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Assessing Spectrum Compatibility for Beyond-Line-of-Sight UAS Control and Non-Payload Communications

Robert J. Kerczewski and Jeffrey D. Wilson
Glenn Research Center, Cleveland, Ohio

William D. Bishop
Verizon, Cleveland, Ohio

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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Robert J. Kerczewski and Jeffrey D. Wilson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

William D. Bishop
Verizon
Cleveland, Ohio 44135

Abstract

In order to provide for the safe integration of unmanned aircraft systems (UAS) into the National Airspace System (NAS), the control and non-payload communications (CNPC) link must be highly reliable. A specific requirement is that it must operate using aviation safety radiofrequency spectrum. Two types of links are required – line-of-sight (LOS) using terrestrial-based communications and beyond-line-of-sight (BLOS) using satellite communications. The 2012 World Radiocommunication Conference (WRC-12) provided a suitable allocation for LOS CNPC spectrum in the 5030 to 5091 MHz band which, when combined with a previously existing allocation fulfills the LOS spectrum requirement. The 5030 to 5091 MHz band is also allocated for BLOS CNPC, but since a significant portion of that band is required for LOS CNPC, additional BLOS spectrum is required. More critically, there are no satellites in operation or in development to provide such services in that band. Hence BLOS CNPC cannot be provided in protected aviation spectrum under current conditions. To fill this gap and enable integration of UAS into the NAS, it has been proposed to allow CNPC to operate over certain Fixed Satellite Service (FSS) bands in which many satellites currently provide commercial services. To enable this, changes in international regulation must be enacted. Agenda Item 1.5 of the 2015 WRC examines the possible regulatory changes needed. As part of the examination process, sharing between potential UAS using satellite communications for BLOS CNPC and other services allocated to the FSS bands being considered must be studied. This paper reviews the technical requirements and approach being undertaken for these sharing studies, with emphasis on study of interference from UAS into digital repeater links operating under the Fixed Service allocation. These studies are being conducted by NASA Glenn Research Center.

Introduction

Many potential applications for civil use of unmanned aircraft system (UAS) have been identified, with additional use concepts emerging almost daily. However, the ability of UAS to operate in the National Airspace System (NAS), in particular in non-segregated airspace, faces many obstacles. The increasing pressure to remove these obstacles has resulted in the establishment of a national goal in the US of enabling UAS to have routine access to the NAS. Among a number of technical barriers that must be overcome to meet this goal is the absence of standard, certifiable communications links supplying the control and non-payload communications (CNPC) function, essentially providing the link over which a pilot on the ground can control the unmanned aircraft (UA). The International Civil Aviation Organization (ICAO) has determined that the CNPC link must operate over protected aviation spectrum. Therefore protected aviation spectrum must be allocated for this function, approved through the processes of the International Telecommunications Union Radiocommunication Sector (ITU-R).

Spectrum requirements have been met for line-of-sight (LOS) CNPC through actions taken at the ITU-R's 2012 World Radiocommunication Conference (WRC-12). However for beyond-line-of-sight (BLOS) CNPC, sufficient protected aviation spectrum has not been allocated. Agenda Item 1.5 (AI 1.5) for the 2015 WRC (WRC-15) looks into the possible use of commercial satellites operating under the Fixed Satellite Service (FSS) allocation to meet spectrum requirements for BLOS CNPC. However since this allocation is not protected aviation spectrum, regulatory issues must be put in place for such use to be approved. This is the primary issue being addressed by AI 1.5.

Studies are underway and regulatory proposals are being developed to address Agenda Item 1.5. These include characterization of CNPC technical and operational aspects, definition of performance requirements, and studies of spectrum compatibility between CNPC and other services in these bands. NASA's UAS in the NAS Project is contributing to these activities by performing spectrum compatibility and sharing studies between unmanned aircraft satellite earth stations and terrestrial services which share the Ku-Band and Ka-Band spectrum. The compatibility studies being undertaken by NASA are submitted to the preparation process for the 2015 WRC and then refined and updated based on decisions made by the ITU-R meeting participants.

