A PRODUCT DEVELOPMENT DECISION MODEL FOR COCKPIT WEATHER INFORMATION SYSTEMS

by

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ABSTRACT

Communication systems have an important role to play in managing the safe and efficient operation of the National Airspace System (NAS). The users of the NAS, from the commercial transport aircraft to hobby airplanes can all benefit from the recent advances in digital communication technology especially as the capacity of the analog voice systems is surpassed by the growth in air traffic. One of the benefits of the new digital data links being developed is to allow delivery of real time weather information to the cockpit of aircrafts. Weather information is essential to flight operations and until recently there were only limited voice and text weather reports available to the pilot. With data links, graphical weather in the cockpit is possible and also highly desired by the aviation community. This thesis will develop a decision model and analysis tool for product developers of weather information systems that need to select appropriate data link technology for which to develop their weather information systems. A comparative analysis of the aeronautical communications systems is done with the view of satisfying end-user requirements for weather information and achieving market success. A study of the various data links is conducted to gain an understanding of their performance characteristics and implementation issues. A consumer survey was designed and valuable insight into the requirements and opinions of pilots was gained. The method of Quality Function Deployment (QFD) was employed to find the most important technical characteristics of the data links to satisfy the consumer requirements captured in the survey. The decision model consisting of the QFD and also further technical assessment was implemented in software to allow any scenario of product requirements and data link to be performed.

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Table of Contents

1. Introduction……………………………………………………….………...…1
1.1 Importance of Aviation Weather Information Systems………..…………………2
1.2 Outline of Thesis…………………………………………..……………...3
1.2.1 Data Link Technology…………………..……………………………...…3
1.2.2 Data Communication Requirements in the Cockpit……………………...3
1.2.3 Implementation of a System Design Decision Model……………..………4
2. Data Link Technology for Aviation Weather Information……………..……5
2.1. Aeronautical Telecommunications Network (ATN) 6
2.2. Wireless Communication in Aviation.. 7
2.2.1. Propagation Environment 8
2.2.2. Media Access 8
2.3. Data Links for Weather Information Dissemination 10
2.3.1. VHF Data Links 11
2.3.2. HF Datalink... 20
2.3.3. Universal Access Transceiver (UAT) 21
2.3.4. Mode S 23
2.3.5. Satellite Link 23
2.3.6. Flight Information Services Data Link (FISDL) 27
2.3.7. Communication Avionics 29
3. Data Communication Requirements in the Cockpit…………………..….…31
3.1 Characterizing Aviation Weather Data……………………………..…...32
3.1.1 Textual Weather Information……………………………………….…33
3.1.2 Graphical Weather Information………………………..……………36
3.1.3 Weather Products by Method of Delivery……………..………….….…37
3.1.4 Weather Products by Phase of Flight……………………………………38
3.1.5 Pilot and Accident Studies…………………………….………………40
3.2 Characteristics of new Cockpit Weather Information Systems from Consumer Perspective…………………………..………………...…………….……40
3.2.1 Pilot Survey…………………………………………………..…………...41
3.2.2 Implication of the Consumer Inputs to the Model……………….……....44
4. Implementation of the Weather Information Systems Decision Model……....46
4.1. The QFD Model and its Application for Weather Information Systems Design 46
4.2. Overview of the Technical Parameters 49
4.2.1. Connection Delay.. 49
4.2.2. Message Latency.. 49
4.2.3. Traffic Information Capability.. 50
4.2.4. Request-reply capability 50
4.3. Processing of the QFD Model... 51
4.3.1. Data Link Matrix.. 53
4.4. Detailed Evaluation... 55
4.4.1. Channel Loading.. 57
4.4.2. Data Rate Analysis - Broadcast Link... 58
4.4.3. Data Rate Analysis – Two-way Link... 60

4.5. Survey Results 62
4.6. Decision Aiding 67
4.7. Sensitivity Analysis 69
5. Conclusion and Future Work……………………………………………………..……74
Abbreviations………………………………………………………………………..…76
Bibliography…………………………………………………………………..……..77
Appendix A……………………………………………………………………………79

List of Tables

2.1 Physical Layer Parameters for VDL Mode 2 14

2.2 Physical Layer Parameters for VDL Mode 3 16

2.3 Physical Layer Parameters for VDL Mode 4 19

2.4 Physical Layer Parameters for HFDL 21

2.5 Physical Layer Parameters for UAT 22

3.1 Summary of Text Standard Products 35

3.2 Messages Size for Textual Weather 35

3.3 Weather Products by Phase of Flight 39

3.4 Survey Questions and Implications on Technical Characteristics 45

4.1 Sample QFD CR-DR Relationship Matrix 52

4.2 Data Link Performance (Weighted) 54

4.3 Data Sizes for NEXRAD Images for different Grid Sizes 58

4.4 Broadcast Channel Loading and Data Rate Estimates 59

4.5 Sensitivity to Changes in Number of Graphical Weather Products Importance 69

4.6 Sensitivity to changes in Grid Size Importance 70

4.7 Sensitivity to changes in Frequent Weather Update Importance 70

4.8 Sensitivity to changes in Weather Alert Importance 71

4.9 Sensitivity to changes in Location Aware Weather Importance 71

4.10 Sensitivity to changes in Traffic Information Importance 72

List of Figures

2.1	Architecture development method for aeronautical data link	5
2.2	Fields in a typical packet of data	9
4.1	QFD Model for Weather Information Systems design	48
4.2	Flowchart for the Detailed Analysis	56
4.3	Importance of graphical weather products	63
4.4	Importance of grid sizes	63
4.5	Importance of weather update interval	64
4.6	Importance of location aware system	64
4.7	Importance of weather alerts	65
4.8	Preferences for the display of weather alerts	65
4.9	Importance of non-wx information	66
4.10	Requirement for non-recurring cost	67
4.11	Requirement for non-recurring cost	67
4.12	Sensitivity to Changes in Individual Inputs	73

Chapter 1

Introduction

The volume of traffic in the National Airspace System (NAS) has been growing along with the needs of the aviation community for better communication in the cockpit. Current communications are mostly voice based over VHF link and are mainly achieved through a request/ reply scheme with the Flight Service Stations. The inefficiency in this method and the desire by the aviation community to have data communication in the form of text and graphics to complement voice is driving the transition to digital communication systems. Thus the communication networks and technology for aviation are evolving and there are programs underway by NASA and the Federal Aviation Administration (FAA) to develop technology for advanced, higher speed and higher capacity communication links.

This research work was undertaken with the support of the NASA Aviation Weather Information (AWIN) program. NASA started the AWIN program to address the weather aspects of aviation safety as part of its Aviation Safety Program. The goal of the AWIN program is to provide improved weather information to users of the National Airspace System, especially to the flight deck, and to foster improved usage of this information. NASA envisions a future that would allow aircraft to be both a source and user of weather information. In this way pilots could more easily monitor possible trouble spots and make safer, more cost-efficient routing decisions.

1.1 Importance of Aviation Weather Information Systems

This research will focus specifically on weather information systems and communication links to support such systems. Weather and weather information is an important part of aircraft communications and is critical to the safety of every flight operation. FAA estimates that weather is a factor in 30% of all aviation accidents. In addition, weather is the biggest cause of air carrier delays greater than 15 minutes [10]. Providing timely weather observations and accurate forecasts to aircrafts en-route, such that weather is avoided and alternate routes can be charted, can reduce the negative effects of weather on flight operations. The constraint on this ability is mainly the inefficient nature of the voice-based communication and analog communication systems that contributes to the saturated communication capacity. Pilots may have to wait minutes to receive in-flight weather briefings due to busy signal and receive it in abbreviated speech and text reports that further hinder their understanding of the weather related threats.

The availability of digital data link communication as well as advancement in weather processing and display algorithms will fill this gap and ensure that adequate and useful weather information will be on hand for the pilots. The need for weather *information* as opposed to data has been emphasized by aviation experts, to prevent an overload of data which can take attention away from the primary task of flying. Weather *information* implies data that have been collected, analyzed, integrated, and placed into context before being presented to the pilot. In the future, weather information will likely grow hand-in-hand with artificial intelligence that anticipates what the pilot needs to know at a given moment in each particular phase of flight [1].

The primary objective of this research will be to develop and demonstrate a product development feasibility model for data link technology that will support weather information systems. This model will integrate data link and hardware performance with a market-based set of performance requirements to assess the success of data link technology to meet specific information system requirements. The chapters will each address a part of the information system model including the data link technology, the characteristics of the meteorological data in relation to the usage and communication requirement, and the development of the demand-based system design decision model.

1.2 Outline of Thesis

1.2.1 Data Link Technology

Several candidate communication systems and data link protocols are in the development and trial stages of deployment. Among these are the VHF data links (VDL Mode 2, VDL Mode 3, VDL Mode 4), HF, UAT and SATCOM. These communication schemes have different physical layers and network protocols which impact their performance and ability to support the various types of aeronautical communication. The second chapter will provide an examination and comparison of the future aeronautical data links, in terms of their performance as well as from an organizational standpoint. The selection of technologies for aeronautical purposes is an issue not only for the individual user but is the concern of governmental agencies in several different countries. Thus policy issues become barriers or promoter of the technologies and have to be taken into consideration.

1.2.2 Data Communication Requirements in the Cockpit

The future air-to-ground communications will be dominated by various forms of aeronautical data link (text, graphics and digitized voice), which will provide the pilot with integrated services on easy-to-read, real-time displays. The basic meteorological information will be provided by the FAA, and some enhanced value added graphical information would be available from private vendors by subscription.

The weather information needs vary with the type of aircraft, the phase of flight, and the preference of the pilot. Thus to obtain the technical and design characteristics of the communication system, the weather information requirements need to be taken into account. A suitably designed pilot survey is a valuable method of obtaining the perception and system requirements of the user.

1.2.3 Implementation of a System Design Decision Model

The product development decision model will aid in the selection of appropriate data link technology and communication architecture for weather information systems through a competitive analysis. A top down approach will be taken with the incorporation of end-user requirements and opinion in the definition of a weather information system product. The QFD model is a tool used in industry to achieve the integration of end-user opinions into product development. This method is applied to facilitate evaluation and comparison across the many characteristics of the weather information system.

Chapter 2

Data Link Technology for Aviation Weather Information

This chapter presents the results of a survey of the candidate data link technologies to support the system design decision model that will be developed. There are many factors to be considered when selecting the technology, or mix of technologies, that will promote viable deployment and modernization of future weather information systems.

The process of selecting viable communication architectures and supporting data links requires an understanding of the desires of the aviation community, estimating the message traffic, and analyzing the link capabilities as the diagram in Figure 2.1 [8] shows.

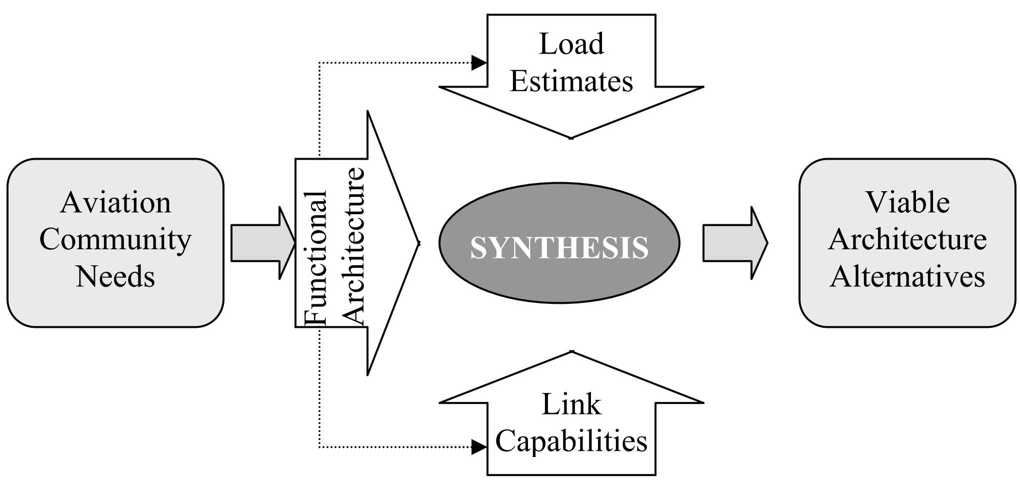


Figure 2.1. Architecture Development Method for Aeronautical Data Link

There are extensive standards development, simulations and experimentation work presently being carried to test the performance and operation of data link technologies. The future aeronautical communication environment is still a conceptual idea that is slowly becoming a reality.

2.1. Aeronautical Telecommunications Network (ATN)

The ATN is the cornerstone of a NAS Architecture plan by the government that supports “Free Flight”. This concept involves a system wide deployment of technology with the goal of providing unsurpassed safety, optimization and capacity for the National Airspace System (NAS). This long-term plan has three phases with the final phase (2008-2015) ending in the deployment of infrastructure and services that will enable advanced automation of traffic flow management through a NAS-wide information service.

The future ATN internetwork architecture is adopting common interface services and protocols based on the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) Reference Model. The basis for developing an open standard is to facilitate system wide collaboration and information sharing among service providers and users. The open communication protocol requirements / features include: provision of link-independent routing i.e. support of multiple subnetworks, efficiency for long and short messages, support of broadcast / multicast, provision of mobile routing etc. [3] ATN subnetworks are compatible if they conform to the lower three layers of the OSI reference model and can be interconnected by an ATN router.

This advanced situational awareness architecture involves modernizing:

- Infrastructure
- Process for data exchange and methods of collaboration
- Tools for NAS analysis and predictions.

To improve flight planning, the NAS Architecture contains new and improved information services in the areas of traffic flow management and flight services that enable collaboration – service providers and users sharing the same data and negotiating to find the best solutions to meet operational needs.

During flight planning, improved tools will be used to predict locations and impact of traffic demand and weather along planned routes and at the destination. As the flight progresses, additional updates on weather, NAS status, and other user-specific data will be provided to the aircrafts en-route and other operational centers as appropriate. This capability for dynamic exchange of data will be facilitated by the development of new digital data links. The next few sections will provide an examination of the architecture of the various data links in relation to Flight Information Services (FIS) and weather information.

2.2. Wireless Communication in Aviation

Aeronautical communication has many similarities and differences with terrestrial based communication systems. The design of the networks are based on the same principles as their counterparts, however, there are separate frequency bands assigned for aviation use and the use of terrestrial communication links for aviation purposes is generally restricted due to a number of reasons. Firstly, the range over which the signal has to travel makes it infeasible for most of the low power terrestrial communication systems such as Private Radio (PMR) Networks. The altitudes at which aircrafts operate preclude them from using cellular links as the airborne terminal can capture numerous frequencies in many cells. In addition, the stricter regulatory requirement for aviation certification makes it impractical for aeronautical users to share the same communication channels as the terrestrial systems.

However, there is use of satellite communication links in aviation and there is at least one system that uses a commercial cellular radio network with a number of modifications to make it compatible with aeronautical use.

