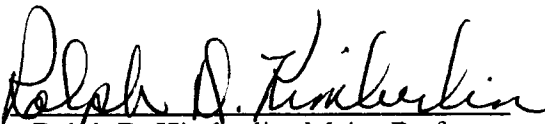


To the Graduate Council:

I am submitting herewith a thesis written by Susan Hanes Wright entitled "The Use of Satellite Communication in Civil Helicopter Operations." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.


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recommend its acceptance:

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**THE USE OF SATELLITE COMMUNICATION
IN CIVIL HELICOPTER OPERATIONS**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Susan Hanes Wright
May 1996

DEDICATION

This thesis is dedicated to my parents

Mr. Charles Wilson Wright

and

Mrs. Virginia Carol Hanes Wright

Without their love and support, I would never have
reached this point.

Acknowledgments

My experiences in the Aviation Systems program at UTSI have been greatly rewarding, thanks to the many people who have lended support and encouragement. I would like to thank Dr. Ralph Kimberlin for taking me on as a research assistant and giving me invaluable work experience. Also, many thanks go to Mrs. Betsy Harbin, who has been my dear friend and confidante from the first day; Mr. Paul Sims, who has supplied a great wealth of information on many topics of my interest; Mr. Roy Smith, who never fails to make me smile; and to Mr. Tom Bailey, whose encouragement has taught me that every idea is worthwhile. Special thanks go to Dr. Ted Paludan and Dr. John Hungerford, who, in addition to Dr. Kimberlin, have taken the time to serve on my thesis committee.

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Abstract

This thesis explores the potential use of satellite communication in helicopter operations. A satcom system is space-based and does not have the problems and limitations of current VHF, UHF, and HF communications systems. Also, the satellite network is not prone to destruction by natural disaster. Motorola and TRW Space and Defense are currently designing satcom systems that may be of interest to the helicopter industry. The FAA is also working with the industry to devise an infrastructure geared toward the unique operating characteristics of helicopters. Further research is necessary to determine helicopter operating parameters and human factors issues involved in instrument flight. With improvements in cockpit displays and computer processors, satcom with voice and data link capability will become an integral part of helicopter operations in the NAS.

Table of Contents

Chapter	Page
1. Introduction	1
2. Current Methods of Communication	3
VHF/UHF-AM	3
HF	5
VHF/UHF-FM	5
Air Traffic Control Radar Beacon System (ATCRBS)	6
LORAN Off-Shore Flight Following	7
3. Fundamentals of Satellite Communication	9
Operation	9
Types of Orbit	11
Multiple Access	13
Space-Division Multiple Access (SDMA)	14
Time-Division Multiple Access (TDMA)	14
Frequency-Division Multiple Access (FDMA)	14
Code-Division Multiple Access (CDMA)	16
Demand Assignment	16
Frequency Selection	16
Satellite Technology--Past and Present	20
Satellite Technology--Future Trends	21
4. Helicopter Characteristics	25
Operational Characteristics	25
Antenna Placement	27
5. Human Factors Issues	30
Data Link	30
6. Current and Future Infrastructure Issues	39
7. Conclusions and Recommendations	42
List of References	43
Vita	46

List of Figures

Figure	Page
1. Mobile satellite communications diagram.	10
2. Satellite Cost Trades.	12
3. Combining three channels (a) by space-division multiplexing, (b) by time-division multiplexing, and (c) frequency-division multiplexing.	15
4. Level of noise versus radio frequency.	17
5. Steerable antennas using (a) steering mechanism, and (b) phased array.	19
6. Satellite mobile communications terminal for the OmniTRACS [®] system.	23
7. Location of main flight controls.	26
8. Multiple Interface Control and Display Unit.	33
9. The left-hand control of the F-18 aircraft.	35

List of Abbreviations

ACARS	Aircraft Communications, Addressing, and Reporting System
ADF	Automatic Direction Finder
ADS	Automatic Dependent Surveillance
AEEC	Airline Electronic Engineering Committee
AM	Amplitude Modulation
ARINC	Aeronautical Radio Incorporated
ARTCC	Air Route Traffic Control Center\
ASTS	Atlanta Short Haul Transportation System
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
ATIS	Automatic Terminal Information Service
Avsat	Aviation Satellite
CDMA	Code-Division Multiple Access
Comm	Communications
DA	Demand Assignment
EFIS	Electronic Flight Instrument Systems
EIRP	Effective Isotropic Radiated Power
EMS	Emergency Medical Service
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FDMA	Frequency-Division Multiple Access
FM	Frequency Modulation
FMS	Flight Management System
GEO	Geosynchronous Orbit
GHz	Gigahertz
GPS	Global Positioning System
GRI	Group Repetition Interval
HAI	Helicopter Association International
HF	High Frequency
HPT	Handheld Personal Telephone
HUD	Head-Up Display
ICAO	International Civil Aviation Organization

IFR	Instrument Flight Rules
INMARSAT	International Maritime Satellite
INTELSAT	International Telecommunications Satellite Consortium
LEO	Low Earth Orbit
LF	Low Frequency
LOFF	LORAN Off-Shore Flight Following
LOP	Line of Position
LORAN	Long Range Navigation
MCDU	Multicontrol Display Unit
MEA	Minimum Enroute Altitude
MEO	Medium Earth Orbit
MHz	Megahertz
MOCA	Minimum Obstruction Clearance Altitude
MSL	Mean Sea Level
NAS	National Airspace System
NWS	National Weather Service
OOOI	Out/Off/On/In
R	Range
Radar	Radio detection and ranging
RF	Radio Frequency
rpm	revolutions per minute
SAS	Stability Augmentation System
Satcom	Satellite Communications
SDMA	Space-Division Multiple Access
TCAS	Traffic Collision Avoidance System
TDMA	Time-Division Multiple Access
TERPS	Terminal Instrument Procedures
UHF	Ultra High Frequency
VDT	Video Display Terminal
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Very High Frequency Omnidirectional Range
WAAS	Wide Area Augmentation System

Chapter 1

Introduction

The first practical helicopter was introduced in the 1940s during World War II. Its unique ability to hover and maneuver at low altitude and in confined areas made it useful for patrol and rescue missions. During the Korean and Vietnam conflicts from 1950 to 1975, the helicopter was used for armed observation of enemy positions and for transportation of supplies and troops to hard-to-reach areas. The helicopter was also used for combat missions in Vietnam.

The helicopter's value to the military has spilled over into the civilian world, being indispensable for emergency rescue, sightseeing, law enforcement, flights to offshore oil platforms, and many other applications. As a result, the helicopter has been described as a "go anywhere, all-terrain vehicle."¹

Regardless of their agility and multi-purpose use, helicopters represent a small portion of the total amount of air traffic in the national airspace system (NAS). According to the Helicopter Association International (HAI), there were 18,926 registered helicopters worldwide in 1990, and they flew about 58 million hours that year.² As of 1991, there were almost 4,500 helipads or helistops for public and private use, 115 of which were located at airports.² These numbers are overshadowed by the numbers of fixed-wing aircraft and airports currently in existence.

Since fixed-wing flight was perfected much sooner than rotary-wing flight, the airspace infrastructure was developed around fixed-wing operating characteristics. VHF voice radio and VOR navigation were found to be well suited for flight in the medium to high altitude range. As a result, minimum altitudes such as minimum obstruction clearance altitude (MOCA) and minimum enroute altitude (MEA) were assigned to each airspace sector in order to ensure adequate signal transmission and reception, while providing sufficient obstacle clearance.

As helicopter flight became more prevalent, helicopters were expected to adhere to the limitations imposed by the current infrastructure on fixed-wing aircraft. This has become a problem for helicopters, with their low altitude and confined area capability. Since VHF signals are blocked by rising terrain and obstructions, communication and navigation are nearly impossible without the help of a vast network of repeaters and microwave links connected by land line to controlling agencies.

The Federal Aviation Administration (FAA) has recognized the benefits of rotary wing aircraft and the fact that flight in these aircraft is seriously hindered by the current infrastructure. The FAA has awarded contracts to various agencies in an attempt to define helicopter operating parameters and subsequently develop an infrastructure that will integrate helicopter operations into the current system. One such study conducted by the University of Tennessee Space Institute entitled "Program Plan for the Development of Helicopter Terminal Area Instrument Procedures (TERPS)" identifies several problems existing in the infrastructure, and it proposes a test plan to evaluate potential solutions to these problems.³

A major problem identified in this particular study is that present modes of communication and navigation are not compatible with the helicopter's unique operating characteristics. The recent commissioning of global positioning system (GPS) has enabled point-to-point navigation in that it has made reliable navigation signals available anywhere on the earth and at any altitude. However, since both VHF and radar are limited by line-of-sight, voice communication and surveillance remain a problem for helicopter flight.

A feasible solution is the use of satellite communication. Satellites have been used to relay telephone and television signals around the world for many years. GPS also uses a network of satellites to provide elevation and position information for surveying, marine use, geodetic monitoring, and surface transportation purposes, as well as for aviation.

A global satellite communication system (hereafter referred to as "satcom") can accommodate many different users, with each user application being free of interference from the others. Due to wider available bandwidths, the satcom user capacity is much greater than that of voice radio, and like GPS, use of the system is not restricted by altitude or surface location of the user. The system is capable of transmitting information by voice or datalink, and it has the potential for much clearer and faster signal transmission. A satcom system will also be much less expensive in the long run than a terrestrial-based network.

This thesis will provide a description of the current communication methods used by helicopters. It will also explain the fundamentals of satellite communication, including basic operation, multiple access, frequency selection, and antenna requirements. The helicopter's operating principles will be discussed, and important human factors issues will be identified. An avionics system will be proposed based on helicopter operating parameters and human factors. The study will be concluded with a look at the current airspace infrastructure, political issues, and future trends, along with recommendations. It should then be obvious to the reader that the helicopter industry could conceivably become a major shareholder in a global satcom system.

