

Existing and Emerging Communication Technologies for Upper Class E Traffic Management (ETM)

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1 Abstract

Upper Class E Traffic Management (ETM) is the system envisioned to support operations above 60,000 feet (ft) msl.¹ Vehicles expected in this airspace include Unmanned Free Balloons (UFBs), High Altitude Long Endurance (HALE) unmanned systems, and reintroduced supersonic passenger aircraft. This paper discusses several existing communication technologies and their applicability to ETM aircraft and operators. These capabilities include Very High Frequency (VHF), Ultra High Frequency (UHF), High Frequency (HF), and satellite voice communication systems. Data communication technologies include VHF Data Link (VDL), HF data link, and satellite-based systems. These technologies were assessed in terms of general advantages, disadvantages, current level of support for ETM, and changes necessary to enable or enhance ETM support.

Communication capabilities were assessed for two ETM Unmanned Aircraft Systems (UAS): NASA's variant of the Global Hawk (the YRQ-4A), and a commercially operated HALE vehicle. These case studies illustrate emerging mechanisms that have been operationally validated in ETM airspace. Additional topics include an introduction to the notion of performance based communication, i.e., Required Communication Performance (RCP). RCP is an Air Traffic Management (ATM) environment paradigm that may serve as a model for a future ETM variant. A survey of additional emerging communication technologies was conducted to identify other potential options for ETM airspace. Lastly, suggestions for further research are provided.

2 Introduction

Activity above 60,000 feet (ft) msl in upper class E airspace is expected to increase. Anticipated vehicles include Unmanned Free Balloons (UFBs), HALE balloons, HALE fixed wing aircraft, HALE airships, and supersonic passenger aircraft [1]. UFBs with short mission durations are expected to operate up to altitudes of 160,000 ft msl. HALE balloons, operating up to similar altitudes, will extend mission durations to an average of 100 days. Solar powered, HALE fixed wing aircraft are expected to loiter between 60,000 ft and 90,000 ft msl for three to six months. HALE airships, currently capable of operating up to 60,000 ft msl, are also expected to be active in this airspace.

Supersonic passenger aircraft are expected to cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between 55,000 ft msl and 70,000 ft msl. Subsequent generations of supersonic aircraft may be capable of even greater speeds. Hypersonic aircraft, while still mostly in the concept phase, should also be considered as potential entrants. Additionally,

¹ 60,000 ft above mean sea level (msl), for the purposes of this report, is used in place of "FL600," which is the elevation of an aircraft when standard pressure (29.92") is set into the altimeter's Kollsman Window, and defines the bottom of ETM.

carrier aircraft for air-launched space vehicles are potential candidates. Figure 1 depicts (clockwise from left) a HALE telecommunications balloon, a conceptual HALE fixed wing aircraft, and a rendering of the Boom supersonic transport.



Figure 1. High Altitude Vehicles

The infrastructure, procedures, and policies in place today may not cost-effectively scale to accommodate the disparate vehicle performance characteristics and operational diversity expected in this environment. The Upper Class E Traffic Management (ETM) concept addresses these shortfalls with principles drawn from ATM, Unmanned Traffic Management (UTM), and operations currently performed above FL600 [1].

Previous work examined potential applications of surveillance and navigation technologies in the ETM environment [2]-[4]. This document assesses multiple communication technologies. Manned aircraft in the ATM environment have traditionally relied upon VHF and UHF voice communication while in domestic U.S. airspace. In oceanic airspace, High Frequency (HF) and satellite voice (SATVOICE) communication are preferred capabilities. Data communication is increasingly being used, and similarly, has VHF, HF, and satellite variants. These capabilities were assessed in terms of general advantages, disadvantages, current level of support for ETM operations, and potential modifications for greater ETM support.

Two UAS were examined in detail to illustrate emerging capabilities. Because both platforms have operated above 60,000 ft msl, their communication systems have been validated in ETM airspace. One vehicle is the fixed wing Global Hawk operated by the U.S. military and NASA. The other vehicle is a commercially operated HALE aircraft.

RCP in the ATM environment is introduced. An RCP specification represents operational parameters for a complete communication transaction and may serve as a baseline for a similar ETM communication specification. Lastly, a NASA commissioned study on potential emerging communication capabilities is discussed.

3 Communication Technologies for Manned Aircraft

3.1 Voice Communication

3.1.1 VHF/UHF Air-to-Ground Systems

Systems used for ATM voice communications in the United States are known as Air-to-Ground (A/G) systems. These enable two-way voice communication between the pilot and the ground-based Air Traffic Control (ATC) and Flight Service Station (FSS) specialists. Voice communications between these entities is important because they allow ATC specialists to provide pilots with critical services such as safety alerts, separation, traffic advisories, and vectoring (directions) in real time. Also, voice communications enable FSS specialists to provide the pilot with weather advisories and flight planning information.

A/G systems are characterized by transmitters, receivers, antennas and cabling on the aircraft and on the ground. Usually, the transmitter and receiver on the aircraft are contained within the same box (known as a “transceiver”), while on the ground the receiver and transmitter are usually in different boxes, in facilities known as Remote Communications Facilities (RCFs), which are owned and maintained by the FAA.

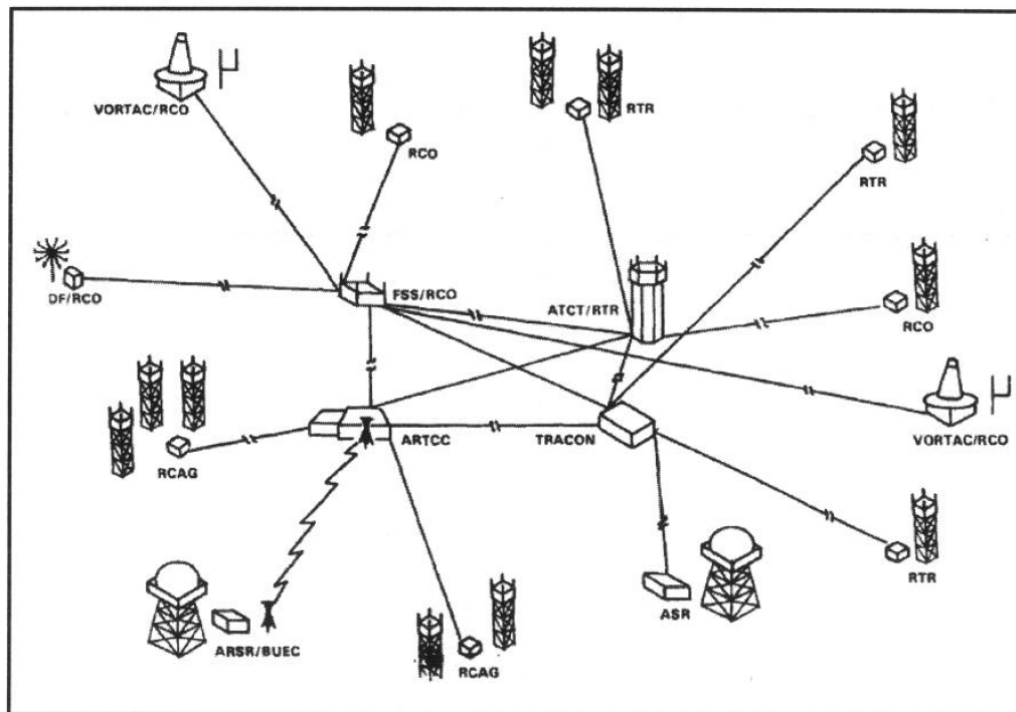


Figure 2. Relationships Between Air Traffic Control Facilities (middle) and Remote Communications Facilities (periphery) [5]

Figure 2 shows the different types of RCFs (around the periphery) and their possible connections to ATC facilities (the ARTCC, ATCT, FSS, and TRACON) [5]. The lists below describe these facilities and the services they provide.

Air Traffic Control (ATC) Facilities:

ARTCC	Air Route Traffic Control Center. An ATC facility that mainly provides pilots with en route (between terminals) radar services. These facilities provide services to the highest-flying aircraft.
ATCT	Air Traffic Control Tower. An ATC facility that provides pilots with (mainly) guidance and clearance services on and near major airports. Occasionally they provide radar services.
FSS	Flight Service Station. An ATC facility that provides pilots with flight services (weather and flight planning information).
TRACON	Terminal Radar Approach Control. An ATC facility that mainly provides pilots with terminal radar services (within several tens of miles of a major airport).

Remote Communications Facilities (RCFs):

RCAG	Remote Center Air-to-Ground Communication. An RCF that provides remote transmitting and receiving capability for the ARTCC en route communications.
RCO	Remote Communications Outlet (RCO). The RCO provides remote transmitting and receiving capability for flight services.
RTR	Remote Transmitter/Receiver (RTR) Facility. The RTR provides remote transmitting and receiving capability for terminal services. They are typically connected to the ATCTs and TRACONs.
BUEC	Backup Emergency Communications (BUEC) Facility. This system provides backup emergency en route channels by using remote VHF and UHF transmitter/receiver pairs. It is similar to the RCAG but provides main-only equipment supporting each en route sector (portion of airspace).

All of the RCFs use VHF and UHF transmitters and receivers, and antennas typically mounted on towers or buildings. They have one or more radio channels operating in the VHF and UHF bands. The VHF (118 MHz to 136.975 MHz) communication channels are for civil aviation use, and the UHF (225 MHz to 400 MHz) channels are for military aviation use.

As shown in Figure 2, RCFs are connected to the ATC facilities (typically by landlines or microwave links). Also shown, RCFs can be collocated with other facilities, such as an Air Route Surveillance Radar (ARSR) or even with an ATC facility itself, such as an ATCT.

Figure 3 shows an FAA RTR facility, collocated with an Airport Surveillance Radar (ASR). An example of an airborne transceiver is shown in Figure 4.



Figure 3. An RTR Collocated with an Airport Surveillance Radar (ASR), with RTR Antennas Indicated



Figure 4. Aircraft Instrument Panel with VHF Communications Transceiver

VHF/UHF Service Volumes

A/G VHF and UHF frequencies are engineered for distinct volumes of airspace and are guaranteed to be free from a preset level of interference from an undesired source [7]. Each specific function has its own Frequency Protected Service Volume (FPSV). Some are cylinders, while others are odd geometric solids. These odd shapes are normally required for en route ATC functions. All FPSVs are valid only within Radio Line of Sight (RLOS).

Cylindrical service volumes (CSVs) are defined by radii in nautical miles (nmi), usually centered on the RCF, with the maximum altitude of the cylinder defined in feet (Figure 5). These parameters are defined for the various ATC functions.

Tailored (or "multipoint") Service Volumes (TSVs) are unique shapes designed to afford necessary coverage within a designed interference-free protection level. The geometric center of the TSV is the center point for the radius that is the distance to the farthest point of the TSV. The geometric center and radius can be found by using the center point and radius of the smallest circle that will cover all of the TSV. [7]. A typical TSV is shown in figure 5.

