of various frequency bands, not to consider or propose regulatory methods for how frequency bands might be used.

2 UAS and satellite system parameters

2.1 UAS control system characteristics

2.1.1 Information data rate

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

– Telecommand, UA control station-to-satellite-to UA: 10 kbit/s.

– Telemetry, UA-to-satellite-to UA control station: 320 kbit/s.

2.1.2 End-to-end link availability

The UA control link is required not only to provide safe control of the UA trajectory by the pilot but also to provide the pilot with information on aircraft status. This status information will include aircraft state as well as situational awareness information on other aircraft, terrain or weather that may require the pilot to manoeuvre the UA to avoid an unsafe condition. In some implementations, the UA control link may also carry voice or data traffic between the UA pilot and the Air Traffic Controller.

Preliminary analysis by RTCA SC 203 indicates that UA safety levels equivalent to a large commercial manned aircraft flying in controlled airspace would require a UA control link availability of approximately 99.999%. To achieve this overall control link availability and reliability and therefore the safe operation of UA in non-segregated airspace, UA of equivalent size to larger manned aircraft will be equipped with more than one control link. If the UA has only two control link sub-systems and the link availability of each control link is 99.8%, then the overall system link availability would be approximately 99.999%.

In this Report, the end-to-end link availability of the BLOS control link subsystem is 99.8%. In order to achieve this link availability, the UA and UACS link availability needs 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 the satellite link and a 99.85% link availability for the UA to/from the satellite were assumed in this Report.

2.1.3 Unmanned aircraft system parameters

As mentioned in § 1, the study results within ITU-R Working Parties, which deal with the 12/14 GHz and 20/30 GHz frequency bands, indicate that GSO satellites operating in the 12/14 GHz and 20/30 GHz can support UA controls links and meet the required level of UAS system link availability. The UAS control link system parameters used in those studies are summarized below:

– 12/14 GHz frequency bands

  – UA antenna diameter: 0.8 m

  – UA transmit power: 10 W

– 20/30 GHz frequency bands

  – UA antenna diameter: 0.5 m

  – UA transmit power: 10 W.

In the studies, the terminal antenna diameter and the transmit power of the UACS are 7.0 m and 500 W, respectively. It should be noted the actual UACS terminal antenna diameter and transmit

power would depend on such factors as the actual earth station location, operational elevation angle, rain climate, etc.

Since the 12/14 GHz and 20/30 GHz frequency bands are very close to the 13/15 GHz (13.25-13.4 GHz/15.4-15.7 GHz) and 22/23 GHz (22.5-22.55 GHz/23.55-23.6 GHz) frequency bands respectively the UAS system parameters for the 13/15 GHz and 22/13 GHz frequency bands analysed in this Report will have similar parameters to those presented for the 12/14 GHz and 20/30 GHz frequency bands already studied.

– UA parameters
  – 13.25-13.4 GHz/15.4-15.7 GHz frequency bands
    – Antenna diameter: 0.8 m
    – Transmit power: 10 W
  – 22.5-22.55 GHz/23.55-23.6 GHz frequency bands
    – Antenna diameter: 0.5 m
    – Transmit power: 10 W
– UACS parameters: For the purpose of this Report, the terminal antenna diameter and transmit power of UACS associated with the 13/15 GHz and 22/23 GHz frequency bands are assumed to be less than or equal to 7.0 m and 500 W, respectively.

2.1.4 Unmanned aircraft uplink transmit power density and off-axis e.i.r.p. density

It should be noted that there are currently no uplink transmit power density limits or off-axis e.i.r.p. density limits in the 13/15 GHz and 22/23 GHz frequency bands. However, in the 12/14 GHz and 20/30 GHz frequency band reports, the values shown below were used:

– 14 GHz uplink: A UA transmit power density input to the antenna port of -14 dBW/4 kHz was used.

– 30 GHz uplink: The off-axis e.i.r.p. density of an Earth station operating in the GSO networks in the fixed-satellite service (FSS) transmitting in the 27.5-30 GHz frequency band based on Recommendation ITU-R S.524-9 is summarized below:

Angle off-axis	*Maximum e.i.r.p. per 40 kHz*
$2.0° \leq \varphi \leq 7°$	$(19-25 \log \varphi)$ dB(W/40 kHz)
$7° < \varphi \leq 9.2°$	-2 dB(W/40 kHz)
$9.2° < \varphi \leq 48°$	$(22-25 \log \varphi)$ dB(W/40 kHz)
$48° < \varphi \leq 180°$	-10 dB(W/40 kHz).

In this Report, a transmit power density of -11 dB(W/4 kHz), measured at the input to the antenna port of the UA operating in the 15.4-15.7 GHz frequency band, will be used (see § 2.3 for more details).

The uplink off-axis e.i.r.p. density levels of the UA in the 23 GHz frequency band are assumed to have the similar levels as the FSS systems in the 27.5-30 GHz band.

2.2 Satellite system parameters

For the purpose of this Report, GSO satellites are assumed to be used to provide BLOS communications for UAS control links. The satellite system parameters in the 12/14 GHz and 20/30 GHz frequency bands are contained in Report ITU-R M.2233.

- 12/14 GHz frequency bands
  - Satellite receive G/T at edge of coverage (EOC): 1.4 dB/K
  - Satellite transmit e.i.r.p. density: 10 dBWi/4 kHz
- 20/30 GHz frequency bands
  - Satellite receive G/T at EOC: 12.2 dB/K
  - Downlink power flux-density: ≤ -118 dB(W/m^2/MHz).

In this Report, the following G/T and transmit power density limits will be used:

- 13/15 GHz frequency bands
  - Satellite receive G/T, at EOC: 1.4 dB/K (see § 2.3 for more details)
  - Satellite transmit e.i.r.p. density: 14 dBWi/4 kHz (see § 2.3 for details)
- 22/23 GHz frequency bands
  - Satellite receive G/T, at EOC: 12.2 dB/K (see § 2.3 for more details)
  - Satellite transmit pfd level, -118 dB(W/m^2/MHz) and -116 dB(W/m^2/MHz) (see § 2.3 for details).

2.3 Unmanned aircraft system and satellite system parameters in the frequency bands 13/15 GHz and 22/23 GHz

Based on the results of studies shown in Report ITU-R M.2233, the performance of the GSO satellite-based UAS control link in the 12/14 GHz and 20/30 GHz bands can be summarized below:

- **12/14 GHz frequency band study summary**
  - Telecommand downlink (Satellite-to-UA): If the UA operates with a 0.8 m antenna and the satellite downlink e.i.r.p. density level at 10 dBW/4 kHz, the system can only achieve a 1.0 dB rain fade margin.
  - Telemetry uplink (UA-to-satellite): If the UA operates with a 0.8 m antenna and the UA uplink transmit power density level at -14 dBW/4 kHz, the system can only achieve a 3.8 dB rain fade margin.

  The low telecommand rain fade margin of 1.0 dB is not adequate to achieve the desired link availability for most locations around the world. However, the telemetry fade margin of 3.8 dB may be adequate to achieve the minimum required link availability for most locations, if the UA operational altitude is 2 km or higher and the rain rate is not greater than 60 mm/hour.

  In order to achieve higher rain margins, several techniques may be considered:
  - Operate with a larger UA antenna diameter. If the UA in the 12/14 GHz frequency bands operates with a 1.0 m antenna, the system can achieve the desired 99.85% link availability for most locations around the world, particularly when the operational altitude of UA is 0.5 km or higher.
  - Utilize spread spectrum techniques, particularly on the satellite-to-UA link to maintain power densities with higher transmitter powers. In this case, the UA can operate with a 0.8 m antenna; however, in the telecommand link, the spread spectrum techniques would be required to achieve the desired link availability.
- **20/30 GHz frequency band study summary**
  - Telecommand downlink (Satellite-to-UA): If the UA operates with a 0.5 m antenna, the system can achieve a 6.7 dB rain fade margin.

– Telemetry uplink (UA-to-satellite): If the UA operates with a 0.5 m antenna and a 10 W transmitter, the system can achieve a 14.6 dB rain fade margin.

These rain fade margins would be adequate to achieve the desired link availability for most locations around the globe, particularly when the UA is operating at altitudes higher than 1.5 km.

Currently, there are no uplink power or downlink power flux-density limits for AMS(R)S in the 13.25-13.4 GHz frequency band. No. 21.8 of the Radio Regulations does specify e.i.r.p. density limits in the 15.4-15.7 GHz frequency band; however, they are equivalent to the levels in the 14 GHz frequency band. Since the 12/14 GHz and 20/30 GHz frequency bands are very close in frequency to the 13/15 GHz (13.25-13.4 GHz/15.4-15.7 GHz) and 22/23 GHz (22.5-22.55 GHz/23.55-23.6 GHz) frequency bands, respectively, the UAS system parameters for the 13/15 GHz and 22/13 GHz frequency bands analysed in this Report will have similar parameters to those presented for the 12/14 GHz and 20/30 GHz frequency bands already studied.

As mentioned above, the UA in 12/14 GHz, which operates with a 0.8 m diameter antenna and a 10 W transmitter, does not have enough rain fade margin to achieve 99.85% link availability for most location around the world. In this Report, in order to meet the desired UA link availability of 99.85%, the uplink and downlink transmit power density levels of the UA and satellite associated with the 13/15 GHz frequency bands will be 3 dB higher in the telemetry link and 4 dB higher in the telecommand link than the levels used in the GSO 12/14 GHz satellite system study.

2.3.1   13/15 GHz system parameters – assumptions

In this Report, the following parameters will be used:
– UA parameters
  – Antenna diameter: 0.8 m
  – Transmit power: 10 W
    – Transmit power density, input to antenna: –11 dB(W/4 kHz)
– UACS parameters
  – Antenna diameter: 7.0 m
  – Transmit power: 500 W
– Satellite parameters
  – Satellite receive G/T at EOC: 1.4 dB/K
  – Satellite transmit power density: 14 dBW/4 kHz
– Interference environment assumption: Receive interference from two satellites from ±6º.

