APPENDIX E

(ENGLISH ONLY)

DRAFT

MANUAL
ON THE IMPLEMENTATION
OF HF DATA LINK
(HFDL)

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1. INTRODUCTION

1.1 Purpose

The purpose of this document is to provide the reader with material to enhance the understanding of high frequency data link (HFDL). This document provides the reader with guidance material to be considered in several areas within the HFDL system including the airborne avionics, the propagation media, and the terrestrial components. A summary of the contents is as follows:

Section	Title
1.	Introduction
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This HF data link design finds its beginning in MIL-STD-188-110A. HFDL had not, until recently, been considered as suitable for the future Aeronautical Telecommunications Network (ATN) utilization. Over the last few years, trials of a prototype system along with recently collected propagation data indicate that HFDL is capable of providing a level of performance suitable for the ATN environment (Figure 1-1).

The HFDL service allows aircraft that are equipped with an HFDL control function (HCF) and HF data radios, or equipped with HCFs, an intermediate HF data unit, and compatible HF voice radios, to send and receive packet data via a network of HFDL ground stations. The ability to exchange packet data via VHF data link and SATCOM networks will, of course, continue to exist.

This document shows that a subnetwork of 15 or 16 HFDL ground stations can extend air-ground communications coverage beyond the coverage of VHF data link subnetworks on a world-wide basis and provide an alternate or/backup to SATCOM on routes over the Atlantic, North and South Poles, South America, Africa, the Pacific, and Asia. The actual number of ground stations needed is dependent upon several factors including system availability and capacity desired by the users and ground station operators.

This document also indicates that HFDL can provide very significant improvements over current HF Voice Communications in terms of system availability, system capacity, ease of use, and information integrity.

1.2 Role of HFDL in CNS/ATM

As the aeronautical industry progresses with the implementation of data links both on the ground and airborne sides (Figure 1-2), a need emerges for HFDL. A networked-based HFDL system satisfies future air traffic service (ATS) and aeronautical operational control (AOC) communication requirements in oceanic areas in a cost efficient and reliable manner. Furthermore, HFDL can provide data link service over other land areas where no current data link service (i.e., VHF) is currently available. In this case, HFDL provides a data link service where numerous VHF data link stations may be impractical due to cost or other factors.

Additionally, HFDL may result in a reduction in the growth of requirements for HF voice services, as many current voice service requirements are accommodated via HFDL.

HFDL fulfills several key roles: 1) provides aircraft that are not SATCOM-equipped with a long-range, cost-effective data link; 2) serves as a data link for polar regions where SATCOM performance degrades and 3) acts in combination with SATCOM as very high performance system capable of meeting future ATN availability requirements. HFDL is seen as a tool enabling communications, navigation, and surveillance/air traffic management (CNS/ATM) to be extended to new regions and to aircraft previously not able to afford a long-range data link.

1.3 HF as a long-range communication medium

1.3.1 HF propagation

Many radio frequency bands are influenced by media such as the neutral atmosphere or the ionosphere, and the HF band is no exception. For aeronautical purposes, the important bands are HF, VHF, and UHF (SATCOM). While VHF signalling is generally unaffected by ionospheric effects, it is restricted to line-of-sight (LOS) ranges. In contrast, the HF band depends upon the ionosphere for its skywave coverage pattern which enables beyond-line-of-sight (BLOS) communication ranges to 4 000 - 5 000 km and beyond (on multi-hop paths) to be achieved. SATCOM circuits are influenced by the requisite ionospheric penetration, a region 60 - 2 000 km above the Earth's surface, but the impacts are deleterious effects, some of which may be significant under prescribed conditions (viz., scintillation during high sunspot conditions and within specified geographic regions). SATCOM coverage is determined by line-of-sight conditions which may limit polar coverage for some configurations (i.e. geosynchronous platforms). HF coverage over the poles is provided by appropriate ground station positioning.

The HF and VHF bands are not influenced by the wide range of atmospheric phenomena but SATCOM can be impacted under severe weather conditions.

The HF band of principal interest (2.850 to 22.000 MHz), is subject to a number of ionospheric influences which lead to signal distortion and these are dependent upon factors such as ionospheric layer shape and densities which are functions of geographical and time-vary conditions. The temporal effects include long-term solar epochal changes related to the eleven-year sunspot cycle, seasonal variations, day-to-day changes, and diverse variations. There are also signal-level fluctuations which arise over a continuum of time scales (i.e. seconds to hours).

The time scale and character of HF signal distortion will define the most appropriate countermeasure or mitigation scheme. Many approaches are now available for mitigation of deleterious HF effects and these include advanced signal processing, dynamic frequency management, and a variety of diversity measures to exploit the wide variety of ionospheric effects.

1.3.2 Networked sites

Due to the vagaries of propagation phenomena current manually tuned HF voice communications is difficult and often unreliable. A great deal of the unreliability is due to the restrictions imposed on voice communications. For example, the HF stations that handle air traffic control (ATC) communications over the North Atlantic are set up so that a single HF station handles most voice communications in each flight information region (FIR), and each FIR's coverage region is limited to a radius of roughly 1 000 - 1 200 km. When a severe ionospheric disturbance affects HF communications within a FIR, a large part of the coverage area may experience degraded communications. Aircraft in the affected area may have no alternate communications path because they are restricted to making their waypoint position reports to the HF station covering that FIR. Furthermore, by designing the HF-voice based ATC system so that the FIR's coverage area is generally limited to 1 200 km or less, the window of frequencies that support HF communications with the FIR's HF station is smaller (often only one frequency or none out of all the station's frequency assignments) than it could be if the aircraft were allowed to report to a station farther away.

With HFDL, aircraft may communicate with any of a number of internetworked HF ground stations providing coverage in the same area (e.g. North Atlantic). Messages are routed to/from the ground end user via dedicated, leased communication circuits or packet switched data public or private networks. The HFDL system is expected to be inherently more reliable (higher availability), because ionospheric disturbances are much less likely to affect the communications from a point in the coverage area to all ground stations at the same time.

1.3.3 Automatic frequency management

Current HF voice based ATC communications procedures require that aircraft monitor a primary pre-assigned frequency to communicate with the responsible ATC center at a given time of the day. A secondary frequency is also pre-assigned for use in the event of heavy traffic or poor propagation conditions on the primary frequency. When HF radio conditions degrade, the task of maintaining the voice traffic flow in order to comply with the flight safety regulations becomes increasingly difficult both for the pilot/radio operator in the aircraft and for the radio operators in the ATC communication stations, as message waiting times increase, and the manual frequency selection task grows more difficult.

With HFDL the crew does not have to assume responsibility for finding and tuning to a good frequency and an HF radio operator trying to reach a specific aircraft does not have to hope that the aircraft is monitoring the appropriate frequencies. The HFDL system on the aircraft automatically searches for a suitable (or even the best available) frequency from all HFDL operational ground station frequencies. To assist with the search, each HFDL ground station broadcasts system management uplink packets (called 'squitters') every 32 seconds on its operational frequencies. The squitters on each of the frequencies are staggered and synchronized to universal time co-ordinated (UTC) to allow a quick search through the frequencies. In order to speed up the search process, an aircraft may limit the search to all operational frequencies assigned to ground stations within 4 000 to 5 000 km of the current aircraft position.

Once a suitable frequency is found, the aircraft establishes a connection by sending a log-on message to the ground station and waiting for a log-on confirmation uplink before continuing. Having established a connection, the aircraft may proceed to send data on time slots assigned for random access, or downlink slots specifically assigned to the particular aircraft, and to receive data on slots reserved for uplinks by the ground station. To facilitate the frequency and slot management process, thirteen slots are grouped into frames having a length of 32 seconds. The assignments for each of the thirteen slots in a 32-second frame are broadcast by the ground station in squitters using the first slot in the frame. The acknowledgments to all downlinks sent in the previous frame interval are also broadcast in the squitters.

An aircraft logged-on a particular frequency continues to use that frequency until it does not detect a useable squitter, which is broadcast every 32 seconds, or when the ground station does not acknowledge three consecutive downlinks sent by the aircraft. At that point the aircraft initiates a search for a new frequency and logs-on the new frequency. The hand-off of the connection from one frequency to another and from one ground station to another is totally transparent to the aircraft user.

1.3.4 **Digital signal processing**

Irregular behavior in the HF channel has left the perception that long-haul HF communications is intrinsically unreliable. This perception has been based upon years of experience prior to the advent of modern digital signal processing techniques. Early efforts in the use of HF as a transmission path for data links failed for reasons including problems with the signal-in-space waveform. The most recent HFDL trials began in 1990 and highlighted progress made in HFDL modems employing new digital signal processing technologies. The modems employed phase shift keying (PSK) modulation, forward error correction, interleaving of coded data and adaptive channel equalization of received data. These techniques enabled the modems to compensate for the distortion of the HF channel.

1.3.5 **Automatic selection of data rates**

HFDL allows for the transmission of data at rates of 300, 600, 1 200, and 1 800 bits/s. The HFDL function uses the slowest possible data rate available to support the message size of the downlink transmission. At any time, each link between the aircraft and ground station will have a maximum downlink and uplink data rate. The maximum uplink rate is determined by the aircraft and provided to the ground station where the maximum downlink rate is determined by the ground station and provided to the aircraft. These data rates are determined by evaluating the received signal. Insufficient or marginal signal-to-noise ratio will lead the aircraft to search for a new frequency from the same or different ground station which provides sufficient signal-to-noise ratio for establishment and use of the data link.

1.4 **Performance**

1.4.1 **Availability**

A six-month HF propagation measurement experiment was conducted to validate availability assumptions. Sites located in Hawaii, continental United States, and Puerto Rico were used to simulate up to four ground stations. A site in Sunnyvale, California was used to simulate an aircraft attempting to communicate with any of the other sites, some as far away as 3 000 km. Availability as high as 99.9 per cent was shown to be achievable over the period of the experiment.

In addition, HFDL trials being conducted over the North Atlantic for the 30 months prior to December 1995 have shown availability better than 95 per cent with three ground stations and two operational frequencies per ground station with no attempt made to optimize the selection of operational frequencies to counteract the effects of propagation disturbances. The availability should improve by adding more active frequencies per ground station, adapting the selection of operational frequencies to changing propagation, and adding more optimally located HFDL sites within regions.

1.4.2 Integrity

When HF voice is used to send waypoint position reports, there is a potential for human operator error when the operator transcribes the report. With HFDL data errors are virtually eliminated through the use of cyclic redundancy code (CRC) checksums appended to every packet. The CRC checksum allows the system to automatically detect all combinations of bit errors in the packet less than 17 bits wide, with the probability of not detecting bursts of errors wider than 17 bits being less than 1 in 10 million. Packets received with errors are discarded and not acknowledged. Unacknowledged packets are automatically retransmitted.

HFDL uses the same 16-bit CRC checksums as those employed by other aeronautical data systems such as SATCOM and VHF data link. Hence, the achievable level of data integrity is the same.

1.5 HFDL system relationship to HF voice

One of the driving forces for the development of data link systems in general is the difficulty of finding sufficient spectrum to allocate enough voice channels in the aeronautical service bands. As an example, the North Atlantic HF-voice based ATC system has a frequency complement of about forty 3 kHz SSB channels, which are kept reasonably interference-free.

