An Integrated Approach for Flight Following for CG Aircraft in the 21st Century

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Abstract

U.S. Coast Guard aircraft are currently limited to unreliable High Frequency (HF) communications systems that do not meet current or projected future operational requirements. In order to meet these ever expanding requirements the Coast Guard is investigating a mix of HF Automatic Link Establishment (ALE) and Satellite communications systems to supply enhanced voice and data services. An important aspect of this is automatic position reports for safety of flight following. A system architecture to provide automatic position reports to Coast Guard operations center personnel has been developed and a prototype system using the ORBCOMM satellite system has been implemented. This system consists of components on the aircraft and on the ground. The aircraft component is a Stellar ST2500 ORBCOMM communicator with a custom-written application to send secure data reports every five minutes. The position reports are sent using the ORBCOMM Report format which consists of just 6 bytes thus part of the functionality of the custom application is packing the desired information (position, time, course, and speed) into the 48 bits. In order to do this, differentials from a reference location are transmitted instead of the actual position. This provides some additional security for the positions in addition to reducing the amount of information to be transmitted. These data reports are processed by a Coast Guard developed gateway to integrate the position reports into a DoD standard Command and Control System. The position report gateway decrypts and decodes the position information and transfers it to the Track Data Base Manager (TDBM). Once the position reports are in the TDBM they can be accessed by both DII COE (Defense Information Infrastructure Common Operating Environment) compliant workstations running GCCS (Global Command and Control System) or Windows NT machines running C2PC (Command and Control PC) anywhere on the Coast Guard network. In order to provide position report capability in Alaska and Hawaii where the aircraft operate outside of the range of an ORBCOMM Ground Earth Station, data reports sent over HF ALE are being integrated into the system. A proof-of-concept demonstration is currently being conducted using several Coast Guard HC-130 Hercules and HH-60 Jayhawk aircraft. Data has been collected and analyzed in order to assess the performance of the system; whether it can provide the position reports in a reliable and timely fashion. In particular actual satellite availability has been compared to that predicted using Satellite Toolkit™ software and the average delivery time for position reports has been determined.

Introduction

Long-range (over-the-horizon) communication with Coast Guard aircraft is currently accomplished primarily with High Frequency (HF) radio. This system has incomplete coverage areas causing periods of no communication and does not provide a data communications capability. At the same time, new mission demands are leading to an increased need for more reliable voice communications, a data communications capability and a means of automatically reporting aircraft position. The current HF radio system cannot meet these needs and the frequent lack of Military Satellite Communications (MILSATCOM) channels for Coast Guard missions increases the need for another source. This need for reliable, secure, and cost-effective data/voice communications makes Commercial Satellite Communications (SATCOM) a viable alternative. To solve the current aviation communication problems, the U.S. Coast Guard Aeronautical Engineering Directorate (G-SEA) has tasked the Coast Guard Academy with the Aviation SATCOM project. This project will develop the architecture necessary to achieve the data communications objectives given in [1], which are to provide two-way messaging and position reports within all operational areas. The prototype for the secure position reporting and message service uses the ORBCOMM satellite system. The ORBCOMM system was selected by the USCG Research and Development Center (R&DC) as the best of the currently available alternatives for satellite data messaging [2]. A prototype system has been designed for both the aircraft and the ground station. The aircraft SATCOM unit automatically reports the aircraft's position to a dedicated ground station. The ground station contains a gateway to decode and transfer the information to a USCG database. Coast Guard leaders can then access this real-time position information from the Command and Control Personal Computer (C2PC), a windows version of the

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Global Command and Control System. Additionally the system has also been expanded to accept reports transmitted via HF ALE data systems to fill in the coverage gaps in the ORBCOMM system.

System Architecture

One of the main goals of this project was to create a shore-side architecture to support automated flight following. Position reports from the aircraft must be received, processed, and displayed to the operator on shore in a user-friendly manner. One of the constraints on the project was that the end-user system must be the Coast Guard standard geographic information system (GIS) which is Command and Control PC (C2PC). This software [3] is a Windows NT™ version of the Department of Defense (DoD) standard GIS, currently known as the Global Command and Control System (GCCS) [4], that runs on top of the Defense Information Infrastructure Common Operating Environment (DII COE) [5]. The C2PC software has been developed by INRI [6] for the Coast Guard and the Marine Corps. It implements the client side of the client-server DII COE environment only and does not have all of the functionality found in the UNIX DII COE environment.