2.3.2   22/23 GHz system parameters – assumptions

In the Report, the following parameters will be used:
– UA parameters
  – UA antenna diameter: 0.5 m
  – Transmit power: 10 W
  – The off-axis e.i.r.p. density levels are within the levels listed below:

Angle off-axis	*Maximum e.i.r.p. per 40 kHz*
$2.0° \leq \varphi \leq 7°$	$(19\text{-}25 \log \varphi)$ dB(W/40 kHz)
$7° < \varphi \leq 9.2°$	-2 dB(W/40 kHz)
$9.2° < \varphi \leq 48°$	$(22\text{-}25 \log \varphi)$ dB(W/40 kHz)
$48° < \varphi \leq 180°$	-10 dB(W/40 kHz)

– UACS parameters
  – Antenna diameter: 7.0 m
  – Transmit power: 500 W
– Satellite parameters
  – Satellite receive *G/T* at EOC: 12.2 dB/K
  – Satellite transmit power flux-density: -118 dB(W/m^2/MHz)
– Interference environment assumption: Receive interference from two satellites from $\pm 6º$

3 Using the 13/15 GHz frequency bands for beyond line-of-sight communications to support unmanned aircraft system control links

3.1 Link availability

The telecommand (UACS-to-satellite-to-UA) and the telemetry (UA-to-satellite-UACS) link budgets are summarized in Tables 1 and 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 desired link availability (99.85% for UA links), the maximum rain fall rate and the operational altitude of the UA are presented.

The CNPC link budget, UACS-to-satellite-to-UA is shown in Table 1.

TABLE 1

Telecommand link budgets – unmanned aircraft control station-to-unmanned aircraft

Forward Link		Clear Sky Conditions		Rain			Terminal parameters		Satellite comms parameters	
Link parameter	Units	UA control uplink	UA downlink	UA control uplink	UA downlink	Parameters	Transmit (UACS)	Receive (UA)	Receive	Transmit
Earth station location		Orlando AP		Orlando AP		**Earth station location**	Orlando AP			
Frequency	GHz	15.55	13.33	15.55	13.33	* Latitude (N=" "; S="-")	28.6			
Transmit EIRP	dBWi					* Longitude (E=" "; W=" ")	−81.4			
Number of carriers						Transmit power (W)	500.0	–		
Output back off	dB					Circuit loss (dB)	2.0	–		
EIRP per carrier	dBWi	52.4	17.5	52.4	17.5	Antenna gain (dB)	59.9	39.1		
Transmit power density	dBW/4 kHz	−11.0	14.0	−11.0	14.0	* Antenna size (m)	7.0	0.80		
Edge of coverage (EOC)	dB	–	3	–	3	* Antenna efficiency	75%	65%		
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5	* Beamwidth (deg)	0.2	1.9		
Space loss	dB	207.7	206.9	207.7	206.9	Pointing error (deg)	0.03	0.28		
Link availability	%	–	–	99.95		Noise figure (dB)	-	2.5		
Atmospheric & scintillation loss	dB	0.30	0.18	–	–	Axial ratio (dB)	2.0	2.0		
Rain loss – ITU combined model		–	–	11.8	–					
Maximum rain fade margin – UA	**dB**				0.4	**Modulation-clear sky**	3/4 QPSK	**Orbital parameters**		
Polarization loss	dB	0.2	0.2	0.2	0.2	Data rate (Mbit/s)	0.010	Type of satellite	GSO	
Rcvd incident Pwr (RIP) (dBw)	**dBW**	**−156.4**	**−193.4**	**−167.9**	**−197.2**	Required bandwidth (MHz)	0.01	Orbital location	−105	
Receiver antenna gain	dB	–	39.1	–	39.1	Required E_b/N_0 (dB)	3.8	Satellite altitude (km)	35.878	
Receiving system temperature	°K	–	239.6	–	389.4	Pfd (dB(W/m²/MHz)	−124.4389	Orbital period (minutes)	1440.8	
Edge of coverage (EOC)	dB	3.0	–	3.0	-	Total rq. bandwidth (MHz)		Or (hours)	24.0	
G/T at EOC	dB/°K	1.4	15.3	1.4	13.2	**Modulation-rain**	**3/4 QPSK**			
						Data rate (Mbit/s)	0.010	U/L elevation angle (deg)	48	
C/N	dB	34.1	11.0	22.5	4.9	Required bandwidth (MHz)	0.009	U/L slant range (km)	37315	
C/I – Self-interference due to freq reuse	dB	–	–	–	–	Required E_b/N_0 (dB)	3.8	D/L elevation angle	20	
C/I1 – Two interference satellites ±2 deg	dB	51.3	33.5	51.3	33.5	Pfd (dB(W/m²/MHz)	−124.4389	D/L slant range (km)	39647	
$C/IM3$	dB	18.0	18.0	18.0	18.0					
$C/(N+I)$	dB	17.4	10.1	16.3	4.7					
Rx $E_b(N_0+I_0)$	dB	–	9.6	–	3.9					
Required E_b/N_0	dB	–	3.8	–	3.8					
Margin	**dB**	–	**5.8**	–	**0.1**					

Based on telecommand link budgets shown in Table 1, the maximum satellite-to-UA link rain fade margin is 4 dB. The telemetry link budgets, from UA-to-satellite-to-UACS, are summarized in Table 2 and show that the system can achieve up to 7.9 dB of link rain fade margin.

TABLE 2

Telemetry link budgets – unmanned aircraft-to-satellite-to-unmanned aircraft control station

Return Link		Clear sky conditions		Rain			Terminal parameters		Satellite comms parameters	
Link parameter	Units	UA uplink	UACS downlink	UA uplink	UACS downlink	Parameters	Transmit (UA)	Receive (UACS)	Receive	Transmit
Earth station location		Orlando AP		Orlando AP		**Earth station location**		Orlando AP		
Frequency	GHz	15.55	13.33	15.55	13.33	* Latitude (N=" "; S="-")		28.6		
Transmit EIRP	dBWi	48.4		48.4		* Longitude (E=" "; W=" ")		-81.4		
Number of carriers		1.0		1.0		Transmit power (W)	10.0	–		
Output back off	dB	0.0		0.0		Circuit loss (dB)	2.0	–		
EIRP per carrier	dBWi	48.4		48.4		Antenna gain (dBi)	40.4	58.5		
Transmit power density	dBW/4kHz					* Antenna size (m)	0.80	7.00		
Edge of coverage (EOC)	dB	–	3	–	3	* Antenna efficiency	65%	75%		
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5	* Beamwidth (deg)	1.6	0.2		
Space loss	dB	208.2	206.4	208.2	206.4	Pointing error (deg)	0.24	0.03		
Link availability	%	–	–	99.85	99.97	Noise figure (dB)	–	2.5		
Atmospheric & scintillation loss	dB	0.52	0.54	–	–	Axial ratio (dB)	2.0	2.0		
Rain loss - ITU combined model	dB	–	–	–	18.9					
Maximum rain fade margin – UA	**dB**	–	–	7.9		**Modulation-clear sky**	**3/4 QPSK**	**Orbital parameters**		
Polarization loss	dB	0.2	0.2	0.2	0.2	Data rate (Mbit/s)	0.32	Type of satellite	GSO	
Rcvd incident Pwr (RIP) (dBw)	**dBW**	**−161.1**	**−178.1**	**−168.5**	**−196.5**	Required bandwidth (MHz)	0.3	Orbital location	−105	
Receiver antenna gain	dB	–	58.5	–	58.5	Required E_b/N_0 (dB)	3.8	Satellite altitude (km)	35.878	
Receiving system temperature	°K	–	260.0	–	492.3	Pfd (dB(W/m²/MHz)	−124.9552	Orbital period (minutes)	1440.8	
Edge of coverage (EOC)	dB	3.0	–	3.0	–	Total rq. bandwidth (MHz)	15.1	Or (hours)	24.0	
G/T at EOC	dB/°K	1.4	34.4	1.4	31.6	**Modulation-rain**	**3/4 QPSK**			
						Data rate (Mbit/s)	0.32	U/L Elevation angle (deg)	20	
C/N	dB	14.3	30.3	6.6	9.0	Required bandwidth (MHz)	0.3	U/L Slant range (km)	39647	
C/I – Self-interference due to freq reuse	dB	–	–	–	–	Required E_b/N_0 (dB)	3.8	D/L Elevation angle	48	
$C/I2$ – Two interference satellites ±6 deg	dB	32.3	46.9	32.3	46.9	Pfd (dB(W/m²/MHz)	−124.9552	D/L Slant range (km)	37315	
$C/IM3$	dB	–	18.0	–	18.0					
$C/(N+I)$	dB	14.3	17.7	6.5	8.5					
Rx $E_b/(N_0+I_0)$	dB	–	12.2	–	3.9					
Required E_b/N_0	dB	–	3.8	–	3.8					
Margin	**dB**	–	**8.4**	–	**0.1**					

The required rain fade margin versus rain rate for the telecommand and telemetry links are shown in Figs 1 and 2. The rain fall rate around the world is summarized in Fig. 3.

Figures 1 and 2 indicate that if the UA operates with a 0.8 m diameter antenna and a 10 W transmitter, the system can achieve 4 dB of rain fade margin in the telecommand link and 7.9 dB in the telemetry link. The UA can achieve 99.85% link availability if:

– Telecommand link (see Fig. 1):
   – UA operation altitude ≥ 1 km and rain rate ≤ 60 mm/hour
   – UA operational altitude ≥ 2 km and rain rate ≤ 87 mm/hour
– Telemetry link (see Fig. 2):
   – UA operational altitude ≥ 0.1 km and rain rate ≤ 82 mm/hour.

The rain fade margin shown in Figs 1 and 2 are adequate to achieve the desired link availability of 99.85% for most locations around the world.