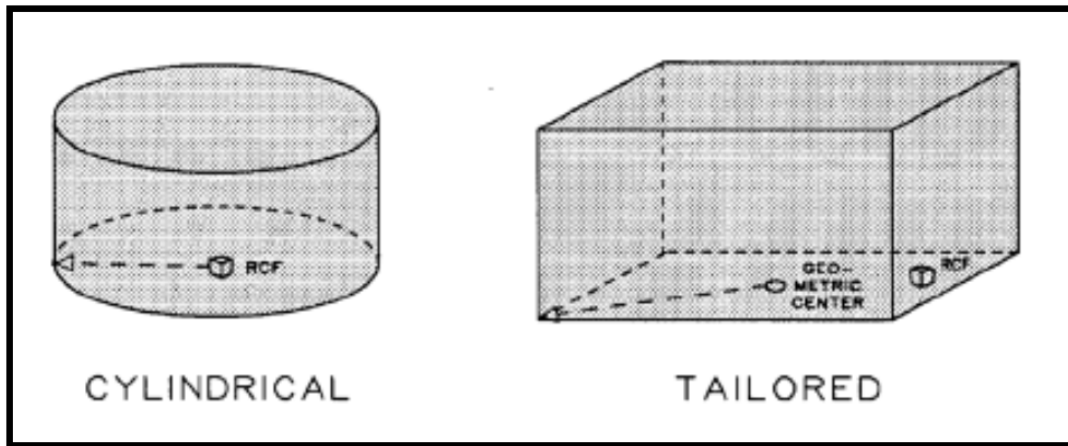


Figure 5. Illustration of Frequency Protected Service Volumes for RCFs [7]

Sufficient signal must be provided at the aircraft's receiver to ensure satisfactory performance at a point in the FPSV furthest from the ground transmitter [7]. RTCA Minimum Operational Performance Standards (MOPS) specify that the input to the aircraft receiver should be -87 dBm^2 , or greater [7][8]. VHF and UHF limits of coverage, for a receiver input power of -87 dBm , are shown in Figures 6 and 7.

The charts shown in Figures 6 and 7 give a vertical section of the volume of airspace within which a proposed FPSV will be provided with the required minimum signal of -87 dBm at the aircraft receiver [7]. All areas to the left of the respective curves are expected to have the minimum required signal level at all azimuths. Note that a 10 watt (W) transmitter is standard, whereas 50 W and 100 W require justification [7].

For the purposes of ETM, the focus is on en route service volumes, since those are required to cover the highest elevations of all service volumes. They are divided into the categories of Low, Intermediate, High, and Super High Altitude En Route. They normally have tailored or multipoint FPSVs, the maximum altitudes and radii usually not exceeding the values shown in Table 1 [7] [9].

² -87 dBm stands for -87 deciBels referenced to one milliwatt," which is a measure of power at the input to the aircraft receiver. This is equivalent to 10 microvolts, across a 50-ohm impedance.

Service	Altitude (feet)	Radius (nmi)
Super High Altitude En-Route	FL-600	150+
High Altitude En-Route	FL-450	150
Intermediate Altitude En-Route	FL-250	60
Low Altitude En-Route	18,000 AMSL	60

Table 1. Altitudes and Radii of En route Service Volumes [9]

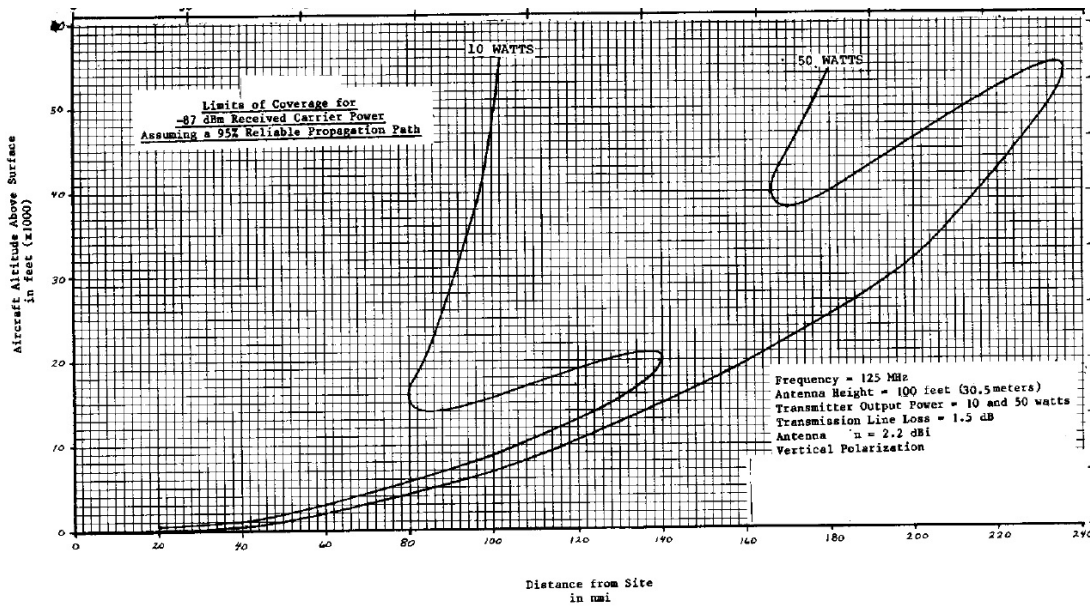


Figure 6. VHF Limits of Coverage (Antenna at 100 ft AGL) [7]

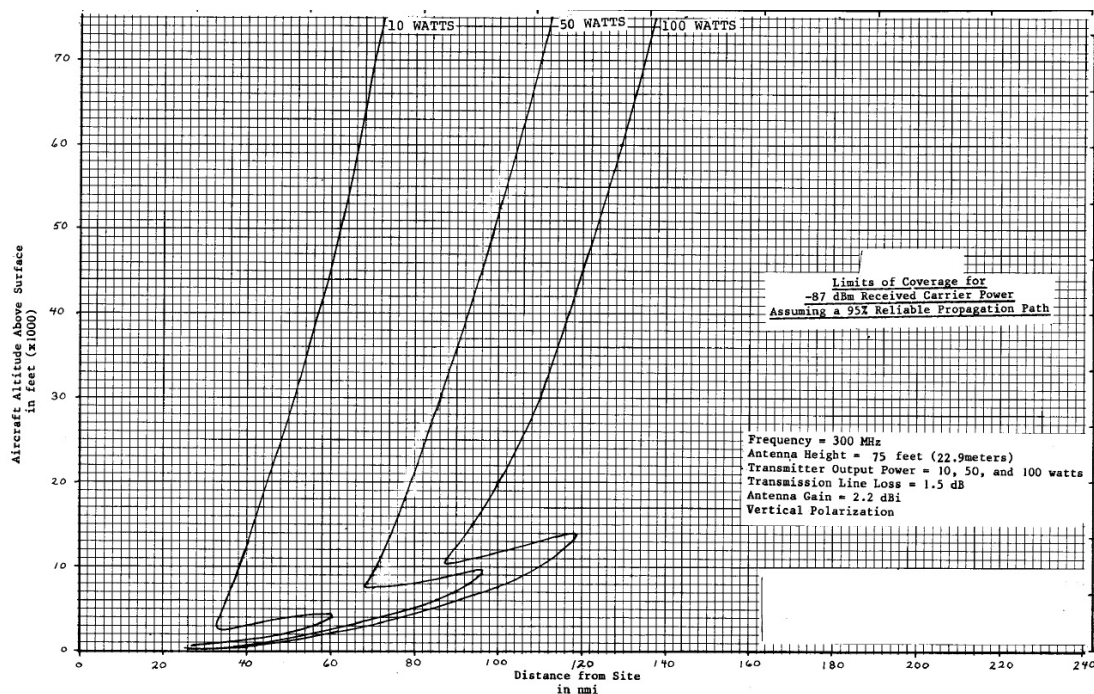


Figure 7. UHF Limits of Coverage (Antenna at 75 ft AGL)[7]

3.1.1.1 Advantages and Disadvantages of VHF/UHF Air-to-Ground Systems

VHF and UHF A/G systems have been used by the FAA for ATM for decades. It is the mainstay of pilot-to-ATC/FSS voice communications. There exist well-established airborne and ground-based industry, infrastructure and maintenance entities.

However, due to the VHF/UHF A/G systems using Amplitude Modulation (AM), they are subject to interference. Generally, this has not been a significant problem. Interference is prevented and remedied by the activities of the FAA's Spectrum Engineering Group, AJW-1C within the FPSVs.

Another disadvantage of VHF/UHF A/G systems is that they require Radio Line of Sight (RLOS) between the transmitter and the receiver to ensure coverage. Thus, they are subject to blockage by structures, foliage, and terrain. Other systems, for example High Frequency (HF), can be used to increase coverage volumes by providing Over-The-Horizon coverage (see section 3.1.2)

3.1.1.2 Current VHF/UHF Use in ETM and Changes Required for Greater ETM Use

Current Use

The Global Hawk UAS is capable of attaining altitudes of 65,000 ft msl. One of its communications methods involves an Iridium to VHF/UHF relay for voice communication between the ground-based operator and ATC. This suggests that VHF/UHF A/G can be used in the ETM environment (see Section 4.1).

The limits of coverage charts shown in Figures 6 and 7 also suggest VHF/UHF Air-to-Ground Systems can be used in ETM airspace. The patterns are shown there for 10 W, 50 W, and 100 W approach (in the case of VHF) and even exceed (UHF) 60,000 ft (AGL) elevation. Figure 8 shows the result of an analysis of the VHF A/G system of Figure 6, using an FAA propagation model of the uplink path, that further suggests that a VHF air-to-ground system could be used up to at least 70,000 ft (AGL) out as far as 150 nmi. A similar modeling of the downlink path confirmed that the standard airborne transceiver could be used at that distance and altitude. More detailed study would be necessary to quantify the actual volume of ETM airspace that is currently covered by VHF/UHF A/G systems. If use of the existing VHF/UHF A/G systems is required in ETM airspace, frequency engineering would be needed to mitigate the possibility of signal interference.

Changes Required for Greater ETM Use

The design changes required of VHF/UHF A/G systems for greater ETM use fall under two major areas: 1) increased power transmission and/or receiver sensitivity and 2) change the ground antenna radiation pattern to be more upwardly focused. Both options 1 and 2 would need frequency engineering and coordination to mitigate the possibility of signal interference. Note from Figures 6 and 7, changes to the existing systems may not even be needed to use them in the lower ETM environment. However, frequency engineering and coordination would still be needed.³

Airborne radio equipment that is expected to operate in the ETM environment would need to be tested in accordance with section 4 in Reference 13 [8][12]. Section 4 only tests the system in an environment up to 70,000 ft msl. For operation above 70,000 ft msl, new testing standards would be needed.

³ An oft-used method for adding to the FPSV of an existing facility is FAA Spectrum Engineering providing an "Expanded Service Volume" (ESV). ESVs extend the standard FPSV in a particular direction, distance, altitude, and shape [7].



