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Maximum Internet Capacity to Aircraft

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ABSTRACT

An Aeronautical Broadcast and Communications System (ABCS) links aircraft in-flight to the Internet via satellite.[i] The proposed (patented) architecture optimizes usable bandwidth by utilizing broadcast beams employing frequencies above 17GHz to illuminate flight routes.[ii] Spatial, frequency and polarization isolation are employed to maximize capacity. Use of frequencies above 17GHz facilitates regulatory coordination and licensing, while taking advantage of minimal atmospheric attenuation to and from aircraft at cruising altitudes. Terrestrial bidirectional satellite feeder links employ spot beams with frequencies below 17GHz to facilitate regulatory coordination.

Conceptual ABCS designs are presented as building blocks for incremental deployment. The tutorial approach provides intercontinental coverage and consists of a 48-channel, 4-beam 12KW satellite payload comprising four, 12-channel transponder segments, each serving a fleet of aircraft beam-by-beam. Satellite transponders perform frequency translations from 14.0 to 19.7 GHz (earth-to-aircraft) and from 29.5 to 10.7 GHz (aircraft-to-earth). A 36 MHz transponder channel is introduced as a basis for comparative link analysis. Each aircraft is equipped with antennas and a 24-channel transceiver. The network operations center (NOC) manages all network activities beginning with the signal traffic between the Internet and the aircraft. Quality-of-Service (QoS) is continuously monitored on each aircraft channel. Bandwidth is dynamically reassigned on a demand basis as air traffic and various data traffic moves between beams.

Analysis identifies baseline forward and return transponder information rates and provides basis for the conceptual ABCS presented. Analysis demonstrates greater capacity available for this conceptual design over a comparable all Ku-band aeronautical system using common transponders. A strategy to provide maximum Internet capacity to aircraft extends ABCS coverage incrementally. Future mobile satellite Ka-band allocations expand after existing capacity saturates, to envision extending ABCS services over multiple generations.

1.0 Introduction

Satellites can potentially offer aircraft far greater bandwidth than is available under other solutions such as terrestrially generated coverage cells, plus provide coverage to international flights over ocean areas. Internet services on-board aircraft are rapidly becoming ubiquitous and hold potential to fill a business and entertainment vacuum. This paper presents a novel approach to deliver Internet capacity to aircraft.

Commercial air travelers will be more productive and enjoy home comforts with Internet access while airborne. How will passenger expectations grow toward their *maximum* in-flight Internet experiences? Will insatiable bandwidth demand grow to become the primary discriminator in customer airline choice?

Cabin Wi-Fi appears to be the predominate means of providing the final link between the aircraft and the passenger.

The Aeronautical Broadcast and Communication System (ABCS) extends architecture for a class of systems that provide aircraft with extensive and efficient bandwidth access. As airlines outgrow the capacity accessible by mobile-satellite service (MSS) and fixed-satellite service (FSS) systems, various systems conforming to the ABCS architecture grow increasingly attractive.

This new category of communication satellite service minimizes the effects of atmospheric attenuation and efficiently gains access to quality spectrum.

2.0 Background

Boeing deployed the first Ku-band FSS solution to provide in-flight aircraft with Internet services.[iii] Presently Ku-band FSS beams offer capacity to passengers through a new generation of efficient aircraft antennas that enable ongoing expansion of cabin Wi-Fi services.

Terrestrial cellular is presently the leading approach to providing feeder links for cabin Wi-Fi service. Airplane access to Internet is occasionally provided via FSS and MSS systems as well. Overall about 33% of domestic flights currently offer Internet access. Products that maximize the Internet experience drive consumer bandwidth demand, portend congestion limits to cabin Wi-Fi service and presage user expectations for a *maximum* Internet experience.

Design and deployment of the first ABCS increment is best phased to address the rapid growth period anticipated for airline Internet services now in their infancy.

The first design step for any ABCS is to observe that atmospheric attenuation slope inflection at about 17 GHz demarks two prime frequency allocations. Satellites use the spectrum above 17GHz for their feeder links to and from aircraft, and that below 17GHz for their feeder links to and from the earth. Figure 1 highlights this observation.