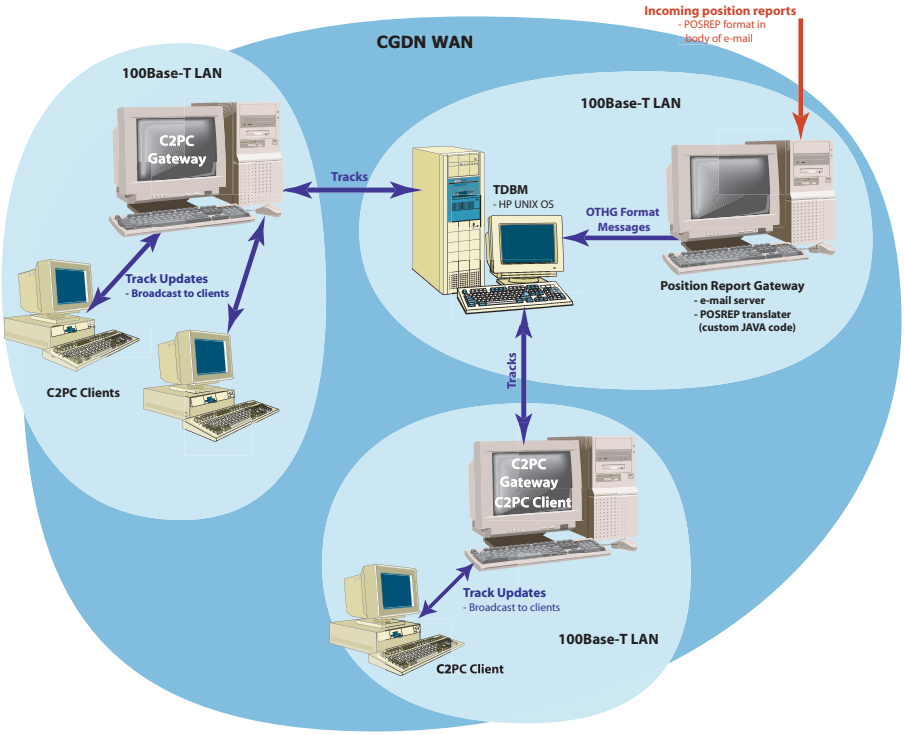

Figure 1 – Shore Architecture for POSREP Distribution

Since C2PC is only the client-side of the equation, it must be used in conjunction with the UNIX-based server know as the Track Database Manager (TDBM). Track information is fed into the TDBM which is then accessed by the C2PC. One additional constraint is that the C2PC implementation cannot connect directly to the TDBM, it must go through another piece of software called C2PC Gateway. However, the use of C2PC Gateway does allow the system to be set up in a hierarchical fashion; one C2PC Gateway on a local area network (LAN) can access the TDBM across the wide area network (WAN) and then supply the track information to all C2PC clients on the LAN. This is the architecture implemented for the Coast Guard. Track information (the position report) is fed into the TDBM which is located on the internal Coast Guard network (known as the CGDN+ – Coast Guard Data Network Plus). At each geographic location on the CGDN+ that needs to access the information, one computer has C2PC Gateway running to connect to the TDBM and supply the information to all of the other users on the local network. The C2PC client can be running on the same machine as C2PC Gateway if desired. This is illustrated in Figure 1. A screen capture from C2PC Gateway is shown in Figure 2; you can see that it is managing just a single connection at the time although many connections can be supported. The C2PC Client is illustrated in Figure 3 with the TrackPlot tool shown. Listed on the left

are the units currently being tracked. Their most recent positions are shown on the map to the right in light blue and overlays of Coast Guard Areas of Responsibility are shown in dark blue.