FIGURE 1

Telecommand rain fade margin versus rain rate
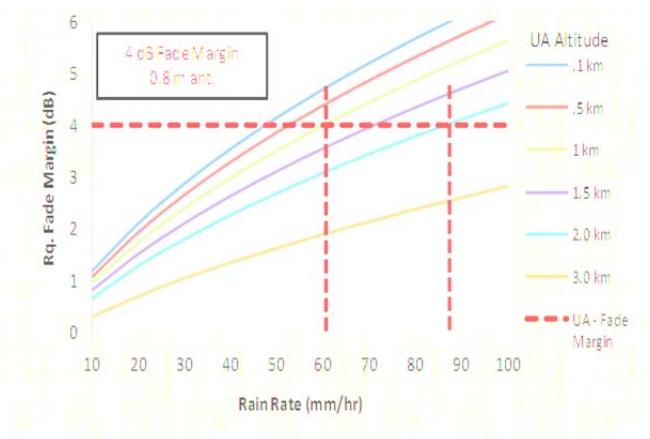
FIGURE 2

Telemetry rain fade margin versus rain rate
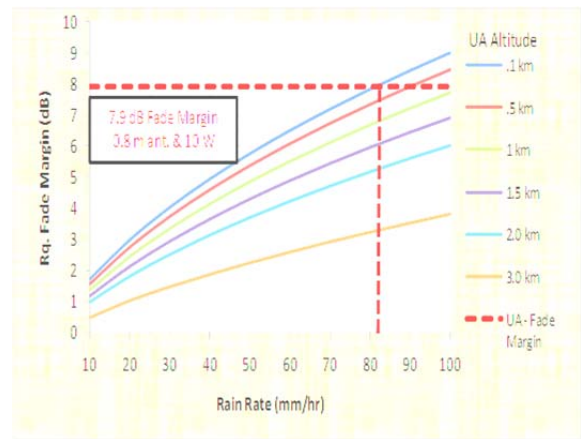
FIGURE 3

Rain rate (mm/h) exceeded for 0.01% of the average year
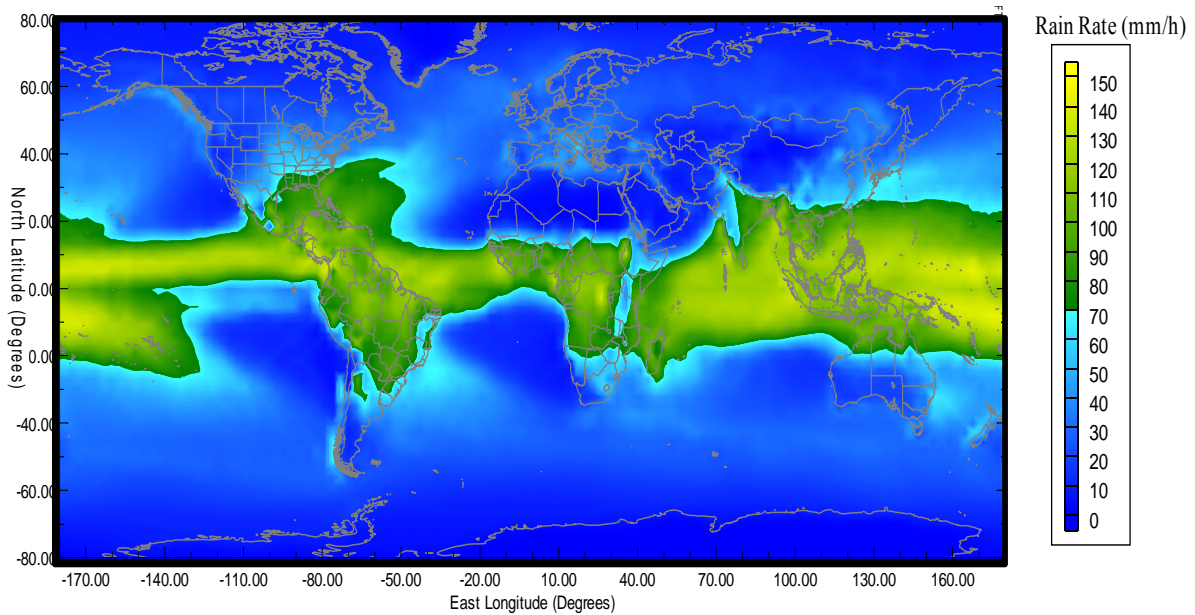
3.2 Frequency sharing with existing and planned systems operating in the same frequency bands

3.2.1 Frequency sharing between radar and unmanned aircraft systems for the downlink in the frequency band, 13.25-13.4 GHz

For the purpose of this Report, the 13.25-13.4 GHz frequency band is assumed to be used for the downlink, space-to-Earth direction. This frequency band is currently allocated to the Aeronautical Radionavigation, Earth Exploration Satellite, and Space Research on a co-primary basis.

Additionally, in some countries, this frequency band is allocated to the fixed service on a primary basis (see RR No. 5.499).

The aeronautical radionavigation service operates worldwide on a primary basis in the 13.25-13.4 GHz frequency band. The airborne navigation systems in this frequency band are installed in aircraft and used for specialized applications such as continuous determination of ground speed and drift angle information of an aircraft with respect to the ground. The radar used for collision avoidance on board unmanned aircraft are also planned to support UAS in non-segregated airspace. The technical parameters of radionavigation radars in the 13.25-13.4 GHz frequency band are shown in Table 3 below (see Recommendation ITU-R M.2008).

TABLE 3

Technical characteristics of radar in the frequency band 13.25-13.4 GHz

Parameter	Units	Radar 1	Radar 2	Radar 3	Radar 4	Radar 5	Radar 6	Radar 7	Radar 8
Platform		Aircraft (helicopter)	Aircraft (helicopter)	Aircraft (airplane)	Aircraft (airplane)	Aircraft (helicopter)	Aircraft (airplane)	Aircraft (airplane)	Aircraft (helicopter)
Platform maximum operational altitude	m	3 600	3 660	10 400	15 000	0-4 500	15 000	15 000	3 500
Radar type		Doppler navigation radar	Doppler navigation radar	Doppler navigation radar	Doppler navigation radar	Doppler radar velocity sensor	Doppler radar velocity sensor	Doppler navigation radar	Doppler navigation radar
The range of measured ground speed	km/h	333	553	750	1 047	250	1 100	180-1 300	50-399
Frequency	GHz	Fixed single channel	Fixed single channel	Fixed single channel	Fixed single channel	Fixed single channel	Fixed single channel	13.25 to 13.40	13.295 to 13.355
Emission type		Continuous wave	Intermittent continuous wave	Frequency modulated-continuous wave	Continuous wave	Frequency modulated-continuous wave	Unmodulated pulse	Unmodulated continuous wave	Unmodulated continuous wave
Pulse width	μs	Not applicable	1 to 4	Not applicable	Not available	Not applicable (FM)	4 to 7	Not applicable	Not applicable
Pulse rise and fall times	ns	Not applicable	20	Not applicable	Not available	Not applicable (FM)	0.2, 0.2	Not applicable	Not applicable
RF emission bandwidth at −3 dB −20 dB −40 dB	kHz	Not applicable	2 800 20 000	100 250 350	Not applicable	Not available Not available 150	1 000 5 600 95 000	Not available	Not available
Pulse repetition frequency	pps	Not applicable	Not available	Not applicable	Not applicable	Not applicable	80 000	Not applicable	Not applicable
Peak transmitter power	W	0.85	0.132	0.18	1.0	0.050	40 20 Average	0.125...10	0.15...10
Receiver IF −3 dB bandwidth	kHz	1.4 Estimated	1.6 Estimated	55 000	2.9 Estimated	14	2 500	15 000	100 000
Sensitivity	dBm	−135 for 0 dB *S/N*	−135	−134 for 0 dB *S/N*	−138 for 3 dB *S/N*	**−130 for 3 dB *S/N* (v = 100 m/s)** **−160 for 3 dB *S/N* (v = hover)**	**−96 for 3 dB *S/N* (v = 100 m/s)**	**−110 (acquisition mode)** **−120 (tracking mode)**	**−144**

TABLE 3 (*continued*)

Parameter	Units	Radar 1	Radar 2	Radar 3	Radar 4	Radar 5	Radar 6	Radar 7	Radar 8
Receiver noise figure	(dB)	22 (Homodyne Receiver)	22 (Dual Conversion Homodyne Receiver)	12 (Double Conversion Super Heterodyne Receiver)	22 (Homodyne Receiver)	22 (Homodyne Receiver)	7.5	Not available	Not available
Antenna type		Parabolic reflector	Phased array	Phased array	Phased array	Printed circuit array	Printed circuit array	Phased array	Horn-reflector
Antenna placement		Points towards Earth	Points towards Earth	Points towards Earth	Points towards Earth	Points towards Earth	Points towards Earth	Points towards Earth (Off-nadir angle 9…11º)	Points towards Earth (Off-nadir angle 18º)
Antenna gain	dBi	27	27	26	29.5	26.5	18	20	27.8
First antenna side lobe	dBi	5.5	Not available	9	14.2 at 4º	−10	−10	7	−7.2
Horizontal beamwidth	degrees	7	3.3	9	4.7	4.0	20	Not available	Not available
Vertical beamwidth	degrees	4.5	5	3	2.5	3.4	4.2	Not available	Not available
Polarization		Linear	Not available	Not available	Linear	Linear	Linear	Not available	Not available
Number of beams		4	4	4	4	4	2	3 or 4	3
Antenna beam configuration		Employs Janus system. Approximate four corners of a pyramid with each 18° off-nadir	Not available	Employs Janus system. Approximate four corners of a pyramid with each 16° off-nadir and 10.5º laterally	Employs Janus system	Employs Janus system. Approximate four corners of a pyramid with each 20° off-nadir	Two beams	Not available	Not available
Antenna scan		Scan is one beam at a time for each corner of the pyramid	Scan is one beam at a time for each corner of the pyramid	Scan is one beam at a time for each corner of the pyramid	Not available	Scan is one beam at a time for each corner of the pyramid	Not available	Not available	Not available
Protection criteria	dB	−10	−10	−10	−10	−10	−10	−10	−10

Notes to the Table

NOTE 1 – The service ceiling of helicopters is generally lower than 7 000 m above mean sea level (MSL), while the service ceiling of fixed-wing maritime patrol aircraft is approximately 15 000 m MSL.

NOTE 2 – The sensitivity calculation (assuming a minimum 3 dB S/N requirement for tracking) for a Doppler system must account for the bandwidth of the receiver's tracker. Sensitivity calculated with respect to the wide-open receiver bandwidth will yield a relatively low figure compared with the sensitivity based on the tracker's dynamic bandwidth. In a current-generation tracker, this bandwidth is comparable to the bandwidth of the back-scattered radar signal's spectrum, which itself varies with the velocity of the aircraft.

NOTE 3 – The actual instantaneous pointing direction of individual antenna beams depends on the installation attitude of the airborne Doppler radar with respect to the aircraft reference axes (it is not always level), as well as the pitch and roll state of the aircraft. Helicopters flying search patterns or making abrupt acceleration/deceleration manoeuvres will often have roll and pitch values in excess of 30º for short periods of time. The attitude excursions for high-performance military helicopters are even higher.

NOTE 4 – For systems where no noise figure is available, assume a value of 12 dB for systems employing IF receivers and 22 dB for Homodyne (zero IF) receivers. Reference Fried, W.R.: Principles and Performance Analysis of Doppler Navigation Systems, IRE Trans., Vol. ANE-4, pp. 176-196, December 1957.