HFDL makes more efficient use of the available HF spectrum than HF voice for a number of reasons. First, HFDL employs short burst transmissions of less than 2.2 seconds duration in time slots of 2.47 seconds duration to send data packets with up to 213 bytes of user data. A waypoint position report can be sent in a single 2.47 second slot. A time division multiple access (TDMA) and a slot reservation protocol described in the Annex to the HFDL SARPs, provides for the assignment of slots for uplink and downlink transmission to and from individual aircraft in order to avoid mutual interference between transmissions from ground stations and from multiple aircraft on the same time slot. A single voice contact to report a waypoint position report typically uses about 1 minute of channel time.

Secondly, by using digital signal processing techniques such as adaptive equalization and forward error correction coding to combat effects such as multipath, impulse noise from lightning and fading, more useable spectrum is available with HFDL than with HF voice. Thus, frequencies which are unsuitable for voice communications have the potential to be used reliably for HFDL. Moreover, HFDL signal processing techniques may enable multipath channels to perform with good reliability.

The more efficient spectrum usage with HFDL translates into greater system capacity per operational frequency. The number of aircraft that can be provided service in a given geographical area during a given hour depends on the number of data packets sent to and from each aircraft during that hour and the number of frequencies propagating to any of the ground stations providing coverage in that area. Simulations of the HFDL protocols indicated that twenty-six aircraft, sending eleven downlinks and receiving 6 uplink packets with 213 bytes of user data or less per hour, can be provided service per propagating frequency with a mean 31 second transfer delay through the network and a 95 per cent transfer delay of less than 36 seconds Table 1-1 provides a comparison of capability of HFDL with HF voice.

1.6 HFDL system relationship to SATCOM

HFDL when combined with SATCOM can provide a higher level of system availability than with a dual redundant SATCOM installation. This is because HFDL and SATCOM are deemed to possess quite independent failure mechanisms, whereas dual SATCOM does not provide the same degree of diversity advantage. The rest of this section presents more detail which illustrates the clear advantage achieved through a diversity combination of HFDL and SATCOM.

Two factors are considered when computing the availability of radio communications systems such as SATCOM and HFDL. One is the availability of the equipment, which is a function of the mean time between failures (MTBF) and mean time to repair (MTTR), and the other is the availability of the "propagation path", which in the case of SATCOM may include the availability of the satellite. The overall system availability is equal to the product of the two.

For simplicity, the ground station equipment availability is assumed to be 100 per cent or is included in the propagation path availability. The propagation path availability, as well as MTBF and MTTR values used should not be construed as actual demonstrated values, but are used for illustration purposes only.

Table 1-2 below compares the total system availability of a single SATCOM installation with that of a dual SATCOM installation. In the example. adding a second identical SATCOM installation on an aircraft increases the average reliability, or MTBF, of the airborne equipment by a factor of 1.5. The higher overall reliability shown improves the airborne equipment availability from 99.81 per cent to only 99.87 per cent and improves system availability from 98.8 per cent to only 98.9 per cent. This is always the case as long as the SATCOM system availability is limited by propagation anomalies which have an equal effect on both airborne installations.

In order to achieve an improvement on the overall system availability, dissimilar propagation paths are necessary. This may be accomplished by using HFDL as an alternate communication link to SATCOM. To illustrate this concept, Table 1-3 below gives the availability of a single HFDL installation as well as that of a SATCOM and HFDL installation. Note that when two dissimilar propagation paths (SATCOM and HFDL) whose outages (1 - availability) due to propagation effects are uncorrelated, the overall system availability is equal to 1 minus the probability that a SATCOM and an HFDL outage occur simultaneously (product of SATCOM and HFDL outage probabilities); hence the availability formula given in Table 1-3.

In the examples in Tables 1-2 and 1-3, even using a conservative value for the HF propagation availability, it is shown that a SATCOM and HFDL installation can achieve an order of magnitude higher availability (99.94 per cent) than a dual SATCOM installation (98.9 per cent).

Table 1-1. Availability of HF voice communications compared with HFDL

	HF VOICE COMMUNICATIONS	HFDL
Availability of Communications	• <80% availability	• >95% availability with coverage from 2 HF stations • >99% availability with coverage from 3 or 4 HF stations
Spectrum Usage	• 1-2 minutes per position report • Large fraction of available (propagating) frequencies unusable due to multipath and fading	• 2.5 s per position report • Adaptive equalization and forward error correction coding allow use of all available frequencies
Frequency Management	• Operator required to select/find good frequency • Ground can only contact aircraft if aircraft HF radio tuned to good frequency	• Automatic search and selection of good frequency based on channel quality measurement • Automatic hand-off of connection between ground stations
Data/message Integrity	• Prone to error when operator transcribes voice contact into a data message	• CRC checksums detect errors • Messages received with errors automatically retransmitted

Table 1-2. Availability of dual SATCOM installations

	Availability Formula	Example
Single SATCOM Installation	A_1 = availability of single SATCOM installation A_s = availability of SATCOM propagation & Ground Station $A_1 = \frac{MTBF_s}{MTBF_s + MTTR} \times A_s$	Single SATCOM $MTBF_s$ = 2575 hrs MTTR = 5 hrs $A_s = 0.990$ $A_1 = (0.998) \times (0.990) = 0.988$
Dual SATCOM Installations	A_2 = availability of dual SATCOM installation A_s = availability of SATCOM propagation & Ground Station $A_2 = \frac{1.5 \times MTBF_s}{1.5 \times MTBF_s + MTTR} \times A_s$	Single SATCOM $MTBF_s$ = 2575 hrs MTTR = 5 hrs $A_s = 0.990$ $A_2 = (0.9987) \times (0.990) = 0.989$

Table 1-3. Availability of SATCOM and HFDL installations

	Availability Formula	Example
Single HFDL Installation	A_1 = availability of single HFDL installation A_{hf} = availability of HF propagation & Ground Station $A_1 = \dfrac{MTBF_{hf}}{MTBF_{hf} + MTTR} \times A_{hf}$	HFDL $MTBF_{hf}$ = 4760 hrs MTTR = 5 hrs A_{hf} = 0.95 A_1 = (0.9986) x (0.95) = 0.949
SATCOM with HFDL Installations	A_2 = availability of SATCOM plus HFDL installation A_s = availability of SATCOM propagation & Ground Station A_{hf} = availability of HF propagation & HF Ground Station $A_2 = 1-(1-\dfrac{MTBF_s}{MTBF_s + MTTR} \times A_s)\times(1-\dfrac{MTBF_{hf}}{MTBF_{hf} + MTTR} \times A_{hf})$	SATCOM $MTBF_s$ = 2575 hrs MTTR = 5 hrs; A_s = 0.990 HFDL $MTBF_{hf}$ = 4760 hrs MTTR = 5 hrs; A_{hf} = 0.95 A_2 = 1 - [1 - (0.9981)x (0.990)] x [1 - (0.9990)x(0.95)] = 1 - 0.012 x 0.051 = 0.9994

Note.— This example shows HFDL availability of 95 per cent, while trials and analysis indicates that 99 per cent availability is realistically achievable.

