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SATELLITE TELEMETRY SYSTEMS:
A CASE STUDY OF TRACKING A MOVING OBJECT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Carey Ruth Roberts

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I would also like to thank God, my family, and friends because without their support, I probably would have bailed out long before finishing this thesis.

ABSTRACT

This paper presents an overview of satellite telemetry tracking systems including applications, and focuses on the tracking of a moving object. The study had two main divisions, the first was stationary testing and the second was motion testing, and involved the use of two different types of satellite transmitters. The purpose of both these divisions was threefold. The first goal was to demonstrate the capability of accurate location of a moving object using a commercially available satellite telemetry technique. The second goal was to compare and evaluate the performance of the solar powered and battery powered transmitters. The third was to demonstrate that an object in an unknown location could be located quickly and accurately. All of these goals were met through the use of two objects in the motion portion of the study, an automobile and an American Bald Eagle. The paper is not intended to be a thorough treatment of satellite telemetry tracking techniques, however, it is intended to be a solid introduction to this technique and show the technique's feasibility for use in tracking commercial shipments and vehicles, and endangered species.

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CHAPTER 1

INTRODUCTION

The use of satellite telemetry tracking is becoming more widely available and affordable. Its uses are many and varied. It provides an accurate method of remote object location. This study demonstrates some applications of this new technology. The study had three main goals. The first goal was to demonstrate the capability of accurate location of a moving object using a commercially available satellite telemetry technique. The second goal was to compare and evaluate the performance of the two transmitter types and models. The third was to demonstrate that an object in an unknown location could be located quickly and accurately. The thesis begins with an introduction to satellite telemetry systems including current uses and recent advances. It includes background on Geographical Information Systems (GIS) that can be used as data analysis tools. It contains the basis for satellite telemetry and the governing equations for Platform Transmitter Terminal (PTT) location, and outlines the specific satellite system (Argos) used in the study. It has the features of the design of both types of transmitters used, and contains a discussion of the signal processing utilized in both phases of the experiment. The main portion of the thesis details the project and presents the results. It then makes recommendations about the implementation of a "friendly" data collection and analysis system and presents the final conclusions about the project.

Definition of Satellite Telemetry Systems

A satellite telemetry system consists of many individual parts that operate together to solve problems. The purpose of these systems is the transmission of real-time data by radio link via digital communications (Gunston, 1988); or the purpose is "a measurement accomplished with the aid of intermediate means

which allows perception, recording or interpretation of data at a distance from a primary sensor" (Gentle and Reithmaier, 1974). These data can be pressure, velocity, angular surface position or any other instrument output (Gunston, 1988). In the case of a satellite telemetry system the measurements are made by the transmitter unit. The transmitter then sends its digitally encoded signal to the satellite at some preset frequency. The satellite then partially processes the data to determine the stability of the transmitter, then it sends its digitally encoded signal at a different frequency to the final distant receiver, called a ground station. The ground station's instruments then extract, interpret, and record the values of the data.

Current Uses of Satellite Telemetry Systems

There are currently many satellite telemetry systems in use worldwide, performing a wide variety of tracking functions. One system is LocStar. It is used over Europe to track the movements of both commercial and military vehicles. It has an accuracy of approximately 350 m distance from the actual location of the object. Some of the systems that perform tracking are not dedicated to telemetry. Argos, the system used in this study, performs meteorological functions in addition to tracking objects. Details on how this system works are provided in a later chapter.

Recent Advances in Satellite Telemetry Systems

Clearly the most exciting recent development in telemetry systems is the NAVSTAR Global Positioning System (GPS). NAVSTAR (NAVigation System with Time And Ranging) has been under development by the U. S. Government for the past several years. The program is administrated by the U. S. Air Force

Space Division and the launches of the satellites should be completed by 1990 (Hartl, Schoeller, and Thiel). The space segment of the system will eventually consist of eighteen satellites and three spares placed in six orbital planes at an altitude of 20,000 km above the earth. All these orbits will be inclined 55° to the equator (Mozgala, 1986). The satellites will have twelve-hour periods and four of these will always be in view at the same time at elevations of more than 20° above the horizon (Rakowsky, 1984).

Geographical Information Systems

In order to make the data useful, it is necessary to provide a means of storing, interpreting, and displaying the data. This can be accomplished through the use of a Geographical Information System (GIS). Much debate exists today about exactly what a GIS is and what its applications are. However, a good definition is a computerized database system that allows manipulation of spatial data which is usually in the form of statistical data or map data. The GIS allows for easy description, display and output of both spatial and associated non-spatial data. A particular GIS has been used in the course of this study to plot locations estimated by the transmitter and satellite versus the actual ground locations of the transmitters.

CHAPTER 2

BASIS FOR SATELLITE TELEMETRY SYSTEMS

In order to more completely understand the methods of calculating PTT location, it is necessary to understand the basis for positioning satellites in general. Therefore, a discussion of the types of orbits used in positioning satellites is presented including some of their advantages and disadvantages.

Positioning Satellite Orbits

There are typically two different types of orbits that positioning satellites are placed in. These are called geostationary and sunsynchronous orbits. Each has distinct advantages and disadvantages over the other. A geostationary, or synchronous, orbit is one where a satellite remains over the same point on the surface of the earth at all times. This is only absolutely true when the satellite's orbit is not inclined with respect to the equator. If it is inclined then its ground track is in the shape of a figure eight. A sunsynchronous orbit, on the other hand, is one in which the orbital plane rotates about the polar axis at the same speed as the earth about its axis. Typically this means that the satellite orbits the earth about 14 to 15 times a day and will pass over a user's PTT at the same local solar time each day (Argos User's Guide).

Geostationary Orbit

The geostationary orbit has the following advantages. It allows data to be sent much more quickly to a ground receiving station because the station is always "in sight" of the satellite. This reduces the cost and the size of the attitude control equipment. A satellite placed in this orbit generally has a slightly longer life span

than a low earth orbit (sunsynchronous) satellite because its higher altitude reduces its contact with the Earth's atmosphere and space debris.

This orbit also has some disadvantages. The first disadvantage is that more than one satellite is required to triangulate the data to provide a location. For example, in the NAVSTAR system mentioned earlier, it takes at least four satellites to calculate a user's actual location (Hartl, Schoeller, and Thiel). However, since these are less costly than the other type of satellite traveling in a sunsynchronous orbit, this disadvantage is not as great as some others. The major disadvantage of a geostationary orbit is that the required altitude is so high (46,200 km) that an additional stage must be added to the launch vehicle in order to place the satellite in its proper orbit. This increases the cost and complexity of the launch itself.

Sunsynchronous Orbit

A sunsynchronous orbit also has some distinct advantages and disadvantages. Among the advantages are a fairly low cost launch requiring a smaller rocket and lower signal transmission power requirements. These low earth orbit satellites can provide coverage of most of the surface of the earth rather than just one geographical area. One disadvantage to operating a positioning satellite in this orbit is the time gap between the time of data transmission and reception and recording at the satellite and the time of data reception, processing, and distribution at the ground receiving station. In a geostationary orbit the satellite can directly transmit its data to the ground receiving station. However, with a sunsynchronous orbit, the satellite can only receive data when a PTT is in view, and can only transmit its data when the receiving station is within view. This can lead to delays of up to seven days in the time between collection and distribution of data. This problem can be alleviated somewhat by having multiple ground receiving stations, but this increases costs tremendously.

PTT Location Methods

Now that the necessary background information has been presented, it is possible to discuss the actual methods used in the calculation of PTT location. The first method used is the Doppler Shift Effect on received frequencies, and the second is triangulation. The two techniques are very different and in some cases a combination of the two methods is used. In the case of the Doppler effect measurement, the user's PTT transmits a signal that is processed by the satellite. In the case of the triangulating Geodetic or Global Positioning System (GPS), the user's receiver does the work of locating the user by processing the satellites' signals. In other words, in a GPS system the satellites transmit a signal continuously. The user's receiver triangulates the position. This position can either be an actual location or a relative location. A relative position is a measurement of a location relative to some known location. A more complete explanation of both methods, including their governing equations follows.

The Doppler Shift

The use of the Doppler Shift Effect on received frequencies depends on a great many variables. First it must be assumed that all PTTs send known individual frequency signals. It is also necessary to know all the satellite orbital parameters and to precisely time-code all measurements. Once all these variables are known, it is possible to measure the Doppler effect. When the satellite receives the PTT's signal, it uses the received frequency to determine the possible locations for the PTT. The possible locations form a half-cone with the satellite at the apex and the satellite velocity vector as the axis of symmetry.

The apex half-angle (A) labeled as (A_1) or (A_2) in Figure 1 is such that:

$$\cos\ (A) = \frac{(fr - fe)}{fe} \cdot \frac{c}{V} \tag{1}$$

where:

c = speed of light

V = satellite speed relative to PTT

fe= transmission frequency

fr= received frequency.

For each measurement made, one cone is obtained. The altitude of the PTT forms the other necessary part of the location formula, the altitude sphere. The intersection of the cone with the sphere gives two possible locations of the PTT (see Figure 1).

Because of the geometry of the intersection between the location cone and the altitude sphere, the possible locations are symmetric with respect to the satellite ground track (see Figure 2). At this point a determination is made as to which of the two possible locations is most likely correct. This is done by examining previous locations, and estimating the velocities that the PTT may be experiencing (Shahrokhi and Luke, 1988).

Triangulation

The Doppler Method works very well and depends on one satellite for object location. However, when more than one satellite is placed in a geostationary orbit, the PTT location may be calculated using different methods. Triangulation is a method that measures the direction from a known location to an unknown location. In the case of a satellite telemetry system, the satellites furnish the known locations and the user's PTT provides the unknown location.

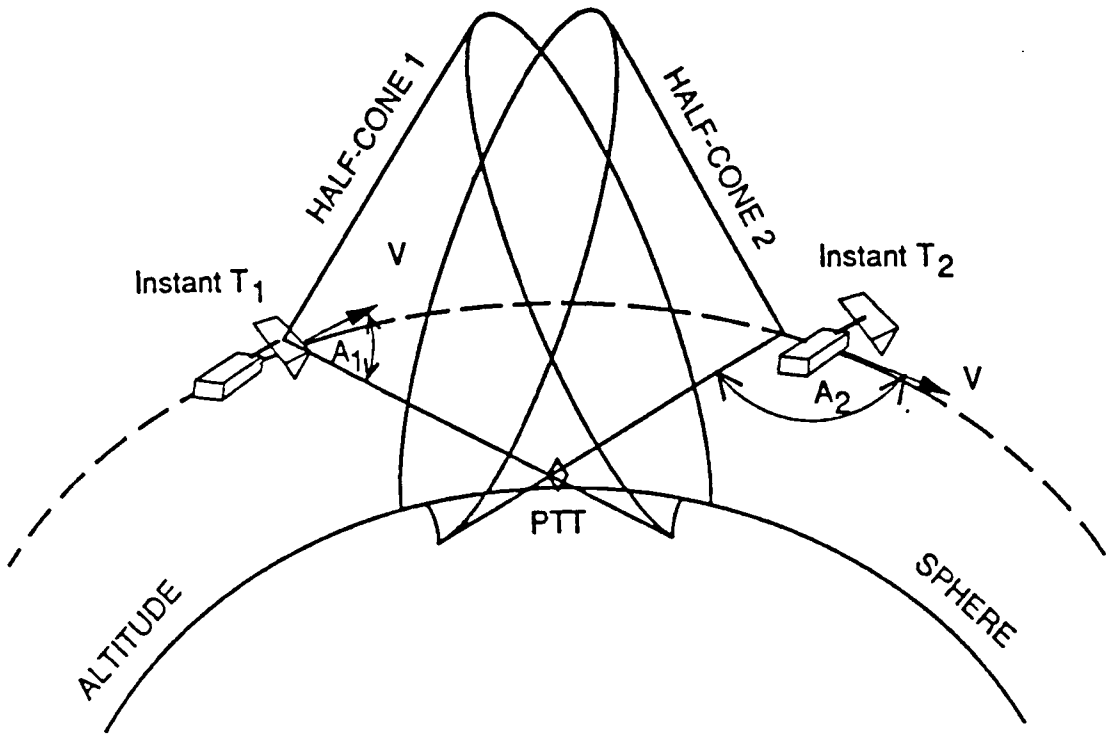


Figure 1. Location Calculations by the Doppler Method

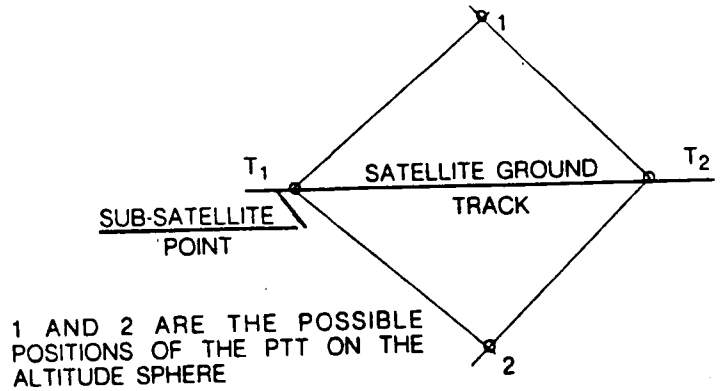


Figure 2. Geometry of Doppler Method Location Calculations

By taking the bearings from the satellites' signals to the receiver and finding their points of intersection, the receiver's processor determines the area or field of the user's location (Hoyt, 1988). For example, if four satellites are used to locate the user's position, the four equations would be the following:

$$R_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + T \cdot c \tag{2}$$

$$R_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + T \cdot c \tag{3}$$

$$R_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + T \cdot c \tag{4}$$

$$R_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + T \cdot c \tag{5}$$

where:

R_n = pseudo ranges or measurement values

x = unknown x coordinate of the user

y = unknown y coordinate of the user

z = unknown z coordinate of the user

$T \cdot c$ = clock bias

x_n, y_n, z_n = nominal corrective values.