2.2.1. Propagation Environment

The aeronautical propagation channel is typically a Gaussian channel due to the relatively low level of multipath scattering and a clear line of sight available en-route. There are terrain effects experienced with VHF links e.g. blocking by mountains as well as fading due to ground bounce. The range of signal propagation is restricted to Line-of-Sight (LOS) for VHF communications. HF and satellite communications are not restricted to LOS coverage and the coverage for these depends on signal strength and footprint respectively. The coverage is also depends on altitude, with maximum of about 80 nm at 5000 feet and 200 nm at 30000 feet for VHF ground station transmitters.

2.2.2. Media Access

The goal in design of any media access scheme is to maximize system throughput, minimize transit delays, and minimize collisions and give equitable use of the channel all the nodes trying to access the channel. There are numerous multiple access schemes in use and they will be discussed along with their merits and demerits in the following sections.

One of the factors determined by the media access is the delay of message transmission. Flight information services, of which weather information is a part, are not as time critical and has less stringent requirements for reliability than ATC (Air Traffic Control) communications. However it is important to take into consideration that the data link will have to support ATC traffic as well. This is given a higher priority in the ATN protocol, and a multiple access scheme that can support ATC traffic should have provision for message prioritization.

The data communications links described in the following sections may be point to point, multicast, or broadcast, and the protocol can only support one of these modes. What is interesting is that with future applications more than one mode may be desired and the challenge being addressed is to fulfil the requirements with the least equipage.

All the communication technologies examined are digital, except ACARS, and have support for data as these are the key features in future ATN. Digital systems like the future VHF data links make better use of the spectrum because of characteristics inherent to digital data communications. Data messages can be delayed automatically until the frequency is vacant, thus using the limited spectrum efficiently. The same information is transmitted in less time with data communication than voice, due to the structured nature of data, thus occupying the channel for less time. Data compression techniques can also be applied with digital data, although the extent of this is limited to prevent the quality of the information from degrading.

Data is transmission is usually packet switched, which means that the data stream is broken into smaller groups or 'packets' all of which have a common structure for that particular communication protocol. All packets have the elements shown in the Figure 2.1 below:

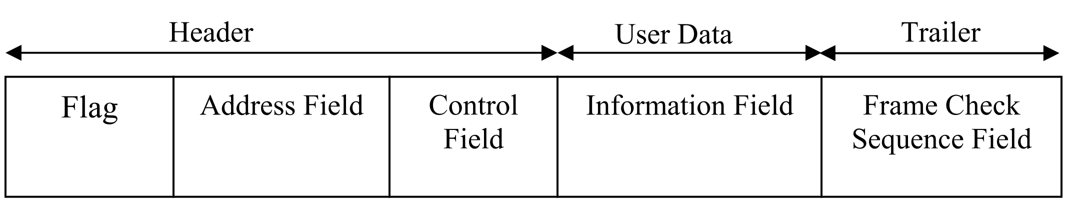


Figure 2.2 Fields in a Typical Packet of Data

The packet structure of a particular communication scheme is useful in giving an estimate of the effective data rate. The effective data rate is the actual instantaneous data throughput realized after overheads imposed by control information, bit stuffing and by any forward error correction encoding are factored in.

2.3. Data Links for Weather Information Dissemination

The choice of data link technology can only be made after detailed analysis of its operational and technical merits. Further more while the superior technical performance of one data link technology over the others is proved, it is further required to assess its suitability to the user requirements and the scope of functions it is required to fulfil. The 'fastest and the best' technique may not be deemed the best fit after considering the cost of upgrade and other operational parameters.

The three main aeronautical applications, namely, communication, navigation and surveillance (CNS) will be using data links in the new NAS architecture. The various data links are better at some applications than others and in the past disparate set of systems have developed for different applications. However, efforts are being made to realize operational efficiency by integrating CNS functions and the use of data links that serve multiple functions are desirable. The applicability towards all the user groups ranging from small GA aircraft to larger commercial carriers is desirable to achieve a better economy of scale. This also implies that that the cost to the user has to be low for the system to be acceptable to GA pilots.

Systems that exist today, or that in consideration to be implemented in the near future, include: Aeronautical mobile satellite service (AMSS), high frequency data link (HFDL), VHF digital links (VDL-2, VDL-3, VDL-4) and secondary surveillance radar (SSR) Mode S.

2.3.1. VHF Data Links

The VHF band is a congested area of the spectrum which is shared by many terrestrial systems and uses line-of-sight communications to a network of VHF ground stations. The present aeronautical VHF spectrum consists of several discrete frequencies allocated to Voice over Radio (VOR) and several other aeronautical services for traffic management. Recently the frequency band was re-organized to allocate four 25 kHz channels to VDL for broadcast FIS (VDL-2) and spectrum will be freed for future VHF Digital Links. However, the scope for supporting the future growth in air traffic is limited due to the limited amount of spectrum available. Ground antennas operate on a line-of-sight basis, so their signals radiate upward in a cone-shaped pattern. The problem with this is that airplanes at too low an altitude, or flying around high terrain, may not be able to receive signals from a ground antenna. The new VDL systems will require ground stations with completely new equipment and thus high infrastructure development costs. Compared to satellite links VHF link is more suitable for terminal area where delay is critical.

The design operations involved in final deployment of the future VDL network include frequency planning, spectrum engineering to ensure protection to existing and planned systems in the spectrum, infrastructure planning i.e. determine correct density of ground stations needed to achieve an acceptable service coverage, and capacity planning, for example determining the best parameter values for CSMA p-persistence in VDL-2.

The US FAA is currently investigating, through OpNet based simulations with ARINC, the use of VDL Mode 2 to support the early introduction of ATS data link services. The FAA considers VDL Mode 3 as a candidate for the next generation of data link systems. While extensive tests ad trials have been conducted for VDL Mode 2 prior to deployment, the implementation strategy for VDL mode 3 has not been formulated. For example, as a result of the interference tests of VDL mode 2 the frequency planning for VDL mode 2 included guard bands of 25 KHz widths between each of the four VDL mode 2 bands. The specifications drafted in the ICAO SARPS were also modified as a result of the experimentation to impose new levels of out of band interference levels. The VDL mode 3 protocol has not reached such a level of maturity. Fine-tuning of the protocol specifications is being carried out for both VDL mode 2 and 3.

2.3.1.1.ACARS

The Aircraft Communication Addressing and Reporting System (ACARS) VHF data link has been in operation for the last twenty years and has enabled a wide variety of Airline Operational and Air Traffic voice communications to migrate to data. Majorities of the airlines now depend on ACARS data link for their operations. However, the existing ACARS system has some inherent protocol limitations that prevent VHF communications to be limited to 2400 bps data rate. The effective throughput is usually even lower – sometimes in the order of 300 bps.

Although ACARS permits the exchange of data, it is a character oriented system more suited to textual data only. It is an analog system with analog AM-MSK (Amplitude Modulation – Minimum Shift Keying) as the modulation. The limited graphical weather capability is made possible by the use of compression algorithms which reduce a limited graphic file into a character string before transmission over the current ACARS infrastructure. ACARS will eventually be replaced by digital links such as VDL-2 but aircraft will potentially operate in mixed mode environment for years to come because the ground infrastructure will be upgraded over a period of time.

2.3.1.2.VHF Digital Link – Mode 2

The VDL Mode 2 radio scheme uses the same VHF frequency band and media access scheme as the current ACARS system. It however delivers an order of magnitude of throughput improvement and capacity increase over ACARS by the use of superior modulation scheme and modern electronics.

VDL-2 has begun deployment as a broadcast link to deliver flight information services (FIS). The VDL-2 system can also be configured to be 2-way data link and this mode of operation is being planned to gradually replace ACARS. The capability for both systems will be maintained during the phase-out period as aircraft fleets gradually upgrade to support VDL-2 in addition to ACARS. The aircraft will automatically switch to VDL-2 when they fly in an area where VDL-2 is available. In other areas the aircraft will revert to ACARS.

The multiple access scheme used in VDL Mode 2 is priority based p-persistent CSMA (Carrier Sense Multiple Access). The transmitter probes the channel to assess if the 'busy' signal is present, and transmits if this is not the case. In the case of a 'busy' channel, it backs off for random period of time after which it tries to probe again. If two stations transmit at the same time contention occurs which results in the re-transmission after a random back-off time. As the aircraft reaches the boundary of one ground station's coverage region, the station sends an autotune command to the aircraft's radio, to hand it over to the next ground station.

There are two modes of the VDL2; a point to multipoint system and a point to point system, which will operate in separate frequency bands. In term of performance, VDL Mode 2 provides a bit rate of 31.5 kb/s at layer one level (modulation) and the useful throughput at the subnetwork layer is approximately 15 kb/s (due to its mechanism based on a CSMA protocol – allowing and managing message collision). The 2-way VDL2 modulation provides a theoretical bit rate of 19.2 kbps per channel.

Capacity of VDL 2 has been investigated already in 1997 (COM.ET2.ST15), and by ARINC in CRDA framework (VDL Mode 2 simulation report, ARINC, N° 96-CRDA-0090, March 98). It was found that one ground-station can serve up to 150 (airport) or 160 (en-route) aircraft. Also, live monitoring and measurements of performance onboard airlines member of the VDL Mode 2 project has started. Through this, fine-tuning of the VDL 2 CSMA protocol and infrastructure deployment scenarios is being done. The physical layer data link parameters are summarized in Table 2.1. These are theoretical values based on link design or protocol specification and may vary in actual conditions.

Frequency Range	118–137 MHz
Channelization	25 kHz centers
Channel Structure	Two Modes of Operation: - Simplex 2-way - Broadcast
Multiple Access Scheme	CSMA
Radio Range	200 nmi for 4 channel capability (fewer channels for greater ranges)
Channel Data Rate	31.5 kbps broadcast 19.5 kpps 2-way
Modulation	D8PSK, non-coherent detection (3 bits/symbol)
Operating Modes	Data only

Table 2.1 Physical Layer Parameters for VDL Mode 2

2.3.1.2.1. Benefits

VDL Mode 2 has the advantages that it has already been standardized in ICAO SARPS. In terms of services, it can support most of the services of except time critical ATS services, and may be applicable to multiple aircraft classes, so the investment costs are shared. It is the first to be deployed with radio equipment currently being introduced by three avionics manufacturers.

2.3.1.2.2. Limitations

One of the problems with VDL Mode 2 protocol scheme is that the throughput and delay degrades significantly in heavily loaded channels due to the random access nature of CSMA. CSMA, due to its non-deterministic access method leads to non-deterministic transfer delay and therefore cannot be used for time-critical and safety applications such as some Air Traffic Services communications.

The disadvantage of VDL Mode 2 broadcast system is that it has no return channel for acknowledgement of the successful receipt of messages. Without acknowledgments a highly reliable message protocol is required to ensure successful message transmission. Thus the error correction coding has to be increased with its associate overheads.

The modulation scheme employed by VDL-2, π/4 DQPSK, is comparatively very bandwidth efficient but pre-deployment trials have shown that it causes significant leakage into adjacent channels [5]. Due to this co-channel interference and leakage problem, the VDL Mode 2 scheme has proposed to introduce sizable guard bands between adjacent VDL Mode 2 channels and other service channels adjacent to VDL Mode 2 channels. Thus a 25 kHz guard band channel is proposed between two VDL Mode 2 channels and up to 4-channel separation for protecting ground voice services [9].

2.3.1.3. VHF Digital Link – Mode 3

VDL Mode 3 is future data link designed with the goal of providing integrated voice and data traffic. It uses a TDMA media access protocol. TDMA is a multiple access scheme based on a time-shared use of a radio frequency (RF) channel employing: (1) discrete contiguous time slots as the fundamental shared resource; and (2) a set of operating protocols that allows users to interact with a master control station to mediate access to the channel. It uses a combination of TDMA and CSMA for providing access to multiple airborne users for the downlink. In VDL 3 each 25 kHz channel is split into 4 slots, each capable of taking a voice or data circuit. Thus the time slot shall be the basic channel resource allocated to a user group for either voice or data transmission. The physical layer parameters of the protocol are given in Table 2.2. Again, these are the design values.

Frequency Range	118–137 MHz
Channelization	25 kHz centers
Channel Structure	Same frequency for uplink and downlink
Multiple Access Scheme	TDMA
Radio Range	200 nmi for 4 channel capability (fewer channels for greater ranges)
Channel Data Rate	31.5 kbps ch data rate (4.8 kbps user data rate)
Modulation	D8PSK, non-coherent detection (3 bits/symbol)
Operating Modes	Dual mode (voice and data) Voice 4.8 kbps encoding, 250 ms end-to end latency Data Functionally simultaneous with voice

Table 2.2 Physical Layer Parameters for VDL Mode 3

The 120 ms "TDMA frame" is the fundamental timing framework and is the basic unit of time (120 ms), which consists of 3 or 4 time slots. A time slot is a TDMA timing unit allocated for either a management (M burst) or a voice/data (V/D burst), a burst that is used for the transmission of a user's voice or data.

The analog speech waveform is converted into an encoded digital stream for transmission as the VDL data packets and the reverse process is used in the receiver to regenerate from the digital voice data block to the corresponding analog speech waveform. In any voice communication, a radio will transmit digitized voice bits periodically once per frame.

Data transmission can only occur for a maximum of 15 consecutive bursts for one access time. The use of the channel has to be negotiated again with the base station for subsequent transmissions. The system configuration defines the allocation of TDMA time slot resources to various user groups supported by ground stations sharing the same 25 kHz VHF channel.

The VDL Mode 3 system is capable of operating in different system configurations to provide voice-only, data-only or integrated voice-and-data service for one to four user groups as shown in Figure 2.2. Each user group consists of up to 60 aircraft under the control of an air traffic controller [14]. The VDL Mode 3 system protocol also has provision for prioritisation, which is beneficial because VDL mode 3 traffic will consist of high priority safety related messages e.g. runway assignment by Air Traffic Controllers. Voice is simplex i.e. only a single channel is available per user for voice transmission and push-to-talk method is used.

2.3.1.3.1. Benefits

VDL Mode 3 will be capable of supporting more time critical aeronautical services than VDL Mode 2 such as air traffic control (ATC) communication and Controller Pilot Data Link Communication (CPDLC). This is due to the support for prioritisation of messages in the protocol, two-way communication, and as well as the fixed access delay and latency provided by TDMA. In contrast the FIS-B system using VDL Mode 2 was conceived solely for the purposes of weather and aeronautical information. VDL Mode 3 has received a support from the U.S. and is envisaged by the FAA to be the ultimate solution for air traffic control and CPDLC in the future.

2.3.1.3.2. Limitations

The main disadvantage of VDL Mode 3 is that it is not planned to be deployed until 2008 – 2015 time frame. The second main limitation is that range operation or coverage area is restricted because the timing synchronization of the TDMA multiple access has to be provided by the ground station. Thus the aircraft has to be within line-of-sight of the ground station which makes it less suitable for aircraft – to – aircraft communication as needed by surveillance applications and E-PIREPs. In order to ensure seamless coverage even at lower altitudes, a denser network of ground stations has to be deployed, raising the infrastructure costs.

