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

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1 Abstract

Vehicles expected to operate at and above Flight Level (FL) 600 include Uncrewed Free Balloons (UFBs), High Altitude Long Endurance (HALE) Uncrewed Aircraft Systems (UAS), as well as reintroduced Supersonic Transports (SSTs). Upper Class E Traffic Management (ETM) is the system envisioned to support these operations. This paper discusses several existing voice and data communication technologies. Voice communication capabilities include Very High Frequency (VHF), Ultra High Frequency (UHF), High Frequency (HF), and Satellite Voice (SATVOICE) systems. Data communication technologies include VHF Data Link (VDL), HF Data Link (HFDL), and satellite-based systems. These technologies were assessed in terms of general advantages, disadvantages, and current level of support for ETM.

Two case studies illustrate communication mechanisms that have been operationally validated above FL600: the National Aeronautics and Space Administration (NASA) variant of the Global Hawk UAS, and a former commercially operated HALE telecommunications balloon.

2 Introduction

Activity above 60,000 feet (ft) is expected to increase. Anticipated vehicles include UFBs, HALE balloons, HALE fixed-wing aircraft, HALE airships, and SSTs [1]. UFBs with short mission durations may operate up to altitudes of 160,000 ft. HALE balloons could potentially operate up to 100,000 ft with extended mission durations. Solar-powered, HALE fixed-wing aircraft are expected to loiter between FL600 and FL900 for several months. HALE airships, currently capable of operating up to 60,000 ft, are also expected to be active in this airspace. Reintroduced SSTs are expected to initially cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between FL500 and FL600. Subsequent generations of supersonic aircraft may be capable of even greater speeds at greater altitudes. Hypersonic aircraft, while still mostly in the concept phase, should also be considered as potential entrants. Additionally, carrier aircraft for air-launched space vehicles and stratospheric "space" tourism balloons with passengers are potential candidates. Figure 1 depicts (clockwise from left) renderings of a HALE telecommunications balloon, a HALE fixed-wing aircraft, and an SST.

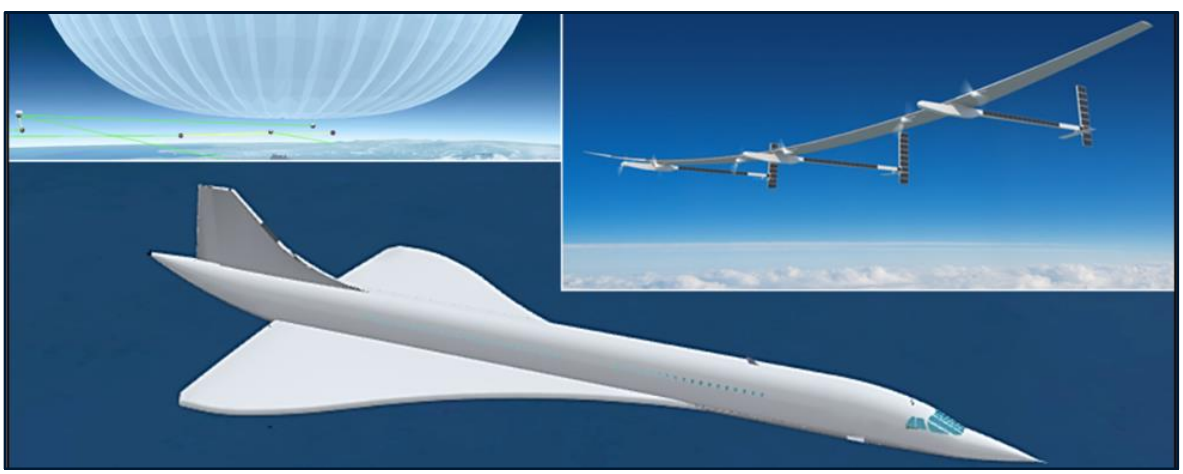

Figure 1: High-Altitude Vehicles

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

Parallel work examined surveillance and navigation technologies in the ETM context [2][3]. This document assesses multiple communication technologies. Crewed aircraft in the traditional ATM environment have historically relied upon VHF and UHF voice communication in domestic United States (U.S.) airspace. In oceanic airspace, HF and SATVOICE communication are preferred capabilities. Data communication is increasingly used and, similarly, is comprised of VHF, HF, and satellite variants. These capabilities were assessed in terms of general advantages, disadvantages, and current level of support for ETM operations.

Two UAS capable of operating above FL600 were examined in detail to illustrate operationally validated capabilities. One vehicle is the fixed-wing Global Hawk UAS operated by the U.S. military and NASA. The other vehicle is a HALE telecommunications balloon, a former commercially operated aircraft.

3 Communication Technologies

3.1 Voice Communication

3.1.1 Very High Frequency (VHF)/Ultra High Frequency (UHF) A/G Systems

Systems used for traditional ATM voice communications in the U.S. are known as Air-to-Ground (A/G) systems. These enable two-way voice communication between a pilot and ground-based Air Traffic Control (ATC) and Flight Service Station (FSS) specialists. Voice communications between these entities are 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 pilots 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. On the ground, receivers and transmitters are usually contained in different boxes, in facilities known as Remote Communications Facilities (RCFs), owned and maintained by the Federal Aviation Administration (FAA). Figure 2 shows the different types of RCFs (around the periphery) and their possible connections to ATC facilities (in the middle) [4].