–   **Potential interference from radar transmitter to unmanned aircraft receiver**: Based on Note 1 of Table 3, the operational altitude of aircraft in this frequency band can be up to 15 km above mean sea level. If the operational altitude of UA is less than 15 km, potential interference from radar systems to UA would occur. The interference to noise ratio, I_0/N_0 can be 23.6 dB (for the case where transmission from the radar antenna's side lobe is received by the UA antenna's back lobe as shown in Table 4 below). Table 4 indicates that the minimum interference level (radar minimum transmit antenna gain 5.5 dBi and minimum UA antenna gain (–10 dBi)) is at least 23.63 dB above the system thermal noise. This is an unacceptable level of interference.

–   **Potential interference from geostationary orbit downlink transmitter to radar receiver**: In order to meet the radar system interference criterion, $I_0/N_0 = -10$ dB, the receive antenna gain of the radar system toward the GSO satellite should be less than or equal to 17.60 dBi as shown in Table 4. Since the antenna of the radar system points toward the Earth, the antenna gain in the direction towards the GSO satellite must be significantly lower than 17.6 dBi. Therefore, the interference level from the GSO satellite operating in the 13 GHz frequency band is within acceptable levels.

It should be noted that no study was made for Radars 6, 7 and 8 detailed in Table 3 above.

TABLE 4

Potential interference to/from radar systems from/to unmanned aircraft telemetry links

Potential interference from ARNS Systems to UA receivers		Potential interference from GSO satellites in 13 GHz to ARNS Systems	
Parameters		Parameters	
Frequency (GHz)	13.40	Frequency (GHz)	13.40
ARNS characteristics		**GSO satellite transmit characteristics**	
Peak transmit power (W)	0.85	Transmit power density (dBWi/4 kHz)	14.00
Transmit antenna gain (dBi)	27.00	Atmospheric/scintillation loss (dB)	0.52
First antenna sidelobe (dBi)	5.50	**ARNS characteristics**	
Bandwidth (kHz)	10.00	UA antenna size (m)	0.80
First antenna sidelobe	5.50	System noise temperature (K)	500.00
UA characteristics		Thermal noise density (dBW/Hz)	−201.61
UA antenna size (m)	0.80	Antenna peak gain (K)	27.00
System noise temperature (K)	300.00	Minimum UA antenna gain (dBi)	5.50
Thermal noise density (dBW/Hz)	−203.83		
Antenna peak gain (K)	39.13	**Interference calculation**	
Minimum UA antenna gain (dBi)	−10.00	Case 1: Elevation angle (dB)	5.00
		* I_0/N_0 (dB)	−22.72
Interference calculation		** ARNS receive antenna gain (dBi)	5.50
Case 1: Distance (km)	10.00		
* Maximum I_0/N_0 level – Peak-to-peak (dB)	114.26	Case 2: Elevation angle (dB)	30.00

TABLE 4 (*end*)

Potential interference from ARNS Systems to UA receivers		Potential interference from GSO satellites in 13 GHz to ARNS Systems	
* Minimum I_0/N_0 level – Min-to-Min (dB)	43.63	* I_0/N_0 (dB) – Interference criterion	−10.08
		** ARNS receive antenna gain (dBi)	17.60
Case 2: Distance (km)	100.00		
* Maximum I_0/N_0 level – Peak-to-peak (dB)	94.26	Case 3: Elevation angle (dB)	30.00
* Minimum I_0/N_0 level – Min-to-Min (dB)	23.63	* I_0/N_0 (dB) – Worst case – unlikely	−0.68
		** ARNS receive antenna gain (dBi)	27.00

Based on the study results summarized in Table 4, frequency sharing between the radar and the UA telecommand link in the 13.25-13.4 GHz frequency band is not feasible, because the interference level from the radar system to the UA receiver is at an unacceptable level.

3.2.2 Frequency sharing between radar and unmanned aircraft systems for the uplink frequency band, 15.4-15.7 GHz

The frequency band 15.4-15.7 GHz is allocated to the aeronautical radionavigation service on a primary basis. A 200 MHz portion of this spectrum, from 15.43 GHz to 15.63 GHz, is allocated to both the aeronautical radionavigation service and the fixed-satellite service in the Earth-to-space direction. Based on RR No. 5.511A, the use of the 15.43-15.63 GHz frequency band by the FSS is limited to feeder links of non-GSO MSS systems.

3.2.2.1 Characteristics of aeronautical radionavigation systems in the 15.4-15.7 GHz frequency band

The system characteristics of the aeronautical radionavigation service in the 15.4-15.7 GHz frequency band contained in Recommendation ITU-R S.1340 are summarized below:

−   Aircraft landing systems and for bandwidths greater than 3 MHz:

$$E_{eff} = \begin{cases} 53 & \text{dBW} & \text{for} & 0 \le \varphi < 8 \\ 53 - 0.833\,(\varphi - 8) & \text{dBW} & \text{for} & 8 \le \varphi < 14 \\ 48 & \text{dBW} & \text{for} & 14 \le \varphi < 32 \\ 48 - 9\,(\varphi - 32) & \text{dBW} & \text{for} & 32 \le \varphi < 34 \\ 30 & \text{dBW} & \text{for} & 34 \le \varphi < 40 \\ 30 - 0.2\,(\varphi - 40) & \text{dBW} & \text{for} & 40 \le \varphi \le 90 \end{cases}$$

−   For general purpose aircraft radars and for bandwidths greater than 1 MHz:

$$E_{eff} = \begin{cases} 62 & \text{dBW} & \text{for} & 0 \le \varphi < 20 \\ 62 - 0.56\,(\varphi - 20)^2 & \text{dBW} & \text{for} & 20 \le \varphi < 25 \\ 48 & \text{dBW} & \text{for} & 25 \le \varphi < 29 \\ 71.86 - 25 \log\,(\varphi - 20) & \text{dBW} & \text{for} & 29 \le \varphi < 68 \\ 29.8 & \text{dBW} & \text{for} & 68 \le \varphi \le 90 \end{cases}$$

Where:

$$E_{eff} = E_p - 15 \log (1 + 5/PW) \text{ dBW}$$

E_{eff}:   e.i.r.p. (dBW) which causes the same level of interference to a phase modulated signal as a continuous noise-like interferer

E_p: peak pulse e.i.r.p. (dBW) of the aeronautical radionavigation station

PW: pulse duration (μs) of the aeronautical radionavigation station

φ: angle of elevation (degrees) above the local horizontal plane.

–   Receiver parameters:

–   Typical antenna gain: 8 dBi to 43 dBi depending on types of radar systems

–   Typical noise figure: 6 dB to 8 dB

–   Antenna patterns in elevation angle

$$G(\varphi) = \begin{cases} 43 & \text{dBi} & \text{for} & 0 \le \varphi < 4 \\ 43 - 5\,(\varphi - 4) & \text{dBi} & \text{for} & 4 \le \varphi < 9 \\ 18 & \text{dBi} & \text{for} & 9 \le \varphi < 16 \\ 43.2 - 21 \log \varphi & \text{dBi} & \text{for} & 16 \le \varphi < 48 \\ 8 & \text{dBi} & \text{for} & 48 \le \varphi \le 90 \end{cases}$$

where φ is the elevation angle in degrees.

3.2.2.2   Satellite receive parameters

In this Report, a satellite receive G/T at the edge of coverage (EOC) of 1.4 dB/K is used, as well as a system noise temperature of 850º K. The satellite antenna peak gain and gain at EOC are 33.7 dBi and 30.7 dBi, respectively. The satellite antenna 3 dB beamwidth is 3.0 degrees or 1 950 km beam diameter (nadir pointing).

3.2.2.3   Potential interference from radar transmitter to geostationary orbit satellite receiver

The potential worst-case interference is presented in Fig. 4. The following assumptions were used in the analysis:

–   Interference off-axis angle, from radar antenna to satellite, is within 4 degrees.

–   Number of radars within the satellite receive antenna beamwidth: two cases will be evaluated.

–   Case 1: Only 1 radar within the satellite receive antenna beamwidth.

–   Case 2: 15 radars within the satellite receive antenna beamwidth.

–   Satellite receive antenna 3 dB beamwidth: 3 degrees.

–   Satellite receive antenna gain at edge of coverage: 30.7 dBi.

Figure 4 indicates that the calculated interference-to-noise ratio is in a range from −15 dB to 33 dB depending on the operational elevation angles. The system would not be able to operate if the I_0/N_0 is 0 dB or higher, because the system margin will be degraded by 3 dB or more.

If the interference off-axis angle from the radar antenna to the satellite is 8 degrees, the interference level can be reduced by 20 dB as shown in Fig. 5. Depending on the number of radars within the satellite's receive beam, the interference-to-noise ratio, I_0/N_0, can still be greater than 0 dB.

The interference-to-noise ratio, I_0/N_0, shown in Figs 4 and 5 are significantly higher than 0 dB (3 dB degradation) for most elevation angles. These interference levels are not acceptable levels for the UA telemetry link. It should be noted that the UA telemetry link clearly plays a very important role in maintaining the safety and regularity of flight for UAS. The interference levels would depend on the characteristics and operational environments of the radar in the 15 GHz frequency band. The UAS cannot operate safely in this unknown interference environment.

In addition, the peak pulse e.i.r.p, EIRP_p or E_p, is significantly higher than EIRP_{eff} or E_{eff} and it can be computed as: $E_{eff} = E_p - 15 \log (1 + 5/PW)$. PW is the pulse duration of the aeronautical navigation radar. The typical pulse duration of radars in this frequency band is 0.4 µs. The peak pulse E_p can be 91.5 dBW. If several radars are within the satellite receive beam, it could potentially damage the RF front end of the satellite receiver.