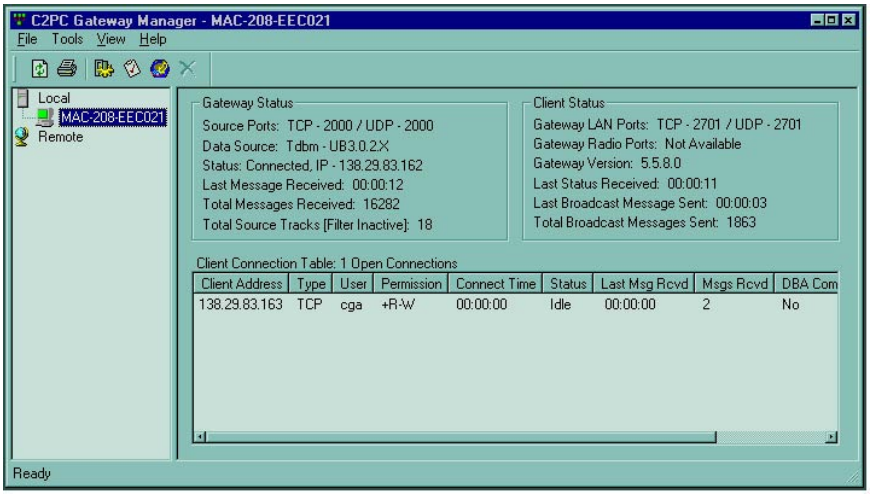

Figure 2 – Screen capture of C2PC Gateway

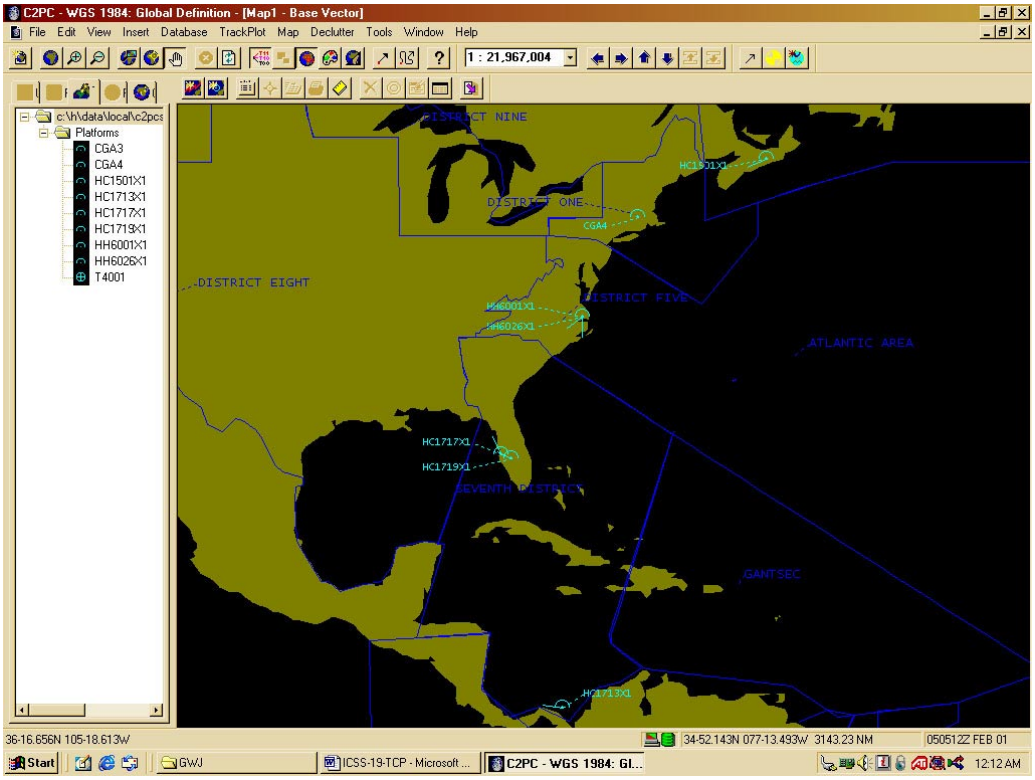

Figure 3 – Screen capture of C2PC Client

The other half of the shore architecture is getting the position reports from the aircraft to the TDBM. The desired information is time, position, course, speed, and altitude. The easiest way to get this information into the TDBM is to send it to the machine as a DoD standard message [7] using the OTH-Gold (Over the Horizon Gold) format [8]. However this is not a format that is native to commercial communications systems or even one that would be desired since it is not a very efficient format. A typical OTH-Gold formatted message is shown in Figure 4. As can be seen, it is not a very compact format and thus unsuitable for transmission across bandwidth constrained links. Instead a more compact format using just 40 bytes (shown in Figure 5) has been defined for the communications systems to transmit and a Position Report Gateway has been implemented as the interface between the

aircraft position report system and the TDBM. This Gateway receives the position reports from the aircraft system, translates them into the OTH-Gold format, and sends them to the TDBM across the LAN using SMTP [9].

```
P 050341Z FEB 2001
FM USCGA
TO JMCIS
BT
UNCLAS
MSGID/OSPREY/GOLD/01960/FEB
CTC/T01960/UNEQUATED-HC1719X1//C130/AIR//US///HIT/03///500/5
XPOS/05031216Z8/FEB01/LL:2714.382N7-
      08136.0179W5/SRN25////294T/067KPH/4730M///PLRS///
RMKS/ENCRYPTED HOURLY POSREP
ENDAT
BT
NNNN
```