Patterns Tool

Worksheet

Summary

Patterns Tool Summary

Date: Wednesday, December 18, 2019

Frequency	125.000 MHz
Range	150.0 nm
Type of Earth	Good
Polarization	Vertical

Transmitter		Receiver	
Power	10.0 Watts	Receive Level	-81.3 dBm >-87 dBm
Ground Slope	0.0		
Antenna Height	100.0 feet	Altitude	70000.0 feet
Antenna Type	Isotropic		
Antenna Gain	2.2 dBi	Antenna Gain	0.0 dBi
Cable Loss	1.5 dB	Cable Loss	4.5 dB

Figure 8. Analysis of VHF A/G System of Figure 6, Showing Power Sufficient at 150 nmi and 70,000 ft AGL

3.1.2 High Frequency (HF) Air-to-Ground Systems

High Frequency (HF) services are available to support NAS A/G international requirements. These are the Aeronautical Mobile (R) and Fixed services [7]. The HF Aeronautical Mobile (R) service provides ATC and airline operations A/G voice communications for flights operating in international airspace beyond the VHF range of RCFs. The A/G communications in support of the ATC function is provided by Aeronautical Radio, Inc. (ARINC), under contract to FAA. Aeronautical HF voice communication is not permitted over the continental U.S. when VHF communications are available, except in times of emergency [7].

HF systems use the concept of “ionospheric skip”: HF signals are bent downward by the ionosphere and can, therefore, reach aircraft that are beyond Radio Line of Sight (RLOS) (Figure 9). HF covers the frequency range from 3 to 30 MHz. It is that portion of the spectrum that has the potential for providing communications worldwide. For this reason, HF is often referred to as a “poor man’s satellite.” The availability of signal reception anywhere in the world depends on many conditions. The time of day, time of year, time of the 11-year sunspot cycle, and the frequency itself are all determining factors. There are five identified layers that are a consideration in HF radio propagation (Figure 9).

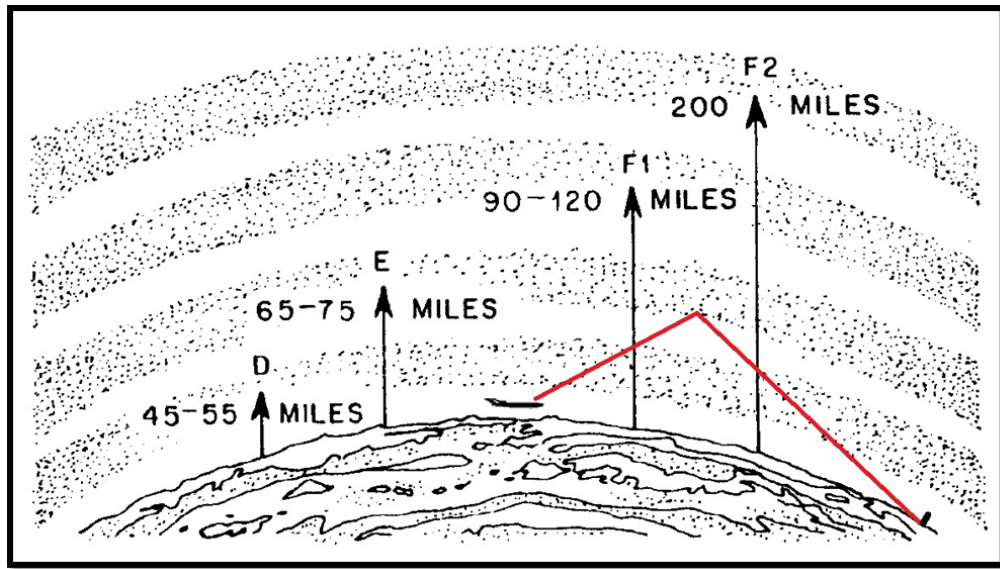


Figure 9. HF Ionospheric Skip with Path from Ground Station to Aircraft [7]

HF Service Volumes

There is no defined service volume for HF A/G service, as opposed to RCFs. There are zones where particular frequencies are assigned in the oceanic environment (Figures 10 and 11). The upper elevation limit of coverage is undefined. Aircraft operating in ETM airspace should have less of a problem receiving and transmitting the skipped signal than those operating in ATM airspace since the skipped signal travels less of a distance, and, therefore, is attenuated less by the atmosphere.



Figure 10. Approximate ARINC HF Station Boundaries [10]

120	ASSOCIATED DATA
AERONAUTICAL RADIO, INC. (ARINC) (Services available for aircraft engaged in international flight)	
ARINC using Pacific common air/ground ATC frequency networks shared with other ground stations are listed below. The frequencies in use will depend on the time and conditions which affect radio propagation. International flights on the ground at ANC or within VHF range of the SEA-ANC network that are entering the NOPAC Route System within Anchorage Centers FIR boundary should contact ARINC on VHF 129.4, to obtain primary/secondary HF frequencies and verify SELCAL before entering NOPAC. If unable 129.4, primary/secondary HF frequencies may be obtained from Anchorage ARTCC, but no SELCAL is available.	
WEB-PAGE FOR CURRENT ARINC FREQUENCIES: Radio.arinc.net Primary and Secondary ARINC frequencies for the Pacific and Atlantic are continuously updated on this webpage.	
CENTRAL WEST PACIFIC (CWP) NETWORK FREQUENCIES San Francisco MWARA—2998, 3455, 4666, 5652, 6532, 8870, 8903, 11384, 13300, 17904 and 21985 kHz LDOCF (c)—3494, 6640, 8933, 11342, 13348, 17925 and 21964 kHz	
NORTH PACIFIC (NP) NETWORK FREQUENCIES San Francisco MWARA—5628, 6655, 8915, 8951, 10048, 13339, 17946 and 21925 kHz LDOCF (c)—3494, 6640, 8933, 11342, 13348, 17925 and 21964 kHz	
CENTRAL EAST PACIFIC NETWORK FREQUENCIES San Francisco Extended Range VHF (a)—131.95 MWARA—2869, 3413, 3452, 5547, 5574, 6673, 8843, 8915, 10057, 11282, 13288, 13354, and 21964 kHz LDOCF (c)—3494, 6640, 8933, 11342, 13348, 17925, and 21964 kHz Seattle Pre-flight checks (b)—129.4 (SEA-ANC), 131.80 (North West), 131.95 (Central CA), and 128.90 (Southern CA).	
SOUTH PACIFIC (SP) NETWORK FREQUENCIES San Francisco MWARA—3467, 5643, 8867, 13261, and 17904 kHz LDOCF (c)—3494, 6640, 8933, 11342, 13348, 17925, and 21964 kHz	

Figure 11. Page from FAA Chart Supplement, Giving HF Frequencies Corresponding to Zones Shown in Figure 10 [11]

3.1.2.1 Advantages and Disadvantages of HF Air-to-Ground Systems

The greatest advantage is, of course, that the range of signal propagation is far greater than that of VHF/UHF A/G systems. They can be used by aircraft several hundreds of miles away from the ground station, rather than only 150 nmi away, as in the case of VHF/UHF RCFs.

The greatest disadvantage is the availability of the signal. Due to the sporadic nature of the ionospheric layers, as mentioned previously, the HF signal is not always available. This is mitigated in the oceanic environment by the requirements of FAR 121.351, “Communication and Navigation Equipment for Extended Over-Water Operations and for Certain Other Operations”:

“...no person may conduct an extended over-water operation unless the airplane is equipped with at least two independent long-range navigation systems and **at least two independent long-range communication systems** [emphases added] necessary under normal operating conditions to fulfill the following functions -

- (1) Communicate with at least one appropriate station from any point on the route;

- (2) Receive meteorological information from any point on the route by either of two independent communication systems. One of the communication systems used to comply with this paragraph may be used to comply with paragraphs (a)(1) and (a)(3) of this section; and
- (3) **At least one of the communication systems must have two-way voice communication capability.”**

Satellite communications can be used as a back-up to HF voice in the oceanic environment, but only if HF Voice is not available [30]. Satellite voice communications will be discussed further in a later section. Also, as was mentioned previously, HF voice communication is not permitted over the continental U.S. when VHF communications are available, except in times of emergency [7].

3.1.2.2 Current HF Use in ETM and Changes Required for Greater ETM Use

Current Use

Further research is necessary to determine whether HF Systems are presently being used in ETM airspace. Manned vehicles flying there would likely be military aircraft (e.g., the U2) or commercial spacecraft, without publicly available information. As mentioned, it is thought that the availability of the HF signal would theoretically be greater in the ETM environment than the ATM environment.

Changes Required for Greater ETM Use

Airborne HF radio equipment that is expected to operate in the ETM environment would need to be tested in accordance with section 4 in Reference 13 [17][18][8]. Section 4 only tests the system in an environment up to 70,000 ft msl. For operation above 70,000 ft msl, new testing standards would be needed.

3.1.3 Satellite Voice (SATVOICE)

Satellite voice services fall under the category of Aeronautical Mobile Satellite (R) Services (AMS(R)S)⁴. An AMS(R)S has four subsystems (Figure 12): The space segment (satellites), the Ground Earth Station (GES), the Aircraft Earth Station (AES), and a Communications Service (or Network) Provider (CSP or CNP). The CSP feeds the Air Traffic Service Unit (ATSU), such as an ARTCC [22].

⁴ The (R) represents that part of the radio frequency spectrum relegated to civil aeronautical services

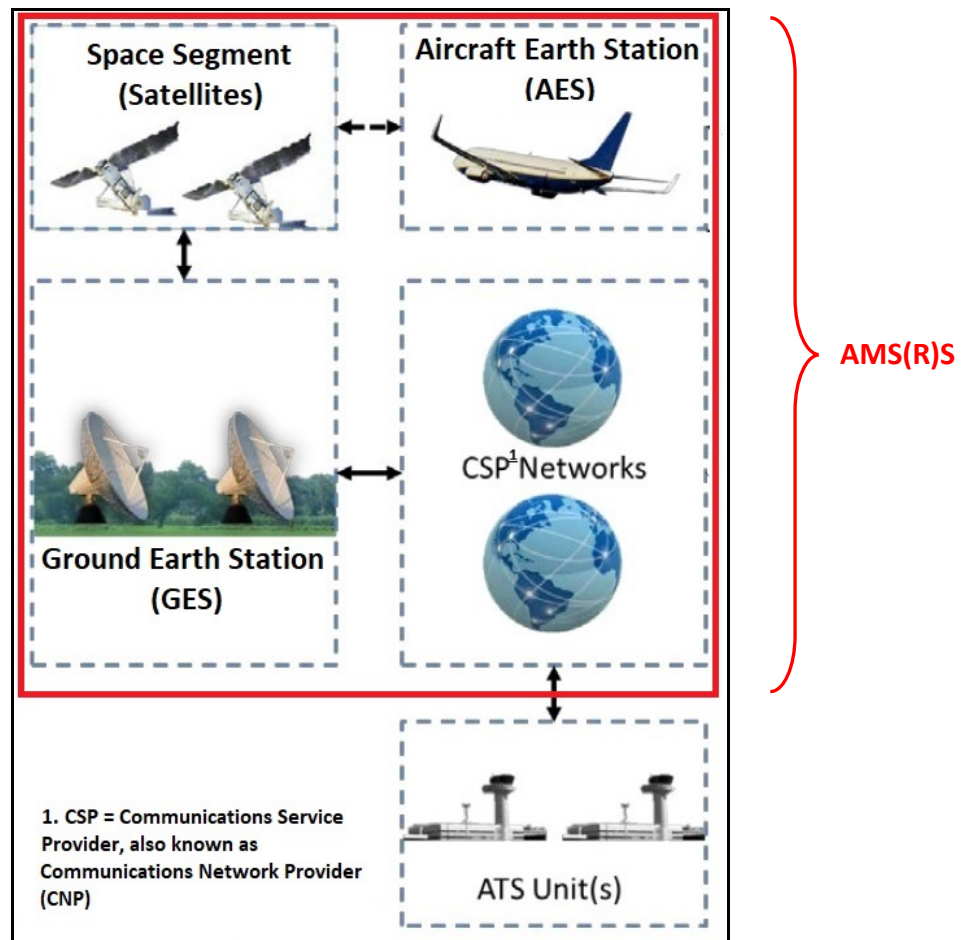


Figure 12. Subsystems of an Aeronautical Mobile Satellite (R) System (AMS(R)S) and How it Feeds an Air Traffic Services Unit (ATSU).