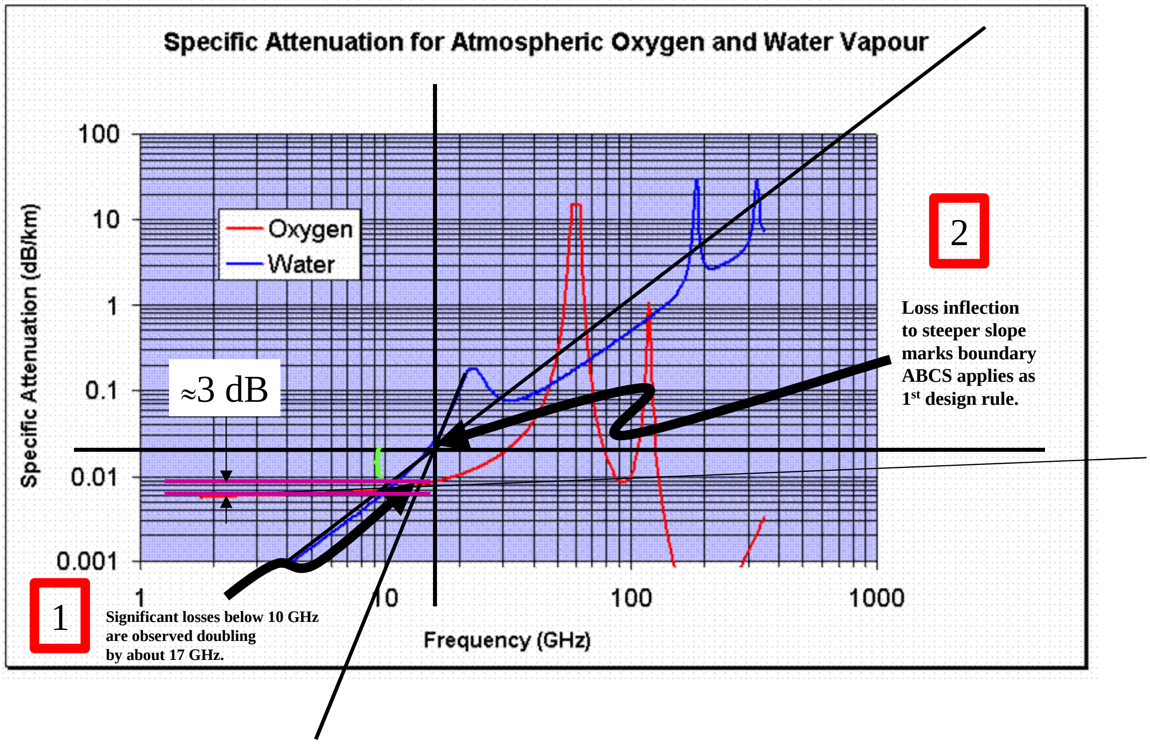

Figure 1. Highlights of the ABCS spectrum allocation demarked about 17 GHz.[iv]

2.1 Elemental ABCS Channels

The *natural* ABCS channel bandwidth is 17 GHz. The ideal ABCS imparts unit channels in increments of 17 GHz: 0-17, 17-34, 34-51…. All information goes between earth and space within this first channel, defined between 0 and 17 GHz. All the accessible bandwidth above 17 GHz is available to transmit information between aircraft and space and is multiplexed into the first channel to provide maximum information capacity for the ideal ABCS.

Current Ku-band FSS ITU allocations offer approximately 1.5 GHz of duplex spectrum between 10.7 and 17.7 GHz. Present Ka-band MSS ITU allocations offer approximately 25 GHz of total spectrum between 17.7 and 50.2 GHz. An arbitrary ABCS with a unit channel bandwidth of 500 MHz compels the notion of a 500 Mbps modem.

2.2 Notional ABCS Channels

A notional 500 MHz channel plan is offered to illustrate the abundant capacity currently allocated. Figure 2 shows Ku-band FSS allocations and two duplex channels to be used as the earth-space increments of spot beam feeder-link capacity. Ka-band channels illustrate a concept that maps 22 Ka-band channels into 11 isolated spot beams, reusing the FSS allocations. The conceptual frequency plan: Twenty two (22) 500 MHz duplex channels between air and space, and eleven (11) isolated 2-channel spot beams, into which the Ka-band channels are multiplexed, plus three (3) spare air-to-space channels.