Chapter 2

Current Methods of Communication

Communication may be defined as a giving or exchanging of information through speech, writing, or various other methods⁴. Since the 1930s, pilots have used radios with voice capability to transmit their locations and intentions to a ground monitoring station. As the volume of air traffic began to increase, radar appeared as a means by which air traffic control (ATC) could identify and route aircraft. Radar surveillance alone does not require voice transmissions between the pilot and ATC; however, it is still a method of communication since it involves the relay of position and altitude information from the aircraft⁵. Thus, there are two methods of communication--voice and surveillance--that are vital for the safety and sequencing of aircraft in today's NAS. Both are accomplished through the use of different types of radio waves.

VHF/UHF-AM

VHF, or very high frequency, radio waves range from 30 to 200 MHz. Amplitude-modulated (AM) VHF radio is the principal air-to-air and air-to-ground frequency band for civil aviation, including voice, navigational aids, and some radar. Since the ground wave is virtually non-existent, VHF waves propagate via skywave. The VHF skywave normally penetrates the ionosphere rather than being strongly reflected by it. VHF range is limited by line-of-sight, which restricts transmissions to destinations above the horizon. The range, R , in nautical miles, can be computed from the following formula:⁶

$$R \text{ (nmi)} = 1.23 \cdot (\sqrt{h_r} + \sqrt{h_t}) ,$$

where h_r = height (ft) above sea level of the receiver;
 h_t = height (ft) above sea level of the transmitter.

Table 1 gives maximum line-of-sight distances for various altitudes. As altitude increases, range of reception also increases. However, at high altitudes, it is possible to receive two transmissions of equal power at once. This may be remedied by reducing the spacing between channels, thereby increasing the available number of channels. Even if the number of available channels is increased, the VHF band will eventually reach a "saturation point," thereby creating delays for pilots and increasing controller workload.

Table 1. Line-of-Sight Distances for VHF Reception.
 (Source: Welch, John F., ed. Van Sickle's Modern Airmanship. 6th ed.
 Blue Ridge Summit, PA: McGraw-Hill, 1990, pp.229.)

Aircraft Altitude (feet)	Transmission Range (nm)	Aircraft Altitude (feet)	Transmission Range (nm)
100	12	4000	70
200	15	5000	80
400	25	8500	100
600	30	10000	115
800	35	12500	125
1000	40	15000	135
2000	50	17500	145
3000	65	20000	160

UHF, or ultra high frequency radio waves, have much the same characteristics as VHF. UHF band ranges from 200 to 3000 MHz and was brought about in order to relieve congestion in VHF band. UHF is used primarily by the military, and most FAA control facilities have UHF capability.

HF

HF, or high frequency, ranges from 3 to 39 MHz. HF waves are subject to ionospheric reflection and may be received as far away as 12,000 miles from the transmitter.⁷ HF reception range is dependent upon the amount of solar radiation in the ionosphere, which is influenced by time of day, season, and time of sunspot maxima.⁷ HF waves propagate by "skipping" from transmitter to receiver. Skip distance is the distance between the transmitter and the first point of return to the earth. With the earth itself being a reflector, many skips are possible, thus greatly increasing HF reception range. Unlike VHF, HF waves are not restricted by line-of-sight. This makes HF useful for long-range aircraft that may operate far away from VHF or UHF facilities. HF is also useful for helicopters flying below the horizon or in rising terrain, which is also out of VHF and UHF range.

Aside from its long range capability, HF voice signals have numerous problems. HF wave propagation is inherently unstable. If there are a great number of signal skips, the signals are subject to multipath fading, giving voice messages the tendency to fade and get lost. Like VHF, HF can also become congested with many users, thereby creating interference and delays.

VHF/UHF-FM

Most radios installed in aircraft flying in the NAS transmit and receive AM signals. While AM radios are necessary for communicating with ATC, there is a high degree of congestion due to the multiple users. Helicopter missions in the interest of public safety require discreteness and timely information transmission, with a minimum of congestion and interference. Depending on the specific mission, helicopters may also be equipped with frequency-modulated (FM) VHF and UHF transceivers. The FM radios are used for tactical communication between personnel on board the helicopter and police, firefighters, ambulance personnel, and others involved in public safety. FM signals are not susceptible to rotor modulation as are AM signals (see Chapter 4).⁸ FM is not susceptible to electrical interference from thunderstorms and precipitation. Also, there is minimal congestion on FM frequencies, since these frequencies are generally reserved for public safety operations.

However, whether amplitude- or frequency-modulated, both VHF and UHF rely upon a vast network of ground-based repeaters and microwave links to communicate with ground stations. Many ground repeaters are necessary for helicopter communication, since helicopters fly at low altitude and in confined areas that are out of normal VHF/UHF reception range. Ground-based facilities are always susceptible to some natural disaster, which could destroy them and interrupt communications indefinitely.

Air Traffic Control Radar Beacon System (ATCRBS)

In today's NAS, radar is used for aircraft separation and identification. In the beginning, primary radar was the sole means of identifying aircraft. In primary radar service, a radar beam is transmitted into a given airspace sector and then reflected from the aircraft in the area. The returns are displayed on the controller's radarscope, and no on board equipment is required by the aircraft. As the amount of air traffic began to increase, primary radar became inadequate for accurate aircraft identification.

The ATCRBS, or secondary surveillance radar, contains the following necessary equipment:

- Interrogator
- Aircraft Transponder
- Radarscope

The interrogator is a ground-based radar beacon transceiver which rotates with the primary radar antenna. It transmits radio signals that request all aircraft transponders in the area to reply. The replies from the aircraft are mixed with primary radar returns, and both are displayed on the controller's radarscope.

The transponder on board the aircraft responds to the interrogation of the ground signal. Upon initial contact, the controller asks the pilot to dial in a certain code on the transponder and "ident," which displays a distinctive return on the radarscope. This same transponder code is used to identify the aircraft as long as it is in radar contact. The transponder replies with the code only to the interrogations being received on the mode to which it is set. Many transponders are encoded with the aircraft's altitude. This feature is called Mode C and is required in Class A, B, and C airspace, and also within 30 nmi of a few selected airports upward to 10,000 feet above sea level (MSL).⁹

The radarscope displays returns from both primary radar and ATCRBS. The returns are used for the control and separation of air traffic.

The pilot initiates "flight-following" by using voice radio to contact ATC. Once radar contact is established, position reports are unnecessary, and voice radio is used only to acknowledge controller's instructions.

Radar service has numerous limitations. Like other radio waves, those used by radar may be bent by temperature inversions. This "anomalous propagation" is dependent upon whether the beam is bent downward toward the ground or upward. Downward bending may cause extraneous returns, and upward bending may decrease detection range. Radar may be attenuated and reflected by heavy clouds, precipitation, and ground obstacles. Radar energy directed toward dense objects may be reflected, thus obscuring returns from aircraft at a greater range. Like VHF, radar is limited by line-of-sight, making it difficult to track aircraft at low altitude. This makes traffic advisory service difficult, if not impossible, for aircraft flying at low altitude or below coverage of the radar beam. Adding more radar facilities to the already vast network has alleviated this problem to an extent.

LORAN Off-Shore Flight Following

LORAN, or Long Range Navigation, was originally designed by the U.S. Coast Guard to be a marine navigation system. It is a ground-based system that operates in the low frequency (LF) range at 100 kHz. LORAN signals propagate via ground wave, giving it a range of 600 to 1200 nmi.¹⁰ This makes LORAN useful as a means of navigation for long-range aircraft and helicopters alike, both over land and offshore.

LORAN determines position by measuring differences in radio signal arrival time from a master station and one or more secondary stations. The master station transmits a group of pulses, then each secondary station transmits at a specified time interval after the master station. The time differences are compared to determine the possible locations of the aircraft, called lines of position (LOP). The points where the LOPs intersect is the point of location of the aircraft. Position is presented by the receiver in latitude and longitude values, which are continually updated throughout the flight.

There are eight LORAN chains covering the continental U.S.; each chain has its own group repetition interval (GRI).⁹ The GRI is the time difference between two master signal group occurrences. Each LORAN chain is identified by its unique GRI.

Due to the curvature of the earth, radar coverage is limited to just a few miles off the U.S. coastline. LORAN Off-Shore Flight Following has proved to be a feasible alternative to radar for helicopters flying to off-shore oil rigs in the Gulf of Mexico. It is a method of automatic dependent surveillance (ADS) in which the aircraft automatically broadcasts

navigation information to ATC. In LOFF, each aircraft broadcasts its LORAN-derived position information to the Houston Air Route Traffic Control Center (ARTCC) through one of its VHF radios. The transmissions are datalinked to a remote VHF outlet, which is usually installed on an oil platform, and then sent via microwave link to shore stations. The signals travel to the ARTCC via land line.

Since LORAN uses low-frequency AM signals, thunderstorms, precipitation static, and other electrical disturbances may cause interference, which, in turn, could cause signal loss. LORAN signals travel at a constant speed over water, but due to differences in surface type and foliage, the signals travel at different speeds over land, thus affecting signal accuracy. For this reason, many LORAN receivers are certified for flight under visual flight rules (VFR) only.¹⁰

LOFF is a fairly new method of ADS, and it has a major limitation. Aircraft transmissions tend to block each other when simultaneous transmissions occur. Therefore, a method of signal time sharing must be developed. Otherwise, a backup system is necessary.