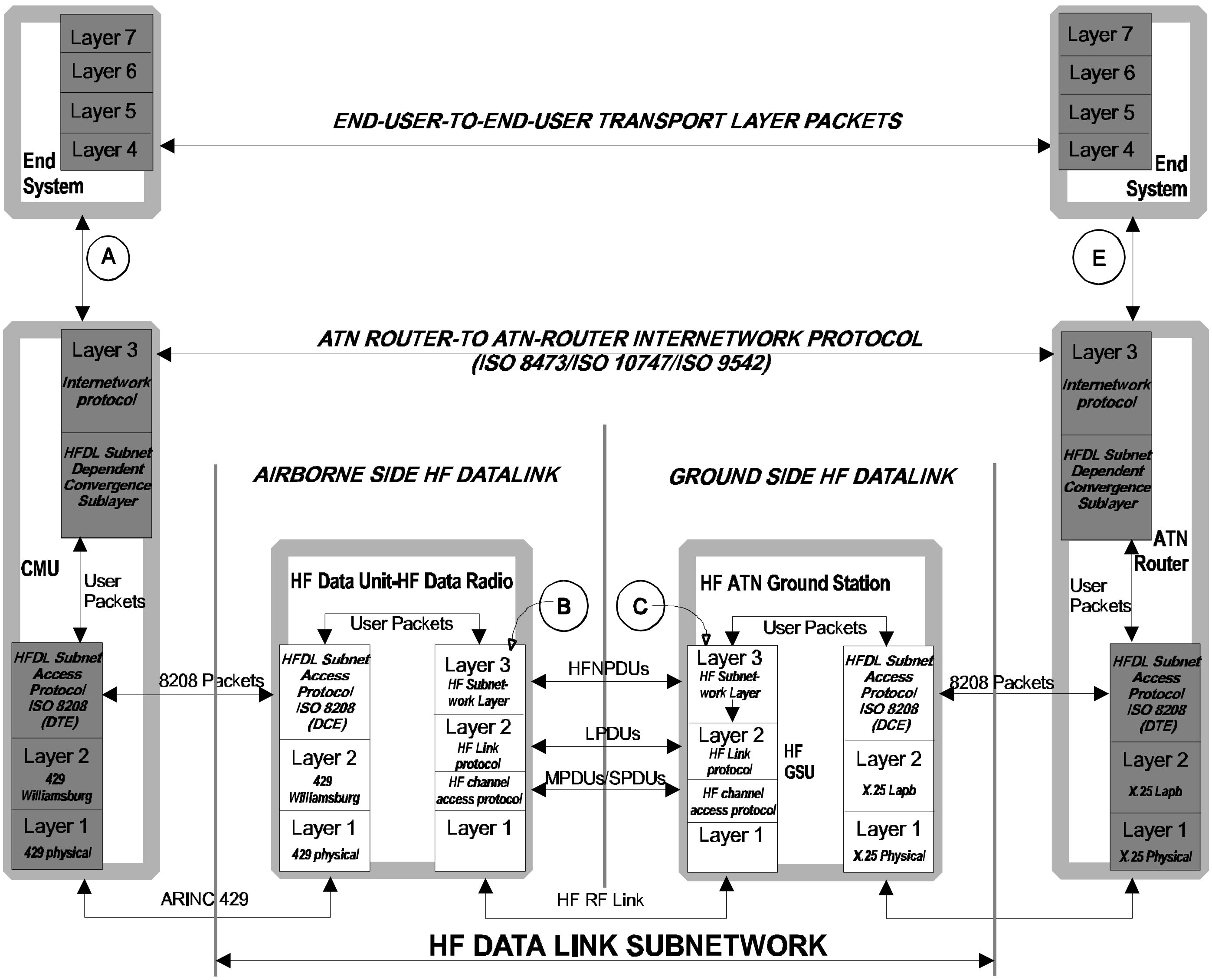

Figure 1-1. HF data link subnetwork protocols in ATN environment

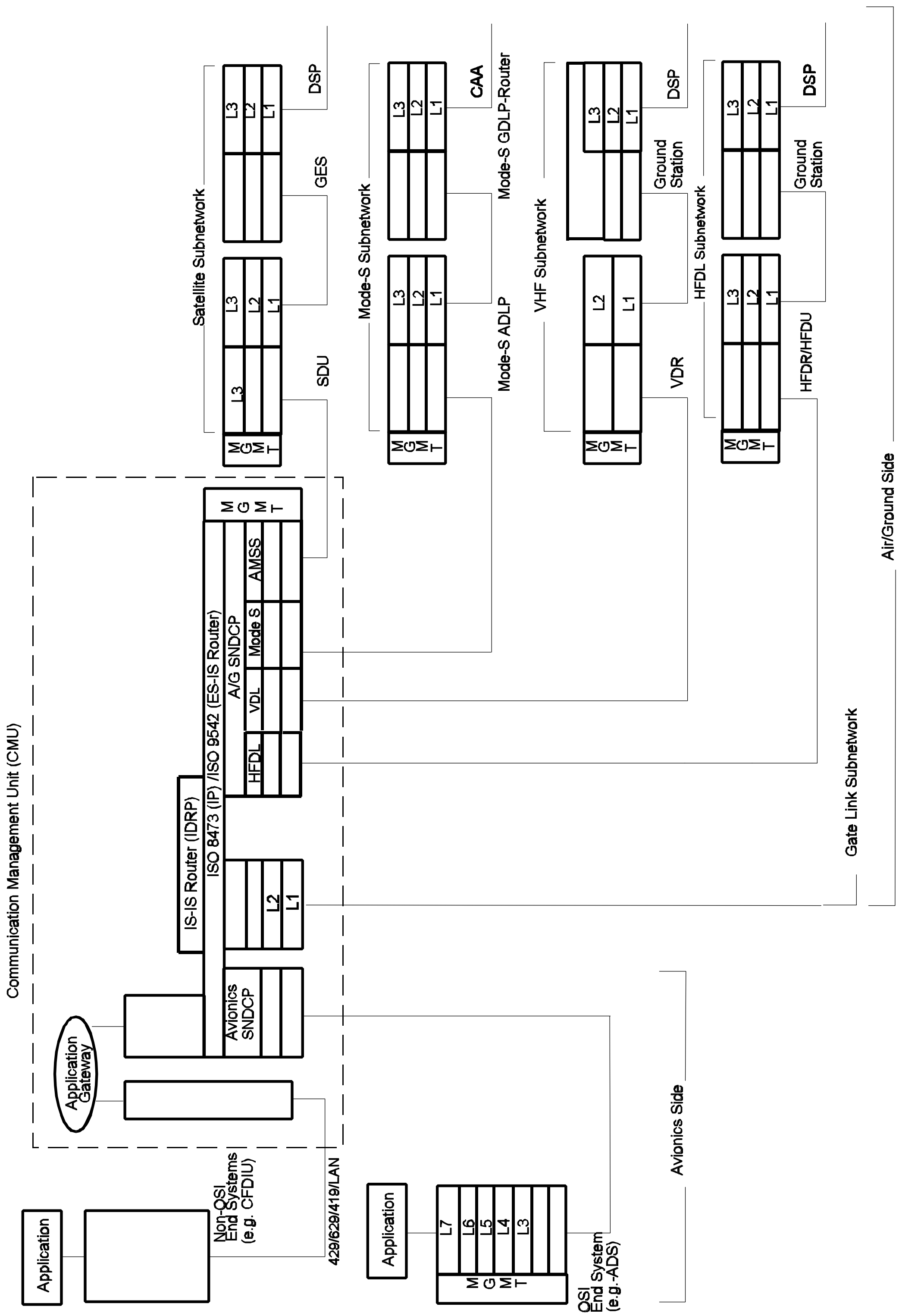

Figure 1-2. Airborne sub-system block diagram

2. HFDL SYSTEM DESCRIPTION

The HF system is described below in general terms. Due to the complex interdependencies of the various sub-systems comprising HFDL, far more detailed information is required for actual system implementation. While there are many ways to implement the functions required, the reader is advised to consult ARINC Specifications 634, 635, and 753 for details of one possible implementation, and ARINC Specifications 559A and 719 for compatible HF SSB voice aircraft radios.

2.1 Introduction

The HFDL system enables aircraft based computers to exchange data with ground based computers. Four separate sub-systems comprise the HFDL system:

a) HFDL aircraft station sub-system;

b) HFDL ground station sub-system;

c) HFDL ground communications sub-system; and

d) HFDL ground management sub-system.

2.1.1 HFDL aircraft sub-system

2.1.1.1 HFDL aircraft sub-system components

The aircraft station sub-system (Figure 2-1) includes the aircraft HFDL equipment and the airborne elements of the HFDL protocol. It provides the interface to the aircraft data link avionics. The following major components are part of the aircraft station sub-system:

a) HFDL transmission and HF data unit (HFDU);

b) Data modulation and demodulation;

c) HFDL protocol and frequency selection; and

d) Interface to the [airborne data link processor].

HFDL capability on the aircraft is provided by one of several methods, depending upon the equipment currently installed in the aircraft:

2.1.1.2 HFDL capability

a) installing an HF data unit (HFDU) which provides an interface between the management unit (MU) or HCF and a conventional HF/SSB voice radio; or

b) installing a service bulletin upgrade into an existing HF/SSB voice radio which adds HF Data Radio (HFDR) functionality into a single line replaceable unit (LRU) and provides interfaces to the MU/HCF; or

c) installing an HFDR as defined by HFDL SARPs.

Interfaces between the aircraft HF antenna couplers and HFDU, HFDR, or HF SSB transmitters and receivers are as specified in ARINC Characteristic 753. The HFDR also interfaces to the HFDL control function which is implemented either by modifying existing radio control panels, or by additional supplemental HFDL control panels. The HFDU and the data modules in the HFDR implement the HF modem, data link layer, and HF subnetwork access. The MU/HCF is a router/end system which, in addition to interfacing to the HFDL equipment, also interfaces to other data link subnetwork data communications equipment (DCE) on board the aircraft as well as end systems such as a flight management computer (FMC), aircraft condition monitoring system, or cockpit display terminal.

2.1.2 **HFDL ground station sub-system**

The HFDL ground station sub-system (Figure 2-1) includes the ground HFDL equipment and the ground elements of the HFDL protocol. It also provides for the interface to the ground-based HFDL end users. The following major components are part of the HFDL ground station sub-system:

a) HF transmission and reception:

- two to six HF/SSB transmitters with 1 kW power or greater, with one antenna per transmitter;

- two to six HF/SSB receivers with a single antenna shared by all receivers;

b) data modulation and demodulation:

- two to six HF modems (one for each transmitter/receiver pair) which implement the HFDL signal-in-space;

c) HF protocol and frequency selection:

- remote control and supervision equipment to tune and monitor the HF transmitters and receivers; and

- an HF ground station controller which implements:

  1) the ground side of the HFDL protocol including the management of the log-on procedures and frequency scheduling; and

  2) all the inter-ground and intra-ground station synchronization and generation of squitters; and

d) interface to the ground communications sub-system.

Each ground station implements the ground side of the HFDL signal-in-space, the HFDL protocol, and the means to interface to the HFDL ground communications sub-system.

Initially, a ground station may be equipped only with two or three transmitters, receivers, antennas and HF modems. Equipment can be incrementally added as more capacity is required.

2.1.3 HFDL ground communications sub-system

A ground communications infrastructure is required to interconnect HFDL ground stations, end users, and the HFDL management sub-system. Regional communication hubs may be used to internetwork regional HFDL ground stations and provide points of access to the HFDL system. Appropriate packet switched data networks will provide the connection between ground stations and hubs. The communications hubs would operate ATN routers to route messages between HFDL users and the HFDL ground stations which then relay the messages to the aircraft logged-on the ground station.

2.1.4 HFDL ground management sub-system

The HFDL ground management sub-system provides the means to operate, manage, and maintain the HFDL System. The HFDL management sub-system provides the following functionality:

a) aircraft log-on status table management;

b) system table management; and

c) frequency management.

The frequency management function is unique to the HFDL system. In order to make efficient use of the limited spectrum available for HFDL and to maximize system availability, the HFDL ground stations should share frequency assignments and co-ordinate their use in real time based on actual propagation data. Initially, when there are very few users of the system, frequency management may be based on predictions of frequency propagation. Available HFDL frequencies may be assigned on a geographic basis. Each HFDL ground station would have a table of frequencies and associated operational times.

As HFDL system usage grows and capacity and availability become more of an issue, dynamic frequency management capabilities should be added to the system. Moreover, dynamic frequency management will be critical during disturbed propagation which arises as a result of increased solar and geomagnetic activity. For example, actual propagation measurements could be used to evaluate HF propagation patterns in real-time and provide input to a frequency management algorithm.

2.2 Ground station synchronization

The HFDL system is designed to take advantage of time synchronization in the broadcast of squitters. These squitters are used to mark the beginning of the 32 second frames, allow the airborne receiving system to determine availability of a communications channel, and to transmit system management information. The ground stations are expected to transmit the squitters in an organized time staggered manner. This assures that within a station, there is a known pattern of transmissions. Additionally, the ground stations are expected to synchronize their squitter transmissions to Universal Time Co-ordinated (UTC). The total synchronization allows the airborne receiving systems to know when to expect a squitter on each frequency, thus allowing improved acquisition times.

2.3 Antennas for HFDL ground stations

2.3.1 General

The Ground station operators (ground station operators) for the HFDL provide communications to and from aircraft, which are located at various distances from the ground station operators. These distances vary from very short to longer distances perhaps as far away as 4 000 to 5 000 km, but are normally in the 2 500 km range. VHF frequencies generally cover communications out to about 400 km; however, there may be instances when HF might be used as an alternate communication medium within this range. Thus the ground station operator ground station antennas should provide communications coverage for distances between less than 400 km to over 4 000 km. For purposes here a short range antenna covers out to about 1 000 km, a moderate range antenna covers about 800 to 3 000 km, and a long range antenna covers 3 000 km and beyond.

At HF the radio waves refract off the ionospheric layers that exist between 100 to 300 km above the Earth. The antenna must direct maximum radiation at the ionospheric refracting layers at desired elevation and azimuth angles that will result in refracted radiation coverage to desired locations. For instance, if an aircraft is 350 km from a ground station operator, maximum radiation from the antenna should occur at an elevation angle near 60 degrees for refraction off the 300 km high ionospheric layer. In this case the ray path from the ground station operator to the ionosphere and then to the aircraft forms an approximate equilateral triangle including a direct line between the ground station operator and the aircraft; this simple one-refraction path is called a one-hop path. As the distance increases, the elevation angle or take-off-angle for the one-hop path decreases; the take-off-angle of the one-hop ray can get as low as about three degrees for the longest paths. Three degrees is typically a minimum take-off-angle being limited by nearby hills, other obstructions and antenna radiation pattern under cutting at the very low elevation angles. In general, the path to the receiver may consist of several hops; for instance, a two-hop path occurs where there is a ground refraction midway between the ground station operator and the aircraft and there are two refractions from the ionospheric layer. The one and two hops may exist singly or simultaneously. When two or more paths occur at the same time, this is known as multipath propagation.

A given ground station operator may be able to use several antennas to provide required short to long-range communications. Antenna selections may include a short-range omnidirectional antenna combined with several moderate to long range directive antennas. Also, a ground station operator may have limited land area available and may need to use a small number of antennas of a single type that provide satisfactory service to all ranges. At HF the transmitting and receiving sites for a single ground station operator are usually spaced at least 5 to 10 km in order to provide high isolation between the HF transmitters and HF receivers and to allow a lower radio noise environment at the receive site.

Antennas for HFDL should cover the band 2 to 30 MHz. The highest aeronautical mobile frequency is 22 MHz.

2.3.2 Antennas for transmitting sites

For transmission of HF radio waves, a horizontally polarized (HP) antenna is generally the better choice over a vertically polarized (VP) antenna because the ground refraction loss for HP waves is small and the ground refraction loss for VP waves is relatively large. The HP antennas typically have at least a 6 dB advantage over the VP antennas in terms of power gain unless extensive ground screens are used under the VP antennas. A VP monopole antenna with a good ground screen can provide satisfactory low angle coverage; however, this antenna has a null overhead and is not satisfactory at ranges shorter than about 800 km, where typically high angle coverage is needed. A VP monopole antenna may be an adequate choice if the ground station operator does not have any short path communications requirements.