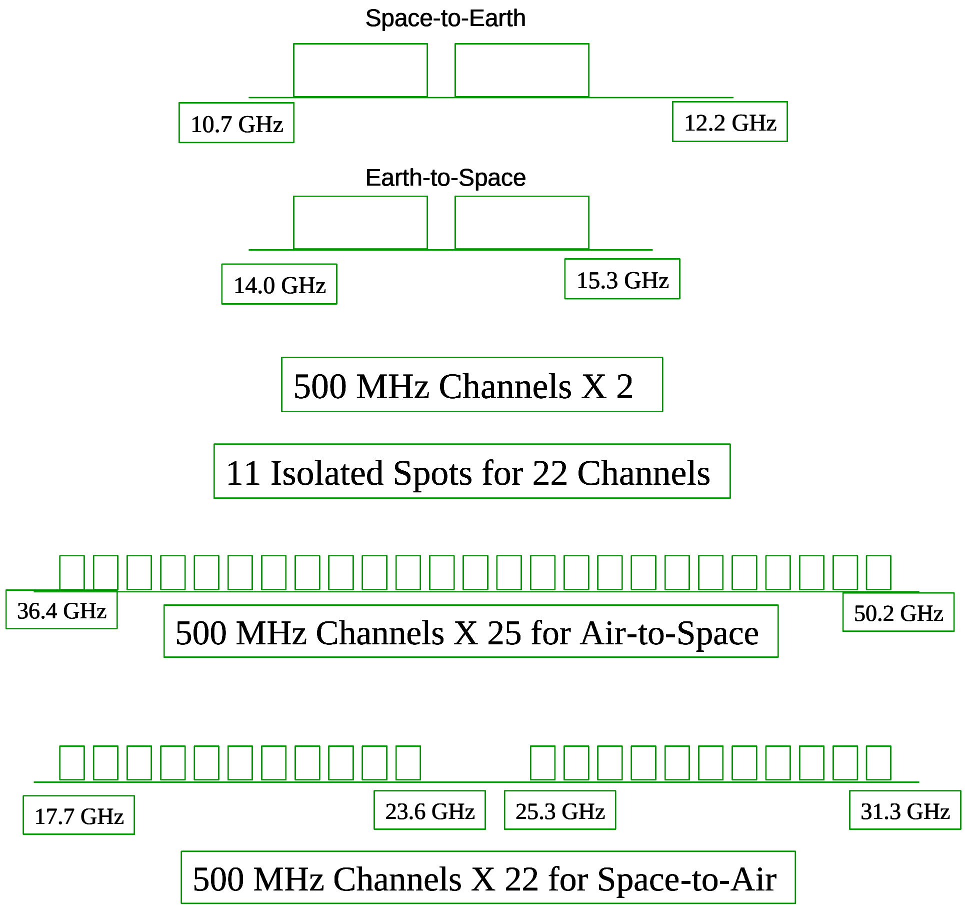

Figure 2. Notional ABCS Channel Plan

3.0 ABCS Conceptual Design

Global treaty governs spectrum allocation. ITU and FCC regulators grant satellite mobile and fixed frequency access through licensing and coordination procedures. Present allocations for commercial Ka-band mobile satellites restrict operation to 19.7-20.2 GHz downlinks and 29.5-30.0 GHz uplinks. Corresponding earth-space traffic is more widely permitted, such as 14.0-14.5 GHz uplinks and 10.7-11.2 GHz downlinks, for example.

3.1 Channel Analysis

An ABCS design is conceived in compliance to the ITU frequency allocations noted above. Link analysis illustrates a baseline embodiment of the architecture. Satellite transponders perform frequency translations from 14.0 to 19.7 GHz (earth-to-aircraft) and from 29.5 to 10.7 GHz (aircraft-to-earth).