As with many of the communication methods mentioned earlier, LOFF requires a great number of ground-based stations for relaying signals. VHF repeaters on oil platforms and coastal lands are likely to be destroyed by gale force hurricane winds. Hurricanes, earthquakes, tornadoes, and floods are capable of destroying inland communications links. Such disaster could render helicopters, with their low-flying and confined area capabilities, virtually useless for disaster relief, the main mission for which these machines were designed. With current VHF, only one user is allowed to transmit on a given frequency at one time. As the number of helicopters and other aircraft entering the NAS increases, the amount of "chatter" on VHF radio will increase to the capacity limit. Once this limit is reached, it will be difficult, if not impossible, for pilots to transmit their intentions. These problems underline the need for a communications system that is usable in all weather, all terrain, and at any altitude, and is not threatened by natural disaster. The new system must also be capable of accommodating the steady increase in user population.

Chapter 3

Fundamentals of Satellite Communication

A satellite is a man-made spacecraft that orbits the earth and relays radio signals between transmitting and receiving earth stations. Communications satellites allow information in the form of telephone conversations, telegraph messages, radio programs, or television shows to travel from coast to coast, and even around the world. They can also handle very large amounts of data, and those positioned over the Atlantic Ocean can handle as many as 30,000 telephone calls at once.¹¹ A major advantage of communications satellites is that information can be received by a large number of users at the same time. Without satellites, an extensive network of wires and cables would be needed to accomplish worldwide communication.

Operation

Communications satellites are launched by rockets or carried into space by space shuttles. Small booster engines guide the satellites into their orbits and help to keep them there. Early satellites were termed "passive," meaning that they acted as signal reflecting "mirrors." Active satellites of today receive, amplify, and transmit radio signals, rather than merely reflect them. The satellite is one component of a satellite relay system. In this system, an earth station transmitter receives signals from one user (e.g., telephone, radio, or television station). The earth station transmits the signals via radio waves to the satellite transponder, which amplifies the waves and retransmits them. The transmitting antenna on the satellite aims the beam of radio waves from the transponder toward another satellite or a receiving earth station. Most satellites are equipped with more than one transponder and antenna so they can relay several sets of radio waves at once.

The transponder, as well as other electronic equipment in a communications satellite, are powered by solar panels and storage batteries. The solar panels serve to collect energy from the sun and convert it to electric power. The storage batteries supply electricity when the satellite does not receive sunlight.

Figure 1 shows the different links between earth and satellite and between satellite and helicopter. The forward link from earth to satellite and the return link from helicopter to satellite may also be called "uplinks." The return link from satellite to earth and the

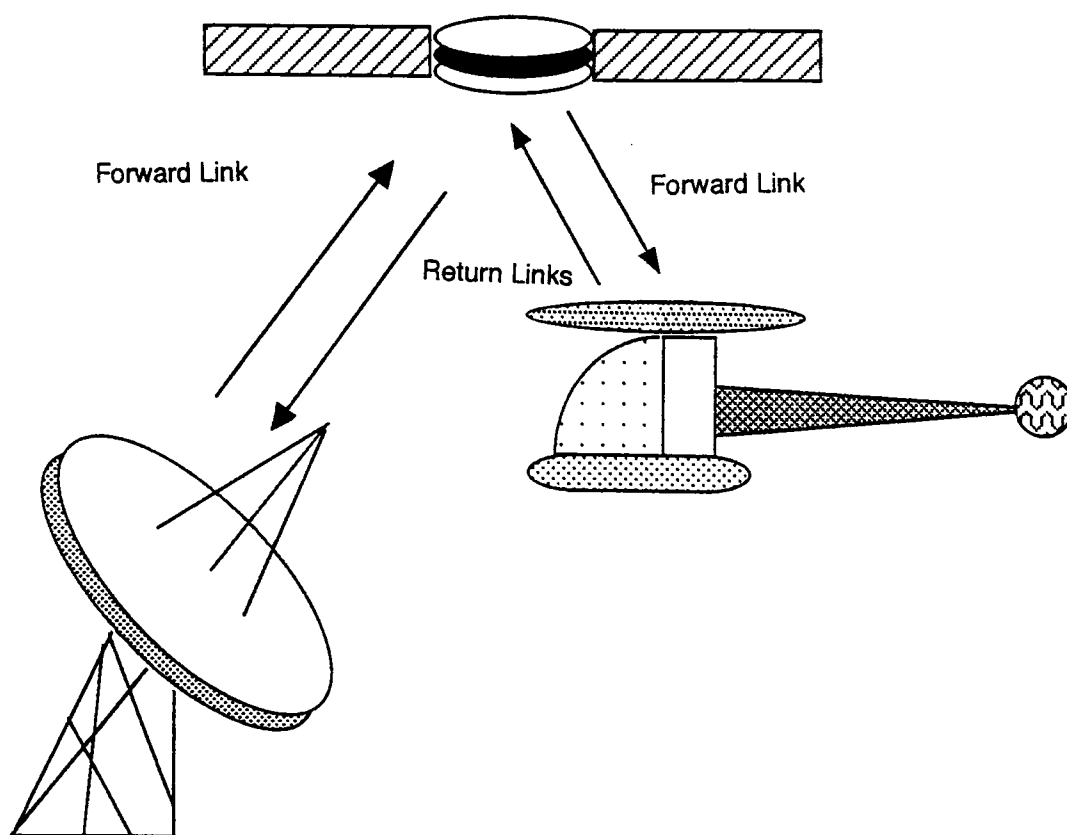


Figure 1. Mobile satellite communications diagram.

forward link from satellite to helicopter are also called "downlinks." It may be deduced that any signal traveling from the satellite is on a downlink path, while a signal traveling to the satellite is an uplink.

Types of Orbit

A satellite constellation may be placed in one of three distinct orbits, with orbit selection being a complex trade-off among the following factors:¹²

- Number of satellites and launch flexibility
- System reliability
- Spacecraft antenna size
- Spacecraft power
- Cost of each satellite and life cycle cost
- Satellite lifetime
- Terrestrial view angle/line of sight elevation angle
- Degree of earth coverage
- Effect of Van Allen belt radiation
- Handset power
- Propagation delay

Figure 2 shows a graphical comparison performed by TRW Space and Defense among two low earth orbit (LEO) systems, a medium earth orbit (MEO) system, and a geosynchronous, or geostationary, orbit (GEO) system. The information is presented as cost in millions of dollars versus orbit altitude in kilometers, while considering the number of satellites per constellation, cost per satellite, cost per launch, and total cost.

The vast majority of satellite constellations, including weather satellites, are placed in geosynchronous (GEO) orbit, about 22,300 miles (35,900 km) above the earth.¹¹ "Geosynchronous" means that the satellite circles the earth at exactly the same speed as the earth's rotation. Therefore, it appears stationary above the earth and is in range of certain earth stations at all times. In other than synchronous orbit, the satellite would pass only briefly over a specific earth station during each orbit. In order to provide worldwide coverage, at least three satellites are needed, since one satellite can cover about one-third of the earth's surface. GEO satellites have the longest life cycle of the three major orbits.

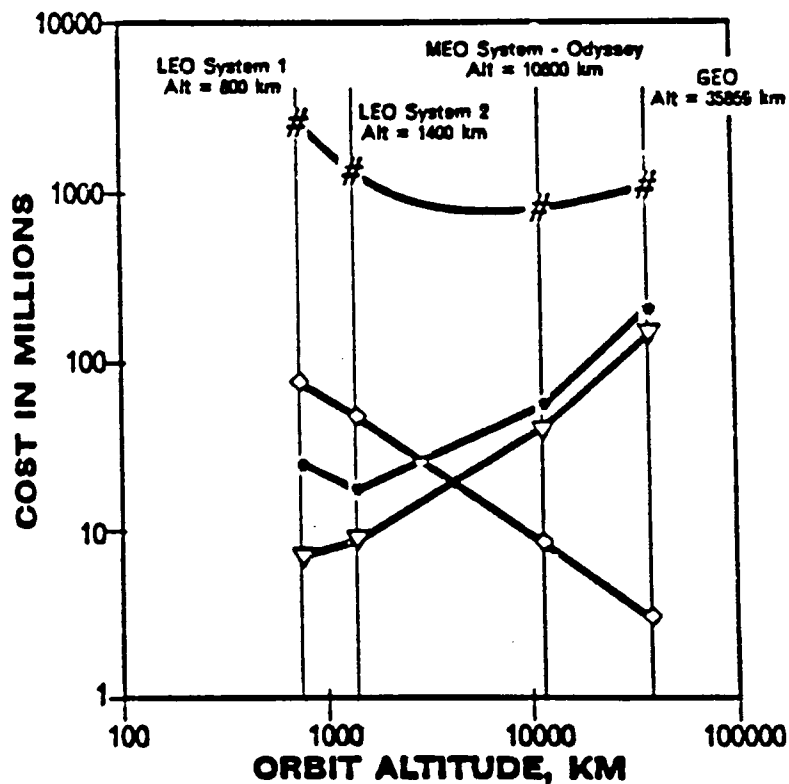


Figure 2. Satellite Cost Trades.

(Source: Spitzer, Christopher J. "Odyssey Personal Communications Satellite System." TRW Space and Defense, Space and Electronics Group. 3rd International Mobile Satellite Conference and Exhibition. Pasadena, CA: June 16-18, 1993, pp.1.)

There are several problems related to the GEO orbit. This orbit is located so far from the earth that 270 milliseconds is required for signal propagation to and from the satellite.¹² In voice transmission, this creates confusion and inefficiency, and the delay is annoying even when echo cancelers are used. At high latitudes, GEO satellites are observed at low elevation angles due to the zero-degree inclination of the orbit. As a result, users may experience signal blockage by terrain, vegetation, or buildings. Even though only three or four satellites are needed to provide total earth coverage, the satellites require more than one hundred very narrow beams, complex transponders, and large amounts of power.

