SATELLITE COMMUNICATIONS FOR UNMANNED AIRCRAFT C2 LINKS - C-BAND, KU-BAND AND KA-BAND

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Abstract

Unmanned aircraft (UA) that require access to controlled (or non-segregated) airspace require a highly reliable and robust command and control (C2) link, operating over protected aviation spectrum. While operating within radio line-of-sight (LOS) UA can make use of air-to-ground C2 links to terrestrial stations. When operating beyond LOS (BLOS) where a group of networked terrestrial stations does not exist to provide effective BLOS coverage, a satellite communications link is required. Protected aviation spectrum for satellite C2 links has only recently been allocated in bands where operational satellites exist. A previously existing C-Band allocation covers a bands where there are currently no operational satellites. The new allocations, within the Fixed Satellite Service bands at Ku and Ka-Bands will not be finalized until 2023 due to the need for the development of standards and technical decisions on the operation of UA satellite C2 links within these bands. This paper provides an overview of BLOS satellite C2 links, some of the conditions which will need to be met for the operation of such links, and a look at some aspects of spectrum sharing which may constrain these operations.

Introduction

Many potential applications for civil use of unmanned aircraft systems (UAS) have been identified, with additional use concepts emerging almost daily. However, the ability of UAS to operate in the US National Airspace (NAS) as well as non-segregated airspace worldwide, requires standard, certifiable communications links supplying UAS Command and Control (C2) communications links over which a pilot on the ground can control and monitor the unmanned aircraft (UA).

C2 communications can operate over terrestrial radio links within radio line-of-sight (LOS). For beyond radio line-of-sight (BLOS), two options exist: a deployment of networked terrestrial stations covering the entire area of expected UAS operations, or satellite communications. A complete network of terrestrial stations covering all possible operational locations is unlikely to be realized, especially considering remote and over-water locations. Hence, satellite communications will need to be a significant component of the C2 infrastructure for UAS.

The International Civil Aviation Organization (ICAO) has determined that the C2 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). Actions taken at the ITU-R 2012 World Radiocommunication Conference (WRC-12) have established spectrum resources to address the LOS spectrum requirement in the C-Band, at 5030-5091 MHz. At the ITU-R 2015 WRC (WRC-15), BLOS spectrum requirements were addressed by providing allocations specifically for UAS in Ku-Band and Ka-Band in Fixed Satellite Service (FSS) allocations. The FSS allocation is not aviation safety spectrum, hence the use of these bands for C2 links will require a number of special considerations in order to meet an equivalent level of safety.

With WRC-15 actions completed, it is now possible to begin experimental studies of UAS C2 links in Ku-Band and Ka-Band, and such studies will be necessary to fulfill requirements imposed by WRC-15 before the UAS C2 allocations can be finalized. For C-Band, there are currently no satellites in operation providing services in the aviation band so no experimental investigations are possible yet.

In this paper we review operational aspects of UAS C2 links, both LOS and BLOS, conditions for the operation of UAS C2 links, as well as the data transfer requirements, bandwidth requirements and link technical characteristics. We review some of the studies regarding sharing of spectrum in Ku-Band and Ka-Band that reveal possible operational constraints, and conclude by noting additional testing and analysis required to finalize UAS C2 BLOS spectrum allocations.

UAS Command and Control Links

The C2 link conveys the communications elements between the UA and the ground control station (GCS), specifically telecommands to the aircraft and telemetry from the aircraft. It may also include information downlinked from the aircraft to the GCS coming from navigational, surveillance, and separation assurance/detect-and-avoid systems, in both data and video form. Air traffic control communications, either voice or data, between the remote pilot and air traffic controllers, may also be relayed through the C2 link.

LOS C2 links can operate between the UA and a ground station connected with a GCS within radio LOS. Ground stations with contiguous coverage can be joined in a network to enable UA to handoff between ground stations to extend coverage beyond radio LOS. However, complete coverage of all land areas by a network of terrestrial C2 stations is not expected to be economically feasible. Thus BLOS C2 communications will in most cases require a satellite communications link.