FIGURE 4

Interference-to-noise ratio, I_0/N_0 @ satellite receiver (worst case)
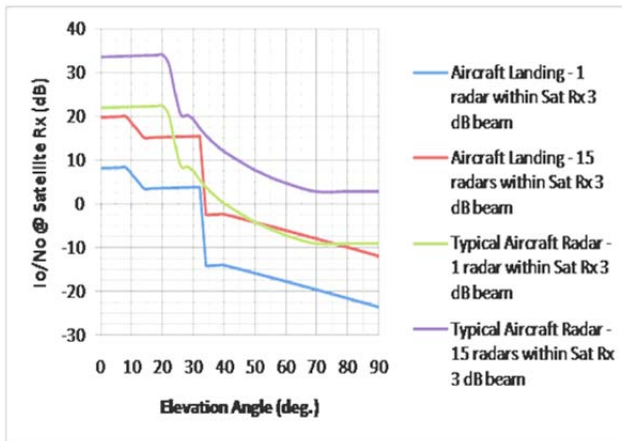
FIGURE 5

Interference-to-noise ratio I_0/N_0 @ satellite receiver (interference off-axis angle = 8 degrees)
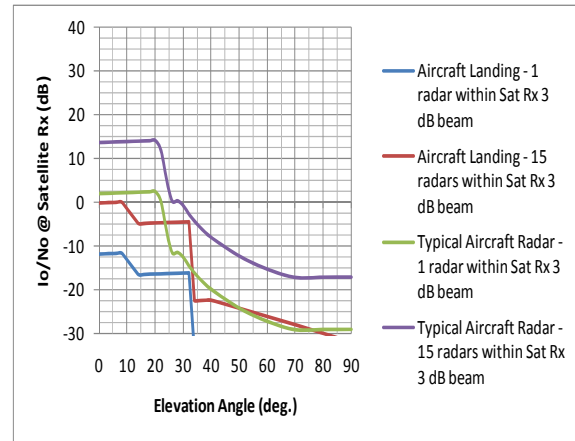
3.2.2.4 Potential interference from unmanned aircraft transmitter to radar receiver – Coordination distance

The geometry used in determining the potential interference from the UA transmitter to the radar receiver is shown in Fig. 6. The coordination distance between the UA transmitter and the radar was based on the following assumptions:

– UA parameters
  – Transmit power density, input to antenna port: −11 dB(W/4 kHz)
  – Antenna diameter: 0.8 m
  – Operational elevation angle: 15º
– Radar parameters
  – Antenna peak gain: 43 dBi
  – Antenna patterns: see § 3.2.2.1
  – System noise figure: 7 dB
  – Antenna noise temperature: 100º K
  – Interference criterion: $I_0/N_0 = -10$ dB.

The coordination distance versus the off-axis angle of the radar antenna in the direction of interference path from the UA transmitter is presented in Fig. 7. The calculated distance was based on a single UA transmitter, and the atmospheric loss was taken into account.

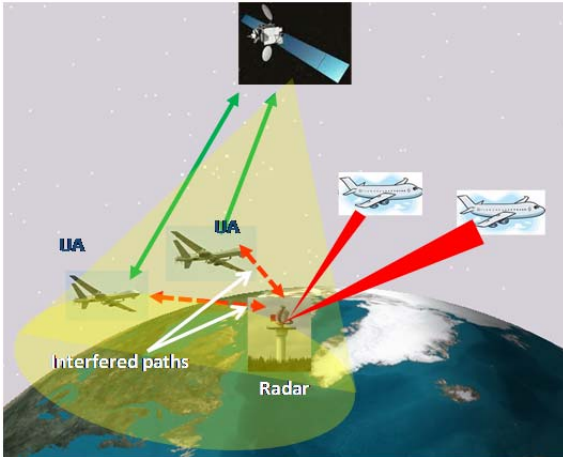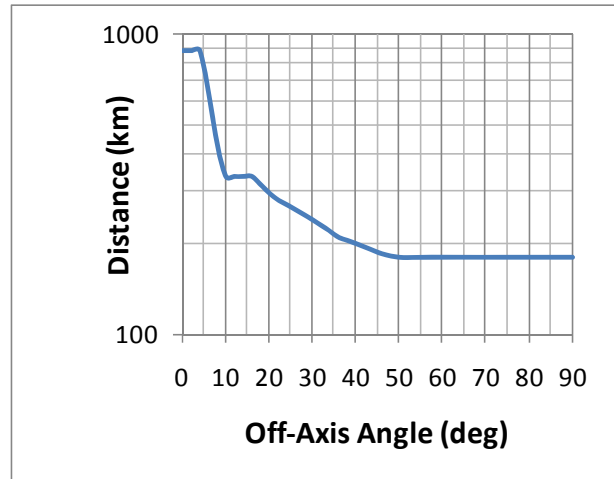| FIGURE 6	FIGURE 7
Interfering geometry	**Coordination**

In the worst case, the required distance between a UA and a radar receiver is 900 km. The interference level at the radar receiver can significantly increase when several unmanned aircraft are in view. The coordination distance method between "high density" UA and radar is not practical.

Based on the study results shown above, frequency sharing between radar and UA in the 15.4-15.7 GHz frequency band is not feasible, because the interference level from the radar to the satellite receiver is not acceptable. In addition, the coordination distance between UA transmitters and radar receivers is not practical.

3.3 Satellite spectrum requirements

Based on Report ITU-R M.2171, it is predicted that 56 MHz of satellite spectrum would be required to support the anticipated growth of UAS operations in non-segregated airspace. It should be noted that for a regional coverage, in order to meet the BLOS spectrum requirements to support UA control links, three or more satellites were assumed to provide service in the same coverage area.

For the purpose of study, it was assumed that two 56 MHz wide frequency segments in the 13.25-13.4 GHz frequency band for satellite downlink and 15.4-15.7 GHz frequency band for satellite uplink are dedicated for UAS control links.

Several satellite antenna spot beams are illustrated in Fig. 8. Each spot beam is assumed to have a 3 dB beamwidth of 3 degrees (1 900 km beam diameter – nadir pointing). For example, in order to support all potential UA in area "A1", a 56 MHz BLOS spectrum is required. In order to support other areas, such as areas "B1", "D1", "C1", additional spectrum would be required. In high frequency bands, above 10 GHz, in order to support the UA operations in non-segregated airspace, it would require four times the "actual" spectrum requirements. Otherwise, the system would not be able to operate due to self-interference.

– Areas "A1", "A2" and "A3" can operate in the same frequency.

– Areas "B1" and "B2" can operate in the same frequency, etc.

Based on the above beam configuration, the following questions arise:

– Since the transmit data is very low (10 kbit/s of the telecommand link and 320 kbit/s for telemetry link), can the system utilize a global beam?

  – In the telecommand link, in theory, the satellites can increase their transmit power to close the link.

  – In the telemetry link, in order to close the link, the UA requires to operate with larger antenna diameter and/or more transmit power – see Fig. 9.

– Can the system operate with smaller beam (small area); each beam would require ¼ of 56 MHz spectrum?

  – Can ¼ of the 56 MHz be adequate to support the number of UAs?

  – The number of spot beams would be increased.

  – More stringent requirement on satellite pointing.

FIGURE 8

Coverage and frequency plan
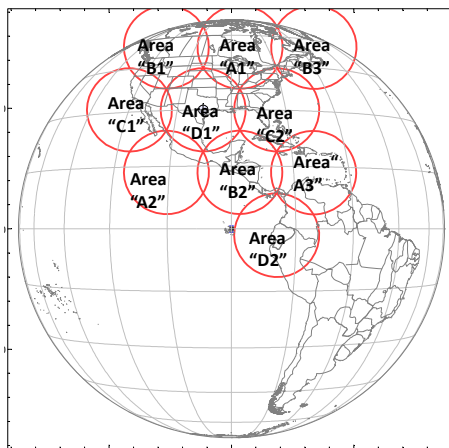
FIGURE 9

Satellite receive beam size vs UA antenna size
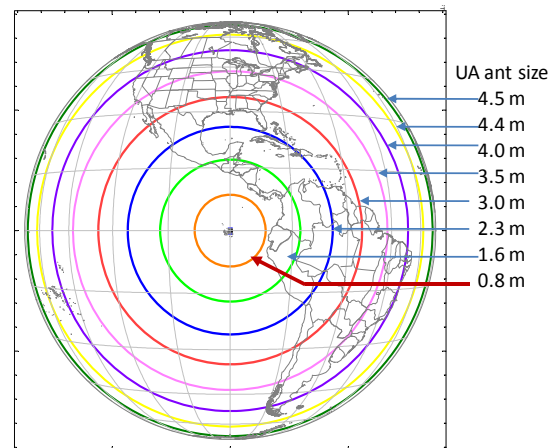
3.4 Summary

The 13.25-13.40 GHz and 15.4-15.7 GHz frequency bands should not be considered as candidate frequency bands to support BLOS UAS control links in non-segregated airspace for the following reasons:

– 13.25-13.4 GHz frequency band

  – The potential interference levels from aircraft radar transmitters in the 13.25-13.4 GHz band into UA receivers are at unacceptable levels, at least 23.6 dB above the receive thermal noise floor.

– 15.4-15.7 GHz frequency band

  – The interference level at the satellite receiver is significantly high, at least 3 dB higher than the satellite thermal noise. In the worst case, the level can be 10 dB or more above the thermal noise floor, which is an unacceptable level. The actual interference levels would depend on the characteristics and operational environments of the radar in the 15 GHz band. The UAS cannot operate safely in this interference environment.

  – The coordination distance between a UA transmitter and a radar is in a range from 200 km to 900 km. The coordination method is not practical between two "high density" services, UA transmitters and radar receivers.

Since the level of interference is unacceptable using the 13 GHz frequency band as the downlink frequency band and the 15 GHz band as the uplink frequency band, a brief review of using the 13 GHz frequency band as the uplink frequency band and the 15 GHz frequency band as the downlink frequency band has also been performed.

–   If the 13.25-13.4 GHz frequency band were used to support the telemetry link (UA-to-satellite) instead of the 15.4-15.7 GHz frequency band, in the worst case, with main beam-to-main beam interference, the interference-to-noise ratio (I_0/N_0) at the radar receiver is 86.9 dB (I_0/N_0 = 48 −10*log(300 kHz) − (92.45+20*log(10 km × 13.4 GHz))+27−(−201.61) = 86.8 dB), which is also an unacceptable level.

–   If the 15.4-15.7 GHz frequency band were used to support the telecommand link (satellite-to-UA) instead of the 13.25-13.4 GHz frequency band, the radar systems in this band will cause harmful interference to the UA receiver.

In addition, even if two 56 MHz sub-bands in the 13.25-13.4 GHz and 15.4-15.7 GHz frequency bands are dedicated, to be exclusively used by UAS, with no other services in these bands, this is still not an adequate amount of spectrum to support UAS control links. In order to avoid self-interference among beams, the system would require at least 4 × 56 MHz of spectrum in each direction.

Based on the study results shown in § 3, the frequency bands 13.25-13.4 GHz and 15.4-15.7 GHz cannot support UAS control links in non-segregated airspace because the frequency sharing between UAS control links and other existing and planned services in these bands is not feasible. However, if these frequency bands were to be considered for UAS control links, then:

–   Additional sharing study with other services in these bands, such as UAS sense and avoid (S&A) ARNS, radiolocation (15.4-15.7 GHz) systems would be required.