2.3.1.4.VHF Digital Link – Mode 4

VDL Mode 4 is an ATN compliant data link, which can support Air / Ground, Air / Air, broadcast and point-to-point services. VDL Mode 4 uses Self-organizing TDMA (STDMA), a multiple access scheme, which is the similar to TDMA except that users mediate access to the time slots without reliance on a master control station (autonomous operation). The STDMA operation relies on a GNSS (Global Navigation Satellite System) for accurate system timing and for the determination of user position. VDL Mode 4 is mainly a technology being developed for ADS (Automatic Dependent Surveillance) but has the potential for providing a weather uplink. However, the main development work is in Europe and there has not been much interest by the FAA for United States. It has better co-channel (CCI) and adjacent channel interference (ACI) performance as compared to VDL Mode 2 and VDL mode 3 because of its use of a different modulation scheme (GMSK) [4].

Comparing the two modulations, D8PSK (used for VDL Mode 2 and 3), and GMSK (used for VDL4), D8PSK provides a higher bit rate (31,500 bps) compared to 19.2 kbps provided by GMSK. The higher bit rate is at the expense of higher co-channel interference values so some of the spectrum provided by the higher data rate must be used in providing larger guard bands. GMSK is found in trials to be relatively resistant to ACI and CCI. GMSK also supports an efficient frequency re-use approach called the 'Robin Hood Algorithm" in the ADS-B application. This approach allows the users to effectively re-use time slots within line-of-sight if required. By using such a modulation method the cellular pattern of tessellating coverage areas can be used thus allowing efficient frequency re-use [4]. Table 2.3 summarizes the physical layer parameters theoretical values.

Frequency Range	118–137 MHz
Channelization	25 kHz centers
Channel Structure	Same frequency for uplink and downlink
Multiple Access Scheme	STDMA
Radio Range	Up-to 400 nmi
Symbol Rate	19.2 kbps modulation data rate
Modulation	D8PSK, non-coherent detection (3 bits/symbol)
Operating Modes	Dual mode (voice and data) Voice 4.8 kbps encoding, 250 ms end-to end latency Data Functionally simultaneous with voice

Table 2.3 Physical Layer Parameters for VDL Mode 4

2.3.1.4.1. Benefits

VDL 4 has a deterministic QoS as is the case with VDL 3. The better performance in terms of ACI and CCI also means it can use bandwidth more efficiently than VDL Mode 2 and 3. The multiple access scheme is able to allocate channels without the control of a central ground station unlike VDL-3, making it a more suitable for ADS-B applications.

2.3.1.4.2. Limitations

One of the main limitations of VDL 4 is the availability of spectrum as the VHF band is congested and there is competition from other VHF technologies. Unlike VDL Mode 2 and 3, for which there has been agreements reached on providing spectrum, the decision to deploy VDL Mode 4 in the United States has not been made and that is a risk for system developers.

2.3.2. HF Datalink

The advantages of HF is that the longer wavelengths permit the signal to be refracted back from the ionosphere and received at great distances from the transmitter i.e. sky waves. This makes HF communications particularly suitable for oceanic and global communications. The frequency bands above HF are limited to direct wave, or 'line-of-sight' propagation and have to be used in conjunction with satellite links to achieve coverage across oceans. The HF frequency band allocated to commercial aviation ranges from 2 MHz to 22 MHz. Another advantage of HF is the low power requirements of the transmitters; for example, a mere 100 W transmitter can provide transatlantic voice communication [16].

HF Datalink (HFDL) is a facility used in Oceanic Control to send and receive information over normal HF frequencies, using the upper sideband of the selected frequency. The single sideband (SSB) transmission is used to economize on power and bandwidth. The signal is phase modulated to send digital information. The advantages claimed for digital HF, whether data or voice, include more rapid initial establishment of the communication link because of the automatic frequency selection. A major benefit of converting to digitized voice is that voice signal clarity is greatly improved.

Frequency Range	118 – 137 MHz
Channelization	25 kHz centers
Direction of Communication	Simplex
Multiple Access Scheme	Slotted TDMA
Radio Range	Similar to VHF
Single channel data rate	1.8 kbps (8-PSK)
Modulation	M-Phase Shift Keying
Operating Modes	Data and voice

Table 2.4 Physical Layer Parameters for HFDL

2.3.3. Universal Access Transceiver (UAT)

UAT is a broadband system that has been proposed for ADS-B (Automated dependent Surveillance), a traffic monitoring service. UAT terrestrial network would have to be developed but if UAT is chosen for ADS-B, then it can be used to provide information as well as controller pilot communications. It is a bi-directional link, however it is not designed as a request-reply system, rather the uplink and downlink behave as if they were separate broadcast channels. The air-ground downlink has been designated for ADS-B reporting only while some of the uplink capacity can be used to broadcast data from ground to air.

The UAT FIS-B products are transmitted using uplink time slots. There are 32 slots per second, and each time slot delivers about 3600 bits of usable payload. Assignment of time slots depends on the configuration of the ground systems and needs to be managed as part of the system configuration, since an airborne aircraft will likely be in range of multiple ground stations. If one time slot is allotted per ground station, the net data rate will 3600 bps.

The physical layer characteristics of the design are listed in Table 2.5. UAT specifications have not been standardized yet and since the system is still an evaluation system, these are expected to change.

Frequency Range	981 MHz – 983 MHz
Channelization	Single 2 MHz channel
Direction of Communication	Two part. Ground broadcasts information to aircraft, aircraft transmit position information.
Multiple Access Scheme	TDMA
Radio Range	Similar to VHF
Channel Data Rate	1 Mbps total
Modulation	Uplink - Binary Continuous Phase Frequency Shift Keying TDMA broadcast
Operating Modes	TBD

Table 2.5 Physical Layer Parameters for UAT

2.3.3.1.Benefits

UAT is a broadband system and can support high data rates. It is also capable of supporting traffic, weather and surveillance functions, thus it is more cost effective when multiple services are required.

2.3.3.2.Limitations

There is no frequency allocation for UAT yet. In addition, the decision to implement this data link for weather data link is tied to the ADS-B link decision.

2.3.4. Mode S

The Mode S sensor is basically a radar sensor whose primary function is to maintain surveillance of air traffic within its observation range. This information is used by Air Traffic Control (ATC) to guide aircraft coming into the terminal and in maintaining separation between them. The rotating beam antenna sweeps 360 every 5 seconds. The extended squitter signal of the Mode S sensor can be used for two-way data link communication. With the radar beam sweep rate of one each 5 sec, the response time to provide weather data to the cockpit is approximately 10 to 15 seconds. A Mode S sensor can provide the service out to a range of 75 nmi, but line of sight does not permit coverage to the surface in the outer regions. This is because the floor of the coverage area is approximately 3500 ft at 75 nmi and therefore low-flying aircraft (below 3500 ft) cannot receive the signal [16]. Mode S link can also be set up in airports that do not have a Mode S sensor, by constructing a Mode S Transmit/Receive Ground Station in those airports. These ground stations will have an omni-directional antenna that allows it to respond to requests faster than the Mode S sensor.

The functionality of Mode S is limited by its primary surveillance function and its rotating antenna structure, which precludes the capability for high data rate communications. In addition the limited communication bandwidth may be used to deliver traffic information to augment the surveillance applications with weather information given a lower priority.

2.3.5. Satellite Link

Satellite systems are capable of providing more bandwidth than the aeronautical VHF networks can provide. A number of existing and upcoming satellite links have the capability of providing a FISDL. Satellites have certain unique advantages. They are unequalled for broadcast applications, i.e. the delivery of the same information to a large group of users. They also preclude the need for a large terrestrial network. In addition the signals can be received by aircrafts operating at any altitude.

A current disadvantage for SATCOM, however, is that receivers must be adapted for aviation use (size, weight and cost) and the patch antennas mounted on the body of the aircraft must be resistant to the significant drag and mechanical vibration. Geosynchronous satellites have approximately a 0.25 second delay which is not desirable for real-time voice applications.

There are currently five commercial satellite systems that provide communication services to aviation users: Globalstar, Orbcomm, Iridium, MSAT and Inmarsat. Given the number and different types of constellations being deployed worldwide there is wider array of choice and more low cost solutions available. Some of the Satcom systems, which are affordable even for the general aviation market, are coming into the market e.g. ARNAV WxLink which uses the Globalstar Low Earth Orbit network, Echoflight which uses the OrbComm LEO network and WSI Inflight which is built upon the MSAT GEO satellite network.

INMARSAT, a geosynchronous system, uses the 6 GHz band for uplink, 4 GHz band for the downlink to ground stations and 1.5 GHz band downlink to the aircrafts. The satellite transponders receive the signals, and re-transmit them on lower frequencies. Lower frequencies are used in the downlink (satellite to ground/aircraft) because, unlike in a ground station, the power on a satellite is limited and lower frequencies have reduced power requirements. A disadvantage of geostationary satellites is that their coverage does not extend to the regions near the poles. Low-earth orbit (LEO) satellites have reduced power requirements for the airborne equipment, but need a phase array tracking antenna to keep in line-of-sight of the satellites as they move in their orbits.

2.3.5.1.Satellite Hybrid Architecture

In the terrestrial UMTS (Universal Mobile Telecommunication System) a hybrid asymmetrical is being proposed which combines multimedia broadcast systems such as DAB (Digital Audio Broadcast) and DVB (Digital Video Broadcast) with mobile multimedia networks such as UMTS. The future graphical information services will be bandwidth-hungry and will require much more downstream capacity than upstream capacity. A system such as this exploits this asymmetric characteristic of multimedia data (such as graphics, video) to offer a cost-effective and high-speed approach to delivering data by combining digital satellite broadcasting technology, for the high-capacity downstream links, with relatively low-speed uplink.

Such a system could conceivably be adapted for the aeronautical weather information use, where a low bit rate forward channel such as ACARS combine with an AMSS (aeronautical mobile satellite service) in an asymmetric data link to give the pilot access to high bit rate and bandwidth intensive graphical weather and other applications.

With a satellite link, it is possible to provide even more services in the future such as SMS, e-mail, internet etc. since there will be relatively more spectrum available and the use of the spectrum will not be as tightly regulated.

The drawback of such a hybrid network would be that commercial satellite systems are not regulated and will not likely be certified for time critical and safety critical ATC type communication. Thus, transport aircrafts will have to be equipped for a separate data link that will handle the traffic information and navigation. However, for general aviation aircrafts, the ATC communication is not needed and thus such a system is feasible.

Whilst there are other possible satellite systems in the market that may be potential providers of Flight Information Services applications, only the ones that have been proven to be standardized, validated and commercially available in the time frame set out by the AWIN project [refer to the AWIN implementation Program] are addressed in this report. Taking into consideration the failure rate among upcoming satellite systems (e.g. Iridium), the question of financial viability/ stability of satellite networks remain to be proven. Some satellite systems currently providing aviation information service are examined in the following sections.

2.3.5.2. GEO Satellite System - WSI Inflight

The satellite communication system broadcasts all the information for the entire continental U.S. (CONUS) to be received by all aircraft within the satellite's footprint. The onboard processor selects the data needed for display based on the pilot's actions. A characteristic of satellite system is the ability to provide wider coverage than VHF radio and unlike VHF radio, at all altitudes.

GEO satellite systems are mainly broadcast and due to the high path delay. Broadcast has the advantage that an unlimited number users can receive the data. Another advantage of broadcast systems over a request/reply system is that the pilot may not always have the knowledge or time to request a specific piece of information that may be critical for safe flight operations.

2.3.5.3. LEO Satellite System - EchoFlight

A number of LEO satellite systems have come up in recent times to provide telephony and low rate messaging to mobile users. LEO systems thus have a significant opportunity to be applied in the aviation arena. The EchoFlight system uses the OrbComm Low Earth Orbit Satellite network to provide 2-way data messaging which includes among other applications weather and navigation. The message flow is circuitous, and contributes to the high end to end delay. First, the request is relayed by the satellite transponder to OrbComm's ground earth station, which further conveys it to

EchoFlight's control center. The requested weather data is then forwarded to ORBCOMM, for uplink to the appropriate ground earth station for delivery to the satellite. The message is then relayed from the satellite to the satellite communicator aboard the aircraft. Thus the round trip delay is about 2 minutes [15]. The bandwidth is 4,800 bps, and it is a packet switched network such that the transmissions are made in burst mode. Billing is not based on a per-minute cost; rather service charges are based on units of in-flight transactions. This billing plan is suitable for high latency data links.

2.3.6. Flight Information Services Data Link (FISDL)

Flight Information Services (FIS) are defined as the non-control, advisory information needed by pilots to operate more safely and efficiently in the National Airspace System (NAS) and in international airspace. The FISDL is being developed by the FAA and industry to provide an automated and continuous delivery of weather and other information to the cockpit through VDL Mode 2 data link. The allocated bandwidth for FISDL services in the United States is four 25kHz spaced frequencies on the aeronautical (non-voice) spectrum - 136.425 through 136.500 MHz. FISDL is designed to provide coverage throughout the continental US through a system of regional broadcast stations for altitudes from 5,000 feet AGL to 17,500 feet MSL. Aircraft operating near transmitter sites will receive useable FISDL signals at altitudes lower than 5000 feet AGL, including on the surface in some locations, depending on transmitter/aircraft line of sight geometry. Aircraft operating above 17,500 MSL may also receive useable FISDL signals under certain circumstances.

The network of land based VHF ground stations is being deployed by two FAA appointed service provider companies. A satellite link can also provide FIS services and some such systems are already being deployed to provide service to major airlines. Initial FIS products for delivery to the cockpit include information on the status of the NAS (Notices to Airmen and Special Use Airspace) and meteorological information, both in textual as well as graphical format. Aircrafts properly equipped with a VDR and a suitable display will receive free basic weather information. Enhanced products are available for a fee.

The broadcast regional centres first processes the data obtained from the weather providers into format suitable for aviation uplink and including encoding and compression. It then distributes them to transmitter sites by microwave links or similar ground infrastructure. Once at the transmitter site, weather information for the local region (50 miles radius or more) is continuously transmitted so that an updated product goes out on the transmitter at least every five minutes as required by the FAA MASPS (Minimum Aviation System Performance Standards).

At the aircraft station the data is received and decoded by the VHF Digital Radio (VDR). Information is stored in memory, being replaced every time a more current version is received. Broadcast FISDL allows the pilot to passively collect weather and operational data and to call up that data for review at the appropriate time. In addition to text weather products, such as METAR's and TAF's, graphical weather products, such as radar composite/mosaic images may be provided to the cockpit. Two-way FISDL services permit the pilot to make specific weather and operational information requests for cockpit display.

One limitation of weather information available in the cockpit through a broadcast FISDL is that in most cases these products are not appropriate to be used in tactical severe weather avoidance. For example, a pilot cannot negotiate a path through a broken line of thunderstorms based on a ground-based radar precipitation map uplinked to the aircraft. Since broadcast relays a large amount of data for a large region, the resolution as well as the time accuracy of the data, would not be sufficient for it to be used in this way. A disadvantage of a more regional broadcast would be that the pilot can receive information about that region only, and be unable to perform strategic planning such as ascertaining the airport conditions at the destination airport.