2.3.3 Antennas for receiving sites

A highly efficient receive antenna is generally not needed because of the relatively high levels of man made and atmospheric radio noise at HF. For receiving, it is much more important to use antennas with a high directive gain so that the signal level picked by the antenna is enhanced relative to the noise. Under the assumption that equal noise power density is being received from all directions, which is usually the case, the total noise power received by the antenna is independent of the antenna directivity. Thus the received signal to noise is increased by increasing receive antenna directivity.

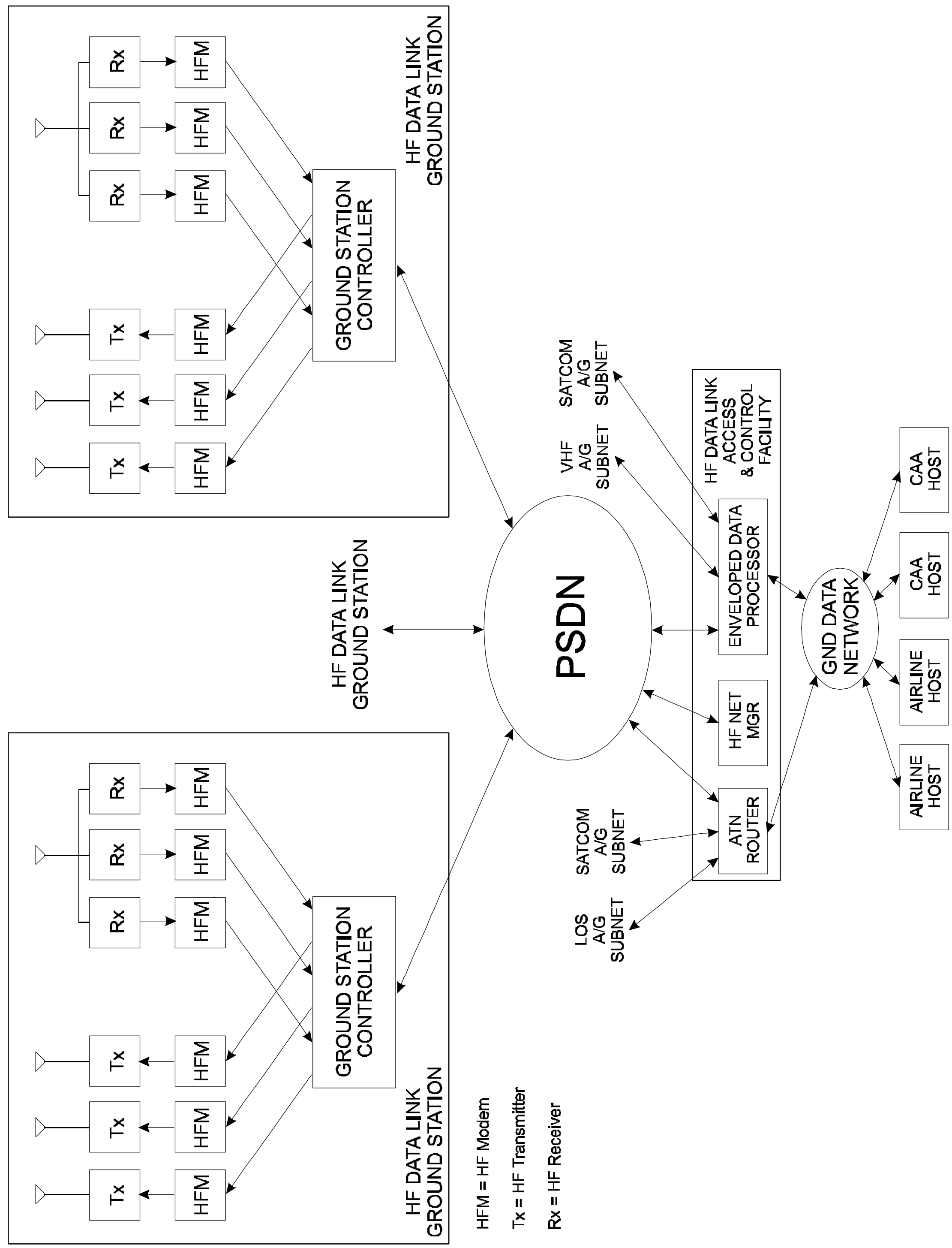

Figure 2-1. HFDL ground sub-systems

3. GROUND STATION NETWORKING/INTEROPERATION

3.1 Overall system concept

The goal of the ICAO CNS/ATM concept is to implement a global system which offers an improvement over current communications, navigation, surveillance and air traffic management solutions. The current concept for the communications solution relies on satellite communications (SATCOM) for global coverage and line-of-sight systems for high-traffic volume communications in the terminal area. Furthermore, the cost-effective communications solutions to satisfy the CNS/ATM concept are expected to have a high degree of availability (communications availability is expected to be 99.4 per cent or greater). To achieve these levels of communications availability in the oceanic regions, aircraft are being equipped with dual SATCOM installations. However, if the actual availability does not meet the expected system availability, a second data link system capable of reliable communications in the oceanic region would be required.

HFDL is capable of providing communications in oceanic and polar regions. A combination of SATCOM with HFDL should provide higher availability of communications than a dual SATCOM installation. In order to fulfill these expectations, the HFDL system should be capable of achieving a significantly higher degree of availability over the current HF voice system, and the recurring per message unit charges should be competitive with those of SATCOM. The HFDL system should also make effective use of the spectrum and utilize a sufficiently low number of frequencies to allow for a smooth transition from a voice based HF communications system to a primarily data link based system with reduced HF voice communications traffic.

An HFDL system with recurring per message unit costs that are competitive with those for SATCOM requires that the number of HFDL ground stations be kept to the minimum number required to achieve the expected coverage, system availability, and capacity. Too many HFDL ground stations result in excess capacity, high recurring per message unit costs and inefficient use of the spectrum. The location of the HFDL ground stations is also important because of their impact on the overall system coverage and availability. Thus, the current practice of individual states operating HF ground station to provide full area radio coverage for air traffic services (ATS) in a flight information region (FIR) is likely an efficient solution. An HF voice ground station for each FIR would be replaced with one in which states responsible for ATS share the communications services provided by fewer optimally located HFDL ground stations much in the same way they may share the communications services provided by SATCOM Ground Earth Station (GES) facilities. As with SATCOM, the control of ATS will remain with the state responsible for the FIR. A reduced number of HF ground stations will result in a more efficient and more cost-effective HFDL communications system.

To achieve a significantly higher system availability over the current HF voice system, the practice of each aircraft communicating with the HF ground station facility covering the FIR should be replaced with a more effective global solution. Each aircraft should communicate with the ATS controllers responsible for an FIR via a link to any HFDL ground station utilizing any assigned frequency which is propagating at that time. This method of operation allows the system to take advantage of propagating frequencies that would not be available to the current voice system. The availability of the proposed HFDL system should be improved considerably when the aircraft is within 4 000 to 5 000 km of three or more HFDL ground stations. This concept of multiple HFDL ground station coverage with multiple frequencies is often referred to as space and frequency diversity and is used effectively in a number of different communications systems.

The HFDL system should employ frequency reuse as much as possible without compromising the integrity and performance of the system to achieve efficient use of the spectrum and allow for the coexistence of HF voice and data link systems. The nature of HF propagation allows HF radio signals propagate over very long distances. Fortunately, frequencies above 8 MHz generally propagate in the day while frequencies below 8 MHz generally propagate in the night . Hence, in the future, the same HFDL frequencies may be assigned to more than one ground station to achieve frequency reuse. Since data link systems are controlled automatically information needs to be exchanged between the computers in real time. Furthermore, in order to be able to maintain system capacity during a variety of propagation conditions , assigned frequencies may need to be monitored at all HFDL ground stations. This can best be accomplished if all HFDL ground stations are able to share and co-ordinate an available pool of HFDL assigned frequencies.

3.2 Ground station networking and HF propagation

Experience with the HFDL trials and research has shown that the optimum design for the worldwide HFDL System requires that HFDL ground stations be located to take advantage of the nature of the HF medium itself, rather than rigid structures based on geopolitical boundaries such as used in traditional FIRs. This methodology depends on a departure from the traditional approach to providing HF based ATS services.

Practical considerations for HFDL ground stations locations may be determined by a number of factors, including:

a) communications coverage of aeronautical routes requiring HFDL support;

b) ability of a site to provide aeronautical frequencies;

c) availability of acceptable HF transmission and reception facilities;

d) availability and cost of telecommunications connections; and

e) interest and co-operation among ground station operators.

With the application of frequency reuse concepts to a network, approximately sixteen HFDL ground stations should be able to provide coverage on a world-wide basis with better than 99.4 per cent system availability and the capacity for over 2 000 aircraft.

3.3 Ground station interoperation

To handle the transition to ATN, at least one of the communications hubs would operate a FANS-1/A service processor to provide HFDL network service access points to FANS-1/A users. At least one of the hubs would also operate as an HF network manager, responsible for real-time management of the frequencies shared by the HFDL ground stations and network performance monitoring. The protocol between the HFDL ground stations and the communication hubs may be connection-oriented (e.g. X.75) or connectionless (e.g. [ISO 8473]). Data terminal equipment (DTE) addresses, which are exchanged during call set-up, are used to route packets between HFDL ground stations and the appropriate communication hub.

For example, assume the regional communication hubs are located in North America, Europe and the Pacific Rim. States responsible for ATS would access the HFDL network via the nearest communication hub using dedicated leased circuits or suitable packet data networks which form part of the ATN. Similarly, aircraft operators whose aircraft are equipped with HFDL would also access the network via the nearest communication hub in similar fashion.

3.3.1 **HF operational changes**

Two critical changes must be made to existing HF operations to ensure the success of the HFDL system. First, aircraft operating in an HFDL environment will no longer be handed off at HF ground station operator boundaries. Instead, aircraft will log-on to new HFDL ground stations as signal strength on the existing HFDL ground station channel fades. Second, HF ground station operators should provide their frequencies to a regional pool of frequencies managed from a central HFDL system management entity. The success of the HFDL System is dependent on successfully adoption of these concepts by the international community.

3.3.1.1 **Number of HF ground stations per geographic region**

Propagation investigations show that typical communication availability's of 80 per cent or better may be achieved for a single ground station over a region with a 5 000 km radius under prescribed conditions. The propagation studies show that at the higher latitudes (viz., geomagnetic latitudes > 60 degrees), the availability of coverage with one ground station decreases significantly during periods of geomagnetic activity. These regions of the ionosphere expand and contract with changing levels of magnetic activity. Hence, a precise determination of which paths may suffer from poor availability cannot be predicted. At midlatitudes, large ionospheric storms may occasionally limit the number of propagating bands, and this may present some difficulty for individual links over which no path diversity measures can be exercised.

The number of HF ground stations needed per geographic region depends on the desired system availability (fraction of the time that coverage is available at a given point within the geographic region). For two or more ground stations, one may achieve 92 - 95 per cent communication availability under benign conditions excluding the regions influenced by auroral phenomena. Availability's of 99 per cent or higher can be achieved with three ground stations, and even higher with four ground stations. Propagation measurements made at midlatitudes during a large magnetic storm have shown that station diversity and the occurrence of sporadic E propagation modes are two factors which may limit or even eliminate outages during ionospheric storm conditions at midlatitudes.

