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THESIS

NETWORK PAYLOAD INTEGRATION FOR THE SCAN-EAGLE UAV
by
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December 2007
Thesis Advisor: Anthony J. Healey

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With the increasing maturity of MESH network technology, it is inevitable that we exploit the synergistic capabilities in networking of autonomous vehicles. The interconnectivity enables the sharing or dissemination of information between various nodes and has the capability to enhance communication range between a Ground Control Station (GCS) and autonomous aircraft which can then be expanded to several GCSs, or in a networked combination of Unmanned Aerial Vehicle (UAV), Unmanned Ground Vehicle (UGV) and Unmanned Surface Vehicle (USV).

This thesis discusses the setup of the MESH network between the ScanEagle GCS and the ScanEagle UAV. It describes the modifications on the high gain antenna and the integration of an ITT MESH card radio into the ScanEagle. A study of the results conducted in Panama City to understand the limitations and constraints of several MESH nodes operating within a specified area is described, together with a discussion of the results and recommendations for further work.

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NETWORK PAYLOAD INTEGRATION FOR THE SCAN-EAGLE UAV

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ABSTRACT

With the increasing maturity of Mesh network technology, it is inevitable that we exploit the synergistic capabilities in networking of autonomous vehicles [1]. The interconnectivity enables the sharing or dissemination of information between various nodes and has the capability to enhance communication range between a Ground Control Station (GCS) and autonomous aircraft which can then be expanded to several GCSs, or in a networked combination of Unmanned Aerial Vehicle (UAV), Unmanned Ground Vehicle (UGV) and Unmanned Surface Vehicle (USV) [2].

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I. INTRODUCTION

A. SCANEAGLE DESCRIPTION

The ScanEagle is an Unmanned Aerial Vehicle (UAV) which is developed by InSitu and deployed by both Boeing and InSitu [3]. It provides a combination of long endurance (up to 24 hours of flight time), low cost, utility, and a small operational footprint.

The aircraft is composed of five major modules: the nose, fuselage, avionics, wing and propulsion. These are field replaceable since the aircraft is modular (See Figure 1 for a description of the modules).

One person is required to operate the UAV and another person to deploy or recover the UAV. ScanEagle is particularly useful as it does not require a runway to launch or land. It uses a pneumatically driven launcher for takeoff, and a taut wire hanging from a boom for recovery, which catches it by locks on the wing tips. Thus, the operational footprint is relatively small.

It has capabilities to operate both on land and at sea. When at sea, the launcher and the recovery boom are mounted on the ship or floating platform. The weights, performance and dimensions of the ScanEagle are specified in Table 1.

ScanEagle has been employed in-theater in Iraq for video reconnaissance and Bomb Damage Assessment (BDA), using a gimble-stabilized camera system made by Hood Technology Inc. and described below.

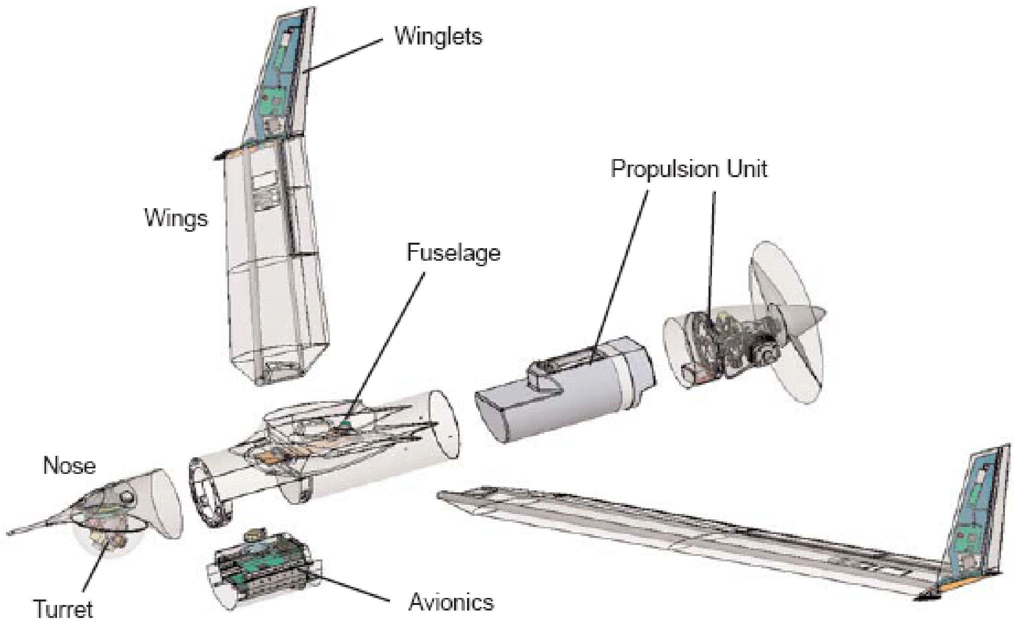

Figure 1 Breakdown of the ScanEagle

Table 1 Summary of ScanEagle Weight, Performance and Dimensions

Weight		
Empty Weight	26.5 lb	12 kg
Fuel and Payload	13.2 lb	6 kg
Maximum Fuel	11.9 lb	5.4 kg
Performance		
Maximum Takeoff weight	39.7 lb	18 kg
Maximum Level Speed	70 knots	36 m/s
Cruise Speed	49 knots	25 m/s
Service Ceiling	16,400 ft	5000 m
Endurance	15 hours	
Dimension		
Wing Span	10.2 ft	3.1 m
Fuselage Diameter	7.0 in	0.2 m
Length	3.9 ft	1.2 m

1. Video Camera

The ScanEagle is fitted with AlticamTM 400 series camera (See Figure 2) [4]. The turret is small and can move within a 7-inch globe. The camera turret weighs about 1.38lb and is fitted with an inertial two-axis gyro stabilized camera point with a 2° to 45° Field of View with NTSC composite video imaging performance and a color optical zoom of 25:1. The output provides thirty frames per second (fps) with resolution of 640 x 680 pixels.

Its articulation could rotate with a continuous $\pm 180^\circ$ pan with $+30^\circ$ /-110° tilt and $\pm 10^\circ$ scan. It incorporates stabilization logic, composition video, and software features for commanding more functions in a broader range of camera payloads.

The camera can slew more than 60° per second dynamically to any point below the belly of the ScanEagle and track objects of interest with a pointing accuracy of 0.015° in all axes, allowing the system to be more effective than aircraft with fixed cameras.

The power requirements are 9V-24V DC with less than 6 Watts. It has a disturbance rejection bandwidth from 0-5 Hz (-3dB) which automatically compensates for the ScanEagle airframe vibration.

Figure 2 Alticam™ 400 series camera turret

2. Ground Control Station

The ground control station, or GCS, generally contains all of the ground support systems needed to operate the ScanEagle [5] and comes in another portable configuration of a laptop and mobile antenna (See Figure 3).

Figure 3 Portable Ground Control Station (GCS)

The GCS can be mounted on everything from a trailer or high mobility multipurpose mobility wheeled vehicle (HMMWV) (See Figure 4) to ships. The GCS hardware is comprised of components which are commercially off the shelf (COTS) for easy maintenance.

Figure 4 Ground Control Station (GCS)

The GCS can be installed in mobile and fixed enclosures. It generally consist of the following:

a. I-MUSE Laptop Computer

The system contains a hardware stabilization board and a video capture board. It hosts the aircraft control and flight path management application software and provides video stabilization software. It is also for communicating with aircraft, managing the GPS receiver, and includes a high gain tracking antenna.

b. Object Tracker

Object Tracker provides video capture. It hosts video object tracking applications which allow the user to point to an object in the camera field of view, which is then stabilized in the center of the screen by automatic pointing control of the camera.

c. Fibre Optic Video Receiver

The Fibre Optic Video Receiver is a COTS system which provides for reception of video signals (dual signal) transmitted over fibre optics from the tracking antenna system.

d. Intercom System (ICS)

ICS is a COTS system, consisting of one master station, three remote stations, multiple headsets, and interconnection cables. It facilitates communication between operators, flight line, mission planners, and observers.

e. Uninterruptible Power Supply

The Uninterruptible Power Supply provides conditioned power to the GCS equipment.

f. Pilot Console

The Pilot console is used by the operator to approve automatic approach and recover, or to control semi-automatic approach and recovery and manage and change aircraft flight paths. Orbit paths around a point are automated, as are loiter boxes.

3. Communication System

The communication system consists of 900 MHz spread spectrum frequency hopping command telemetry with a 2.4 GHz analog video feed.

Two receiving antennae are mounted in a tracking system which includes a COTS high gain dish antenna and RF box containing power supply, transceiver, receiver, and copper-to-fiber-optic conversion. The high gain antenna system tracks the aircraft as it moves and is used for medium- and long-range communications with aircraft. It has a range of communication of about 100 km with line of sight. The dish pointing system is a pan-and-tilt motorized drive with angles computed from the GPS data from the aircraft.

For short-range communication with the UAV, an COTS Omni-directional antenna is used.

4. Method of Flight Control

The method of flight control is similar to the Piccolo Autopilot [6] and is therefore discussed in this thesis. The packet protocols are managed by the stream manager within the avionics. The flight control commands are sent in packets and consist of turn-rate, airspeed, altitude, and navigation controls which are intended for a conventional aircraft. All of the mixings are required to provide set points for the Autopilot on the UAV.

a. Stream Manager

For the incoming streams, the receive stream manager pulls incoming packets off the buffer and stuffs the packet into the appropriate stream buffer. Individual streams are responsible for pulling the data from the stream buffer and sending it to the appropriate software service routine or hardware port.

For the outgoing streams, the transmit stream manager multiplexes outgoing streams onto the bi-directional link in the order of priority. Each time, the transmit stream manager fills the available space in the outgoing buffer with packets constructed from the outgoing stream buffers. These stream buffers are examined in a specific order: first the autopilot buffer, then the CAN [7] buffers. The last thing the transmit stream manager does is send the frame termination packet on the network control stream. In this way, the high priority streams get first shot at the available outgoing bandwidth on the link.

b. Autopilot and Pilot in the Loop Stream

The autopilot stream is used to carry system commands from the operator interface to the avionics, autopilot state information from the avionics to the operator interface, and sensor telemetry information from the avionics to the operator interface.

For the pilot in the loop stream, the ground station samples the pilot's console which forms the pilot command packet from the console data, and sends that data to the pilot in loop stream on the avionics. However, the ground station will intercept and discard any user-supplied pilot command data addressed to the pilot address if the pilot console has manual control selected.

c. Avionics Interface

The avionics interface contains all the logic to run the polling scheme [8]. In addition, it determines the frame time used for each polling cycle by examining the pilot commands received from the pilot console.

When manual pilot control is selected, the frame time decreases. In either case, if pilot-in-the-loop commands are available, the ground station sends them out as the first packet of each frame. The pilot command packet will always contain the same address, which is specified by the operator interface for pilot-in-the-loop commands. If no such specification has been received then the ground station does not send pilot-in-the-loop commands.