2.3.7. Communication Avionics

The communication hardware in the aircraft is comprised of the antenna(s), the transceiver, the processor and the display and controls. Depending on the system architecture, the on-board unit will have various levels of storage and computation and control requirements. Thus the hardware requirements depend on the amount of processing done by the on-board unit. The control system allows the user to selectively retrieve and display the information and performs various other automatic functions. The communication unit may interface with other on-board equipment such as the GPS/ navigation system, TCAS (Traffic Alert and Collision Avoidance System), terrain information, and/or on-board weather radar. In aircrafts equipped with a number of avionic systems, there is a multi-function display (MFD) to display the information from all the various sources.

According to GA pilots [Pilot Survey, Appendix A], 85.6% of the pilots surveyed indicated that the non-recurring cost of the system should be less than $5000 which puts a limit on the complexity of the on board equipment. Also some types of units (e.g. handheld) do not have the processing capacity due to their physical constraints as compared to panel-mounted systems. This may also determine the choice of the control and display unit (CDU). Pilots have indicated a preference to display the position of the aircraft with reference to the weather hazard [Pilot Survey, Appendix A]. This entails the integration of a LORAN or global positioning system (GPS), and there are two configurations that can be supported: i) transmission of the position of the aircraft to the ground processor which uplinks position-based information in case of a two way link or, ii) an interface of the position signal directly to the CDU.

In all of these a trade-off can be made about on-board processing and memory, against the uplink of pre-formatted, tailored products i.e. two way link

The current high-end displays have weather overlaid onto navigation moving maps giving a higher level of situational awareness. In the future, the research in decision aiding algorithms, coupled with the increase in computation power, will lead to expert systems that will provide continuous recommendations on the course, altitude, alternate route and airport information based on the current and forecasted information received from the ground. The reliability and certification of such systems in safety critical aeronautical applications is the limiting factor in their deployment.

2.3.7.1. Weather Information Systems Hardware

The hardware for the weather information system is an integral part of the system and is one of the main factors in the display and presentation of graphical weather information. The question of whether the processing is done on the ground or in the air has a large part to play in the complexity of the on-board avionics for the display and processing.

The constraint on bandwidth puts a limit on the size of the graphic files that can be transmitted to the cockpit via data link. The amount of bits needed to transmit and display a weather graphic depends on three things: I) the number of colours used in the graphic representation, a 16-colour image will need 4 bits to represent each colour, whereas 16 bit colour coding is used to display 65,536 individual colours, ii) the dimensions of the screen/ graphic i.e. the pixel count iii) the grid size used i.e. the square area of the smallest block of graphic.

The grid size is variable on the total area to be represented or the scale of the map in case of weather. Thus to display a map of the whole United Sates a grid size of 64km x 64km is sufficient while to display a specific terminal area, a smaller grid size of 8km x 8km may be needed. The smallest resolution or grid size of the data is currently limited by the resolution of the weather observation/forecasting models. The transmission of graphical weather information is further discussed in terms of the communication requirements in Chapter 3.

Chapter3

Data Communication Requirements in the Cockpit

This chapter will provide an analysis of the en-route weather information with a view of ascertaining the data communication requirements.

Predicting the data flow between the cockpit and the variety of information sources and options, available in the future aeronautical network environment, is a challenge facing system developers and designers. Determining the usage of the communication link and communication loads is vital to determining such overall architecture definition issues as frequency planning, choice of data links, and infrastructure deployment. Adding to the complexity of determining communication link usage are the variable levels of equipage in aircrafts, and the variable service requirements. The usage of a particular data link is also dependent on the other data links available, the mix of broadcast and request-reply communication environment and as always market factors.

This research specifically focuses on the requirements of the general and business aviation segment that could significantly benefit from the widely accessible and affordable weather information dissemination systems and avionics. The general aviation segment of civil aviation constitutes more than half of the domestic operations and includes personal flights, and business and corporate flights. General aviation airplanes spend the most time at lower altitudes, and are therefore often the most highly threatened by weather. At the same time they also have the least money to spend on equipage. Thus the need to develop better weather information dissemination systems and avionics while keeping the cost low.

3.1. Characterizing Aviation Weather Data

The systems analysis approach to determining the ground-to-air data communications load is to identify and define the various information products that will be data linked to the future cockpits through requests or broadcasts. This includes the value added weather products. The next step is to determine the communications load for those value-added products. Then to add the value added commercial products to the basic National Weather Service (NWS) weather products and arrive at a final communications load that would establish the communications requirement for ground to air data communications. From this analysis, the bandwidth required or desired to deliver given weather products can be determined for the particular communication scheme used. The bandwidth will depend on four main factors: the number of products available, their sizes, how often they are needed, and immediacy of need for the product. In most cases only a worst–case scenario can be derived considering that the total load (say per flight per hour) is highly variable depending on a multitude of factors such as the type and intensity of weather encountered, the preference of the pilot, the equipage of the aircraft etc.

Weather 'products' are defined as information (measured data, processed data, forecasts) that have been packaged for interpretation by the recipient to aid in making both strategic and tactical decisions affecting aviation safety [8]. Aviation weather products are specialized and there are many individual types of weather information products that serve specific functions and provide the weather information pilots need under various conditions and circumstances. Weather products have different attributes such as type, coverage area, update rate and product life that affect how they are used in the cockpit and the communication requirements. Some weather products are tailored to specific portions of the flight phase, while some are limited in their availability, for e.g. they are available at only certain locations or may be accessible only to certain classes of aircrafts.

Weather hazards can be grouped into eight major categories: weather systems, air motion, precipitation, icing, visibility and ceiling, lightning, volcanic ash, and wake vortices [8]. There is a general requirement that aviation weather products address each of the weather hazards in terms of: forecast, observations, intensity, location, extent, movement, and life cycle.

Many standard weather products and formats have been defined by international agencies such as ICAO (International Civil Aviation Organization), for example, weather charts and graphs use standard ICAO symbology. Weather information is usually required to be given to pilots in this standard format for basic weather products. For graphical weather information, this requirements is not so stringent and the service provider may process the raw data from the NWS and deliver it in a different format, for most aircraft classes except commercial carriers which may be required to obtain weather information from approved sources. The standardized formats are to ensure common understanding across the aviation community around the world.

3.1.1. Textual Weather Information

Currently, almost all aviation weather information provided in-flight in the USA is in analog voice format or textual weather information via ACARS. The main standard text weather products are given in the Table 3.1 below with a brief description.

Name	Full Name	Description
METAR/SPECI	Aviation Routine Weather Report	It is an international standard code format for hourly surface weather observations. Weather related information provided includes: wind, visibility, weather type, obstructions to visibility, sky conditions, temperature, dewpoint, and altimeter setting.
TAF	Terminal Aerodrome Forecast	It is an international standard format for providing a concise statement of the expected meteorological conditions at an airport during a specified period (usually 24 hours).
AIRMET (WA)	AIRman's METeorological Information	Advises of weather of less severity than that covered by SIGMETs or Convective SIGMETs but which is of operational interest to all aircraft and potentially hazardous to aircraft having limited capability because of lack of equipment, instrumentation, or pilot qualifications. AIRMETs cover moderate icing (AIRMET Zulu bulletin), moderate turbulence (AIRMET Tango bulletin), and visibility conditions and/or extensive mountain obscurement (AIRMET Sierra bulletin).
FA	Area Forecast	It is a forecast of Visual Flight Rules (VFR) clouds and weather conditions over an area as large as several states. The area forecast together with the AIRMET Sierra bulletin is used to determine forecast en route weather.
AWW/ WW	Severe Weather Forecast Alerts / Severe Weather Watch	These messages define areas of possible severe thunderstorms or tornado activity. The messages are unscheduled and issued as required.
SIGMET	SIGnificant METeorlogical Information	It is a weather advisory that covers severe and extreme turbulence, severe icing, and widespread dust or sandstorms that reduce visibility to less than 3 miles. A Convective SIGMET may be issued for any convective situation which the forecaster feels is hazardous to all categories of aircraft.
CWA	Center Weather Advisories	It is an unscheduled weather advisory issued by Center Weather Service Unit meteorologists for ATC use to alert pilots of existing or anticipated adverse weather conditions within the next 2 hours. A CWA may modify or redefine a SIGMET.

Winds Aloft	Winds Aloft	Winds aloft are computer prepared and contain forecast wind direction and speed as well at forecast temperatures. Forecast winds and temperatures aloft are prepared for: 6,000, 9,000, 12,000, 18,000, 24,000, 30,000, 34,000, and 39,000 feet.
PIREP	Pilot Reports	It is a report of meteorological phenomena encountered by aircraft in flight. Pilots report such information as: thunderstorms, icing, turbulence, windshear, cloud base, tops and layers; flight visibility; precipitation; visibility restrictions such as haze, smoke and dust; winds at altitude; and temperature aloft.

Table 3.1: Summary of Text Standard Products

Previous studies and FAA documentation was surveyed to obtain message sizes of the textual weather products. This information is summarized in the table below:

User message type	**Message Length (bits)**	**Frequency (msgs per hour)**
Notice to Airmen (NOTAMS)	1800	3
Automate Terminal Information System	1600	3
Individual Weather products:		
- Radar Summary	780	3
- Pilot Reports (PIREPs)	1800	3
- Surface observations	1800	3
- Winds aloft forecast	800	3
- Terminal forecast	1800	3
- General Hazard	1800	3

Table 3.2. Messages Size for Textual Weather

3.1.2. Graphical Weather Information

Current and future graphical weather products that will be made available to the cockpit include precipitation maps, NEXRAD radar mosaics, satellite images, graphical TAFs and METARs. The size of the graphic depends on the model grid sizes, desired/available fidelity, and desired/available area of regard and color depth.

The future delivery of in-flight aviation weather tools involves a mix of government services and private sector provided value-added weather products. The products that will enhance or replace the current tools in the near future will come primarily from the private sector and will be in graphical form e.g. graphical METARs and TAFs.

Radar weather sensors provide one of the most useful ways of observing and forecasting a wide range of atmospheric conditions as well as providing graphical weather products for use in aviation. NEXRAD is the commonly used acronym for the Next Generation of Weather Radar, which began to be tested and implemented by the National Weather Service and the Federal Aviation Administration during the 1980s. These new Doppler radar systems, now more appropriately known as the WSR-88D (Weather Surveillance Radar - 1988 Doppler), have recently replaced the aging network of WSR-57 and WSR-74 radar systems which the National Weather Service and the Federal Aviation Administration had been using for the last several decades. The WSR-88D provides several advantages over the its older predecessors, including:

- Greater Sensitivity
- Higher Resolution Data
- The ability to detect the relative motion of echoes within a storm
- Multiple volumetric views of the atmosphere
- Algorithms to estimate the amount of liquid in the atmosphere
- Algorithms to estimate the amount of precipitation that has fallen

From NEXRAD data, meteorologists can estimate important information such as where precipitation is right now, how much precipitation is falling, and where thunderstorms are likely occurring.

The completeness of the NEXRAD radar coverage and the extensive amount of derived weather information makes it a generator of a highly desirable and useful weather product for display in the cockpit. The NEXRAD radar produces 17 different types of data based on 3-Dimensional, 360-degree volumetric coverage of the atmosphere. NEXRAD data is generated at different radar sites and then composited to give regional, national or customized coverage image maps. The NEXRAD composites are derived from combining the data from multiple ground-based radar sites by a specialized algorithm by the National Weather Service (NWS). NEXRAD imagery is output in two modes: Precipitation and Clear Air, which has an implication on how the image is interpreted. In clear-air mode, the frequency at which the information is updated is less, as there is no precipitation detected.

For the airborne display of precipitation data the 16 levels of NEXRAD base reflectivity are converted to 4 levels - None, Light, Moderate, Severe and color-coded before transmission to aircrafts. For example for precipitation, showing light precipitation in green, moderate precipitation in yellow, and heavy to severe precipitation in red. Fewer colors are used in these images than the normal ones to conserve file sizes. Special compression for weather images is usually applied prior to transmission. The size of the uncompressed NEXRAD mosaics range from about 10kB to about 30kB depending on the type of derived information and the density of the NEXRAD data. Depending on the type and level of compression used, the images can range from approximately 2000 bits to 15000 bits.

3.1.3. Weather Products by Method of Delivery

The method of delivery of information can be either broadcast or request/reply.

3.1.3.1. Broadcast Products

The nature of weather information is such that a large number of users can benefit from the same information i.e. most of the products are not flight dependent. Although two-way communication facilitates the greatest flexibility and utility, the bandwidth required increases in proportion to the number of users, which preclude its use for wide scale dissemination, unless a broadband data link is used. Weather products that can be more effectively transmitted using a broadcast data link are large radar images, weather hazards and temperature and moisture graphics or textual products among others. The final mix of the two, broadcast and two-way will have a significant impact on total bandwidth required for the data link. With a given core of these available, pilots (and dispatchers) will likely fill in any informational gaps with specific, addressed products.

3.1.3.2. Addressed Products

Most addressed products are likely to be fairly specific, and therefore, smaller in file-size than the same products broadcasted. Even so, a high demand for relatively small products in the vicinity of a weather hazard could easily tax future available bandwidth [6]. There are some weather products, however, that may benefit from a request/reply link such as terminal weather information, forecasts, and information on a smaller scale with higher resolution. Differentiating products in this way and defining boundaries and overlaps between 2-way and broadcast products may help in planning to have a more efficient architecture.

3.1.4. Weather Products by Phase of Flight

Weather products can be grouped by the phase of flight that they are used in: terminal area, climb, en-route (cruise) and approach. The bandwidth requirements for each phase of flight should be determined separately since the bandwidth available in each of these arenas is different. In addition, weather information needs of the pilot change with the phase of flight.

En-route products are the ones most often pictured when discussing weather products on the flight deck. For airlines, this information is sometimes already provided in a very diluted form, through various links to the dispatcher. Broadcast to the cockpit, these products will help enable more pro-active, quicker, smarter, more collaborative decisions. For non-dispatched traffic, including GA, these products represent information previously available only through fairly arduous searching. [11]

Terminal areas are where the highest volume of traffic will be and where a large volume of weather information will be needed. In addition, the terminal area is of a more time–critical nature. The following table provides a summary of weather information product requirements by phase of flight.

Phase of Flight	Weather Information of Interest	Weather Products Received
Climb	Radar Imagery, Wind Shear, Visibility/Ceiling, IFR, Convection, Winds and Temperature Aloft, Forecast.	AIRMET, FA, SIGMET, SIGMET, PIREP, NEXRAD Imagery, Forecast Maps
En-Route	Turbulence, Convection, Icing, Winds and Temperature Aloft, Surface conditions, Radar Imagery, Forecast.	METAR, TAF, AIRMET, FA, SIGMET, PIREP, NEXRAD Imagery, Forecast Maps
Approach	Terminal Radar Mosaic, Wind Shear, Runway Conditions, Visibility/Ceiling, IFR.	METAR, TAF, PIREP, NEXRAD Imagery
Terminal	Terminal Radar Mosaic, Wind Shear, Runway Conditions.	METAR, TAF, PIREP, NEXRAD Imagery

Table 3.3: Weather Products by Phase of Flight

3.1.5. Pilot and Accident Studies

Since the study is on general aviation weather information requirements, it is important to determine the weather conditions that the GA pilots most concerned with. According to the FAA's Weather Joint Safety Analysis Team (JSAT), research indicates that weather-related GA fatal accidents are attributable to, in order:

- Instrument Meteorological Conditions
- Convection
- Icing
- Turbulence

3.2. Characteristics of new Cockpit Weather Information Systems from Consumer Perspective

In this study, attempt has been made to integrate the perspective of the end-user to arrive at the integrated product development model for weather information systems. The question of what would be the data requirement in different scenarios, with future requirements for text/ graphic and broadcast/ 2-way mix and ascertain if the system can support the same in terms of latency and capacity.