A 36 MHz transponder channel with properties of INTELSAT 907 enhanced by Ka-band is used as the basis for a comparative study of link budgets. The earth station is located in Leuk, Switzerland while the aircraft flies above Monte Carlo, Monaco. Results from analyses, performed using Satmaster+, are summarized in Table 1.

Single-carrier saturation in the forward direction compares with 4-carriers per transponder at 8 dB input back off in the return direction. A single forward transponder channel illuminates the broadcast area with a single saturating high data rate carrier. The return link allows four aircraft to have duplex transponder access within the same beam. Forward link capacity is twice that of the return.

Link Parameters	**Forward Link**		**Return Link**	
	Earth-Space-Aircraft		Aircraft-Space-Earth	
	Up	Down	Up	Down
Frequency (GHz)	14.0	20.0	30.0	10.95
Polarization	Vertical	Circular	Circular	Vertical
Antenna Dia. (meters)	6.0	0.65	0.5	5.6
Antenna Gain (dBi)	65	32	35	65
EOC EIRP (dBW)	90.2	50	47.43	47.6
Bandwidth (MHz)	34		36	
Carriers per transponder	1		4	
Modulation	4-PSK			
Information Rate (Mbps)	**8.14**		**1.045 x 4 = 4.18**	
BW Allocated per Carrier (MHz)	8		2	
Availability (%)	99.0		99.8	
Bit Error Rate (BER)	10^{-11}			
Input Back-Off (dB)	0		8	

Table 1. Summary of link budget study using 36 MHz satellite channels

Information rates of 8 and 4 Mbps, forward and return, respectively, are shown with acceptable BER at 99% availability, using 4-PSK.

3.2 Equipment Configuration

Aircraft transmit/receive antenna diameter is assumed to be 0.5 meters. Aircraft antennas of this size are amenable to various active array implementations, each electronically auto-tracked and fuselage conformal. A mechanical auto-track, dual-band, dual-polarized reflector antenna may initially prove as attractive. Efficient aircraft accommodation drives antenna performance that in turn drives any ABCS design. The scaling up, from Ku-band to Ka-band, of field-proven products is a straightforward approach.

Satellite transmit/receive aperture is assumed 0.65 meters with 32-dBi of gain at 20 GHz. This implies transponder power amplifier output on the order of 100 Watts. TWTAs at 20 GHz provide 100 Watts at roughly 50% efficiency. Each Ka-band power amplifier has a corresponding Ku-band return power amplifier that requires significantly less dc power and thermal dissipation due to the high gain spot beam. Each transponder consumes about 250 Watts of dc power.