In sending the pilot command, the ground station broadcasts differential corrections to all avionics. Then the ground station sends any data from the operator interface which was destined for the avionics addressed in that frame, up to the maximum amount of data allotted in that frame.

Finally, the ground station sends the polling packet with whatever data space remains in the frame. Any reply from the aircraft is forwarded to the operator interface.

5. Launch/Recovery

a. Launch

In the launch of the ScanEagle, the SuperWedge™ Launcher [9] is used. Figure 5, shows the launcher, which is pneumatically driven. It allows operations in environments that are usually not accessible to more traditional UAVs, such as high winds, crosswinds, the ocean or rugged terrain.

The weight of the launcher is 800 lb and the maximum launch speed is 89 ft/s. The nominal launch pressure from the launcher is 70 psi and the nominal acceleration is 12 G. The launch angle is 12° to 25° of elevation. The dimensions at stowage are 4.3 ft by 6 ft by 16 ft while at deployment they are 10.5 ft by 10 ft by 21 ft.

Figure 5 SuperWedgeTM Launcher

b. Recovery

The SkyHookTM [10] (Figure 6), is used for the recovery of the ScanEagle process. It does not depend on the runway for the recovery of the UAV, and therefore has a small operational footprint.

SkyHookTM is comprised of a rope hanging from the boom and catches the aircraft on a wingtip hook for the recovery. On land, operations are possible in windy conditions. It can be positioned into the wind with one crew and a tow vehicle, allowing for recovery operations in a wide range of weather conditions.

The system is deployable both on sea and on land. It can be easily packed and transported. Its stowage dimensions for transportation are 4.8 ft by 6.4 ft by 14.2 ft; its deployed dimensions are 11.1 ft by 45.0 ft by 34.0 ft. The weight of the SkyHookTM is approximately 3000 lb and requires a power source of 24 VDC.

Figure 6 SkyHookTM

On approach, the aircraft uses a differential GPS signal to compute track offset for recovery so that the airframe can be precisely positioned to within a centimeter's accuracy. Recovery can be specified to occur on either port or starboard wingtip.

B. OBJECTIVE OF THE THESIS

The main objective of this work was to integrate a Mesh network into the ScanEagle UAV and understand the limitations of the Mesh network in operations for the UAV, acting first as a data relay and second as a video surveillance system.

For this thesis, the ScanEagle is used for integration; the thesis discusses the modifications done in the ScanEagle and ground control station to accommodate this new capability.

To understand the limitations of Mesh network operations for a UAV, an analysis was conducted on the communication between the ScanEagle and Sea Fox during operation, via an experiment conducted on 10 June 2007 in Panama City. This analysis to understand what happened during the communication between the ScanEagle and Sea Fox comes under the heading of “bent pipe” communications—that is, Non Line of Sight (NLOS) communications—which represent a powerful tactical advantage using combined UAV and USV operations.

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II. NETWORKING BACKGROUND

A. NETWORKING

Great tactical advantages occur when networks of autonomous vehicles are used. Networks allow control commands and sensor data to be relayed between nodes in the network. With mobile nodes, link parameters are highly dynamic and the Mesh network increases the reliability of operations.

1. Wireless Mesh Networking

A wireless mesh network is a mesh network implemented over a wireless network system using wireless Local Area Network, LAN [11].

Mesh networking is a method to route data between nodes. It allows for continuous connections and reconfiguration around broken or blocked paths by “hopping” from node to node until the destination is reached. Figure 7 shows a mesh network.

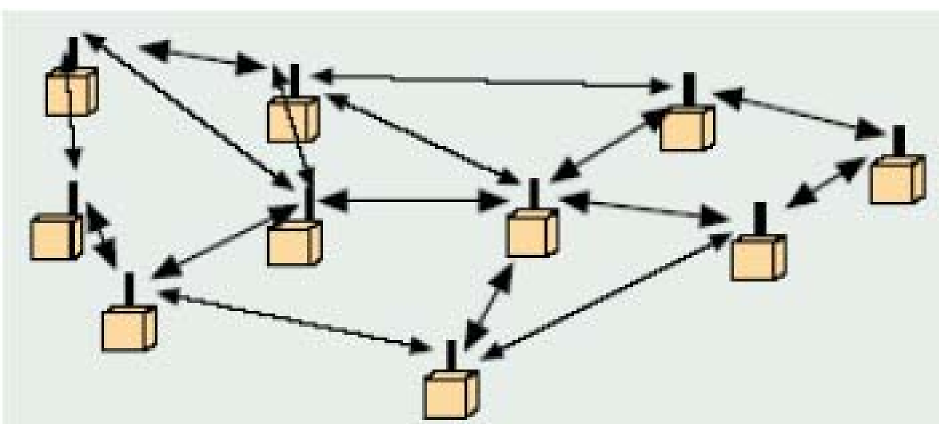

Figure 7 Mesh Network

Mesh networks differ from other networks in that the component parts can all connect to each other via multiple hops.

Mesh networking is typically implemented in two basic modes: infrastructure and/or client meshing [12]. Both modes need to be supported simultaneously and seamlessly in a single network.

a. Infrastructure Meshing

Infrastructure meshing creates a wireless backhaul mesh among wired Access Points and Wireless Routers, reducing system backhaul costs while helping increase network coverage and reliability.

b. Client Meshing

Client meshing enables wireless peer-to-peer networks to form between and among client nodes and does not require any network infrastructure to be present. In this case, clients' nodes can hop through each other to reach other clients' nodes in the network.

In order to create a robust and scalable network, Mobility Enabled Access (MEA) technology is used. Client meshing enables other nodes to instantly form a broadband wireless network among themselves.

The Multi-Hopping technology changes every node into a router/repeater. As other nodes join the network, they improve network coverage and increase network throughput.

The self-forming, self-healing routing intelligence distributes nodes among the Access Points, eliminating bottlenecks and improving overall network performance. The MEA technology allows client nodes to hop to alternate Access Points if their current Access Point is congested or fails. It also lets client nodes form large, ad hoc peer-to-peer networks anywhere, anytime. Peer-to-peer networking reduces the demand on network Access Points, freeing up capacity for other nodes. All these capabilities create a low-cost, seamless and easily deployable wireless LAN.

2. Networked Control of ScanEagle

The proposed networked control block diagram is show in Figure 8:

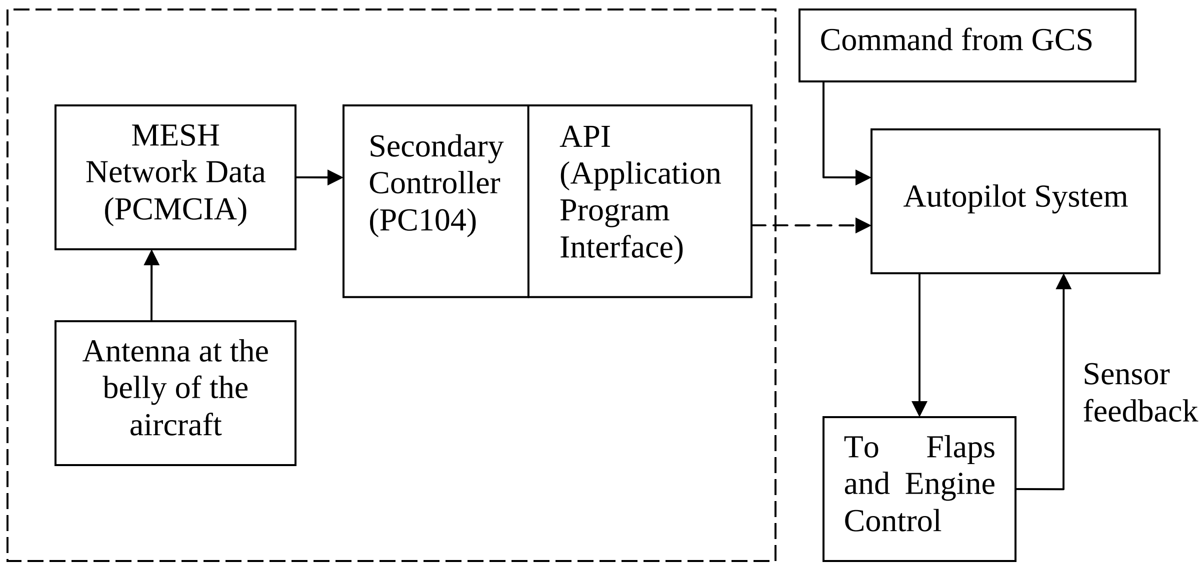

Figure 8 Network Control Block

In data relay mode, where it functions without API software and secondary control computer, the aircraft simply carries the network radio in a data relay mode (shown on the right of the block diagram) that consists of command from GCS, the Autopilot system and the control for the flaps and engine. This network radio functions as a rebroadcast station, as it receives and transmits commands to other nodes in the network.

In the network control of the flight path with API, modifications are added (shown on the left of the block diagram). The modification will be further elaborated in Chapter III. C. (ITT Mesh Card to Autopilot).

The ITT MESH card is connected to the Secondary Controller. The MESH network receives data from other nodes in the network from the antenna at the belly of the aircraft.

The secondary controller streams the received mesh data to the API, where it is processed into commands which are read by the Autopilot system. If there is an overriding command from the GCS for manual control, it will send the command to the autopilot system, which has priority to override existing control from the API.

The autopilot includes controls that stabilize the aircraft motion and generate commands to the flaps and/or engine controls where there will be a feedback from the sensors to the Autopilot. The Autopilot has several modes that may be initialized through the API, including waypoint track following, orbit following, and camera modes for lock on target and target following.

B. ITT MESH CARD

The ITT Mesh [13] is a PCMCIA wireless card, shown in Figure 9. It provides scalable, high-performance mobile ad hoc networking. The card could support up to 6 Mbps of transmission data rate which is available for data, video and/or audio. It operates on a 2.4 to 2.48 GHz RF frequency with spread spectrum capability for building penetration.

The data rate depends on the signal strength and, with low-power signal levels down at -80 or -100dB, reduces the data rate to levels around 200 Kbps. This means that only at higher power levels around -30 to -40dB could rates of 1Mbps be sustained. To achieve range in the order of several kilometers, a 1-watt amplifier has been used in the ScanEagle, and the high-gain tracking antenna ranges out to 20km.

Figure 9 ITT Mesh Card

C. TS 5700 PC 104 EMBEDDED SBC

The PC 104 is a standardized, reduced-form-factor implementation of the IEEE P996 specification for the PC and PC/AT busses, for embedded applications. The PC 104 specification adopted the P996.1 Standard for Compact Embedded-PC Modules. This increases the form factor, enables a unique self-stacking bus with pin-and-socket connection and relaxed bus drive, thus reducing power consumption.

The PC 104 provides processing power from the integration of the MESH network. It computes the received information to output, which is translated by the API as commands to the autopilot system.

In the ScanEagle, it uses a Technologic Systems, TS 5700 PC 104 Embedded Single Board Computer (Figure 10) with a 133 MHz AMD 586 Processor [14].