By comparing the nominal values to the unknowns it is possible to linearize these non-linear equations. Once this has been done, it is possible to use numerical methods to solve the equations (Hartl, Schoeller, and Thiel). For a complete discussion of the pseudo range method, the reader is referred to the above reference.

CHAPTER 3

THE ARGOS SYSTEM

The Argos satellite system is a joint National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and Centre National d'Etudes Spatiales (CNES) venture whose main function is providing meteorological information. However, the secondary objective of the system is to provide satellite-based location of both fixed and moving PTTs as well as the collection of environmental data. The Argos system has four segments. The first is the platforms which can be in the form of buoys, boats, animals, or any object which can have the PTT attached to it for data collection and uplinking. The second is the space segment that is composed of the NOAA/TIROS-N satellite and its onboard equipment. The third segment is the ground telemetry receiving and processing system that is headquartered at Service Argos, Toulouse, France and the fourth segment is the results distribution system (Argos User's Guide).

Argos Satellite Design

The space segment of the Argos system consists of two NOAA satellites in simultaneous low altitude orbit. Each satellite is equipped with the Argos Data Collection and Location System (DCLS) which receives and processes the transmissions from the visible PTTs during a pass. This information is then downlinked to the ground segment when the satellite passes one of the three ground telemetry stations in the system. The DCLS will be discussed later in this chapter.

The satellites that carry the DCLS are NOAA's polar orbiting TIROS-N series. The first in this series was launched in 1978. The operations of the satellites are managed by NOAA's National Environmental Satellite and Data Information Service (NESDIS). The series began as an R&D prototype and then became

designated by a letter. After successful launch, the letters were changed so that NOAA-A became NOAA-6, NOAA-C became NOAA-7 and so on. The present launch series is called ATN (Advanced TIROS-N) and is an extension of the original series. The first of the new series (NOAA-E / NOAA-8) was launched in 1983. An exploded view (Figure 3) shows the main components of the satellite.

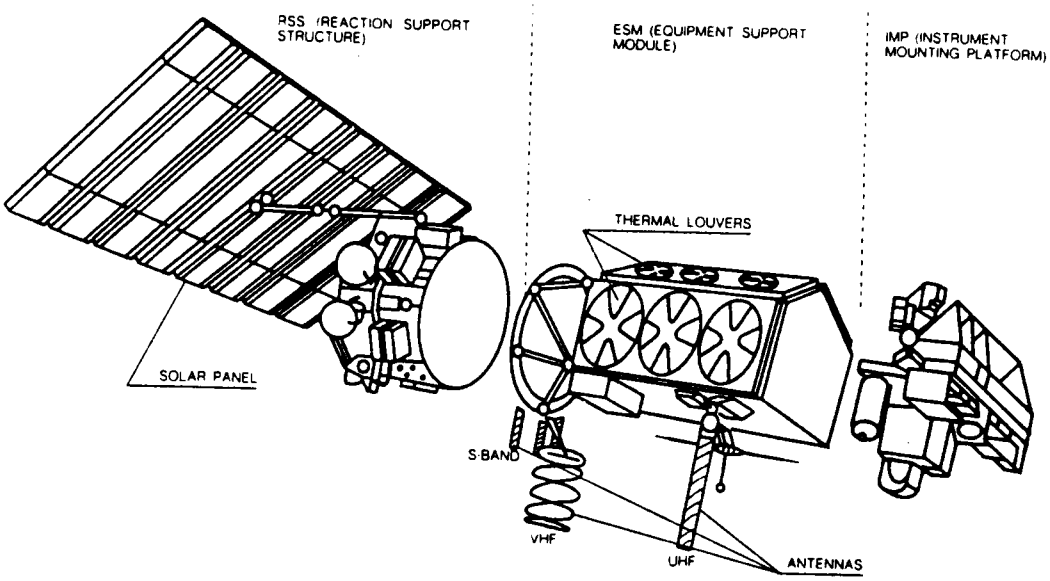


Figure 3. Exploded View of ATN Satellite

The Equipment Support Module (ESM) is a box-like, five-sided structure that carries the DCLS and other earth pointing antennas. The antennas are located on the largest side while the other four sides contain thermal louvers that help maintain proper equipment temperature during orbit. The next section, the Reaction Support Structure (RSS), is at one end of the ESM. This section contains the final stage orbit injection motor, attitude control and propulsion system and the solar array. The array itself is boom-mounted and is 11.6 m^2 in area. It is equipped with a separate motor that allows it to track the sun by rotating once per orbit so that it is always facing the sun. The third section is the Instrument Mounting Platform (IMP) and is located at the other end of the ESM. This highly stable platform contains the attitude control sensors and the main earth observation instruments. It also contains the Attitude Determination and Control Subsystem (ADACS) that is responsible for antenna pointing and attitude control to within 0.2^o of geographic references (Argos User's Guide).

Orbital Parameters

The satellites travel in a circular, low earth, near polar, sunsynchronous orbit. The altitude of satellite 1 is 830 km $\pm$ 18 km and the altitude of satellite 2 is 870 km $\pm$ 18 km. Near polar orbit indicates that each satellite sees the North and South Poles once during each orbit. Both satellites' orbital plane is inclined 98.7^o with respect to the equatorial plane. Each orbit then transects the equatorial plane at certain fixed local solar times. In other words, the user's PTT comes into satellite view at the same local solar time each day. It takes approximately 101 minutes to complete each orbit, and each satellite orbits the earth 14 times daily. This choice of orbit ensures complete coverage of the earth's surface. The orbital planes of each satellite are offset 75^o from one another and the altitudes are slightly

different to guarantee that the period of one satellite is one minute longer than the period of the other.

Another important consequence of the choice of orbit is the visibility zones available for data collection. Each satellite sees all PTTs within a 5000 km diameter circle at a minimum elevation angle of 5°. The elevation angle is defined as the angle between the horizon and the satellite-PTT line of sight. The circle is centered on the satellites' ground track and sweeps a 5000 km path along the surface of the earth (see Figures 4 and 5). Due to the earth's rotation underneath the satellites, each ground path is 25° longitude west of the previous one. At the equator this means an overlap of 2800 km (see Figure 6). The ground tracks of two successive orbits do cross each other at a latitude of 82°. This sidelap increases with latitude and the number of passes that a PTT is seen also depends on the latitude. At and near the poles every PTT is seen on every pass by both satellites, that is 28 times each day. Pass duration is not dependent on latitude and the mean duration of each pass over a stationary PTT is 10 minutes while the zenith pass time is 13 minutes. Table 1 shows important total pass characteristics for both satellites (Argos User's Guide).

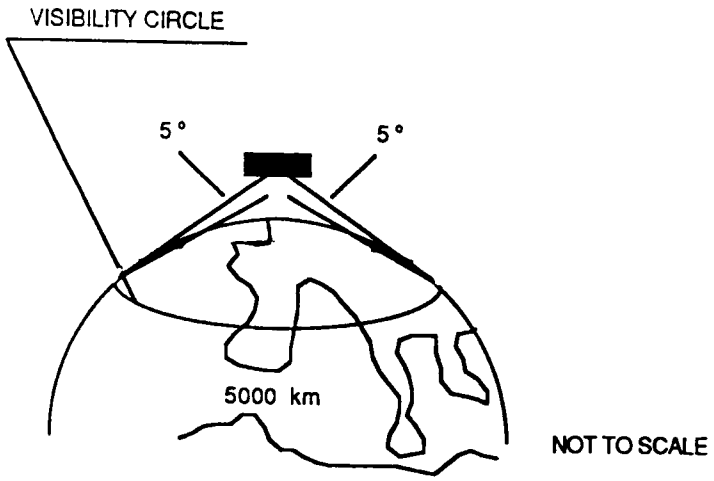


Figure 4. 5000 km Visibility Circle of Satellite at 5° Elevation

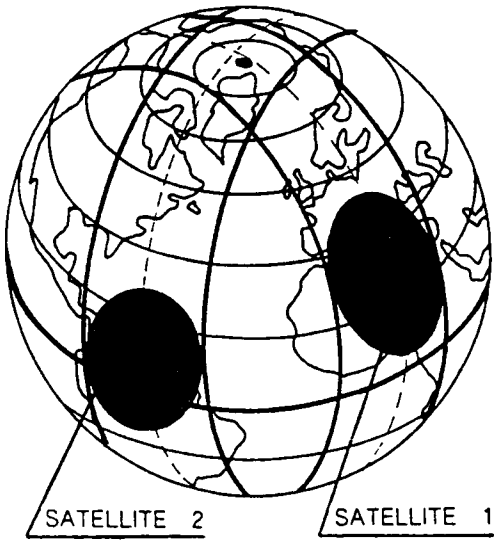


Figure 5. 5000 km Satellite Visibility Zones of Both Satellites

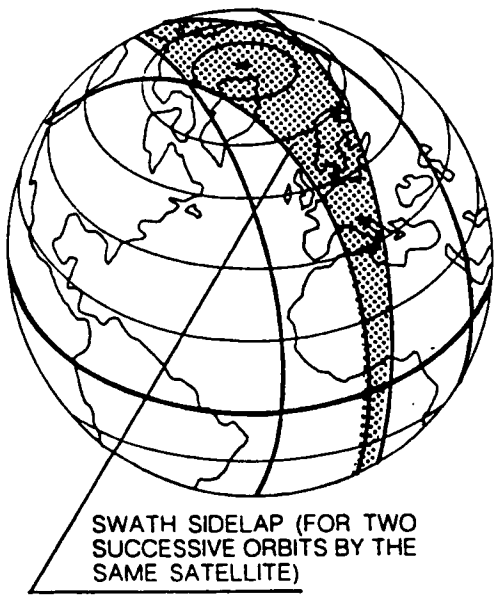


Figure 6. Satellite Swath Overlaps for Two Successive Orbits

Table 1. Pass Frequency and Duration of Visibility

PTT LATITUDE	CUMULATIVE VISIBILITY OVER 24 HOURS minutes	MINIMUM NUMBER OF PASSES PER 24 HOURS	MEAN NUMBER OF PASSES PER 24 HOURS	MAXIMUM NUMBER OF PASSES PER 24 HOURS
0°	80	6	7	8
± 15°	88	8	8	9
± ± 30°	100	8	9	12
± ± 45°	128	10	11	12
± ± 55°	170	16	16	18
± ± 65°	246	21	22	23
± ± 75°	322	28	28	28
± 90°	384	28	28	28

Source: Argos User's Guide

Argos Data Collection and Location System

The DCLS receives the messages from all PTTs within the satellites' visibility zones. The receive process is random and not selective, and the received signal is a mixture of all the messages transmitted by all the PTTs. The DCLS attempts to handle the maximum number of messages, but the number of channels available is limited. Message separation is carried out through asynchronization of transmission and the use of varied repetition periods. It also utilizes the separation of frequencies through the Doppler Shifts of the different carrier frequencies.

The Argos DCLS is composed of two sections (See Figure 7). The first unit, the receiver section, is a receiver and a search unit both of which are duplicated to guarantee redundancy. The second unit contains the processing equipment, and is made up of four identical units in parallel, each processing one message at a time, a control unit, a telemetry encoder, and a buffer memory.