The C2 link may operate at data rates ranging from 2 kbps to 250 kbps, with higher data rates required for the downlink from the aircraft. Bandwidth requirements to support these data rates for a UA density projected for the year 2030 have been estimated as 34 MHz for the terrestrial-based LOS C2 and 56 MHz for the satellite based BLOS C2 links [1].

The International Civil Aviation Organization (ICAO) is in the process of developing Standards and Recommended Practices (SARPs) for the UAS C2 link. Minimum Operational Performance Standards (MOPS) for LOS C2 terrestrial communications developed by RTCA Special Committee 228 are under final review, after which development of MOPS for BLOS C2 satellite communications will commence.

Spectrum for UAS BLOS Command and Control Links

ICAO has determined that C2 links are aviation safety links and are required to be operated using aviation safety spectrum. Actions taken at the WRC-12 have established spectrum resources to address the LOS spectrum requirement in the 5030-5091 MHz band by adding an Aeronautical Mobile (Route) Service (AM(R)S) allocation. The allocation is in addition to other allocations in that band including Aeronautical Radionavigation Service (ARS) and Aeronautical Mobile Satellite (Route) Service (AMS(R)S). The AM(R)S and AMS(R)S allocations are both intended to be able to support UAS C2 – for LOS terrestrial and BLOS satellite links, respectively. The ARS supports Microwave Landing System (MLS), an aircraft navigation system in use in a few locations. In addition, an AM(R)S allocation in L-Band (960-1164 MHz) may provide some additional LOS spectrum, although that band is heavily used for other aviation services. By combining spectrum from L-Band and a portion of the 5030-5091 MHz band, it is expected to be possible to meet the 34 MHz LOS spectrum requirement.

The BLOS spectrum requirement of 56 MHz is not met by the 5030-5091 MHz AMS(R)S allocation, which must be shared with LOS C2. In addition, there are currently no satellites operating in this band to provide BLOS C2 service, and no announced plans to develop and launch satellites providing such service. To identify additional spectrum to meet the BLOS requirements, Agenda Item 1.5 (AI 1.5) was undertaken by the 2015 World Radiocommunication Conference (WRC-15). AI 1.5 considered *"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…"* recognizing that existing satellite networks operating in the fixed satellite service (FSS) in the frequency bands at 14/12 GHz (Ku-band) and 30/20 GHz (Ka-band) have potential spectrum capacity to meet the requirements for UAS BLOS C2. However, the FSS is normally not recognized in the ITU as a safety service. Therefore ICAO identified the conditions required for UAS C2 use of FSS bands to meet an equivalent level of safety in non-segregated airspaces. ICAO identified the required conditions in the ICAO Position for WRC-15.

Taking into account the ICAO conditions, WRC-15 was able to come to an agreement to make new allocations in the FSS Ku and Ka frequency bands, identifying over 2.2 GHz of spectrum in WRC-15 Resolution 155. The Resolution specifies that these frequency bands can be used for the UAS C2 links in non-segregated airspace and any other airspace under the control of civil aviation authorities. This use is contingent on the successful development of ICAO SARPs. The Resolution goes into considerable detail to protect the current FSS environment against being disrupted by the introduction of a service that is virtually the same as an aviation safety service. The Resolution requires ICAO to report on its progress in the development of SARPs for the UAS C2 link to WRC-19 and WRC-23, including identification of any problems in the application of the Resolution and potential means by the WRC to address those. The Resolution comes fully into force by WRC-23 [2].

Conditions for UAS BLOS Command and Control Links

When a satellite providing AMS(R)S service for UAS C2 BLOS in the 5030-5091 MHz band comes into service, it will have to share spectrum with LOS systems. Proposals for sharing arrangements are being considered, which must also take into account sharing with MLS in a few locations. Spectrum sharing between a satellite and terrestrial system has been envisioned to partition the spectrum into three sections, with the middle section allocated to the LOS terrestrial application and the top and bottom sections allocated to the BLOS satellite communications forward and return links, with a separation of at least 20 MHz to provide sufficient isolation between the satellite uplink and downlink signals [3].