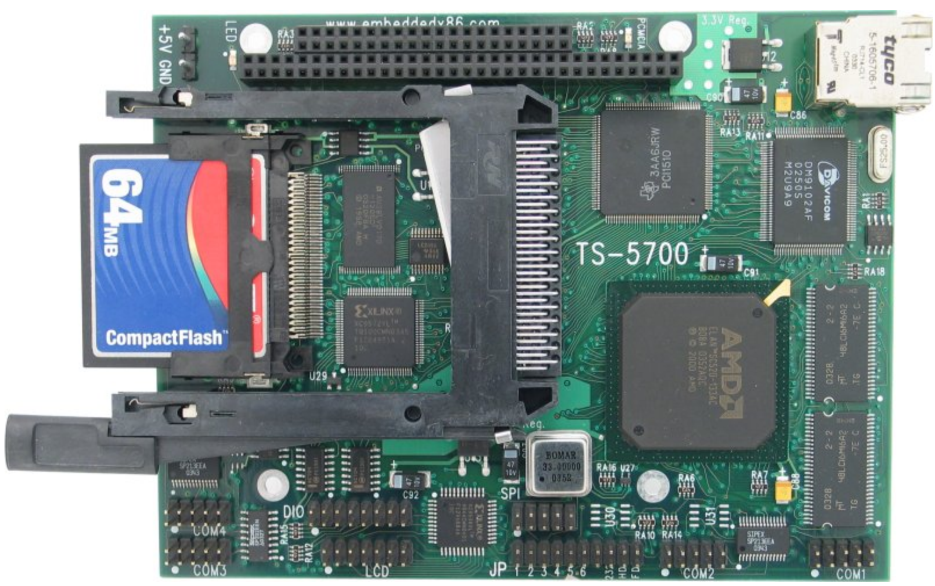

Figure 10 TS-5700 PC/104 Embedded SBC

It is a x86-based embedded PC that runs without fan or heat sink. The build of the SBC is based on the 586 architecture. The processor is an AMD Elan 520 CPU running at 133 MHz. The specification of the TS 5700 SBC is as follows:

1. 1 x PCMCIA Type II slot
2. 32 MB high-speed SDRAM
3. 2 MB flash disk with full bios support
4. Compact Flash card interfaced as IDE0
5. 10/100 Ethernet interface
6. 23 DIO lines
7. External reset DIO input
8. Alphanumeric LCD interface
9. Matrix Keypad interface on DIO2
10. PC/104 8/16 bit bus
11. Rugged quick-release terminal strips used for power
12. Dimensions are 4.3” x 5.6” (PC/104 mounting holes)
13. Power requirements are 5V DC @ 900 mA
14. Operating Temperature Range: Fanless -20° to +70°C

The operating system onboard the TS 5700 uses the TS-Linux 3.0 that supports Intel x86 processors on the TS 5700. The TS-Linux 3.0 is a PC-compatible embedded Linux distribution built from open source, where it uses a standard file structure with a scaled-down System V Release 4, currently the most widely used initialization scheme across Linux distributions.

III. MODIFICATIONS TO HIGH-GAIN DISH ANTENNA

A. ANTENNA INTERFACE MODULE TO HIGH-GAIN DISH

The high-gain dish has been modified to boost the performance of the signal received from the ScanEagle. Figure 11 illustrates the modifications from the High-Gain Dish to the Antenna Interface Module (AIM). The signal received from the ScanEagle comprises the video feed, network link and commands and the high-gain antenna sends the command and control link and network link to the ScanEagle.

The command-and-control link for flight control, which operates bi directionally on the 900 MHz bandwidth, is transmitted from the ScanEagle and received on the High-Gain Dish; it is then sent to the AIM which is directly connected to the GCS.

The video, which is receive only, is fed from the ScanEagle and transmitted via 2.3 GHz bandwidth to the High-Gain Dish. The High-Gain Dish receives the video feed and sends it to the filter box where it is filtered and forwarded to the AIM box.

The ITT Mesh card from the ScanEagle, which operates bi directionally, sends its network link via the 2.4 GHz frequency (which is the 802.11 wireless frequency protocol) to the High-Gain Antenna. It is received by the High-Gain Dish and sent to the Filter Box where the signal is filtered and delivered to the AIM.

The purpose of shifting the video feed from the 2.4 GHz bandwidth to the 2.3 GHz bandwidth is to reduce conflict with the 802.11 wireless frequency protocol. It is further filtered by a 15 μm filter to reduce noise in the signal.

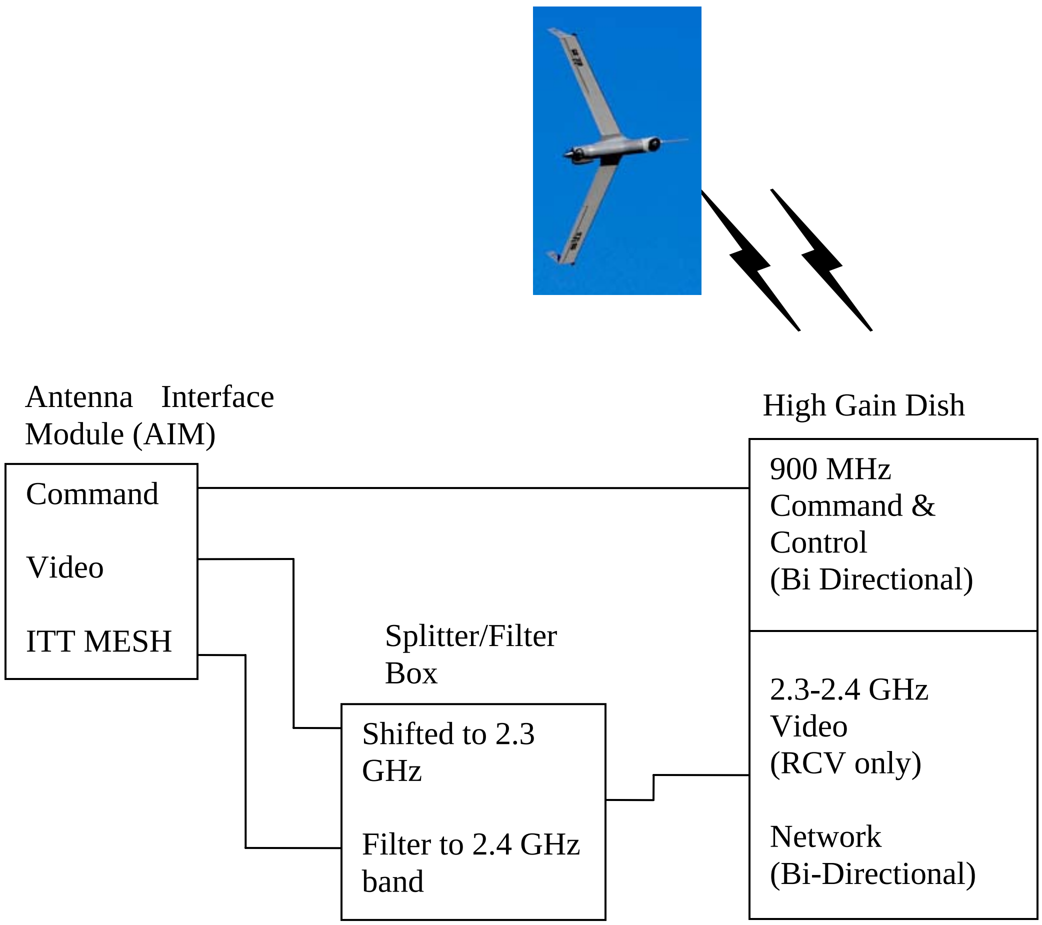

Figure 11 Modification to the high gain dish, accomplished by contract to Insitu, Inc., 2007.

B. GROUND CONTROL STATION TO ANTENNA INTERFACE MODULE

The command-and-control link, video feed and network link signal from the AIM are sent to the GCS where a human operator manages them. The video feed and command link are carried by fiber optic cable while the network link is carried by Cat 5e Ethernet cable to the GCS. This is illustrated in Figure 12.

The video feed (which is in NTSC format) can be displayed on a monitor and/or recorded onto the hard disk onboard the GCS.

The command-and-control link is streamed to the Graphic User Interface (GUI) for flight control on the GCS; flight paths are displayed on the GUI, as is a small icon giving current aircraft location and direction.

The network link will be streamed to the network card on the GCS where it will establish and maintain network link with the ScanEagle or with surrounding Mesh networks.

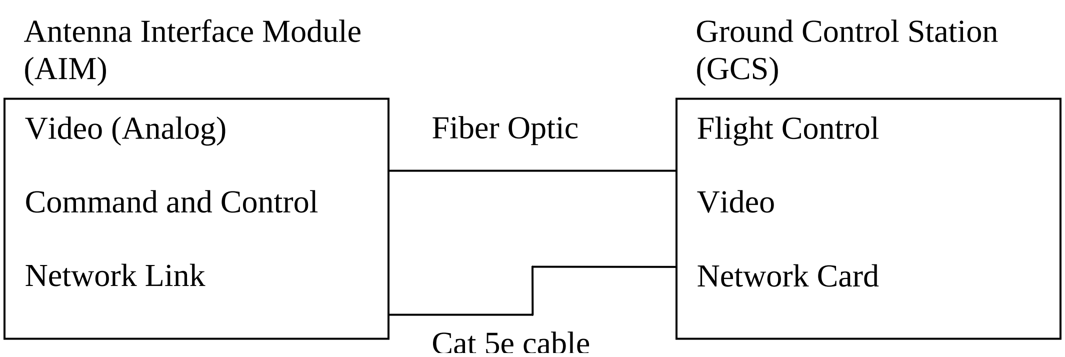

Figure 12 Connection from AIM to GCS

C. ITT MESH CARD AS A PAYLOAD FOR A DATA RELAY

The avionics module from the ScanEagle is shown in Figure 13 [15]. The power of 5VDC to the TS 5700 is connected to the avionics module. The ITT Mesh Card, which is a PCMIA card Type II, can be slotted into the TS 5700 SBC. The Linux OS software is loaded into the CF card, which is slotted into a compact flash card interface on the TS 5700 SBC.

The ITT Mesh card is connected to the 1W amplifier, which will boost its signal, and transmitted through the 2.4 GHz Antenna.