–   In addition, the potential interference from UAS control links in the 15.4-15.7 GHz frequency band to the passive services (Earth-exploration satellite, radio astronomy and space research services) in the adjacent frequency band, 15.35-15.4 GHz frequency band should be taken into account.

4   Using the 22/23 GHz frequency bands for beyond line-of-sight communications to support unmanned aircraft system control links

4.1   Link availability

Since the 22.5-22.55 GHz (22 GHz band) and 23.55-23.6 GHz (23 GHz band) bands are very close in frequency to each other, the 22 GHz or 23 GHz band can be used either for the uplink or downlink. In this Report, the 22 GHz band is used for downlinks and the 23 GHz band is used for uplinks.

The telecommand (UACS-to-satellite-to-UA) and the telemetry (UA-to-satellite-UACS) link budgets are summarized in Tables 5 and 6. Again, the purpose of these link budgets is to compute the maximum available rain fade margin. Based on the available rain fade margin and the desired link availability (99.85% for UA links), the maximum rain fall rate and the operational altitude of the UA are presented.

The UAS and satellite system parameters used in Tables 5 and 6 are summarized in § 2.3.2.

TABLE 5

Telecommand link budgets – unmanned aircraft control station-to-satellite-to-unmanned aircraft

Forward Link		Clear sky conditions		Rain			Parameters	Terminal parameters		Satellite comms parameters	
Link parameter	Units	UA control uplink	UA downlink	UA control uplink	UA downlink		Parameters	Transmit (UACS)	Receive (UA)	Receive	Transmit
Earth station location		Orlando AP		Orlando AP			**Earth Station location**	Orlando AP			
Frequency	GHz	23.58	22.53	23.58	22.53		* Latitude (N=" "; S="-")	28.6			
Transmit EIRP	dBWi						* Longitude (E=" "; W=" ")	−81.4			
Number of carriers							Transmit power (W)	500.0			
Output back-off	dB						Circuit loss (dB)	2.0			
EIRP per carrier	dBWi	45.7	24.1	65.7	24.1		Antenna gain (dB)	63.5	39.6		
Edge of coverage (EOC)	dB	–	3	–	3		* Antenna size (m)	7.0	0.50		
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5		* Antenna efficiency	75%	65%		
Space loss	dB	211.3	211.5	211.3	211.5		* Beamwidth (deg)	0.1	1.8		
Link availability	%	-	-	99.95	–		Pointing error (deg)	0.02	0.27		
Atmospheric & scintillation loss	dB	1.65	1.23	-	–		Noise figure (dB)	–	2.5		
Rain loss - ITU combined model		–	–	21.1	–		Axial ratio (dB)	2.0	2.0		
Maximum rain fade margin - UA	**dB**				7.1		**Modulation-clear sky**	3/4 QPSK	**Orbital parameters**		
Polarization loss	dB	0.2	0.2	0.2	0.2		Data rate (Mbit/s)	0.01	Type of satellite		GSO
Rcvd incident Pwr (RIP) (dBW)	**dBW**	**−168.0**	**−192.4**	**−167.4**	**−198.2**		Required bandwidth (MHz)	0.0089	Orbital location		−105
Receiver antenna gain	dB		39.6		39.6		Required E_b/N_0 (dB)	3.8	Satellite altitude (km)		35.878
Receiving system temperature	dB/°K		294.8		377.8		Pfd (dB(W/m^2/MHz)	−118.35735	Orbital period (minutes)		1440.8
Edge of coverage (EOC)	dB		-		-		Total rq. bandwidth (MHz)	13.8	Or (hours)		24.0
G/T at EOC	dB/°K	12.2	14.9	12.2	13.8		**Modulation-rain**	**3/4 QPSK**			
							Data rate (Mbit/s)	0.0100	U/L elevation angle (deg)		48
C/N	dB	33.3	11.6	33.9	4.7		Required bandwidth (MHz)	0.0089	U/L slant range (km)		37315
C/I – Self-interference due to freq reuse	dB	–	–	–	–		Required E_b/N_0 (dB)	3.8	D/L elevation Angle		20
$C/I1$ – Two interference satellite systems ±6 deg away	dB	51.9	31.0	51.9	31.0		Pfd (dB(W/m^2/MHz)	−118.35735	D/L slant range (km)		39647
$C/IM3$	dB	20.0	18.0	20.0	18.0						
$C/(N+I)$	dB	19.8	10.7	19.8	4.5						
Rx $E_b(N_0+I_0)$	dB	–	9.7	–	3.8						
Required E_b/N_0	dB	–	3.8	–	3.8						
Margin	**dB**	**–**	**5.9**	**–**	**0.0**						

TABLE 6

Telemetry link budgets – unmanned aircraft-to-satellite-to-unmanned aircraft control station

Return link		Clear sky conditions		Rain		Parameters	Earth terminal parameters		Satellite comms parameters	
Link parameter	**Units**	**UA uplink**	**UACS downlink**	**UA uplink**	**UACS downlink**	**Parameters**	**Transmit (UA)**	**Receive (Feeder)**	**Receive**	**Transmit**
Earth station location			Orlando AP		Orlando AP	**Earth station location**		Orlando AP		
Frequency	GHz	23.58	22.53	23.58	22.53	* Latitude (N=" "; S="-")		28.6		
Transmit EIRP	dBWi	48.0		48.0		* Longitude (E=" "; W=" ")		−81.4		
Number of carriers		1.0		1.0		Transmit power (W)	10.0	–		
Output back-off	dB	10.0		0.0		Circuit loss (dB)	2.0	–		
EIRP per carrier	dBWi	38.0	39.5	48.0	39.5	Antenna gain (dBi)	40.0	63.1		
Edge of coverage (EOC)	dB	–	2	–	2	* Antenna size (m)	0.50	7.00		
Total pointing loss (Tx & Rx)	dB	0.5	0.5	0.5	0.5	* Antenna efficiency	65%	75%		
Space loss	dB	211.9	210.9	211.9	210.9	* Beamwidth (deg)	1.7	0.1		
Link availability	%	–	–	–	99.8	Pointing error (deg)	0.26	0.02		
Atmospheric & scintillation loss	dB	2.42	4.09	–	–	Noise figure (dB)	–	2.5		
Rain loss – ITU Combined Model		–	–	–	27.7	Axial ratio (dB)	2.0	2.0		
Maximum rain fade margin – UA	**dB**	–	–	14.7		**Modulation-clear sky**	3/4 QPSK	**Orbital parameters**		
Polarization loss	dB	0.2	0.2	0.2	0.2	Data rate (Mbit/s)	0.320	Type of satellite	GSO	
Rcvd incident Pwr (RIP) (dBw)	**dBW**	**−177.1**	**−178.3**	**−179.4**	**−201.9**	Required bandwidth (MHz)	0.285	Orbital location	−105	
Receiver antenna gain	dB		63.1		63.1	Required E_b/N_0 (dB)	3.8	Satellite altitude (km)	35.878	
Receiving system temperature	dB/°K		391.5		495.2	Pfd (dB(W/m²/MHz))	−118.032 74	Orbital period (minutes)	1440.8	
Edge of coverage (EOC)	dB		–	3.0	–	Total rq. bandwidth (MHz)	14.2	Or (hours)	24.0	
G/T at EOC	dB/°K	12.2	37.2	12.2	36.2	**Modulation-rain**	**3/4 QPSK**			
						Data rate (Mbit/s)	0.320	U/L elevation angle (deg)	20	
C/N	dB	9.2	32.9	6.9	8.3	Required bandwidth (MHz)	0.3	U/L slant range (km)	39647	
C/I – Self-interference due to freq reuse	dB	–	–	–	–	Required E_b/N_0 (dB)	3.8	D/L elevation Angle	48	
$C/I1$ – Two interference satellite systems ±6 deg. away	dB	28.36	54.5	28.4	54.5	Pfd (dB(W/m²/MHz))	−118.032 74	D/L slant range (km)	37315	
$C/IM3$	dB	–	18.0	–	18.0					
$C/(N+I)$	dB	9.1	17.9	6.9	7.9					
Rx $E_b(N_0+I_0)$	dB	–	8.1	–	3.8					
Required E_b/N_0	dB	–	3.8	–	3.8					
Margin	**dB**	–	**4.3**	–	**0.0**					

Based on the link budgets shown in Tables 5 and 6, the system can achieve up to 7.1 dB of rain fade margin in the telecommand link and 14.7 dB of the rain fade margin in the telemetry link.

The required rain fade margin versus rain rate for the telecommand and telemetry links are shown in Figs 10 and 11.

FIGURE 10

Telecommand rain fade margin versus rain rate
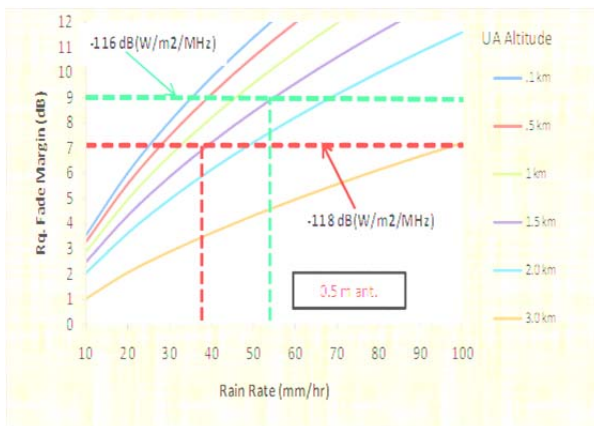
FIGURE 11

Telemetry rain fade margin versus rain rate
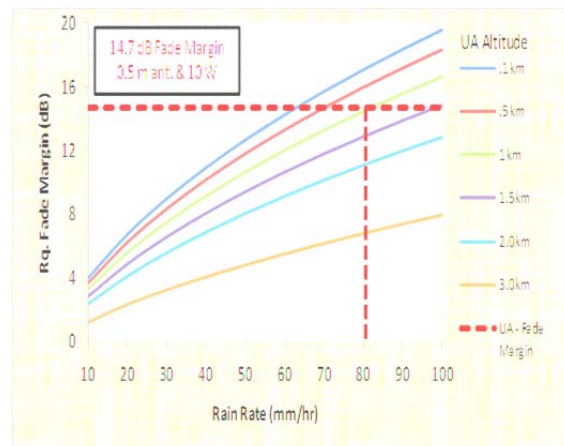
Figures 10 and 11 indicate that if the UA operates with a 0.5 m antenna and a 10 W transmitter, the system can achieve 7.1 dB rain fade margin with the downlink power flux-density level at -118 dB(W/m^2/MHz) in the telecommand link and 14.7 dB of rain fade margin in the telemetry links. The UA can achieve 99.85% link availability if:

–   Telecommand link (see Fig. 10):
  –   7.1 dB fade margin with the pfd level at -118 dB(W/m^2/MHz).
  –   UA operation altitude $\geq$ 1.5 km and rain rate $\leq$ 37 mm/hour.
  –   9.1 dB fade margin with the pfd level at -116 dB(W/m^2/MHz).
  –   UA operation altitude $\geq$ 1.5 km and rain rate $\leq$ 55 mm/hour.
–   Telemetry link (see Fig. 11):
  –   UA operational altitude $\geq$ 1.0 km and rain rate $\leq$ 80 mm/hour.