Allocations made at WRC-15 for UAS C2 links in FSS bands were difficult to achieve, primarily due to other service allocations existing in those bands. In applying a type of aeronautical mobile application to bands with fixed (non-mobile) services, a number of conditions are required. First, the UAS C2 BLOS links must not interfere with nor otherwise disturb existing satellites services, interfere with adjacent satellites or impose conditions on link performance that would exclude other applications.

Second, the UAS BLOS C2 receiver must be able to accept interference from other in-band services that are operating within their prescribed limits. The primary such in-band service is the Fixed Service (FS) which supports terrestrial wireless point-to-point and point-to-multipoint digital communications.

The third and most significant condition that UAS BLOS C2 systems must meet is to avoid interfering with other in-band services. Again the primary such service is the FS. Being a primary service in portions of both Ku –Band and Ka-Band, the FS have established protection criteria which the UAS BLOS C2 transmitters must not exceed.

As part of the process of developing methods to resolve WRC-15 AI 1.5, spectrum sharing studies between the UAS BLOS C2 transmitter and the FS receiver were performed. In the following sections, these sharing studies are reviewed in order to illustrate the conditions which UAS C2 BLOS systems will need to meet in order to operate in these bands.

Ku-Band BLOS Spectrum Sharing

The sharing studies performed for WRC-15 AI 1.5 analyzed the interference from the UA earth station transmitter into a FS station – link 3, interfering into the FS station receiver via potential interference path 3s, as shown in Figure 1 [4]. The sharing study covered the 14.0-14.5 GHz uplink band. The long term protection criterion requires that the interference to noise power density, I/N, to the FS receiver shall not exceed -10 dB for more than 20% of the year [5]. The short term protection criteria requires that the I/N shall not exceed +20 dB for more than 1x10-4 % of the time [6].

Visualyse Professional software [7] was used to create models of a number of scenarios involving interference from UA into FS. These scenarios were used to analyze both long term and short term interference criteria with small and large UA antennas, UA altitudes from 3000 to 19000 feet, and FS locations from 10^0 N to 70^0 N latitude at 90^0W longitude. Figure 2 illustrates the analysis scenario. Characteristics of the UA satellite communications link were defined in [4], for three UA antenna sizes.