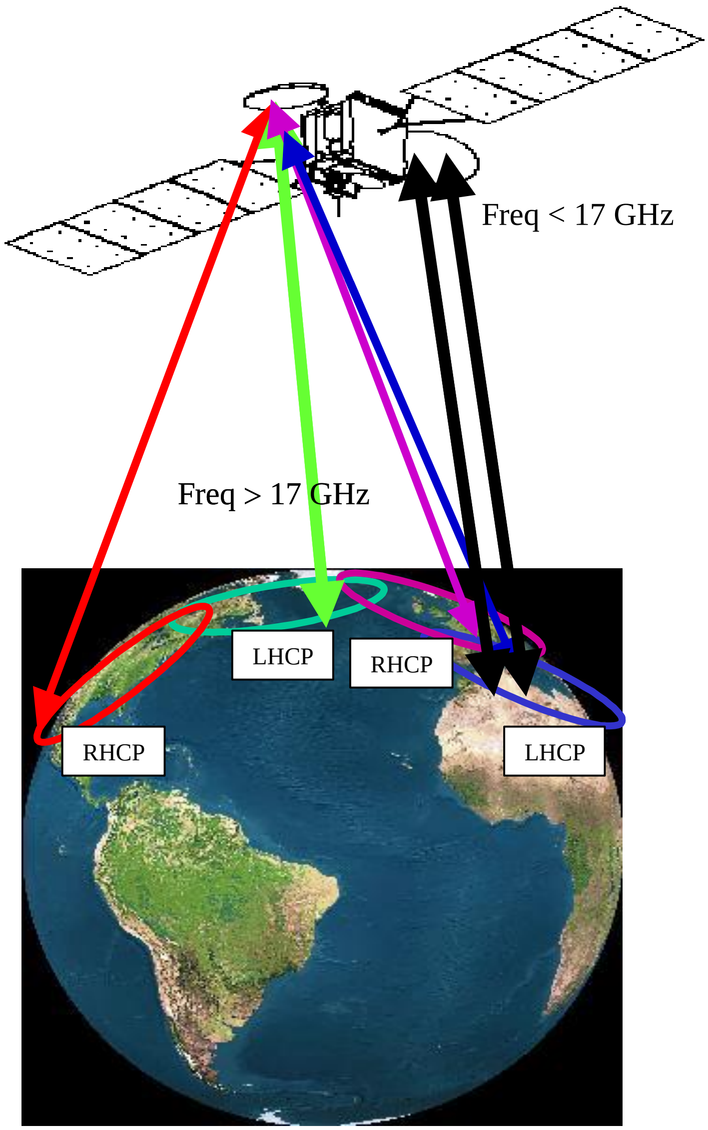

Figure 3. 4-Beam ABCS Ka-band Aircraft Coverage: 12-Channels/Beam

There are 12 channels available for each polarization of the 500 MHz system bandwidth. A 4-beam approach that employs a single circular polarization for each beam reuses channels by spatial isolation to provide 12 channels per beam. This 48-channel concept is shown in Figure 3.

An ABCS employs three segments: ground, space and air, to provide Internet aboard aircraft in-flight, end-to-end. In this example a single 12 KW satellite payload, a primary satellite ground station; network and satellite operation centers, an aircraft equipment installation site and a second autonomous ground station comprise a network that maintains 99% availability. The system is depicted in Figure 4.

3.3 Ground

The network operations center (NOC) manages all network activities to optimally maintain traffic between the Internet and the aircraft. Quality-of-Service (QoS) is continuously monitored on each aircraft channel. Bandwidth is dynamically reassigned on a demand basis as air traffic and various data traffic moves between beams.

The NOC manages the payload through the satellite operations center (SOC). The NOC staffs and provisions the aircraft equipment service site. The SOC maintains the satellite 24/7/365. It provides real-time payload monitoring and control to the NOC. It deploys and maintains both primary and autonomous ground stations. Aligned to the primary goal of highest traffic QoS, the SOC provides quality control, oversight, training and certification that regard all aircraft equipment installation and maintenance. The SOC determines causes and corrective actions in dispositions of defective ground equipment. The SOC collects and maintains QoS metrics that guide the NOC towards the primary goal.