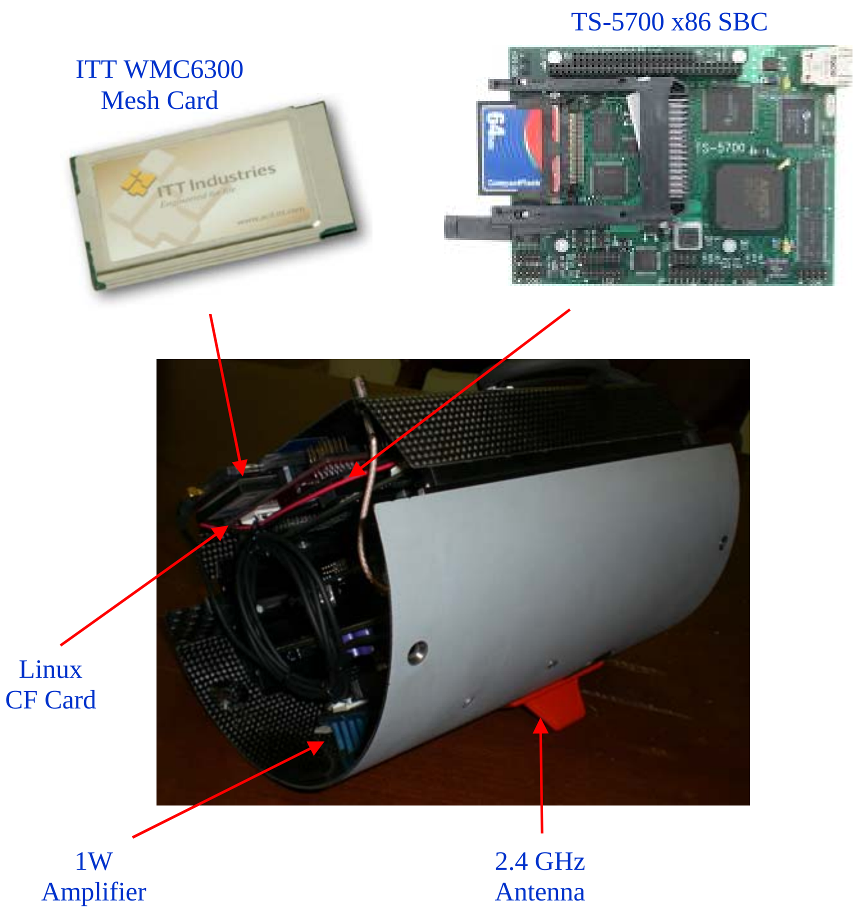

Figure 13 Integration configuration

IV. PANAMA CITY EXPERIMENT

A. INTRODUCTION

In June 2007, the Center for AUV Research participated in the AUVFEST 07 exercise conducted by the Office of Naval Research (ONR). The objectives of the exercise (as far as this thesis work is concerned) were to demonstrate networked communications in a distributed autonomous vehicle system, and to demonstrate high-bandwidth communications at long range using ScanEagle as a data communications relay. The experiments were conducted at Tyndall Air Force Base (AFB) where a section of the base has airspace over water. Of particular use, a short waterway between land and a barrier reef formed a simulation of a riverine waterway for the USV, SeaFox. Figure 17 shows an example of a ScanEagle flight path overlaid on the map of the pertinent section of Tyndall AFB.

The Panama City experiment was conducted on 10 June 2007, and consisted of collaborative operations between UAV and USV and testing of the aerial communications relay performance from GCS to USV via ScanEagle, within the Mesh wireless network. Later, in August 2007, complementary exercises were conducted with ScanEagle at Camp Roberts, CA.

In the Panama City experiment, there were a total of three UAVs and two USVs involved in the experiment. The following autonomous vehicles were involved:

1. ScanEagle – UAV
2. NPS Rascal – UAV
3. VT Rascal – UAV
4. SeaFox – USV
5. VT ASV - USV

Each vehicle had a direct link to its own GCS. Only the SeaFox and VT ASV used Mesh for the primary link. All aircraft had a 900 MHz radio link for command and control from their GCS. They used Mesh to communicate with the other vehicles. The NPS Rascal did not have a Mesh Card, while the ScanEagle had a Repeater module to receive commands from SeaFox GCS and broadcast to SeaFox if there was no direct link from the SeaFox GCS to SeaFox.

There was a Mesh card logging data system connected to the ScanEagle antenna located next to the runway with coordinates of GPS Latitude $30^{\circ}2'20.47"$ and Longitude $85^{\circ}31'40.26"$. A map with coordinates of GPS Latitude $29^{\circ}50'$ to $30^{\circ}04'$ and GPS Longitude $85^{\circ}28'$ to $85^{\circ}42'$ is shown in Figure 14 and highlights the Area of Operation, while Figure 15 shows the location of the Antenna.

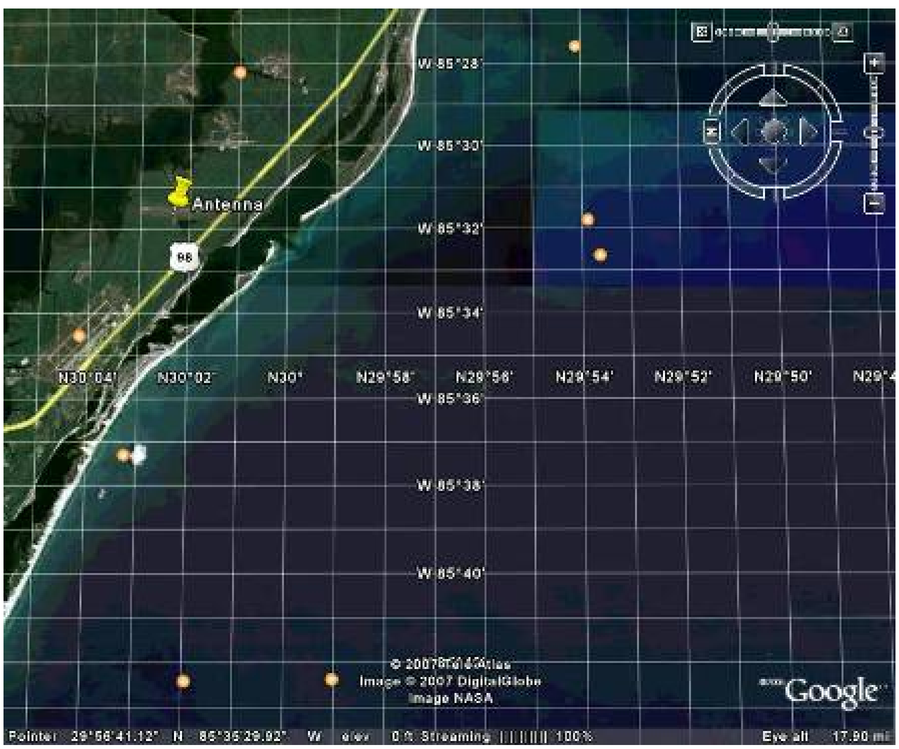

Figure 14 Map of Area of Operation

Figure 15 Antenna Location

B. DATA ANALYSIS

There were problems with the Mesh data logger, so that the system failed to acquire the entire duration of the experiment. In the data analysis, the time of interest was obtained from data acquired from the neighboring and routing table, in two durations:

1. 16:14:14 to 16:44:37 UTC Time
2. 17:10:49 to 17:26:28 UTC Time

All the data acquired from ScanEagle, SeaFox, NPS Rascal and VT Rascal were used except for VT ASV. The VT ASV had no data available within the time of interest. The vehicle logging software had its own preset time reference. The times analyzed for individual vehicles were converted to Coordinated Universal Time (UTC) for comparison.

For the ScanEagle, the time was referenced in GPS time, which is 14 seconds faster than UTC time. Therefore, to standardize the time to UTC time, 14 seconds had to be subtracted from the GPS time obtained from ScanEagle data set.

For the SeaFox, the time was referenced in Unix time. It had to be divided by 86400 (Referenced to 01 January 1970), followed by adding 25569 to convert to UTC time.

For both the NPS and VT Rascal, both their time data sets had to be referenced to the UTC time; therefore, no conversion was required.

1. Longitude vs. Latitude Plots

All the vehicles' paths were plotted using GPS Longitude and Latitudes which were converted from radians to degrees. The coordinates were extracted from the time of interest and then super positioned on the map.

2. Signal Level and Range vs. Time Plots

The range of each vehicle at every time step was calculated from the data acquired, with reference to the location of the GCS. The Great Circle assumption was used to calculate the range. The calculation of the range is shown below.

The Longitudes and Latitudes are in degrees and r is assumed to be Altitude + 6,370,000m for UAVs and only 6,370,000m for USVs.

At the location of the GCS:

P0 = $\left(x_0, y_0, z_0\right)$

$$x_0 = r \times \cos\left(Lat_0\right) \times \sin\left(Long_0\right)$$

$$y_0 = r \times \sin\left(Lat_0\right)$$

$$z_0 = r \times \cos\left(Lat_0\right) \times \cos\left(Long_0\right)$$

At the current position of the vehicle:

P1 = $\left(x_1, y_1, z_1\right)$

$$x_1 = r \times \cos\left(Lat_1\right) \times \sin\left(Long_1\right)$$

$$y_1 = r \times \sin\left(Lat_1\right)$$

$$z_1 = r \times \cos\left(Lat_1\right) \times \cos\left(Long_1\right)$$

The range can be calculated using the equation below:

Range = $\sqrt{\left(x_1 - x_0\right)^2 + \left(y_1 - y_0\right)^2 + \left(z_1 - z_0\right)^2}$

The signal level is extracted from the routing table and expressed in dB. For the purpose of clear presentation of the signal plots, the actual measured results have been normalized by subtracting 100. The 100 dB represents a strong signal and 0 dB represents a weak signal. The signal level is plotted on the secondary axis with the same time of interest as when the vehicle is in operation.

For the ScanEagle, it includes an additional plot for the range, and the roll angle is plotted vs. time. In Figure 16, the positive sign convention represents that the right wing of the aircraft is down and the aircraft is turning clockwise.

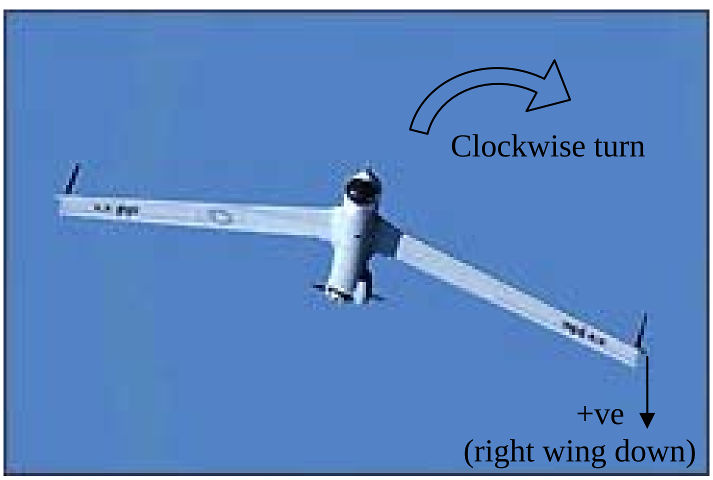

Figure 16 ScanEagle positive roll convention

C. SCANEAGLE

The ScanEagle operated from 15:03:46 to 19:51:26. The following figures display the flight path for the two sets of duration which were logged from the ScanEagle GCS.

1. Set 1

The Longitude vs. Latitude plot for Set 1 shows that the ScanEagle maneuvers anti-clockwise from the start point, followed by moving down where it move inland. At the water channel, it maneuvers up then makes a loop and reverses back down along the channel, followed by two loops. This is illustrated by the arrows shown in Figure 17.