If the UA operates with a 0.5 m diameter antenna and a 10 W transmit power and a downlink power flux-density level of -116 dB(W/m^2/MHz), the system can achieve the desired link availability of 99.85% for most locations around the globe.

4.2 Frequency sharing with existing and planned systems operating in the same frequency bands

4.2.1 Frequency sharing between the fixed service and unmanned aircraft systems

The frequency bands 22.5-22.55 GHz and 23.55-23.6 GHz are allocated to the fixed and mobile services on a co-primary basis. The fixed service (FS) system parameters can be found in Tables 19 and 20 of Recommendation ITU-R F.758-4.

Currently, there are no power flux-density limits in the 22.5-22.55 GHz and 23.55-23.6 GHz frequency bands. However, the power flux-density levels of the FSS in the 22.55-23.55 GHz frequency band are in a range from -115 dB(W/m^2/MHz) to -105 dB(W/m^2/MHz) depending on the elevation angles.

If UAS systems in the 22.5-22.55 GHz and 23.55-23.6 GHz frequency bands operate with a pfd level below -116 dB(W/m^2/MHz), the potential interference levels from the UA telecommand link, in the satellite-to-Earth direction to the FS receivers in these bands, would be within the acceptable level.

4.2.2 Frequency sharing between unmanned aircraft system command and non-payload control links and fixed service

4.2.2.1 Potential interference from fixed service transmitter to satellite receiver

The potential interference from an FS transmitter to the satellite receiver is presented in Table 7. Since the operational elevation angles of the FS systems in the 22/23 GHz frequency bands are low, less than 3 degrees, the interference-to-noise ratio, I_0/N_0, at the satellite receiver is very low, at least 14.7 dB below the thermal noise floor. Therefore, the FS systems will not cause unacceptable interference level at the satellite receiver.

TABLE 7

Potential interference levels at the satellite receiver

Parameters	FS parameters				
	4 PSK	**16 QAM**	**4 PSK**	**64 QAM**	**4 PSK**
Frequency (GHz)	23.55	23.55	23.55	23.55	23.55
Data rate (Mbit/s)	34.0	155.0	34.0	140.0	4.0
Bandwidth (MHz)	28.0	56.0	28.0	40.0	7.0
Antenna gain (dBi)	47.0	45.0	47.0	38.5	47.0
EIRP (dBWi)	40.0	47.0	50.0	31.5	40.0
Satellite parameters					
Satellite receive G/T @ 3 dB EOC	12.2	12.2	12.2	12.2	12.2
Receive system noise temperature (K)	550.0	550.0	550.0	550.0	550.0
Minimum operation elevation angle (º)	10.0	10.0	10.0	10.0	10.0
Interference calculation					
FS operation elevation angle (º)	3.0	3.0	3.0	3.0	3.0
Case 1					
* FS to satellite elevation angle (º)	50.0	50.0	50.0	50.0	50.0
* I_0/N_0 – Single FS transmitter (dB)	**−64.6**	**−58.1**	**−54.6**	**−64.0**	**−58.6**
* I_0/N_0 – 100 FS transmitters (dB)	**−44.6**	**−38.1**	**−34.6**	**−44.0**	**−38.6**
Case 2					
* FS to satellite elevation angle (º)	10.0	10.0	10.0	10.0	10.0
* I_0/N_0 – Single FS transmitter (dB)	**−44.7**	**−38.2**	**−34.7**	**−44.1**	**−38.7**
* I_0/N_0 – 100 FS transmitters (dB)	**−24.7**	**−18.2**	**−14.7**	**−24.1**	**−18.7**

4.2.3 Potential interference from an unmanned aircraft transmitter to a receiver in the fixed service

In order to meet the FS interference criterion, $I_0/N_0 = −10$ dB, a coordination distance between the UA transmitter and the FS receiver operating in the 23 GHz band is required. The coordination distance is presented in Table 8. The calculated distance was based on the following assumptions:

– Single UA transmitter
  – UA at the ground level and at 5 km altitude
  – UA operates at the maximum transmit power

– Off-axis-angle was taken into account (10º for Case 1 and 40º for Case 2)
– FS operation elevation angle: 0 degree
– Atmospheric loss was taken into account.

TABLE 8

Coordination distance between an unmanned aircraft transmitter and a fixed service receiver

Parameters	FS parameters				
	4 PSK	16 QAM	4 PSK	64 QAM	4 PSK
Frequency (GHz)	23.55	23.55	23.55	23.55	23.55
Data rate (Mbit/s)	34.0	155.0	34.0	140.0	4.0
Bandwidth (MHz)	28.0	56.0	28.0	40.0	7.0
Antenna gain (dBi)	47.0	45.0	47.0	38.5	47.0
EIRP (dBWi)	40.0	47.0	50.0	31.5	40.0
Receiver thermal noise (dBW/Hz)	−198.5	−200.1	−205.0	−199.0	−199.5
UA parameters					
Transmit antenna size (m)	0.5	0.5	0.5	0.5	0.5
Transmit antenna gain (dBi)	40.0	40.0	40.0	40.0	40.0
Transmit power (W)	10.0	10.0	10.0	10.0	10.0
Circuit loss (dB)	2.0	2.0	2.0	2.0	2.0
Transmit data rate (kbit/s)	320.0	320.0	320.0	320.0	320.0
Transmit bandwidth (kHz)	285.0	285.0	285.0	285.0	285.0
Interference calculation					
FS interference criterion, I_0/N_0 (dB)	−10	−10	−10	−10	−10
Case 1 – UA @ ground level					
* UA to satellite elevation angle (º)	10.0	10.0	10.0	10.0	10.0
* FS elevation angle (º)	0.0	0.0	0.0	0.0	0.0
* FS antenna gain – interference direction (dB)	47.0	45.0	47.0	38.5	47.0
* UA transmit antenna off-axis angle (º)	10.0	10.0	10.0	10.0	10.0
* UA transmit e.i.r.p. density toward FS receiver (dBW/Hz) – Worst case (rain – wanted path; clear sky – interference path)	−39.5	−39.5	−39.5	−39.5	−39.5
* **Coordination distance (km)**	**280.0**	**278.0**	**313.0**	**240.5**	**285.5**
* I_0/N_0 **(dB)**	**−10.0**	**−10.0**	**−10.0**	**−10.0**	**−10.0**
* UA transmit e.i.r.p. density toward FS receiver (dBW/Hz) – Clear sky in wanted path and interfering path (see § 2.3.2)	−49.0	−49.0	−49.0	−49.0	−49.0
* **Coordination distance (km)**	**233.0**	**231.4**	**265.0**	**195.0**	**238.5**
* I_0/N_0 **(dB)**	**−10.0**	**−10.0**	**−10.0**	**−10.0**	**−10.0**

TABLE 8 (*end*)

Parameters	FS parameters				
	4 PSK	**16 QAM**	**4 PSK**	**64 QAM**	**4 PSK**
Case 2 – UA @ 5 km altitude					
* FS to UA elevation angle (º)	10.0	10.0	10.0	10.0	10.0
* FS elevation angle (º)	0.0	0.0	0.0	0.0	0.0
* FS antenna gain – interference direction (dBi)	4.2	4.7	4.2	6.3	4.2
* UA transmit e.i.r.p. density toward FS receiver (dBW/Hz)	−54.6	−54.6	−54.6	−54.6	−54.6
* **Coordination distance (km)**	**38.5**	**44.0**	**57.0**	**45.5**	**41.2**
* I_0/N_0 **(dB)**	**−10.0**	**−10.0**	**−10.0**	**−10.0**	**−10.0**

Based on the study results shown in Table 8, the coordination distance between a UA transmitter and a FS receiver is in a range from 38.5 km to 313 km depending on the interference geometry. The coordination method between two "high density" systems, UA transmitters and FS receivers, is not practical, so frequency sharing between UA telemetry link and FS systems in the 23 GHz frequency band is not feasible.

4.3 Potential issues associated with unwanted emission levels to protect the passive services in the nearby frequency bands

If the 22.5-22.55 GHz and 23.55-23.6 GHz frequency bands were used for UAS control links, the potential interference levels from the satellite transmitter in the 22.5-22.55 GHz band and from the UA transmitter in the 23.55-23.6 GHz frequency band may exceed the protection levels of the passive remote sensing satellites in the 22.21-22.5 GHz and 23.6-24 GHz frequency bands. The interference geometry is illustrated in Fig. 12.

FIGURE 12

Interference geometry

4.3.1   Downlink interference from satellite transmitter to the passive remote sensing satellites

The system parameters of the passive remote sensing satellites and interference analysis are presented in Table 9.

Table 9 shows that the interference levels at the passive remote sensing satellite receivers exceed the interference criterion.

–   Downlink in the 22.5-22.55 GHz frequency band

  –   The unwanted emission level falling into the 22.21-22.5 GHz assumed to be 10 dB down from the peak (based on Recommendation ITU-R SM.1541-2).

  –   It exceeds the interference criterion by 6.9 dB.

  –   In order to meet the interference criterion of the passive remote sensing systems in the 22.21-22.25 GHz frequency band, the required guardband between the two services is 42 MHz (based on Recommendation ITU-R SM.1541-2).

–   Downlink in the frequency band 23.55-23.6 GHz

  –   The unwanted emission level falling into the 23.6-24.0 GHz frequency band assumed to be 10 dB down from the peak (based on Recommendation ITU-R SM.1541-2).

  –   It exceeds the interference criterion by 15.3 dB.

  –   In order to meet the interference criterion of the passive remote sensing systems in the 23.6-24.0 GHz frequency band, the required guardband between the two services is 80 MHz (based on Recommendation ITU-R SM.1541-2).