The results of the GTRI study [8] show that some deficiencies exist in the areas of data format, support systems, sensors, and forecasting and modeling. In the area of data format, the lack of a graphical display capability in the cockpit limits the pilot's ability to consume and interpret weather products as they become available. In the area of weather information support systems, an identified deficiency is the shortfall in tailoring weather products to the spatial and temporal needs of the aviation community. This indicates that the information is at too wide a scale for precisely determining what lies a few miles ahead. The temporal needs of the pilot may not be satisfies if the weather is not up to date. This makes it difficult to make routing decision en-route.

A survey was developed to get further details and insight into pilot requirements for graphical weather information in the cockpit, which would have an impact on specific data link and/ or hardware characteristics.

3.2.1. Pilot Survey

The survey was designed to get information on key features and capabilities whose need and usage patterns were to be determined. The other major objective of the survey to was to get the relative importance of the various requirements, in order to get an accurate assessment of the design requirements for future comparison. The survey would obtain results from different categories of aircraft and pilots. The questions were formulated around a set of consumer requirements (CR's) related to graphical weather that were collected from a previous survey and discussions with pilots. The survey had two sections; one to establish the communication system related needs of graphical weather transmission and the second to ascertain the features and usability of the weather information display and interface.

The following general facts are known about pilot preference for weather information from literature and a previous survey.

- Graphical products in preference to voice briefs.
- Timely updates of real-time weather.
- Type and intensity of the weather phenomenon must be provided.
- Multiple services integrated into the same display.
- Automated weather alerts for notable weather phenomenon.

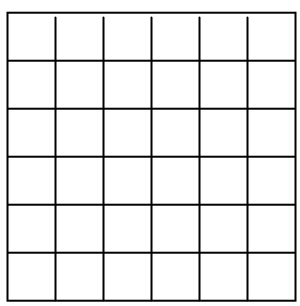
The survey questions were based on these preliminary findings and expanded to get a measure of the requirement. Please see Appendix A for the pilot survey. The following section gives an explanation for the topics addressed in the survey.

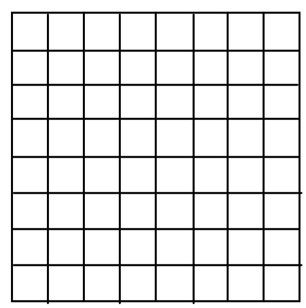
3.2.1.1. Graphical Weather (Type and Number)

The introduction of Graphic Weather charts and Images will have the greatest impact on the usage of bandwidth and frequency resources. The number of graphical weather products desired by the user group is the target of the question here. A number of weather products are listed and the participant is asked to rate the importance of each.

3.2.1.2. Grid Size (or Resolution)

To compare the effect of grid size on the file size of a picture, the two pictures below, which are of the same size, are given as an example. One picture is made up of a 6 x 6 grid or 36 blocks (data points) while the other picture is composed of an 8 x 8 grid, or 64 blocks (data points). Information is the gridded binary format is represented by colors for each of the block. Most weather graphics that are going to be transmitted to the cockpit will be 16-color images. Thus each block or data point is represented by one 4-bit color.





The first picture uses 36 x 4 bits or 144 bits while the second picture uses 64 x 4 bits or 256 bits. Thus grid size is the same as pixel count is to a screen.

The survey enquires the minimum grid size, which is necessary to calculate the worst-case scenario for the data sizes.

3.2.1.3. Frequency of Weather Updates

The frequency of update or the refresh rate of one of the most graphical maps is enquired. Weather graphics cannot realistically be updated at the same rate as some of the routine textual information such as METARs. Knowledge of the pilots preference and need for this refresh rate will help in calculating data rate requirements per second.

3.2.1.4. Location-Aware Weather Information

This is a concept of providing en-route aircraft information that is relevant to their current location and may be a feature used by future weather delivery systems to provide more detailed information for a limited area or for a specific route.

3.2.1.5. Weather Hazard Alert/ Warning Messages

This is the capability of having weather warnings in the cockpit when unexpected hazardous weather conditions occur. The importance of weather alerts in different conditions will affect the message latency and connection delay requirements of the data link. It also has an impact on the decision aiding and hardware features of the system.

3.2.1.6. Additional services (e-mail, telephony, SMS, Internet)

The pilot is asked whether these services are important to be included with the new weather information system. There are only a few data links that are capable of supporting communications if this nature, and pilot preference will be one of the factors in considering the data link of choice in this scenario.

3.2.1.7. Other Questions

The remaining questions are about the decision aiding which is an open-ended question and about the cost. The questions of the survey will be processed in the product development model developed in the next chapter.

3.2.2 Implication of the Consumer Inputs to the Model

Each consumer requirement has an impact on the data link or the display hardware as shown in the Table 3.4.

Consumer requirements	Information obtained from Survey	Additional Information	Characteristics of Data Link Impacted	Impact on Equipment
Graphical Weather	Type and Number of Graphical Products.	Update Frequency, File Size	Bandwidth, Data Rate	Suitable Display
Grid Size	File Size (depends on Resolution)	-	Bandwidth, Data Rate	-
Weather Update Frequency	Weather Update Frequency	-	Bandwidth, Data Rate, Latency (i.e Set-up Delay)	-
Indicate Direction and Rate of Hazardous weather	Mode of Presentation	Processing Requirements	-	Suitable Display, Ground Processing
Location-Aware Services	Needed / Not needed	-	Possible 2-way link	GPS Integration
Weather alert	Weather Alert Condition	-	Broadcast link needed, Good range of coverage	Good Warning/Indication capability
Traffic information	Demand for TIS	Same data link or separate	Bandwidth, Data Rate	Suitable Display, Integration of Info or another Screen
Additional services e.g. Short Message Service (SMS), e-mail, Internet	Needed / Not needed	Same data link or separate	Type of Link (compatible with TCP/IP), Bandwidth, Data Rate	Suitable Display, Integration of Info or another Screen
Both Voice and Data communication	Relative Data Traffic Load/ Voice Traffic Load	-	Voice and Data Link	-
Data entry	Data entry Options	-	-	Suitable Interface
Decision-aiding information	Open ended	-	Depending on the type – can reduce total B/W required	Type of Display needed

Costs	Non-recurring costs, Recurring costs	-	Service Provider Charges	Cost of Display
Time to market	Time the desired WIS should be introduced (and would be adopted?)	Time frame for deployment of various data links	Can data link satisfy the time criteria	-

Table 3.4: Survey Questions and Implications on Technical Characteristic

Chapter 4

Implementation of the Weather Information Systems Decision Model

A technique used by system developers to select between the numerous architecture and data link solutions that have potential for future deployment is to assess the capability of the system with a view of meeting end-user requirements. A user-centric decision model is developed in this research to find the appropriate data link and hardware for a weather information system for different segments of aviation. The task of developing this model was a joint effort with Yesim Sireli of the Engineering Management Department of Old Dominion University. This section will describe the elements of the model and its implementation.

4.1. The QFD Model and its Application for Weather Information Systems Design

In the technical evaluation, a two-step process was employed: a preliminary analysis using a Quality Function Deployment (QFD) method, and a more detailed analysis where comparative performance evaluation for the successful data links was conducted to determine the most feasible data links and for the particular product characteristics in consideration. The QFD method, widely used in industry, is a decision support tool that can aid in the decision-making processes associated with large, complex technical systems. It is useful for the translation of customer needs and expectations into design specifications for a conceptual product or to find the best match between alternative technologies. QFD started as a means to prevent market failures by reducing the gap between the customer's desires and the product's performance. It is applied to various industries and products ranging from vehicle concept to software application design.

The QFD model was adopted in this weather information systems study due to the following:

- The evaluation of the data links is based on numerous and sometimes inter-related attributes that can be abstracted using the QFD model to ease in the comparison.
- The future weather information technologies are being developed specifically for the aviation community to enhance safety and operational efficiency and thus the customer plays a key role in the definition as well as eventual success of the system. Therefore a consumer-centered approach based on the QFD is needed.
- The QFD Matrix is a useful tool to factor in the customer needs and predicted usage that were captured in a survey.
- The QFD approach results in benchmarking competing technologies which helps in finding their relative strengths and weaknesses.

The QFD model uses a method of abstraction to benchmark the performance of the various competing technologies. The pilot's requirements were obtained form a suitably designed survey, that was distributed to pilots on pilot organizations web sites. The survey was designed to measure the importance of the product features/ capabilities as described in Section 3.3.1. The importance values were ascertained by measuring the strength of agreements or disagreements with the choices presented. The results of the survey allowed us to establish the capabilities required of the system and also the prioritizing of the needs.

The consumer requirements from the survey were translated to a set of technical requirements - or design requirements (DR's) for the communication link. The data links would be evaluated based on the following major considerations: physical layer attributes or protocol parameters, network architecture, operational and implementation issues. The above categories yield the following design requirements which are applicable to the system we are studying: user data rate, request-reply capability, traffic information capability, network coverage, capacity, connection delay, message latency, position reporting. Most of the technical parameters are related to the physical layer performance characteristics of the data link. These design characteristics are further elaborated in Section 4.2 below.

Figure 4.1 shows a diagram of how the QFD Matrix is constructed and how the relationships between the requirements/technical characteristics developed.

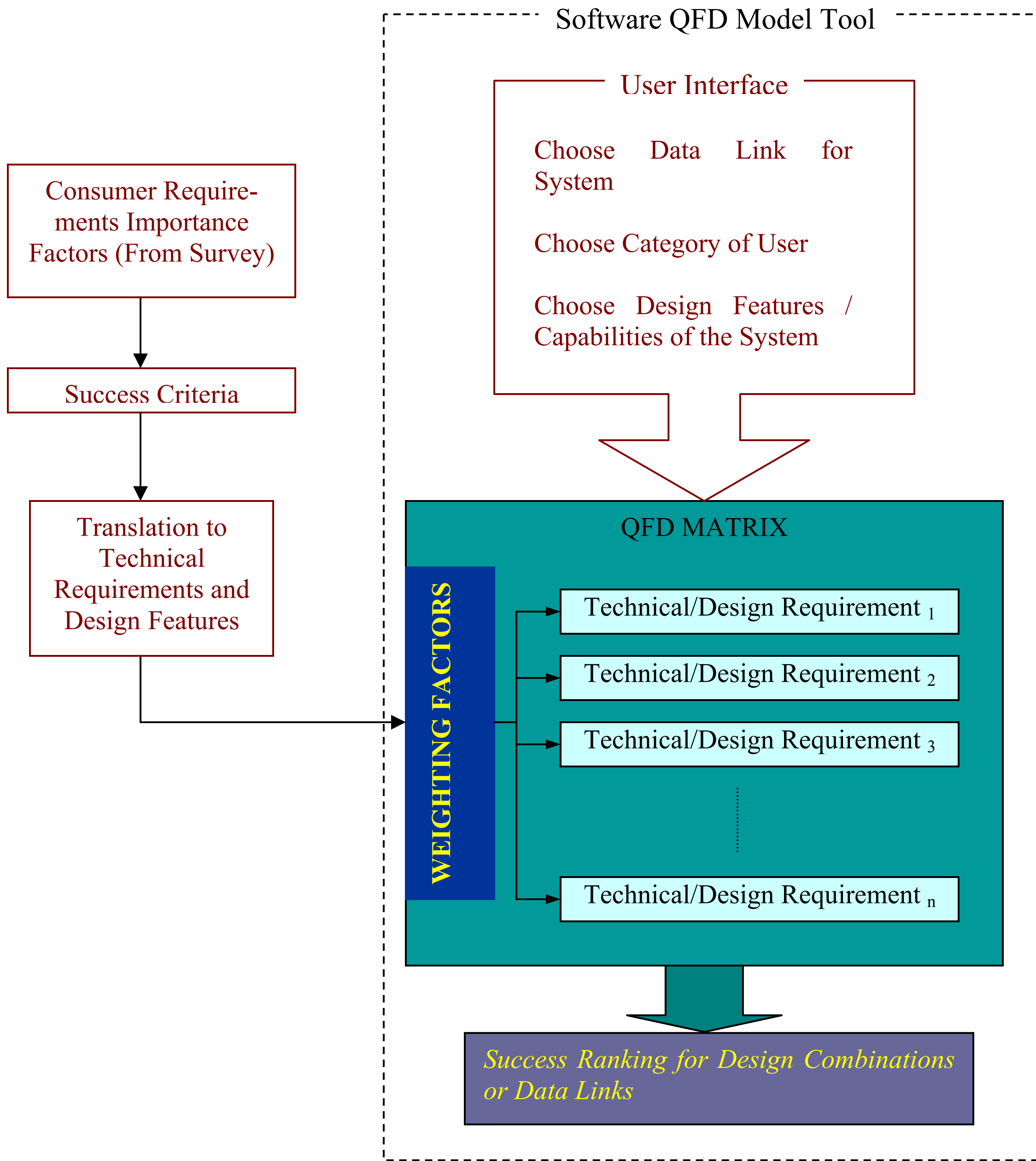


Figure 4.1 QFD Model for Weather Information Systems Design

In summary, the following steps were followed to produce the QFD-based product decision model:

- Identification of the design and technical parameters;
- Designing a survey to gather information about consumer preference and predicted usage of the system;
- Translation of the consumer requirements (CRs) to design requirements (DRs) or performance measures;
- Analysis and prioritization of the performance measures or design parameters;
- Processing the QFD matrix.

4.2. Overview of the Technical Parameters

4.2.1. Connection Delay

This is a characteristic of the data link protocol that determine the end to end delay between a message is ready to be transmitted to the time it receives access to the channel i.e. when the connection is actually established. It also depends on the traffic density at different times and phases of flight, although certain data link due to their protocol or channel allocations perform better than others under the same conditions.

4.2.2. Message Latency

The bit rate of the system determines the message latency i.e. the time elapsed from the instance the message was transmitted to the time it was received. Latency is also dependent on the propagation delay that is proportional to the square of the distance traveled by the electromagnetic wave. This is the main reason why satellite links have a longer delay or message latency.

4.2.3. Traffic Information Capability

Some data links have capability to support multiple aeronautical functions of communication, navigation or surveillance. This is particularly useful for general aviation aircrafts that do not have the means or need to equip with separate specialized data links, and investment in one system can solve all the needs. Traffic information with ADS-B or TIS-B is important to supplement the voice communication with controllers, and is useful to general aviation and smaller commercial couriers to integrate with the weather link. ADS-B shows the location, speed, heading, and altitude of other planes that are in the vicinity of the aircraft. Data links such as UAT, VDL Mode 3 and VDL Mode 4 support some or all of services such as ADS-B, and controller-pilot data link communications. In order to handle traffic with varying QoS requirements the data link has to be capable of message prioritization. Candidate links should also be capable of supporting very high data rates.