Middle earth orbit, or MEO, extends about 10,800 km above the earth.¹² This orbit houses the 24-satellite GPS constellation. Since propagation loss is inversely proportional to the square of the orbit altitude, the antennas on MEO satellites, as well as transmission power, can be reduced. Also, due to the lower power requirement, satellites can be smaller and less expensive. Launching costs are lower than for GEO satellites since MEO satellites are smaller and therefore require less energy to be placed into orbit. These satellites are also designed for a 10 year on-orbit lifetime.¹²

In orbits closer to the earth, slant range distance for transmission becomes is reduced. Due to low slant range distance at MEO, a large number of satellites is required for total earth coverage. Even though there are perceived cost savings due to the lower power and smaller payload required, much of the savings is absorbed by the larger number of satellites needed.

Low earth orbit, or LEO, is the lowest orbit altitude of the three orbits, ranging from 800 km to 1400 km above the earth.¹² Being in low orbit, LEO satellites require even less power and payload size, likewise reducing both manufacturing and launching costs. However, the number of satellites needed for total earth coverage is even greater than that for MEO constellations, possibly requiring up to 100 satellites. At low altitudes, LEOs must be able to endure effects of atmospheric drag. As a result, LEOs have the shortest lifespans of approximately five to seven years.¹²

Multiple Access

Communications satellites would not be very useful and their large cost unjustified if user capacity were not sufficiently large. Since there are only a limited number of frequencies allotted for a certain bandwidth, a way of "sharing" must be developed so that many users can use the system at the same time. Multiple access is any process by which several users are able to share one communication system without interfering with one

another. In multiple access, each user is provided with a channel, which appears to be a private communication system, even though the user is actually sharing one larger system with many others. Choosing a system of multiple access has been called the real problem of satellite communications.¹³ Figure 3 illustrates three basic methods of multiple access: space-division multiple access (SDMA), frequency-division multiple access (FDMA), and time-division multiple access (TDMA).

Space-Division Multiple Access (SDMA)

Space-division multiple access, or SDMA, is a method by which several lines are provided in one connection (uplink or downlink), with each line being devoted to a separate channel (Figure 3a). SDMA amounts to several separate communication systems that are only loosely associated. It involves using different antenna beams and separate amplifiers within the satellite. SDMA is rarely used since it is space consuming and expensive due to complications within the satellite. It also requires more weight and is prone to occasional operational difficulties.

Time-Division Multiple Access (TDMA)

Time-division multiple access, or TDMA, is a method by which users "time share" a line (Figure 3b). Each sender takes turns transmitting a piece of message, and at the far end, the messages are separated and reformed without gaps. Each earth station is assigned a time slot for its transmission, and all earth stations use the same carrier frequency within a particular transponder. TDMA is superior to FDMA in that the intermodulation noise is eliminated, and capacity is increased.¹³ However, more complex ground equipment is needed for TDMA.

Frequency-Division Multiple Access (FDMA)

Signals can also be efficiently combined on to one channel by frequency-division multiple access, or FDMA (Figure 3c). In this method, each transmitting station uses a different carrier frequency. This permits many stations to use the same transponder amplifier until the noise level limits the capacity of that amplifier. At the receiving end, filters tuned to each frequency separate the messages, and they are distributed to their respective users. FDMA is the most popular technique for commercial communications satellites.¹³

The multiple carriers in the amplifier raise the apparent noise level to cause intermodulation. As a result, the carrier level received is less, and thermal noise effects

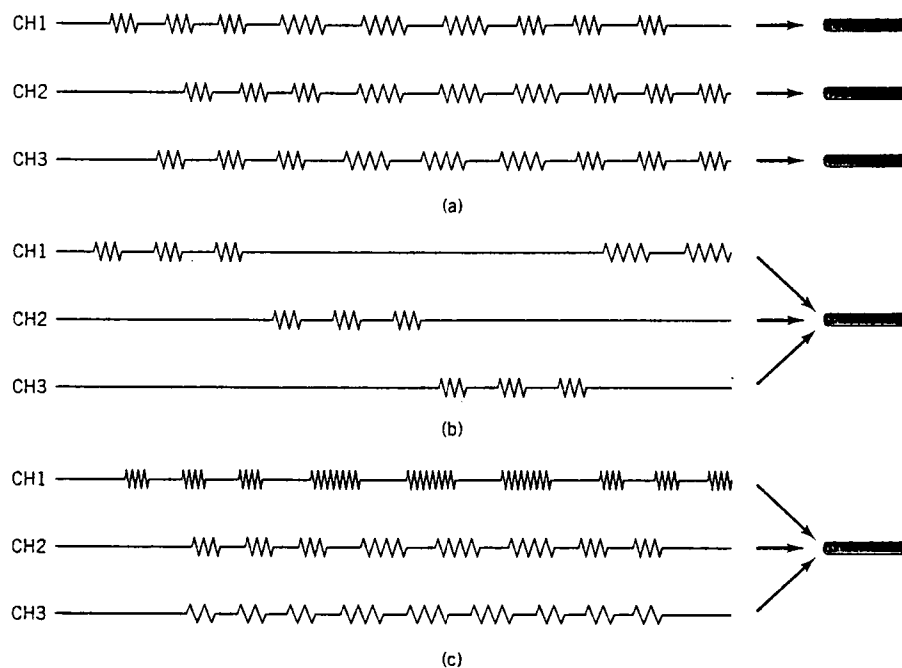


Figure 3. Combining three channels (a) by space-division multiplexing, (b) by time-division multiplexing, and (c) frequency-division multiplexing.

(Source: Roadstrum, William H., and Dan H. Wolaver. Electrical Engineering For All Engineers. 2nd ed. New York: John Wiley and Sons, Inc., 1994 pp. 319.)

from the earth station are increased. This reduces capability of the transponder. This intermodulation noise can be reduced by a "back off" of drive on the amplifier.¹³

Code-Division Multiple Access (CDMA)

CDMA, or code-division multiple access, is a fourth basic method of multiple access. It is also called "spread-spectrum" multiple access because elements of the message signal's energy are present across the entire bandwidth. The transmission from each earth station is combined with a pseudo-random code so as to cause the transmission to occupy the entire bandwidth of the transponder. The station for whom the transmission is intended has a duplicate of this pseudo-random code and by cross-correlating techniques can extract it from the "noise level" created by the simultaneous use of many other stations. CDMA is advantageous for military applications because the satellite receiver is hardened against possible jamming. The pseudo-random codes are necessary for cryptographic security. CDMA inherently provides automatic multiple access. A disadvantage is that power and frequency spectrum are not used efficiently.¹³ Also, extra equipment is required at both ends of the link.

Demand Assignment (DA)

Channels may be preassigned or "locked in" to a certain link, or they may be made available to users in other links. The latter is called demand assignment, or DA. DA offers more efficient utilization of the space segment and more efficient utilization of the terrestrial interconnect facilities.¹³ It does this by making unused channels available to other users. Without DA, when traffic to a particular destination is light, channel utilization is poor.

Frequency Selection

Traditionally, communications satellites have relayed messages using the VHF and UHF bands.⁷ The use of higher frequencies has been investigated because of spectrum crowding in the lower frequency bands and the desire for broader system bandwidths. The broad system bandwidths associated with the high frequency regime are necessary to achieve rapid transmission rates.

In passing through the atmosphere, radio waves may be attenuated in two ways: absorption and scattering. Absorption occurs due to the presence of oxygen and water vapor in the atmosphere, while scattering is caused by rain. Figure 4 shows that the higher frequencies are substantially more susceptible to atmospheric attenuation than the lower

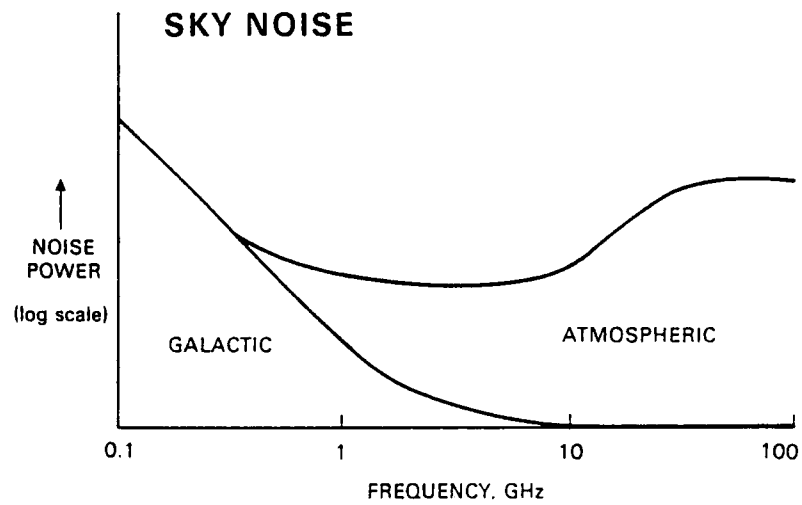


Figure 4. Level of noise versus radio frequency.

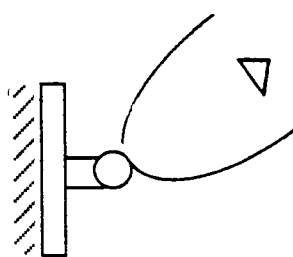
(Source: Stimson, George W. Introduction to Airborne Radar. El Segundo, CA: Hughes Aircraft Company, 1983, p. 124.)

frequencies. Atmospheric noise is a minimum at frequencies between 1 and 10 GHz (S-band through X-band) and increases to reach a steady value at around 100 GHz.