This paper will expand on the background of the BLOS CNPC and spectrum requirements and then focus on the nature of the spectrum compatibility problem, the approach and methodologies being applied to the studies, and example results.

Spectrum Requirements and Solutions

Spectrum requirements were established with the adoption of Report M.2171 by the ITU-R (Ref. 1). In this report, the requirements of 34 MHz for UAS LOS and 56 MHz for UAS BLOS (satellite) were identified. Actions taken at the ITU's WRC-12 have established sufficient spectrum resources to meet the LOS spectrum requirement with a new Aeronautical Mobile (Route) Service (AM(R)) allocation in the 5030 to 5091 MHz band combined with a portion of an existing AM(R)S allocation in the 960 to 1164 MHz band. The BLOS spectrum requirement remains unfulfilled. A previously existing Aeronautical Mobile Satellite (Route) Service (AMS(R)S) allocation in the 5030 to 5091 MHz band meets a portion of the requirement, however communication satellites required to provide service in this band do not exist and none are currently planned. As a result, the UAS community is searching for a solution to meet the BLOS CNPC needs.

The most likely solution is to use existing satellites operating under the Fixed Satellite Service (FSS), of which many operate in several bands. Given the size of most unmanned aircraft, higher frequency bands are required in order to have antennas small enough to fit onto the aircraft. Therefore the use of FSS in Ku-Band (12 to 18 GHz) and Ka-Band (26.5 to 40.0 GHz) for BLOS CNPC has been proposed. Agenda Item 1.5 for the 2015 WRC (WRC-15) examines this proposal and what regulatory requirements would need to be addressed to allow such an application in those bands.

WRC-15 Agenda Item 1.5

At WRC-12, Resolution 153 was adopted: "To consider the use of frequency bands allocated to the fixed-satellite service not subject to Appendices **30**, **30A**, and **30B** for the control and non-payload communications of unmanned aircraft systems (UAS) in non-segregated airspaces."

The resolution (Ref. 2) considers the possible regulatory actions to support the use of FSS frequency bands for the UAS CNPC links ensuring their safe operation, including the necessary studies leading to technical, regulatory and operational recommendations and sharing and compatibility studies with services already having allocations in those bands.

ITU-R has chartered Working Party 5B (WP5B) to develop the documents and proposals for AI 1.5 that will be considered for approval at WRC-15. Sharing studies, including those under development by NASA, are submitted through WP5B.

Sharing Studies for Agenda Item 1.5

The sharing studies involved in AI 1.5 include several scenarios and frequency ranges in the Ku- and Ka-Band FSS Bands. These were proposed for further study at WRC-12 and subsequently approved for full analysis with results to be shared and reviewed at WRC-15 as AI 1.5. NASA's Glenn Research Center (GRC) has been requested to conduct sharing studies on UAS Control and Non-Payload (CNPC) Link 3 and the potential interference, Path 3s, shown in Figure 1. The frequency bands under study for Link 3 are 14.0 to 14.5 GHz in Ku-Band and 27.5 to 30.0 GHz in Ka-Band.

Sharing Study Scenarios for 14.0 to 14.5 GHz

Based on the existing allocations in 14.0 to 14.5 GHz for terrestrial co-primary services, three interference scenarios exist:

- Interference from UAES uplink transmitters into Fixed Service (FS) (i.e., terrestrial microwave) receivers at 14.3 to 14.5 GHz;
- Interference from UAES uplink transmitters into Mobile Service (MS) (except aero mobile) receivers at 14.3 to 14.5 GHz;
- Interference from UAES uplink transmitters into Radionavigation Service (RNS) receivers at 14 to 14.3 GHz.