For general aviation, a data link that supports both Weather and E-PIREPs is also very desirable and using the same data link will enable deployment on a wider scale and lower cost. It is desired by government to have a large-scale equipage of GA with E-PIREPS as this will improve the accuracy of weather forecasts and observations for all users by providing more data to forecasting models as well as increasing weather observation points. Thus it is noted that other aeronautical requirements / services besides weather will also determine the choice of a communication system

4.2.4. Request-reply capability

A number of data links such as ACARS, VDL Mode 3, VDL Mode 4 some SATCOM are bi-directional links. Request-reply is particularly useful if voice capability or flight-specific information is needed. Each aircraft has an address and each airport has an ICAO code identifier that makes the point-to-point communication possible. The ground station receives requests in a coded format and sends the requested information or performs the necessary action. For weather information systems a bi-directional link is not necessary, though it may be desirable to have one. This capability would allow specific information to be requested by the pilot which may be pertinent to the fight plan and location. Thus a radar mosaic of the region of interest may be requested by selecting a location and radius.

The amount of information transferred on a two-way link is also usually smaller since it involves a specific area of regard. Therefore, a NEXRAD map showing only the regional information will have a lower data size than a national NEXRAD image.

4.3. Processing of the QFD Model

The data from the pilot survey was processed to obtain the importance and preference information for the consumer requirements. The next step is translation of the consumer requirements to the technical attributes described in the previous section. The design attributes impact the consumer requirements in varying degrees, and this is reflected in the CR-DR relationship, which is assigned a 1, 3, or 9 weighting according to the QFD method.

The market data obtained is split into focus groups, for example the category of aircraft, and processed separately for the focus groups or market segments. Data from each segment can then be expected to have more uniformity and the model will produce more accurate results.

Table 4.1 shows the basic relationships between the consumer requirements and the communication and data link parameters. The QFD matrix consists of the set consumer requirements on one axis against the set of design requirements. The importance ratings derived from the survey for the particular market segment are entered as shown in the sample QFD matrix in Table 4.1 below:

Consumer Requirement	CR Imp	User Data Rate	Request / Reply Capability	Traffic Info Capability	Capacity	Network Coverage	Latency	Connection Delay	Position Reporting
Large No. of Graphical Wx Products	60%	9	0	0	3	1	9	9	0
Small Grid Size	29%	9	3	0	3	1	9	3	9
Frequent Weather Updates	60%	9	0	0	3	3	9	9	0
Hazardous Wx Alert	90%	1	1	1	9	3	1	1	3
Wide coverage	30%	1	0	0	1	9	0	0	0
Location-Aware Weather Information	11%	1	9	0	1	0	0	0	9
Integrated weather and traffic	62%	3	0	9	3	1	3	3	0
DR Importance Values:		16.58	2.76	6.48	14.84	8.71	16.17	14.43	6.3

Table 4.1: Sample QFD CR-DR Relationship Matrix

Explanation:

9: Strong Relationship/Dependence

3: Medium Relationship/Dependence

1: Weak Relationship/Dependence

0: No relationship

In this way the importance ratings of the data link attributes are obtained. The DR importance (DAI) values are calculated by summation of the CR Importance values (CRI) factored into CR-DR relationship indexes (w):

$$DAI_k = SUM(CRI_i * w_i), i = 1,\dots,n$$

Relative Importance of DR_k:

$$DRIk = DAI_k / SUM(DAI_j), j = 1,\dots,m$$

QFD is based on the principle that the process of maximizing the customer satisfaction function results in the best design choice. The following relation shows how this is done:

$$\text{Max } f(x) = DAI_1x_1 + DAI_1x_1 + DAI_1x_1 + DAI_1x_1 + \ldots.$$

where x_k : performance index of technology x for the attribute DAI_k.
f(x): Customer satisfaction function

4.3.1. Data Link Matrix

After arriving at the requirements and relative importance of the system performance metrics for the class of user in question, these can be matched with the actual data links and their characteristics. Based on the study of the various data links as detailed in Chapter Two, the data link performance was abstracted using a similar weighting system as was done for the QFD model. The resulting matrix is shown in Table 4.2.

WIS Data Link	User Data Rate	Request/ Reply	Traffic Information	Capacity	Coverage	Connection Delay	Latency	Position Reporting	Equipment Cost	**TOTAL SCORE**
DR IMP	**16.58**	**2.76**	**6.48**	**14.84**	**8.71**	**16.17**	**14.43**	**6.3**	-	
ACARS	1	3	1	1	2	1	1	3	1	**113.1**
VDL-2	2	3	1	2	2	1	2	2	2	**154.39**
VDL-B	3	0	2	3	2	2	3	0	1	**202.01**
VDL-3	2	3	1	2	2	2	2	2	2	**168.82**
VDL-4	2	2	3	2	2	2	3	3	2	**188.08**
UAT	3	0	3	3	2	3	3	3	1	**241.82**
Mode S	1	1	3	1	2	2	1	3	2	**137.73**
Aircell	2	3	0	1	2	2	2	2	2	**147.5**
EchoFlight (LEO Satellite)	2	3	1	1	3	1	1	3	1	**192.19**
WSI Inflight (GEO Satellite)	3	0	2	3	3	1	1	0	2	**194.55**

Explanation of the Weights:

3: Best; Available

2: Moderate Performance; Restricted Availability

1: Poor Performance; Insufficient

0: No provision

Table 4.2: Data Link Performance (Weighted)

The decision model consisting of the QFD and the detail technical assessment was implemented in software to allow any scenario of product requirements and data link to be performed.

Using the QFD approach, the procedure first focuses on the must-have functions. Those have to be satisfied otherwise the failure of the technology will be assessed without further analysis. Then the ‘like to have’ functions have to be met. The first step is an elimination step, that with the aid of the QFD matrix, yields technologies that are likely to be successful and those that are not, based on the results of the consumer requirements. An algorithm that scans the data link attributes to find any which has a value of 1 for the attributes that have the highest CR importance ratings (e.g. 80 percentile) are eliminated as unsuccessful. The data links are also ranked as a result of the QFD and the three ranked lowest out of the ten candidate links can be eliminated to narrow the focus on the most suitable links for further analysis.

4.4. Detailed Evaluation

The detailed analysis is described pictorially in the flowchart of Figure 4.2.

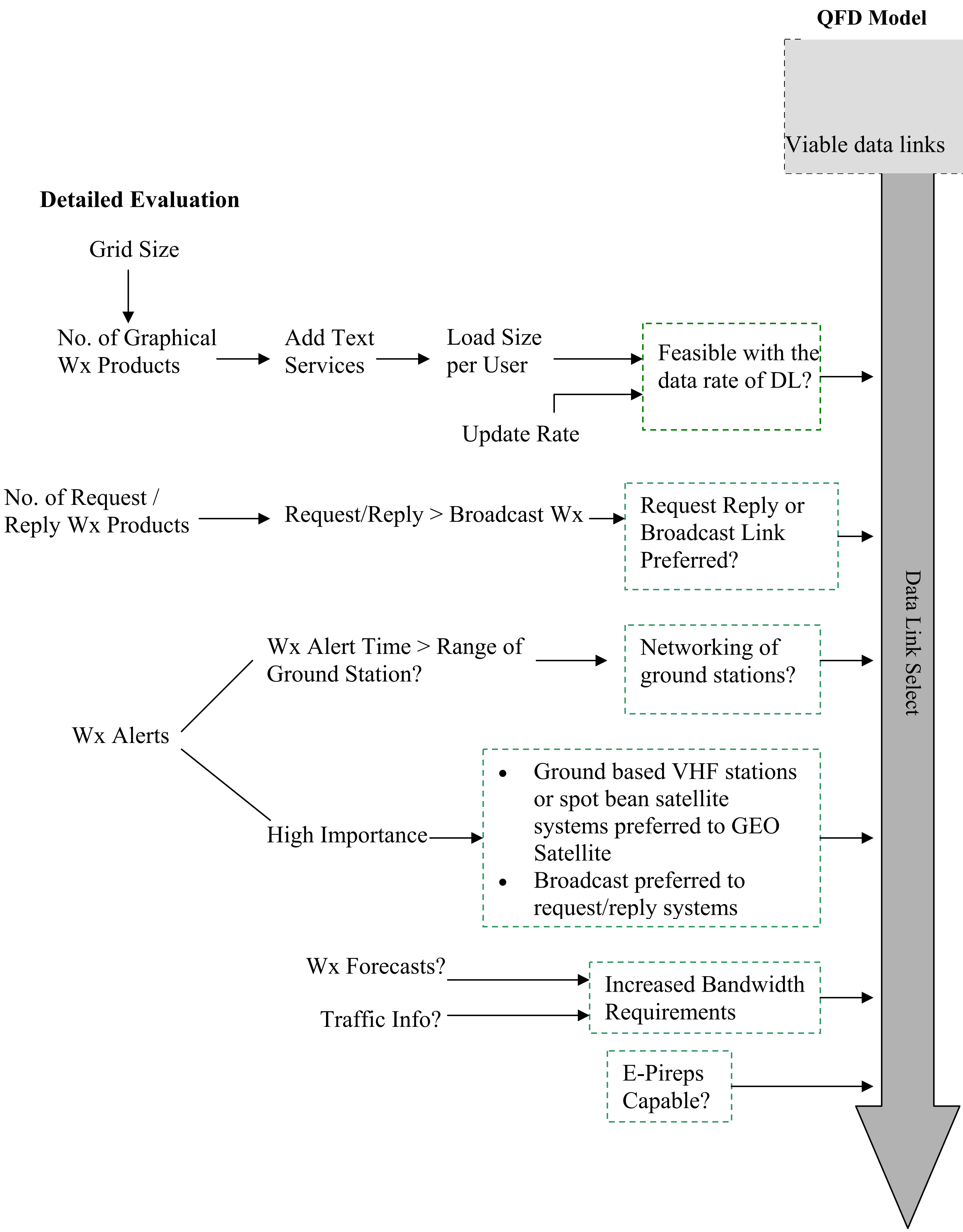


Figure 4.2 Flowchart for the Detailed Analysis

The analysis was done from the perspective of a single user and the link performance that will likely to be experienced. The analysis was also carried out for the en-route domain, since this is the main region of interest for the purpose of weather dissemination for strategic weather avoidance planning. More importantly, the high availability of weather information en-route may lead to a reduced demand for the more congested communication capacity in the terminal area.

The data rate required to transmit a message of a given length and within a required update time was the chosen as the first performance criteria in the detailed analysis. The number of weather products was obtained from the survey and the total message length calculated. In addition, the survey results for minimum grid size, update interval, and number of graphical products can be used to construct several scenarios in the software decision tool to assess the candidate links' capability to support the required data load, as detailed in the following sections.

4.4.1. Channel Loading

The data loads imposed on the communication link as a result of graphical weather information requirements are discussed in this section. Weather maps and graphics are encoded for transmission using schemes that are different from the transmission of normal images. A gridded binary scheme is normally used in producing and transmitting a weather graphic. This divides the total area into a grid with each square representing an actual area for which weather information is collected and encoded. Thus the factors governing the size of a weather graphic is the density of the information, the grid size, the color depth, and the total area of regard. Grid size used for transmission is variable depending on the amount of resolution or precision to be achieved in the image. When transmitting information for a large geographical area, the grid size is made larger to save on transmission time.

The following table shows the size of a NEXRAD image calculated for different grid sizes and geographical areas.

Grid Size	Data Size @ 4 bits resolution		
	National	Regional (620,000 mi^2)	Local (70,000mi^2)
40 mi x 40 mi	9.2 kB	1.53 kB	
10 mi x 10 mi	145.3 kB	24.2 kB	2.7 kB
8 mi x 8 mi		37.8 kB	4.3 kB
4 mi x 4mi			17.1 kB
2 mi x 2mi			68.4 kB

Table 4.3: Data Sizes for NEXRAD Images for different Grid Sizes

As can be seen making the grid size smaller by a factor of two increases the data size by a factor of four. The national map yields a prohibitively large size even at a 100 mi^2 grid size and usually a gird size of 1600 mi^2 is used to transmit a NEXRAD image at that scale.

Taking data compression and differential transmission into account a data reduction factor of 30% can be applied [13] for certain images as shown in Table 4.4. Differential transmission is a bandwidth saving technique whereby the changes in the image since the last image are only transmitted. This factor was applied to NEXRAD images. Text and pictures, that represent information as objects or symbols, e.g. graphical METARs, cannot be compressed to the same degree as NEXRAD images, therefore a lower compression ratio was applied.

4.4.2. Data Rate Analysis - Broadcast Link

In a broadcast link, the amount of data transmitted is fixed for a given interval and does not vary with the number and requirements of the users. The same data is transmitted to all users, and the terminal equipment decodes and de-crypts the message to obtain the information that is applicable to it. Given that the broadcast is meant to cater for all types of users, whether commercial transport or general aviation, the candidate broadcast data links will broadcast all the weather products that are available, at regular update intervals.

The weather products have different required update intervals as required by the FAA for the FIS broadcasts. The RTCA Minimum Aviation System Performance Standards (MASPS) stipulate that the FIS data link be based on a repetitive cycle such that the pilot will receive the entire broadcast content within minimum time after entering communications coverage [2]. It specifies that the basic weather products be broadcast at least every 5 minutes. The following products are classified as basic: METAR, TAF, SIGMET, AIRMET, PIREPs, Alert Weather Watches. NEXRAD graphics may be uplinked at a higher update interval but as a worst-case scenario it will be assumed to be in every second broadcast cycle for the analysis. Table 4.4 shows the estimate of the total data rate for a broadcast link.

Graphical Weather Product	**Data Size (bits)**	**Data Size using BW Reduction Techniques[1]**	**Update Interval (mins)**
PIREPs	6,000	4,800	5
AIRMETs	6,000	4,800	5
METARs	6,000	4,800	5
TAFs	6,000	4,800	5
SIGMETs	6,000	4,800	5
Winds Aloft	10,000	8,000	10
Icing	6,000	4,800	10
Convective (NEXRAD)	68,400	20,520	10
Convective forecast (NEXRAD)	68,400	20,520	10
Storm Tops (NEXRAD)	68,400	20,520	10
Turbulence	10,000	8,000	5
Ceiling/Visibility	6,000	4,800	5
Other Products		6,000	5
Text Data	8800	8800	5
Total Data Size		125,960	
Data Rate Required (bps)		**419.87**	

Table 4.4: Broadcast Channel Loading and Data Rate Estimates

[1]With compression and differential transmission (30% updated)

A bit rate of approximately 420 bps is required to transmit the total broadcast set of weather products at an update interval of 5 minutes and a NEXRAD resolution of 2mi. Since this is a broadcast link and the channel is not shared, this is the total required data rate. This requirement is can be met by most of the broadcast data links except Mode S and possibly some of the low rate satellite links. Mode S has a capacity of 300 bps per broadcasting station and in addition is likely to share this capacity with surveillance functions. Depending on the requirements, a lower data rate may be acceptable with perhaps more importance being placed on having an integrated traffic information capability and possible cost advantage. Most likely, however, a higher data rate capable link such as VDL-B or UAT will be preferred especially if the preference of large number of graphical products is more important.