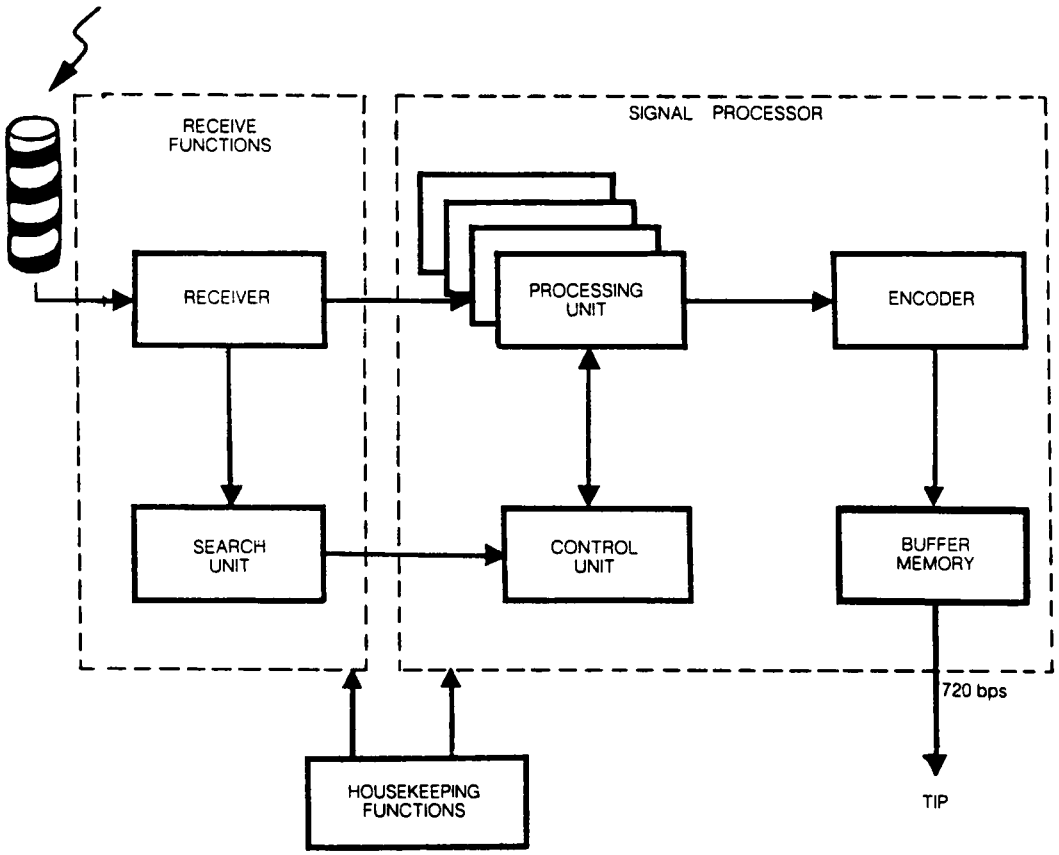


Figure 7. Schematic of Argos DCLS

Each processing unit contains a phase lock loop for rapid frequency and phase synchronization on the unmodulated portion of the PTT message and a bit synchronizer that generates a clock signal at the correct bit rate for signal restitution. In addition to these, the unit contains a Doppler Counter for determination of receive frequency and an encoder-formatter which generates the telemetry messages to be downlinked. These messages are in the following digital format: PTT ID number, sensor data, measured frequency, and time and date of measurement. Once this is complete, the signal is sent to the Tiros Information Processor (TIP). The data from the PTT's signal is downlinked at a rate of 720 bps (bits per second). The entire TIP processor and signal rate is 8320 bps, which includes the Argos information and data from other low-data-rate experiments that are run on board the satellite. The on board DCLS comprises the major portion of the Argos data flow but not all of it. Figure 8 shows a complete schematic of the Argos data flow.

Location Calculations and Accuracy of Results

The calculation of locations and the accuracies of these calculations in the Argos system are important, especially to the end user. As mentioned earlier, the Argos system uses a combination of the triangulation and Doppler Shift techniques to determine PTT location. The Argos system uses a different triangulation method than the one described before. The system performs certain geometric tests on a PTT's signal before it attempts to measure the Doppler Shift effect. This helps to eliminate PTTs for which an acceptable accuracy cannot be guaranteed.

On the average, 33 percent of all PTTs visible during a pass are determined to be unacceptable. The reasons for non location or rejection after location are quite varied. The first cause for rejection is an excessive deviation in frequency, where the deviation is greater than 24 Hz between the average transmission frequencies

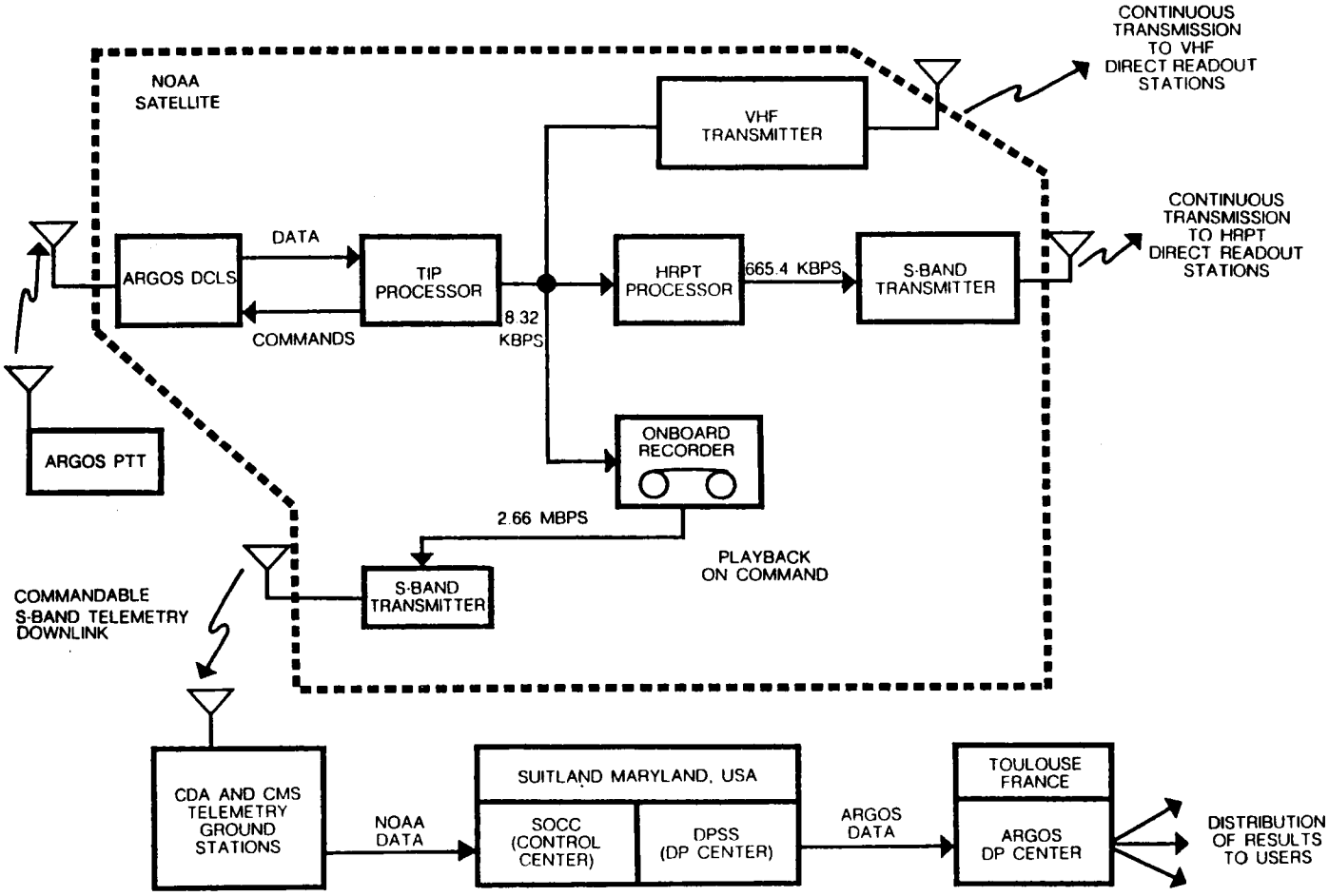


Figure 8. Argos Data Flow Diagram

in two passes by the same PTT. The second cause for rejection is unsatisfactory convergence caused in most cases by a "noisy" or slightly unstable PTT oscillator. The value for rejection during a pass is 4 x 10^{-5} percent instability. The third major cause for rejection is an unacceptable distance from the ground track of the satellite. Figure 9 shows the acceptable PTT location zones on the earth's surface.

The accuracies of the locations are related to two different sources of errors. The first error source is related to problems with the satellite orbit and time coding of measurements. The second and more common error source is related to the PTT itself. The main factors involved in this are PTT altitude, oscillator stability, and PTT movement. The first factor, the error because of PTT altitude, only comes into play when balloon PTTs are involved. The third factor, PTT movement, is significant because the PTT is considered to be stationary at the moment of transmission. If the PTT is actually moving, errors can result. For example, an Argos PTT transmitting at 401.65 MHz moving at 1 m/s can cause an error of up to 300 m. By far the most significant factor in location accuracy is oscillator stability. There are three classes of stability, short term, medium term, and long term. Short term is defined as up to 100 milliseconds and leads to inaccuracies in the Doppler effect calculations and causes random error locations by changing the message transmission duration. Medium term instability is defined as up to 20 minutes and relates to duration of PTT visibility and leads to frequency drift and inaccurate locations. It has the most effect on location error and Table 2 shows the relationship between medium term oscillator stability and location accuracy. Long term instability is defined as the period separating two satellite passes over the PTT which is about 100 minutes. This type of instability is compensated for in the location calculations if it does not exceed 1 x 10^{-6} percent (Argos User's Guide).

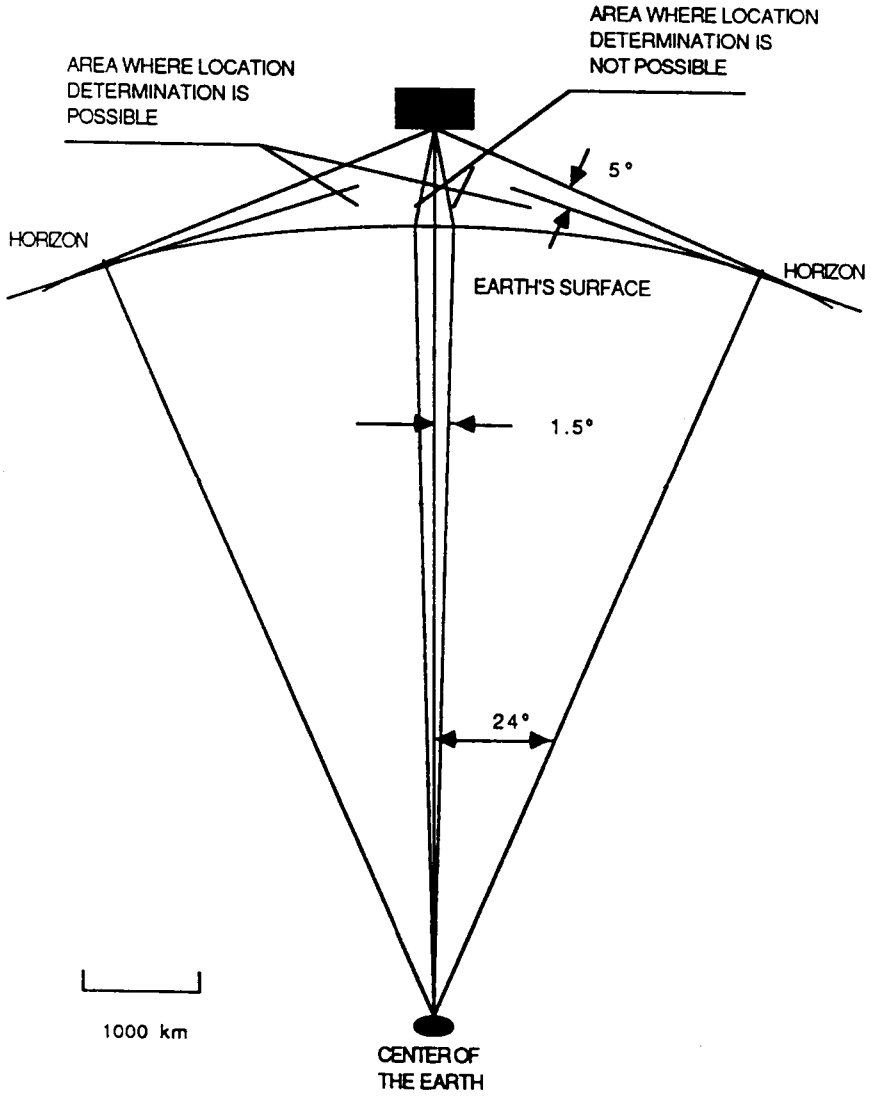


Figure 9. Location Zones Where Satellite Can Locate PTT

Table 2. Oscillator Stability and Location Accuracies

MEDIUM TERM STABILITY	ACCURACY IN METERS	
%	in 65 % of cases	in approx. 95% of cases
$2.\ 10^{-9}$	150	500
$5.\ 10^{-9}$	500	1300
10^{-8}	1100	2000
$2.\ 10^{-8}$	2100	3600
$5.\ 10^{-8}$	4000	6000
10^{-7}	5500	9000
$2.\ 10^{-7}$	approx. 50 km	
$> 2.\ 10^{-7}$	calculation aborts	

CHAPTER 4

SATELLITE TRANSMITTERS

Another important part of the entire satellite location system is the transmitter. It does not matter whether the transmitter is in the satellite as in a GPS or on the object as in a telemetry satellite system, like the one used in this study.

General Design of Transmitters

All transmitters have several main components, regardless of whether they transmit to a satellite or to some other receiver. These basic components are the sensors, the transmitter circuit, the antenna, and the power supply. The housing is also important and its selection is very dependent on the application planned. For the tracking of large objects such as trucks or railroad cars, the design of the housing is not critical. It is sufficient to contain it in a tubular case that gives easy access to the internal components. It should also be able to withstand fairly minor shocks without damage. Most of these types of housings are made of coated aluminum or of high impact plastic. If the transmitter is being considered for use in animal studies, the housing design becomes critical. Most of the housings used in animal studies are rectangular and fairly flat. They are made of lightweight impact and shock resistant plastics. They are also basically weatherproof and must be able to withstand a great deal of punishment. For instance, PTTs have been attached to whales in order to track their movements. In this case the transmitter had to be able to survive the tremendous fluctuations in pressure when the whale dived for food.

The first component is the transmitter circuit, and a generalized block diagram of a transmitter layout adapted from the operational manual of one of the transmitters used in the study (Figure 10) shows the major components and their

innerconnectivity. The CPU is responsible for controlling the flow of sensor data, and with the clock oscillator and timer switch, it also controls the sleep-wake cycle of the transmitter. A detailed diagram of the transmitter circuit is found in the Toyocom T-2028 Manual. The CPU along with the other internal components are responsible for sending the correct signal to the satellite. This signal includes the appropriate ID code, keying, and modulation information necessary for PTT location.