Sharing Studies Conducted Based on Available System Characteristics for 14.0 to 14.5 GHz

No technical characteristics of land mobile systems in the land mobile service for the frequency band 14.0 to 14.5 GHz are available, so no sharing study is being conducted for the mobile service. Similarly WP5B has not identified any current radionavigation uses of the 14.0 to 14.3 GHz band. Therefore, equipment parameters are not available for consideration in frequency sharing studies and no sharing study is being conducted for the radio navigation service. The sharing study in the 14.0 to 14.5 GHz band is therefore limited to interference from UAES (UA Earth Station) uplink transmitters into the fixed service receivers at 14.3 to 14.5 GHz.

Sharing Study Scenarios for 27.5 to 30.0 GHz

Based on the allocations, two interference scenarios exist:

- Interference from UA uplink transmitters into Fixed Service (i.e., P-P terrestrial microwave) receivers at 27.5 to 29.5 GHz;
- Interference from UA uplink transmitters into Mobile Service (except aero mobile) receivers at 27.5 to 29.5 GHz.

There are no fixed, mobile or other terrestrial services allocated in the 29.5 to 30.0 GHz band, so no sharing studies are needed for this portion of the 27.5 to 30.0 GHz band.

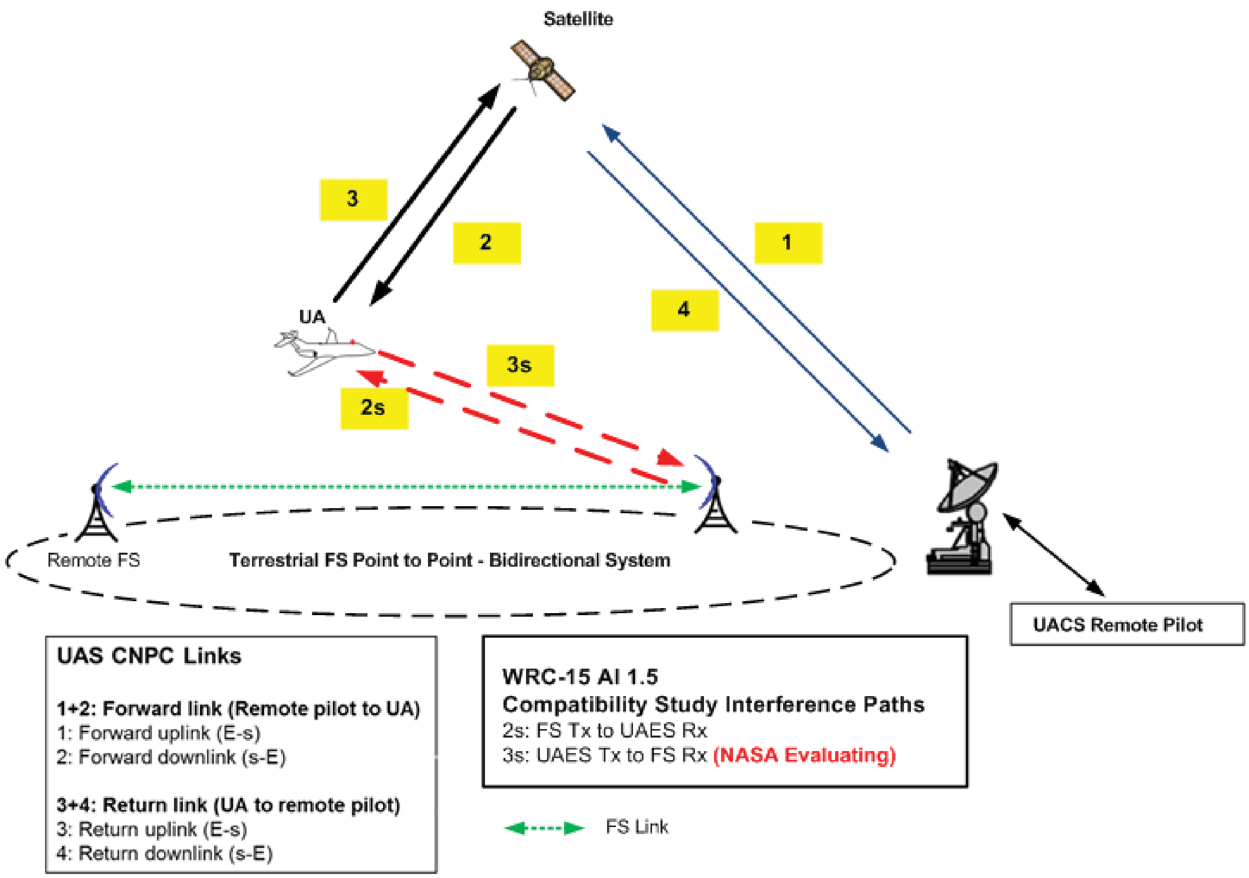

Figure 1.—NASA studying link 3 and potential interference, from Reference 3.

Sharing Studies Conducted Based on Available System Characteristics for 27.5 to 30.0 GHz

No technical characteristics of land mobile systems in the land mobile service for the frequency band 27.5 to 29.5 GHz are available. Therefore no analysis is conducted for the mobile service.

The sharing study in the 27.5 to 30.0 GHz band is therefore limited to interference from UA earth station uplink transmitters into the fixed service receivers in 27.5 to 29.5 GHz.

Flight Scenarios

Relevant UAS flight scenarios have been provided by the International Civil Aviation Organization for use in the sharing studies (Ref. 3). Based on the flight scenario descriptions, scenarios 2 and 7 identify the altitudes required for the sharing studies for the UAES transmitter-FS receiver case as shown in Table 1.

TABLE 1.—UAS FLIGHT SCENARIOS FOR SHARING STUDIES