Antenna size is directly related to frequency. The width of the antenna beam is directly proportional to the ratio of the wavelength to the width of the antenna.¹⁴ For a given beamwidth, if a frequency of longer wavelength is used, the antenna must be wider. At low frequencies, a very large antenna must be used to produce a narrow beam, whereas at higher frequencies, a small antenna may be used. As beamwidth becomes narrower, the amount of power concentrated in a particular direction is greater. Gain is defined as the ratio of power directed in a certain direction to power radiated in that same direction by an isotropic antenna. This isotropic antenna is one that radiates waves of equal power in all directions. The denominator in the gain equation is also called effective isotropic radiated power, or EIRP. The narrower the beamwidth, the higher the gain. The higher the frequency, the narrower the beam that may be achieved with an antenna of given size.

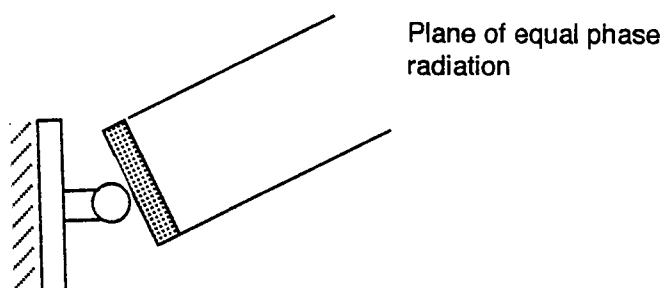
Antenna gain is the factor that determines system channel rates, which, in turn, determines level of service available. Small, high-gain antennas permit voice, facsimile, and high-speed communications rates of up to 21,000 bits per second, whereas a low-gain antenna is capable of low-speed data transmissions of 600 bits per second.¹⁵

While the satellite is relatively stationary, an aircraft is constantly moving in space. This aspect, coupled with the use of narrow beamwidths, requires steerable antennas, since the beam must be precisely aimed at and "locked on" to the satellite. There are two forms of steerable antennas: mechanically steered parabolic antennas and phased-array antennas. Both types are shown in Figure 5. Being rather large "dishes," parabolic antennas create a tremendous drag penalty on other than very large aircraft, since these aircraft usually have the capability to house the radome in areas such as a fin cap. Parabolic antennas require steering mechanisms to direct the antenna beam toward the satellite. This steering mechanism also adds more weight. With a phased-array, the antenna itself remains stationary while the phases of the radio waves emitted by individual radiators are differentially shifted.¹⁴ If the phases of the emitted waves are the same, then the maximum radiation will occur at 90° to the plane of the antenna. If, however, the phases are shifted at each radiator, the direction of maximum radiation will likewise be shifted. In this way, the antenna beam can be steered without mechanically steering the antenna itself. A high-gain phased array antenna with smaller size and less weight is desirable for small aircraft, especially helicopters, that may be equipped with satcom systems.



Steerable parabolic
antenna

(a)



(b)

Figure 5. Steerable antennas using (a) steering mechanism, and (b) phased array.

Satellite Technology--Past and Present

In the 1950s, the development of communications satellites was spurred by the rapid expansion of telephone systems and television and radio stations. The Echo satellite, launched in 1960, was a metallic balloon that reflected signals. The Telstar and Relay satellites were among the first to include transponders. Syncom II was the first satellite to be placed in geosynchronous orbit. In 1965, the Intelsat I became the world's first communications satellite, being placed over the Atlantic Ocean to relay telephone and television signals between North America and Europe.

The satellite revolution in the communications industry led to the need for regulation. INTELSAT, or the International Telecommunications Satellite Consortium, was started in 1964. Its membership was made up of eleven sovereign nations, and its purpose was to design, develop, construct, establish, and maintain the operation of the space segment of a global commercial communications satellite system.¹³ INMARSAT, or International Maritime Satellite, was established in 1979 as a part of INTELSAT. INMARSAT was a 48-nation consortium, and it was created to provide communications services to the shipping and offshore oil drilling industries. At first, INMARSAT operated only in the maritime frequency band; in 1985, its service was expanded to include the aeronautical market. COMSAT was started in 1989 as the United States participant in INTELSAT. The purpose of COMSAT was to enable telephone, television, and other forms of signals to be sent between the United States and other countries worldwide. COMSAT was also granted rights to provide satcom services in the United States using the INMARSAT system.

INMARSAT demonstrated two-way satellite datalink capability in 1985. It is currently working with the International Civil Aviation Organization (ICAO) and Aeronautical Radio Incorporated-Airline Electronic Engineering Committee (ARINC-AEEC) to establish standard characteristics and protocols for satcom. Avsat, or Aviation Satellite Corporation, is an airline-owned communications company started in March 1986 as a subsidiary of ARINC.

As of 1993, INMARSAT leased eight satellites, along with 19 earth stations, which provided telephone, telex, low/medium-speed data over telephone channels, facsimile, leased circuits for voice and high-speed data, data communications, limited land mobile applications, group calls, and distress and safety communication services to shipping and offshore communities.¹⁶ That same year, INMARSAT was in the process of launching four new second generation satellites, known as INMARSAT-2. The new satellites were designed to have four times the present capacity of the largest satellite in the

INMARSAT system. Currently, a third-generation constellation called INMARSAT-3 is in the launch stage. Due to such large user equipment needed, the INMARSAT system is only compatible with ships and large aircraft. It is currently unsuitable for small aircraft such as helicopters. INMARSAT currently has a monopoly over aeronautical satellite communications, catering exclusively to the airlines and the corporate fleet aircraft.

Satellite Technology--Future Trends

The relatively small size of the helicopter places a restriction on the amount and placement of equipment on the airframe and inside the cockpit (see Chapter 4). A satcom system for a helicopter must be small in both size and weight, and external airframe equipment must not impose a drag penalty. TRW, Motorola, and Qualcomm have developed land mobile satcom systems that could easily be adapted to helicopter operations.

The Odyssey system designed by TRW Space and Research promises economical access without the need for heavy, expensive satellite earth terminals.¹² The constellation includes 12 MEO satellites, three of these for redundancy, with service provided to most of the world's land mass. Two satellites will be visible anywhere in the world at all times, leading to high line-of-sight elevation angles, thereby minimizing obstructions by terrain, trees, or buildings.

The Odyssey system is forecast for launch in the late 1990s, and it will provide voice, data, and paging/messaging services.

Odyssey will conduct uplink (user terminal to satellite) transmissions at L-band (1610 to 1626.5 MHz) and downlink at S-band (2483.5-2500 MHz) while using the CDMA spread spectrum method of capacity sharing.¹² Transmissions between ground stations and satellites will be at Ka-band, with distinct subbands for transmissions to and from each cell.

The land mobile user terminal will be a modified cellular handheld personal telephone (HPT) capable of operating at either satellite or cellular frequencies. The HPT will transmit 0.5 Watt average power, which provides an appropriate margin against loss due to rain, vegetation, path distance, etc.¹²

For CDMA, the capacity of an antenna beam is determined by thermal noise and "self noise" of the spread spectrum system.¹² Each satellite in the Odyssey constellation will be capable of serving 2300 voice circuits; since dual coverage will be provided for any region, the capacity for the region will be 4600 voice circuits.¹² The entire constellation will serve approximately 2.3 million subscribers, with at least one voice circuit provided for each 100 subscribers. Increasing the number of satellites, using a synchronous

waveform, and orthogonal codes would increase the number of subscribers to 18.4 million.¹²

Each Odyssey cell will be 800 km (500 miles) in diameter over regions 4000 km across. Since most calls are completed within this distance, there is no need for call hand-off to another satellite. Thus, there will be no risk of call drop-out.

The Odyssey system has a low initial investment cost due to its using a small constellation of satellites in MEO (see Figure 1). It promises a user rate comparable to terrestrial-based cellular systems (approximately \$0.65 per minute)¹². It also promises a low-cost, easy-to-use HPT.

Like Odyssey, the Iridium system designed by Motorola will be capable of providing global voice, data, facsimile, and paging services. It is also in the post-design stage and will consist of 66 satellites in LEO. It will use a 0.5 Watt handset, with uplink and downlink frequencies in the L-band (1616.0 and 1626.5 MHz, respectively). Iridium will have 48 spot beams, with a peak capacity of 960 channels, 780 of which will be full duplex telephone voice channels.¹⁶ It will employ a combination of both TDMA and FDMA capacity sharing.

Due to the shorter mission life of LEO satellites, the Iridium system will require highly reliable launch vehicles to provide spares. The multiple access methods used will make it more susceptible to jamming, or enemy flooding of the system with calls. In order to prevent jamming, the satellite beam "footprint" would have to be very large, about one million square miles, or 15,000 calls per satellite.¹⁶

The OmniTRACS[®] system developed by Qualcomm is currently in use in the United States. It provides two-way messaging and position reporting services, with position information being derived from LORAN-C. OmniTRACS[®] perhaps has the lowest initial investment cost, since it uses Ku-band transponders on a GEO communications satellite that has already been in existence for many years.

OmniTRACS[®] uses the spread spectrum (CDMA) method to distribute the instantaneous power spectral density of each uplink over a bandwidth of 1 MHz.¹⁷ Since there is no voice capability, the cost per message is significantly reduced compared to the other two systems. Data transmission is more rapid than voice transmission, and time spent sending and receiving messages is reduced. This results in a substantial cost saving.