The second major component is the antenna. The choice of antenna type and size depends almost completely on the particular application of the transmitter. Most satellite transmitters, including the two used in this study, utilize a line antenna that is approximately one quarter of a wavelength long. This reduces the cost of the manufacture and the replacement of the antenna because of their simple shape. Also line antennae exhibit very stable transmission characteristics and are reasonably free from excessive frequency deviation. Another advantage to line antennae is that they can be made of many different materials including flexible cable. This helps to reduce the damage to the antenna during use.

The final major transmitter component is the power supply. Although the choice of power supplies varies with the application, the two major supplies currently in use are battery power and solar power. Battery powered transmitters are generally used in applications where the PTTs are readily accessible. For example, in the tracking of automobiles, trucks, or railroad cars, a battery operated transmitter would be more practical than a solar powered unit. This is because the battery powered transmitter could be placed in total darkness without affecting its transmissions. This is not true for the solar transmitter.

The best uses for the solar transmitters are in situations where it is either impossible or impractical to change the batteries. This makes them ideal for tracking

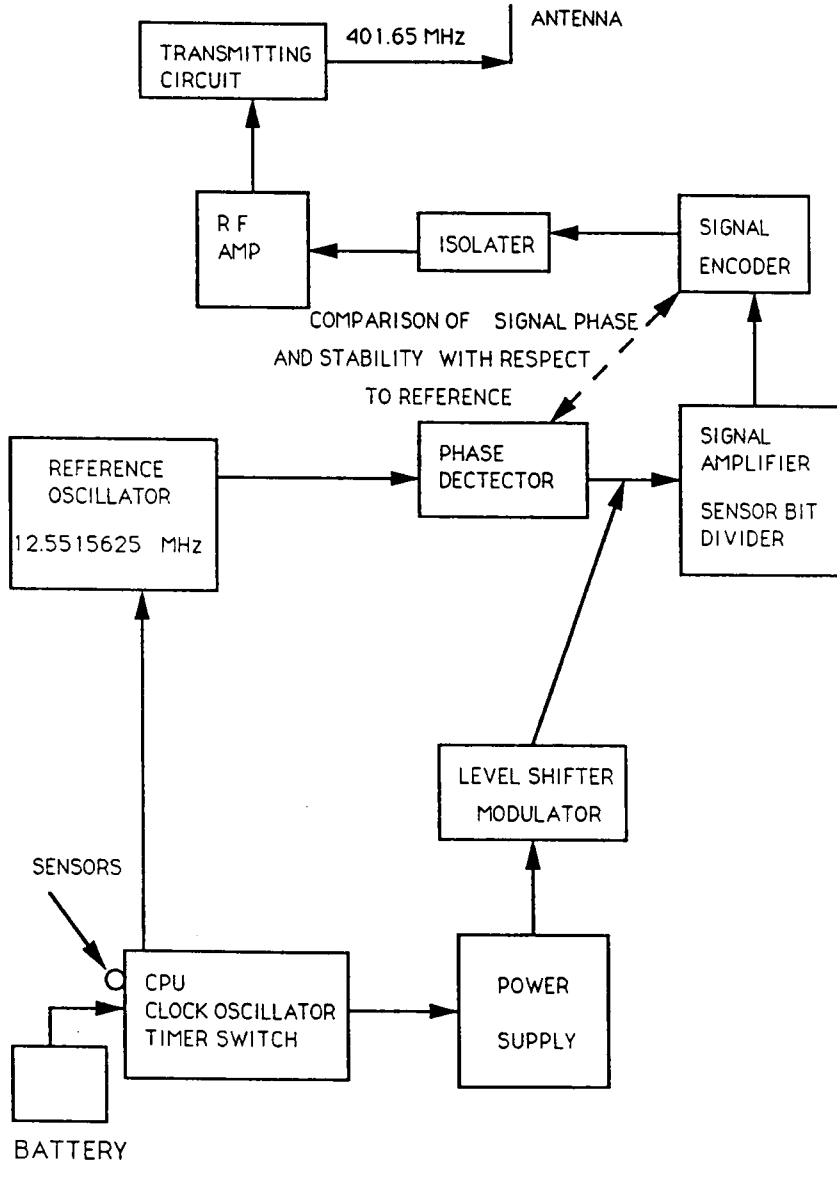


Figure 10. Generalized Block Diagram of Transmitter

all kinds of migratory wildlife, where the main concern is minimizing human contact with the animals. Constant recapture to change batteries in the transmitter would alter the animal's behavior so that the animal would be useless in helping researchers learn of its natural habits.

The kinds of data transmitted from the units depend on the application planned for the unit. In the Argos system there are two main choices in data sent. The first is a location only signal. This reduces the complexity of the transmitter and provides only a location by sending a unmodulated signal to the satellite that carries no information. If the only value needed is an object's location, the PTT-satellite receiver is the most economical system available.

However, if it is necessary to know more about the object than just where it is, then the transmitter must have additional sensors within it to measure quantities. These other measured quantities can include temperature, both ambient and body; atmospheric pressure; activity counts for measuring object mobility and activity counters to measure the number of times the transmitter has been active over a certain period of time. The transmitter activity counters are helpful in determining if a transmitter is operating correctly without retrieving the transmitter.

Transmitting Frequencies

The frequency at which the transmitters send their signals is unique to each individual transmitter-receiver system. In the Argos system, the nominal frequency used is 401.65 MHz $\pm$.0012 MHz. This insures that the signal has the proper wavelength to escape the atmosphere and reach the receiver. In addition to this, the power requirements of the transmitter are less with the higher frequency given identical atmospheric conditions. PTT transmission powers vary between 0.25 W and 1.0 W.

The signals transmitted by each of the transmitters used in this study had information digitally encoded in the location signal. This process of sending the encoded message to the satellite receiver is called the uplink. Every transmitter used in this study followed the Argos standard message format. Table 3 shows this format. The message consists of the following parts in this sequence:

- 160 milliseconds of unmodulated carrier, to allow the Argos onboard receiver to lock onto the carrier;
- a 15-bit preamble to synchronize the Argos onboard equipment with the message bit rate;
- an 8-bit format synchronization word, followed by one spare bit and 4 bits defining sensor data length (the number of 32-bit blocks);
- the PTT identification (or ID) number, assigned by Service Argos and encoded by 14 bits;
- 6 error check bits;
- 32 to 256 bits of sensor data, in steps of 32; if sensor data processing is to be performed by Service Argos, encoding and format must comply with certain rules laid down in §5.3 of the Argos User's Manual.

The first five of the above items (unmodulated carrier through error check) provide the actual signal that is necessary to calculate the PTT's location. The sensor data transmission is optional. The transmitters used in the study sent identical information sequences composed of the unmodulated carrier, the 15-bit preamble, the 8-bit format synchronization word, their PTT ID code, 6 error check bits and one 32 bit block of sensor data. The sensor data was set up so that the

Table 3. PTT Message Structure and Format

UNMODULATED CARRIER LENGTH T1	MODULATED CARRIER . LENGTH T2					
	PREAMBLE	FORMAT SYNC.	INITIALIZATION	NUMBER OF 32-BIT GROUPS	ID N° (+ Check bits)	SENSOR DATA
T1 = 160 ms ± 2.5 ms	15 bits (= 1)	8 bits (00010111)	1 bit (= 1)	4 bits	20 bits	N x 32 bits (1 < N < 8)

first 16 bits were a measurement of the ambient temperature that the PTT was experiencing, the next six bits were a transmitter activity counter over the last 60 seconds and the last ten bits were a transmitter activity counter showing activity over the last 24 hours.

Specifications of Transmitters Used

The transmitters used in this study were of two different types. The first is a battery powered unit built by the Tokyo Communications Company, Ltd. (Toyocom) in Tokyo, Japan. The second unit, solar powered, is manufactured by Telonics, Inc. of Mesa, Arizona. These transmitters have several characteristics in common mainly due to their certification as Argos transmitters. They both transmit at a nominal frequency of 401.65 MHz and operate over a wide temperature range. The Toyocom transmitter model T-2028 is cylindrical in shape with a 35 mm diameter and a 160 mm length vinyl housing. It has a line antenna that is 155 mm in length. Table 4 shows a breakdown of the major specifications of this transmitter. The other transmitter used in the study was the Telonics model ST6-B. It is a solar powered unit that is rectangular and has the solar cells mounted on the

top of the vinyl housing, and also has a line antenna. It utilizes a battery backup system to allow transmission of signals when there is insufficient light available. This transmitter was designed for use in the wildlife telemetry portion of this experiment. It is a modification of their ST6 solar transmitter used to track large wildlife. Table 5 shows the specifications for the ST6-B. Although the prices of these kinds of transmitters are falling rapidly, the cost of the T-2028 is still around $2900 in U. S. currency, and the cost for the special building of ST6-B is $3500.

Table 4. Toyocom T-2028 Specifications

Dimensions	
Vinyl Housing	Max. 35 mm (diameter) x 160 mm (length)
Aluminum Housing	Max. 35 mm (diameter) x 170 mm (length)
Antenna	Max. 155 mm
Total Weight	240 g
Operating Temperature	-20^{o} C $+50^{o}$ C
Storage Temperature	-40^{o} C $+60^{o}$ C
Relative Humidity	95 % at 35^{o}
Vibration Proof	1-25 Hz, amplitude 2 mm
Shock Proof	11 ms, 30 g
Current Consumption	
Standby	Max. 1.5 mA
Transmission	Max. 250 mA
Operating Voltage	DC 7 V - 12 V
Transmitter	
Carrier Frequency	401.65 MHz
Modulation Mode	PCM - PSK
RF Output Power	.5 W
Duration of Each Transmission	360 ms
Spurious and Harmonic Emission	- 43 dB
Battery	
Battery Type	Lithium Battery
Number of Cells	3
Battery Voltage	10.8 V
Capacity	2.0 AH
Life Time	227 days at 25 % wake & 75 % sleep
Control Timer	Set for 25 % wake & 75 % sleep time cycle

Source: Toyocom T-2028 Operational Manual

Table 5. Telonics ST6-B Specifications

Dimensions	
Measurements	11.94 cm L x 4.95 cm W x 2.67 cm H
Weight	
PTT plus 11.43 cm flexible antenna	138.2 g
Current Drain	167 mA
Operating Temperature Range	-20° C $+50^{\circ}$ C
Repetition Rate	60 s
Power Output	.25 W
Carrier Frequency	401.65 MHz
Power Source	Solar Cells with Lithium Battery Backup
Contains an activity switch to measure temperature	
Housing	Plastic

Source: Telonics ST6-B Manual

CHAPTER 5

SIGNAL PROCESSING

Once the signal has left the PTT antenna and reached the satellite receiver, the signal must be processed for use. In satellite systems there are two major divisions of processing tasks that are performed. The first is uplink processing and the second is downlink processing. Uplink processing operates on the raw signal sent from the PTT and downlink processing operates on the satellite transmitter's signal to prepare and transmit it to the ground station. Before discussing the particulars of the uplink and downlink process used in the study, it is necessary to discuss the paths that the signals from the PTT and satellite travel. Figure 11 shows the transmission links from the Argos system. The PTT sends its signal to the NOAA satellite which preprocesses it, modulates its frequency and then sends it to one of ground stations. The other satellites in the figure are communication satellites that help transfer the results to users.

Uplink Processing

The processing of the uplink signal received from the PTT is an important phase in the signal processing loop. The satellite is constantly receiving a jumbled mixture of signals from all PTTs that are within its sight. Contained in this mixture are all the ID codes of the transmitters and their sensor data. In order to separate this mixture into a form suitable for further use, it is necessary to perform several processes on the data mixture. The steps in this process are to multiplex the signal, then amplify the signal, modulate it and send it to the downlink transmitter. Each signal is separated according to frequency, then sent to the multiplexer.

The multiplexer's job is to combine the information from many different and independent sources into a single common communications channel.