Similar to HF Voice, the FAA contracts with a CSP, such as Rockwell Collins (ARINC), who, in turn, receives SATVOICE services from one of two Satellite Service Providers (SSPs), either Iridium Satellite LLC or Inmarsat, who provides the GES and the Satellites [23].

Iridium

The Iridium satellite system is characterized by a network of 66 satellites that are in Low Earth Orbit (LEO) at an altitude of 781 km (485 mi), with nearly polar orbits. This provides complete global coverage (Figure 13). An uplink signal goes from the GES to a satellite. The signal can go from satellite to satellite before being sent down as an L-band signal to the aircraft's AES. The return signal, also L-band, from the aircraft can follow the same path back to the GES. This concept is called "satellite networking," and enables world-wide communications [24].

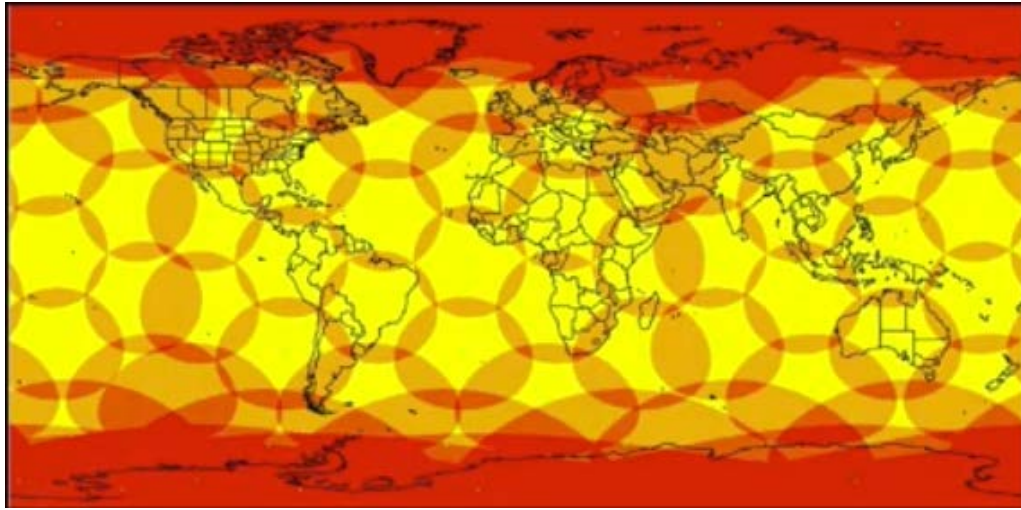


Figure 13. Instantaneous Iridium Coverarage [24]⁵

Inmarsat

The Inmarsat satellite system is characterized by four satellites in Geostationary Earth Orbit (GEO) at an altitude of 35,786 km (22,236 miles) with equatorial orbits. The signal is sent up to one satellite from the GES and then resent to an aircraft's AES. It would follow the same path for the return signal. Both the forward and reverse paths are L band. There is not quite complete global coverage by the four satellites, due to some signal loss at the poles [24].

⁵ Yellow shows coverage by one satellite; orange, by two; red, by three.

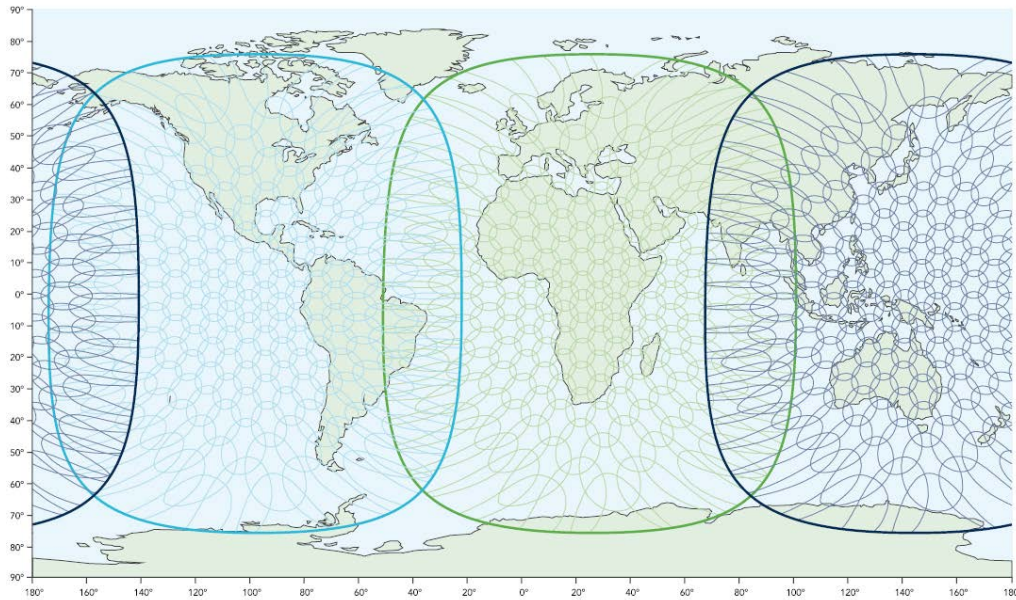


Figure 14. Inmarsat Coverage [25]

SATVOICE Coverage Volumes

As with HF Voice, there are no defined service volumes for SATVOICE. As shown in Figures 13 and 14, coverage is worldwide (except for small volumes near the poles, in the case of Inmarsat). The maximum altitude would be governed by the avionics and what environment they can operate in, rather than signal availability: the signal in the ETM environment is expected to be better than that in the ATM environment since the signal travels less of a distance between satellite and aircraft, and, therefore, is attenuated less by the atmosphere.

3.1.3.1 Advantages and Disadvantages of SATVOICE Systems

The biggest advantage in SATVOICE systems is that there is complete world-wide coverage. As shown in Figures 13 and 14, the entire globe can be reached by SATVOICE. Also, the signal is not as affected by ionospheric changes, as with HF voice.

A disadvantage in SATVOICE is its latency, due to the long path lengths involved. Satellite Voice is now only secondary to HF voice in the oceanic environment, to be used only if HF Voice is not available [30].

Note that SATVOICE is not yet approved for use over the domestic U.S., only in the oceanic and remote continental airspaces [31][21].

Because of frequency congestion and ionospheric/solar conditions in oceanic and remote flight operations, aircraft operators have requested the use of SATVOICE

equipment as one of their two long range communication systems (LRCS) in the oceanic environment [21]. (See previous section on HF Voice.) An investigation was performed and both Iridium and Inmarsat were shown to meet the existing RCP for latency for voice services (RCP 400 – see section 5) [26]. It is possible SATVOICE will be accepted as a sole voice communication system in the oceanic environment toward the end of 2020, but its use in the domestic U.S. ATM environment is not forthcoming [31].

3.1.3.2 Current SATVOICE Use in ETM and Changes Required for Greater ETM Use

Current Use

Further investigation would be needed to determine if SATVOICE is currently used in the ETM environment. Manned vehicles flying there would likely be military aircraft (e.g., the U2) or commercial spacecraft, without publicly available information. As with HF, it is thought that the availability of the signal would be greater in the ETM environment than the ATM environment: the aircraft would be at a higher altitude, so the signal's path distance between the satellite and the aircraft would be less; thus, it would be attenuated less.

Also, due to the propagation pathlengths being less for aircraft in the ETM environment, latency will not be as great as with the ATM environment. Note that the oceanic environment is not as demanding as the domestic U.S. environment for voice services, so RCP 400 is likely not a sufficient performance specification for use in ETM airspace above the continental U.S. [31]

The Global Hawk UAS is capable of attaining altitudes of 65,000 ft. One of its operator-to-ATC voice communications methods involves Iridium (as well as VHF/UHF A/G) (see section 4.1). Although it does not have the same mechanism as direct aircraft-to-ATC SATVOICE, this suggests that SATVOICE could be used in the ETM environment.

Changes Required for Greater ETM Use

The maximum speed for an aircraft using Iridium SATVOICE with its Aircraft Earth Station (AES) still conforming to [23], is 800 kts. With Inmarsat SATVOICE, that

maximum speed is one which would create a ± 2.5 KHz⁶ doppler shift or a + 30 Hz/sec rate of change in the doppler shift [23]. This could create a problem for supersonic and hypersonic aircraft.

Airborne SATVOICE equipment that are expected to operate in the ETM environment would need to be tested in accordance with section 4 in Reference 13 [14][23]. Section 4 only tests the system in an environment up to 70,000 ft msl. For operation above 70,000 ft msl, new testing standards would be needed.

3.2 Data Communication (Data Link)

With Data Communication, Air Traffic Controllers can send text-like instructions with route information to pilots, instead of speaking over the radio [15]. Air carrier dispatchers can simultaneously receive the same information, giving all decision makers a shared awareness for faster reaction and approval of changes. Flight crews review the instructions and signal acceptance by pushing a button, and the instructions are loaded into the aircraft's flight-management system (Figure 15). This process is presently being used in the airport ground environment for departure clearances and, in an increasing amount, in the en route environment for rerouting and control handoff between ARTCCs.

The overarching Data Communications systems (also known as Data Link) in use today are the following: FANS 1/A(+), ATN Baseline 1 (B1), Baseline 2 (B2), and ACARS Air traffic Service (ATS) [16].



Figure 15. A Flight Management System (FMS)

⁶ 2.5 KHz corresponds to about 950 kts, depending on the exact L-band frequency. This would be the maximum aircraft speed if the aircraft were going directly toward the satellite – maximum speed would likely be greater due to an angle between the direction of flight and the satellite.

The “sub-networks” or underlying technologies that enable these Data Link systems are VDL radio stations, HF data link radio stations, and satellite communications (Table 2) [27]. There are Communications Service Providers (CSPs) that provide the interconnectivity between the sub-networks and the Air Traffic Service (ATS) units (ATSUs), such as ARTCCs and ATCTs (Refer to Figure 16). The Global Navigation Satellite System (GNSS) is shown in Figure 16 since the Aircraft’s position, derived from GNSS, can also be transmitted to the ATSU.⁷

Sub-network Designator	Description of designator
VDL M0/A	Very high frequency data link – mode 0/A
VDL M2	Very high frequency data link – mode 2
HFDL	High frequency data link
SATCOM (Classic Aero)	Inmarsat or MT-SAT – Classic Aero satellite communications
SATCOM (SBB)	Inmarsat – Swift Broadband satellite communications
SATCOM (SBD)	Iridium – short burst data satellite communications

Table 2. Technologies that Enable Data Link (Sub-networks) [27]

⁷ One such service is known as “ADS-C,” or Automatic Dependent Surveillance – Contract.