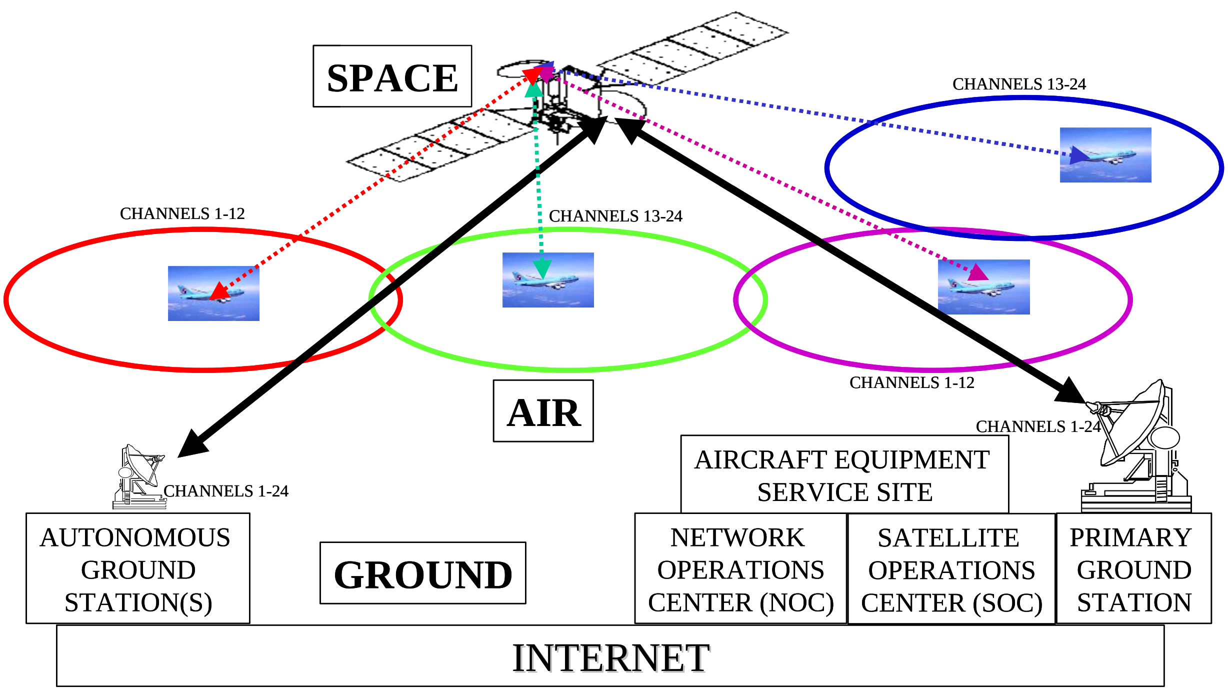

Figure 4. 48-Channel ABCS: 36 MHz Channels

3.4 Air

Each aircraft is equipped with tracking antennas and a 24-channel transceiver, at 3 GHz intermediate frequency, that takes received signals from the down-converter and delivers transmit signals to the up-converter, power amplifier chain. It interacts between the modem and the cabin Wi-Fi server. The arrangement accepts multiple modems allowing for incremental capacity. A conceptual block diagram of aircraft equipment configuration is shown in Figure 5.

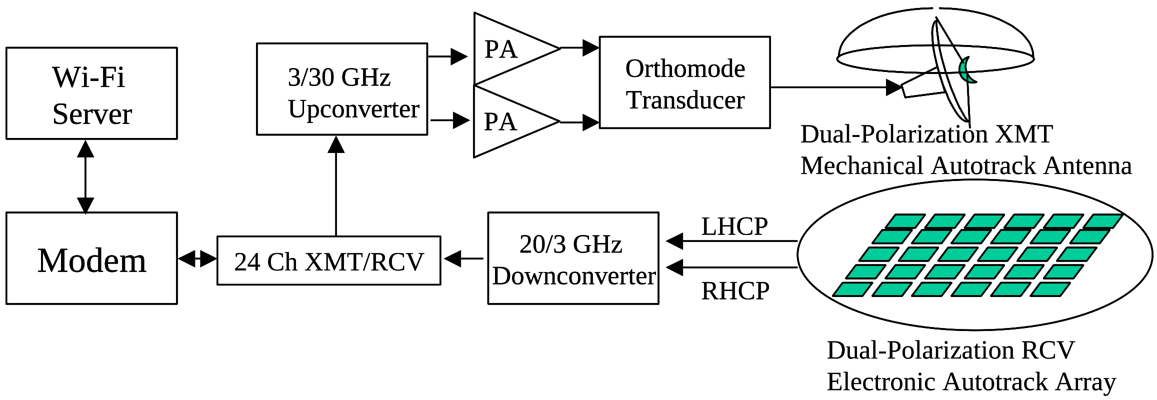

Figure 5. Aircraft Equipment

3.5 Space

Link analyses demonstrate a capacity advantage of 1.23x for this conceptual design when Ka-band ABCS is compared to an all Ku-band aeronautical system based upon study of common transponders.

An ABCS approach follows the path of least loss to employ extreme frequency reuse and increasing bandwidth efficiency along a distant path toward greatest information capacity to aircraft. Once the channel plan and system waveforms are established then precisely shaped broadcast beams are tailored to flight corridors. Optimized beams enable extensive frequency reuse. The multiplexing of many broadband broadcast beams into many times that number of spatially isolated (and relatively) narrowband spot beams extrapolates toward frequency reuse extremes. Avoidance of rain loss allows less error correction overhead and favors application of higher order modulation waveforms. Both features enhance system bandwidth efficiency.