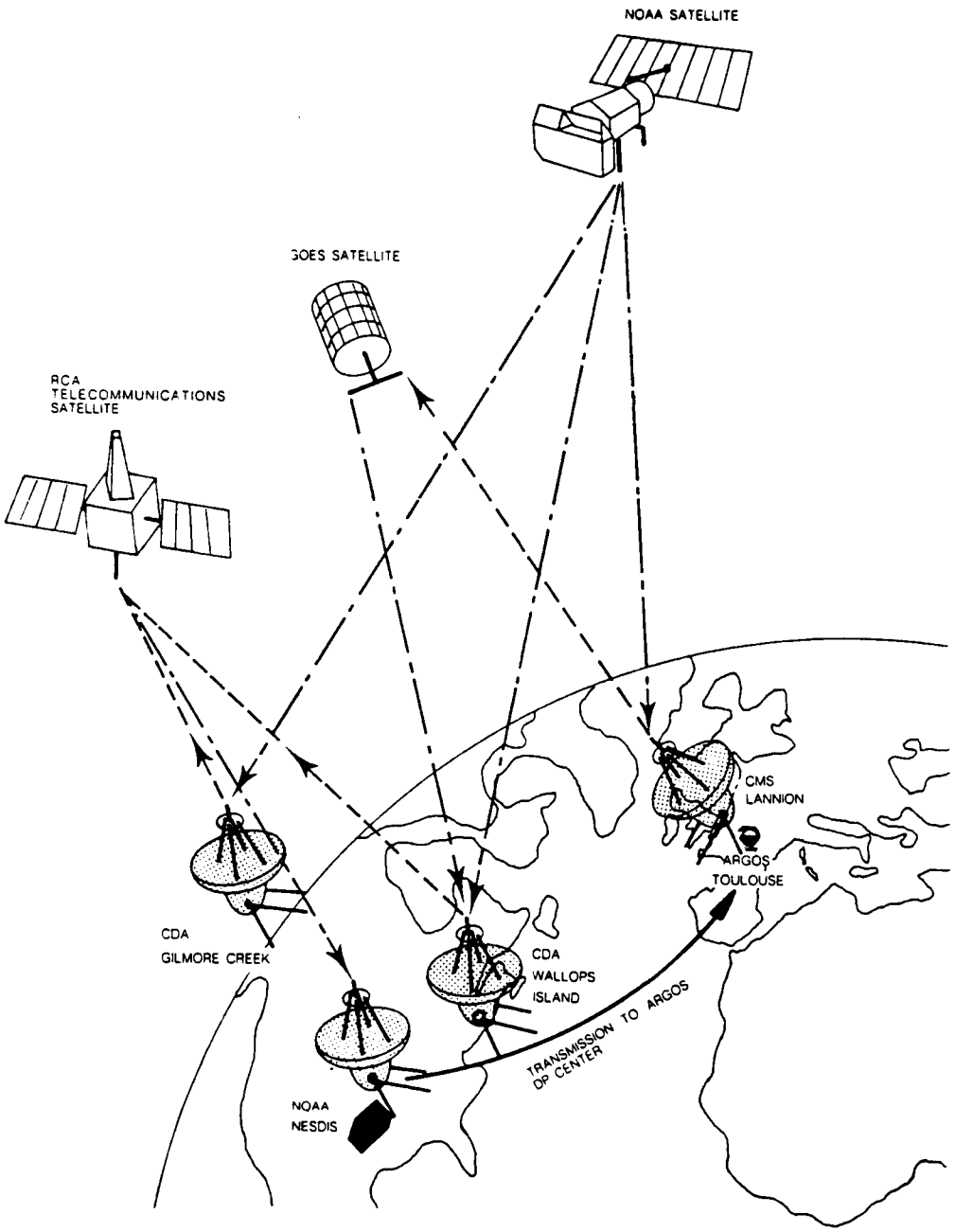


Figure 11. Telemetry Transmission System Showing Signal Flow

The multiplexing of the signals can be performed by either time division or frequency division. Frequency division multiplexing uses voltage controlled subcarrier oscillators. These oscillators' frequency varies as the signal voltage varies. These frequencies are then amplified and combined into a complex waveshape that contains all the information from all subcarrier oscillators. Time division multiplexing involves transmitting signal information as a series of pulses. The signals received at the satellite are sent to a commutator that samples each channel sequentially several times each second. Each input channel has a time slot assigned to it that is sufficiently short to allow all channels to be sampled in a very small amount of time. All of the samples collected form a time sequential pulse train that has the spectrum of the full bandwidth of the channel. The commutators used in this process are either mechanical or electrical. Mechanical commutators are used when low sampling rates are needed. For higher sampling rates, the electrical commutators are used.

Once the signals have been multiplexed, they are sent to the amplifier. This signal amplification allows the sensor information and ID codes to be extracted more easily. The modulator then takes the signal and alters its frequency to the proper downlink frequency. Once the signal has been changed to the proper form, it is downlinked from the satellite's transmitter to a ground station.

Downlink Processing

When the signal reaches the ground receiving station, the first step performed is the demodulation of the carrier. This demodulation extracts the original signal from the carrier and restores it to its pre-modulated form. This can be accomplished by a number of different methods. The three basic methods of modulation are amplitude, frequency, and phase modulation. Amplitude modulation uses the amplitude of the carrier to send the signal. If a sine wave is used as the carrier, the

modulated carrier's amplitude varies continuously to follow the modulating sine signal. In frequency modulation, the frequency of the carrier is varied over a small range using the modulating signal's amplitude as a function. In the case of phase modulation, the phase of the carrier is varied to correspond to variations in the amplitude of the modulation signal. In order to properly demodulate the carrier, an exact duplicate of the original signal is required. There are four different ways to accomplish this. The first is to generate a reference frequency with a high precision oscillator. The second is to derive the carrier from the modulated carrier, in other words pull out the sine wave. The third way is to simply transmit an unmodulated carrier along with the modulated carrier. The fourth is to interrupt the signal at certain intervals to transmit the unmodulated carrier.

The choice of demodulation technique depends on the type of signal being transmitted. If the signal is analog, like music and voice, all the important traits of the signal, amplitude, frequency, and phase of the carrier vary continuously. If however, the modulating signal is binary, it will have only two levels. This is known as digital modulation and in this kind of modulation, amplitude modulation is called amplitude-shift keying (ASK), frequency modulation is frequency-shift keying (FSK) and phase modulation is phase-shift keying (PSK). The signals transmitted by the Argos satellite are binary, and it uses PSK modulation (Montgomery, 1989).

Data Collection

Now that the carrier signal has been processed and the original signal separated, it is time to collect the data sent by the DCLS. The Argos center first records all the data from the signals before it begins the separation process. It processes in real time and performs these operations in this order. First it manages the data flows, then separates the auxiliary data from the PTT data, next it processes the

auxiliary data under control of the DCLS parameters. It then sorts the messages according to PTT, processes the sensor data, performs location calculations, and creates and updates the proper results file. Figures 12 and 13 show the setup of the Argos data processing center and the sensor processing operations. The data is then collected and written to update the appropriate files for each user program and PTT. In addition to this, Argos also provides a way for users to have real time access to their results through the use of direct readout stations. These stations, also known as local user terminals (LUTs), receive either the VHF or S-band signals as they are transmitted from the satellite. One of these stations can receive satellite transmissions when the ground track is 2500 km from it. Figure 14 shows the relationship between the station and the satellite. The station will receive PTT transmissions while both it and the PTT are within view of the satellite. This means that the PTT and station visibility circles must overlap. Figure 15 shows this overlap and Figure 16 shows the efficiency factor of the station. This factor is simply the ratio of S/S1 where S is the overlap in Figure 15 and S1 is the area of the PTT visibility circle (Argos User's Guide).

Data Distribution

The distribution of results to users in the system is the weakest link in the whole chain. Without use of a direct readout station it can take up to seven days to receive information about a PTT location. The reason for this delay is because of the lag in process time between the downlink of the signal to the writing and updating of the results files. Argos provides three different results files containing different information about the PTT. The first is the AJOUR file that contains the most recent location and sensor data. The second is the TELEX file that has one sensor message and corresponding location per satellite pass for the PTT arranged in chronological order. The third file is the DISPOSE file that contains