ICAO Scenario	2	7
	Medium altitude surveillance/ Aerial work (search pattern)	Departure descent above 3000 ft above ground level (AGL)
Max altitude (feet above MSL, unless otherwise specified)	30 000	19 000
Min altitude (feet above MSL, unless otherwise specified)	19 000	3 000
Max latitude (deg)	70	70

The Sharing Case of UA Earth Station Uplinks

The ITU-R has established interference criteria to protect the FS from time varying aggregate interference from other radiocommunication services sharing the FS band on a co-primary basis. They have issued recommendations relative to specific frequency bands for both long- and short-term interference. In the studies NASA is performing, the UAES transmit and FS receive characteristics are the primary parameters used in the analysis.

UA Earth Station Transmit and Fixed Service Receive Parameters

The UA earth station transmit parameters that are applied to sharing studies for AI 1.5 are being developed through WP5B. The parameter values under consideration can be found in Annex 25 of (Ref. 3). Antenna parameters and transmit powers have been specified for antenna diameters of 0.45, 0.8, and 1.25 m for both the 14.0 to 14.5 GHz and 27.5 to 29.5 GHz bands. The FS parameters applied to the sharing are derived primarily from (Ref. 4) for the 14.0 to 14.5 GHz and 27.5 to 29.5 GHz bands.

Distribution of UA

The number and distribution of UA are defined in Reference 1. The UA density projections for the 2030 time-frame based on estimated UAS usage rates in both the commercial and government sectors is described in Table 2. Based on the flight scenarios that will be studied, the total of the medium and large UA densities are considered, since small UA operate only below 3000 ft. For the sharing studies, UA are randomly distributed in an area bounded by the radio horizon relative to an FS receiver using the relative densities shown in Table 2.

Fuselage Attenuation

The fuselage of the UA can provide significant attenuation of the signal between the earth station mounted on the top of the UA and systems on the ground. Figure 2 depicts the calculated fuselage attenuation factored into the analysis as a function of elevation angle of the UAES antenna and frequency.

