NASA

National Aeronautics and
Space Administration

John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

(NASA-CR-157040) AUTOMATED TRACKING OF THE FLORIDA MANATEE (TRICHECHUS MANATUS) Final Report, Mar. 1977 - Jun. 1978 (Georgia Inst. of Tech.) 172 p HC A08/MF A01 CSCL 06C

N78-25752

Unclas

G3/51 22452

REPORT NAS10-9097-F

AUTOMATED TRACKING OF THE FLORIDA MANATEE (*Trichechus manatus*)

By

Robert C. Michelson
Jean Breedlove
Herndon H. Jenkins

Prepared for

JOHN F. KENNEDY SPACE CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
KENNEDY SPACE CENTER, FLORIDA 32899

Final Report for the period March 1977 – June 1978

June 1978

GEORGIA INSTITUTE OF TECHNOLOGY

Engineering Experiment Station
Atlanta, Georgia 30332

1978

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NAS10-9097-F	2. GOVT ACCESSION NO
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): AUTOMATED TRACKING OF THE FLORIDA MANATEE (Trichechus manatus)	5. TYPE OF REPORT & PERIOD COVERED: Final Report March 77 - June 78
	6. PERFORMING ORG REPORT NUMBER: NAS10-9097-F
7. AUTHOR(s): R. C. Michelson, J. Breedlove, H. H. Jenkins	8. CONTRACT OR GRANT NUMBER(s): NAS10-9097
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia 30332	10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: John F. Kennedy Space Center, NASA, Kennedy Space Center, Florida 32899	12. REPORT DATE: June 1978
	13. NUMBER OF PAGES: 172
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same	15. SECURITY CLASS (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited Announce STAR

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Manatee	Automated Tracking System	Energy Sources
Trichechus manatus	Shallow Water Acoustic Tracking	DF Algorithms
Tracking	ELF Tracking	Marine Mammals
Direction Finding	HF Tracking	Biotelemetry
Remote Positioning	VHF Tracking	Electronics Encapsulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study identifies the electronic, physical, biological and environmental factors involved in the automated remote tracking of the Florida manatee (Trichechus manatus). The current status of the manatee as an endangered species is provided. Brief descriptions of existing tracking and position locating systems are presented to identify the state-of-the-art in these fields. An analysis of energy media is conducted to identify those with

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ABSTRACT Continued

the highest probability of success for this application. Logistic questions such as the means of attachment and position of any equipment to be placed on the manatee are also investigated. Power sources and manatee-borne electronics encapsulation techniques are studied and the results of a computer-generated DF network analysis are summarized. In each area of investigation, a recommendation is made based on the conclusions of the study. For questions where little or no information is available, a brief outline is given for experiments necessary to obtain this information. Those areas in which experimentation is required relate, for the most part, to the response of a tagged individual to the methods of tagging. The possibility of an ELF implementation is investigated in some detail since ELF frequencies (unlike any other electromagnetic or acoustic frequency) are capable of low attenuation propagation through great distances of both air and water. Experimentation is necessary to provide the additional information needed to demonstrate ELF viability; however, the extent of the current study indicates that an ELF implementation will likely be unsuitable in this application. The systems recommended by this study can be broadly classified (in order of performance) as (1) VHF time-of-arrival with time-segmented identification, and (2) acoustic proximity with VHF transponder and time-segmented identification.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Background

The Fish and Wildlife Service of the U. S. Department of the Interior has expressed their concern over the survival of the West Indian manatee (Trichechus manatus) and has placed it on the Endangered Species List. Insufficient information is presently available concerning the migratory habits of this species to initiate the proper steps to insure its preservation. The current population appears to be decreasing as a result of a loss of grazing territory and an increase in boating activity. If more information were known about their numbers, location at various times of the year, mating and feeding habits, and conditions relating to their decline, the appropriate agencies could take the necessary action to enhance their survivability.

In this regard, the Engineering Experiment Station at Georgia Tech has undertaken a study, the purpose of which is to develop a workable concept of an automatic tracking system which will enable the Fish and Wildlife Service to determine the location and movements of manatees in order to obtain more information concerning them.