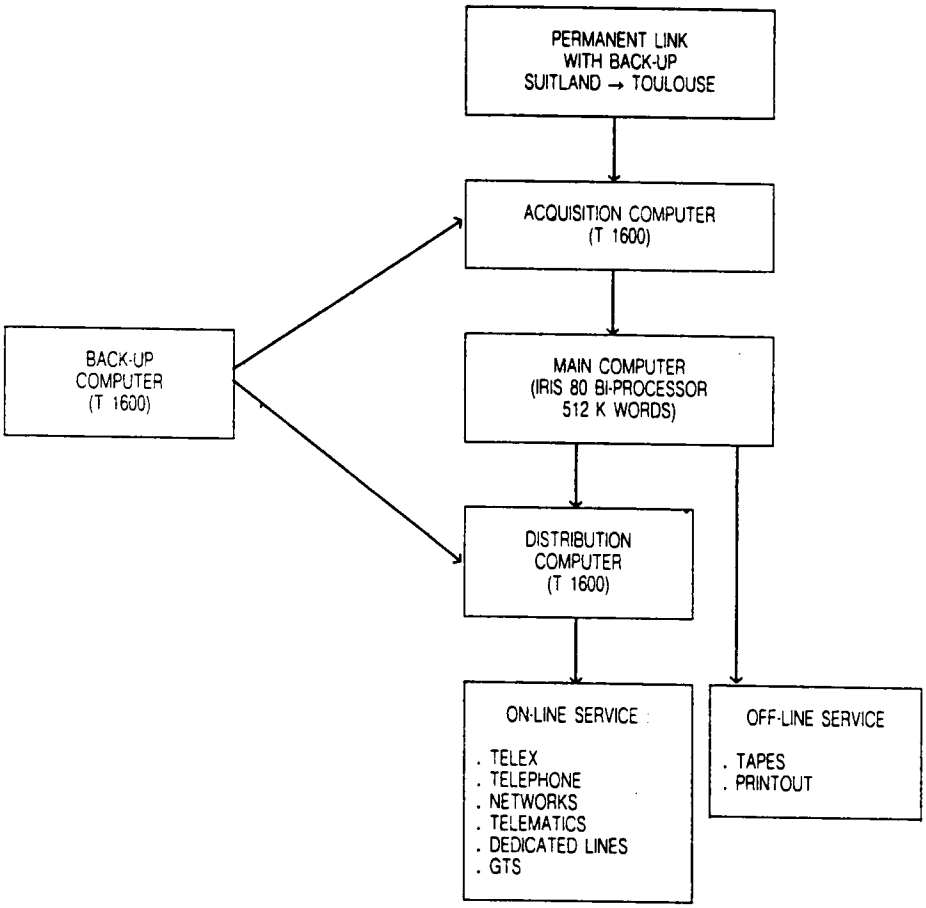


Figure 12. Argos Data Processing Center

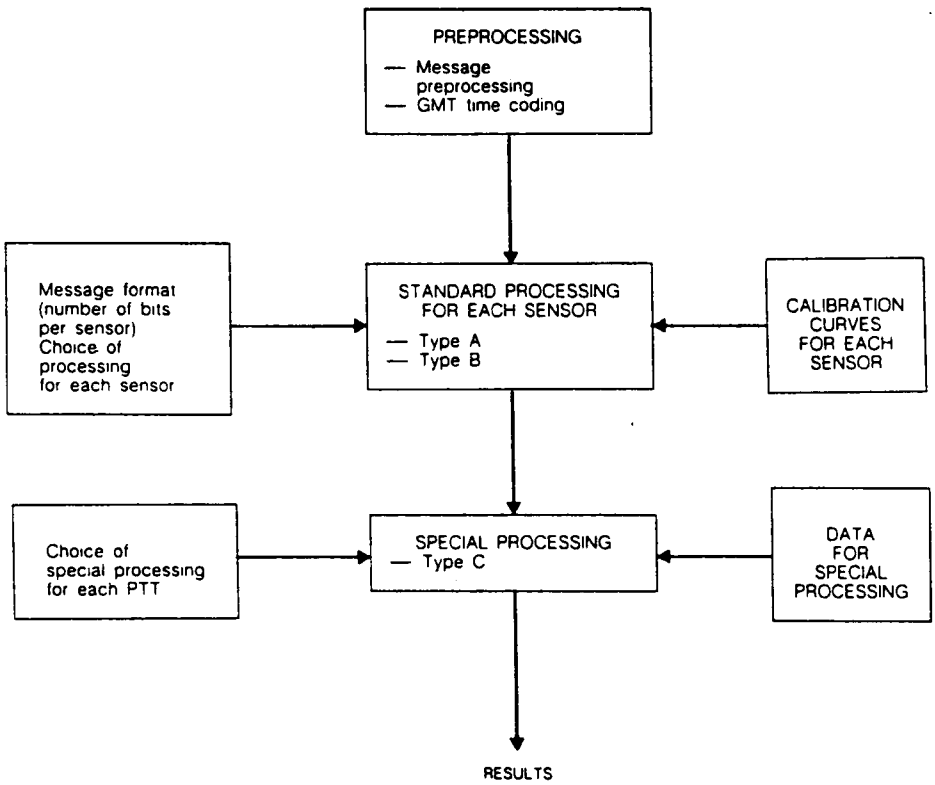


Figure 13. Argos Sensor Data Processing

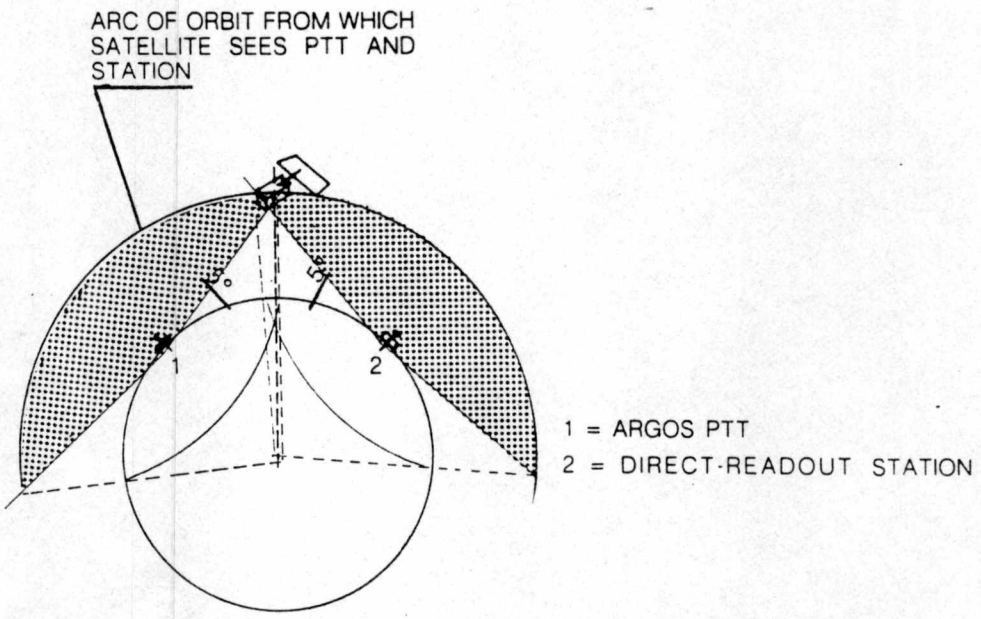


Figure 14. Direct Readout Station and PTT Locations Showing Satellite Orbit

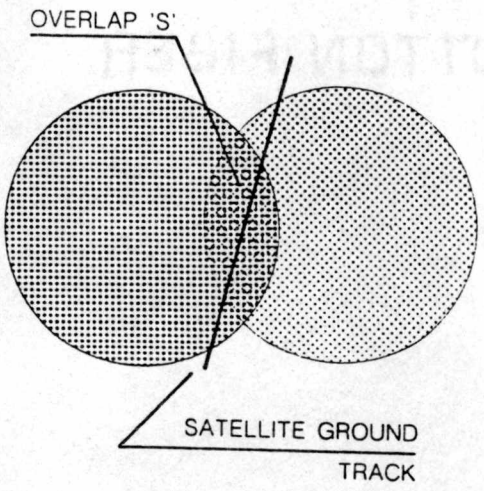


Figure 15. Station and PTT Visibility Circle Overlap with Satellite Ground Track

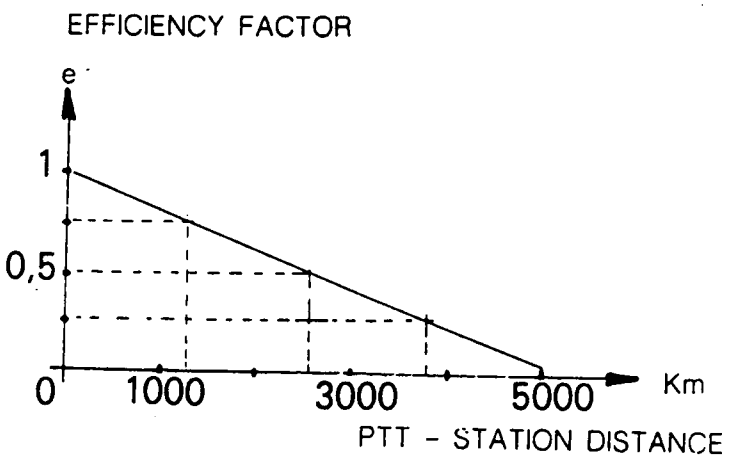


Figure 16. Direct Readout Station Efficiency Factor

in chronological order all location and sensor data for each satellite pass for the PTT. Although there are several methods for accessing the results such as via telephone; telex, or TRANSPAC, the French data distribution network, receiving results is a relatively slow process. As is shown by Figure 17, it is a very complicated process to transmit the data on-line to users. In addition to data retrieval delays, the access charges to the on-line system are expensive and the on-line acquisition is time consuming, requiring several calls a day to try and access results. However, the results are available on printouts that are sent to the user every fortnight.

The main reason for the length of the delay between acquisition and distribution is the throughput time. In order for the signals to be processed they first must be downlinked to one of the major data processing ground receiving stations.

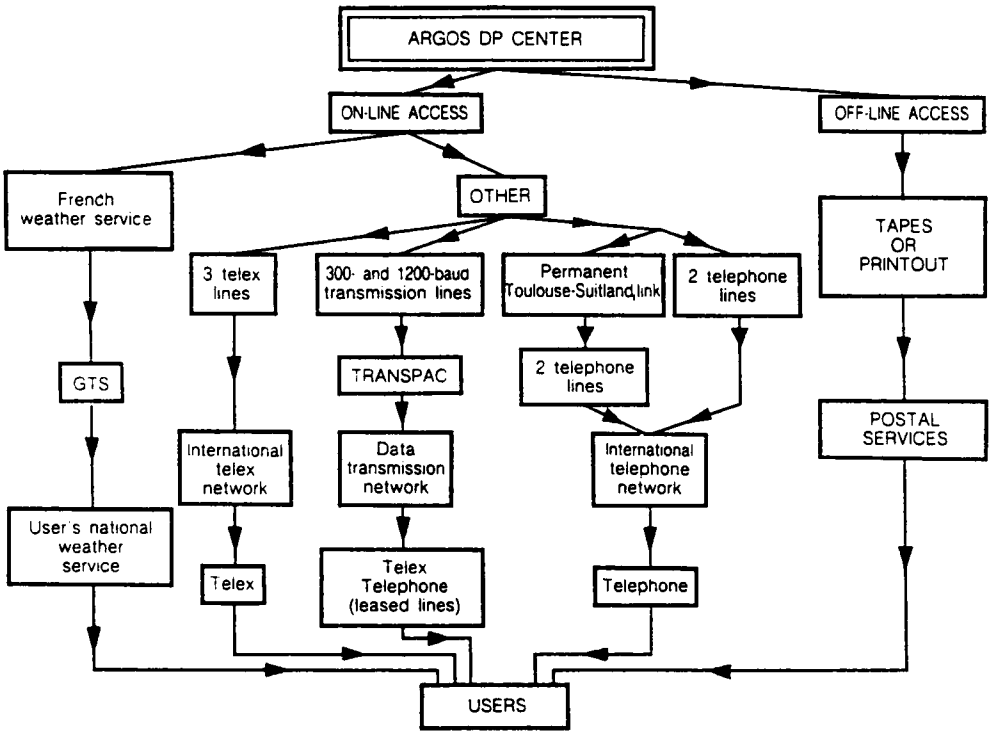


Figure 17. Distribution of Results to Users

Since there are only three ground receiving stations this means that it takes about 50 minutes for the signal to make it through the satellite and into the downlink queue for transmission to a receiving station. The next delay is because of the complicated method of transmitting the received signal to the main processing station. A typical signal travels the following route after reception at the ground receiving station. First it is transmitted to Suitland, Maryland from the stations, then it is sorted at NESDIS and transmitted to Toulouse, France. There it is finally processed and then made available to on-line users. This process itself can take up to ten hours to complete. If the user is unable to call and check data after this delay and before the next group of messages arrives, valuable data may not be readily available until the written report arrives. This can cause the user delays in using the information. This is a problem with regards to both tracking vehicles, and tracking wildlife, where quick access to results can identify a minor problem before it becomes unmanageable.

CHAPTER 6

PROJECT DESIGN

The project had three main goals. The first goal was to demonstrate the capability of accurate location of a moving object using a commercially available satellite telemetry technique. The second goal was to compare and evaluate the performance of the two transmitter types and models. The third was to demonstrate that an object in an unknown location could be located quickly and accurately. In order to accomplish these goals several factors need to be considered. The first is the accuracy of the transmissions themselves. Although technical details of this topic were discussed earlier, it is now necessary to detail the criteria with which the test locations were judged. Table 6 shows the quality of the location and its corresponding class. Class 3 is the most accurate location with an error of up to 150 m; Class 2 is the next accurate location with an error of up to 350 m; and Class 1 is the least accurate location with an error of up to 1 km. The quality is determined by a number of factors including the number of repeat transmissions from the same location as well as their relative strength. The distance associated with each quality refers to the maximum error boundary of the true location as opposed to the calculated location. This error is radially measured with the true location lying somewhere within the circle having a radius equal to the value of the error boundary. This degree of confidence in the accuracies of the transmitters is very important, especially when used with wildlife tracking.

Wildlife Telemetry

The habits of many migratory wildlife species have been a mystery to biologists for many years. With the advent of conventional radio transmitters and receivers, it became possible to track migratory wildlife over limited ranges. The next step

Table 6. Argos Location Qualities

	Required Conditions	Accuracy
Class 3	At least seven minutes between first and last message of pass At least five messages recieved Very good oscillator stability Very good geometric configuration	Location accuracy: 0-150 m
Class 2	At least seven minutes between first and last message of pass At least five messages received Good oscillator stability	Location accuracy: 0-350 m
Class 1	At least four minutes between first and last message of pass At least four messages recieved Reasonable oscillator stability	Location accuracy: 0-1km

in the evolution of tracking techniques came when airplanes were used as part of the tracking system. By using fixed wing craft to make the biologists and their receivers airborne, researchers were able to increase the area over which the wildlife could be followed. Unfortunately, this also increased the costs so that only the well funded were able to use the technique. The next advancement came with the use of satellite transmitters to track animals. In the beginning this technique had very limited usefulness. The transmitters were heavy and bulky, so that their use was restricted to large animals. They were usually attached to collars and placed on animals such as caribou and moose. Although the PTTs performed well, the species used in the early studies did not have long migration routes and the transmitters were usually used to provide a "headcount" of the animals. Most of this work was done in Alaska by the U. S. Fish and Wildlife Service (USFWS) who were responsible for counting the caribou. Another use of the larger transmitters was to track the movements of whales. Their migration routes were certainly long enough to provide much data about how, where and when they traveled, but the tremendous deep water pressures the transmitters were subjected to led to transmitter failure. Currently work is in progress to develop a transmitter that measures the pressure and shuts itself off when the whale begins to dive (Argos User's Update).

The technology has been increasing in sophistication with the transmitters becoming smaller, lighter and even using new, non-battery power sources. As the transmitters became smaller their range of applications became larger. By 1984 the transmitters had become small and light enough to allow them to be attached to large migratory birds. One of the first studies of this kind was performed by the USFWS using a transmitter developed for them by Johns Hopkins researchers (Strikwerda, et. al., 1986). They tested this battery powered transmitter on a

number of species, and their first experiment used trumpeter and tundra swans. These birds are very large, typically weighing 6 to 9 kg and have long distance migrations about which very little is known. This made them good candidates for use in the study. The birds were harnessed with the transmitters while on their breeding ponds in Alaska during molt when flight feathers are lost. They had limited success with these birds (two trumpeter swans and two tundra swans plus a tundra cygnet) even though they provided good information until the researchers either lost contact with the transmitters or the transmitters became stationary indicating the death of the bird. These same researchers also have used an American Bald Eagle that was captured in Maryland; it provided more data over a longer time period than the swans. They also have done satellite telemetry work with Southern Giant Petrels as well, and with these studies they demonstrated that with their specifically designed transmitters it was possible to track birds by satellite (Strikwerda, et. al., 1986).

Before the Bald Eagle project could be started at The University of Tennessee Space Institute (UTSI), it was necessary to develop a harnessing technique that would not interfere with the birds ability to fly and fish. This work was done with the cooperation of several agencies including the Wildlife Preservation Corp (WPC), formerly the Cumberland Wildlife Foundation, the Tennessee Wildlife Resources Agency (TWRA), and Dr. Winston Smith of Tennessee Technological University. This cooperative effort brought about the harnessing of a captive adult female Bald Eagle at the WPC on September 7, 1988. The dummy transmitter was positioned in the middle of her back and did not exceed the set maximum of five percent of the bird's body weight. The harness itself is made of a flat Teflon ribbon sewn with polyurethane coated cotton thread. This thread was chosen because it will degrade after a period of time allowing the transmitter and harness to release

without injuring the bird. The dummy transmitter holder also has padding on it to help reduce trauma to the bird and increase its comfort. The harnessed eagle was then allowed to interact with other eagles in a large open air pen. John Stokes of WPC checked the bird to determine the physical effects of the transmitter and harness. No ill effects were evident on the bird and no physical wear of the harness or dummy transmitter housing was observed. Once the relative safety of the harness and transmitter was determined, it was decided to place a real transmitter on a wild eagle (Shahrokhi and Luke, 1988).

The eagle harness and transmitter setup was used in the motion portion of this study. The details about the actual experiment with the eagle will be shown here and the results and interpretations of the results are given in the next chapter which also describes the preliminary stationary test procedures in some detail. The eagles used were obtained from the TWRA hacking program, a program designed to repopulate Tennessee with Bald Eagles. The eaglets are captured either from the Northern U. S. or from Alaska; all the eagles used in this study were from Alaska. The eagles are captured from nests at an age of about four to six weeks. They are then transported by plane and truck to the hack site, and are placed in large cages that sit atop telephone poles called hack towers. They are fed, watered, and monitored with a minimum of human contact in the hack cages on top of the hack towers. When the eaglets reach 12 to 14 weeks of age, they are removed from their cages and have either radio transmitters, satellite transmitters or both attached to them. They also are legbanded and patagial or wing tagged with a unique color coded wing tag. The radio transmitters have a very limited range and are useful for keeping track of the birds within about a five mile radius of the hack site. Once the birds are ready for flight, the front of the cage drops down and the birds are free to fly whenever they feel ready.

To date two American Bald Eagles have been harnessed with the solar powered transmitter. The first eagle, named Phoenix, was a bird that was obtained through a rehabilitation center. He began life as an Alaskan eagle who was hacked from Dale Hollow Lake in Northern Middle Tennessee in September 1988. By October he had flown into Michigan, a distance of almost 1000 miles. An unidentified person or persons shot him and broke a bone in his wing. Another bone was broken when he hit the ground. The Michigan state wildlife officers found him and sent him to the University of Minnesota Raptor Rehabilitation Center for recovery. Since he was a Tennessee eagle, TWRA was notified of his condition. It was decided that he would make a good candidate for the tracking study because of his size and demonstrated wanderlust. In March 1989, a team of eagle harnessers, Mike Luke and Dr. Winston Smith, traveled to the University of Minnesota to place the transmitter on Phoenix. When this was done and all that remained was for him to be released. Originally the release was to take place in Minnesota near the end of March or the first of April. Unfortunately Phoenix had some problems and had to have his tail feathers surgically replaced. This delayed the release until the end of May. During this time it was decided that Phoenix should be released from Tennessee instead of from Minnesota.