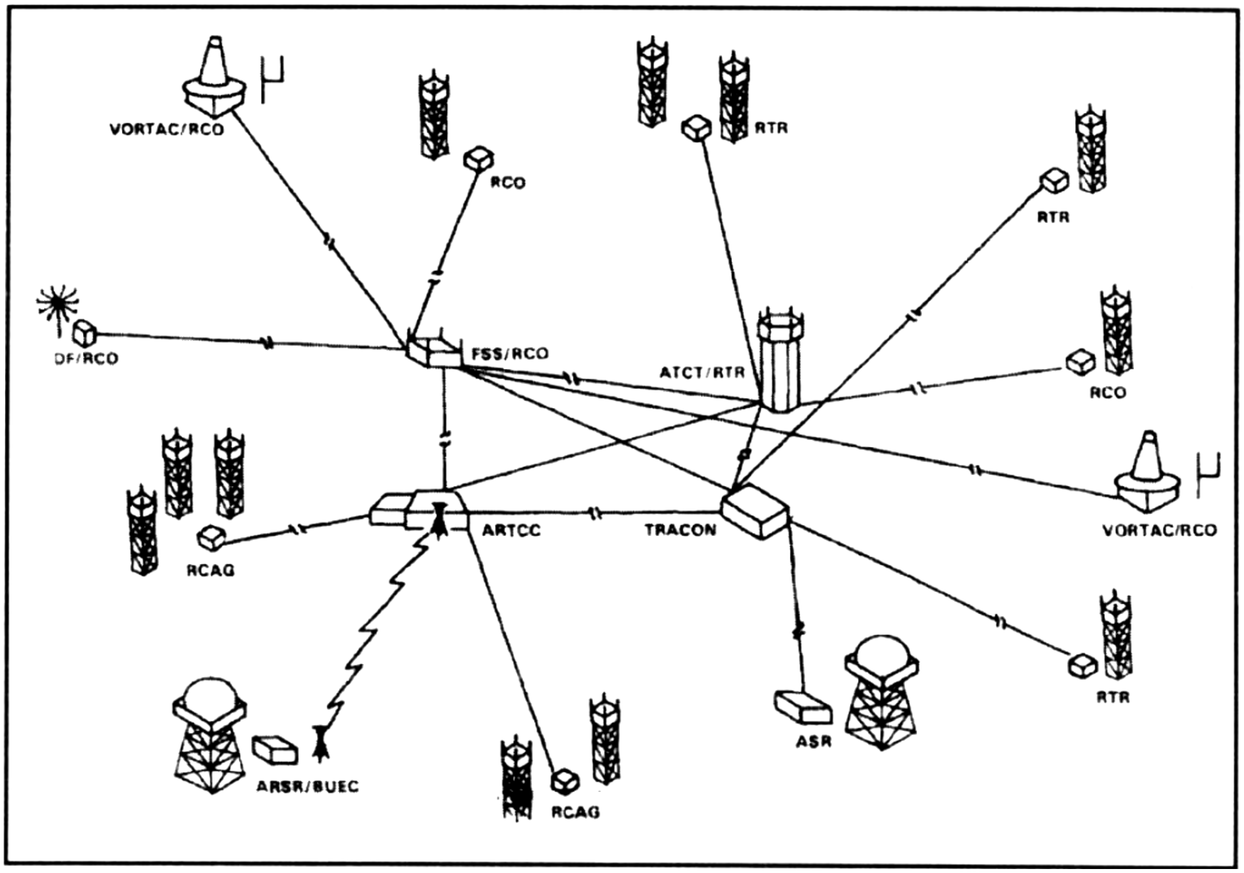

Figure 2: Relationships Between ATC Facilities and RCFs [4]

The lists below describe these facilities and the services they provide.

- **ATC Facilities**
  - **Air Route Traffic Control Center (ARTCC)** – An ATC facility that mainly provides pilots with en route radar services (between terminals).
  - **Air Traffic Control Tower (ATCT)** – An ATC facility that provides pilots with (mainly) guidance and clearance services on and near major airports. Occasionally they provide radar services.
  - **Flight Service Station (FSS)** – An ATC facility that provides pilots with flight services (weather and flight planning information).
  - **Terminal Radar Approach Control (TRACON)** – An ATC facility that mainly provides pilots with terminal radar services (typically within 50 Nautical Miles (NM) of an airport).
- **Remote Communications Facilities (RCFs)**
  - **Remote Center A/G (RCAG) Facility** – An RCF that provides remote transmitting and receiving capability for ARTCC en route communications.

- **Remote Communications Outlet (RCO)** – RCOs provide remote transmitting and receiving capabilities for flight services.
- **Remote Transmitter/Receiver (RTR)** – RTRs provide remote transmitting and receiving capabilities for terminal services. They are typically connected to the ATCTs and TRACONs.
- **Backup Emergency Communication (BUEC) Facility** – This system provides backup emergency en route channels by using remote VHF and UHF transmitter/receiver pairs. It is similar to an RCAG but provides main-only equipment supporting each en route sector (portion of airspace).

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

As shown in Figure 2, RCFs are connected to ATC facilities (typically by landlines or microwave links). Also shown, RCFs can be co-located 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 with an antenna indicated, co-located with an Airport Surveillance Radar (ASR). Figure 4 shows an example of an airborne transceiver.

Figure 3: RTR Co-Located with ASR

Figure 4: Aircraft Instrument Panel with VHF Communications Transceiver

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 [5]. Each specific function has its own Frequency Protected Service Volume (FPSV). Some are cylinders, while others are polyhedrons. Polyhedrons 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 NM, usually centered on an RCF, with the maximum altitude of the cylinder defined in feet (Figure 5). These parameters are defined for 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 the whole TSV [5]. A typical TSV is shown in Figure 5.

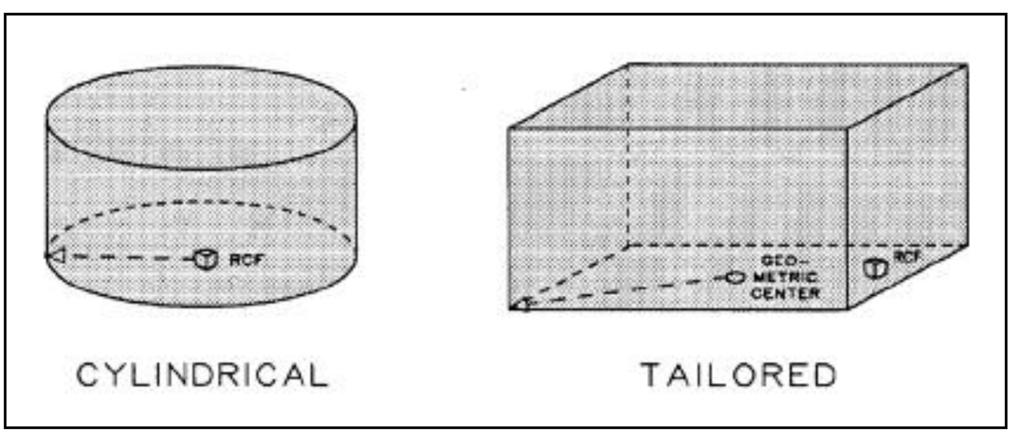

Figure 5: Illustration of FPSV for RCFs [5]

Sufficient signal must be provided at an aircraft receiver to ensure satisfactory performance at a point in the FPSV furthest from the ground transmitter [5]. Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standards (MOPS) specify that the input to the aircraft receiver should be -87 decibels (dB) referenced to one milliwatt (dBm) or greater [6]. VHF and UHF limits of coverage, for a receiver input power of -87 dBm, are shown in Figure 6 and Figure 7.

The charts shown in Figure 6 and Figure 7 depict 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 [5]. 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 [5].

For the purposes of this assessment, 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, with maximum altitudes and radii usually not exceeding the coverage values shown in Figure 8 [7].