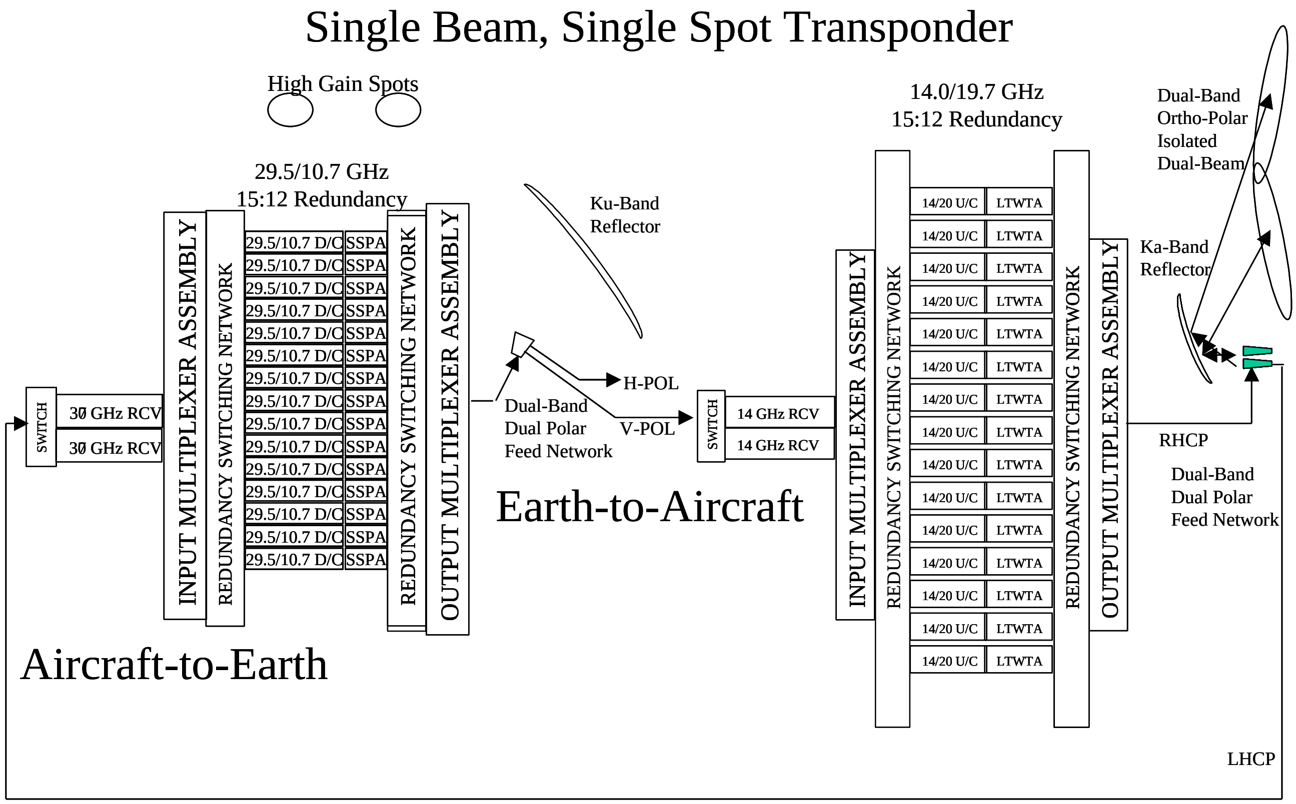

Figure 6. 12-Channel Building Block Increment of 48-Channel Payload

Incremental deployment, beam-by-beam, offers a flexible, long-term, pay-as-you-grow strategy to migrate the bandwidth from on-board Wi-Fi systems as they outgrow their first generation bandwidth allocations.

This tutorial example of an ABCS concept embodiment is deliberately conservative with regard to bandwidth utilization, antenna performance and information capacity. The transponder block diagram given in Figure 6 is primitively illustrative. Diverse paths toward enhancement are apparent. A space segment may be built, block-by-block, 12-channel increments in this case, of single-beam-to-single-spot transponders: as 3 KW small satellites, as pairs of medium satellites, as a single large spacecraft or as a variety of hitchhiker payloads.