TABLE 2.—UAS TRAFFIC DISTRIBUTION

Type	Altitude	UA/km^2	UA/10,000 km^2	UA/Spot beam	UA/Regional coverage beam
Medium	300 to 5500 m	0.000195	1.950	93	1515
Large	>5500 m	0.000044	0.440	21	341

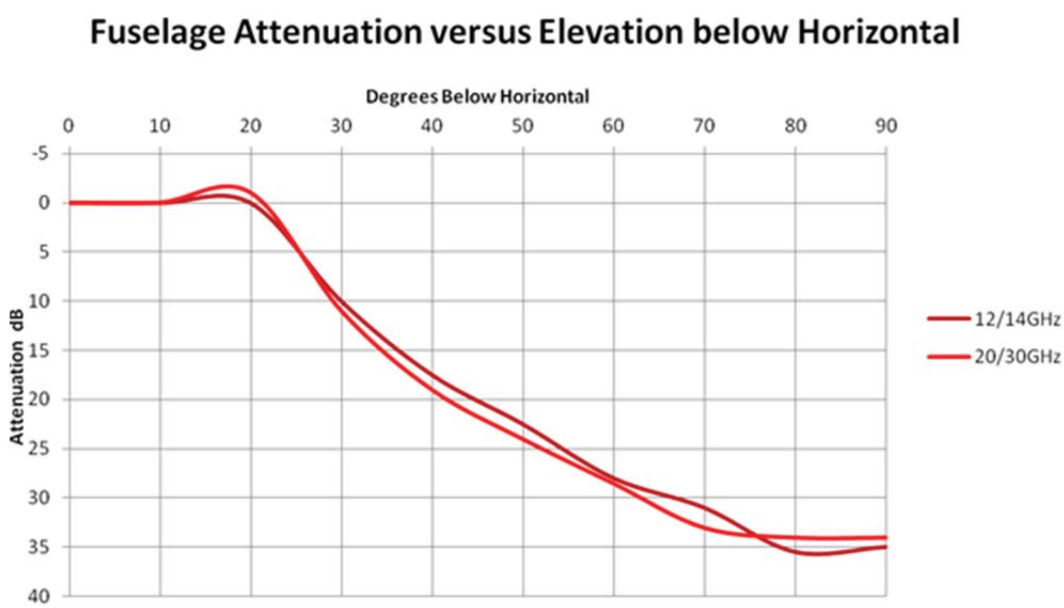

Figure 2.—Example off-axis attenuation plot due to the fuselage of the aircraft (measurements were made at 14.2 GHz).

TABLE 3.—PROTECTION CRITERIA FOR THE FIXED SERVICE IN THE 14.0 TO 14.5 AND 27.5 TO 29.5 GHz BANDS
(Input to FS receiver)

Parameter	Frequency range	Value	ITU-R source document	Comments
I/N (Long Term)	Both	–10 dB	F.758-5 (Ref. 4)	Not to exceed for more than 20 percent of the year
I/N (Short Term)	Ku	+20 dB	F.1494 (Ref. 8)	Not to exceed for more than 1×10^{-4} percent of the time
I/N (Short Term)	Ka	+14 dB	F.1495-2 (Ref. 9)	Not to exceed for more than 0.01 percent of the time in any month
I/N (Short Term)	Ka	+18dB	F.1495-2 (Ref. 9)	Not to exceed for more than 0.0003 percent of the time in any month

Protection Criteria for Fixed Service Stations

Table 3 provides the long and short term protection criteria for the fixed service receivers for the 14.0 to 14.5 GHz and 27.5 to 29.5 GHz bands.

Sharing Study Approach

Visualyse Professional software (Ref. 5) was used to create models of a number of scenarios involving interference to FS's from UA. These scenarios were used to analyze both long term and short term interference criteria at Ku-band and Ka-band frequencies, with small and large UA antennas, UA altitudes from 3000 to 19000 ft, and FS locations from 10° N to 70° N. For the Ku-band calculations, the antennas were centered at 14.4 GHz. The FS antenna has a diameter of 1.2 m, efficiency of 0.6, and an ITU-R F.699-7 gain rolloff (Refs. 3 and 6).