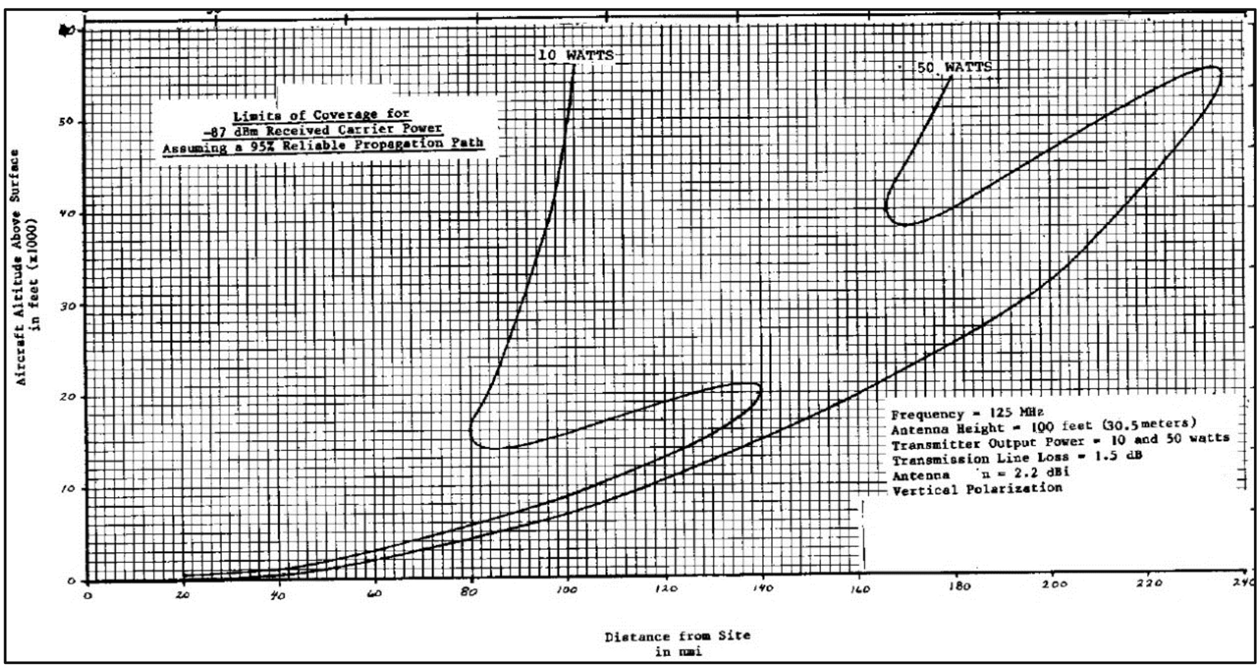

Figure 6: VHF Limits of Coverage (Antenna at 100 ft AGL) [5]

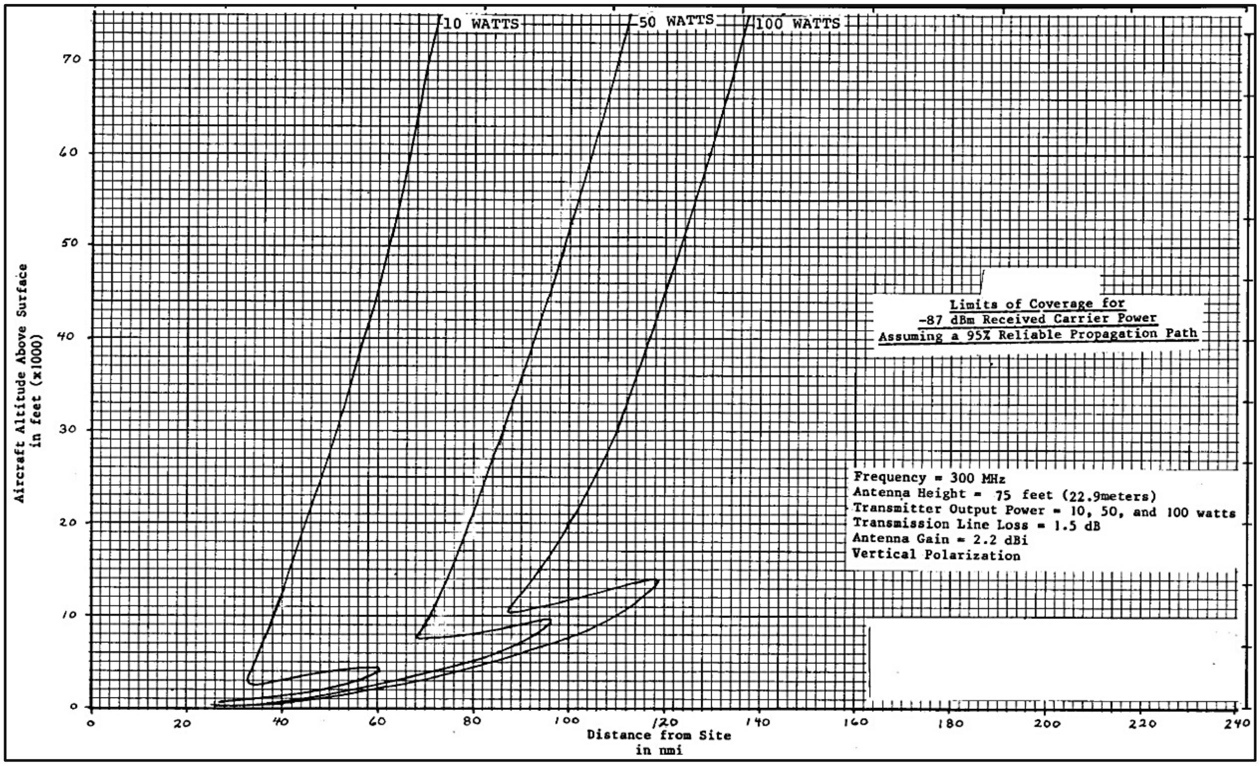

Figure 7: UHF Limits of Coverage (Antenna at 75 ft AGL) [5]

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

Figure 8: Altitudes and Radii of En Route Service Volumes [7]

3.1.1.1 VHF/UHF Advantages

VHF and UHF A/G systems have been used in traditional ATM for decades. They are the mainstay of pilot-to-ATC/FSS voice communications. Well established airborne and ground-based industry, infrastructure, and maintenance entities exist.

3.1.1.2 VHF/UHF Disadvantages

Due to VHF/UHF A/G system employment of Amplitude Modulation (AM), interference can occur. Generally, this has not been a significant problem. Interference is typically prevented and remedied by the activities of the FAA Spectrum Engineering Group through the design and use of FPSVs.

Another disadvantage of VHF/UHF A/G systems is that they require RLOS between a transmitter and the receiver to ensure coverage. Thus, they are subject to blockage by structures, foliage, and terrain. Other systems, for example HF (discussed later), can be used to increase coverage volumes by providing over-the-horizon coverage.

3.1.1.3 Current VHF/UHF Support for ETM

A civilian variant of the Global Hawk UAS had a mission planned to an altitude of 65,000 ft. 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 could be used in the ETM environment (see Section 4.1).

The limits of coverage charts shown in Figure 6 and Figure 7 also suggest that VHF/UHF A/G systems could potentially be used in upper Class E airspace. The patterns shown approach (in the case of VHF) and even exceed (UHF) 60,000 ft elevation Above Ground Level (AGL). Figure 9 shows the result of an analysis of the VHF A/G system, using an FAA propagation model of the uplink path, that further suggests that a VHF A/G system could be used up to at least 70,000 ft (AGL) with a range of 150 NM. A similar modeling of the downlink path confirmed that the standard airborne transceiver could be used at that distance and altitude. A more detailed study would be needed to quantify the actual volume of expected ETM airspace that is currently covered by VHF/UHF A/G systems. Airborne radio equipment testing standards [8] specify operating environments up to a pressure altitude of 70,000 ft, however, required performance above FL700 is not characterized. It should also be noted that because FPSVs are only specified to FL600, standards do not protect against potential interference above that altitude.

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 9: Analysis of VHF A/G System at 70,000 ft AGL

3.1.2 High Frequency (HF) A/G Systems

HF services available to support National Airspace System (NAS) A/G international requirements include Aeronautical Mobile (R)[1] and fixed services [5]. 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 Collins Aerospace (ARINC), under contract to the FAA. Aeronautical HF voice communication is not permitted over land in the U.S. when VHF communications are available, except in times of emergency [5].