On May 30, 1989 Phoenix arrived at the Memphis, Tennessee airport and was transported by van to the hack site at Reelfoot Lake in northwest Tennessee. On the morning of May 31, 1989 the team of eagle researchers, including the author, Dr. Winston Smith, Robert Hatcher, Mark Greenwald, and Paul Brown of TWRA and four news crews waited for Phoenix to fly. The front of the cage was dropped and about 45 minutes later Phoenix and his satellite transmitter were on their way. The only problem was that when the Argos data were checked, it showed that Phoenix was not flying north as expected. Instead he stayed very close to Reelfoot

for a few days, and on June 8, 1989 he went into Hickman County, Kentucky then across the Mississippi River into Missouri. He took up residence at Bob Burney's house in Dorena, Missouri located about 1.5 miles west of the Mississippi River. Mr. Burney, a farmer, began to feed him and he stayed. On June 10, the farmer contacted the Missouri wildlife office who contacted the TWRA. On June 14, TWRA sent Don Miller and Corky Morgan to recapture the eagle. This was done using a rod and reel with a fish attached, a leg noose and a net. Phoenix was led into the leg noose by the fish on the line, and while he was eating the noose was tightened and the net thrown over him. He was then transported to WPC where he is being kept until he can be sent to a zoological park to be used as a breeding eagle. The author recovered the transmitter in late June and made plans to find another eagle.

The second eagle used in the study was not named but was identified as patagial tag 26. This bird was an Alaskan eagle that was to be hacked from a new site at Chickamauga Lake near Cleveland, Tennessee. This subadult bird was assumed to be female due to its size. The adult female bald eagle can weigh up to 14 pounds and have a wingspan of eight feet. The males are somewhat smaller with weights of up to 12 pounds and wingspans of six feet. As a 12 to 14 week old subadult, this eagle weighed 11 pounds which made it just big enough to attach the transmitter. This bird had limited human contact which almost guaranteed that it would not go to a farm to be fed. 26 was harnessed with the transmitter on the night of August 28, 1989 by the author, Dr. Winston Smith and Robert Hatcher. The harness was then checked for proper alignment the following day and was found to be too loose, allowing 26 to get her beak under the front strap. Robert Hatcher, the author and Tom Pride, who manages the farm where the hack site is located, tightened the harness.

The release was scheduled to take place one week after the initial harnessing. This was to allow time for researchers to watch the harness to insure proper fit and to observe 26's behavior and attitude toward the transmitter. The evening before 26 was to be released, Robert Hatcher noticed that the harness had again become loose. She was taken from the cage that night and the harness was tightened again. The next morning 26 and the other eagles at the hack site took off. All of them were being monitored by TWRA officers using radio transmitters that were attached to their tail feathers. The satellite transmitter was functioning well and it showed that 26 was fishing and roosting in the area around the hack site. This is typical behavior in that most of the birds stay near the hack site for up to a month before deciding to leave.

However, after about a week of good strong signals and data, the transmitter suddenly stopped its transmissions. The TWRA also reported that the radio transmitter had become stationary. The officers began to search for 26 and eventually found her. Apparently she had learned how to loosen the harness sufficiently to allow the transmitter to slide over her right wing, causing her to make a crash landing. She was taken to the hack tower for a checkup and kept there for a week to allow her bruises to heal. The transmitter and harness were removed and returned to UTSI. 26 was released and tracked by her radio transmitter until she left the area. Current modifications are being made to the harness configuration to allow a tighter, more comfortable fit using a different kind of fastener that does not stretch like the polyurethane cotton thread.

Vehicle Telemetry

Wildlife telemetry is certainly one fascinating application of commercially available satellite telemetry systems, but not the only one. Another important use of this technique is in vehicle tracking. Many companies, especially long haul

cross country trucking firms spend hundreds of thousands of dollars in telephone charges just to keep up with their shipments. Until the advent of satellite tracking, it was the most inexpensive way to monitor the movements of their vehicles. Now it is possible to track trucks and shipments by using satellite transmitters. The tracking of trucks via satellite has been done for several years by many different companies, such as LocStar that uses a GPS system that is similar to NAVSTAR, but only covers Europe (Space Calendar, 1989). Most of these companies utilize some form of GPS that requires a receiver to show the truck location to the operator. This information can then be relayed to the base office using some form of telecommunication such as a portable PC with a modem and a phone. It is also possible to have receivers in the vehicles and have the base office perform relative positioning to show the vehicles' position relative to the office. Either of these methods provide the best locations of the vehicles available.

The above methods work extremely well when trained operators are in the vehicle or office, however, if the object is not the vehicle but a portion of the shipment such as single crate, the use of GPS receivers becomes less practical. In such cases, or in cases where it is not feasible to train all operators to use receivers, the transmitter-satellite system becomes more practical. With transmitters attached to shipping containers or vehicles, the operators would not have any additional duties other than to try and insure that the transmitters were not ripped off the vehicles or ripped out of the containers. This way the base office could have an up to the minute record of not only where their vehicles were but also of where all their shipments were. The only current problem with the dissemination of this kind of service is the limited availability and high cost of commercial tracking satellites. However, if a dedicated tracking satellite system was launched, it would be possible to handle many companies' data and distribute results much faster than the Argos

system because the satellite would be dedicated to tracking PTT movement.

In order to show that the transmitter was a viable option to the GPS receiver, an experiment of tracking a vehicle was designed. Several different vehicles were used in this portion of the study and the transmitter was carried in a variety of places within the vehicles to determine the best place for it. The battery powered Toyocom unit was used primarily in this part of the study, although after removal from the eagles the Telonics unit was also transported in vehicles. After trying the transmitter in various areas of the vehicle, including the trunk and glove compartment, it was decided that the PTT would be most secure in the front seat of the vehicle. The Toyocom unit was held in place by a string tied around it and the seatbelt supports and the Telonics unit was secured to the dash with tape. It was necessary to have the Telonics unit on the dash to insure that it had adequate sunlight to operate.

Once mounted securely, the transmitter or transmitters were driven throughout the Southeast. A typical trip is shown in Figure 18; a log of each trip was kept to provide actual locations to compare to the satellite calculated locations; a page from the log of the trip, and the corresponding Argos report is shown in Figure 19. Trips to several different states were made to show the capabilities of tracking a far ranging object accurately. In fact, when the Toyocom transmitter was returned to the factory for battery replacement and inspection, the author was able to track its movements in Japan. Although the tracking of vehicles is not as exciting as tracking migratory wildlife, it still provides a valuable research tool when comparing the accuracies of the different types of transmitters. Vehicle telemetry also illustrates that this telemetry technique has real commercial value for tracking and monitoring shipments.

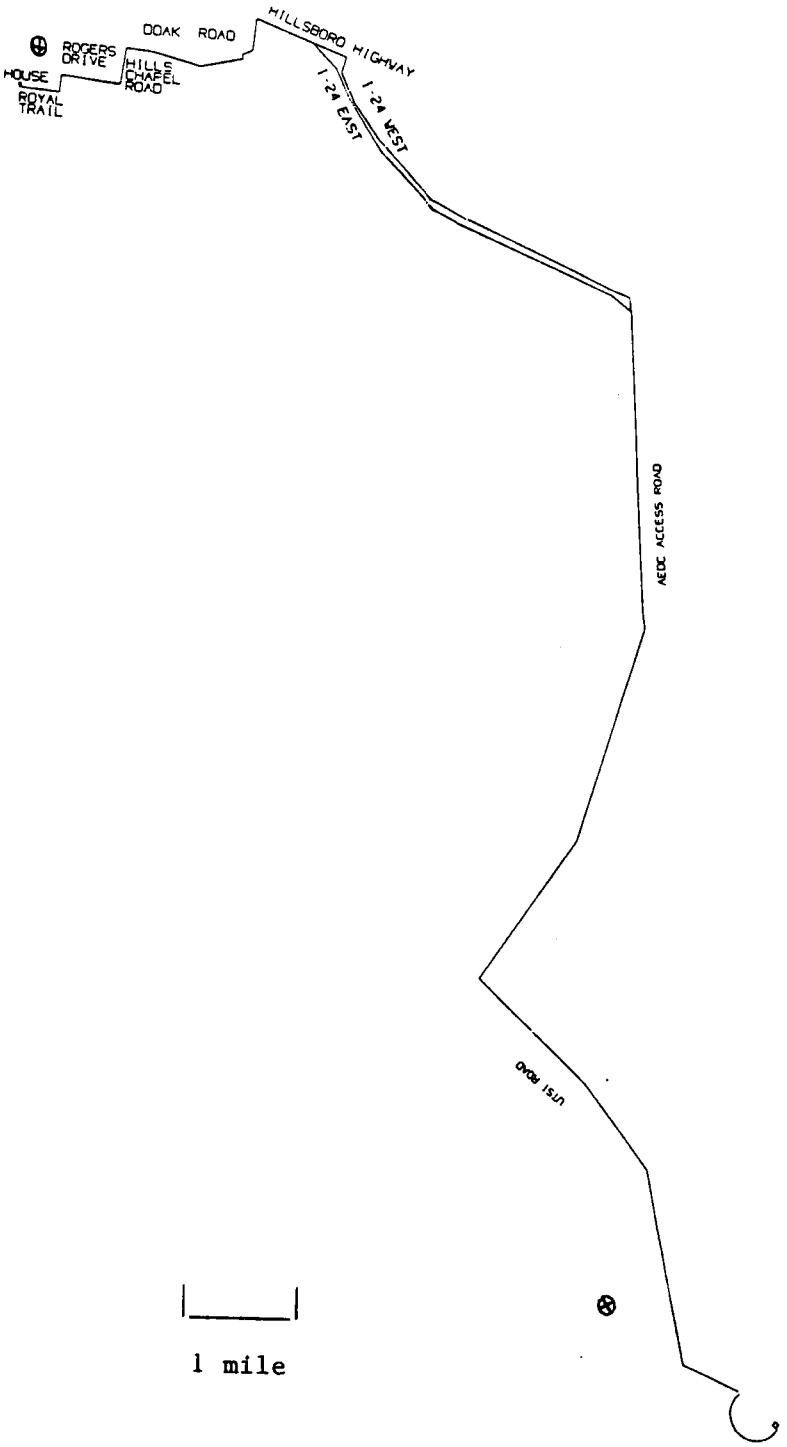


Figure 18. Trip From House to UTSI on May 17, 1989

Date	Time	Actual Location	
5-17-89	12:33 am	35°26′45″ N	
		86° 05′30″W	
5-17-89	12:38 am	35°26′45″ N	
		86°05′30″ W	House
5-17-89	7:16 am	35°19′20″ N	
		86°06′30″ W	
5-17-89	7:21 am	35°19′20″ N	
		86°06′30″ W	UTSI Road

*Note all Argos Times are Zulu Time, all other times are CDT.

Argos Report

Order number 88/0650 Batch #

DD.MM.YY	HH.MM.SS	NQ	LATITUDE	LONGITUDE
17.05.89	07.33.38	1	35.451	273.911
17.05.89	07.38.08		35 27 09	86. 05 20
17.05.89	14.16.43	1	35.327	273.856
17.05.89	14.21.43		35 19 37	86 08 38
17.05.89	14.16.43	1	35.327	273.856
17.05.89	23.51.21		"	"
17.05.89	23.57.21		"	"

Figure 19. Page from Log and Corresponding Argos Report of Trip to UTSI

CHAPTER 7

RESULTS OF ACCURACY TESTING

Since August of 1988, UTSI has been conducting several different kinds of performance tests on two Argos registered satellite transmitters. The tests can be divided into two main categories, stationary tests and motion tests. The details of the motion test procedures used by the author were described in the previous chapter. This chapter provides details of previously completed work in the form of stationary tests, and a comparison of results obtained in these stationary tests and the motion tests.

Stationary Tests

The first set of tests were performed by Dr. F. Shahrokhi and Mike Luke. The test procedure was to mount the two transmitters at a specified known location and to monitor them both by modem contact through the Argos data system and through the use of a hand held satellite uplink receiver. The uplink receiver helped to determine whether the two transmitters were functioning properly. The uplink receiver, manufactured by Telonics, Inc., is capable of showing exactly what the transmitter is sending. This helped researchers determine the probable cause of either a nonlocation or extremely poor location.

The transmitters were placed on top of the main building at UTSI at a coordinate location of 35°19′8″ N latitude , 86°6′4″ W longitude. The transmitters were mounted on separate platforms twenty feet apart. The transmitters were monitored each week day from August 30, 1989 through October 15, 1988, and they were checked with the uplink receiver two to three times daily. This was done so that the check corresponded to the daylight wake and sleep times of the Toyocom

battery powered unit. This PTT has a cycle of two hours awake and transmitting, and six hours asleep and not transmitting. This gives a total of six hours transmitting and 18 hours not transmitting in a 24 hour period. The solar powered Telonics unit transmits constantly as long as there is either enough light to run it from the solar cells or a charge is left in its storage batteries. It was checked periodically even during the Toyocom's sleep times to insure that the batteries were remaining charged and functioning properly. Also measured were the pulse rate timing, time of day, weather conditions, ambient air temperature, transmitter message content, wake and sleep status, and satellite location message. The six weeks of data points collected were analyzed and statistical results were calculated and are shown in Table 7 (Shahrokhi and Luke, 1988).