The Ku-band UA small antenna has a diameter of 0.45 m, efficiency of 0.55, an ITU-R S.580-6 rolloff, and an equivalent isotropic radiated power (e.i.r.p.) density of 43.78 dBW/250 kHz. The Ku-band UA large antenna has a diameter of 1.25 m, efficiency of 0.55, an ITU-R S.580-6 gain rolloff, and an e.i.r.p density of 57.68 dBW/250 kHz (Refs. 3 and 7).

For the Ka-band calculations, the antennas were centered at 28.5 GHz. The FS antenna has a diameter of 0.3 m, efficiency of 0.6, and an ITU-R F.699-7 gain rolloff (Refs. 3 and 6). The Ka-band UA small and large antennas have the same diameters, efficiency, and rolloff as the Ku-band antennas. The Ka-band UA small antenna has an e.i.r.p. density of 42.38 dBW/250 kHz and the Ka-band UA large antenna has an e.i.r.p. density of 48.08 dBW/250 kHz.

Long Term Interference Criteria

For the long term interference criterion, we use guidance from Table 4 of (Ref. 4) which recommends that the aggregate interference to noise ratio I/N be less than –10 dB for frequencies above 3 GHz. In the Visualyse calculations, we placed the FS at specific locations and populated the surrounding airspace with 300,000 randomly located UA's. The FS antenna azimuthal and elevation angles were randomly assigned values from –180 to +180° and –5 to +5°, respectively. The expected percentage of time that I/N exceeds –10 dB, P, is then

$$P = QRA\rho \quad (1)$$

where Q is the percentage of the locations that contributed an I/N of greater than –10 dB to the FS; R is the probability ratio that a UA is transmitting in a channel that is within the FS bandwidth (for the Ku-band cases, the FS has a maximum bandwidth of 28 MHz, thus the probability that a UA is transmitting at a channel that is within the FS bandwidth is 28/500 = 0.056; for the Ka-band cases, the FS maximum bandwidth is 112 MHz, thus the probability that a UA is transmitting at a channel that is within the FS bandwidth is 112/2000 = 0.056, the same as for Ku-band), A is the airspace area; and ρ is the projected UA traffic density from Table 2, 2.39 UA/10,000 sq km.

UA altitudes of 3000 and 19000 ft and UA small and large antennas were modeled with FS locations at 10, 40, and 70° N. The results for the Ku-band cases are shown in Table 4 and for the Ka-band cases in Table 5. In all the Ku-band cases, the percentage of time that I/N is over the threshold of –10 dB is less than 0.8 percent, far below the protection criterion value of 20 percent. In all the Ka-band cases except two, there were no instances of I/N over the threshold. The only cases with I/N instances over the threshold were the small and large UA antenna cases for an altitude of 3000 ft at 70° N. But in these two cases the percentage of time over the threshold was only 0.02 percent, also far below the protection criterion value of 20 percent.

TABLE 4.—PERCENTAGE OF TIME I/N IS WORSE THAN –10 dB FOR FS WITH BANDWIDTH OF 28 MHz WITH FEEDER LOSS = –6 dB AND POLARIZATION LOSS = 0 FOR KU-BAND
[Also shown are the worst values of I/N.]

Case	Altitude, ft	Antenna size	Latitude, degrees	Percentage time over interference threshold, percent	Worst I/N, dB
1	3000	Small	10	0.13	4.07
2	3000	Large	10	0.31	9.07
3	3000	Small	40	0.15	4.35
4	3000	Large	40	0.38	9.35
5	3000	Small	70	0.24	3.21
6	3000	Large	70	0.76	8.21
7	19000	Small	10	0.14	–3.75
8	19000	Large	10	0.24	1.25
9	19000	Small	40	0.17	–2.92
10	19000	Large	40	0.37	2.08
11	19000	Small	70	0.41	–1.33
12	19000	Large	70	0.72	3.67

TABLE 5.—PERCENTAGE OF TIME I/N IS WORSE THAN –10 dB FOR FS WITH BANDWIDTH OF 112 MHz WITH FEEDER LOSS = 0 dB AND POLARIZATION LOSS = 0 for KA-BAND
[Also shown are the worst values of I/N.]