HF systems use the concept of ionospheric skip in which HF signals are bent downward by the ionosphere and can, therefore, reach aircraft that are beyond RLOS (Figure 10). HF covers the frequency range from 3 to 30 MHz. It is a portion of the spectrum that has the potential for providing communications worldwide. 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 solar cycle, and the frequency itself are all determining factors. There are five identified layers of the ionosphere that are a consideration in HF radio propagation (Figure 10).

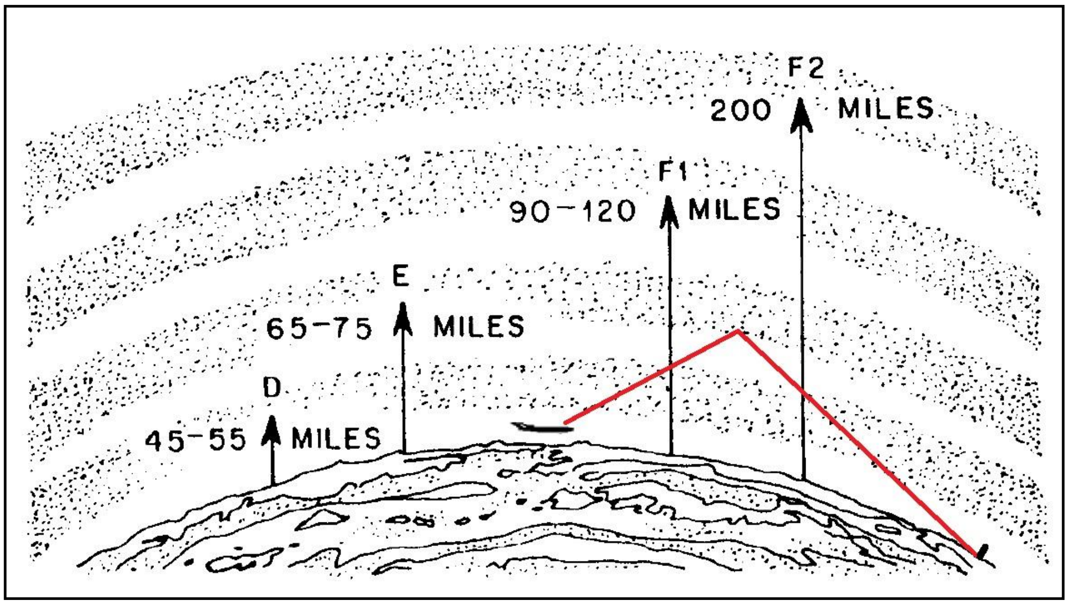

Figure 10: HF Ionospheric Skip [5]

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; Pacific zone information is shown in Figure 11. The upper elevation limit of HF coverage is undefined. Aircraft operating above FL600 should have less of a problem receiving and transmitting the skipped signal than those operating at lower altitudes since the skipped signal travels less of a distance and, therefore, is attenuated less by the atmosphere.

[1] The (R) represents that part of the radio frequency spectrum relegated to civil aeronautical services.

Figure 11: Approximate Pacific ARINC HF Station Boundaries [9]

3.1.2.1 HF Advantages

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

3.1.2.2 HF Disadvantages

The greatest disadvantage of HF is the availability of the signal. Due to the sporadic nature of the ionospheric layers, the HF signal is not always available. This is mitigated in the oceanic environment by the requirements of Code of Federal Regulations (CFR) Title 14, Part 121.351, "Communication and Navigation Equipment for Extended Over-Water Operations and for Certain Other Operations" [10]:

> "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 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."

SATVOICE can be used as a backup to HF voice in the oceanic environment, but only if HF voice is not available [11]. Additionally, as mentioned previously, HF voice communication is not permitted over land in the U.S. when VHF communications are available, except in times of emergency [5].

3.1.2.3 Current HF Support for ETM

Further research is necessary to determine whether HF systems are presently being used in upper Class E airspace. Crewed vehicles would likely be military aircraft (e.g., the U-2) or commercial spacecraft, without publicly available information. As mentioned, the availability of the HF signal would theoretically be greater in the expected ETM environment than at lower altitudes. As with VHF/UHF, airborne HF radio equipment testing standards [8] only specify operating environments up to a pressure altitude of 70,000 ft. Required performance above FL700 is not characterized.

3.1.3 Satellite Voice (SATVOICE)

SATVOICE services fall under the category of Aeronautical Mobile Satellite (R) Services (AMS(R)S). An AMS(R)S has four subsystems (shown in Figure 12): the space segment (satellites), Ground Earth Station (GES), Aircraft Earth Station (AES) (i.e., airborne terminal), and Communications Service (or Network) Provider (CSP or CNP). The CSP feeds an Air Traffic Service Unit (ATSU), such as an ARTCC.

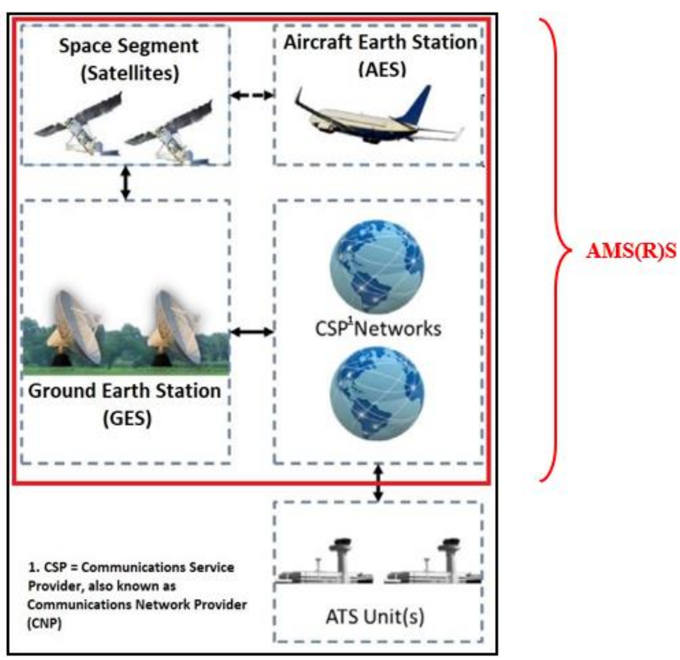

Figure 12: Subsystems of an AMS(R)S and How It Feeds an ATSU

Similar to HF voice, the FAA contracts a CSP, such as Collins Aerospace (ARINC), who, in turn, receives SATVOICE services from one of two Satellite Service Providers (SSPs), either Iridium or Inmarsat, who provides both GES and satellite constellations [12].

The Iridium satellite system is characterized by a network of 66 satellites in Low Earth Orbit (LEO) at altitudes of 781 kilometers (km) with nearly polar orbits. This provides complete global coverage (Figure 13). An uplink signal travels from a GES to a satellite. The signal can go from satellite to satellite before being sent down as an L-band signal to an aircraft. 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 Iridium communications. In Figure 13, yellow indicates coverage by one Iridium satellite, orange indicates coverage by two satellites, and red indicated coverage by three satellites.