Study Objectives and Scope

The overall objective of this study is to perform an exploratory analysis to evaluate various existing active and passive monitoring systems of potential application to the tracking of manatees, and if the results of the study warrant further development, a follow-on effort is to be proposed.

Statement of Work Requirements

In the execution of this study, three main requirements are set forth. First, a review of available background material and literature relevant to the technology of animal tracking must be performed. Next, the technical characteristics of an automatic tracking system must be defined, which is capable of identifying any of various manatees in the Banana River between KSC crawlerway and the Bennett Causeway (State Road 528) and record their locations at least once each hour. Finally, a proposal must be prepared for the construction of the tracking system defined above with the stipulation that the system be practically expandable to monitor most of the waterways in Brevard County, Florida.

The study evaluates tracking techniques and then identifies those techniques that satisfy near term requirements as well as having growth potential for satisfying the far term requirements. A brief technical description of each technique studied has been provided which describes limitations, capabilities, high risk areas and problem areas. In addition, existing systems capable of tracking multiple targets are identified.

Study Approach

The approach taken for this study was to define ten major tasks that would satisfy the statement of work requirements. The following major tasks were defined:

- Literature Search
- Overall System Technology
- System Configuration
- Power Source
- Electronics Placement
- Transducer Placement
- Passivation of Electronics Package
- Estimated System Effect on Subject Manatee
- System Release or Retrieval at End of Useful Life
- System Impact on Environment

Where applicable, selection criteria will be applied to each task in order to optimize the final recommended tracking system. The selection criteria are (not necessarily given in order of importance):

1. Performance
2. Cost
3. Reliability
4. Operational Life
5. Size
6. Weight
7. Interface to Manatee
8. Environmental Impact

Basically, overall performance will be rated in terms of range and accuracy of measurement. Performance is intimately linked to cost which is frequently proportional to complexity when applied to electronic systems. Reliability criteria consider such factors as mean-time-before-failure (MTBF) and ease of servicability. This includes all facets of the total tracking system, both electronic and mechanical (e.g., devices for securing electronic tag to the manatee , antenna masts, etc.). Operational lifetime, size and weight are all quantities to be optimized with trade-offs occurring between operational lifetime and size-weight limitations of the manatee-borne electronics in particular. The manatee-system interface involves a very important and largely unknown set of criteria. The objective here will be to modify the individual's behavior as little as possible as a result of the electronic tag. Also, extreme precautions must be taken to assure that the tag or the tagging process has no detrimental effect on the manatee. Finally, the environmental impact of each component of the tracking system must be assessed. Not only is it undesirable to perturb the natural setting (the manatee's habitat) but man's habitat (the airwaves, boating channels, etc.) must go unabused as well.

HISTORY AND ECOLOGY OF THE MANATEE

Design of an effective tracking system presupposes knowledge about the object being tracked. This section presents some of the background information assimilated during the literature search concerning the manatee both historically and from a behavior and physiological standpoint.