Figure 4 – Typical OTH-Gold formatted message

GG/HHMMSS/+LL.llll/+LLL.llll/CCC/SSS/AAAA

Field	Meaning
GG	GPS status, 2 bytes
HHMMSS	Time of Position, hours, minutes and seconds, 6 bytes
+LL.llll	Latitude, + or – degrees , leading zero if needed, accuracy to 1/10000 of a degree, 8 bytes
+LLL.llll	Longitude, , + or – degrees , leading zero if needed, accuracy to 1/10000 of a degree, 9 bytes
CCC	Course, degrees True, to nearest degree, 3 bytes
SSS	Speed, mph to nearest mph, 3 bytes
AAAA	Altitude, 10's of meters, to nearest 10m

Figure 5 – Desired Position Report Information Format

The Position Report (POSREP) Gateway is a piece of Coast Guard developed software that acts as the translator between the aircraft position reporting system and the TDBM. This enables the overall system to be very flexible in that different aircraft systems can be used but all positions are displayed on the common, Coast Guard standard, GIS. The POSREP Gateway will work with any communication system that reports the position information defined in Figure 5 using standard e-mail [10] as the transport mechanism. The Gateway consists of two parts; a commercial off-the-shelf (COTS) mail-server program and some custom code written in JAVA (POSREP Translator). Position reports are transmitted by the aircraft communications systems to a specific e-mail address. The Coast Guard POSREP Translator retrieves the e-mail messages from the mail-server and translates them into OTH-G format. The exact translation required at the Gateway; however, depends upon the position reporting system on the aircraft and its capabilities. Currently two systems have been implemented, ORBCOMM and HF, both of which are described in the following sections.

Communication Technologies

ORBCOMM

The ORBCOMM system consists of a constellation of Low Earth Orbit (LEO) satellites, a set of ground earth stations (GES) and a network control center (NCC). The satellite constellation is 35 small satellites at an altitude of 875 km in both Polar and inclined orbital planes (2 Polar planes of 2 satellites each and 3 planes at 45 degree inclination). There are four United States GES's located roughly in the four corners of the continental U.S. (Arcade NY, Tifton GA, Chandler AZ, and Wenatchee WA). The NCC is located in Washington, DC near Dulles airport. Extensive additional information on the ORBCOMM system can be found in [2,11,12,13]. Currently 30 of the 35 satellites are operational. All four U.S. GES's are in operation along with the Curacao GES which is currently in

operation under U.S. control. These five GES's act as remote antenna sites for the NCC; handling RF communications to/from the satellites with all data processing being handled at the NCC.

This combination of operational satellites and Earth stations gives a predicted coverage as shown in Figure 6. This diagram has been created using Satellite Toolkit™ (STK) software [14] and shows the percent of time that satellite coverage is available for any geographic location. The predicted coverage is fairly good (>80%) within most of the areas of interest to the U.S.C.G. (Continental United States out to 200 NM, plus the Caribbean). However, there is very poor or no coverage in Alaska and Hawaii. This is due to the location of the GES's. Since the satellites operate in a bent-pipe mode to provide real-time service, the satellite needs to be in view of both the user and a GES. The gold circles on the diagram show the approximate area in which the satellites are in view of the GES. For users within this area, if a satellite is in view of the user then a link is possible. Links are also possible for users outside of these areas, but only when the satellite is located such that it is within this area and can also see the user. This of course reduces the coverage percentage for areas outside the gold circles.