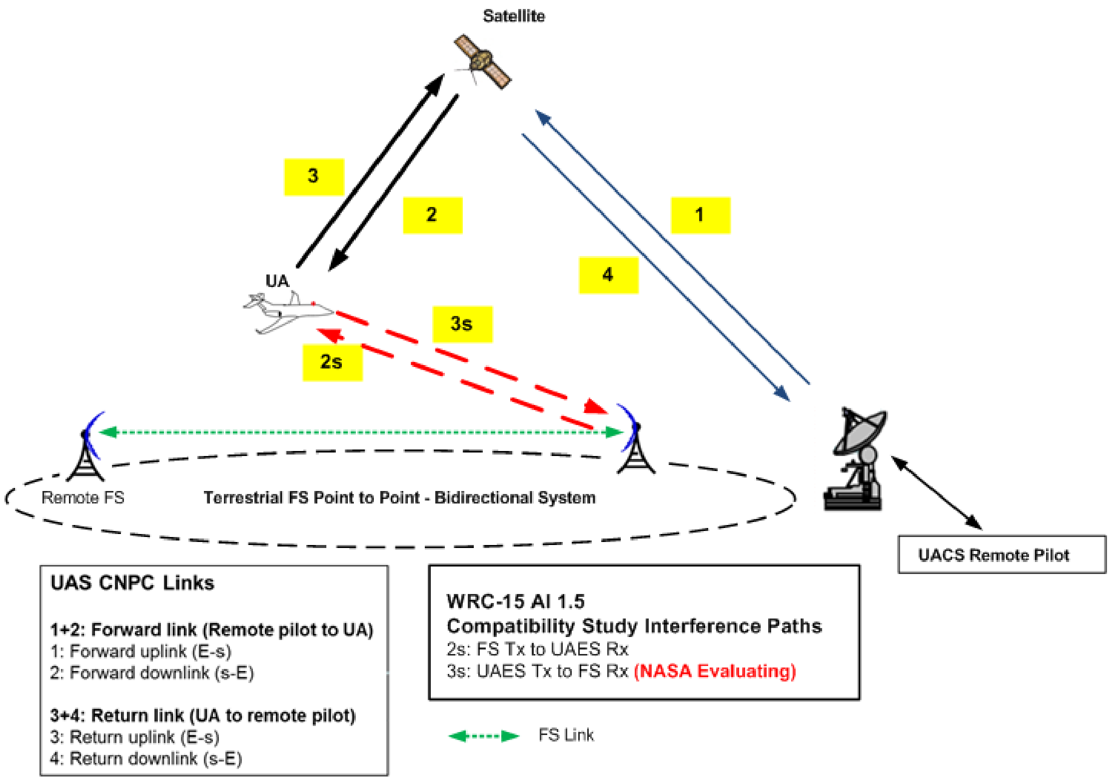

Figure 1 – UA Satellite Communications C2 BLOS Links under Study

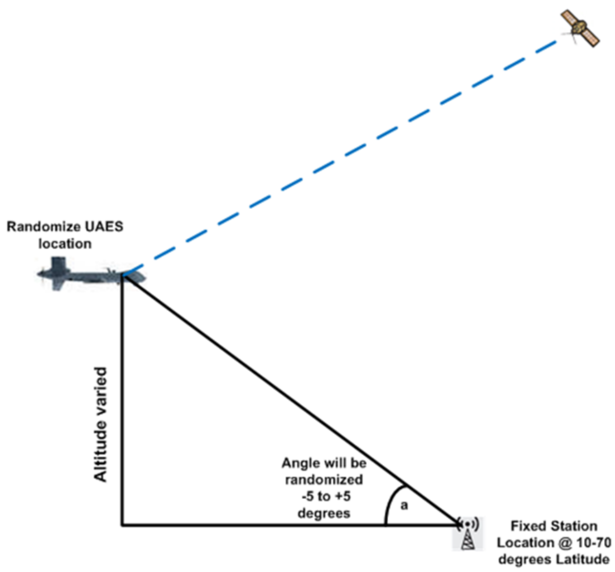

Figure 2 - Analysis Characteristics

The Ku-band analyses used a center frequency of 14.4 GHz. The FS antenna model had a diameter of 1.2 m, efficiency of 0.6, and an ITU-R F.699-7 gain rolloff [4, 8]. The Ku-band 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 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 [9].

For the long term analyses, the FS is placed at specific locations and the surrounding airspace is populated with one million randomly located UA's. The FS antenna azimuthal and elevation angles were randomly assigned values from -180 to +180 degrees and -5 to +5 degrees respectively. The expected percentage of time that I/N exceeds -10 dB, P, is then

$$P = QRA\rho$$

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), A is the airspace area; and ρ is the projected UA traffic density 2.39 UA/10,000 sq. km [1]. UA small and large antennas were modeled at altitudes of 3000 and 19000 feet, with FS locations at 10, 40, and 70 degrees N latitude. In all the cases, the percentage of time that I/N is over the threshold of -10 dB is less than 0.8 %, far below the protection criterion value of 20%.