For example, the propagation studies suggest that frequency assignments in six to eight different bands between 4 MHz and 22 MHz are necessary to provide an availability of 99.4 per cent or better with 3 or more ground stations. Sufficiency is regulated by other factors including magnetic activity, the geomagnetic latitude of the aircraft track, and the aircraft local time. In general, if frequencies in each of the aeronautical mobile bands are available in concert with four ground stations, then the following service availability's are achievable in designated geophysical regions:

a) polar (99.2 per cent);

b) auroral (99.5 per cent);

c) trough (99.92 per cent); and

d) midlatitude (99.94 per cent).

The incremental improvement in service availability is finite, but clearly exhibits a diminishing return beyond three to four stations when long-term average availability's are examined. The lower availability's normally experienced at high latitude paths and occasionally at midlatitude paths can be mitigated by employing station selection flexibility and dynamic frequency management.

3.3.1.2 **Minimum number of operational frequencies to serve the peak load per region**

Propagation studies show that eleven frequencies and four ground stations may provide optimum service availability's for an HFDL system. However, it is possible to achieve acceptable service with fewer stations and a reduced set of assigned operational frequencies. Under some conditions, the system may deliver availability's approaching 99.4 per cent with 6 to 8 frequency bands using three ground stations. The actual number of frequencies needed in each band depends on the number of aircraft that are to be provided service at the peak hour and the number of messages sent per aircraft per hour.

The HFDL simulation studies indicate that a single HF propagating frequency can provide simultaneous service to at least twenty-six aircraft sending an average of eleven downlinks per hour and receiving an average of six uplinks per hour, with a mean 34-second transfer delay through the network and a 95 percentile transfer delay of less than 120 seconds. The actual required communication performance (RCP) standards for HFDL should impact the actual number of aircraft supported on each frequency. Simulations show that by managing the number of slots used for random access and by using the polling method, up to forty aircraft may be supported. Thus, one frequency between 4 to 8 MHz propagating to/from any of the HF ground stations in the geographic area can typically provide service to twenty-six to forty aircraft at night, one propagating frequency between 8 to 10 MHz can typically provide the same service in the early evening/early morning hours, and one propagating frequency between 12 to18 MHz can typically provide the same service during the late morning and afternoon hours.

To provide service to 130 aircraft, five frequencies propagating to/from any of the HF ground stations in the geographic area are needed. Twice as many propagating frequencies are needed to service 260 aircraft.

3.3.1.3 **Number of operational frequencies per station and geographic region**

To provide service to 130 or more aircraft during the busiest hour with 99.4 per cent availability, three ground stations with three transmitters/receivers each are needed. Thus, at any one time there would be nine operational frequencies providing coverage over the geographic region. Only five of the nine operational frequencies are needed to propagate to the actual locations of the aircraft within the geographic region to guarantee service to the aircraft. Higher availability of 99.9 per cent or more can be achieved and service to more than 130 aircraft can be provided with four ground stations each operating on three or more frequencies.

Because each ground station operates on at least three frequencies simultaneously, and assuming there are three ground stations per geographic region, there are at least nine operational frequencies “on-the-air” that each aircraft can use. To facilitate an aircraft's choosing a frequency that is propagating well at a given time of day for its particular location, all ground stations broadcast messages, called squitters, on each of their operational frequencies every 32 seconds. Each aircraft periodically and momentarily monitors each of these frequencies during system squitter time, and selects one that is appropriate to the selection criteria. Aircraft dispersed throughout a geographic region would most likely select different frequencies because it is highly unlikely that the same frequency can be received everywhere within a large geographic region such as the Atlantic or Pacific. The traffic from all aircraft would, thus be distributed among the various frequencies, thus enhancing the efficiency of frequency utilization. Aircraft should have the freedom to communicate with any of the ground stations on any of its available frequencies regardless of its location within the geographic region in order for the system to be efficient and reliable.

Since not all operational frequencies are guaranteed to be propagating to twenty-six aircraft in the coverage region, the number of operational frequencies in a geographic region should exceed the minimum number of propagating frequencies needed to serve the peak load in the region by 20 to 50 per cent. The closer the number of operational frequencies is to the minimum number of propagating frequencies needed to serve the peak load, the more important is the use of dynamic frequency management. On the other hand, when the number of actively monitored frequencies exceeds the minimum number of propagating frequencies needed by 100 per cent or more, dynamic frequency management should not be needed.

3.3.1.4 **Number of operational frequencies needed on a global basis**

The total number of frequencies needed on a global basis depends on whether or not frequencies are reused in different geographic regions. Note that in this context, “frequency reuse” means that two transmitters operating in two different regions of the world operate at the same time on the same frequency; while “frequency sharing” means that two transmitters in different regions or in the same region may use the same frequency, but not at the same time. Both frequency reuse and frequency sharing depend on co-ordinated dynamic frequency management.

HFDL needs to utilize full frequency sharing and frequency reuse to provide a world-wide service to more than 1 000 aircraft. The total number of frequencies needed on a global basis with full frequency sharing, but no frequency reuse should be equal to the total number of operational frequencies needed to service the peak load for all regions, plus 30 to 40 per cent. This is to account for the fact that frequencies above 17 MHz do not propagate during certain portions of the solar cycle. In addition, when these higher frequencies do propagate, they propagate over very long distances. Therefore, they either cannot be used at all or can only be used by one ground station.

The following example illustrates the concept for frequency sharing and reuse. Assume that there are fifteen ground stations in the network, with five stations in each of three regions. Each region is assumed to be eight time zones wide. Frequencies can be used simultaneously by one ground station in each region provided the stations are eight time zones apart. To help identify the frequency assignments, each station has a unique group of frequencies assigned to it. These groups are labeled A, B, C, D, and E. Also, assume that there is a pool of sixty frequencies available that are divided into twelve families of five frequencies. The frequencies within a family are typically selected from different aeronautical bands with a common geographical area assignment. The families are labeled a, b, c, d, e, f, g, h, i, j, k, and l. If each station is pre-assigned twenty frequencies, then each station is assigned four of the 12 families. For example, assume the following assignments are made:

A = {a, f, k, d},

B = {b, g, l, e},

C = {c, h, a, f},

D = {d, i, b, g},

E = {e, j, c, h}

Within each region, two stations may share frequency assignments, e.g. the two stations assigned groups A and C share families a and f. However, only two out of the four families are primarily used at each station, and the other two are to be used only when necessary on a non-interfering basis with the other station sharing the assignments. For example, the first two families in each group may be defined as the primary families in region 1, the second and third families as primary in region 2, and the third and fourth families as primary in region 3. Stations sharing group assignments in different regions do not need to co-ordinate use of their frequencies, but it would help if they did. And, by assigning different primary frequencies within each region, at most only two stations may be on the air on the same frequency at the same time as long as they are using their primary frequencies. In order to limit potential interference on uplinks to transmissions from ground stations, the squitters should be synchronized.

3.3.1.5 **Dynamic frequency management**

In order for the system to work efficiently and be free of mutual interference between HFDL ground stations, each transmitter/receiver at each ground station within overlapping coverage areas should operate at a different frequency at a given instant in time. The operating frequency of each transmitter/receiver may need to be changed periodically to maximize the system availability. In practice, the HFDL trials have shown that maximum availability depends on the capability to change frequencies on an hourly basis. In any 24-hour period the same frequency may be used at the two, three, or four ground stations covering the same geographic region, but never at the same time. Therefore, frequency assignments for all the HFDL ground stations should be co-ordinated from a single HFDL system management function. Initially, when the system is providing service to only a few aircraft, the frequency scheduling at each ground station can be fixed from day to day. As the system utilization grows, a more sophisticated approach using real-time HF propagation data and frequency utilization techniques is needed to maximize the capacity, efficiency and availability of the system.

3.3.1.6 **HFDL geographic regions ground stations**

One possible way to estimate number of ground stations in the geographic regions is to define them to fit the predominant use of HFDL in oceanic and remote areas. Using this approach the estimated number of ground stations per each of the three regions are identified as follows:

REGION	AREA	No OF HFGS FOR REGION	AIRCRAFT FLYING IN REGION
Atlantic	Atlantic, Caribbean and South America	5	700
Pacific	Pacific, Australia and Micronesia	6	800
Asia	Indian Ocean, Russia, and	5	500

REGION	AREA	No OF HFGS FOR REGION	AIRCRAFT FLYING IN REGION
	Africa		
TOTAL		16	2 000

Each of these regions is eight time zones wide. These three regions provide for the smallest HF coverage areas that can support frequency reuse, given the stringent availability requirements of ATS communications, and the largest areas within which continuity of service can be expected on a routine basis.

The sixteen ground stations should share a pool of about forty-eight to sixty frequencies with real-time co-ordination between them in order to make efficient use of the frequencies. Otherwise, a larger pool of frequencies would be needed. The ground stations should operate simultaneously on three to six frequencies depending on the capacity required. Thus some frequencies in the HFDL pool would be used simultaneously at two or three HF ground stations. The HFDL ground stations should be internetworked to one or more hubs as described in Section 3.

3.3.1.7 **HFDL coverage and flight information region considerations**

The flight information regions (FIRs) have been traditionally divided on the basis of sovereign airspace and/or operational technical size limitations. ATS service provided within the FIRs usually involves the use of HF voice and typically has been the responsibility of the State operating the FIR.

Experience with the HFDL trials and research to date has shown that the optimum design for the world-wide HFDL system will require that HFDL ground stations be located to take advantage of the nature of the HF medium itself, rather than rigid structures based upon geographical boundaries such as a FIR. This methodology requires a departure from the traditional approach to providing HF voice based ATS services.

From the end-users perspective, e.g. the oceanic ATC controller, the location of the HFDL ground station will not be an issue. In an HFDL environment, the source and destination of the air/ground data packets will both reside within the responsible States operational boundary, regardless of the location of the HFDL ground station. In order to combat HF propagation anomalies effectively by means of HF ground station diversity and make efficient use of the HF spectrum, each FIR need not operate its own HFDL ground station and aircraft should no longer be required to communicate with the ATC authority responsible for the FIR via the FIR's HF ground station. In fact, if aircraft were to be required to communicate via a specific HFDL ground station within each FIR, the availability of the HFDL system would be seriously degraded, perhaps to the point where HFDL would not be viable as an oceanic data link, and the amount of HF spectrum needed for HFDL would be greater than it need be.

3.4 HFDL operational issues

There are a number of operational issues which may impact the operation of the HFDL system.

3.4.1 Sharing HF propagation knowledge between the voice and data systems

Aircraft crews currently maintain contact with HF voice operators when in oceanic airspace. Over time as the equipage with HFDL and SATCOM increase, the operational requirement to use HF voice may be relaxed. However, HF voice will probably still be used as a backup media. The challenge will be to maintain situational awareness of what HF frequencies are propagating to the aircraft at any given point of time. The HFDL system maintains this knowledge and at some point in time it may be appropriate to provide this information to the HF voice radio operators.

3.4.2 HFDL use on the ground

Some users may have interest in using HFDL as their only data link media. In order to move in this direction, some of these users will require HFDL to be used while on the ground. This is primarily a safety issue that each user will have to address on a case-by-case basis. If the ground crew grounds the airplane in accordance with standard operating procedures, there is no problem. If the ground crew does not, and the aircraft is being fueled, and the aircraft transmits over HF, there is a potential for problems. Even with its own HF radio disabled, an adjacent aircraft could transmit over HF and create problems for an improperly grounded aircraft being fueled.