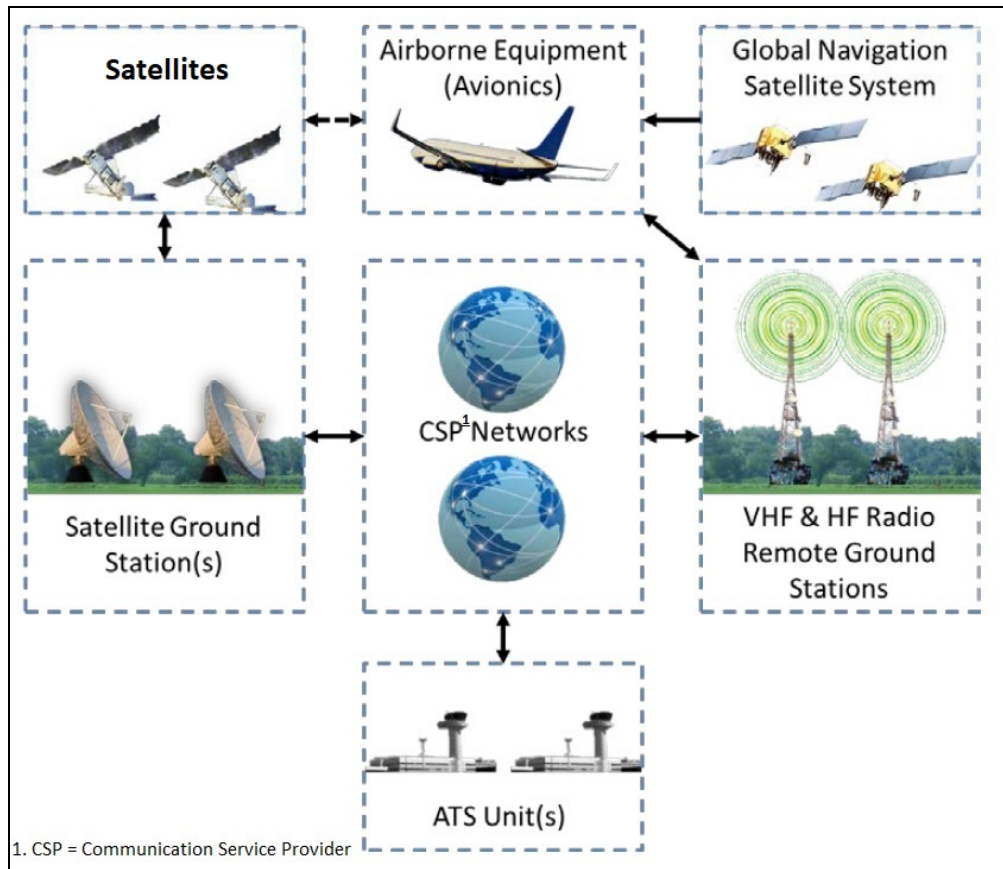


Figure 16. Data Link System Elements [16].

3.2.1 VHF Data Link (VDL)

The VHF radio systems (sub-networks) used for Data Communications are known as VDL. There are two types of VDL used in the United States: VDL Mode 0/A and VDL Mode 2 [16]. They are both used to provide Air Traffic Services (ATS) data messages⁸ in the airport ground environment (e.g., departure clearances), and VDL Mode 2 is starting to be used for ATS messages in the en route environment (e.g., rerouting and handoffs)[15][16]. These messaging services are known collectively as Controller-Pilot Data Link Communication (CPDLC). Also, both radio systems are used by the airlines for non-safety Aeronautical Operations Control (AOC) messages. Harris is the prime contractor to the FAA for the CPDLC service, and Collins (ARINC) and CITA are the

⁸ ATS messages are safety related messages between the Air Traffic Services Unit (ATSU) and the aircraft, as opposed to Aeronautical Operations Control (AOC) messages, which are lower priority, non-safety related communications, typically between the airline's control center and its aircraft.

subcontractors providing the VDL mode 0 and mode 2 ground radio subnetworks [31]. Note that VDL systems are not used for Data Link in the oceanic/intercontinental environment because of the necessity for ground-based facilities [16].

VDL Service Volumes

For each of the Data Link sub-networks, the reliability, maintainability, and availability performance requirements must be met, including ensuring the necessary RF signal levels of both the ground and airborne transmitters/receivers over the “ordered service volume” [16]. Thus, theoretically, if the ETM airspace were ordered to be covered by the FAA, it would be provided to fulfil a contractual requirement.

The technical requirements for VDL Mode 2 are given by TSO-C160a, “Very High Frequency (VHF) Mode 2 Communications Equipment,” which points to RTCA DO-281B, “Minimum Operational Performance Standards for Aircraft VDL Mode 2 Physical, Link, and Network Layer, dated March 21, 2012.” This in turn points to RTCA DO-224D, “Signal-in-Space MASPS For Advanced Digital Data Communications Including Compatibility with Digital Voice Techniques.”

Tables 3-117 and 3-120 of DO-224D give typical signal to noise link margins for the VDL uplink and downlink, respectively. Both show margins at 70,000 ft that are greater than 5 dB. Paragraph 3.7.4 of DO-224D, “Link Availability” states that the link margin should be a minimum of 5 dB to ensure link availability is no worse than the present analog voice system. Thus, presently, VDL can theoretically be used at 70,000 ft.

3.2.1.1 Advantages and Disadvantages of VDL

The main advantage of the VDL systems is that they enable reduced communication errors and radio frequency congestion, improve capacity, and increase efficiency [15]. Also, as with VHF/UHF A/G radio systems, there are a well-established industry, infrastructure and maintenance entities (albeit, not directly FAA administered).

The disadvantages are that they do not allow for real time communications, as does voice communications. Therefore, they are not used for the most demanding ATM communications in the domestic US area: the terminal ATM environment. In addition, VDL is only available within the RF coverage volume of the ground transmitting facility (like A/G Voice). If the aircraft goes beyond the coverage of the ground facility, such as in intercontinental flight, there will no longer be communication via VDL.

3.2.1.2 Current VDL Use in ETM and Changes Required for Greater ETM Use

Current Use

Further research is necessary to determine whether VDL Systems are presently being used in ETM airspace. Manned vehicles flying there would likely be military aircraft (e.g., the U2) or commercial spacecraft, without publicly available information. The link margins of the “typical” data link of Tables 3-117 and 3-120 of DO-224D suggest, theoretically, there would be sufficient signal strength at 70,000 ft so that they could be used in the ETM environment.

Changes Required for Greater ETM Use

Since VDL is currently an FAA contracted system, it would be necessary to specify the particular ETM service volume and expect fulfillment by the contractor / subcontractor (likely by the same methods called out above for VHF/UHF A/G voice systems - see section 3.1). Changes to technical and procedural requirements (e.g., Advisory Circulars, Technical Standard Orders, and RTCA documents) for use of VDL in the ETM environment may also be needed.

3.2.2 HF Data Link (HFDL)

HF communication provides another means of sending and receiving digital communications [16]. HFDL complements existing VHF and satellite communications (SATCOM) sub-networks. A sub-network of 15 HFDL ground stations extends worldwide communication coverage beyond that of VDL sub-networks. This is typically in the intercontinental environment. As with VDL, HFDL is contracted out by the FAA. The contractor is Rockwell Collins (ARINC).

As mentioned previously, HF is subject to temporary signal distortion due to changes in the ionosphere layer shape and density. Because of multiple HFDL ground stations, ionospheric disruptions are less frequent than in the early days of HF voice. Modern aircraft HFDL systems automatically search for the best available frequency from all HFDL operational ground station frequencies. Once a suitable frequency is found, the aircraft establishes a connection by sending a logon/ notification message to the ground station. A logon/notification confirmation uplink is established enabling the pilot to send data [16].

Service Volume

As with HF voice communications, there is no defined service volume for HFDL radio systems.

3.2.2.1 Advantages and Disadvantages of HF Data Link Systems

As with HF voice, the advantage of HF DL is a distant coverage range from the ground station. The HF DL sub-network provides communication to both ATSU and AOC in the intercontinental airspace and can be used for [16]:

- “1. Non-SATCOM equipped aircraft with a long-range, cost-effective data link communication capability,
2. Data link communication in polar regions where geostationary satellite connections may not exist or be degraded, and
3. A back-up means of data link communication for SATCOM (CPDLC and ADS-C) equipped aircraft.”⁹

The disadvantage is the unpredictable signal reception. This is mitigated by the automatic searching of multiple HF channels by the newer-technology aircraft receivers.

Another disadvantage is a relatively low data rate. HF DL has the lowest data transfer rate of all the Data Link sub-networks.

Note that HF DL is not yet approved for Data Link over the domestic U.S., only in the oceanic and remote continental airspaces [16].

3.2.2.2 Current HF DL Use in ETM and Changes Required for Greater ETM Use

Current Use

Further research is necessary to determine whether HF DL Systems are presently being used in ETM airspace. Manned vehicles flying there would likely be military aircraft (e.g., the U2) or commercial spacecraft, without publicly available information.

For the same reasons as for HF voice, the signal received at both the ground and aircraft transceivers, is expected to be stronger in the ETM environment than in the ATM environment since the aircraft is at a higher altitude.

⁹ Note that HF DL is secondary to SATCOM [16], whereas HF Voice is primary to SATVOICE [30]

Changes Required for Greater ETM Use

HFDL radio equipment that is expected to operate in the ETM environment would need to be tested in accordance with section 4 in Reference 9 [17][18][8]. Section 4 only tests the system in an environment up to 70,000 ft msl. For operation above 70,000 ft msl, new testing standards would be needed.

3.2.3 Satellite Data Link (SATCOM)

SATCOM uses the same transmission mechanisms as SATVOICE, which were discussed in section 3.1.3. As shown in Table 2, both Inmarsat and Iridium offer SATCOM services. Inmarsat has two services that provide it: Classic Aero and Swift Broadband (SBB). Classic Aero is Inmarsat's first-generation aviation data link service and has less performance and capability as SBB. Iridium uses the Short Burst Data (SBD) service for data link.¹⁰ SATCOM is not presently used for Data Link over the domestic U.S. but only in the oceanic and remote continental areas [16].

Commercial and business aviation have been increasing their "connectivity," substantially over the last few years to improve the passengers' flying experience. This enables passengers (and pilots) to have similar data communication experiences as when they are on the ground. Features such as texting, emailing, web browsing, and video streaming on aircraft have become more and more common. These services may share the same satellite communications system as that used for SATCOM (but considered a lower priority)[22].

3.2.3.1 Advantages and Disadvantages of SATCOM

The advantages and disadvantages are the same as SATVOICE (see paragraph 3.1.3.1), but SATCOM is not considered secondary to HF for the purpose of Data Link, as it is for voice communications.

An advantage that SATCOM has over the VDL and HFDL is that it has a higher data transfer rate than both.

Note that SATCOM is not yet approved for Data Link over the domestic U.S., only in the oceanic and remote continental airspaces [16].