The OmniTRACS[®] mobile terminal shown in Figure 6 contains the following components: an outdoor unit, a communications unit, and a display unit. The outdoor unit, which includes the antenna, is small enough to be mounted on the top of any vehicle. The communication unit includes the necessary electronics hardware. Since it does not

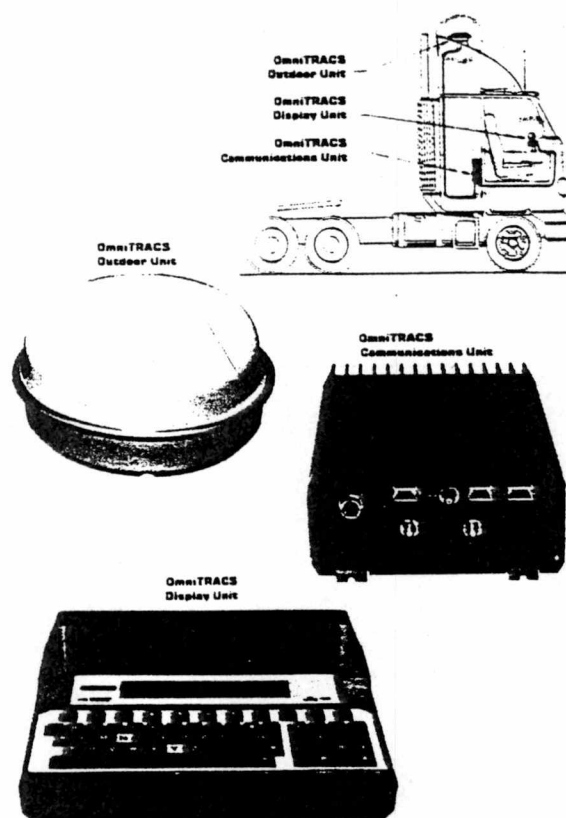


Figure 6. Satellite mobile communications terminal for the OmniTRACS® system.

(Source: Jacobs, Irwin M. "An overview of the OmniTRACS®: the first operational two-way mobile Ku-band satellite communications system." QUALCOMM, Inc., 1989, pp.32.)

require operator access, it can be mounted most anywhere in the vehicle. The display unit contains a typewriter keyboard for user input, as well as pre-programmed user functions. It can be located anywhere within easy access to the operator. Cost of the mobile terminal setup ranges from \$4000 to \$4500.¹⁷

All three satcom systems described above are good choices for helicopter use. However, of the three, TRW's Odyssey system has superior qualities due to its use of CDMA to prevent satellite jamming, low initial investment cost, low user fees, and dual voice and data capabilities. The TDMA and FDMA methods used by Iridium make it more susceptible to jamming. OmniTRACS[®]' restriction to data transmission, along with the necessary use of a keyboard, make this system less attractive for helicopter purposes. OmniTRACS[®] is more suitable for land mobile applications, where the operator is more free to remove his hands from the controls of the vehicle to type a message on the keyboard. Once the Odyssey system is implemented, the helicopter industry should consider it as a possible solution to the current problem of helicopter communication at low altitude and in confined areas.

Chapter 4

Helicopter Characteristics

Fixed-wing aircraft are the primary users of the current NAS. Helicopters make up a very small percentage of the total number of operations. This is due in part to the fact that the airspace infrastructure is rather "helicopter-unfriendly," meaning that it does not take advantage of the helicopter's unique capabilities, and it forces helicopters to adhere to fixed-wing aircraft rules and limitations.

Operational Characteristics

From appearance alone, the helicopter and the airplane have some obvious differences. Instead of two wings rigidly mounted on either side of the fuselage, the helicopter has a main rotor made up of two or more rotor blades that function as "rotating wings." Most helicopters also have a tail rotor instead of a rudder to counteract the torque effect produced by the main rotor. The complex mesh of hardware around the rotor hub and tail rotor require much more attention from the pilot during pre-flight.

The helicopter must adhere to the same aerodynamic principles of lift, weight, thrust, and drag as the airplane. Lift is produced by varying the angle of attack of the main rotor blades. Thrust is produced by tilting the main rotor forward, backward, or sideward, depending on the desired direction of flight. As for an airplane, the weight of the aircraft is due to the pull of gravity and opposes lift, while drag is a by-product of inertia and air resistance, and it opposes thrust.

The four basic helicopter controls are the cyclic, collective, throttle, and tail rotor or antitorque pedals. The locations of each in the cockpit are shown in Figure 7. The collective is moved by the pilot's left hand, and it varies the pitch on each rotor blade by the same amount, or collectively. As blade pitch increases, angle of attack increases, and the helicopter moves upward. The opposite happens as pitch decreases, with the helicopter moving downward. The pilot varies blade pitch by moving the collective up or down.

The throttle is necessary to maintain rotor rpm. If pitch is increased without increasing power, rpm will decrease due to the increase in drag. Likewise, rpm will increase with a decrease in blade pitch unless power is decreased. The throttle is co-located with the collective, and the pilot adjusts power as he moves the collective in order to maintain a constant rotational speed. Newer models replace the throttle with electronic

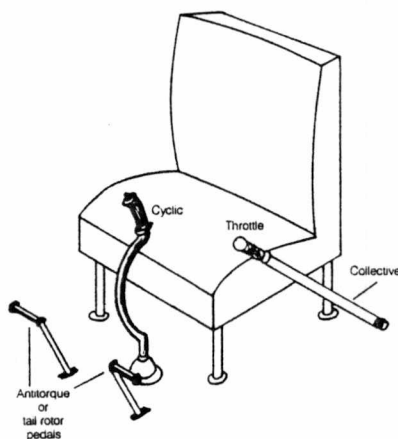


Figure 7. Location of main flight controls.

(Source: Padfield, R. Randall. Learning to Fly Helicopters. New York: TAB Books, 1992, pp.42-43.)

devices that change power automatically whenever they sense a change in collective position.¹⁸

The cyclic is controlled by the right hand and is used to move the helicopter forward, backward, or sideways. In forward flight, the cyclic is used to bank into turns, climb, descent, and adjust airspeed. The cyclic changes pitch on the main rotor blades in only one section of the overall rotor disc. As a result, lift is increased on one side of the disc and decreased on the other. As each blade rotates around the rotor mast, its pitch is increased or decreased, depending on the position of the cyclic. The cyclic is so named because the pitch on each blade changes as it cycles around the rotor disc.¹⁸

The tail rotor pedals are necessary to counteract the torque produced by the main rotor. The tail rotor can be viewed as a small main rotor mounted in the vertical plane that provides lift horizontally to cancel the torque effect. The tail rotor pedals change tail rotor blade pitch in the same way the collective changes the pitch of the main rotor blades.

In helicopter flight, a change in one control input requires a corresponding change in the others. For instance, if a right turn is desired, the cyclic is moved to the right. This means that the lift vector is canted to the right, with the vertical component of lift being reduced. This requires an increase in collective pitch, which likewise requires an increase in throttle to maintain rotor rpm. As throttle is increased, main rotor torque effect also increases. Torque must be counteracted by using the tail rotor pedals.

Unlike an airplane, which can be trimmed for "hands-off" flight, the helicopter demands constant control inputs during flight due to its inherent instability. Since both hands and feet are occupied during flight, there is little ability for the pilot to attend to other tasks, such as changing radio frequencies on the audio stack. Chapter 5 looks further at the human factors issues that result from this, and it proposes an avionics system that is compatible with the pilot's limited capabilities during flight.

Antenna Placement

Helicopters such as those used by police and EMS usually have several different transceivers and many antennas mounted on the airframe. The helicopter's small size limits the area in which radio antennas may be mounted. The mounting area is restricted to the top and bottom of the fuselage, as well as the nose and tail boom. Several factors need to be considered when choosing a location for an antenna:⁸

- Rotor modulation effects for top mounting;
- Radio frequency (RF) coupled interference;

- Composite content in the structure and external skin of the helicopter;
- Obstructions on the airframe.

The basic AM comm radios are highly influenced by rotor modulation, which is an interruption of the carrier sounding like severe AM modulation. The main rotor acts as a revolving "shutter" at ground potential which interrupts the signal path either by reflection or shielding. This renders AM comm transceivers with top-mounted antennas useless unless a grounded layer is inserted between the rotor disk and the antenna. This can be accomplished by placing the antenna on the bottom of the fuselage, with the fuselage acting as the ground plane between the antenna and the rotor. A composite rotor system may also be used to prevent rotor modulation.

Due to the small amount of available space for mounting antennas, comm radio antennas are very closely spaced. This creates high levels of RF coupled interference. Helicopters fabricated from composite materials have reduced RF shielding, thus complicating radio interconnections. This causes high levels of ground return noise and cross-talk and also increases the occurrence of stray RF coupling into other systems.

These factors relating to avionics installation in mission-specific helicopters create a challenge for helicopter avionics designers. Aside from the problem of antenna placement, the multitude of radios needed calls for a densely packed avionics stack in the cockpit. Radios that are mounted in close proximity to each other generate interference, e.g., transponders may generate automatic direction finding (ADF) interference, and GPS systems adversely affect FM radios.⁸ The generated interference is often difficult to predict. Dense packing also facilitates heat build-up within the stack. Therefore, cooling is required to preserve the service life of the avionics equipment.

GPS has been shown to work with a top-mounted antenna. When placed clear of obstructions on top of the fuselage, it is not subject to interference from rotor modulation, RF coupling, or composite content. Since GPS is based on information from satellites, it is conceivable that a satcom system would likewise be free from interference with a top-mounted antenna. Many helicopters have equipment such as wire strike protection systems, searchlights, and pop-out float kits, which require bottom mounting. Nose-mounted equipment may create a drag problem by disrupting airflow over the nose and also may hinder visibility. For these reasons, top mounting of the satcom antenna should be considered.

EMS and search-and-rescue personnel often need to communicate with several different agencies at once in order to facilitate disaster relief. The satcom transceiver should have multiple user per channel capability. This will be possible through the use of one or more of the multiple access techniques discussed in Chapter 3. The satcom system will require only one high-gain phased-array antenna on board the aircraft. The antenna's small size and weight will be ideal for helicopter use. Interference characteristics among multiple satcom transceivers placed in the cockpit in close proximity will need further investigation.