4. SYSTEM IMPLEMENTATION AND GROWTH

4.1 Transition/capacity growth

The transition from voice based ATC/AOC services to packet data services has been documented as showing an exceptional increase in channel utilization efficiency. In the case of operational VHF AOC communications, VHF ACARS data link service was introduced in 1978. At that time, ARINC VHF voice network contacts numbered some 400 000 per month. Ten years later, that quantity was about 25 000, over an order of magnitude lower, while the number of data messages was about 5 000 000 per month. Conservatively assuming that one “voice contact” is equivalent to two ACARS messages (i.e., a query-response pair), then the number of voice contacts would be 2 500 000. Further, the data link messages were handled on a single nation-wide frequency, as contrasted with a large number of frequencies that would have been required to accommodate the equivalent voice messages.

In the case of HFDL, the achievement of operational benefits tied to CNS/ATM capability is expected to facilitate and promote a more rapid transition. HFDL is designed to become a fully compatible element of ATN communications capabilities, in association with SATCOM, for those aircraft where SATCOM is implemented, and as a cost effective alternative to SATCOM for aircraft where SATCOM installation might be economically difficult. An understanding of the transitions and capacity growth for HFDL should begin with a review of the existing HF voice system, the major differences of the HFDL system, the early implementation spectrum issues, the projected freeing up of HF voice spectrum for use in the full implementation of HFDL, and the fact that there are many viable paths to full implementation.

The existing HF services available are voice based and are designed to be delivered with a ground station within a State's FIR (flight information region). Experience with frequent outages and channel interference are common knowledge to the users. The long range goals of the HFDL service is to increase useful capacity through digital communications techniques and increase the availability through multiple propagation paths. The use of multiple ground stations will bring with it a need for a change of how ATC messages are processed.

4.1.1 Coverage transition

Initially the coverage will be along high density routes and on a regional basis. The transition from the initial regional coverage towards a global HFDL coverage could happen in a number of ways. One service coverage area may grow towards a global service or various service coverage islands may merge into a global network. No single path to global service coverage is assured, but there may be a combination of methods employed.

4.1.2 Implementation scenario

HFDL has been used for aeronautical operational communications (AOC) since the inception of an early North Atlantic service in 1994, and the benefits for such "company communications" was immediately recognized. However, the viability of carriage and use of such a specialized safety communications service requires that benefits also be realized from the domain of air traffic services (ATS). This is foreseen as occurring in an incremental fashion over the course of ATS trials during the next several years.

The number of aircraft equipped with HFDL capability is expected to grow to more than 2 000, over a period of fifteen years. Hence, a planned implementation of the HFDL ground stations is envisioned. One of many possible implementation scenarios would be to start with three HFDL ground stations to provide coverage over the North Atlantic, Caribbean, and northern part of South America. An additional four ground stations would be added to the network to provide coverage over the Pacific. These HFDL ground stations would have more than sufficient capacity to handle the projected traffic load in these regions beyond the end of this decade using four families of six frequencies provided the same four families can be used in both regions.

World-wide coverage including the Indian Ocean/Asia/Africa region is expected to be needed after 2002. The network of HFDL ground stations would be expanded to twelve by adding three in the Asia region. That would establish coverage to all major air routes with the five stations in the Pacific, four in the Atlantic and three in the Indian Ocean/Asia/Africa regions. Expansion to a full network of sixteen HFDL ground stations would occur because of capacity needs and improved coverage demands.

4.1.2.1 Increment — information services and simple clearance deliveries

Following successful trials and experience in operation with waypoint reporting, a next step might be flight information services and weather such as may be available via an ACARS service. Further, simple clearance deliveries (e.g., oceanic clearance delivery) as is currently supported by Transport Canada over VHF ACARS may be supported. Of course, such use of HFDL would be viewed as a backup to VHF ACARS, as the aircraft would be expected to be in line-of-site range under normal circumstances.

4.1.2.2 **Increment — ACARS/ARINC 622 environment/FANS-1/A routing**

Significant further incremental benefits would be dependent on upgrading the HFDL capabilities to compliance with the ACARS/ARINC 622 environment. HFDL may be deemed satisfactory for communication requirements associated with reduced vertical separation minimums (RVSM). An ACARS/622 capability, if combined with other upgrades in navigation, flight management system and message-handling capabilities in accordance with FANS-1 standards, could lead to ATS scenarios utilizing direct controller-pilot data link communications (CPDLC) and possibly automatic dependent surveillance (ADS). Significant benefits accrue to aircraft so equipped and using SATCOM in the South Pacific, Southeastern Asia, and potentially elsewhere, resulting in limited longitudinal separation reductions and more nearly optimized routing. Such operations would also depend on the demonstration that HFDL can meet the operational requirements which are based on the expectations of SATCOM performance; and perhaps on the full utilization of AM(R)S frequencies. The timing of this increment with respect to the development of the HFDL system could be such that additional benefits may be accorded to FANS-1 equipped aircraft, such as limited lateral separation reductions.

4.1.2.3 **Increment — ATN scenarios**

With further positive experience with HFDL and implementation of ATN with corresponding equipage of aircraft and ground facilities, increasingly optimized flight profiles will be possible. Aircraft equipage would include a GPS navigation, flight management system (FMS) with autoload, full CPDLC data communications, an ATN router, and optionally ADS. Ground equipment would include ATN-compliant networking, ODAPS with conflict probe and ADS, CPDLC and an on-line data interchange (OLDI) workstation. Initially, CNS/ATM-1 would be used which may provide a reduction to ±1 000 foot vertical separation. Experience and enhanced ATN implementations are expected to provide longitudinal and latitudinal separation reductions to 50 per cent of today's standards, increased use of cruise climbs and a 25 per cent reduction in mandatory fuel reserve. In this realm, the data link traffic for a typical oceanic flight is projected as follows:

1) one altitude assignment per flight, with following WILCO altitude;

2) one DARPS route message per oceanic flight (containing fifteen way-points), with following WILCO;

3) one extended ADS report per 15 min;

4) two AOC messages per hour; and

5) twenty per cent additional traffic for miscellaneous ATS, WX, AOC and system management messages.

ATTACHMENT 1

1. OPERATIONAL CONCEPT (SCENARIOS)

1.1 HFDL operational concepts

This section provides a description of a future HFDL equipped flight as a means of introducing HFDL operational concepts. It should be emphasized that there are a number of different methods for implementing some of the technical aspects of the HFDL system and this description is provided only as a means to explain some of the more important features of the HFDL system.

1.2 AOC operational concept

HFDL provides the medium for efficient, long range exchange of safety information for AOC reasons. Routine long range AOC communication involves elements of international travel and increasing use of twin engine aircraft in an Extended Twin Engine Operations (ETOPS) environment. HFDL provides the AOC data exchange that the operator needs to deal with routine, urgency and emergency situations efficiently. HFDL provides relief from cumbersome voice contact and telephone patches.

1.2.1 Flight crew need for AOC HFDL

The need for long range data exchange varies widely by airline. However, as a minimum, HFDL permits the flight crew the timely access to the operator's flight-following personnel for flight position, schedule tracking and fuel burn projections. In addition, HFDL provides the flight crew the means to request automatic terminal information service (ATIS) and weather information and NOTAM for alternate and destination airports from the airline host computer and an increasing number of airports while in areas where line of sight data is not available. HFDL allows the exchange of fixed format messages such as [hijack] or free text messages between the flight crew, dispatchers, and maintenance personnel. Keystroke errors can be minimized by an airline transmitting route changes to compatible flight management systems (FMSs). These types of messages are typically short (less than 100 characters), and are routinely sent throughout the course of a flight. The system design provides a transparent selection of air/ground medium. HFDL, so integrated, becomes invisible to the flight crew as media transitions are automatically performed by the avionics system.

1.2.2 Other operator need for AOC HFDL

The HFDL medium is useful for many purposes other than flight crew use. Some airlines send automatic position reports, weather reports, and real time, automatic engine performance monitoring. These messages are rather long (over 100 characters) and are sent frequently during the en- route phase of the flight. Infrequent, but important reports are needed during en- route flight phases, such as when an engine or APU exceeds a normal operation or is shut down. Ground maintenance personnel may use HFDL to poll certain engine functions on demand.

1.2.3 Synergy and comparison with SATCOM

HFDL provides full compatibility with SATCOM as a complementary air-ground medium. Section 1.6 indicates the increased availability that HFDL and SATCOM provide simultaneously. HFDL combined with SATCOM provides a lower acquisition cost alternative to a dual SATCOM system. HFDL may provide lower recurring cost of operation than SATCOM and in some cases, VHF data link. HFDL provides a technical advantage over SATCOM by eliminating single points of failure which are inherent in SATCOM (the satellite link itself) by providing potential communications with multiple ground stations.

1.2.4 Typical HFDL flight scenario

The HFDL operational concepts are presented in terms of a possible flight at some point in the future. HFDL operational concepts associated with the flight are presented from the perspective of the airline using HFDL to support airline operational control (AOC) and from the HFDL ground station operator. These concepts are presented given the following scenario: Flight 14 (FL14) is an Atlanta to Frankfurt flight departing Atlanta at 7:35 PM. This aircraft is equipped with VHF and HFDL (ACARS), two HF data radios and an HFDL capability.

1.2.4.1 Initial log-on

FL14 uses an "out" event (all passenger doors closed and the anti-collision strobe lights on) to trigger the initial log-on to the HFDL system. This log-on is transparent to the flight crew. There are a variety of other possibilities for automatically triggering the log-on process to include loss or failure of the VHF data link or use of geographic filters.

Note.— The HFDL function is disabled when the aircraft is at the gate as a safety feature. When an HF Transmitter is keyed a high voltage differential could be generated between the aircraft and the ground. This voltage differential could produce a spark during refueling operations if the aircraft is not properly grounded.

The HFDL function in the HF data radio initiates the log-on process by scanning for HFDL squitters. Every HFDL ground station (GS) broadcasts uplink squitters on each operational frequency. The squitters are broadcast every 32 seconds and provide a means for aircraft to determine which frequencies are usable. The squitter indicates the start of a 32-second HFDL frame consisting of thirteen slots. The squitters also serve several other functions including HFDL system timing, distribution and synchronization, and broadcasting time slot assignments for uplink and downlink transmission. The downlink slots may be assigned to individual aircraft in response to reservation requests or may be designated for use by all aircraft in a random access fashion. Some HFDL avionics implementations may continuously scan for squitters even when the HFDL function has been disabled while the aircraft is at the gate. This permits a much faster log-on sequence once the HFDL function is enabled.

The aircraft HFDL function maintains a list of HF frequencies in use by the HFDL system. The aircraft HFDL function scans this list from the highest to the lowest frequency and listens for a squitter on each frequency for at least 35 seconds. This particular implementation of the HFDL function selects the first acceptable frequency as opposed to searching the entire frequency list and choosing the best available frequency. A 12 MHz frequency squitter from the Long Island GS is received without error, with available downlink slots, and the signal quality is acceptable. The squitter includes the identification of the transmitting GS. An HFDL frame has thirteen slots and could consist of a squitter, two uplink slots, three assigned downlink slots and seven random access downlink slots. The GS configures each frame to support the expected uplink and downlink traffic. The HFDL function generates a log-on request message and randomly selects one of the available random access downlink slots for the downlink transmission.

The HFDL function uses the slowest possible data rate that can support the message size of the downlink transmission. The four data rates available are 300, 600, 1 200, and 1 800 bits/s. At any given time, each link between an aircraft and a GS will have maximum downlink and uplink data speeds which can be supported. The maximum uplink rate is determined by the aircraft and provided to the GS in the downlink protocol data unit (PDU). The maximum downlink rate is determined by the GS and provided to the aircraft in the uplink PDU. These data rates are determined by evaluating the received signal-to-noise ratio on each reception of a PDU.