¹⁰ MT-SAT is mentioned in Table 1 as being another satellite technology that offers Data Link. It is a JCAB (Japan Civil Aviation Bureau) GEO, meant to provide communication services to the Japanese and Asia-Pacific ATM environment. As mentioned in [30], "Neither the ARTCCs nor the RADIO facilities can contact flights logged into the MSAT," and thus, it will not be discussed here further.

3.2.3.2 Current SATCOM Use in ETM and Changes Required for Greater ETM Use

Further investigation would be needed to determine if SATCOM is currently used in the ETM environment. If so, it would likely be used by pilots of military aircraft (e.g., the U2) and commercial spacecraft; the information about both have little public availability.

Data communications (not necessarily SATCOM) using satellites are being used by UAS in the ETM environment (see Section 4). This suggests SATCOM could also be used there.

Aircraft maximum velocities are the same as with SATVOICE (section 3.1.3.2)[23].

4 Communication Technologies for Unmanned Aircraft

Two UAS capable of operating in ETM airspace were examined as case studies. One vehicle is the fixed wing Global Hawk operated by the U.S. military and NASA. The other vehicle is a commercially operated HALE aircraft.

4.1 Global Hawk

Publicly available information on the Global Hawk, RQ-4 (Figure 17), often indicates a maximum operating altitude of 60,000 ft. However, consultation of domain subject matter experts, including engineers associated with the Global Hawk program, revealed that the aircraft was routinely operated up to altitudes of 67,500 ft msl during testing. Additionally, publicly available information indicates a NASA variant, type YRQ-4A, planned a mission with a maximum altitude of 65,000 ft [28]¹¹. These characteristics qualify the Global Hawk as an ETM vehicle. Its Communication, Navigation, and Surveillance capabilities have been validated in ETM airspace.

¹¹ It is unknown if the mission was flown as planned, but Reference [28] contains much detailed information including segment by segment flight maps that show much seriousness of intent.

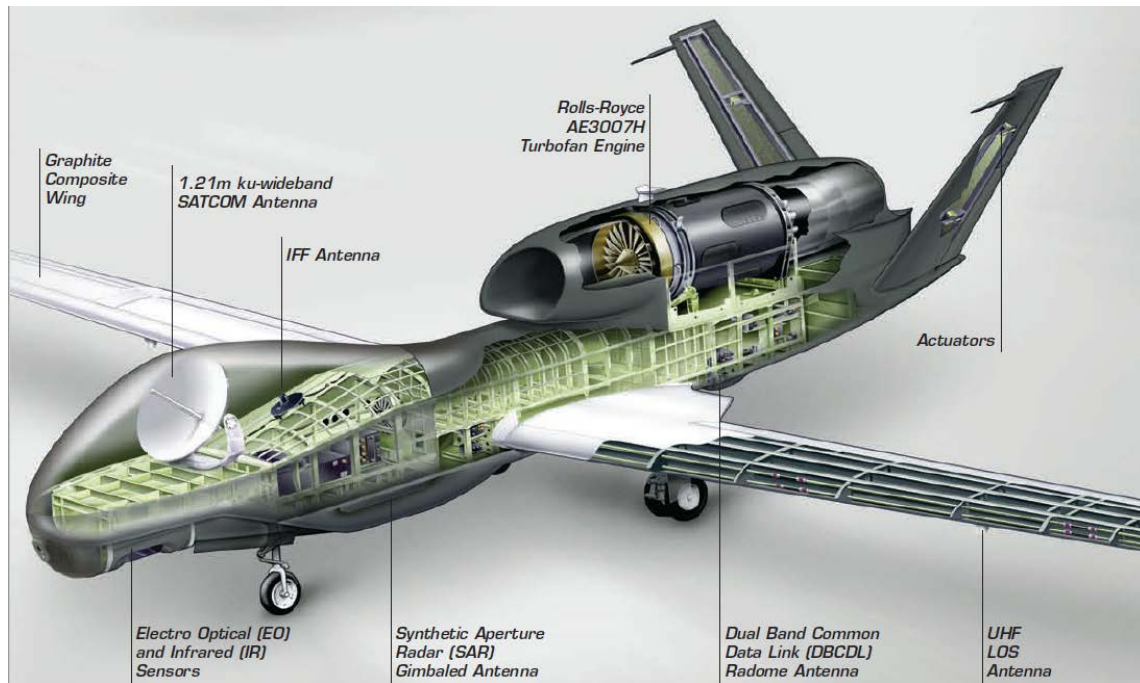


Figure 17. Global Hawk System Components

The NASA YRQ-4A mission of Reference 28 provides a good case study for communications in the ETM environment. There are two main modes¹² of communication for the YRQ-4A, an aircraft Command and Control (C²) mode and an ATC mode. Both modes will be described here.

Command and Control (C²) Communications of the YRQ-4A

C2 communications are for the purposes of controlling the aircraft and receiving information regarding location and condition of the aircraft. Communication is divided into two scenarios (Refer to Figure 18): Line-of-Sight (LOS) and Beyond-Line-of Site (BLOS). These have to do with whether or not the aircraft is within LOS of the pilot's location at the Global Hawk Operations Center (GHOC). When the aircraft is within LOS of the GHOC, the standard Air Force RQ-4A UHF system is used for communication between the GHOC and the aircraft. For the BLOS scenario, either Inmarsat or Iridium is used. In the case of Inmarsat, the C² signals go over phone lines from the GHOC to a ground station, to the satellite, and then to the aircraft. In the case of Iridium, the GHOC has its own terminal which communicates with the satellite directly.

¹² There is actually a third mode, the Research/Science Data Communication mode, but for the purposes of this paper, it is thought unnecessary to describe.

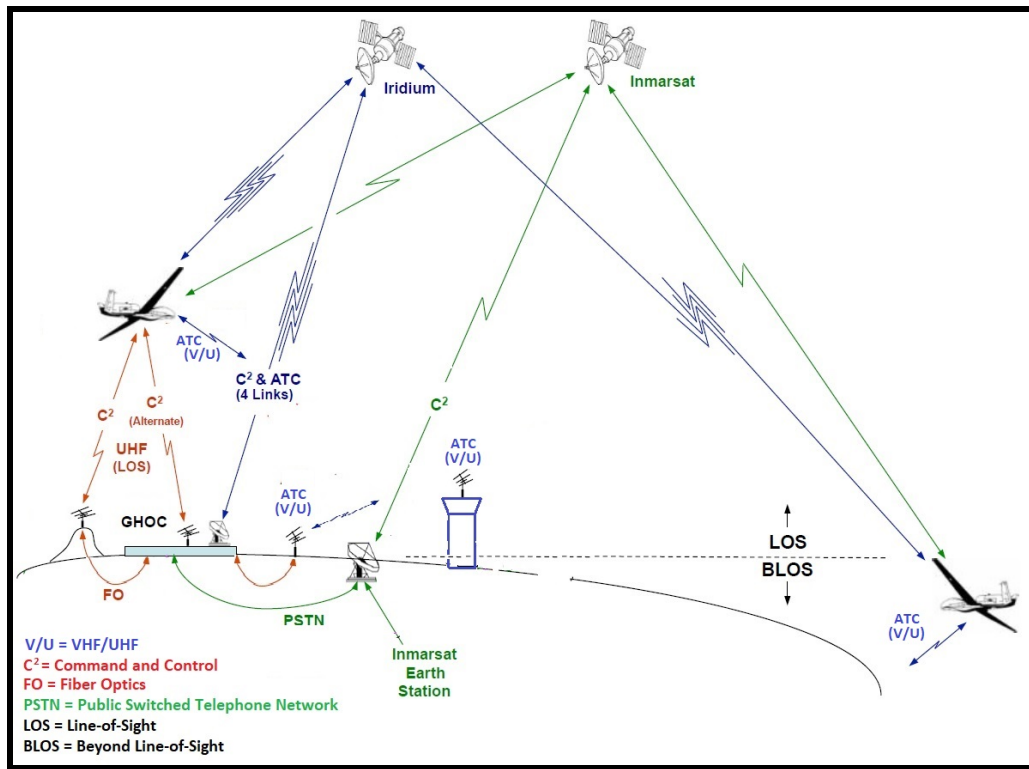


Figure 18. YRQ-4A C² and ATC Communications

ATC Communications of the YRQ-4A

For voice communications between the pilot and ATC, whether the aircraft is at LOS or BLOS of the GHOC, voice communication can be done by a GHOC-to-aircraft-to-ATC relay. The leg from GHOC to the aircraft uses the Iridium satellite system. The leg from the aircraft to ATC uses a standard VHF/UHF transceiver on the aircraft. An alternate method of communication is from the GHOC to ATC via a ground-to-ground VHF/UHF connection. The GHOC ground radio in this case needs to be within LOS of the ATC antenna. The third method of pilot to ATC communication is via phone lines. On the mission of Reference 28, ATC stipulated that “the use of land-line and/or cellular telephones is prohibited as the primary means for in-flight communication with ATC.”

This case study suggests Inmarsat and Iridium can be used for Data Link in the ETM. The case study does not necessarily mean that Iridium and VHF/UHF Air to Ground can be used for voice, but it is possible. (It is unknown whether the pilots had to go to the ground GHOC-to-ATC method when the aircraft went over 60,000 ft.) Theoretically, however, it is likely that both Iridium and UHF/VHF were used for voice in the ETM environment.

4.2 Commercially Operated HALE Vehicle

A second vehicle that routinely operates in lower ETM airspace was examined. For proprietary reasons, the operator and exact vehicle type are not revealed. This aircraft is capable of achieving altitudes up to 70,000 ft msl.

Engineering representatives from the operator were interviewed and provided detailed information on the communication system. Iridium and Inmarsat connections are employed to send commands to a vehicle, as well as downlink position, altitude, and sensor data from the aircraft. Multiple mechanisms are employed to enable operator communication with air navigation service providers (ANSPs). These capabilities include telephone notification of operations, email exchanges for advance notice (to a lesser extent), voice over internet protocol (VoIP), faxing mission sheets, and WhatsApp communication in some instances. Vehicles are also equipped with Automatic Dependent Surveillance – Broadcast (ADS-B), enabling surveillance of the aircraft.

Publicly available information indicates that data downlinks are sent to an operations control center and feed decentralized, cloud-based automation. This provides automated reports on the ETM vehicles and supports a real-time tracking website. There are also indications that these vehicles support ground-to-vehicle and vehicle-to-vehicle communication to enable networking capabilities.

This case study may have implications for future ETM operations. The operator-to-ANSP communication mechanisms could just as easily support operator-to-operator exchanges. Additionally, the onboard ADS-B transmitters could be employed to enable detect and avoid (DAA) capabilities in some instances (e.g., manned aircraft maneuvering around UAS).

5 Performance Based Communication

An ATM paradigm for RCP may serve as a baseline for future ETM requirements. Per [16], an RCP specification represents operational parameters for a complete communication transaction. It is identified by a designator (e.g., RCP 240 or RCP 400) in order to simplify the naming convention and to make the RCP Expiration Time (ET) readily apparent to airspace planners, aircraft manufacturers, and operators. The designator represents the value for the communication ET, in seconds, after which the initiator is required to revert to an alternative procedure. The RCP specifications are applied to achieve the performance required of the communication process and may support aircraft separation minima.