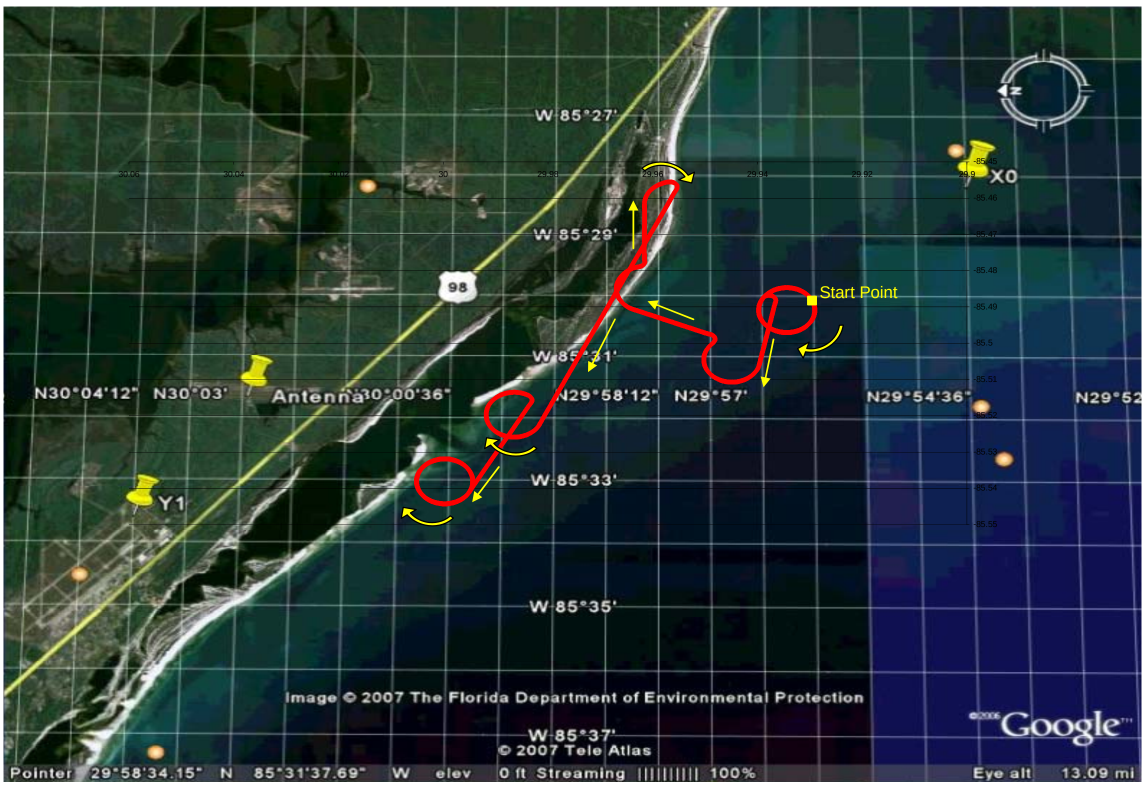

Figure 17 Plot of Longitude vs. Latitude of ScanEagle from time 16:17:14 - 16:44:37

The signal level and range vs. time are shown in Figure 18. The illustration shows that the range reduces at the later time. The signal levels show fluctuation during the initial and near-final section as the aircraft maneuvers in a loop.

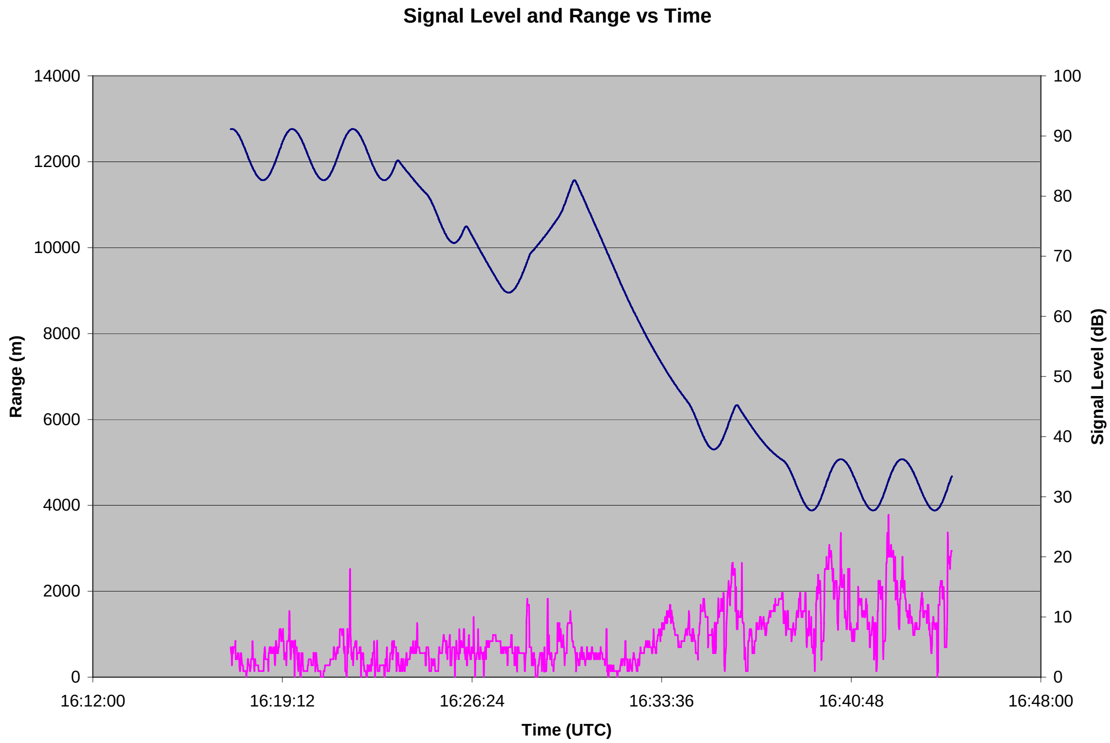

Figure 18 Plot of Signal Level and Range vs. time of ScanEagle from time 16:17:14 - 16:44:37

To further elaborate the flight profile, the roll angle and range are plotted against time in Figure 19. The roll angle of the aircraft can be seen at different ranges.

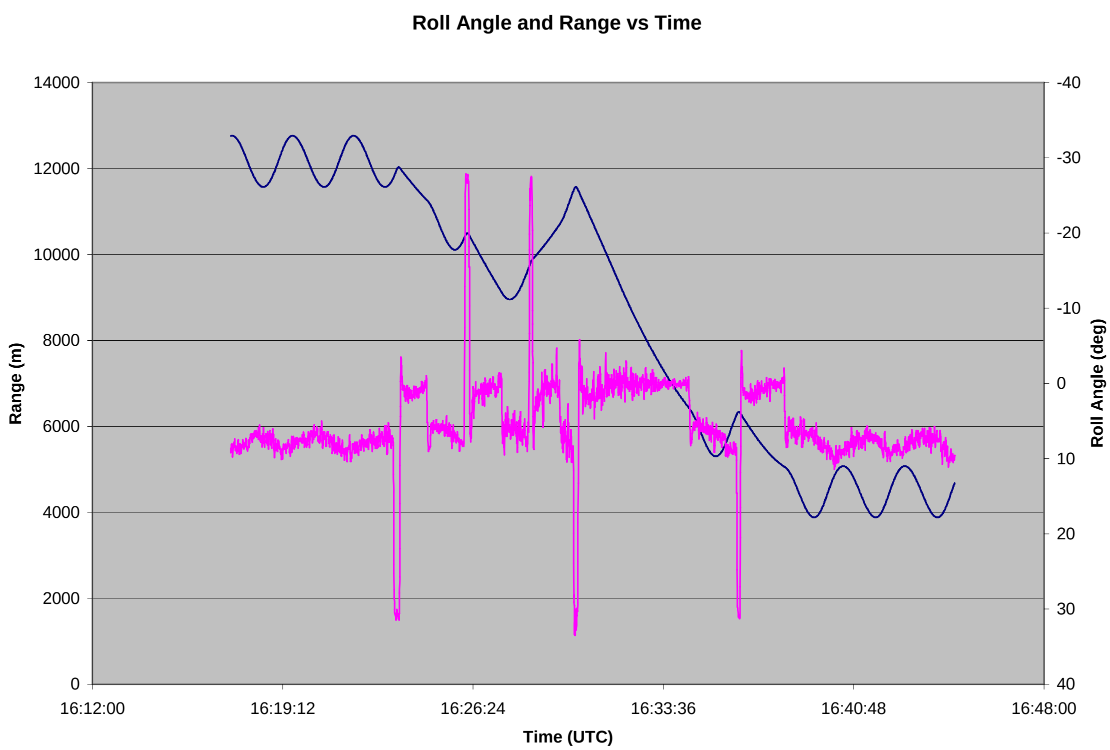

Figure 19 Plot of Range and Roll Angle vs. time of ScanEagle from time 16:17:14 - 16:44:37

2. Set 2

In the Longitude vs. Latitude plot, the ScanEagle is maneuvering in a clockwise loop. It makes approximately three loops from the start point up further inland and back down to the channel toward the sea. This is illustrated in Figure 20.

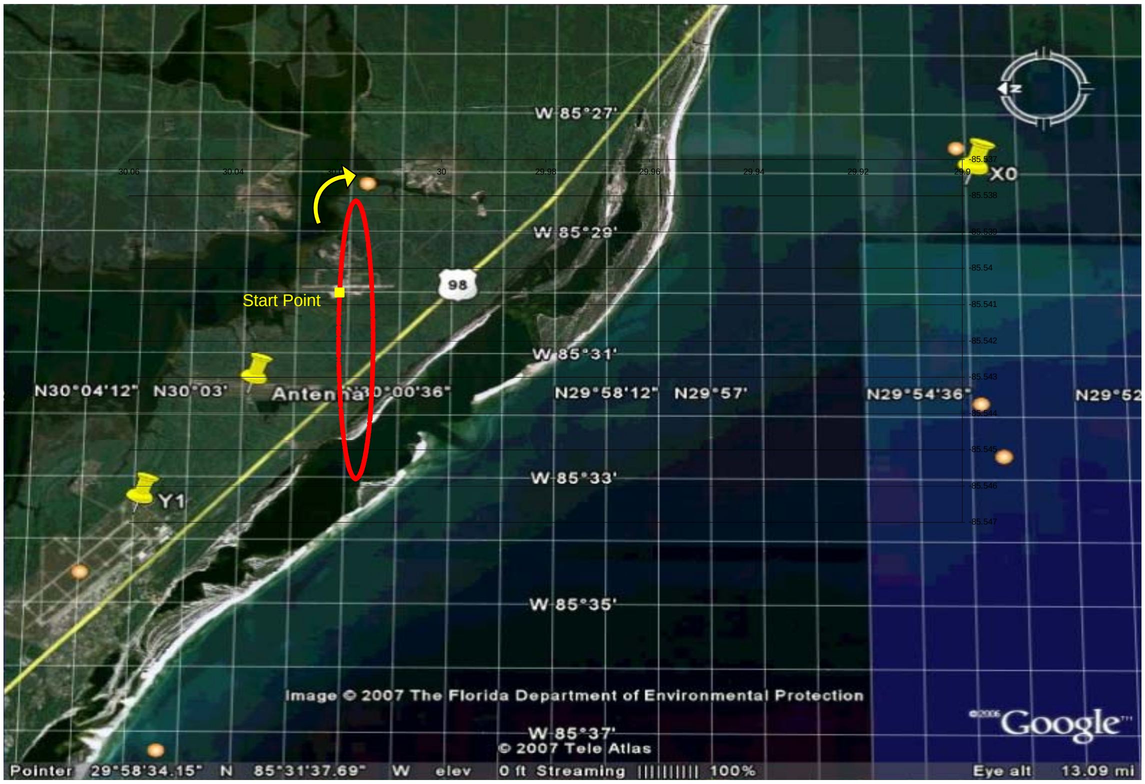

Figure 20 Plot of Longitude vs. Latitude of ScanEagle from time 17:10:49 - 17:26:28

In the signal level and range vs. time plot, it can be seen that the range increases as it moves inland and reduces as it moves toward the antenna. The signal level displays repetitive fluctuations as it performs the loop maneuvers. This is illustrated in Figure 21.