Figure 13: Iridium Coverage [13]

The Inmarsat satellite system is characterized by four satellites in Geostationary Earth Orbit (GEO), each at an altitude of 35,786 km with equatorial orbits (Figure 14). The signal is sent up to one satellite from the GES and then resent to an aircraft. It would follow the same path for the return signal. Both the forward and reverse paths are L-band. Signal loss at the poles contributes to diminished polar coverage of the Inmarsat system [13].

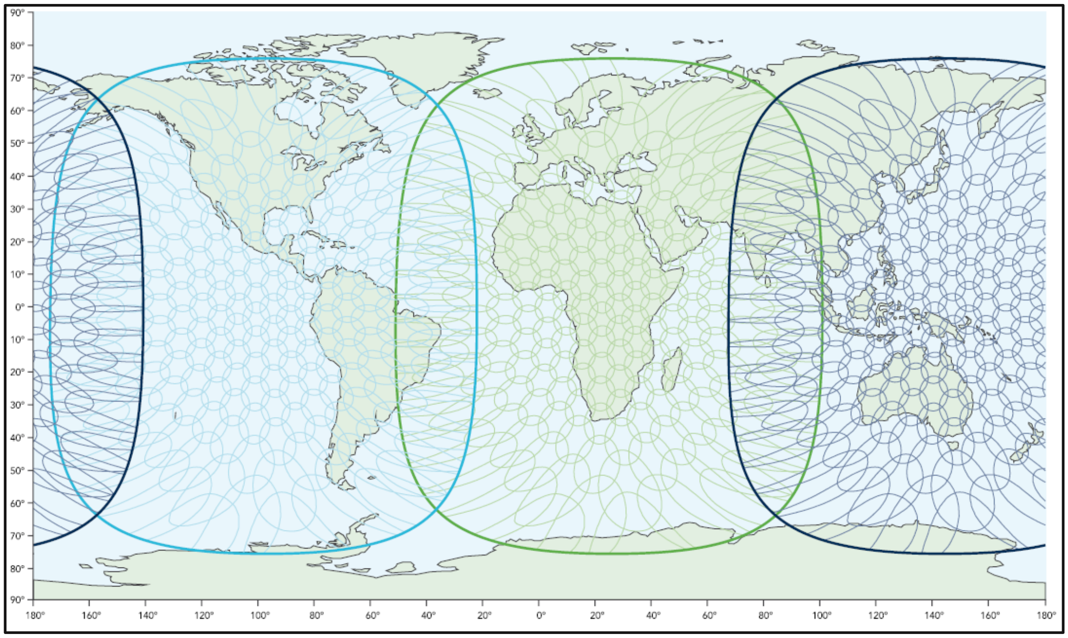

Figure 14: Inmarsat Coverage [14]

As with HF voice, there are no defined service volumes for SATVOICE. The maximum altitude would be governed by the avionics and what environment they can operate in, rather than signal availability. Signal reception to aircraft in the ETM environment is expected to be better than that in the traditional 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 SATVOICE Advantages

The biggest advantage of SATVOICE systems is that worldwide coverage is provided between available services. Additionally, signals are not as affected by ionospheric changes, as with HF voice.

3.1.3.2 SATVOICE Disadvantages

A disadvantage of SATVOICE is its latency, due to the long path lengths involved. SATVOICE is secondary to HF voice in the oceanic environment, to be used only if HF voice is not available [11]. SATVOICE is not yet approved for use over the domestic U.S., only in oceanic and remote continental airspace [15].

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 [15]. An investigation was performed and both Iridium and Inmarsat were shown to meet the existing RCP for latency of oceanic voice services (RCP 400) [16]. It is possible that SATVOICE will eventually be accepted as a sole voice communication system in the oceanic environment, but its use in the domestic U.S. environment is not forthcoming.

3.1.3.3 Current SATVOICE Support for ETM

Further investigation would be needed to determine if SATVOICE is currently used above FL600. Crewed vehicles flying there would likely be military aircraft (e.g., the U-2) or commercial spacecraft, without publicly available information. As with HF, it is possible that the availability of the signal would be greater in the ETM environment than in the traditional ATM environment. Aircraft would be at higher altitudes with smaller path distances to satellites and less signal attenuation. Airborne SATVOICE equipment testing requirements specify an environment up to 70,000 ft [8], but do not characterize performance above that altitude.

Additionally, due to shorter pathlengths between aircraft in the ETM environment and satellites, latency could potentially be reduced in contrast to the traditional ATM environment. However, the oceanic environment is not as demanding as the domestic U.S. environment for voice services. The RCP 400 standard is likely not a sufficient performance specification for use in ETM airspace above the land in the U.S.

A Global Hawk UAS mission was planned to an altitude 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 potentially be used in the ETM environment.

The maximum speed for an aircraft using Iridium SATVOICE is 800 kts [12], which equates to roughly Mach 1.4 at FL600. With Inmarsat SATVOICE, the maximum speed is one that would create a +2.5 kilohertz (kHz) doppler shift or a + 30 Hertz per second (Hz/s) rate of change in the doppler shift [12]. A 2.5 kHz doppler shift corresponds to a speed of roughly 950 kts (or Mach 1.66), in a direction toward a satellite, and depends on the exact L-band frequency. The maximum speed for Inmarsat SATVOICE would likely be greater than Mach 1.66 due to typical angles between the direction of flight and satellites. With these characteristics, it is expected that at least one SATVOICE service would likely be capable of supporting initial SST deployments, with cruise speeds up to Mach 1.7. However, subsequently deployed vehicles capable of greater speeds, including hypersonic aircraft, could encounter issues caused by doppler shift.

3.2 Data Communications (Data Link)

With data communications, ATC can send text-like instructions with route information to pilots instead of speaking over the radio. 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 an aircraft Flight Management System (FMS) (Figure 15). This process is presently being used in the airport ground environment for departure clearances and increasingly in the en route environment for rerouting and control handoff between ARTCCs.

The overarching data communications systems (also known as data link) currently in use are the Future Air Navigation System (FANS) 1/A(+), Aeronautical Telecommunications Network (ATN) Baseline 1 (B1), Baseline 2 (B2), and Aircraft Communications Addressing and Reporting System (ACARS) Air Traffic Service (ATS) [17].

Figure 15: FMS

The sub-networks (or underlying technologies) that enable these data link systems are VDL radio stations, HFDL radio stations, and satellite communication (SATCOM) systems (shown in Figure 16). CSPs provide the interconnectivity between the sub-networks and ATSUs, such as ARTCCs and ATCTs (Figure 17). A Global Navigation Satellite System (GNSS) is depicted in Figure 17 since the aircraft's position, derived from the GNSS, can also be transmitted to the ATSU through satellites via Automatic Dependent Surveillance – Contract (ADS-C).