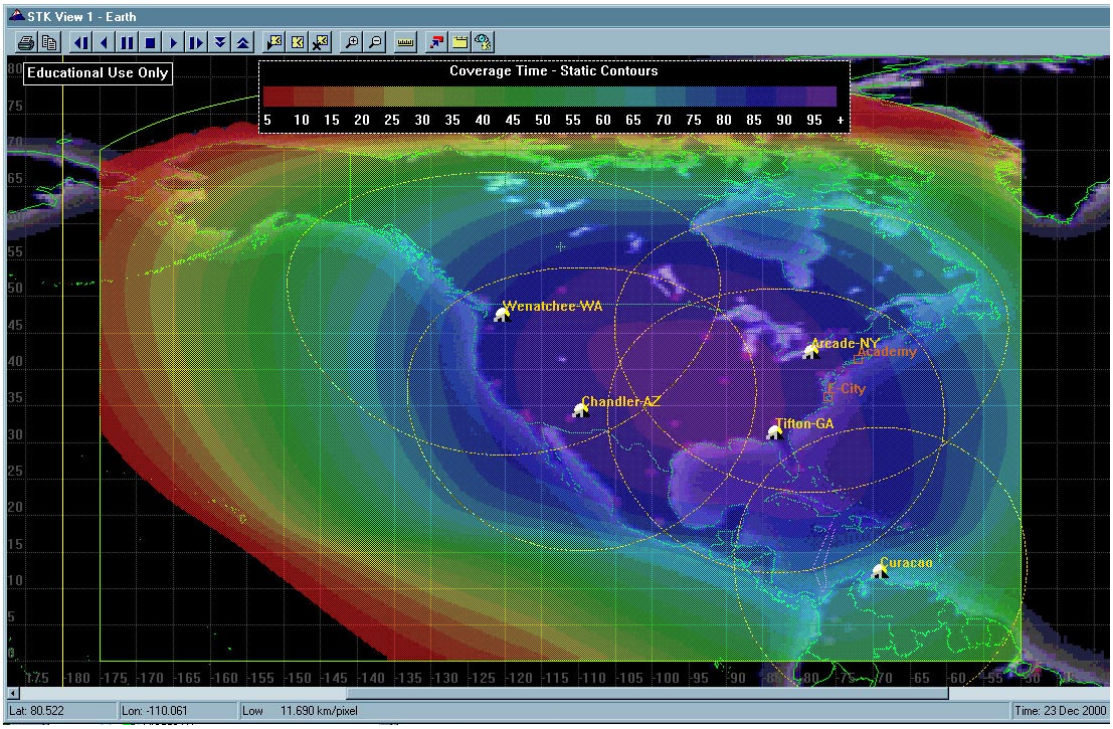

Figure 6 – Predicted ORBCOMM coverage

There are two service types available with the ORBCOMM system; store-and-forward and real-time. Store-and-forward service (called GlobalGram) is available to provide service when the user can see a satellite, but the satellite is not in range of an earth station. This mode must be selected at the time the message is created and is only valid if the satellite cannot see an earth station. This service is not used in our system; only the standard "real-time" mode, which requires that the user can see a satellite and the satellite is in range of an earth station, is used. Messages are sent between the ORBCOMM subscriber communicators (SC) and the GES through the satellites using ORBCOMM's proprietary air interface. The GES's all connect to the NCC and all traffic is routed there for processing. At the NCC the message data is inserted into a standard e-mail [10]. The destination address can either be specified directly or as one of 8 shorthand "speed-dial" numbers (these are predefined for each SC and the translation from speed-dial number to address is done at the NCC). The origination address is added by the NCC based upon the electronic serial number of the SC that transmitted the message. These e-mail messages are routed across the Internet just like any other e-mail message (see Figure 7).

There are two types of "real-time" messages possible with the ORBCOMM system, both of which are used by our system. In addition to the standard message described above, there is also a special 6-byte

Report format. This message type sends exactly 6 (8-bit) bytes (for a total of 48 bits) to a specified speed-dial address. The difference between a regular message and a Report, in addition to the size, is that it is transmitted differently over the air; there is less handshaking involved between the SC and the satellite, so that it is transmitted much more quickly [15]. In addition, since the data is full 8-bit bytes, it is inserted into an e-mail message as an attachment, and encoded by the NCC using Base64 encoding as per the MIME standard [16] for transmittal across the Internet.

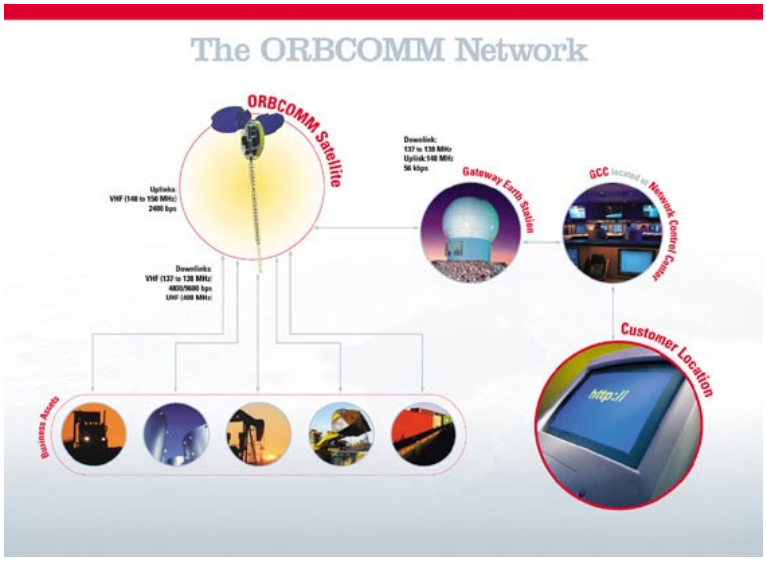

Figure 7 -- ORBCOMM System Operation [19]