Case	Altitude, ft	Antenna size	Latitude, degrees	Percentage time over interference threshold, percent	Worst I/N, dB
13	3000	Small	10	0	–12.86
14	3000	Large	10	0	–15.96
15	3000	Small	40	0	–10.20
16	3000	Large	40	0	–13.30
17	3000	Small	70	0.02	–0.83
18	3000	Large	70	0.02	–3.93
19	19000	Small	10	0	–23.04
20	19000	Large	10	0	–26.14
21	19000	Small	40	0	–18.64
22	19000	Large	40	0	–21.74
23	19000	Small	70	0	–17.36
24	19000	Large	70	0	–20.46

Short Term Interference Criteria

The short term interference criterion at Ku-band is that I/N should exceed 20 dB no more than 0.0001 percent of the time from Table 3. For Ka-band, from Table 3 it is that “I/N should not exceed +14 dB for more than 0.01 percent of the time in any month” and “should not exceed +18 dB for more than 0.0003 percent of the time in any month”.

In the Visualyse calculations, we again placed the FS at specific locations and populated the surrounding airspace with 300,000 randomly located UA. The Visualyse simulations were performed as in the Long Term Interference Criteria section, except that the worst possible scenario was modeled with the FS antenna azimuthal direction pointing northward and the elevation angle at the worst value between –5 to +5° which is +5°.

Simulations were performed at FS latitudes from 10° N to 70° N in 100 intervals and at UA altitudes from 3000 to 19000 ft in 1000 ft intervals. The minimum UA altitude that avoids exceeding the interference threshold is shown in Figure 3 for the large UA antenna at Ku-band and in Figure 4 for the small UA antenna at Ku-band. For the large Ku-band antenna we see that the threshold altitude drops rapidly from 18,000 ft at 70° to 7000 ft at 50° to 6000 ft at 30° and lower. For the small Ku-band antenna we see that the threshold altitude drops rapidly from 10,000 ft at 70° to 4000 ft at 50° to 3000 ft at 10°. For the Ka-band cases, an altitude of 3000 ft was sufficient to stay under the interference threshold at all latitudes for both large and small UA antennas.

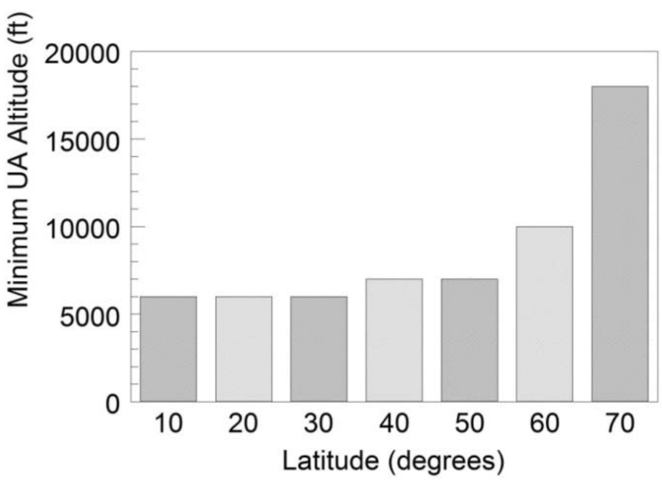

Figure 3.—Minimum UA altitude to avoid exceeding I/N interference threshold for large UA antenna at Ku-band.