TABLE 9

Passive remote sensing satellite parameters and interference analysis

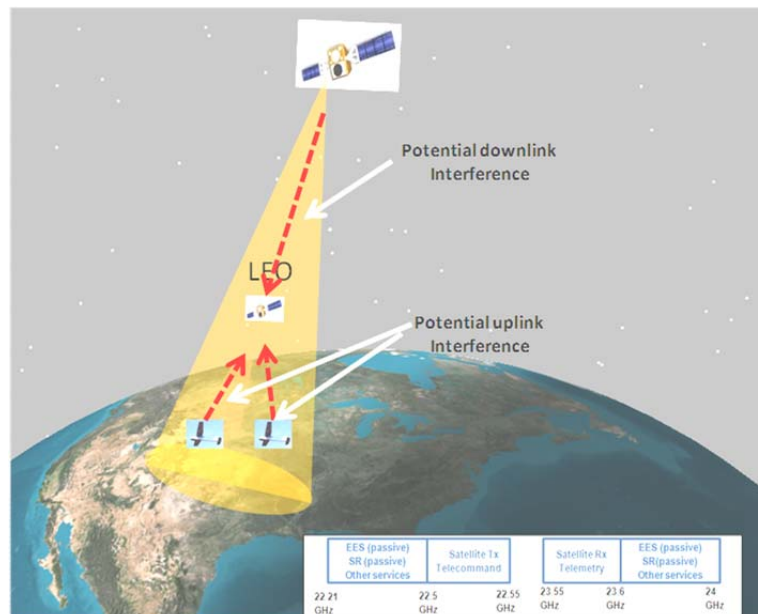| Parameters	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]
Frequency (GHz)	22.21	23.8	23.8	22.21	23.8	23.8
Satellite altitude (km)	705.0	833.0	850.0	705.0	833.0	850.0
Inclination angle (º)	98.2	98.6	98.0	98.2	98.6	98.0
Maximum satellite antenna gain (dBi)	46.7	34.4	45.0	46.7	34.4	45.0
3 dB beamwidth (º)	0.9	3.4	1.1	0.9	3.4	1.1
Beam area – Nadir (km)	11.4	49.0	16.7	11.4	49.0	16.7
Total bandwidth (MHz)	300.0	400.0	400.0	300.0	400.0	400.0
Reference bandwidth (MHz)	100.0	200.0	200.0	100.0	200.0	200.0
Interference threshold (dBW/MHz) (based on Rec. ITU-R RS.1029-2)	−180.0	−189.0	−189.0	−180.0	−189.0	−189.0
Operational elevation angle (º)	40.0	40.0	40.0	40.0	40.0	40.0

TABLE 9 (*end*)

Parameters	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]
Satellite parameters	Downlink: 22.5-22.55 GHz			Downlink: 23.55-23.6 GHz		
Frequency (GHz)	22.5	22.5	22.5	23.6	23.6	23.6
Transmit power flux-density (dB(W/m^2/MHz)	−116.0	−116.0	−116.0	−116.0	−116.0	−116.0
Out-of-band level – dBSc (below the peak) (dB)	10.0	35.0	35.0	35.0	10.0	10.0
Interference calculation						
Space loss (dB)	210.3	210.9	210.9	210.3	210.9	210.9
Satellite antenna peak gain – back lobe (dBi)	0.0	0.0	0.0	0.0	0.0	0.0
Interference noise density (dBW/MHz)	−173.1	−198.7	−198.7	−198.1	−173.7	−173.7
Interference threshold (dBW/MHz) (based on Rec. ITU-R RS.1029-2)	−180.0	−189.0	−189.0	−180.0	−189.0	−189.0
Margin (dB)	**−6.9**	**9.7**	**9.7**	**18.1**	**−15.3**	**−15.3**

4.3.2 Uplink interference from unmanned aircraft transmitter to the passive remote sensing satellites

The potential uplink interference from the UA transmitter to the passive remote sensing satellite receiver is summarized in Table 10. The interference levels exceed the interference criterion by more than 32 dB.

TABLE 10

Uplink interference from the UA transmitters to satellite receivers

Parameters	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]	Sensor E1 [AMSR-E]	Sensor E2 [AMSU]	Sensor E3 [PUSH-BROOM]
Frequency (GHz)	22.21	23.8	23.8	22.21	23.8	23.8
Satellite altitude (km)	705.0	833.0	850.0	705.0	833.0	850.0
Inclination angle (º)	98.2	98.6	98.0	98.2	98.6	98.0
Maximum satellite antenna gain (dBi)	46.7	34.4	45.0	46.7	34.4	45.0
3 dB beamwidth (º)	0.9	3.4	1.1	0.9	3.4	1.1
Beam area – Nadir (km)	11.4	49.0	16.7	11.4	49.0	16.7
Total bandwidth (MHz)	300.0	400.0	400.0	300.0	400.0	400.0
Reference bandwidth (MHz)	100.0	200.0	200.0	100.0	200.0	200.0
Interference threshold (dBW/MHz) (based on Rec. ITU-R RS.1029-2)	−180.0	−189.0	−189.0	−180.0	−189.0	−189.0
Operational elevation angle (º)	40.0	40.0	40.0	40.0	40.0	40.0
UA parameters	Uplink: 23.55-23.6 GHz			Uplink: 22.5-22.55 GHz		
Frequency (GHz)	23.6	23.6	23.6	22.6	22.6	22.6
Transmit power density (dBW/MHz) (clear sky)	3.2	3.2	3.2	3.2	3.2	3.2
Antenna gain (dBi)	40.0	40.0	40.0	40.4	40.4	40.4
Unwanted emission level – dBSc (dB)	60.0	60.0	60.0	60.0	60.0	60.0
Out-of-band transmit e.i.r.p. density (dBW/MHz)	−16.8	−16.8	−16.8	−16.4	−16.4	−16.4
Interference calculation						
Space loss (dB)	179.6	181.6	181.8	179.6	181.6	181.8
Satellite receive gain – 3 dB EOC (dBi)	43.7	31.4	42.0	43.7	31.4	42.0
Interference noise density (dBW/MHz)	−152.7	−167.0	−156.5	−152.3	−166.6	−156.1
Interference threshold (dBW/MHz) (based on Rec. ITU-R RS.1029-2)	−180.0	−189.0	−189.0	−180.0	−189.0	−189.0
Margin (dB)	**−27.3**	**−22.0**	**−32.5**	**−27.7**	**−22.4**	**−32.9**

Based on the study results shown in § 4.3, the frequency bands 22.5-22.55 GHz and 23.55-23.6 GHz are not good candidate bands to support UAS control links, because the interference levels in either the UA uplink or in the satellite downlink bands will cause unacceptable interference levels in the passive sensor frequency bands, 22.21-22.5 GHz and 23.6-24.0 GHz.

4.4   Summary

The frequency bands 22.5-22.55 GHz and 23.55-23.6 GHz should not be considered as candidate frequency bands to support BLOS UAS control links in non-segregated airspace for the following reasons:

–   In order to meet the FS interference criterion, a coordination distance between UA
         transmitter and FS receiver is required. The coordination distance is in a range from
         38.5 km to 331 km. Because of the distances required, the coordination method is not
         practical between these two "high density" services.

–   The emission levels from satellite and UA transmitters would cause unacceptable
         interference to passive remote sensing satellite receivers.

5   Conclusion

Based on the analysis in this Report, the following conclusions can be drawn:

The frequency bands 13.25-13.40 GHz and 15.4-15.7 GHz should not be considered as candidate
frequency bands to support BLOS UAS control links in non-segregated airspace for the following
reasons:

–   13.25-13.4 GHz frequency band: The potential interference levels from aircraft radar
         transmitters to UA receivers are at unacceptable levels, at least 23.6 dB above the receive
         thermal noise floor.

–   15.4-15.7 GHz frequency band

    –   The interference level at the satellite receiver is significantly high, at least 3 dB higher
            than the satellite receive thermal noise. In the worst case, the level can be 10 dB or
            more above the thermal noise floor, which is an unacceptable level. The actual
            interference levels would depend on the characteristics and operational environments of
            the radar in the 15 GHz frequency band. The UAS cannot operate safely in this
            interference environment.

    –   The coordination distance between a UA transmitter and a radar is in a range from
            200 km to 900 km. The coordination method is not practical between two "high
            density" services, UA transmitters and radar receivers.

The frequency bands 22.5-22.55 GHz and 23.55-23.6 GHz should not be considered as candidate
frequency bands to support BLOS UAS control links in non-segregated airspace for the following
reasons:

–   In order to meet the FS interference criterion, a coordination distance between UA
         transmitter and FS receiver is required. The coordination distance is in a range from
         38.5 km to 331 km. Because of the distances required, the coordination method is not
         practical between these two "high density" services.

–   The unwanted emission levels from satellites and from UA transmitters would cause
         unacceptable interference to passive remote sensing satellite receivers

Based on the study, it can be concluded that the frequency bands 13.25-13.4 GHz, 15.4-15.7 GHz,
22.5-22.55 GHz and 23.55-23.6 GHz cannot support UAS control links in non-segregated airspace.

Annex 1

Glossary

BLOS   Beyond line-of-sight
CNPC   Control and non-payload communications

dB	Decibel(s)
dBi	dB referred to the gain of an isotropic antenna
dBm	dB referred to one milliwatt
dBm/Hz	dB referred to one milliwatt per hertz
dBr	dB relative to a maximum value
dBW	dB referred to one watt
DL	Downlink
e.i.r.p.	Equivalent isotropically radiated power
E/S	Earth-to-space
FL	Forward link
FS	Fixed service
FSS	Fixed-satellite service
GES	Ground earth station (for SATCOM CNPC system)
GPS	Global Positioning System
GS	Ground station (for terrestrial CNPC system)
G/T	Ratio of receiving-antenna gain to receiver thermal noise temperature in kelvins
INR	Interference-to-noise ratio
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
kHz	Kilohertz
LEO	Low Earth orbit (or a satellite in that orbit)
LOS	Line-of-sight
MHz	Megahertz
MLS	Microwave Landing System
MS	Mobile service
MSS	Mobile-satellite service
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
PFD	Power flux-density
QPSK	Quadrature phase-shift keying
RF	Radio frequency
RL	Return link
Rx	Receiver
Sat.	Satellite
S/E	Space-to-Earth
SNR	Signal-to-noise ratio
TDD	Time-division duplex
Tx	Transmitter
UA	Unmanned aircraft
UACS	UA control station
UAS	UA system(s)
UL	Uplink
W	Watt

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