The original position report system was developed in 2000 using the ORBCOMM system as the communications link and Stellar ST2500's as the subscriber communicators [17,18]. The ST2500's were chosen as they contain a second embedded microprocessor (AMTEL Mega103) that can be programmed to control the operation of the transceiver. Additional details of this system are described in [12]. To meet the operational requirement of 15 or 30 min reports, it was decided to use transmissions at 5 min intervals to allow for some messages not being successfully transmitted. Two additional design considerations were cost and security. In order to minimize costs, it was decided to use the Report format as much as possible. However; the 6-byte format did not allow for sufficient information to be transmitted. The standard messages could transmit as much information and to whatever precision desired, but at much greater cost. From a security standpoint, since the information was being sent from the NCC to the POSREP Gateway across the Internet, they needed to be encrypted to protect against unauthorized viewing.

To accomplish these design goals, a combination of the two message types was used. Regular messages using the 40 character format described above are created and transmitted hourly. Since these are easily readable if intercepted on the Internet they are encrypted prior to transmission. The encryption algorithm chosen was the International Data Encryption Algorithm (IDEA) [20] because it uses a 128 bit key and is very secure and also because the C-code implementation is small enough to run in the small memory space of the AMTEL processor in the ST2500. The IDEA algorithm is a block cipher and the encryption is implemented in a stream mode using cipher-feedback mode (CFB) [20]. This converts the 40 characters into 48, 8-bit characters that are transmitted to the NCC. A typical position report is shown in Figure 8. Since these are 8-bit bytes they are further encoded at the NCC for transmission across the Internet using Base64 encoding as described above.

Full report, 40 Bytes

20/194529/+37.3463/-071.5348/095/201/014

Encrypted, 48 Bytes transmitted

•ÝŒè«--[\£ùJÿt•DS#öeANt•HÖóHrÈÅ]¸-²Ø¨•&®R©WÌ%ç

Figure 8 – Sample ORBCOMM Hourly Position Report

The intermediate reports are sent using the Report (48 bit) format. In order to provide security and be able to include sufficient information in the 48 bits, differential positions are used – instead of reporting actual position the difference between the last hourly position and the current position is reported. Also the time reported is the number of seconds since the last hourly report. The 48 bits are divided up as indicated in Table 1 . The information encoding into the number of bits is performed much as an A/D converter quantizes analog data into digital information. Using the specified number

of bits and the range allowed for the original data yields a precision as also shown below. This scheme allows almost all of the desired position report data to be encoded into just 48 bits while still maintaining sufficient precision. In addition, the position report is secure even though it is not encrypted since the actual position is not transmitted; rather the difference from the previous hourly (encrypted) report is sent.

Table 1 -- 5-minute Report Format

Data	# of Bits	Range	Precision
Δ Time	9	3360 sec	±3.28 sec
Δ Latitude	13 + 1 bit sign	800 km	±48.8 m
Δ Longitude	13 + 1 bit sign	800 km	±48.8 m
Course	6	360°	±2.81
Speed	5	500 mph	±7.81 mph

The Position Report Gateway has three additional features added to the basic functionality to support the ORBCOMM originated reports. First, all of the message data (hourly or five-minute) that arrives in the e-mail is 8-bit data and has been Base64 encoded therefore the Gateway must Base64 decode the received data to get back the original 8-bit data. Second, the hourly reports are encrypted so they must be decrypted in order to recover the original position report. And third, the five-minute reports are encoded as described above so the information must be pulled out of the 48 bits. In addition, since the time and position are differentials, the Gateway must store the hourly position reports so that the differentials can be applied to this reference to recover the current time and position.

HF ALE

One major shortcoming of the ORBCOMM system is the lack of coverage for Alaska and Hawaii. This can be seen in Figure 6 and is due entirely to the fact that ORBCOMM does not have a GES located in Alaska or Hawaii. One alternative communications system that can provide coverage in these areas is High Frequency (HF) radio. HF radio using Automatic Link Establishment (ALE) for frequency management and link control in combination with HF data modems is a viable communications link for the position reports.

An architecture to support this mode of operation has been developed (see Figure 9). On the aircraft side, the existing HF radio is either modified or replaced (depending upon model) to a radio with ALE capability. An HF data modem (currently we are using the Rockwell-Collins Q9600 [21]) is then connected to the HF ALE radio. To send the reports we are using a combination of Coast Guard written software and commercial software (HF Messenger [22] from Rockwell-Collins). The HF Messenger software provides the interface to the HF ALE radio. It acts as an e-mail server to send and receive e-mail via the HF data link. It can also send/receive e-mail across an attached network which allows it to act as a gateway between an HF net and a terrestrial network. The Coast Guard written software (HF POSREP) generates the position reports using the 40 byte data format specified above and sends them as e-mail using SMTP to the HF Messenger mail-server. In this case, HF POSREP acts as an e-mail client to HF Messenger. HF POSREP receives the raw position data from an attached GPS receiver in NMEA 0183 format via the computer's serial port.