System, and thus payload, performance optimization follows trade-off analysis and selection between various specific satellite bus accommodations that define quantities of apertures, their shapes and sizes, equipment layouts, mass budgets, pointing and power budgets, both dc and thermal. A conceptual 12KW 4-beam payload may be configured by increments of a 12-channel transponder unit such as described by the block diagram in Figure 6.

After the aircraft passenger logs on, the Internet request uplinks at 30 GHz on a left hand circularly polarized (LHCP) channel then translates through the transponder to downlink at 11.2 GHz (H-POL) to the primary ground station. The Internet reply is an uplink at 14.5 GHz on vertical polarization (V-POL) through the transponder to the aircraft at 20.2 GHz using RHCP. Linearized traveling wave tube amplifiers (TWTAs) are used at Ka-band to enhance linearity near saturation for increased efficiency. Solid-state power amplifiers are used at Ku-band for their low mass and inherent linearity at back off.

This building block is designed to double the transponder count while using the same number of custom shaped antenna surfaces as shown in Figure 6. One additional feed is required for the second Ka-band antenna dual-band elliptical beam pair. The increment then becomes half a payload: 24-channel transponders at 6 KW with dual-elliptical beams and single spot.

Evolution from low to high data rate aeronautical broadcast beams will eventually encounter a 500 Mbps modem that enables single-transponder beams such as considered in Figure 7. ABCS payload increments of single-transponder beams obviously follow.

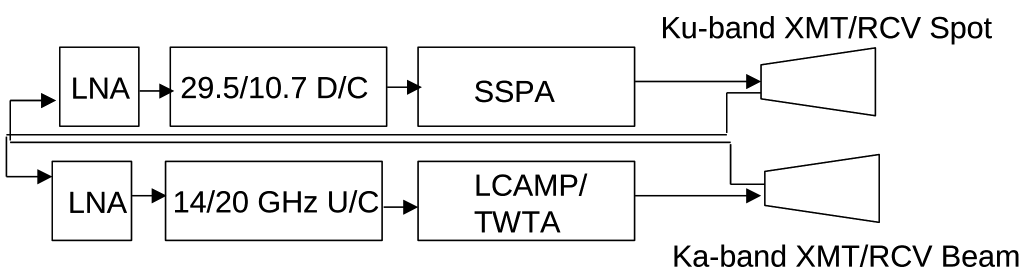

Figure 7. ABCS 500 MHz Single-Transponder Beams

Anticipation of many challenges begins with the novel payload; frequency converters, efficient broadband linear power amplifiers, shaped beam and spot beam antennas, to finally center upon the aircraft antennas and their bandwidth-efficient modems.

4.0 Conclusion

Use of frequencies above 17GHz facilitates regulatory coordination and licensing, while taking advantage of minimal atmospheric attenuation to and from aircraft at cruising altitudes. A strategy to provide maximum Internet capacity to aircraft deploys incrementally. Analysis confirms inherently greater capacity available at Ka-band, versus Ku-band, identifies baseline forward and return transponder information rates and provides basis for the concept presented: A 12-channel transponder segment illuminates a fleet of aircraft equipped with 24-channel transceivers, beam-by-beam, to comprise a 48-channel, 4-beam 12 KW payload and conceive an ABCS with intercontinental flight coverage. High data rate (500 MHz) single-transponder beams are the targeted enablers of an efficient incremental deployment path.

An ABCS strategy, extended over multiple generations, provides maximum Internet capacity to aircraft.

[i] Brian B.K. Min, "Aeronautical Broadcast and Communication System", 22nd AIAA International Communications Satellite Systems Conference & Exhibit 2004, 9 - 12 May 2004, Monterey, California, AIAA 2004-3169

[ii] US 7,505,736

[iii] Ed Laase, William R. Richards, "Connexion by Boeing℠ A Satellite Solution for In-flight Aircraft", 22nd AIAA International Communications Satellite Systems Conference & Exhibit 2004, 9 - 12 May 2004, Monterey, California, AIAA 2004-3188

[iv] http://www.mike-willis.com/Tutorial/PF5.htm