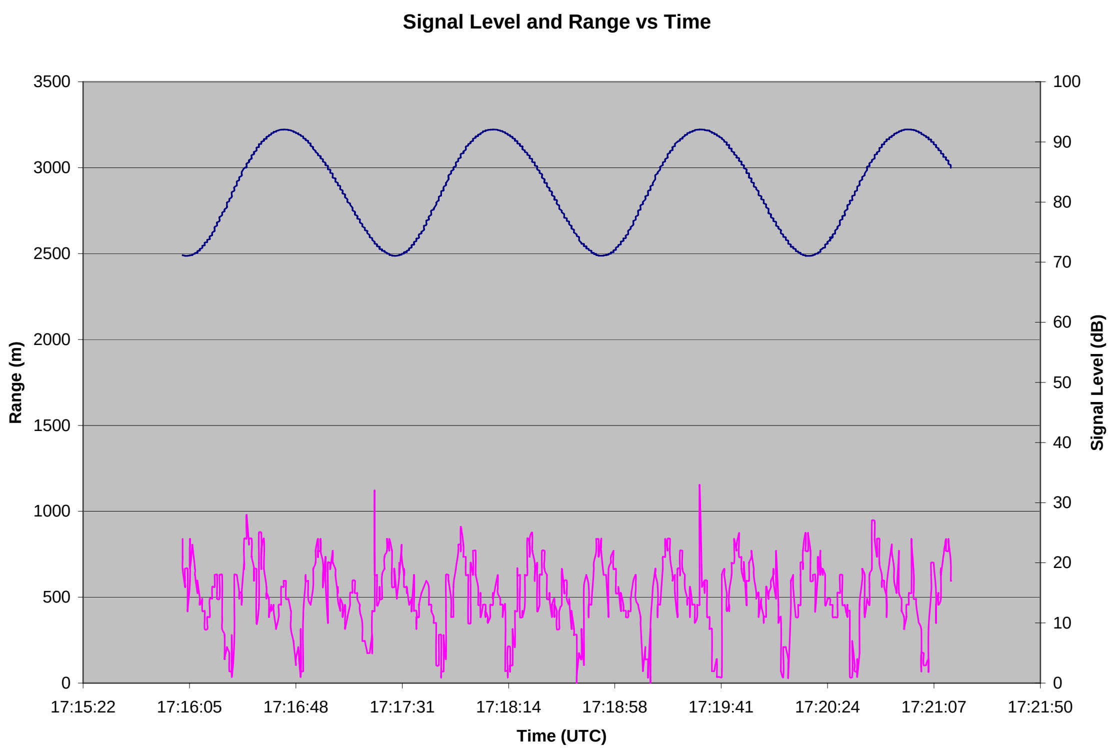

Figure 21 Plot of Signal Level and Range vs. time of ScanEagle from time 17:10:49 - 17:26:28

The fluctuation of the signal level could be due to the Scan Eagle’s rolling when it makes its loop maneuvers. The antenna is located at the belly of the UAV, and could be block as the UAV rolls to make its turns. Since the body is completely shielded, the received signal from the high-gain antenna at the ScanEagle GCS reduces as the UAV rolls.

To further elaborate the flight profile, the roll angle and range is plotted against time in Figure 22. The roll angle of the aircraft can be seen at different ranges.

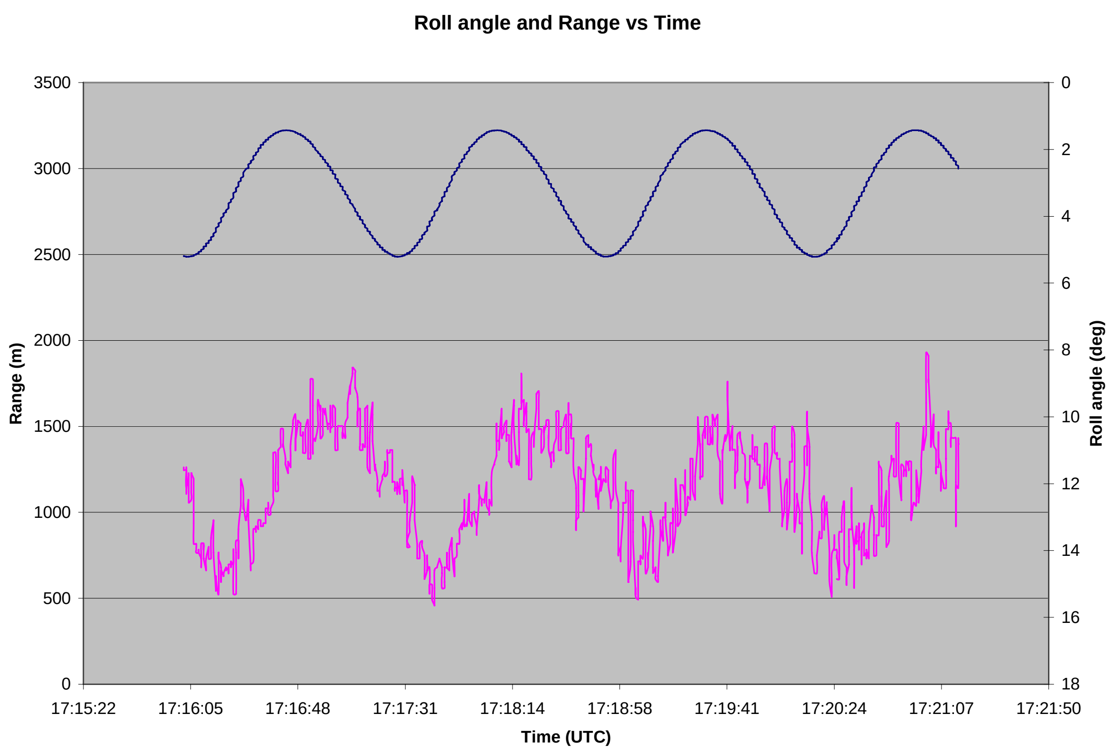

Figure 22 Plot of Range and Roll Angle vs. time of ScanEagle from time 17:10:49 - 17:26:28

D. SEAFOX

The SeaFox is an Unmanned Surface Vehicle (USV), shown in Figure 23. It is a 16-foot, aluminum hull, rigid inflatable boat manufactured by Northwind Marine, Inc. SeaFox is propelled by a 200 HP JP5 jet engine power plant that will propel the craft at 40 knots.

Figure 23 SeaFox

The SeaFox data acquired from 16:56:57 to 19:46:43. In the Mesh data logger has no data from the neighboring and routing table for SeaFox. The data used is from 16:56:57 to 17:04:14 to generate the Longitude vs. Latitude and Range vs. Time plots which is logged from the SeaFox GCS. There is no signal level included in the Range vs. Time plot.

In the Longitude vs. Latitude plot, it shows that SeaFox was cruising up and down within the sea channel. Although there is not much data retrievable from the SeaFox GCS, it traveled on the same path throughout the entire duration of the experiment. This is shown in Figure 24.

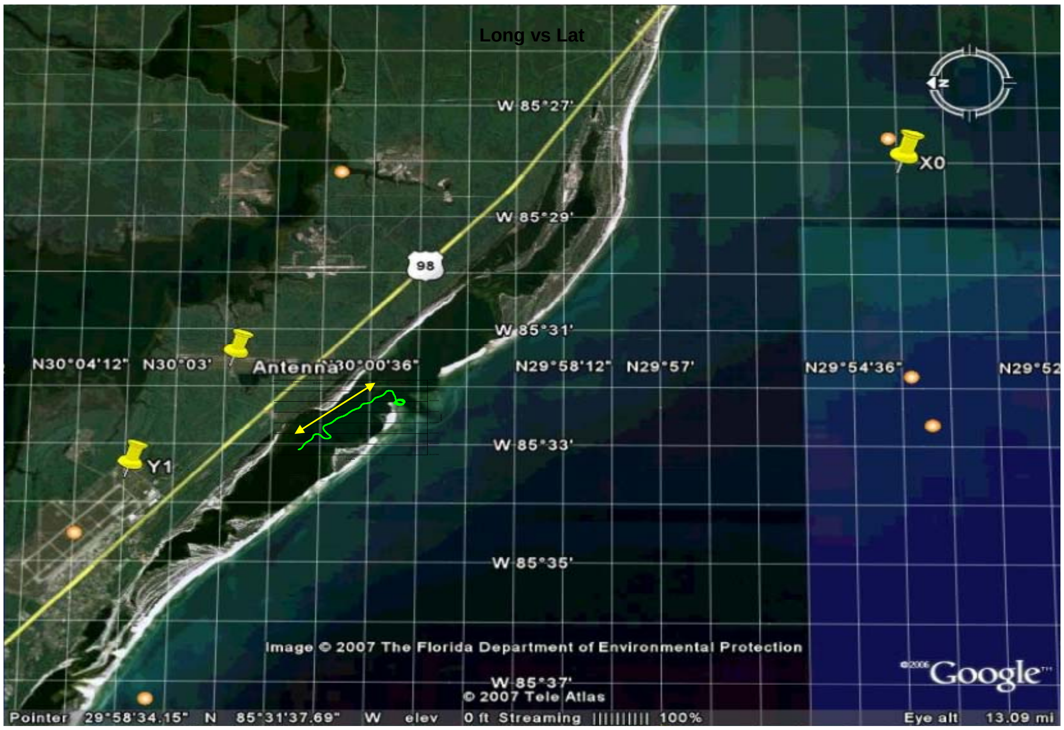

Figure 24 Plot of Longitude vs. Latitude of Sea Fox from time 16:56:57 - 17:04:14

In the Range vs. Time plot, it can be seen that the SeaFox was cruising farther away from the SeaFox GCS located next to the ScanEagle GCS. This is shown in Figure 25.