On the ground side of the link, an HF gateway is established by connecting a computer running HF Messenger to both an HF radio and a terrestrial network. Currently there is one operating in Cleveland, one at the Coast Guard Academy, and one at Rockwell-Collins (Cedar Rapids IA). Position Reports are created by the HF POSREPS program and sent to HF Messenger on the aircraft (both programs running on the same computer). When HF Messenger recognizes that it has mail to send, it automatically initiates an HF ALE data connection to the designated ground station (designated in the HF Messenger routing table using STANAG 5066 addressing [24]). Once the HF ALE connection is established and the HF modems connect, the message is sent to the HF Messenger on the ground, which then routes it on the terrestrial network just like standard e-mail. The position report will thus arrive at the POSREP Gateway in the same manner as the ORBCOMM Position Reports. The only

difference being that the HF radio link is "free" so all reports are sent in the full 40 character format and encrypted.

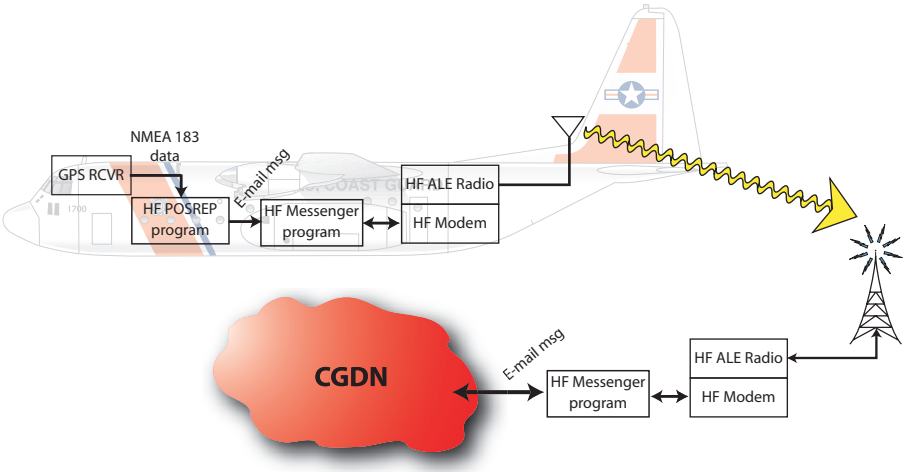

Figure 9 – HF Position Report Architecture

Performance

Performance data on the HF system has not been collected or analyzed yet as the HF system is still in development at the time of writing this paper. Hopefully this data will be available for presentation at the conference. The ORBCOMM system; however, has been in operation for several months and data has been collected and analyzed. The data was analyzed to determine the average time delay for a position report to be received at the POSREP Gateway as well as the average time between reports to determine if the system met the operational requirements.

Currently we have the Stellar ST2500's with the Coast Guard position report program installed on six aircraft: three HC-130's (Figure 10) located at Air Station Clearwater FL, and one HC-130 and two HH-60 helicopters (Figure 11) located at Air Station Elizabeth City NC. Position reports from these aircraft were collected over the period of 12 Dec 2000 – 4 Jan 2001. This data was analyzed with the following results.

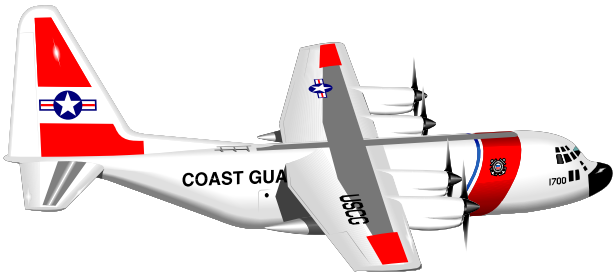

Figure 10 – HC-130

Delay

Each position report is logged at the Gateway with several time tags: the time of the position (as reported by the unit), the timestamp put on the e-mail message by the ORBCOMM NCC, and a time tag attached to the POSREP at the time processed by the Gateway. This allowed three delays to be calculated: the time for the POSREP to be delivered to the NCC, the time for the message to be delivered from the NCC to the POSREP Gateway, and the total time from message creation to delivery at the Gateway. The average times from the SC to the NCC and from the SC to the Gateway for the 6 aircraft are listed in Table 2 . The time of position is derived from the GPS receiver in the ST2500 and is thus normally accurate; however there are times when it appears that the GPS receiver lost lock and was thus providing false data to the ST2500 (discussed more later). The clock on the Gateway computer is synchronized to NIST time using a time synch program and thus these are generally accurate as well. However, the clock at the NCC is not under our control and at times appeared to be not accurate. Also, this time tag was only reported in hours and minutes vice hours, minutes, and seconds like the other two time tags. This caused some inaccuracies in the data such as the appearance that the reports get to the Gateway quicker than they get to the NCC for unit HC1501.