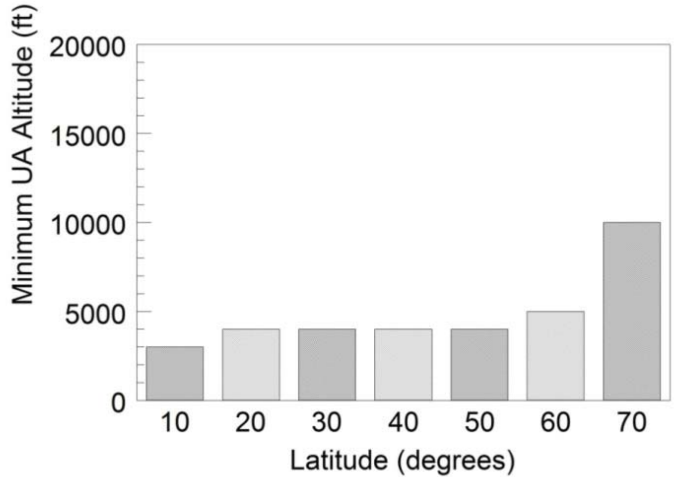

Figure 4.—Minimum UA altitude to avoid exceeding I/N interference threshold for small UA antenna at Ku-band.

Interpretation of Results

The sharing studies described above, as well as characterization of CNPC technical and operational aspects, definition of performance requirements, and proposed regulatory changes to enable UAS CNPC over FSS satellites are described in draft documents being reviewed and updated in an iterative process through several WP5B meetings occurring between WRC-12 and WRC-15. In regards to the sharing studies in particular, agreement within WP5B on technical characteristics of CNPC, CNPC performance requirements, and appropriate protection criteria and technical characteristics of other systems in the bands being studies is still being developed.

Changes to these various characteristics and parameters impacting the results of studies are expected. Hence, results shown here are examples and do not necessarily define the final results that will be approved as part of a new ITU-R report that will guide WRC-15 deliberations on AI 1.5.

Nevertheless, the results serve to illustrate the sharing study approach and indicate the complexities of the analysis problem and the differences between long-term interference analyses and short-term interference analyses. These preliminary examples show that while sharing between UAES and FS is emerging as compatible in terms of long-term protection criteria, compatibility regarding the short-term protection criteria is still being determined. Additional modifications to the short-term analyses will be applied to refine the analyses and are expected to impact the results. At upcoming WP5B meetings these latest results will be presented and discussed by the WP5B members to determine where agreement on the results and their application to the resolution of AI 1.5 can be achieved.

Conclusions

For the integration of UAS into the NAS, protected aviation spectrum for BLOS CNPC is required. Since sufficient radiofrequency spectrum allocations do not currently exist, and there are no existing satellite systems operating in an existing allocation that could be applicable to BLOS CNPC, WRC-15 will consider the possible use of FSS satellites for CNPC. A number of difficult regulatory questions must be addressed in order to enable use of non-aviation-protected spectrum to be used for a protected-aviation spectrum application under WRC-15 AI 1.5. To support AI 1.5, studies of sharing between systems in several proposed FSS frequency bands that could be applied to CNPC is required. These studies look at sharing between earth stations operating on UA and terrestrial services operating in the same band, in particular FS stations. The subject of this paper is the study of sharing between UA earth station transmitted and FS receivers.

The sharing studies involve complex analyses considering many parameters such as UA earth station characteristics, FS receive characteristics, antenna radiation patterns, relative signal bandwidths, expected UA densities and operational scenarios. Studies must consider different UA altitudes and FS receivers operating over a range of FS antenna elevation angles operating at a range of latitudes, and must address both short-term and long-term protection criteria. All of these parameters as well as other related criteria are subject to agreement within ITU-R WP5B which is still in process.

This paper has provided background on the sharing studies supporting AI 1.5, the key technical parameters being applied, the analysis approach and example results. The studies will continue to be refined and review and discussion of the results by ITU-R WP5B will occur at upcoming meetings.

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