Interpretation of the results showed that the performance of the two transmitters were both satisfactory. The Telonics unit provided more locations and had a smaller mean distance from the reference point and its closest measurement was more accurate than the Toyocom unit. However, the Telonics unit had a greater error in measurement of the farthest point from reference. This is shown by the Telonics solar powered unit's higher variance. Both units' signal frequencies were within acceptable range from the standard 401.650 MHz, and the most received quality location from both transmitters was Class 1. Since both units performed so closely in the stationary tests, it was difficult to choose the proper use for them. After all factors had been weighed including size, shape, and overall weight, the Telonics unit was chosen to be placed on the eagle and the Toyocom unit was chosen to be used in the vehicle portion of the motion tests. Other advantages existed in using the Telonics unit for wildlife tracking especially its more aerodynamic design and indefinite life span.

Table 7. Stationary Test Results

Test Information	Telonics ST6-B	Toyocom T-2028
Energy Source	Solar Powered	Battery Powered
Mean Distance from a Reference Point	1198.33 m	1385.36 m
Population Standard Deviation	1244.02 m	1093.55 m
Variance of a Population	1547599.86	1195852.66
Total Points of Population	117	60
Closest Point from Reference Point	38.109 m	152.43 m
Farthest Point from Reference Point	6326.21 m	4268.29 m
Average Number of Receptions per Day	3.95	1.48
Highest Number of Receptions per Day	11	3
Lowest Number of Receptions per Day	0	0
Signal Frequency Mean	401.65035 MHz	401.65001 MHz
Signal Frequency Standard Deviation	.000051454	.000110565
Life Expectancy of Transmitter	Indefinite	227 Days
Most Received Location Quality Location	1	1
Air Temperature Range During Testing	45-80 ^{o} F	45-80 ^{o} F
Potential Transmitter Operating Problems	Storage of Solar Unit	Turning Transmitter OFF

Motion Tests

The actual harnessing of the eagle and mounting of the transmitter in the vehicle were described in the previous chapter. The results and interpretations of the data of these tests are presented in this section. The results of these motion tests are shown in Table 8, and they have been divided according to transmitter used, just as they were in the stationary tests. This allows for easy comparison of the accuracies of the two transmitter types.

The Toyocom unit provided a smaller mean difference from a reference point than did the Telonics unit and also had a smaller population variance. This may in part be because of the larger number of sample points provided by the Toyocom unit. The closest point from reference was the same for both transmitters and their farthest points from reference were very close, with the Telonics unit having a slightly smaller value. The Telonics unit also had a larger average number of receptions per day and also had the highest number of receptions per day. This was expected because of its constantly active signal output. The signal frequency mean for both units was acceptable and the signal frequency standard deviations were also within acceptable range. The Toyocom unit experienced a higher standard deviation than did the Telonics unit, but this difference was attributed to the higher velocity of the Toyocom at the moment of location of the transmitter. As discussed in earlier chapters, motion at the time of location changes both the received frequency and the Doppler Shift calculation of location. Even though there were differences between the results for these PTTs during the motion tests, they were found to be statistically insignificant at the 95 percent confidence interval. Once again the most received location was a Class 1, indicating a maximum error of 1 km.

Table 8. Motion Test Results

Test Information	Telonics ST6-B	Toyocom T-2028
Energy Source	Solar Powered	Battery Powered
Mean Distance from a Reference Point	570.328m	338.158m
Population Standard Deviation	467.223m	251.222m
Variance of a Population	218297.0	163112.39
Total Points of Population	81	211
Closest Point from Reference Point	41.769m	41.769m
Farthest Point from Reference Point	1225.226m	1559.378m
Average Number of Receptions per Day	5.79	2.88
Highest Number of Receptions per Day	18	16
Lowest Number of Receptions per Day	0	0
Signal Frequency Mean	401.65030 MHz	401.64998 MHz
Signal Frequency Standard Deviation	.00057895	.01339609
Life Expectancy of Transmitter	Indefinite	227 Days
Most Received Location Quality Location	1	1
Air Temperature Range During Testing	45-90° F	45-90° F
Potential Transmitter Operating Problems	Storage of Solar Unit	Turning Transmitter OFF

Results of the motion tests were similar to those obtained in the stationary tests, but there were differences. During the motion tests, both transmitters provided smaller mean distances from a reference point than they did in the stationary tests. The Toyocom PTT provided a smaller mean than the Telonics PTT in this category during the stationary tests, but the opposite was true during the motion tests. In all but one of the categories evaluated, the PTTs performed more satisfactorily during the motion tests.

The one category that was seemingly better in the stationary tests was the signal frequency standard deviation, although access to the raw data for the stationary tests precluded the performance of a t-test to actually compare the motion and stationary test results. This value was considerably higher than the stationary value and is explained by the velocities experienced by the transmitters. The differences in the number of points in the populations is attributed to the differences in use that the transmitters experienced. For example, in the stationary tests the Telonics PTT was located away from any shade and so had plenty of sunlight to transmit signals constantly. It was able to hit the satellite with messages more often than the sleep-wake cycle of the Toyocom unit. However, in the motion tests, the Telonics unit was on an eagle and experienced much time out of sunlight, thereby reducing its ability to transmit signals to the satellite. The Toyocom unit, on the other hand, was able to follow its usual sleep-wake cycle and was able to hit the satellite more often. Despite this each transmitter still averaged more than two receptions per day, indicating that the gaps in information caused by satellite non-reception of the signal would not be a problem. The much higher value in the motion tests for the Toyocom unit in the category of highest number of receptions per day was attributed to the replacement of weakening batteries that had caused less accurate and sporadic results.

CHAPTER 8

FRIENDLY DATA SYSTEMS

The more than satisfactory performance of the transmitters in the accuracy-comparison stationary and motion tests encouraged confidence in this technique of location. The process of collecting the data, entering it into a database or statistical analysis package, and interpreting the results is a very laborious and time consuming task. A system of recording the location of the PTTs and their sensor values was needed to speed the analysis and interpretation data. This chapter describes systems that could be used to help speed the collection and interpretation of results.

pcArc/Info GIS

This study provides a real application for this relatively new technology. The pcArc/Info GIS is manufactured by Environmental Systems Research Institute, Incorporated (ESRI) and is a smaller version of their industry standard mainframe GIS. It is full featured, allowing the user to input any spatial data with its associated non spatial attributes in a variety of ways. The most common method of building a geographical database is by digitization of existing data such as maps. The digitization is carried out generally either by a scanner in automated mode, or a digitizing pad in manual mode. The scanner is faster, but the equipment is more expensive than a digitizing tablet. The digitizing tablet involves the use of a trained operator who must follow every line on the data source by hand. These data sources may be existing maps, or aerial photographs; this is a very slow and labor intensive process and is prone to error. Scanners allow for quicker initial input, but often require more time to process inside the GIS than do tablet input data because of the amount of data editing necessary. It is also possible to enter

coordinate locations by hand, but this is even slower than directly digitizing the data source.

Once the data has been input into the pcArc/Info GIS, it can be manipulated in a number of ways. This GIS is set up in the form of modules that operate either as stand alone programs or as an integrated system. One of the operations performed by this system is the "cleaning" of data, that is the removal of any errors included in the original digitization process and the isolation and removal of certain features and to place them in a separate layer. This isolation and removal of features is a very powerful tool allowing a large amount of data about one particular area to be stored in a convenient format. There are many other important and powerful uses for these and other modules in this GIS, but its main importance to this study is its possible application to automation of data collection and interpretation.

The collection, interpretation and display of data could be speeded greatly by the implementation of such a system in conjunction with the Argos system. With an interface program, the GIS could acquire data on-line from the Argos computer and transform it into the correct structure for the GIS database. The new location data could then be overlaid onto existing digitized map bases. Once the information is stored in a file, the operator begins the process of cleaning, separating, and displaying the data. The pcArc/Info GIS provides for display of maps on a monitor or plotted on paper. This capability allows for the creation of specialized maps. For example, the locations of the eagles could be plotted over a pre-existing habitat base to allow evaluation of the habitat preference of the monitored eagles. The implementation of this or other similar GIS would be a great improvement over the current manual data entry and map production methods.

ELSArgos System

The ELSArgos system is a new software product developed in 1989 by North American Collection & Location by Satellite (NACLS). It does not have as wide a range of applications as does the pcArc/Info GIS because it is intended only for use with the Argos System. This package allows the user to automatically log into an Argos processing center and import data in the user's internal database. It allows for both on-line and off-line access to data through the use of a modem connection alone or a modem connection and the reading of a standard Argos TELEX format file. It is designed as a series of modules that provide communication, location, data management and analysis as an integrated package. NACLS has also developed specialized application modules for dedicated applications, and is willing to develop new ones to accommodate any user need.

The program itself has the ability to show PTTs on a world map, or on other available regional maps. The screen generates the PTT tracks during the time period of interest. The maps are also easily configured so that individual users can customize their maps to suit their applications. In addition to being a comprehensive graphics software package and a modular communication tool, ELSArgos is also a means of managing the data transmitted by the PTTs. It contains a resident database that interfaces with most commercially available database management systems. One of the most unique features of the ELSArgos package is its ability to make satellite pass predictions. It automatically plots the satellite ground track on the screen map and supplies the times and durations of each pass. This means that users would know the times that their PTTs would be located (NACLS ELSArgos Documentation, 1989). All of these features would allow for a much reduced collection and data interpretation time, and would allow the user to have a more accurate and complete basis for making conclusions based on the data.

Both of these packages provide improvements over manual entry and display of satellite data. System choice depends greatly on the applications planned by the user. If the user is interested in applications other than just the Argos system, for example planning transportation routes, the GIS system would be more suitable. However, if the user is only going to use the Argos system to track a number of PTTs and is not interested in using the software for any other application, the ELSArgos would be the logical choice. In general, a GIS may not be necessary unless a great number of data points from a large number of sources need to be plotted, and may be too powerful for the narrow application of tracking PTT movement.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

As stated in Chapter 6, this project had three main goals. The first was to demonstrate the capability of accurate location of a moving object using a commercially available satellite telemetry technique. This goal was accomplished in the motion portion of the study, where it was demonstrated that a moving object could be located with an error as small as 41 m ± 1.5 m at 90 percent confidence interval, this was the smallest error for both the Toyocom and the Telonics transmitters in the motion tests. This amount of error is certainly within sight distance and for most applications, such as tracking vehicles or endangered species, this accuracy would be more than adequate. Even the maximum error of 1393 m ± 167 m is still within acceptable accuracy ranges for all but the most demanding applications.

The second project goal was to compare and evaluate the performance of the two transmitter types. As discussed in Chapter 7 the results of both the stationary tests and the motion tests showed that there was no significant difference in the performance of the two types of transmitters. The main difference between them is their suitability for the specific project planned. The Telonics unit was chosen over the Toyocom unit for harnessing to the eagle solely on the basis of its lighter weight, its smaller, more aerodynamic design and its indefinite lifespan. In turn, the Toyocom unit was selected for use in the vehicle portion of the study because it was easily accessible and this made it easy to change the batteries. The limited lifespan of the battery powered transmitter is its largest handicap in wildlife applications, but makes it an ideal candidate for tracking the movements of commercial vehicles and shipments.

The third goal was to demonstrate that an object in an unknown location could be located quickly and accurately. This was most definitely accomplished by the successful or unsuccessful, depending on the viewpoint, flights of Phoenix and 26. Both these objects were tracked, became distressed and lost, and were located with a minimum of time and a maximum of accuracy. Locating injured birds is perhaps one of the most important aspects of the study. Aid can be rendered quickly with a minimum of participation from the distressed object. In generalized form, this technique is viable for keeping track of delicate shipments, as well as endangered species.

Even though all the goals of the study were met, much remains to be done. This was only a preliminary study into the feasibility of this technique of object location and was not meant to encompass all applications or identify all problems. However, the more than satisfactory accuracy results obtained from both transmitters should encourage confidence in this technique of location and prompt further study into broadening its range of applications. In order to make this process less demanding with respect to time, one of the systems mentioned in Chapter 8 should be implemented. This will allow a much more complete study to be undertaken in less time and would further understanding of how valuable this technique could become into today's fast paced society.

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VITA

My career goal is to continue to work with remote sensing and computer geographical information systems to help solve environmental problems. I feel that this will allow me to utilize my diverse background in geology, computer science, mathematics, engineering and physics.

I was born in Knoxville, Tennessee in May 1963. I graduated in the top ten percent of my class from Coffee County Central High School in Manchester, Tennessee in May 1981 and then went on to Tennessee Technological University in Cookeville, Tennessee. There, I was a member of the varsity riflery team, Alpha Lambda Delta Honor Society and was appointed to the President's Advisory Council before transferring to the University of Tennessee, Knoxville where I completed my Bachelor's Degree in Geology with honors in March, 1987. At UTK I was captain of the varsity riflery team and President of the Undergraduate Geology Association. I also received the C. E. Tarr Award as the outstanding Senior in Geology, 1986 and was voted the most valuable field partner that same year.

I began my postgraduate work in August, 1988 after completing three Associate Degrees in Mathematics, Physics, and Engineering from Motlow State Community College in Tullahoma, Tennessee. At Motlow I was captain of the College Bowl Team and a member of the Gamma Beta Phi Honor Society. While at The University of Tennessee Space Institute, I have worked for the Department of Energy's Magnetohydrodynamics Energy Conversion Programs and on the satellite tracking system that my thesis is based on. I also served as the Vice President of the Space Institute Student Government Association. I currently reside in Manchester, Tennessee but plan to seek employment elsewhere.