The short term interference criterion at Ku-band is that I/N should exceed 20 dB no more than 0.0001 % of the time. In the simulations, the FS were placed at specific locations and the surrounding airspace was populated with one million randomly located UA. For the short term analysis the worst possible scenario was modeled with the FS antenna azimuthal direction pointing northward and the elevation angle at the worst value, $+5^0$. For the large Ku-band antenna, the minimum UA altitude that avoids exceeding the interference threshold drops rapidly from 18,000 feet at 70^0 to 7000 feet at 50^0 to 6000 feet at 30^0 and lower. For the small Ku-band antenna, the threshold altitude drops rapidly from 10,000 feet at 70^0 to 4000 feet at 50^0 to 3000 feet at 10^0.

The initial set of studies looked at the average case where the FS station can vary in its configuration, such that the FS antenna can be pointing in azimuth over a range of $\pm180^0$ and the antenna elevation angle can vary over a range of $\pm 5^0$. The peak-envelope Bessel function antenna pattern was used to model the UA antenna. The process employed for the sharing study analyses is described in [10].

The results showed that for all cases, the long-term protection criteria were met – the received I/N did not exceed -10 dB for more than 20% of the time. Figure 3 shows the cumulative distribution functions for the long-term criteria at 14.4 GHz with FS station at 10^0, 40^0, and 70^0 latitude, the UA at 3000 ft, using a large UA antenna. These curves show that the protection criterion (indicated by a red diamond) is met with a minimum of 18 dB of margin in each case. The short term criteria are met, but with much less margin. The areas in which a UA causes violation of the protection criteria are shown in Figure 4 for an FS station at 40^0 N and UA at different altitudes. Figure 5 shows the result with the smallest margin, for the Ku-Band case at 700 latitude, 3000 ft altitude using the large UA antenna.

Ka-Band BLOS Spectrum Sharing

For Ka Band, the uplink band under consideration is the 27.5-30.0 GHz uplink band. However, since there are no Fixed Service allocations in the 29.5-20.0 GHz portion of this band, sharing studies covered 27.5-29.5 GHz. 29.5 GHz. The protection criterion for the long term analysis is the same as that for Ku-band: I/N to the FS receiver shall not exceed -10 dB for more than 20% of the year [5]. The short-term protection criterion is that I/N should not exceed +14 dB for more than 0.01% of the time in any month and should not exceed +18 dB for more than 0.0003% of the time in any month [11].

The Ka-band analyses used a center frequency of 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 [4, 8]. 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. 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.

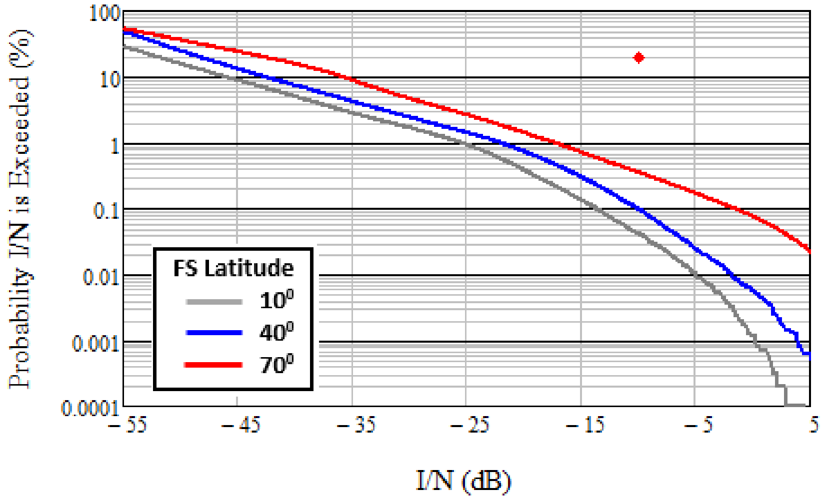

Figure 3 - Long-term analysis results for 14.4 GHz with FS station at 10^0, 40^0, and 70^0 latitude, UA at 3 000 ft altitude, large UA antenna