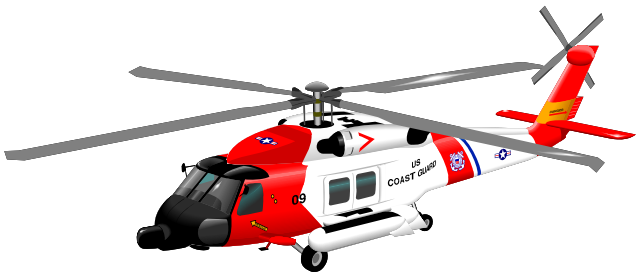

Figure 11 – HH-60

The delay time between NCC and Gateway is normally fairly short, most of the delay in the reports getting to the Gateway is the delay getting to the NCC. This is caused by two factors: waiting for satellites to be in view of the aircraft since there is not coverage 100% of the time and poor communications links when the satellites are in view. Aircraft HC1713 in particular had some communications problems on some flights that caused the average to be very high. The helicopters also seemed to experience more communication problems than the fixed-wing aircraft leading to longer delay times. The long delay times in general do not correspond to times when there wasn't a satellite in view according to post-analysis using STK. In general when a good communications link was available, reports were transmitted through the system within 2-3 minutes.

Table 2 -- Average Delay time in Seconds

Aircraft	To NCC	To GW
HC1501	137.5	133.7
HC1713	2128.5	2130.0
HC1717	158.0	163.5
HC1719	206.4	215.4
HH6001	761.7	774.7
HH6026	597.5	609.6

Time Between Reports

Using the time of position time tags of the position reports received at the Gateway, the time between reports can be calculated. This data is summarized in Table 3 and all aircraft met the design goal of 15 minutes for helicopters and 30 minutes for fixed wing aircraft. However, here is where some errors were noticed in the data. There were many cases (about 25-30% of the time) where the received reports had an obviously incorrect time of position. Since this time originated from the GPS receiver, it appears that many times the GPS receiver in the ST2500 lost lock though it is impossible to determine this through post-analysis since the 6-byte Report format does not include the GPS status information. These position reports could not be included in any calculations since it could not be determined definitively what the correct time was or if the position was accurate and thus were not included in the averages in Table 3 . Therefore, from a communications perspective, the system actually worked better than it appears from the results below as many more reports were received than could be used. Why the GPS receiver is losing lock is currently being investigated. If this problem can be corrected, then the average time between reports will be much lower (less than 6 minutes).

Conclusions

Table 3 Average Time Between Reports in Minutes

Aircraft	Avg. Time
HC1501	7.6
HC1713	22.2
HC1717	8.3
HC1719	9.8
HH6001	11.6
HH6026	11.2

This paper has described an architecture for automatic position reporting for Coast Guard aircraft. The architecture has been designed to utilize the mandated standard command and control system to graphically track the aircraft. This system allows for aircraft positions to be monitored from multiple locations; thus the data is available to be viewed by any or all people who need access to it. A system such as this provides many valuable benefits such as increased safety and reduced pilot workload. The architecture includes a Position Report Gateway to enable multiple different communications links be used to transmit the position reports from the aircraft to the TDBM. Two communications links have been implemented; ORBCOMM and HF ALE. The ORBCOMM system has been tested and shown to meet the design and operational requirements. In addition, the proof of concept has demonstrated the utility of a system such as this.

One major advantage of this type of system for flight following is that numerous users can access the data simultaneously. The Air Station Operations Center can keep an eye on their aircraft while they are flying. The various operational command elements (Group, District, and Area) can monitor the location of all aircraft within their areas of responsibility. And even other staff elements who have a need to know the location for mission reasons (whether it is Law Enforcement, Search and Rescue, Environmental Protection, etc) can have access to the position information in real-time. From a safety

of flight perspective, the Operator tasked with monitoring the aircraft (the aircraft guard) can do so easily and efficiently through the C2PC. From the aircraft commander perspective, this can be accomplished automatically, without any action on the part of the aircrew (the current method requires voice radio checks every 15 or 30 minutes depending upon the type of aircraft) thus freeing up the aircrew to focus on the mission at hand.

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