4.4.3. Data Rate Analysis – Two-way Link

In the case of a two-way link, the message length is variable and depends on the requested data. Several considerations need to be taken into account for calculating the data rate performance of a two-way link. The amount of data traffic generated for a two-way link depends on numerous factors including equipage levels, cost of services, the mix of different users (carrier, business or general aviation) and their information needs. It is also difficult to predict the traffic load as various users may request data at arbitrary intervals of time. In addition, the links which support multiple traffic such as ATC have a lower priority assigned to information services and lower priority of data over voice. However, since this is a comparative analysis, an estimate of the data transmitted is sufficient, as the same loads will be applied to all the data links in consideration.

The two-way links are ATN compliant and this entails a higher overhead necessary for the additional networking layer bits that guarantee interoperability. Thus an ATN overhead of 21 bytes as a worst case estimates are included in the total data size. The required maximum message delay can be determined from the survey. An indication of how many of the weather products pilots want to see in the cockpit can also be obtained from the survey.

4.4.3.1. Worst Case Scenario

In a sample worst-case scenario, we can consider a situation where all those products will be requested by the pilot and within the desired message delay. Thus a data load of 80% of the total broadcast data load is taken for this scenario. That will require a data rate of 335 bps. Usually in a request-reply system, fewer products will be uplinked at a time and a message delay of not more than a minute is acceptable.

The capacity of a two-way link is limited due to a dedicated channel being allocated to each user. For VDL 3, only two time slots are allocated to data and a random access is used to reserve a time slot. For CSMA contention, the data rate is taken to reduced by a factor of approximately 34% from the 4.8 kbps per user data rate to about 1.6 kbps. Thus we see that the data rate is sufficient for a single user. A two-way link however needs to support multiple users and the total capacity of the link must exceed the sum of all the individual data requirements. Thus in terms of capacity, VDL Mode 3 is limited especially since weather information is going to have lower priority and less access to the channel than its primary support of ATC communications.

A similar analysis can be done for different scenarios for the data links under consideration. After the data rate analysis is done, the candidate links which satisfy this requirement can be compared for capability to provide such services as traffic information, E-PIREPS, location sensitive information, weather alert, decision aiding information, internet, deployment timeline, and last but not least cost. Scenarios of user preferences can be developed and using the knowledge of the data links, the most appropriate data link technology can be determined.

4.4.3.2. Result of the QFD Model

Based on the data obtained from the survey, the QFD analysis, yields UAT as the best candidate data link for a cockpit WIS system. There are a number of advantages of a broadband system like UAT. A number of data services can be supported and with proper frequency planning can provide high data rate for applications such as moving map graphics and radar animation loops. The survey also revealed a high importance of traffic information, and UAT is capable of providing both TIS-B and ADS-B for traffic applications. A broadcast system is considered more suited for the large-scale weather information dissemination as that which is provided by the FAA. Broadcast links such as UAT, are also better suited for the weather alert capability that is much desired by the users. The connection delay will be relatively less than VDL-B and VDL-2 and the high transfer rate and corresponding small latency assures the capability for frequent weather updates. The competing technologies of VDL-B and GEO are also rated highly and can provide the same level of services as UAT but with lower performances in latency, connection delay and traffic information makes UAT a better choice.

4.5. Survey Results

The data obtained from the responses of 181 people are presented in this section. The importance of a requirement is a rating based on the satisfaction criteria obtained from the survey. A rating of 40% and above is considered to be very important or ‘need to have’ level for that feature. A lesser rating can indicate requirements which are ‘like to have’ and then ‘indifference’.

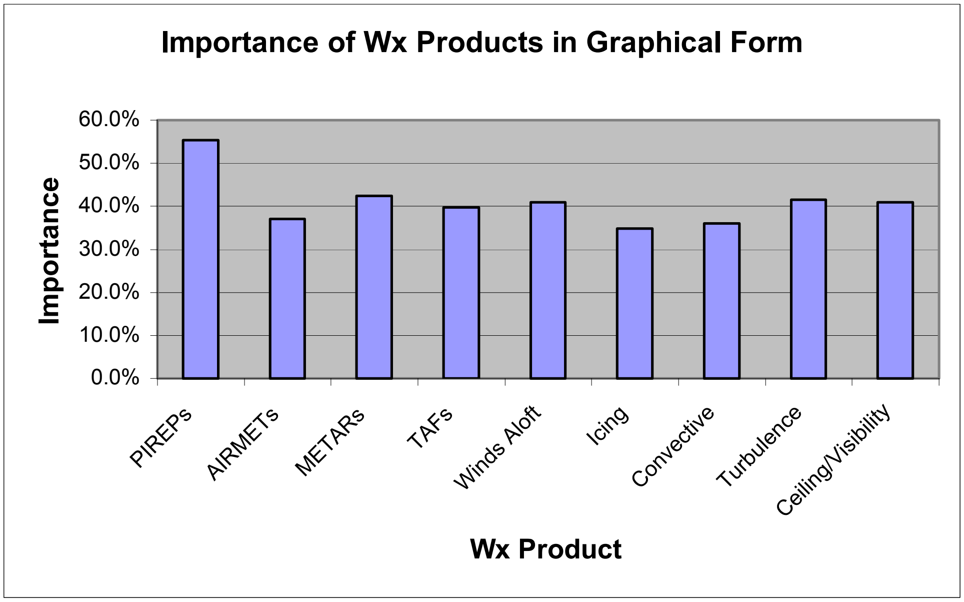


Figure 4.3 Importance of graphical weather products

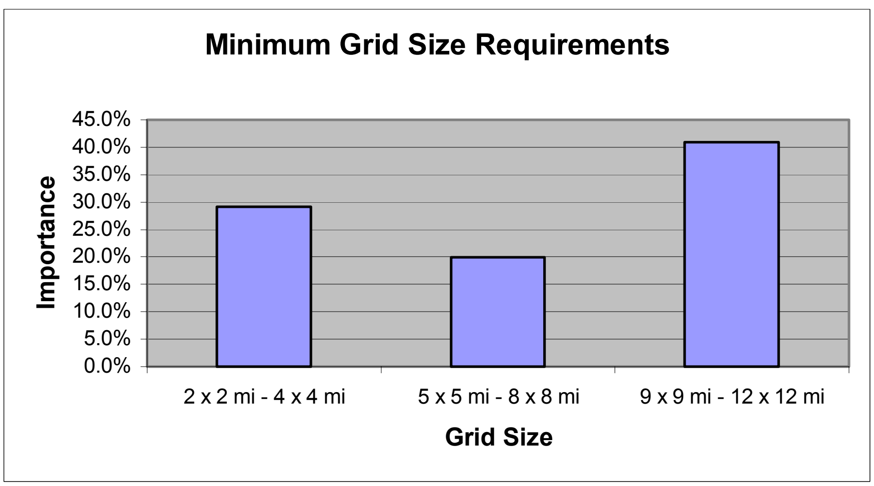


Figure 4.4 Importance of grid sizes

This graph shows that the grid size of 81 – 144 sq miles is needed and is a basic requirement whereas the lower grid sizes are desired features.

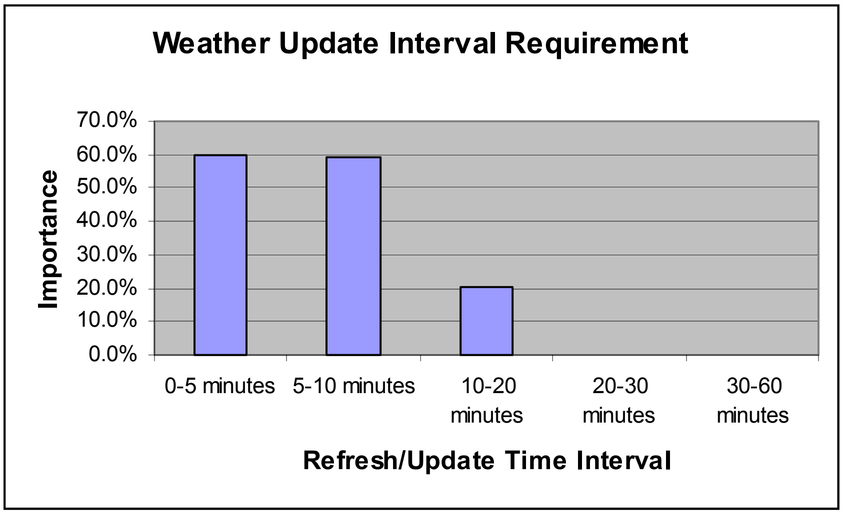


Figure 4.5 Importance of weather update interval

The results for weather update interval show that an update time of more than 20 minutes has reverse importance i.e. undesirable, and that low update times are very important to pilots.

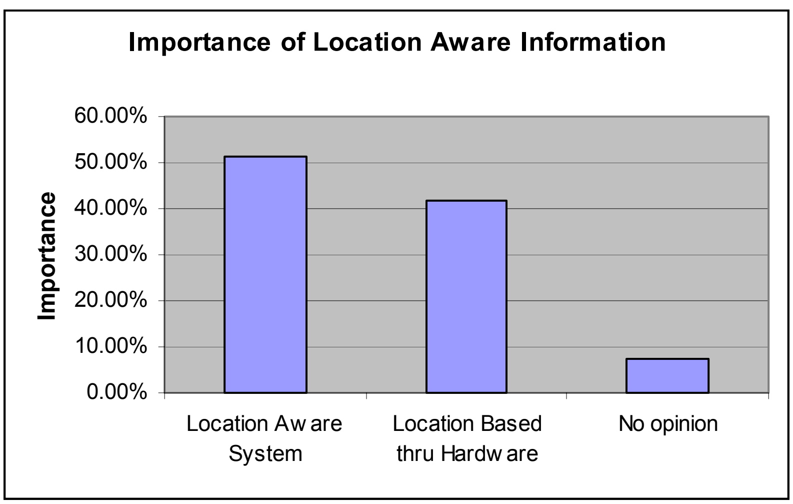


Figure 4.6 Importance of location aware system

This result shows that the importance for the system to send weather updates based on your location or position is not important. The pilots will be satisfied if the weather information system broadcasts the wide-scale weather information for a large geographical area and the on-board system selects the area of interest.

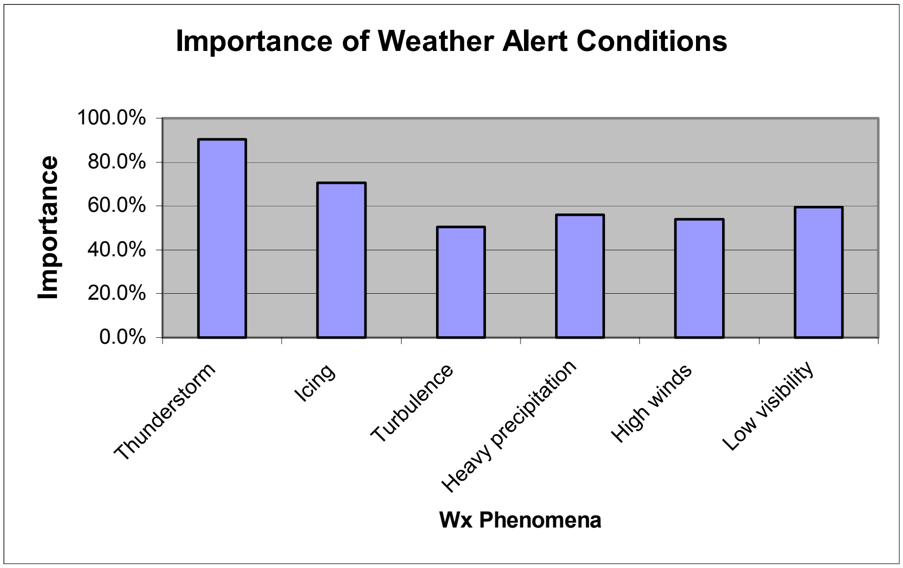


Figure 4.7 Importance of weather alerts

The results for weather alerts show a high importance for all the hazardous weather conditions this indicating that the overall importance of weather alerts is very high for pilots.

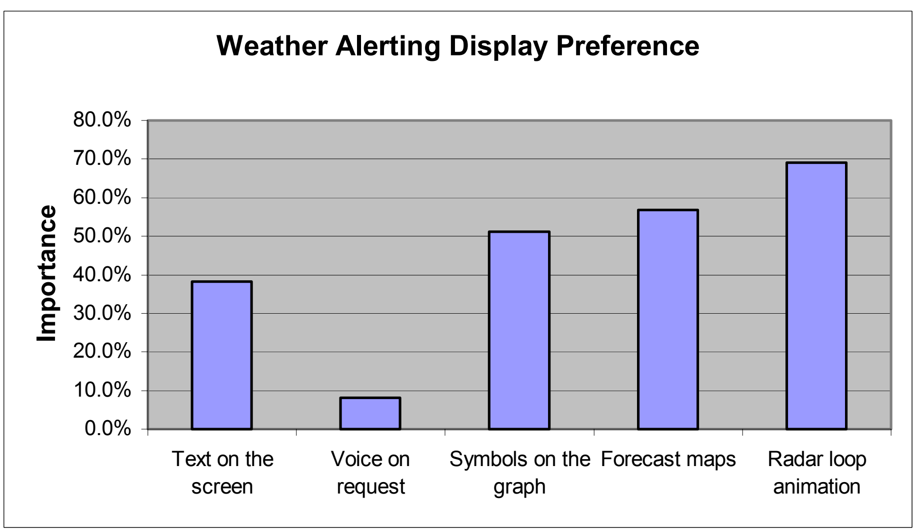


Figure 4.8 Preferences for the display of weather alerts

This question helps us determine some of the display and presentation preferences of the pilot.

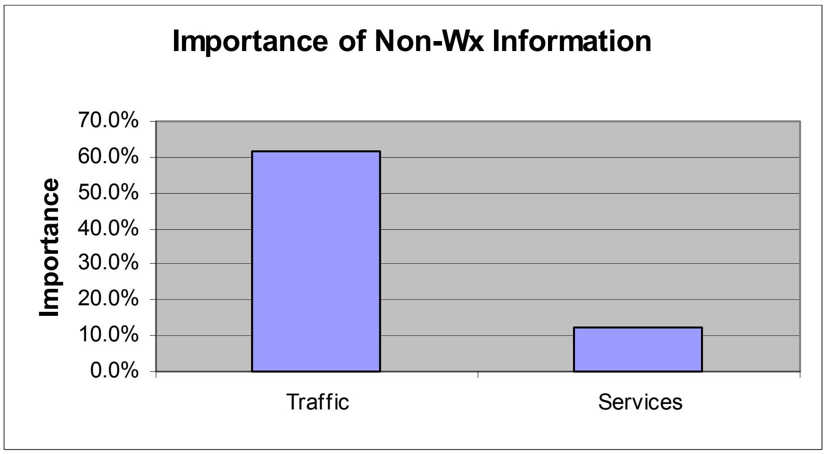


Figure 4.9 Importance of non-wx information

The results show that most pilots give a very high importance to traffic information. The next category 'services' was given as internet, e-mail and messaging, and is not considered very important.