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

Figure 16: Data Link Sub-Networks

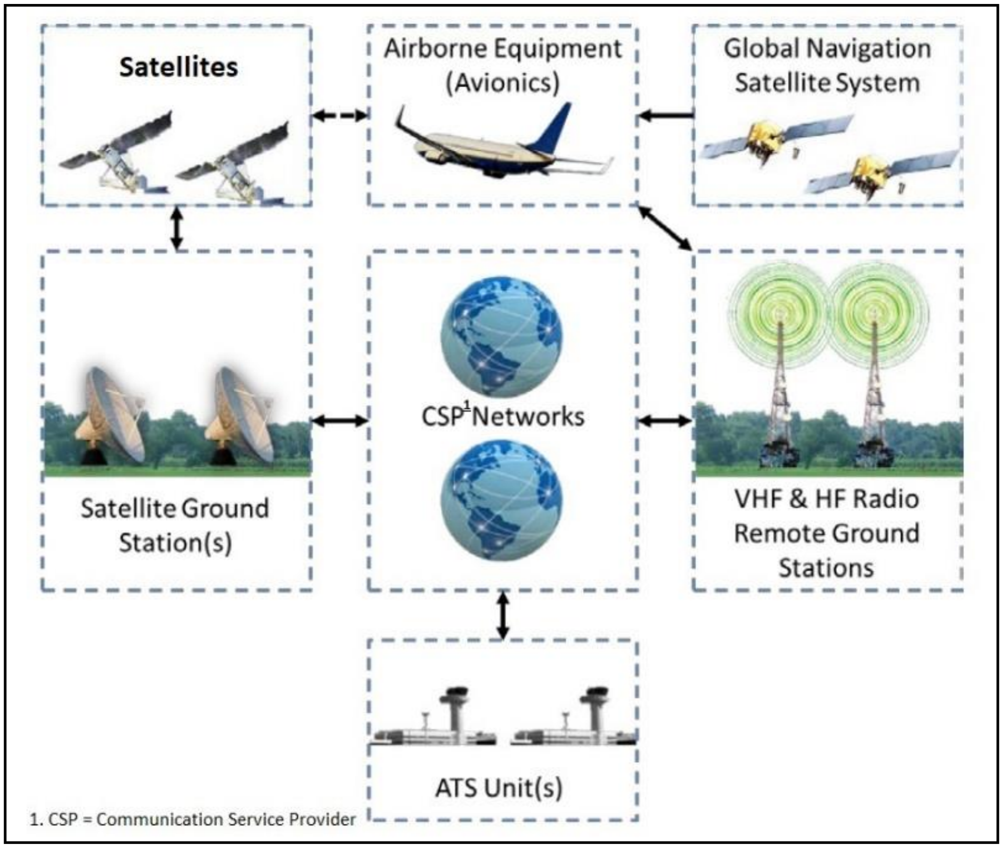

Figure 17: Data Link System Elements [17]

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 U.S.: VDL Mode 0/A and VDL Mode 2 [17]. They are both used to provide ATS data messages[2] 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) [17]. These messaging services are known collectively as Controller-Pilot Data Link Communication (CPDLC). Also, both radio systems are used by airlines for non-safety Aeronautical Operations Control (AOC) messages. L3Harris is the prime contractor to the FAA for the CPDLC service, and Collins Aerospace (ARINC) and CITA are the subcontractors providing the VDL Mode 0 and Mode 2 ground radio subnetworks. Note that VDL systems are not used for data link in the oceanic/intercontinental environment because of the necessity for ground-based facilities [17].

For each of the data link sub-networks, the reliability, maintainability, and availability performance requirements must be met, including ensuring the necessary Radio Frequency (RF) signal levels of both the ground and airborne transmitters/receivers over the "ordered service volume" [17]. The technical requirements for VDL Mode 2 are given by Technical Standard Order

[2] ATS messages are safety related messages between the ATSU and the aircraft, as opposed to AOC messages, which are lower priority, non-safety related communications, typically between the airline's control center and its aircraft.

(TSO)-C160a, “Very High Frequency (VHF) Mode 2 Communications Equipment” [18], which points to RTCA DO-281B [19] and RTCA DO-224D [20].

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.

3.2.1.1 VDL Advantages

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

3.2.1.2 VDL Disadvantages

The primary disadvantage of VDL is a lack of support for real time communications in contrast to VHF voice capabilities. VDL is not used for airborne communications in terminal environments of the domestic U.S. Additionally, VDL is only available within the RF coverage volume of the ground transmitting facility (similar to A/G voice).

3.2.1.3 Current VDL Support for ETM

Further research is necessary to determine whether VDL systems are presently being used in upper Class E airspace. Publicly available information on military and space operations is limited. However, characteristics of the typical data link in DO-224D suggest, theoretically, that there would be sufficient signal strength for VDL communications at 70,000 ft.

3.2.2 HF Data Link (HFDL)

HFDL provides another means of sending and receiving digital communications [17]. HFDL complements existing VDL and 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 by the FAA to Collins Aerospace (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, impacts caused by ionospheric disruptions are less frequent than with initial HF implementations. 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. An uplink is established enabling pilots to send data [17]. As with HF voice communications, there are no defined service volumes for HFDL radio systems.

3.2.2.1 HFDL Advantages

As with HF voice, the advantage of HFDL is a distant coverage range from the ground station. The HFDL sub-network provides communication to both ATSUs and AOC facilities in intercontinental airspace. HFDL can be used for [17]:

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.[3]

3.2.2.2 HFDL Disadvantages

A key disadvantage of HFDL is unpredictable signal reception. However, this is mitigated by the automatic searching of multiple HF channels by modern aircraft receivers. Another disadvantage of HFDL is a relatively low data rate; HFDL has the lowest data transfer rate of all current data link sub-networks. Additionally, HFDL is not approved for data link over the domestic U.S., only in oceanic and remote continental airspace [17].

3.2.2.3 Current HFDL Support for ETM

Further research is necessary to determine whether HFDL systems are presently being used above FL600. As with HF voice, the signal received at aircraft transceivers is expected to be stronger in the ETM environment than in the traditional ATM environment since the aircraft would be at a higher altitude. HFDL radio equipment could potentially operate in the ETM environment up to FL700 based on current testing criteria, however, performance above this altitude is uncharacterized.

3.2.3 Satellite Data Link (SATCOM)

SATCOM uses the same transmission mechanisms as SATVOICE. Both Inmarsat and Iridium offer SATCOM services. Inmarsat has two services: Classic Aero and Swift Broadband (SBB). Classic Aero is Inmarsat’s first-generation aviation data link service. Iridium uses the Short Burst Data (SBD) service for data link.[4] SATCOM is not presently used for data link over the domestic U.S.; it is only used in oceanic and remote continental areas [17].

Commercial and business aviation operators have been increasing connectivity to improve the passenger flying experience. Features such as texting, emailing, web browsing, and video streaming on aircraft have become more and more common. These services may share the same

[3] Note that HFDL is secondary to SATCOM, whereas HF voice is primary to SATVOICE [11].

[4] MT-SAT is another satellite technology that offers data link. It is a Japan Civil Aviation Bureau (JCAB) GEO system, meant to provide communication services to the Japanese and Asia-Pacific ATM environment. As mentioned in [11], “Neither the ARTCCs nor the RADIO facilities can contact flights logged into the MSAT.”

satellite communications system as that used for SATCOM (but are considered a lower priority) [21].