The GS responds with a log-on confirm PDU which includes the aircraft identification (AID) number and maximum downlink transmission rate. Receipt of the log-on confirm results in an HF DATA icon being displayed on the engine identification crew alerting system (EICAS) to let the flight crew know they have an HFDL connection established.

1.2.4.2 **Downlink message processing**

Once the aircraft HFDL function has completed the log-on process, the aircraft can send and receive messages via HFDL. The first downlink sent by the aircraft is an ACARS media advisory message. This message is sent to the ground station operator and the airline to provide information needed to maintain data link addressing and routing tables. The HFDL function encapsulates the ACARS media advisory message in the HFDL protocol and randomly selects one of the available random access downlink slots identified in the squitter and transmits the PDU. The GS acknowledges receipt of the downlink PDU by sending the AID in one of the next two squitters in the slot acknowledgment field.

If the GS does not acknowledge the PDU, the aircraft HFDL function assumes that another HFDL equipped aircraft competing for the same downlink slot interfered with the GS reception of the message. The aircraft HFDL function then invokes an exponential back-off algorithm to identify a new HFDL frame for the next downlink attempt. The aircraft HFDL function once again randomly selects one of the available random access downlink slots identified in the squitter and transmit the PDU. In the event that another PDU is unacknowledged, the HFDL function repeats the process one more time. If this third attempt is unacknowledged, the HFDL function reinitiates the log-on process and look for a new HF channel.

Even though FL14 has now successfully logged into the 12 MHz HF Channel at the Long Island GS, the aircraft is only sending and receiving ACARS messages over the VHF data link. The MU/HCF is configured to use HFDL only if VHF data link is not available. The media advisory message is an exception to this rule. The ACARS media advisory message is sent over the most recently acquired data link.

1.2.4.3 **Uplink message processing**

The aircraft HFDL function receives an uplink PDU from the Long Island GS. The uplink PDU is received without error and in accordance with HFDL protocol. The resulting ACARS Acknowledgment message is forwarded to the communications management unit/HCF. The uplink PDU contained a downlink slot assignment. The aircraft HFDL function acknowledges receipt of the uplink PDU in the downlink PDU generated for the downlink slot assignment. The aircraft HFDL function generates a downlink PDU even if there are no downlink messages ready, by providing HFDL performance data.

1.2.4.4 **Frequency change**

The frequency used by the aircraft HFDL function will probably change during the course of the flight. These changes can be initiated either by the GS or by the aircraft HFDL function.

1.2.4.4.1 **GS initiated frequency change**

As FL 14 crosses into North Carolina, the aircraft HFDL function receives a squitter with the change notice flag set. This flag triggers the aircraft HFDL function into reinitiating the log-on process. At the same time the change notice code bits are set, the GS updates the operational frequency data within the squitter. In this case, the aircraft HFDL function frequency search algorithm first tries the operational frequencies of the current GS. The operational frequencies of the current GS, as well as operational frequencies from two adjacent GSs, are broadcast within each squitter. If the operational frequencies of the current GS can not be heard, then the aircraft HFDL function tries the operational frequencies of the two adjacent GSs.

The FL14 aircraft HFDL function first listens on the other operational frequencies transmitting from the Long Island GS. In this case, the aircraft hears the new squitter on the 6 MHz frequency and initiates a log-on-resume process.

1.2.4.4.2 **Aircraft initiated frequency change**

As FL14 heads north into Canada, the signal strength of the squitters heard on the 6 MHz frequency degrades below the acceptable threshold. The aircraft HFDL function then initiates a search for another frequency. The aircraft HFDL function first listens on the other operational frequencies transmitting from the Long Island GS. In this case, the aircraft does not hear any of the other transmitting frequencies from the Long Island GS. The aircraft HFDL function then listens on the frequencies for the adjacent GSs. The FL14 HFDL function is able to receive the squitter on the 3 MHz frequency transmitting from the Newfoundland GS and FL14 initiates the log-on process.

1.2.4.5 Flight crew use of HF voice

Prior to departing radar controlled airspace, the Gander air traffic control (ATC) authorities provide FL14 with an HF selective calling (SELCAL) code via VHF voice radio and verify the SELCAL is functional. Once out of VHF range, the flight crew of FL14 may use HF voice for ATC or AOC voice communications. In the event that HF voice is used, the aircraft HFDL function disables downlink HFDL transmissions. Downlink HFDL transmissions remain disabled for the duration of the HF voice use and for a specified period of time after the last use of the HF voice.

Once downlink HFDL transmissions are no longer disabled, the aircraft HFDL function initiates a log-on process starting with the last frequency it was logged on. If the squitter is acceptable and the ground station address is the same, the aircraft HFDL function sends a log-on-resume message. If the squitter is for a new ground station, the aircraft HFDL function sends a log-on-request message to the GS.

1.2.4.6 Transition to VHF data link

Once FL14 nears the coast of the United Kingdom, it enters VHF data link coverage. At this point the MU no longer uses the HFDL for downlink message traffic. The AOC will have received a media advisory message and will no longer use HFDL for uplink message traffic. The aircraft HFDL function continues to maintain the HFDL.

1.2.4.7 Flight arrival

The “in” event (first passenger door open or anti-collision strobe lights off) of FL14 arriving at the gate is used to disable the aircraft HFDL function.

1.3 HFDL ground station operator operational concept

HFDL service for the flight scenario over the North Atlantic is provided by four networked HFDL Ground Stations (GSs) (located in Sweden, Iceland, Newfoundland, and Long Island. Each GS has three HF transmitter/receiver pairs dedicated for HFDL. These three HF channels are operational at all times at each site. Each GS has a global positioning system (GPS) based time source. This common time source is used to synchronize the transmission times of all of the GSs. If practical, each GS is connected to two intermediate routers to provide diverse communication paths. The intermediate routers are connected to the ground station operator network interface router. The Iceland and Sweden HFDL ground stations are connected to a intermediate router in London and the Newfoundland and Long Island HFDL ground stations are connected to an intermediate router in Chicago. The HFDL ground network infrastructure interconnects the GSs with the ground station operator back-end processor (BEP) and the HFDL management function. The HFDL management function manages the GSs and the frequency assignments for each of the four GSs.

1.3.1 Initial log-on

Each GS broadcasts an uplink squitter on each operational (transmitting) frequency. The squitters are broadcast every 32 seconds and provide a means for aircraft to determine which frequencies are usable. The squitter indicates the start of an HFDL frame. The squitters also serve several other functions including HFDL System timing, distribution and synchronization, and broadcasting time slot assignments for uplink and downlink transmission. The downlink slots may be assigned to individual aircraft in response to reservation requests or may be designated for use by all aircraft in a random access fashion. The squitter includes the identification of the transmitting GS. An HFDL frame comprises thirteen slots and could consist of a squitter, two uplink slots, three assigned downlink slots, and seven random access downlink slots. The GS configures each frame to support the expected uplink and downlink traffic.

The GS receives a log-on request from FL14 (the aircraft is actually identified by the 24-bit ICAO identifier as opposed to the flight ID) and checks for the availability of an aircraft identification (AID) number. The ground station assigns each aircraft on a particular HF frequency with a unique 8-bit identification number. This aircraft ID is used in all subsequent message exchanges. If there are no aircraft IDs available, the GS responds with a log-on denied message. System design, aircraft flight patterns, and HF propagation characteristics reduce the possibility a ground station will ever exhaust all of a channels aircraft ID numbers.

In this case, there are aircraft IDs available and the GS responds with a log-on confirm uplink. The GS adds the aircraft to the software table containing the list of operational aircraft and sends an Q0 label message to the BEP. The BEP uses the Q0 message to update its aircraft routing table. The GS also sends an aircraft log-on notification message to each of the other GSs. This message contains the aircraft ICAO 24-bit identification number (provided in the log-on PDU header) and is used to remove outdated records from the operational aircraft table of other GSs.

The GS also stores the maximum uplink transmission rate for the aircraft in the operational aircraft table. This rate is determined from the received signal-to-noise ratio (SNR) on each reception of a downlink. The maximum uplink transmission rate is used by the GS to determine the maximum size of an uplink message and is used by the HF data modem to set data and interleaver rates for the uplink transmission.

1.3.2 Channel capacity

The only limit placed on channel capacity by the GS is the restriction of 256 operational aircraft per channel imposed by the 8-bit aircraft identification field within the squitter. The GS sets the frequency utilization bit in the squitter after twenty-five aircraft have logged into the channel. The aircraft HFDL function will not log into a HF channel with this bit set unless it is the only HF channel the HFDL function can use.

It is possible to have situations which produce excessive loading on a single channel. Aircraft may have to log-on to an already loaded channel because it is the only channel the aircraft can hear. In this case, there may be aircraft on the loaded channel that may very well be able to hear other squitters, but remain on the loaded channel because the signal strength is still acceptable.

The GS does not directly manage load sharing between transmitting HF frequencies. The GS also does not have the capability to change aircraft to a new frequency to balance the load on the GS. However, the GS can set the frequency utilization bit in the squitter once an HF channel has twenty-five aircraft logged-on. The ground stations broadcast the squitters, but have no knowledge of what frequencies the aircraft can receive. The aircraft listens to the squitters and selects the optimum frequency for a given situation.

The HFDL channel access protocol provides a limited load balancing capability. The excess channel loading results in increased competition for the random access slots. If an airborne HFDL transceiver cannot access a channel after three attempts, the channel access protocol searches for another channel. This process should result in off-loading of some of the aircraft from the overloaded HF channel over time.

1.3.3 **Downlink message processing**

The GS receives a downlink PDU from FL14. The message is received without error and in accordance with the HFDL protocol. The resulting message is forwarded to the ground station operator BEP. The GS acknowledges receipt of the downlink PDU by sending the aircraft ID in one of the next two squitters in the slot acknowledgment field.

1.3.4 **Uplink message processing**

The BEP receives the ACARS media advisory message from FL14, reformats the message for the ground network, sends the message to the AOC, and generates an ACARS acknowledgment message. The BEP knows which channel and ground station it received the FL14 ACARS media advisory message from and sends the acknowledgment message back to the Long Island GS.

The GS encapsulates the ACARS acknowledgment message in the HFDL protocol and assigns a slot for the uplink message. The GS also assigns a downlink slot for the aircraft in the next available frame. The downlink slot assignment is communicated to the aircraft in the appropriate squitter by placing the aircraft ID for FL14 into the appropriate slot assignment field. The aircraft HFDL function acknowledges receipt of the message in the next downlink message sent in response to the downlink slot assignment by the GS. By assigning a downlink slot, the GS increases the speed uplink messages can be processed.

If the aircraft HFDL function responds to the downlink slot assignment request, yet does not acknowledge receipt of the message in the assigned downlink slot, the GS assigns a second downlink slot to the aircraft in the next squitter. If the aircraft still responds with a downlink message in the assigned downlink slot, yet does not acknowledge the message, the GS retransmits the message and repeats the above process.

If the aircraft HFDL function does not respond with any message in the assigned downlink slot, the GS assigns another downlink slot. If the aircraft still does not respond, the GS repeats the slot assignment one more time. In the event of a third non-response, the GS assumes the aircraft HFDL function is no longer operational for this HF channel and removes the aircraft from the operational aircraft table.