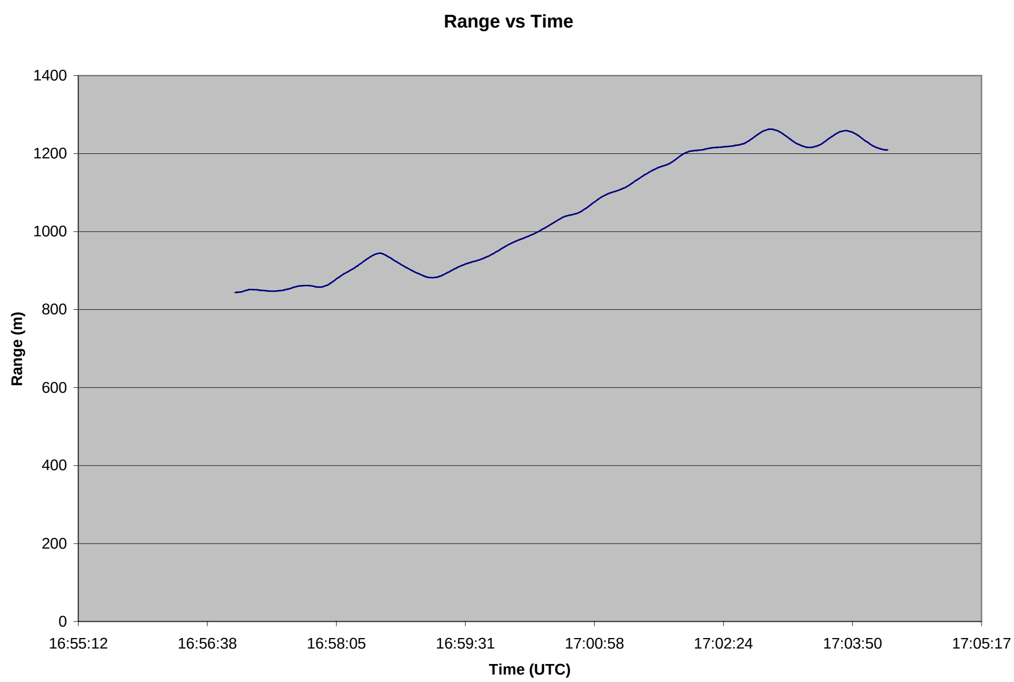

Figure 25 Plot of Range vs. time of Sea Fox from time 16:56:57 - 17:04:14

E. NPS RASCAL

Figure 26 shows the NPS Rascal; it is a UAV operated by NPS. The NPS Rascal operated from 14:48:47 to 18:40:09. The data used is from 16:29:46 to 16:52:46 which is logged from the NPS Rascal GCS.

Figure 26 NPS Rascal

From the Longitude vs. Latitude Plot, it can be seen that the NPS Rascal is maneuvering in loops inland. It rotates clockwise from the start point and moves down and continues to make clockwise loops. This is illustrated in Figure 27.

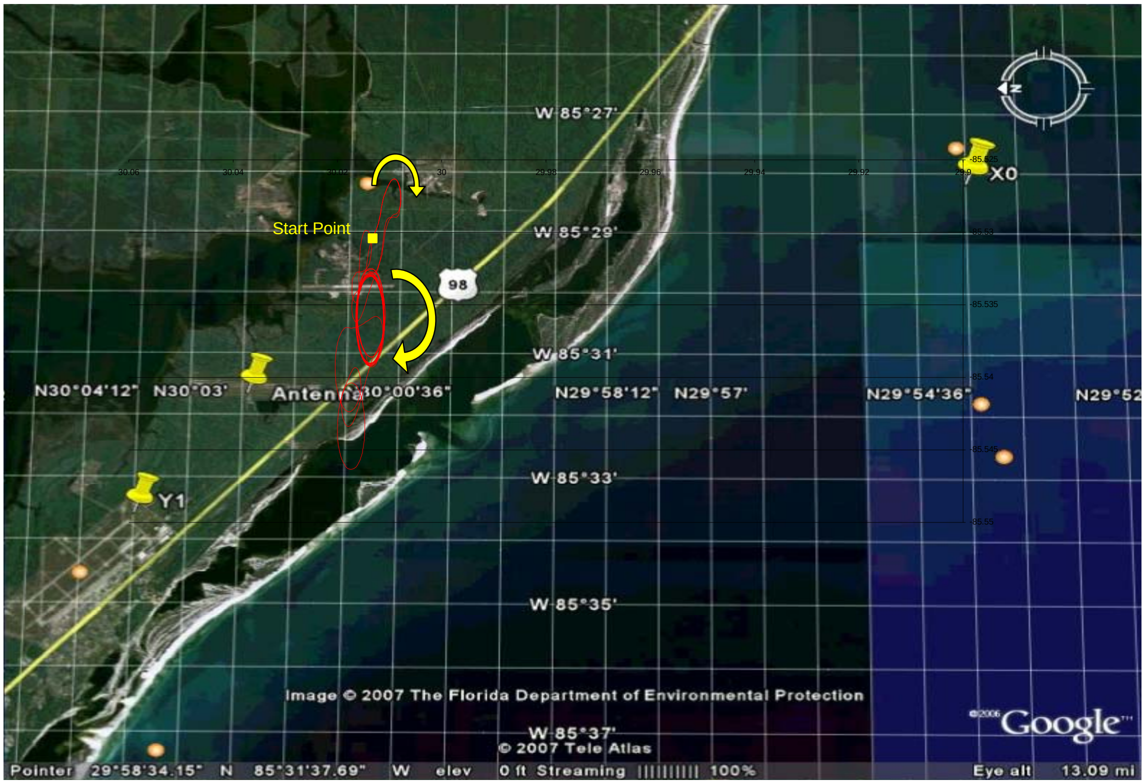

Figure 27 Plot of Longitude vs. Latitude of NPS Rascal from time 16:17:14 - 16:44:37

Figure 28 shows that the range changes as the NPS Rascal maneuvers in loops. As it maneuvers close to the antenna, the range reduces. The signal also fluctuates as the NPS Rascal makes it loops. The signal is also affected by the rolling of the UAV. It can also be seen that the signal is weaker as it approaches the right of the antenna, with reference to the Figure 27.

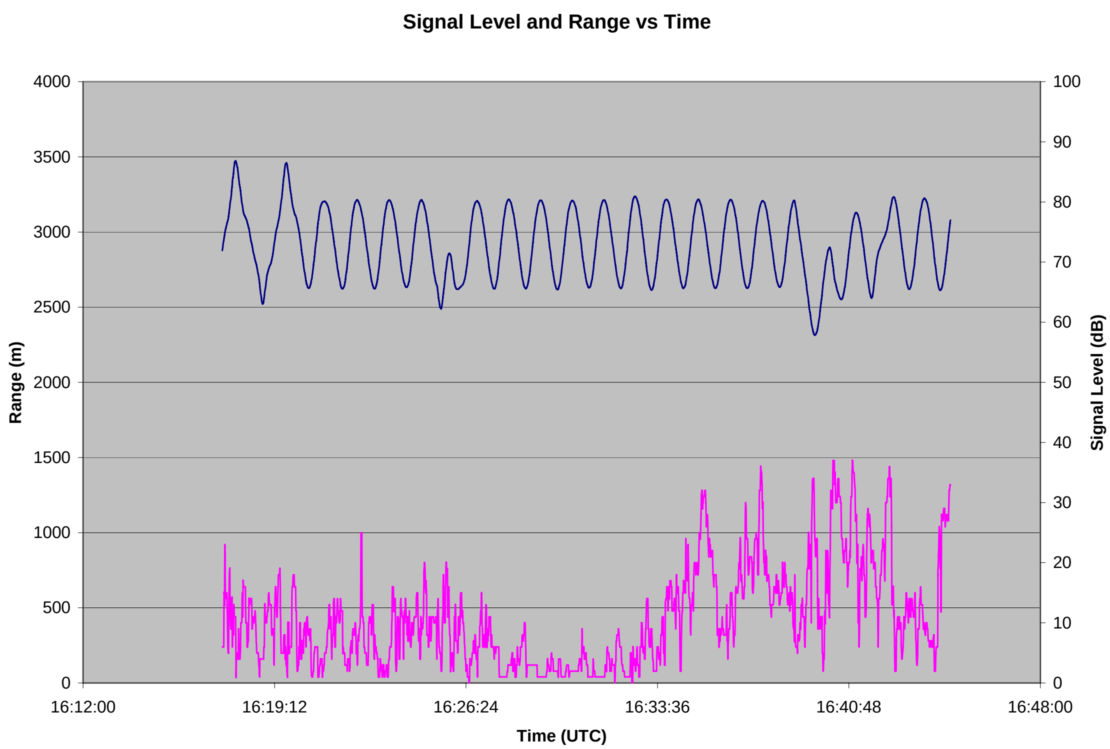

Figure 28 Plot of Signal Level and Range vs. time of NPS Rascal from time 16:17:14 - 16:44:37

F. VT RASCAL

The NPS Rascal operated at two period of time: from 14:54:18 to 16:40:54 and 18:11:19 to 18:00:57. The data used is from 16:19:14 to 16:40:57 which is logged from the VT Rascal GCS located near the ScanEagle GCS.

From the Longitude vs. Latitude Plot, the VT Rascal was loitering in loops at the channel and returned back to the runway where it landed. This is illustrated in Figure 29.

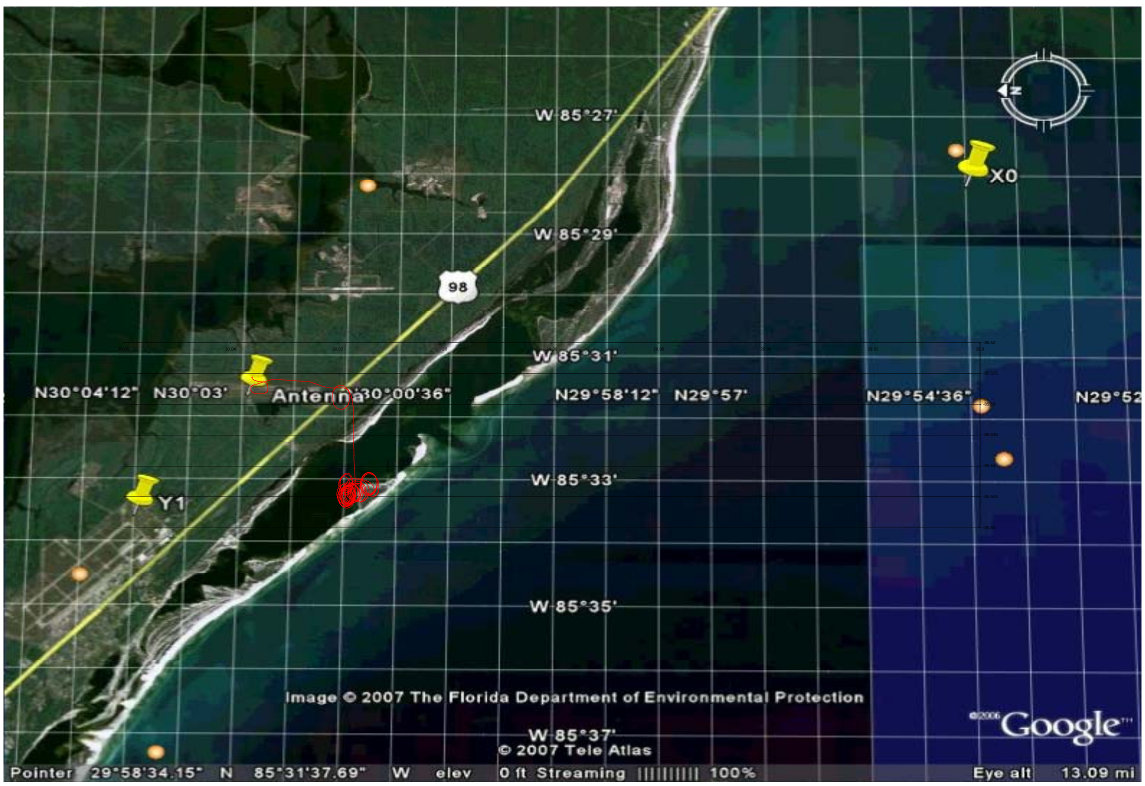

Figure 29 Plot of Longitude vs. Latitude of VT Rascal from time 16:17:14 - 16:40:54

From Figure 30, the range shows that the VT rascal has been moving in loops and landed back on the runway near the VT Rascal GCS. The signal level also shows that near the return flight, the signal level increases as the range decreases. The signal level did not fluctuate as much because the antenna on the VT Rascal may be located at a position which is not shielded by the body of the plane.