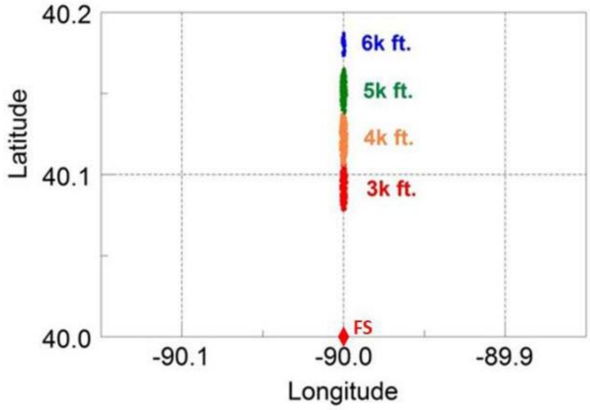

Figure 4 - Areas in which unmanned aircraft at altitudes of 3000, 4000, 5000, and 6000 feet need to reside in order to produce an I/N greater than 20 dB for an FS station at 40^0 N

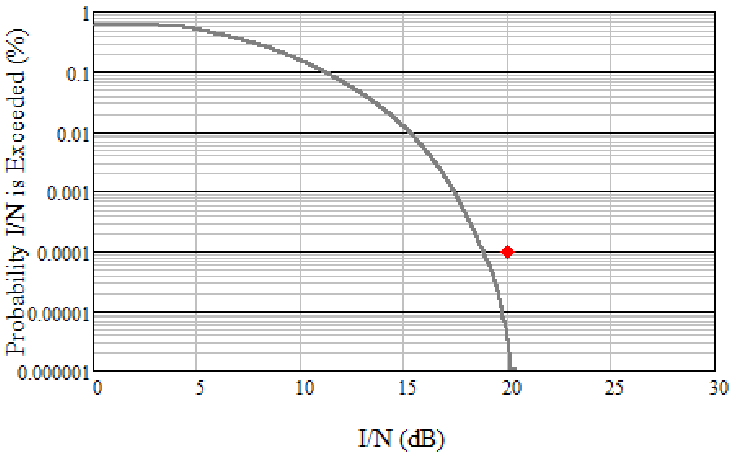

Figure 5 – Short-term analysis for 14.45 GHz with FS station at 70^0 latitude, UA at 3 000 ft above ground level, large UA antenna

The results indicated that the protection criteria for both long and short term were very easy to meet at Ka-band. For the Ka-band cases, an altitude of 3000 feet was more than sufficient to stay under the interference threshold at all latitudes for both large and small UA antennas for latitudes from 10^0 up to and including 70^0. The cdf for the Large UA antenna Long Term case is shown in Figure 6.

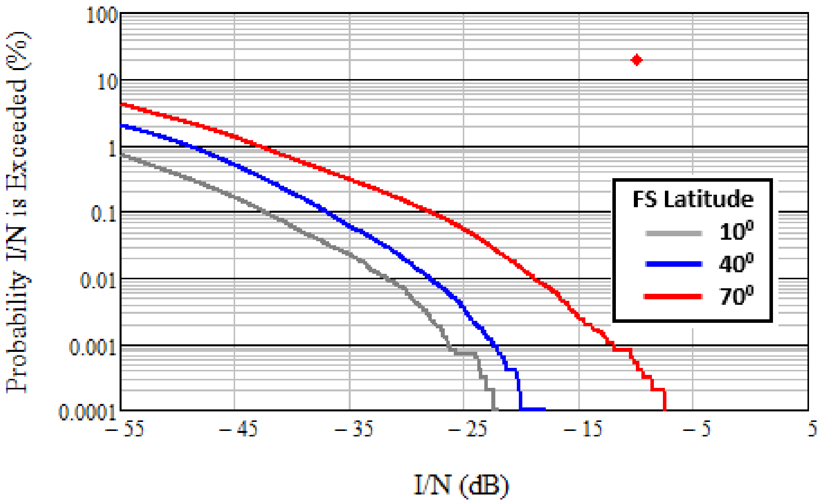

Figure 6 - Long term analysis results for 28.5 GHz with FS station at 10^0, 40^0, and 70^0 latitude, UA at 3 000 ft above ground level, large UA antenna

Figure 7 shows the short term Ka-Band Case cdf for a UA altitude of 3 000 ft at an FS latitude of 70^0, the worst case latitude, for the small 28 GHz antenna, which is also the worst case antenna size. The analyses for all other altitudes, latitudes and antenna sizes produce I/N results lower than that shown in Figure 6, therefore only the small antenna case is shown.