1.3.5 GS initiated frequency change

As FL 14 crosses into North Carolina, the GS begins the process of changing to a better frequency. The propagation models and HF sounders used to develop the HFDL frequency management plan have determined that the 12 MHz HF channel will go off the air at 8:00 PM local time and the HF transmitters and receivers will switch to a 6 MHz frequency. The GS reads a frequency selection table, which is the physical representation of the HFDL frequency management plan, to determine when to switch HF frequencies. This table is periodically updated by the HFDL system management function.

At 8:00 pm the GS sets the change notice code in the squitter to indicate the GS is changing the HF frequency within four frames. At the same time the change notice code bits are set, the GS updates the operational frequency data within the squitter. This continues for another three frames with the squitters indicating a change notice. At the completion of the fourth frame, the GS changes the HF transmitter frequency and starts transmitting squitters on the new HF frequency.

1.3.6 Aircraft polling

The GS keeps the operational aircraft table updated to ensure enough aircraft IDs are available to support new aircraft logging on to the system. In addition to using the aircraft log-on event to update the tables, the GS periodically polls aircraft to determine if they are still operational. Polling is used if an aircraft has not sent a downlink within the last 30 minutes. The GS assigns the aircraft a downlink slot using the next available squitter. The aircraft responds with a downlink message in the assigned slot, even if a message is not in the queue. If the aircraft HFDL function responds with a downlink, the time field is updated in the operational aircraft table. If the aircraft does not respond, the GS repeats this polling process two more times. If the aircraft HFDL function does not respond to three polling requests, the GS removes the aircraft from the operational aircraft table.

Once FL14 arrives in Frankfurt, the aircraft HFDL function is disabled. The GS polling process determines that FL14 is no longer listening to the channel, removes the aircraft from the operational aircraft table, and releases the aircraft ID number for reassignment to another aircraft.

1.4 Air traffic services (ATS) operational concept

The use of HFDL for air traffic services (ATS) is foreseen as growing incrementally with time, as the current (early 1996) North Atlantic HFDL system evolves from its current status as a system supporting data link trials. In order to be considered a fully operational data link medium for support of a particular ATS service, the system will have to meet certain qualification criteria, which are:

a) the demonstration of the ability of HFDL to meet required communications performance (RCP) criteria; namely, the performance, availability and integrity parameters required for each particular ATS service to be supported;

b) the utilization of appropriately designated spectrum for ATS service, namely the AM(R)S (reference Article 50 of the ITU radio regulations and Appendix 27 Aer2, thereto);

c) design approval of airborne equipment and its installations to include safety assessment considerations evaluated from an end-through-end perspective; and

d) operational authorization based on the verification and validation of derived safety and interoperability requirements/procedures which apply to the aircraft, space, and ground domains.

As HFDL is a new technology and certain aspects of the above criteria will require some time for their qualification, an incremental approach to the utilization of HFDL for ATS is considered to be the most effective. It is foreseen that trials of several ATS applications will be conducted, using ATS applications with corresponding incremental progression of benefits to the users. Eventually, the performance, availability and integrity parameters of which HFDL is capable will be determined by analysis, simulation and test; and HFDL will be deemed an acceptable means, either solely or in conjunction with other communications media, of ATS data link communications operation.

1.4.1 Typical ATS scenarios

It is assumed that the HFDL system used for ATS during the trials periods is essentially the same as that described in Section 3.2, AOC operational concept. Within the HFDL air/ground subnetwork, the aircraft log-on and log-off processes are similar, as are also the several link management exchanges described therein. It is assumed that the initial utilization of HFDL will be as an alternative RF medium for ACARS operations as described in that section. Benefits linked to ATS will be constrained by the evolution of the data link (e.g., a FANS-1 like ACARS/ARINC 622 followed by a “Data-3”/ATN implementation) as well as the proof of HFDL *per se* through trials and demonstration periods. However, it can be assumed that rapid progress will be made in the implementation of the Aeronautical Telecommunications Network (ATN) during the trials period, resulting in an evolution of supporting subnetworks and end systems for ATS corresponding to the evolution of HFDL applications.

1.4.1.1 Initial North Atlantic trials

Potential users of HFDL need to anticipate benefits accruing from ATS applications as well as AOC applications. In the context of an incremental timeline of benefits as outlined above, the first ATS benefit has been identified as the substitution of waypoint position reports (WPR) via HFDL for the current practice of making WPRs via HF radio voice.

A trial of HFDL in an ATS environment began in December 1995 in North Atlantic airspace and continued into 1996. During the trial United Airlines and Continental Airlines aircraft sent WPRs over HFDL (and SATCOM and VHF ACARS) to the Canadian and Iceland Civil Aviation Authorities (CAAs). These WPRs were automatically generated by the aircraft’s flight management computer and took place without pilot intervention. One key aspect of the trial was the CAA did not have to change or upgrade any of its controller end systems to receive data link WPRs.

A WPR is required when the aircraft is over, or as soon as possible after passing, compulsory reporting points if the approved flight plan contains such designated points. Reporting points in oceanic airspace frequently are associated with every ten degrees of longitude (for routes having a major East-West component), which generally corresponds with a report every 45-60 minutes. Currently, a WPR is delivered by HF radio voice from the cockpit via HF ground station to a ground radio operator who transcribes the report in message form. The message format is the standard WPR as prescribed by the ICAO PANS/RAC (Document 4444). The radio operator acknowledges receipt of the WPR via HF voice response, then transmits the message via a network (or dedicated line) to the controlling center where it may be printed and/or displayed on a monitor. A copy of the message is normally also routed to the aircraft operator's dispatch center.

In the HFDL WPR trial, the message is automatically generated on the aircraft, in a flight management computer (FMC). Actual position, altitude, time and other data as necessary will be automatically generated in an ACARS-compatible format using data available from the onboard flight management and navigation systems. The message generation and transmission will be triggered automatically when the waypoint is reached. There is also a capability for generating a report message on command from the crew or on request from the ground. When received at a ground station, the message is forwarded to the ground station operator who reformats the message and then routes the message to the appropriate center. A message copy is also delivered to the aircraft operator.

The goal of the trial was, once operational, to replace HF voice WPRs with data link WPRs. Data was collected comparing HFDL and SATCOM performance to that of HF voice. Most of the WPRs generated in the trials were SATCOM and VHF ACARS due to the medium selection schemes employed the ACARS MU. Although HFDL performance met its goals, not enough data was collected by 3Q96 to make HFDL operational.

ATTACHMENT 2

HFDL COVERAGE

HF coverage varies dramatically for any given ground station. At any propagating frequency, it is possible to develop contours of signal strength as a function of distance from a specified transmitter. The aggregate coverage of multiple frequencies must be used to obtain adequate radio coverage. When the signal strength is sufficient to provide a reliable HFDL communication capability, it may be said that one has HF coverage for HFDL service. The median range of coverage varies with time of day, day of year, and average sunspot number. The actual coverage varies because of short term ionospheric effects which are not predictable. The median contours may be deduced with computer prediction program such as Voice of America Communications Analysis and Prediction Program (VOACAP). Coverage at a fixed frequency is distended in a direction opposing electron density gradients, so this means that equatorward coverage is generally smaller than poleward coverage, and nocturnal coverage is greater than midday coverage. Coverage is dependent upon the height of the ionospheric layer which controls the refraction process, and for many practical situations this is the F2 layer. It is important to recognize that while layer height controls the maximum coverage for HFDL, the electron density (and the corresponding critical frequency) at the “refraction point” within the layer controls the largest frequency (or coverage MUF) for which that coverage may be achieved. Daytime electron densities are higher than nighttime values, and this means that the daytime critical frequencies (foF2) are also higher along with the corresponding MUFs. Since layer height and critical frequency variations are evidenced in actual operations, and are not fully accounted for in median models, it is seen that coverage at a specified set of aeronautical-mobile frequencies change in manner which is not subject to accurate prediction.

The maximum single hop coverage may vary from 3 500 to 4 200 km for layer heights between 250 and 350 km respectively, with the greater ranges corresponding to nighttime conditions. Under a 4/3 earth radius approximation, which nominally accounts for the influence of tropospheric refraction, the coverage ranges may increase by approximately 600 km. Since the communication path is generally above a few degrees of elevation and involves high altitude aircraft at one end of the link, a more conservative enhancement in coverage due to tropospheric refraction is generally assumed. For our purposes we may use 300 km. This implies diurnal coverage variation between 3 800 and 4 500 km.

It is important to recognize that a single frequency is not sufficient for a communication link for a long period of time. There are two components of variability: ionospheric variability associated with changes in the local time at the ionospheric refraction point, and variability associated with changes in path geometry. Both factors are in operation for HFDL service. For fixed links, we need only be concerned with diurnal variations which are rather slow for motionless platforms, except during sunrise and sunset periods.

For HF frequencies which are well below the maximum coverage MUF, a reduction in the coverage range occurs. This is because the ionosphere interacts more strongly with the lower frequencies, and the apogee of the ray trajectory is well below the peak height of the layer. A provision for continuous single-frequency coverage is possible by using a frequency sufficiently below the MUF during the day so that it might have a chance to provide HFDL service during the nocturnal period as well. This could enable a single frequency to be utilized over a 24 hour period provided the aircraft is contained within the coverage envelope. There may be problems of high multipath and enhanced absorption during the day, and MUF exceedance during the night. The range of coverage at below-the-MUF frequencies may be quite dramatic. Factors of 3:1 are often observed over a diurnal cycle.

So far we have been discussing single hop coverage variability. However, HF also admits to multiple hops, and these modes of propagation may be operationally effective if terrestrial refraction points are oceanic, and especially during the nighttime when ionospheric absorption is minimized. There are also ducted and chordal modes of propagation which may be excited by natural ionospheric gradients such as the day-night terminator, certain auroral features, and the equatorial anomaly. Long-distance propagation by unconventional modes has been well established. Predictability is at the core of any practical application for HFDL service, and long distance propagation generally requires special circumstances which limits its utility if long-term planning is required. Nevertheless the effects are observed quite frequently, and the impact of propagation beyond the one-hop relates specifically to frequency reuse.

The location of ground stations may be determined by factors which have been identified in this section, recognizing that optimum coverage patterns are defined by ionospheric heights and electron densities which are highly variable. Optimum performance would be achieved if aircraft could be within the single-hop coverage of all transmitters for all allocated frequencies. This would enable diversity in frequency and station selection to be complete, allowing optimal availability's to be achieved. In view of ionospheric fluctuations and the temporal and spatial variations in the aircraft position, it is not generally possible to achieve an optimal design. But, this does not mean that high availability's have to be sacrificed. Access to the global network, and utilization of low-loss multi-hop and unconventional modes of propagation can augment the diversity gain. The network architecture should take this into account.

In order to identify the number of HFDL ground stations to support worldwide coverage and to enable effective reuse of HFDL frequencies, it is convenient to partition the world into the three geographic regions, where natural propagation effects allow for frequency reuse. The reuse of frequencies at a fixed time of day depends upon a number of factors including sunspot epoch, magnetic activity, season, and the particular frequency utilized. If the geophysical conditions and path geometry are fixed, then an algorithm may be developed for frequency reuse for any of the specified frequencies in the aeronautical mobile bands. Frequency reuse, to first order, depends upon the propagation environment governed by the diurnal cycle. Based upon experimental investigations during solar minimum, but for a range of magnetic activity conditions, frequency reuse is possible when ground stations are separated by at least eight time zones. Hence, it is convenient to divide the world into three geographic regions:

a) Atlantic (including Caribbean and South America);

b) Pacific (including Australia and Micronesia); and

c) Indian Ocean (including Asia and parts of Africa).

These three regions provide for the largest HF coverage areas that can support frequency reuse, given the stringent availability of ATS communications while providing continuity of service on a routine basis.

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