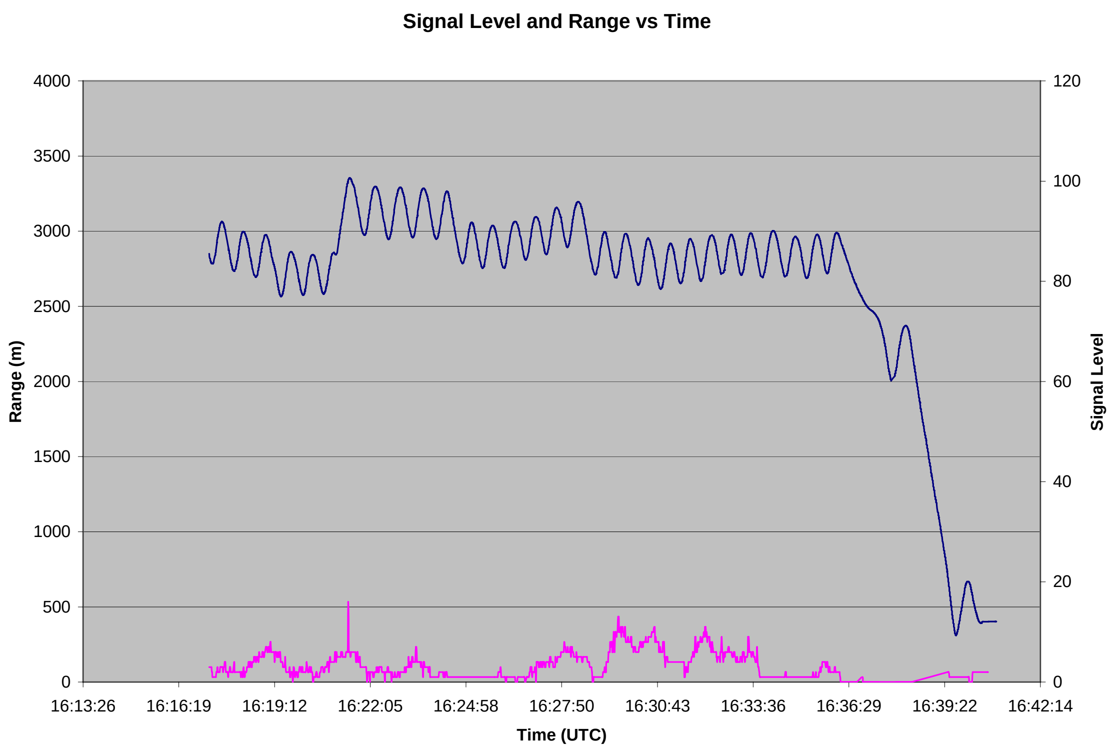

Figure 30 Plot of Signal Level and Range vs. time of VT Rascal from time 16:17:14 - 16:40:54

G. ROUTING TABLE

The following is the routing table for time 16:17:14 to 16:44:24. Figure 31 shows the Number of Hops vs. Time for NPS ScanEagle, SeaFox GCS and SeaFox. The figure shows that during the period of time, SeaFox experiences a high number of hops. There is no data for the ScanEagle except for the beginning of the experiment. For the SeaFox GCS, there is also no data except for the later part of the experiment.

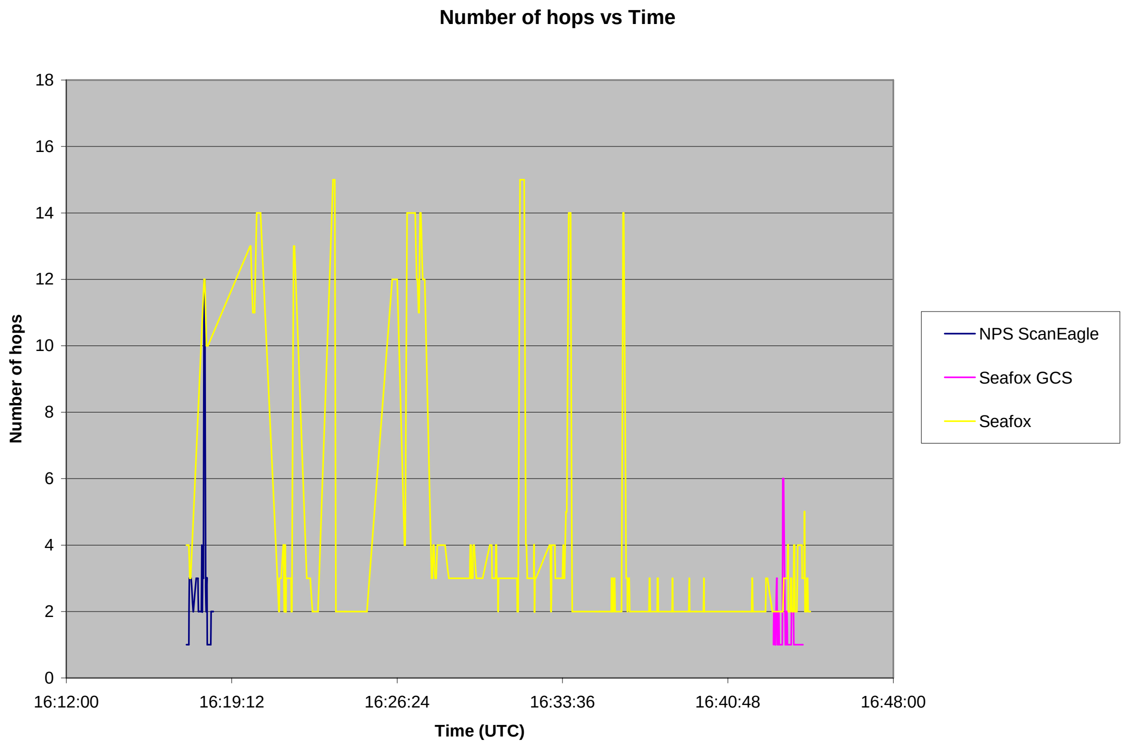

Figure 31 Number of Hops vs. Time

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

1. Modifications

In the modification of the ScanEagle, the components (i.e., ITT Mesh Card, Amplifier and TS 5700 SBC) used are mainly COTs. Therefore, it is less expensive to implement and easily replaced. The main advantage is that, as the technology of the components continues to mature; they can be upgraded with no significant increase in cost.

It is important to achieve high data rate between the ScanEagle and GCS. The high data rate permits more data to be transferred—thus, lesser or no losses in data. Since the data rate is directly proportional to the signal strength, a one-watt amplifier is required at the antenna end of the aircraft to boost or amplify the signal strength when transmitting or receiving, respectively.

The ITT Mesh card onboard the ScanEagle would allow seamless forming of network capabilities with other nodes. It will be able to recognize commands meant for the control of ScanEagle, or rebroadcast if the data is addressed to another node, and will also act as another station available for hop in the network. With this capability, it enables “bent pipe” communication that is Non Line of Sight (NLOS) between various nodes in the network.

The secondary controller, TS 5700 is the interface between the ITT Mesh card and API. The secondary controller is loaded on the CF card with the Linux TS-3.0 (with a scaled down System V initialization scheme), which renders the TS 5700 compatible with the ITT Mesh Card.

The high-gain antenna modification's main purpose is to deconflict the 802.11 wireless frequency protocol and video feed, which initially ride on the same 2.4 GHz bandwidth. The video feed after the modification is shifted to 2.3 GHz with a 15 μm filter to reduce noise in the signal.

2. Panama City Experiment

The ScanEagle results shows that range affects the signal strength. At increased range the signal strength reduces. Judging from the set 1 results, at 12000m the approximate signal strength is 5dB, while at about 4500m it is 15dB.

Besides the range, the roll angle of the aircraft displays signal strength fluctuations in the results of set 2, where the aircraft flight path is elliptical. One reason could be that the beam of the transmitted signal at the belly of the aircraft points away from the GCS location when the aircraft rolls away in the direction of the GCS. A second may be that the aircraft is shielded; thus, the beam side lobes block the signal transmission to the GCS.

The routing table shows that the number of hops from the ScanEagle increases inconsistently. The reason for this could be the positioning of the ScanEagle GCS. There is a tall metal truss structure between the GCS and ScanEagle during the period where the number of hops increased. The signal could have been reflected away by the structure, thus hopping through other vehicles or GCS.

There is insufficient data to understand signal strength of the SeaFox during the period of interest. During the period of interest, the travel path of the SeaFox was within the waterway between the land and the reef barrier.

The NPS Rascal shows similar characteristics to the ScanEagle, with the signal level increasing with increasing range. However, the VT Rascal did not show similar characteristics.

B. RECOMMENDATIONS

1. Modifications

The signal strength needs to achieve and maintain a maximum data rate. The current implementation of a one-watt amplifier will have a range limitation for a specific flight path. It would be important to identify the maximum range before the data rate starts to decay, and also if the data rate decays exponentially or linearly with respect to the range.

A study of the beam pattern of the transmitted signal from the ScanEagle would be useful for the design and location of the antenna on the aircraft. This is to minimize or eliminate transmission “blind spots.”

The effects of signal strength at different altitudes and with different weather conditions could be explored. This could be used to understand how clouds and different weather conditions affect the signal strength, if at all.

The current design for the antenna could be modified by adding another antenna fin on the top side of the aircraft so regardless how the aircraft rolls, the signal will not be blocked by the aircraft.

With increasing power requirements, the heat generated within the avionics section will increase. Additional design will be required for heat removal.

2. Experiments

In the Mesh Card data logging system, it is recommended to have all the logs include the time for all the hops from start to finish. There should be a common time standard used for all the data logged, for easier processing and comparison. This information can be used to identify where and why a signal hopped at a given time.

The location of the high-gain dish antenna for the ScanEagle should be considered as it may affect the transmission and receiving signal to the ScanEagle. It is recommended to be located where it is not obstructed by any nearby structures.

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