Chapter 5

Human Factors Issues

The helicopter presents a complex scenario for human factors research. Its high cockpit noise level, small size, and unique control characteristics must be accounted for in developing an ergonomically sound environment. Chapter 4 discussed the basic operating principles of the helicopter and the fact that constant manipulation of the cyclic, collective, throttle, and tail rotor pedals is necessary to maintain control during flight. As a result, the pilot's hands and feet are constantly occupied from liftoff to touchdown, and the pilot is not free to attend to other in-flight tasks. This is especially true for helicopters not equipped with stability augmentation systems (SAS) or autopilots.

The low frequency noise created by the turning rotor is objectionable to the pilot and passengers. Long exposure times can not only cause hearing loss, but also can induce pilot fatigue. Noise-cancelling intercoms and headsets have been developed to reduce noise levels. Cockpit insulation has also been used for corporate and EMS helicopters to provide greater passenger and patient comfort.

The noisy cockpit environment is also a problem because it tends to drown out voice radio transmissions. The pilot is likely to misunderstand or altogether miss important instructions. The use of a data link may improve communication and reduce chances of misinterpretation.

Data Link

Data link describes the means of sending non-voice information by radio from the ground to the aircraft, from aircraft to ground, and from aircraft to aircraft.¹⁹ Data link has existed for many years, but on a small scale. In the 1960s, the airlines began using ACARS, or Aircraft Communications, Addressing, and Reporting System. It was developed by ARINC as a VHF voice network to allow its members to report Out/Off/On/In (OOOI) times to a ground radio operator. The operator then relayed the information via telex to the dispatch office. In 1979, ARINC switched to all-data transmission, and its use has been expanded to include the uplink of ATC clearances via the INMARSAT network. ACARS service is now provided to airline traffic worldwide.

Data link is used in the traffic collision avoidance system (TCAS), which is now mandated for all airliners flying within the U.S.¹⁹ The TCAS on board the aircraft

receives Mode S altitude and position responses that are datalinked from other aircraft in the area. The TCAS then determines whether or not the aircraft pose a collision risk.

Data link is expected to become the transmission medium for automatic terminal information service (ATIS), pre-departure and landing clearances, and weather information, most of which are currently voice-only broadcasts. Data link will enable ATIS reception by aircraft several miles away from the transmitter. ATIS via data link is being tested at some U.S. and Canadian airports.

Data link has numerous advantages over voice transmission. It can pass information much more rapidly and accurately, and it cannot be overridden by other transmissions. Reception quality is also better for data link than for voice. Data link does not require the pilot to "stop what he's doing and listen" as with voice radio.¹⁹

Information that is data linked to the cockpit is less likely to be misunderstood by the pilot since it is presented in text form. Human factors research suggests several criteria for using a visual form of presentation:²⁰

- The message is long;
- The message is complex;
- The receiving location is noisy;
- The job allows the person to remain in one position;
- The message will be referred to later.

Clearances and ATIS information may be long and difficult to remember. Usually, the pilot must write down the instruction for later referral during flight. Therefore, the information presented on a video display terminal (VDT) or printed out as hard copy in the cockpit would be most beneficial to the pilot.

Several items have been shown to influence reading ease:²⁰

- Monitor resolution
- Density of text on display
- Grouping of text
- Complexity

Research has shown that people read much more slowly from a VDT than from hard copy due to the difference in image quality. High resolution monitors that closely parallel the

resolution of hard copy improve reading ease. Also, higher resolution results in better user performance.

Density applies to the percentage of available character spaces being used.²⁰ A small amount of information spread out on the display can increase search time if searching for one item. However, if density is too high, information may become crowded, thereby decreasing performance.

Grouping refers to how well the data fits into perceptual groups.²⁰ A general rule is to form data groups that subtend no more than 5° of visual angle.²⁰ Larger groups tend to increase the search time for a piece of information, while smaller groups with a visual angle of 5° or less is optimal.

Complexity is determined by the general layout of text on the display. For instance, the use of columns provides a predictable visual scheme, since the reader knows where to direct his eyes for the next piece of information.²⁰ Elements within a column should also be aligned in order to improve readability.

Routine clearances given to the pilot by ATC always follow a certain format and order. For example, a pilot departing on an instrument flight rules (IFR) flight plan may be given the following clearance: "Piper N22UT, cleared Knoxville-Downtown as filed, maintain 3000, expect 6000 10 minutes after departure, departure frequency 126.75, squawk 4035." The items in the clearance will always be read in the following order: 1) clearance limit; 2) cruising altitude; 3) expect further clearance time; 4) departure frequency; 5) transponder code. This predictable sequence allows the pilot to extract pertinent information more efficiently. ATIS, as well as departure and landing clearances, always adhere to a certain format.

The pilot must acknowledge any instruction received from ATC to indicate that he has received and understands the message. This is done via voice radio by depressing a key on the microphone or other push-to-talk switch mounted on the control yoke or cyclic.

An example of a cockpit data link terminal is shown in Figure 8. This unit is manufactured by Teledyne Controls and is used in corporate aircraft. It has a keypad below the display for custom data link messaging, and it also has pre-programmed messages stored in memory. The unit is capable of reporting the aircraft's estimated time of arrival at its destination (ETA), OOOI, engine data, and emergency information. This type of system works well for an airplane that can be trimmed for hands-off flight. The EMS or corporate helicopter equipped with an autopilot may benefit from this system as well. However, the pilot flying a helicopter with no SAS or autopilot most likely will not be able to type messages on the keypad. He may also be hindered from reaching up to

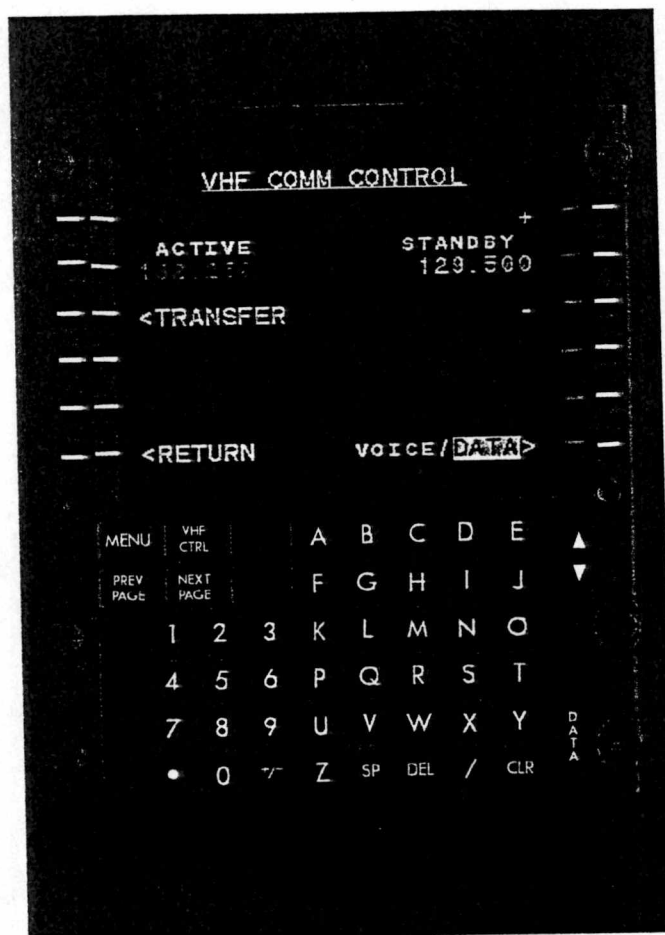


Figure 8. Multiple Interface Control and Display Unit.

(Source: Teledyne Controls Business and Commuter Avionics Data Link Products, Redmond WA, 1996.)

acknowledge radio transmissions. In this case, a method of signaling must be devised that is within the helicopter pilot's limitations during flight.

Since the pilot's hands are on the collective and cyclic throughout flight, a sensible solution would be to place the data link terminal keys on the cyclic and collective. The pilot will rely on his tactile sense to determine where the buttons are and activate them, thereby acknowledging any data link transmissions. However, if more than one terminal control button is placed on each flight control, confusion may result, and the pilot may depress the wrong button.

The pilot will most likely need access to the following basic responses to uplinked data messages: 1) acknowledge; 2) repeat clearance; 3) reject clearance; 4) emergency. The pilot may also need scrolling capability when choosing from numerous options on a menu.

Figure 9 shows the left-hand control of the F-18 aircraft. The principles underlying the design of this multi-function control are as follows:²⁰

- The pilot should be able to operate the control without looking at it;
- The pilot's hand should remain in contact with the primary controls throughout critical system operations;
- The auxiliary controls should be activated without loss of physical contact with the primary controls.

The hand control in Figure 9 has numerous knobs and switches for activating various functions. The pilot must be able to distinguish among the different controls without looking at them. Tactual cues such as size, shape, and texture may be varied for each switch or knob so that it can be readily identified. This coding method has been used successfully for power clusters (propeller, throttle, and mixture controls), as well as gear and flap controls in airplanes. The flap and gear handles in a cockpit also resemble the actual controls that they are activating.

Audio signals are used to describe conditions surrounding a user. A siren is used by an emergency rescue vehicle to alert other drivers of its urgency to get to an accident scene. A train whistle alerts automobile drivers at a railroad crossing to stay clear of the track. Some auditory signals have become so commonplace that when heard, a person automatically knows how to respond.