RCP parameters are defined as follows:

RCP Transaction Time. An RCP parameter that specifies the maximum time, in seconds, for the completion of a proportion of operational communication transactions after which the initiator should revert to an alternative procedure. Two values are specified.

RCP Transaction Time (TT). The maximum nominal time within which 95 percent of operational communication transactions is required to be completed; and

RCP Expiration Time (ET). The maximum time for the completion of the operational communication transaction, after which the initiator is required to revert to an alternative procedure.

RCP Continuity (RCP C). The minimum proportion of operational communication transactions to be completed within the specified RCP transaction time, given the service was available at the start of the transaction.

RCP Availability (RCP A). The required probability that an operational communication transaction can be initiated.

RCP Integrity (RCP I). The required probability that an operational communication transaction is completed with no undetected errors. While RCP I is defined in terms of the “goodness” of the communications capability, it is specified in terms of likelihood of occurrence of malfunction on a per flight hour basis (e.g., 10^{-5}), consistent with RNAV/RNP specifications.

In Figure 19, Actual Communications Performance (ACP), the combined uplink and downlink performance of ground systems, communication service, and aircraft systems is the Actual Communication Technical Performance (ACTP). Pilots and controllers should respond as soon as possible as part of the overall human performance. Human performance combined with ACTP results in ACP. ACP is an indicator of the operational performance of a communication system which includes the human and technical components. Human performance considers such factors as training, procedures, and human-machine interface (HMI). Technical performance comprises the installed elements of communication performance operating together to meet the intended function. ACP is assessed in the same terms and parameters as an RCP specification, its allocations, and other relevant operational criteria provided by an RCP specification. Operationally, an appropriate level of communication performance is required for aircraft systems, communications networks, and ground systems.

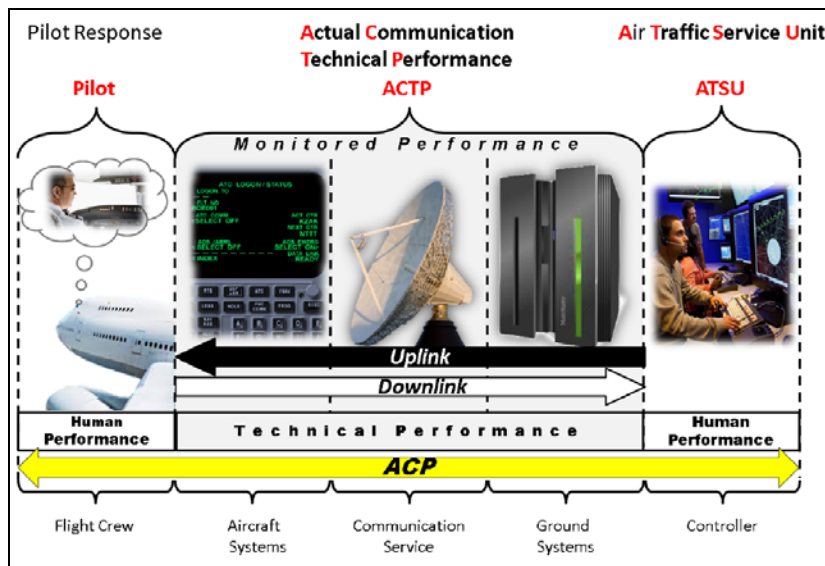


Figure 19. Actual Communications Performance (ACP) [16]

As illustrated in Figure 20, which shows the tolerances for RCP 240, the controller sends a data link communication message through the ATSU via the CSP to the aircraft. The Required Communication Technical Performance (RCTP) is the overall time for the communication to travel from the ATSU to the flight deck and return excluding human response time. RCTP should be less than or equal to 150 seconds for 99.9 percent of the operational time (ET) and must be less than or equal to 120 seconds for 95 percent of the nominal time (TT). The message arrives at the flight deck and the pilot should respond as soon as possible (i.e., ROGER (DM3)/WILCO (DM0), UNABLE (DM1), or STANDBY (DM2)). The pilot responds to the message back to the ATSU.

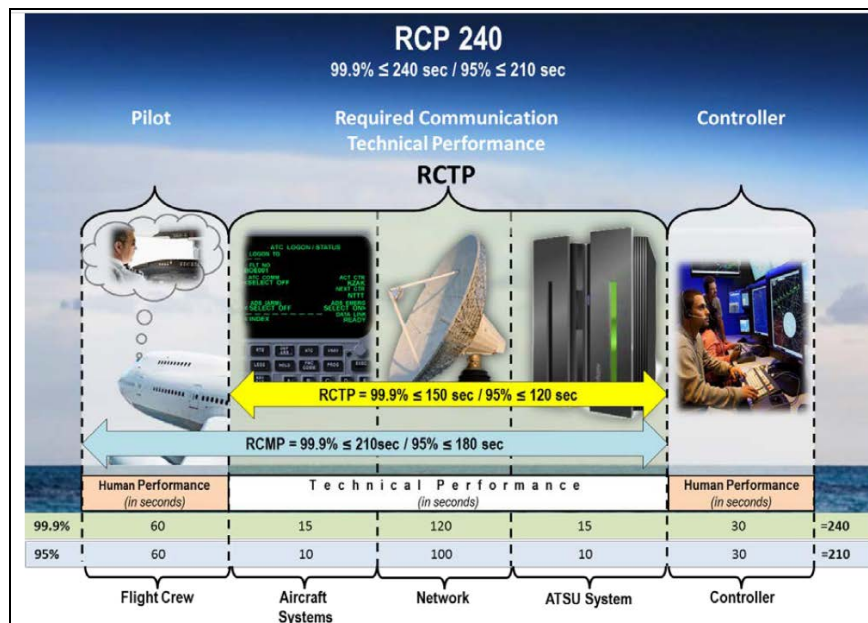


Figure 20. RCP 240 Illustration [12]

Note that RCP is not used for Data Link over the domestic U.S., only in the oceanic and remote continental environments (Reference 16, Table C-1). Also, there exists an ICAO RCP specification for voice communications, RCP 400 [29]. As mentioned earlier, SATVOICE using Iridium and Inmarsat meets this specification [26]. Reportedly, however, this specification is only acceptable in the oceanic environment and would not be acceptable for pilot-to-ATC communications in the domestic U.S. environment. Reportedly, much more work would be needed to determine a good voice RCP specification for use in the the domestic U.S. [31].

6 Emerging Communication Systems in the ETM Environment

A comprehensive report was completed for NASA in August 2015 by Rockwell Collins.¹³ This report, “Identification and Analysis of Future Aeronautical Communications Candidates: A Study of Concepts and Technologies to Support the Aeronautical Communications Needs in the NextGen and Beyond National Airspace System [32],” provides a good reference to examine future potential ETM communication technologies, even though it focused on existing and future ATM communication technologies. The time horizon of the report was to 2060. The report methodology was as follows:

- Characterize existing and emerging ATM technologies
- Identify relevant trends and technologies
- Identify potentially suitable spectrum
- Identify potentially feasible A-A and A-G NAS Comm candidates, using screening criteria

Twelve Air-to-Air (A/A) and nineteen Air-to-Ground (A/G) communications candidates were identified in the report (refer to Table 3). The A/A candidates consisted of line-of-sight (LOS) candidates including VHF, UHF, L-band, S-band, C-band, X-band, optical, and hybrid RF/optical as well as one hop routing through future SATCOM¹⁴ systems that include satellites in Geosynchronous (GEO) as well as in Low, Medium, or High Earth Orbits (referred to as LEO, MEO, and HEO, respectively).¹⁵ The A/G candidates consisted of LOS candidates from VHF to optical and beyond line-of-sight candidates that included HF, SATCOM, and long range A/G communications enabled by A/A LOS communications hopping to one or more intermediate aircraft. Note that the hopping candidates are not expected to become a primary mode of long-range A/G communications, but they may

¹³ Rockwell Collins was one of three researching entities performing a study for NASA on the future communications subject. The NASA project, “Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange” also involved Honeywell International, Inc. and Xcelar [33].

¹⁴ SATCOM here could be voice or data communications.

¹⁵ Iridium is considered LEO SATCOM, and INMARSAT is considered GEO SATCOM.

provide a backup means of communicating with aircraft in oceanic, remote, and polar airspace when the primary means of communications (likely SATCOM) is not available.

	Current NAS Comm.	Future NAS Communications Candidates	
Air-to-Air (A-A)	VHF: 122-123 MHz (CTAF) L-Band (Used for TCAS, ADS-B is Emerging on 1090 MHz and 978 MHz)	VHF UHF L Band C and X Bands Optical & Hybrid RF/Optical SATCOM (A-A One Hop Routed Through Satellite)	A-A Air-to-Air (A-A) Communications Candidates 1 VHF A-A 2 UHF A-A 3 L-Band A-A 4 S-Band A-A 5 C-Band A-A 6 X-Band A-A 7 Optical A-A 8 Hybrid RF/Optical A-A 9 LEO SATCOM A-A (One Hop through Satellite) 10 GEO SATCOM A-A (One Hop through Satellite) 11 MEO SATCOM A-A (One Hop through Satellite) 12 GEO + HEO SATCOM A-A (One Hop through Sat.)
	HF: ~3-30 MHz VHF: 118-137 MHz (VHF Data Broadcast for LAAS is just emerging in 112 – 118 MHz) L-Band (ATCRBS Transponder, FIS-B, ADS-B is Emerging) SATCOM <i>Note: "Air-to-Ground (A-G)" communications category also includes Ground-to-Air communications.</i>	HF VHF: 108-137 MHz UHF L Band C and X Bands Optical & Hybrid RF/Optical SATCOM Terrestrial K to W Band A-G Com. Via A-A Hopping	A-G Air-to-Ground (A-G) Communication Candidates 1 HF A-G 2 VHF A-G 3 UHF A-G 4 L-Band A-G 5 S-Band A-G 6 C-Band A-G 7 Optical A-G 8 Hybrid RF/Optical A-G 9 Terrestrial K to W Band Network (e.g., Ku Band QualComm+) 10 DTV VHF/UHF Network 11 Cellular Network (e.g., Aircell) 12 LEO SATCOM Network (e.g., Iridium Next+) 13 GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+) 14 MEO SATCOM Network (e.g. GlobalStar+) 15 VHF A-A Hopping for long range A-G Com. 16 UHF A-A Hopping for long range A-G Com. 17 L-Band A-A Hopping for long range A-G Com. 18 X-Band A-G 19 GEO + HEO SATCOM Network

Table 3. Future Technology Candidates Identified in NASA/RC Report [32]

In the NASA report, twenty five (25) evaluation criteria were identified for the purposes of evaluating and prioritizing the communication candidates to meet the long-term NAS communication needs. The criteria are traceable to the necessary elements of future aeronautical communications systems as articulated in various documents developed by the FAA, NASA, Eurocontrol, and ICAO, including RCP criteria. The set of evaluation criteria encompass a broad range of factors that can be grouped into three categories: technical performance, cost, and risk.