3.2.3.1 SATCOM Advantages

The biggest advantage of SATCOM systems is that worldwide coverage is provided between available services. Additionally, signals are not as affected by ionospheric changes as with HF voice. Another advantage that SATCOM provides over VDL and HFDL is a higher data transfer rate. SATCOM is primary to HF for the purpose of data link, in contrast to voice communications.

3.2.3.2 SATCOM Disadvantages

SATCOM is not yet approved for data link over the domestic U.S., only in the oceanic and remote continental airspace [17]. Additionally, latency can be a concern for SATCOM data transmissions similar to SATVOICE.

3.2.3.3 Current SATCOM Support for ETM

Publicly available information indicates that satellite data communications have been used by UAS above FL600 (described in Section 4). Aircraft velocity limits for SATCOM are the same as those for SATVOICE [12]. Due to these characteristics, it is expected that at least one SATCOM service would likely be capable of supporting initial SST deployments, with cruise speeds up to Mach 1.7. However, subsequently deployed vehicles capable of greater speeds, including hypersonic aircraft, could encounter issues caused by doppler shift.

4 UAS Case Studies

Two UAS capable of operating above FL600 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 HALE balloon that provided commercial telecommunication services.

4.1 Global Hawk

Publicly available information on the Global Hawk (Figure 18) often indicates a maximum operating altitude of 60,000 ft. However, consultation of domain subject matter experts revealed that the aircraft was routinely operated up to altitudes of 67,500 ft during testing. Additionally, publicly available information indicates that NASA planned a mission with a maximum altitude of 65,000 ft for their variant of the aircraft [22].[5]

[5] It is unknown if the mission was flown as planned, but [22] contains much detailed information including segment by segment flight maps that show seriousness of intent.

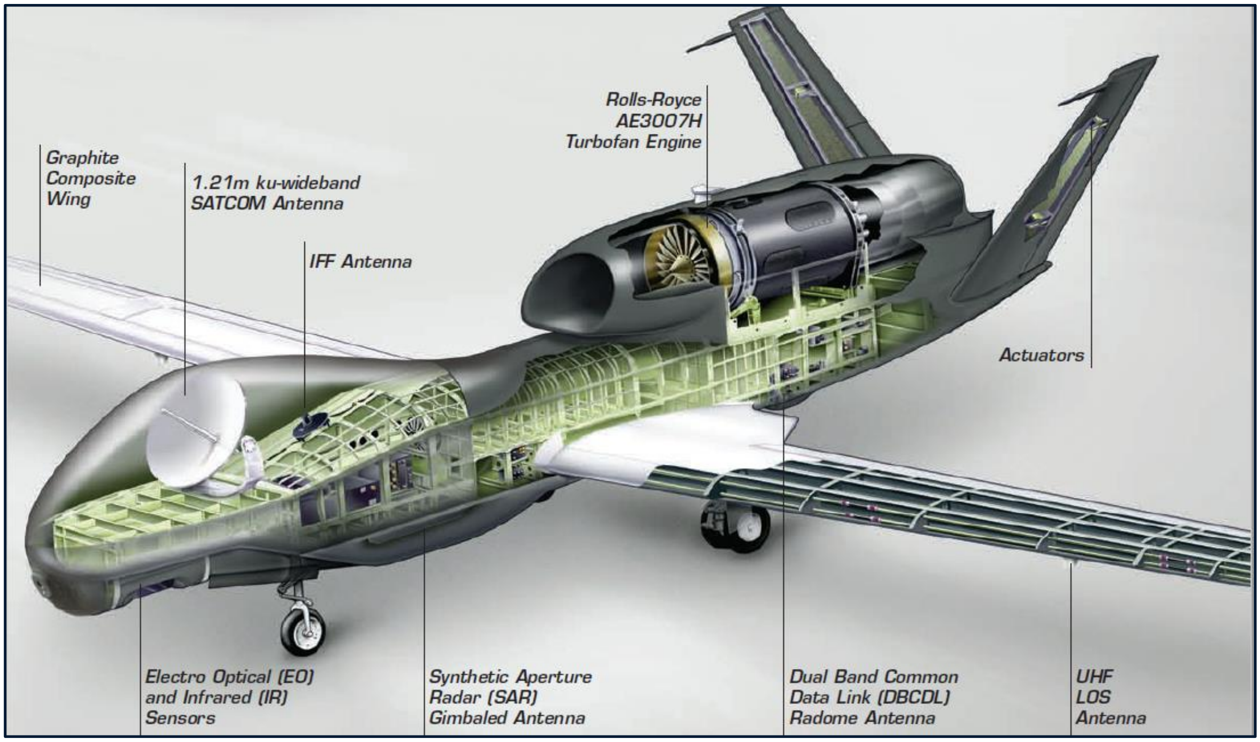

Figure 18: Global Hawk System Components

There are two main modes of communication for the Global Hawk: an aircraft Command and Control (C2) mode and an ATC mode. Communication is divided into two scenarios, as illustrated by Figure 19: Line-of-Sight (LOS) and Beyond-Line-of Site (BLOS). Note that in this context, LOS and BLOS refer to geometry of RF signal transmissions between relevant entities. When the aircraft is within LOS of the Global Hawk Operations Center (GHOC), the standard Air Force UHF system is used for communication between the GHOC and the aircraft. For the BLOS scenario, either Inmarsat or Iridium satellite communication channels are used. In the case of Inmarsat, C2 signals are sent via 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. It should be noted that Global Hawk C2 satellite links are likely provided with dedicated military channels offering superior performance over similar commercial mechanisms (e.g., significantly lower latency).