Audible warnings are used in the cockpits of military jet fighters to indicate certain conditions. Research conducted on the audible warnings in these aircraft revealed the following problems:²⁰

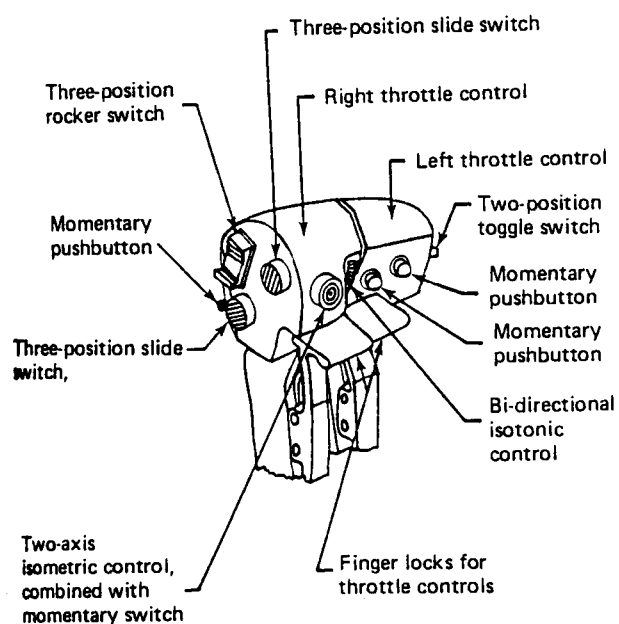


Figure 9. The left-hand control of the F-18 aircraft.

(Source: Sanders, Mark S., and Ernest J. McCormick. Human Factors in Engineering and Design. New York: McGraw-Hill, 1993, pp. 355.)

- Auditory signals are not well standardized;
- A large number of potentially confusing auditory signals are used within the same cockpit;
- The urgency of the condition is not reliably indicated by the signal characteristics.

Audible signals would be beneficial to pilots receiving data link messages to alert them of the type of message they are receiving. Messages may be placed into seven different categories: 1) ATIS; 2) clearance delivery; 3) departure; 4) enroute; 5) arrival instruction; 6) taxi information; 7) non-routine/emergency. Table 2 presents the characteristics and features of certain types of audio alarms. A different signal may be used for each type of message. This will prepare the pilot to expect a specific type of instruction. If the message is transmitted in a format known by the pilot, his time spent searching for pertinent information will be reduced. Less time will be taken away from the instrument scan, and pilot performance and response time will be augmented.

Information on a VDT must be readable in a variety of cockpit lighting conditions. In addition to density and grouping of data on the screen, the letter and number characters themselves must be examined for optimum stroke width, letter height, and text color against a background of a certain color. The same factors must be accounted for if the text is printed out on hard copy. The VDT must be placed at a distance that ensures optimum reading ease by the pilot.

The placement and tactual coding of data link terminal controls on the cyclic and collective will require substantial human factors research. The hand controls must be within the normal range of motion of the pilot's hand and fingers. The different controls must be readily identifiable with little confusion. When responding to a data linked message, the pilot must be subject to a minimal amount of scrolling through items on the display. Excessive scrolling is time consuming and detracts from the pilot's normal instrument scan.

In choosing an audible signal for each message type, the researcher must ensure that the signal will be heard over any background noise. Startling, high-frequency tones must be avoided. The different audible tones must be readily distinguishable so as to avoid pilot confusion. As in the case of airplane cockpit controls, the sound for each message may be designed to correlate with the message type, e.g., siren for emergency, a bell for takeoff or landing clearance.

Table 2. Characteristics and Features of Certain Types of Audio Alarms.
 (Source: Sanders, pp. 178.)

Alarm	Intensity	Frequency	Attention-getting ability	Noise-penetration ability
Diaphone (foghorn)	Very high	Very low	Good	Poor in low-frequency noise
Horn	High	Low to high	Good	Good
Whistle	High	Low to high	Good if intermittent	Good if frequency is properly chosen
Siren	High	Low to high	Very good if pitch rises and falls	Very good with rising and falling frequency
Bell	Medium	Medium to high	Good	Good in low-frequency noise
Buzzer	Low to medium	Low to medium	Good	Fair if spectrum is suited to background noise
Chimes and gong	Low to medium	Low to medium	Fair	Fair if spectrum is suited to background noise
Oscillator	Low to high	Medium to high	Good if intermittent	Good if frequency is properly chosen

The VDT must be located so that it integrates efficiently with the pilot's instrument scan. It should be positioned so that no rapid head movements or unnatural posture is necessary. A head-up display (HUD) would allow the pilot to maintain a natural posture while providing pertinent flight information. Data link messages may also be included in a HUD.

Data link is a fairly new concept that is currently used exclusively by the airlines and the corporate fleet. Although data link promises faster and more accurate information transmission rates, voice capability should be retained for non-routine transmissions and emergency use. As ergonomic and in-flight tests reveal the capabilities and limitations of data link for helicopter flight, voice radio will become a secondary method of communication. Satellite data link will provide the "missing link" that the helicopter industry needs to improve the quality of its operations in the current NAS.

Chapter 6

Current and Future Infrastructure Issues

The report by Kimberlin, et al. entitled "Program Plan for the Development of Helicopter Terminal Area Instrument Procedures (TERPS)" identifies several unresolved issues relating to helicopter flight in the current NAS, some of which are as follows:³

- Alternate airport weather minimums were written for airplanes and do not consider the helicopter's ability to fly only short distances to an alternate;
- The safe separation distance for helicopters flying under IFR needs to be determined;
- The navigation method needs to be resolved;
- VHF communications are inadequate at low altitudes and confined areas. The frequencies are also congested due to many users;
- How will the new system connect with the current route structure, and will safety demands be satisfied?

Until recently, the published Terminal Approach Procedures included very few "copter" approaches. These approaches were usually VOR approaches to a fixed-wing airport. They often involved terminating the approach under visual flight rules (VFR). After termination of the IFR approach, the pilot would subsequently proceed to his intended point of landing under VFR, which could be as far as three miles away.

GPS has been determined to be the navigation method upon which the new helicopter infrastructure will be based. The recent advent of GPS nonprecision TERPS has made way for nonprecision helicopter GPS approaches at the Mayo Clinic in Rochester, Minnesota, and Erlanger Hospital in Chattanooga, Tennessee. Erlanger's Life Force unit reported saving 34 lives during the first year of implementation of the GPS approach by not having to divert.²¹ The implementation of the Wide Area Augmentation System (WAAS) for differential GPS will provide the necessary accuracy for GPS precision approaches in the near future.

GPS will serve multiple functions during the 1996 Summer Olympics in Atlanta. The FAA and industry have established the Atlanta Short-Haul Transportation System (ASTS) in which helicopters will fly low-altitude routes to transport goods and provide public safety services around the city. These low routes will be over multi-lane highways in order to minimize noise complaints. GPS position information will be broadcast via VHF data link to ATC and other aircraft. Of the 100 helicopters flying in ASTS, 50 will be equipped with data link terminals.²² According to Steve Fisher of the FAA's Vertical Flight Program Office, during tests conducted in November, the aircraft were tracked at every landing site to a three-foot hover.²² The helicopters will obtain weather information such as wind speed and direction, temperature, humidity, and turbulence from the atmosphere. This information will then be data linked every 10 to 15 seconds to the National Weather Service (NWS) and other aircraft in the area.

GPS position reporting may be viewed as being superior to the TCAS system. TCAS interrogates transponders on nearby aircraft, and it plots the relative positions of the traffic. TCAS has a limitation in that transponders may be incapable of responding to both the TCAS inquiries by other aircraft and the radar interrogations from ATC.²³ GPS will use automatic cooperative position reporting in which a cooperative network will allow aircraft to exchange position, altitude, and track information.

GPS used in this manner will make way for "free flight." The air traffic control plan announced in March indicates that in free flight, controllers will monitor traffic and step in only to make sure the planes keep a safe distance apart, avoid prohibited airspace, and to prevent congestion in high traffic areas.²⁴ According to Lane Speck, a spokesperson for the FAA, the planes will go where they want at any speed and at any altitude.²⁶ Necessary on-board equipment will include electronic flight instrument systems (EFIS), flight management systems (FMS), and multifunction control display units (MCDU), such as shown in Figure 8.²⁵ These instruments will provide the pilot with a display of his own "situational awareness". This means that the pilot will have a cockpit display of his own path, the paths of other aircraft in the vicinity, and any precipitation in the area. The airlines will benefit economically from free flight, since altitude and route chosen are directly related to fuel consumption. The ability to choose a direct point-to-point route at an optimum altitude for minimum fuel consumption could save the airline industry millions of dollars. Free flight is expected to spill over into the general aviation community as well.

With the implementation of helicopter TERPS and GPS nonprecision approaches, a new infrastructure geared toward helicopter flight is rapidly becoming a reality. However,

the problem of VHF communication at low altitude and in confined areas still remains. The helicopter industry has expressed interest in communications systems ranging from cellular telephones to satellite-based. The cost of new avionics for helicopters is quite high, which is the primary reason that commercial operators are hesitant to invest in new systems.²⁶

Chapter 7

Conclusions and Recommendations

Enhancements in computer processing, displays, and databases will increase the helicopter pilot's capability to fly in all types of weather. These enhancements, along with a satellite communications system, will allow helicopter operations at virtually any point on the earth. The author of this study concludes and recommends the following:

- A satellite-based communications system would solve the problems of communicating from low flight altitude and confined areas;
- A data link would reduce the need for voice communications;
- Particular attention needs to be paid to the human factors issues in the system;
- The FAA should work with the helicopter industry to develop an ergonomically sound, satellite-based communications system with both voice and data link capability;
- TRW's Odyssey system, with possible modification to the user handset, is a feasible candidate for a helicopter satcom system.

There are still many unresolved issues relating to the current airspace infrastructure as well. The FAA, in cooperation with the helicopter industry, has made excellent strides in redefining the infrastructure, thereby allowing the helicopter to fulfill its intended use as a "go anywhere, all-terrain vehicle."¹

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Vita

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