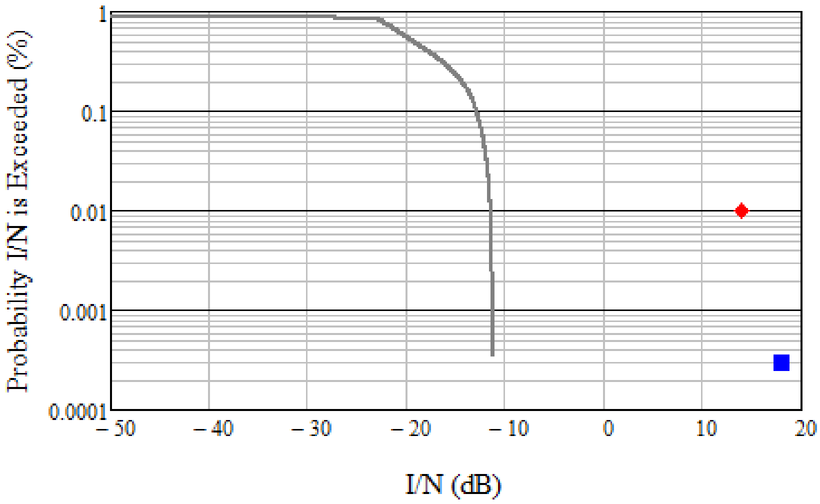

Figure 7 - Short term analysis I/N results for 28.5 GHz with FS station at 70^0 latitude, UA at 3 000 ft above ground level, small UA antenna

Spectrum Sharing and WRC-15 Results

The spectrum sharing analyses described above indicate that sharing between UAS using FSS satellite communications for the C2 link and terrestrial Fixed Service stations should be possible. But the short-term interference criteria places some constraints on UA operations in Ku-Band at the higher latitudes, where the minimum altitude to avoid exceeding the interference criteria increases. In addition, during the WRC-15 process, additional parameters were introduced for Fixed Station characteristics and protection criteria that make the sharing situation much more difficult.

WRC-15 Resolution 155 addressing Agenda Item 1.5 specified an allocation in Ka-Band covering only the 29.5-30.0 GHz band for the uplink, effectively eliminating sharing difficulties since there are no FS allocations in that band segment. For Ku Band, the uplink allocation covered 14.0-14.47 GHz but specified a requirement for UAS earth stations to meet a power flux density (pfd) limit in order to protect the FS from interference. This specific pfd limit was not agreed to at WRC-15 and so must be further studies in order to develop a consensus at the next WRC in 2019.

Conclusions and Further Work

The application of satellite communications to provide BLOS UAS C2 links is progressing. Sufficient spectrum allocations have been made, at least provisionally, in C-Band, Ku-Band and Ka-Band. However these bands have restrictions. In C-Band, the bandwidth available will be constrained by the need to share with terrestrial applications. In Ku-Band and Ka-Band, finalization of the allocations will not occur until 2023. In addition, some technical aspects of the Ku-Band allocation, in particular UAS transmit power flux density limits, are not yet determined.

Sharing studies demonstrated the possibility that sharing between UAS BLOS C2 links and in-band terrestrial services should be possible. But changes in FS characteristics and protection criteria being introduced into the ITU-R process are likely to impose some operational constraints in Ku-Band.

Further sharing studies in order to validate power flux density limits will be performed to support WRC-19. Flight testing of prototype Ku-Band and Ka-Band links will be necessary to validate UAS BLOS C2 link characteristics and performance and provide more accurate technical characteristics for study.

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