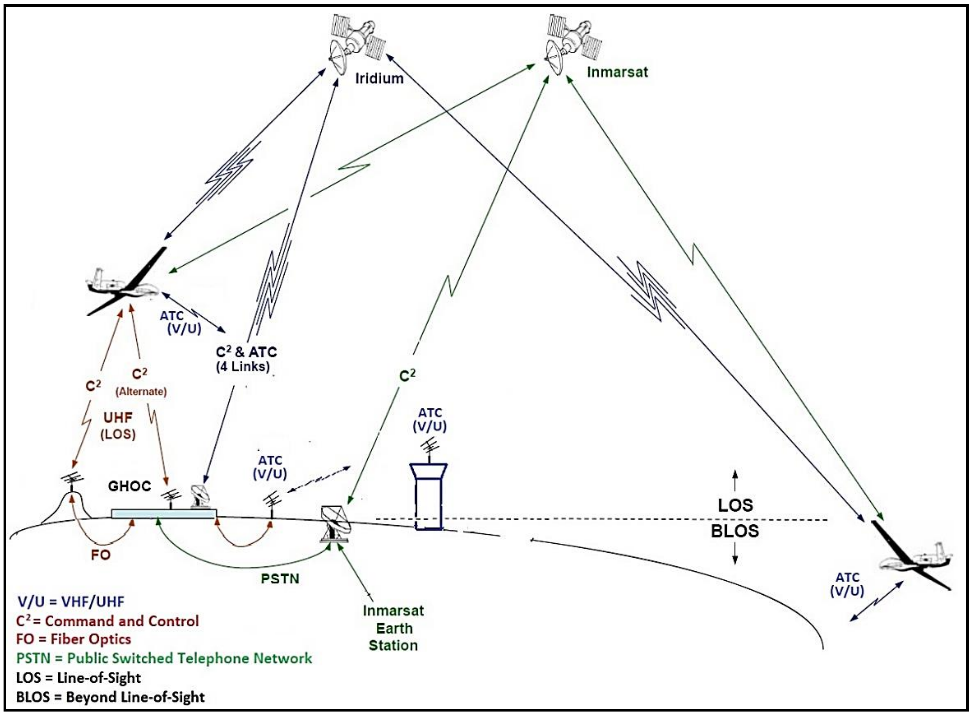

Figure 19: Global Hawk C2 and ATC Communications

For LOS or BLOS Global Hawk operations, voice communications between a Remote Pilot in Command (RPIC) and ATC can be provided by an aircraft relay. The leg from the 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 (G/G) VHF/UHF connection; the GHOC ground radio in this case needs to be within LOS of an ATC antenna. The third (backup) method of RPIC to ATC voice communication is via phone lines. For the mission described in [22], ATC stipulated that "the use of landline and/or cellular telephones is prohibited as the primary means for in-flight communication with ATC."

This case study suggests that Inmarsat and Iridium services could potentially be used for data link in the ETM environment. SATVOICE could potentially be employed with an appropriate aircraft relay (e.g., VHF/UHF converter), however, the performance of non-military satellite voice communication channels may not be sufficient to support commercial operations in the NAS. It is unknown whether Global Hawk RPICs have employed the G/G voice communication mechanism when aircraft have operated above FL600.

4.2 HALE Vehicle

A second vehicle that routinely operated at high altitudes was also examined. A commercial entity designed and operated HALE telecommunication balloons up to altitudes of 70,000 ft. Engineering representatives from the operator were interviewed and provided detailed information on the communication system. Iridium and Inmarsat connections were employed to send commands to the vehicles, as well as downlink horizontal positions, altitudes, and sensor data from the aircraft.

Multiple mechanisms were employed to enable operator communication with Air Navigation Service Providers (ANSPs). These capabilities included 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 were also equipped with Automatic Dependent Surveillance – Broadcast (ADS-B), enabling surveillance of the aircraft.

Publicly available information indicates that data downlinks were sent to an operations control center and fed decentralized, cloud-based automation. This provided automated reports on the HALE operations and supported a real-time tracking website. There are also indications that these HALE balloons employed RLOS A/G and Vehicle-to-Vehicle (V2V) communication mechanisms to enable networking capabilities.

5 Conclusions

Operations above 60,000 ft are expected to increase in the future. A diverse range of vehicles is anticipated to be active in this airspace, including but not limited to UFBs, HALE aircraft (e.g., fixed-wing, balloons, and airships), reintroduced SSTs, 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 traditional ATM, UTM, and operations currently performed above 60,000 ft. This paper discussed existing communication technologies and their applicability at and above FL600.

5.1 Voice Communications

Theoretically, as suggested by signal characteristics and Global Hawk operations, VHF/UHF A/G could be used in the lower band of expected ETM airspace (e.g., up to 70,000 ft AGL). However, because VHF/UHF FPSVs are only specified to FL600, standards do not protect against potential interference above that altitude.

HF voice could also potentially be used in the ETM environment. The availability of the HF signal would theoretically be greater in the expected ETM environment than at lower altitudes. Similarly, SATVOICE potentially offers smaller path distances between aircraft and satellites than those in the traditional ATM environment, which could provide less signal attenuation. However, both HF voice and SATVOICE are not approved for use over land in the U.S. Additionally, assessed SATVOICE services possess an upper limit on the speed of aircraft; while this is not expected to impact initial SST deployments, it could present a challenge for subsequently developed, faster SSTs, or hypersonic aircraft.

For all voice capabilities examined in this analysis, airborne radio equipment testing standards [8] only specify operating environments up to a pressure altitude of 70,000 ft. Required performance above FL700 is not characterized.

5.2 Data Communications

Based on typical signal-to-noise link margins, VDL could potentially support ETM operations up to 70,000 ft over necessary ground infrastructure. HFDL could also conceptually support ETM operations with greater coverage than VDL. As suggested by Global Hawk operations, SATCOM could also potentially be used in the ETM environment, albeit with the same speed limitations as SATVOICE. SATCOM has the advantage of the highest data transfer rate of existing data communications technologies. However, testing standards for airborne transceivers do not characterize performance above FL700. Additionally, HFDL and SATCOM are not approved for data link over the domestic U.S., only in oceanic and remote continental airspace.

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Appendix B Acronyms

All acronyms used throughout the document are provided in Table 1.

Table 1: Acronyms

Acronym	Definition
ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
AES	Aircraft Earth Station
A/G	Air-to-Ground
AGL	Above Ground Level
AM	Amplitude Modulation
AMS(R)S	Aeronautical Mobile Satellite (R) Services
ANSP	Air Navigation Service Provider
AOC	Aeronautical Operations Control
ARSR	Air Route Surveillance Radar
ARTCC	Air Route Traffic Control Center
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATCT	ATC Tower
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Service
ATSU	Air Traffic Service Unit
BLOS	Beyond-Line-of Site
BUEC	Backup Emergency Communications
C2	Command and Control
CFR	Code of Federal Regulations
CNP	Communications Network Provider
CPDLC	Controller-Pilot Data Link Communication
CSP	Communications Service Provider
CSV	Cylindrical Service Volume
dB	Decibels
dBm	Decibels Referenced to One Milliwatt

Acronym	Definition
ETM	Upper Class E Traffic Management
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FL	Flight Level
FMS	Flight Management System
FPSV	Frequency Protected Service Volume
FSS	Flight Service Station
ft	Feet
GEO	Geostationary Earth Orbit
GES	Ground Earth Station
G/G	Ground-to-Ground
GHOC	Global Hawk Operations Center
GNSS	Global Navigation Satellite System
HALE	High Altitude Long Endurance
HF	High Frequency
HFDL	High Frequency Data Link
Hz/s	Hertz per Second
kHz	Kilohertz
LEO	Low Earth Orbit
LOS	Line-of-Sight
LRCS	Long Range Communication Systems
MHz	Megahertz
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NM	Nautical Miles
RCAG	Remote Center A/G Communication
RCF	Remote Communications Facility
RCO	Remote Communications Outlet
RCP	Required Communication Performance
RF	Radio Frequency
RLOS	Radio Line of Sight
RTCA	Radio Technical Commission for Aeronautics

Acronym	Definition
RTR	Remote Transmitter/Receiver
SATCOM	Satellite Communications/Data Link
SATVOICE	Satellite Voice
SBB	Swift Broadband
SBD	Short Burst Data
SSP	Satellite Service Provider
SST	Supersonic Transport
TRACON	Terminal Radar Approach Control
TSO	Technical Standard Order
TSV	Tailored Service Volume
UAS	Uncrewed Aircraft Systems
UFB	Uncrewed Free Balloon
UHF	Ultra High Frequency
U.S.	United States
UTM	UAS Traffic Management
VDL	VHF Data Link
VHF	Very High Frequency
VoIP	Voice over Internet Protocol