Table 4 gives the resultant rankings of the A/G candidates. As can be seen, the top tier candidates include VHF and SATCOM, which are both thought to be viable in the ETM environment by the current study. Furthermore, in the body of the NASA report there are notes under both the A/G and A/A analyses sections (pages 523 and 535) that state:

“Optical SATCOM may service high altitude aircraft,” and

“To support very high altitude communication services as might be needed by space vehicles (e.g., space planes), GEO SATCOM may contain a subsystem to support such high altitude users.”

It is unclear what the NASA report considers as “high altitude” and “very high altitude.” Note that in Table 3, Inmarsat is considered GEO SATCOM.

Free Space Optical and Hybrid RF/Optical Communications, according to the NASA report, are technologies that use lasers to send data between a satellite and aircraft. They have the benefits of much higher data rates and less frequency interference than Radio Frequency (RF) technologies. The disadvantages are atmospheric attenuation, and, since the beam is much narrower than with RF technologies, there are beam steering challenges. Another disadvantage of optical technologies for A/G and A/A is that it is not a mature technology. It is rated in the lowest tier of communication technologies.

Note that in the section describing Iridium (p 80), there exists the statement, “Aeronautical services are planned for altitudes up to 30 km above mean sea level and at speeds up to 2800 km/hr.” This suggests that Iridium will have (or has already) provisions for aircraft and spacecraft in the ETM and above environments.

A-G Communication Candidate Rankings					
Single Airspace Flight Domains					
Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar
1	VHF	VHF	VHF	LEO SATCOM	LEO SATCOM
2	C-Band	LEO SATCOM	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	L-Band	L-Band	GEO SATCOM	GEO + HEO SATCOM
4	LEO SATCOM	Cellular	Cellular	GEO + HEO SATCOM	HF
5	Cellular	C-Band	MEO SATCOM	HF	L-Band A-A Hopping
6	S-Band	S-Band	UHF	L-Band A-A Hopping	VHF A-A Hopping
7	UHF	UHF	S-Band	VHF A-A Hopping	UHF A-A Hopping
8	MEO SATCOM	MEO SATCOM	C-Band	UHF A-A Hopping	#N/A
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	X-Band	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	DTV VHF/ UHF	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	Terrestrial K to W	Terrestrial K to W	#N/A	#N/A
14	Hybrid RF/ Optical	Hybrid RF/ Optical	HF	#N/A	#N/A
15	Optical	Optical	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A

Shading for Combined APT, TMA, and ENR Flight Domains

Shading for Combined Oceanic/Remote & Polar Flight Domains

A-G Communication Candidate Rankings			
Multiple Airspace Flight Domains			
Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	VHF	LEO SATCOM	LEO SATCOM
2	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	GEO + HEO SATCOM	L-Band LOS & A-A Hop
4	Cellular	HF	VHF LOS & A-A Hop
5	MEO SATCOM	L-Band A-A Hopping	UHF LOS & A-A Hop
6	UHF	VHF A-A Hopping	GEO + HEO SATCOM
7	C-Band	UHF A-A Hopping	#N/A
8	S-Band	#N/A	#N/A
9	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	#N/A	#N/A
14	#N/A	#N/A	#N/A
15	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A

Figure 5 – Prioritized List of A-G Candidates by Flight Domain
Table 4. NASA/RC Report Results for Future A/G Communications Technologies in ATM Environment [32]

7 Conclusions

Operations above 60,000 ft msl are expected to increase significantly in the near future. A diverse range of vehicles is anticipated to be active in this airspace, including but not limited to: Unmanned Free Balloons, HALE aircraft (fixed wing, balloons, and airships), reintroduced supersonic passenger flights, air launched space vehicle carriers, and potentially hypersonic aircraft. The policies, infrastructure, and procedures in place for current operations may not accommodate the diversity expected in this airspace. The ETM concept addresses these shortfalls with principles drawn from ATM, UTM, and operations currently performed above 60,000 ft msl. This paper discussed existing and emerging ATM and UTM communication technologies and their applicability to aircraft in the ETM environment. The

intention of this work was to survey operational and hypothetical communication technologies. No effort was made to promote one alternative over another.

Conclusions Regarding Existing Systems

Voice Communications:

Theoretically, and as suggested by the Global Hawk, VHF/UHF Air-to-Ground (A/G) could be used at the lower elevations of the ETM environment, as is. The elevation of coverage in the ETM environment could be increased by making relatively simple changes to the antennas and radios.

Theoretically, HF could be used in the ETM environment.

Theoretically, and as suggested by Global Hawk satellite communications, SATVOICE could be used in the ETM environment, albeit with an upper limit on the speed of the aircraft.

Data Communications:

Theoretically, VDL could be used at the lower elevations of ETM environment. Since VDL is contracted out, it would be a matter of making coverage of the ETM environment a contractual requirement.

Theoretically, HFDL could be used in the ETM environment.

Theoretically, and as suggested by Global Hawk command and control communications, SATCOM could be used in the ETM environment, albeit with an upper limit on the speed of the aircraft. SATCOM has the advantage of the highest data transfer rate of the two other existing Data Communications technologies.

Before RCP can be used in the ETM environment over the domestic U.S., it would need to be approved for use in the ATM environment there.

There are activities that would be needed to enable existing systems to be used in the ETM environment over the domestic U.S. These include frequency engineering and coordination in the case of VHF/UHF A/G, new testing standards for transceivers expected to operate above 70,000 ft msl, and the acceptance of HF Voice, SATVOICE, HFDL, and SATCOM in the ATM environment over the domestic U.S.

Conclusions Regarding Emerging Systems

In a NASA study of possible future communications technologies in the ATM environment, VHF and satellite communications held the most promise for A/G. Both of these, as they presently exist, are also thought able to be used in the ETM environment by the current study. Optical communication has some promise for use in ETM in the future but would likely need much development. Optical communication uses lasers to send communications signals between satellites and aircraft.

8 Suggestions for Further Research

Results from NASA-sponsored experiments, which occurred in 2016 and 2017, may have implications for ETM communication capabilities. These experiments involved high-altitude

balloons fitted with standard VHF, Mode-S, and ADS-B transceivers and operated in the ETM environment. It is recommended that the results of those experiments be obtained.

If results from those experiments are inconclusive, experiments could be chartered with high altitude balloon companies. One such experiment would be to lift VHF/UHF, HF DL, and SATVOICE transceivers into the ETM environment and check their functionality. Mode-S, ADS-B and DME [3] transceivers could also be lifted to check their functionality.

Additionally, an existing FAA VHF/UHF ground radio station could be modified (e.g., with antenna and/or transmitting power changes) to check coverage in the ETM environment, using a balloon carrying a VHF/UHF radio.

The military and commercial space and balloon industries could be consulted further to determine current use of existing communications systems in the ETM environment (including UAS).

Any efforts to qualify SATVOICE, SATCOM and RCP for use over the domestic U.S. should be tracked. Efforts by Iridium to provide aeronautical services for altitudes up to 30 km, as asserted by [32] should also be investigated.

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10 References

1. Federal Aviation Administration, 2018, Upper Class E Traffic Management (ETM) Operational Shortfalls Analysis, Washington, D.C., U.S. Department of Transportation.
2. Eftekari, R., 2019, Preliminary Assessment of Surveillance Alternatives for Upper Class E Traffic Management (ETM), Washington, D.C., Regulus Group.
3. Markus, P., R. Eftekari, 2019, Existing Navigation Capabilities for Upper Class E Traffic Management (ETM), Washington, D.C., Regulus Group.
4. Eftekari, R., 2019, Emerging Navigation Technologies for Upper Class E Traffic Management (ETM), Washington, D.C., Regulus Group.
5. FAA Joint Order 6580.6, Remote Communications Facilities Siting Process, 12/21/10
6. FAA Joint Order 6400.1, Maintenance of Air Traffic Control Communication Services, 3/6/14

7. FAA Order 6050.32B, Spectrum Management Regulations and Procedures Manual, with Change 2, 11/12/08
8. RTCA DO-186B, Minimum Operational Performance Standards for Airborne Radio Communications Equipment, Issued 11-08-05
9. Joint Order 6400.1, Change 2, Maintenance of Air Traffic Control Communication Services, Issued 7/16/19
10. Website wiki.radioeference.com/index.php/MWARA
11. FAA Chart Supplement, Pacific, 5 Dec 2019 to 30 Jan 2020
12. FAA TSO-C169A, VHF Radio Communications Transceiver Equipment Operating Within Radio Frequency Range 117.975 To 137.000 Megahertz
13. RTCA DO-160G, Environmental Conditions and Test Procedures for Airborne Equipment
14. FAA TSO-C159d, Technical Standard Order, Avionics Supporting Next Generation Satellite Systems (NGSS), dated 7/31/18
15. FAA Website: Data Comm in Operation, dated 12/19/18
https://www.faa.gov/nextgen/how_nextgen_works/new_technology/data_comm/in_depth
16. FAA Advisory Circular AC 90-117, Data Link Communications, dated 10/3/17
17. FAA TSO-C170, High Frequency (HF) Radio Communications Transceiver Equipment Operating Within the Radio Frequency Range 1.5 to 30 Megahertz, 12/20/04
18. RTCA DO-163, Minimum Performance Standards-Airborne HF Radio Communications Transmitting and Receiving Equipment Operating Within the Radio-Frequency Range of 1.5 to 30 MHz
19. FAA TSO-C158, Aeronautical Mobile High Frequency Data Link (HFDL) Equipment
20. RTCA DO-165, Minimum Operational Performance Standards for Aeronautical Mobile High Frequency Data Link (HFDL)
21. FAA AC 20-150B, Airworthiness Approval of Satellite Voice (SATVOICE) Equipment Supporting Air Traffic Service (ATS) Communication, 12/23/14

22. RTCA DO-343A, Minimum Aviation System Performance Standard for AMS(R)S Data and Voice Communications Supporting Required Communications Performance (RCP) and Required Surveillance Performance (RSP), dated May 31st, 2017
23. RTCA DO-262C, Minimum Operational Performance Standards for Avionics Supporting Next Generation Satellite Systems (NGSS), dated May 31st, 2017
24. Coursera Course Material: Introduction to Satellite Communications, offered by the Institut Mines – Telecom, 2019
25. Swift broadband Coverage Chart from Inmarsat.com, dated February 2009
26. Satellite Voice Project Report, by the Performance Based Operations Aviation Rulemaking Committee Communications Working Group, as submitted to the FAA’s Associate Administrator for Aviation Safety, May 2018.
27. FAA AC 20-140C, Guidelines for Design Approval of Aircraft Data Link Communication Systems Supporting ATS, dated 9/28/16
28. UAV FAA Certificate of Authorization (COA), ASN 2012-WSA-78-COA, 6/26/2012
29. ICAO Doc 9869, Performance-based Communication and Surveillance Manual
30. Airman’s Information Publication (AIP), Part 3, ENR 7.1, General Procedures, Section 6, Dated 30 January 2020
31. Informal discussion with personnel from AVS-400 and AIR-600, February 2020.
32. Identification and Analysis of Future Aeronautical Communications Candidates: A Study of Concepts and Technologies to Support the Aeronautical Communications Needs in the NextGen and Beyond National Airspace System, NASA Contract NNA12AB82C, August 2015
33. NASA Report, A Study of Future Communications Concepts and Technologies for the National Airspace System–Part 1V,” March 7, 2015