The last two questions asked the pilots how much they would pay for the weather information system. Non-recurring costs are one-time costs for purchase and installation of the system (hardware plus installation). Recurring costs are annual costs for the services of the system.

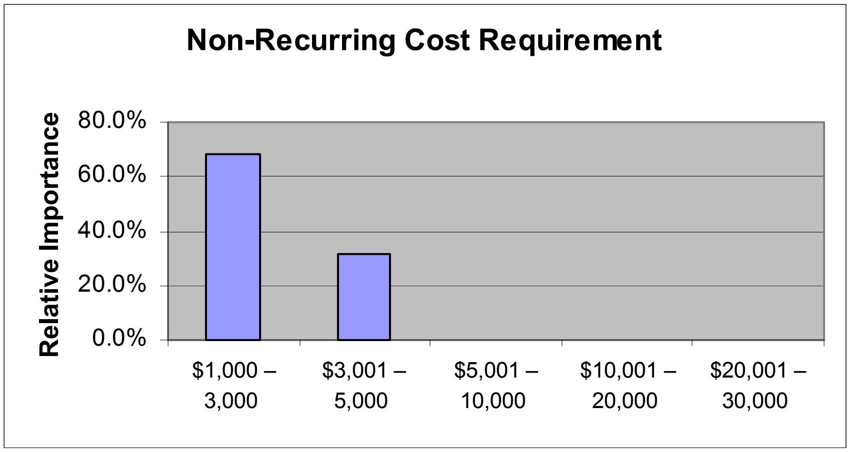


Figure 4.10 Requirement for non-recurring cost

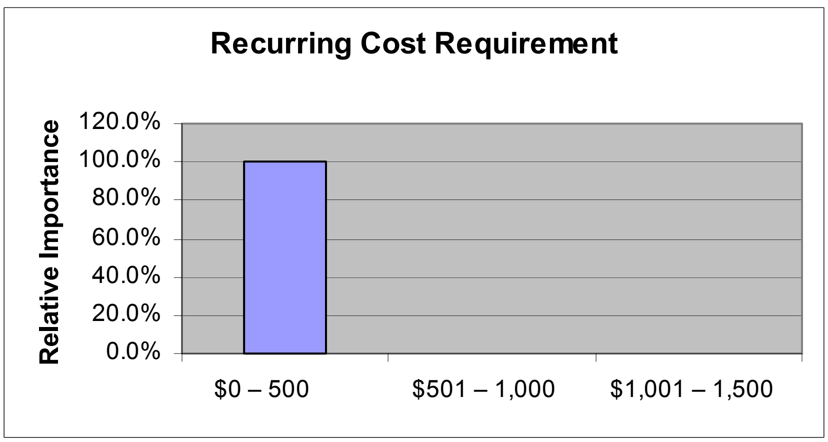


Figure 4.11 Requirement for non-recurring cost

4.6. Decision Aiding

An important aspect of the WIS system is the ability to provide decision aiding to the pilot. Decision aiding is essentially adding intelligence to the system - processing, correlating, fusing disparate pieces of information for the pilot to use in making flight decisions, thus saving on the workload of the pilot. In the GTRI study [8], it was identified that deficiencies exist in the area of tailoring weather products to the spatial and temporal needs of the aviation community. An example of decision aiding is an algorithm that links the intensity, and the temporal and spatial coverage of the various weather phenomenon to the aircraft speed, heading etc. to compute the when the aircraft will ‘meet’ the weather. Other ways use processing to make information easier to assimilate and interpret can be implemented as some of the following examples show:

- For weather alerts a small box on the main window opens up with a message like “Ice on the runway” or “Wind Shear of such magnitude and in such direction”.
- Alternate Safe Airports
- Highlight the areas which have changed since the last update.
- Present the forecasted info in a way in which it will be easily discernible from the current conditions and presented only the forecasted which is relevant to the flight time.

In the survey, an open-ended question was posed about decision aiding functions in order to find out areas that this function would be needed. The number of responses obtained for this question showed that there is significant need for this capabilities and a number useful suggestions were obtained. The main issues that emerged from the responses are summarized below:

- Show areas high risk e.g. of icing, severe turbulence
- Uplink alternate routes and airports for areas where severe weather conditions exist
- Best routes including vector and altitude
- Estimate of encounter time of weather phenomenon
- Weather trend information
- Best cruise altitude based on actual winds aloft
- Predicted turbulence en-route
- Weather information for aircraft altitude
- Weather available notification
- One touch buttons (e.g. emergency button)

4.7. Sensitivity Analysis

In a process that relies on variable and sometimes irregular set of inputs, such as the information derived from survey results in our QFD model, it may be required to simulate how changes in the input can affect the outcome. Thus a sensitivity analysis was carried out on the input data into the QFD model i.e. the set of CR importance values. The effect of the variations in the importance values on the outcome of the QFD model or the ranking of the data links was determined. The importance ratings that are calculated as percentages were varied incrementally until there is a change in the change in the outcome (ranking order of the data links). These results show the sensitivity to changes in the importance rating of one of the CRs while the others remain constant. The change in one CR usually does not bring about a big change in the order as the results show as the QFD takes into account the importance of all the other inputs to calculate the ranking.

		Importance Rating Variations	
		-27	-50
Importance Rating	**60% (Actual)**	33%	10%
Data Link Rankings (Top 5)	UAT	UAT	UAT
	VDL-B	VDL-B	VDL-B
	GEO	LEO	LEO
	LEO	GEO	VDL-4
	VDL-4	VDL-4	GEO
	VDL-3	VDL-3	VDL-3
	VDL-2	VDL-2	VDL-2

Table 4.5 Sensitivity to changes in <u>*Number of Graphical Weather Products*</u> *Importance*

The importance for the CR "Number of graphical weather products" was calculated as 60% from the survey. It would require a drop in importance to 33%, to change the data link ranking as the Table 4.11 shows. The benefits of a GEO for providing a high bandwidth link would be less useful if a fewer weather products were needed, hence the decline in the ranking of a GEO system.

	Importance Rating Variations				
		+9	+29	+55	+70
Importance Rating	**29% (Actual)**	38%	58%	84%	99%
Data Link Rankings (Top 5)	UAT VDL-B GEO LEO VDL-4 VDL-3 VDL-2	UAT VDL-B LEO GEO VDL-4 VDL-3 VDL-2	UAT VDL-B LEO VDL-4 GEO VDL-3 VDL-2	UAT LEO VDL-B VDL-4 GEO VDL-3 VDL-2	UAT LEO VDL-B VDL-4 GEO VDL-3 VDL-2

Table 4.6 Sensitivity to changes in Grid Size Importance

Providing lower grid size is mainly dependent on the data link's user data rate, the provision for position reporting and whether it is a request/reply system as Table 4.1 shows. It is possible to provide much higher resolutions if the data link has these attributes. Therefore with increasing importance of grid size, the ranking of the LEO and VDL-4 systems, which provide a much better request-reply capability, increases over a GEO-based system.

		Importance Rating Variations	
		-30	-44
Importance Rating (IR)	**60% (Actual)**	30%	16%
Data Link Rankings (Top 5)	UAT VDL-B GEO LEO VDL-4 VDL-3 VDL-2	UAT VDL-B LEO GEO VDL-4 VDL-3 VDL-2	UAT VDL-B LEO VDL-4 GEO VDL-3 VDL-2

Table 4.7 Sensitivity to changes in Frequent Weather Update Importance

Table 4.7 shows that a 30% decrease in the importance of the CR "Frequent Weather Update Interval" changes the ranking. With a reduction in the requirement for frequent weather updates the capability of GEO system is outweighed by the other data links and it decreases in ranking. It is seen from some of the results presented above that the benefits of GEO outweigh its disadvantages, in comparison with its competitors LEO and VDL-4, when large amount of data is required to be transmitted within a short time.

Importance Rating	**90% (Actual)**	-47% 43%
Data Link Rankings (Top 5)	UAT	UAT
	VDL-B	VDL-B
	GEO	GEO
	LEO	VDL-4
	VDL-4	LEO
	VDL-3	VDL-3
	VDL-2	VDL-2

Table 4.8 Sensitivity to changes in Weather Alert Importance

A decrease in importance of the CR "Hazardous Weather Alert", may mean less requirement for the coverage and capacity, which is the number of people simultaneously able to access the network, both important for good weather alert capability. The LEO system declines in ranking to a VDL-4 system consequently, as seen in the sensitivity analysis. The model is also not very sensitive to changes in this CR as can be seen from the amount of change needed to impact the ranking.

		Importance Rating Variations				
		+5	+13	+19	+25	+61
Importance Rating	**11% (Actual)**	16%	24%	30%	36%	72%
Data Link Rankings (Top 5)	UAT	UAT	UAT	UAT	UAT	UAT
	VDL-B	VDL-B	VDL-B	LEO	LEO	LEO
	GEO	LEO	LEO	VDL-B	VDL-4	VDL-4
	LEO	GEO	VDL-4	VDL-4	VDL-B	VDL-B
	VDL-4	VDL-4	GEO	GEO	GEO	VDL-3
	VDL-3	VDL-3	VDL-3	VDL-3	VDL-3	GEO
	VDL-2	VDL-2	VDL-2	VDL-2	VDL-2	VDL-2

Table 4.9 Sensitivity to changes in Location Aware Weather Information Importance

Providing location aware weather services is mainly dependent on the data link's position reporting and request-reply capability as Table 4.1 shows. Therefore it is expected that as the importance of this CR is increased, ranking of broadcast systems such as GEO and VDL-B would decline in favor of two way VDL-4, VDL-3 and LEO systems. A small change in this CR is sufficient to change the outcome indicating a higher sensitivity.

		Importance Rating Variations			
		+18	0	-14	-44
Importance Rating	**62% (Actual)**	80%	62%	48%	18%
Data Link Rankings (Top 5)	UAT	UAT	UAT	UAT	UAT
	VDL-B	VDL-B	VDL-B	VDL-B	LEO
	GEO	GEO	GEO	LEO	VDL-B
	LEO	VDL-4	LEO	GEO	GEO
	VDL-4	LEO	VDL-4	VDL-4	VDL-4
	VDL-3	VDL-3	VDL-3	VDL-3	VDL-3
	VDL-2	VDL-2		VDL-2	VDL-2

Table 4.10 Sensitivity to changes in <u>Traffic Information</u> Importance

An increase in importance of traffic information as well as a decrease in the importance is seen to cause a change in the outcome. VDL-4 which has traffic information capability gains in ranking in the former scenario, while the LEO system gains in importance if the traffic information capability is less important.

The sensitivity of the model to changes of the individual importance ratings of the CR's is summarized in Figure 4.12. The smallest change in the input importance that causes a change in the data link ranking is taken as an indication of the sensitivity and is inverted to show the relative sensitivity level.

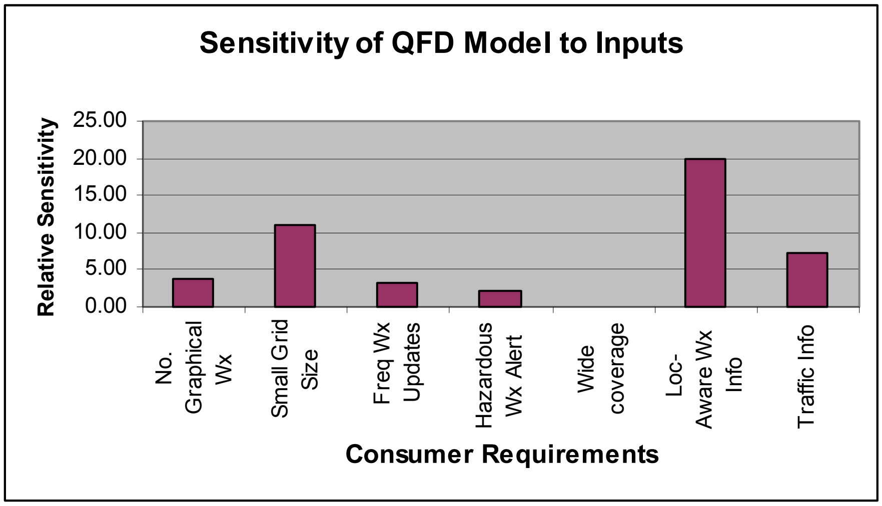


Figure 4.12 Sensitivity to Changes in Individual Inputs

The result shows that the model is fairly resistant to small changes in inputs. The highest relative sensitivity was for location aware information. It was noted that, the individual inputs, although having a significant impact on the rankings, were not enough to change the data links that were among the top five and these remained the same throughout the analysis. In addition, the data link that scored the highest in the QFD analysis, i.e. UAT, did not decline in its position, due to changes in the importance of any one of the CR's.

Chapter 5

Conclusion and Future Work

This thesis develops a consumer-centric communication systems analysis model for future aviation weather information data links. This model enables high-level architectural decisions to be made with respect to selecting the most feasible data links, and the services to be supported by them. The integration of end-user requirements is considered essential in characterizing the WIS system and tailoring it to meet the specific needs of different market segments.

Pertinent issues related to the performance and implementation of the data links were discussed. It was found that the choice of a data link depends on the preferences and needs of the set of users and there is no universal solution. For example, airlines are likely going to employ Satcom in the future because it can also support such services as passenger television, Internet and additional capacity to meet future traffic growth. The choice of data link for the lower end general aviation market is varied and will be determined by the requirements of the user in terms of features and cost. Different scenarios can be constructed to assess market feasibility of different feature/service combinations based on the consumer data available from the survey.

We obtained some key requirements concerning the control and display hardware. The presentation of weather information is very important to enable effective decision-making and prevent information over-load by the pilots. A relation exists between the bandwidth requirements of the data link and weather processing hardware both on the ground and in the air. More processing and intelligence on the ground as well as keeping static information and map databases on-board can reduce the data transmitted.

Future work that may be conducted is a detailed cost analysis to investigate infrastructure cost of leasing the network / bandwidth and the cost of providing the packaged weather products, against the capabilities of the data link and pricing to the customer. Including the control and display characteristics derived from the survey, and data link choices, will help define the complete WIS product.

Abbreviations

ACARS	Aircraft Communication Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance - Broadcast
ATC	Air Traffic Control
ATN	Aeronautical Telecommunications Network
CNS	Communication, Navigation and Surveillance
CPDLC	Controller Pilot Data Link Communication
CR	Consumer Requirements
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
DR	Design Requirements
E-PIREPs	Electronic Pilot Reports
FIS	Flight Information Services
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
MFD	Multi-Function Display
NAS	National Airspace System
QFD	Quality Function Deployment
QoS	Quality of Service
RF	Radio Frequency
STDMA	Self-organizing TDMA
TCAS	Traffic Alert and Collision Avoidance System
TIS-B	Traffic Information Services - Broadcast
TDMA	Time Division Multiple Access
UAT	Universal Access Transceiver
VDL-2	VHF Digital Link – Mode 2
VDL-3	VHF Digital Link – Mode 3
VDL-4	VHF Digital Link – Mode 4
VHF	Very High Frequency
WIS	Weather Information System

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