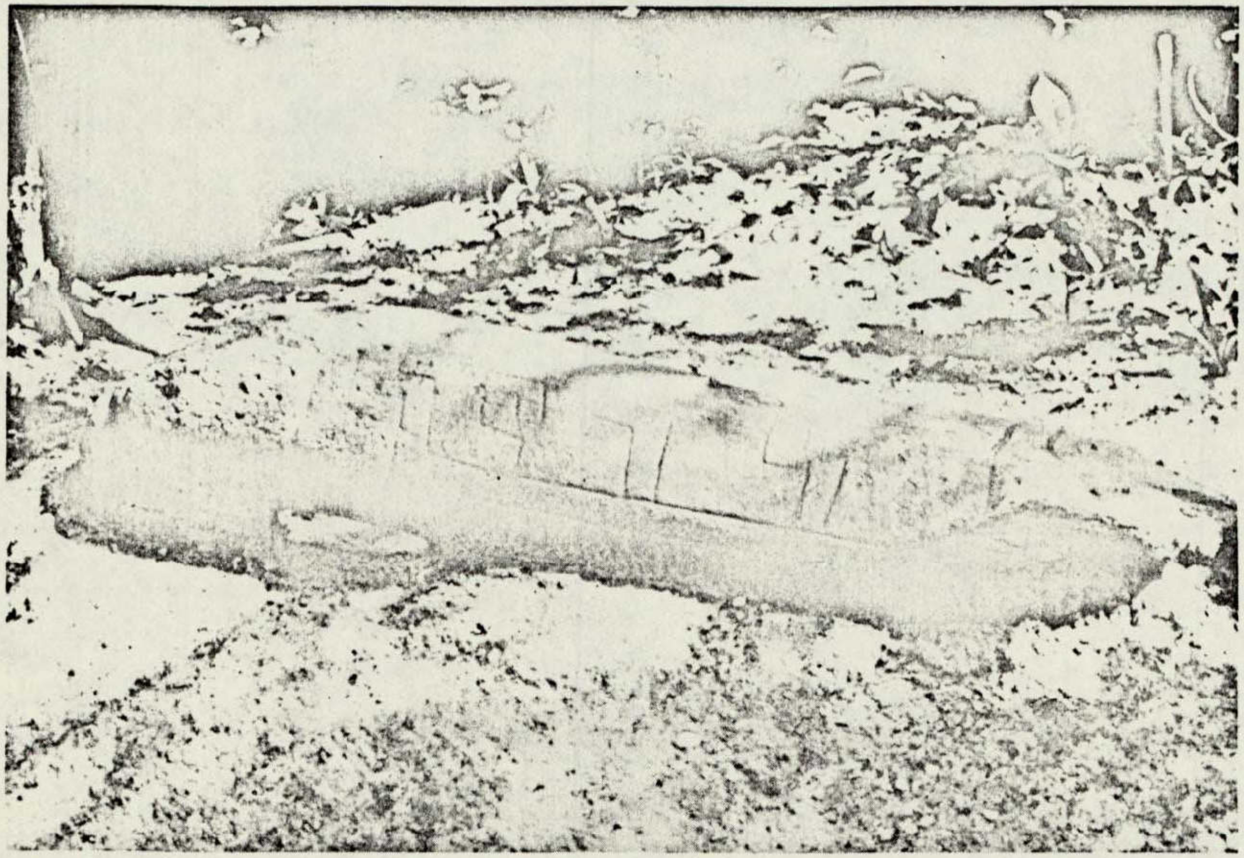
Early Sightings

Wednesday, January 9, 1493. Christopher Columbus, on his first voyage to the New World made the following observation in the ship's log as he sailed along the coast of what today is the Dominican Republic...

> *The day before when the Admiral* (C. Columbus) *went to Rio del Oro, he said that he saw three sirens, who rose very high from the sea, but they were not as beautiful as they are depicted, for somehow their faces had the appearance of a man. He says that on other occasions he saw some in Guinea.* [excerpt from a translation (1960) of the Bartolomé de las Casas manuscript based on the Admiral's original logbook]. [15]

Obviously Christopher Columbus was interpreting a manatee sighting in terms of the siren legends and sketches that he had encountered before coming to the New World, for this myth was widespread by his time. The seductive sirens of Greek mythology probably resulted from early sightings of sirenia in the Mediterranean area. Stories such as these permeated man's concept of aquatic life for centuries and even crept into German Romantic literature in the form of Lorelei who was a siren on a rock in the Rhine that lured boatmen to shipwreck by her singing.

These are actually relatively recent accounts, however, for there is evidence of man-sirenia interaction occurring over one thousand years earlier. Figure 1 is a photograph of a full sized manatee carving produced by the Olmecas, a mysterious people that flourished in the Yucatan before the time of Christ. In fact, there is some indication that the Ark of the Covenant, taken by the Israelites on their journey through Sinai was covered with Dugong (Dugong dugon) leather [7].



Olmeca Manatee Carving found
near Villahermosa, Mexico
Figure 1

Sirenian Range

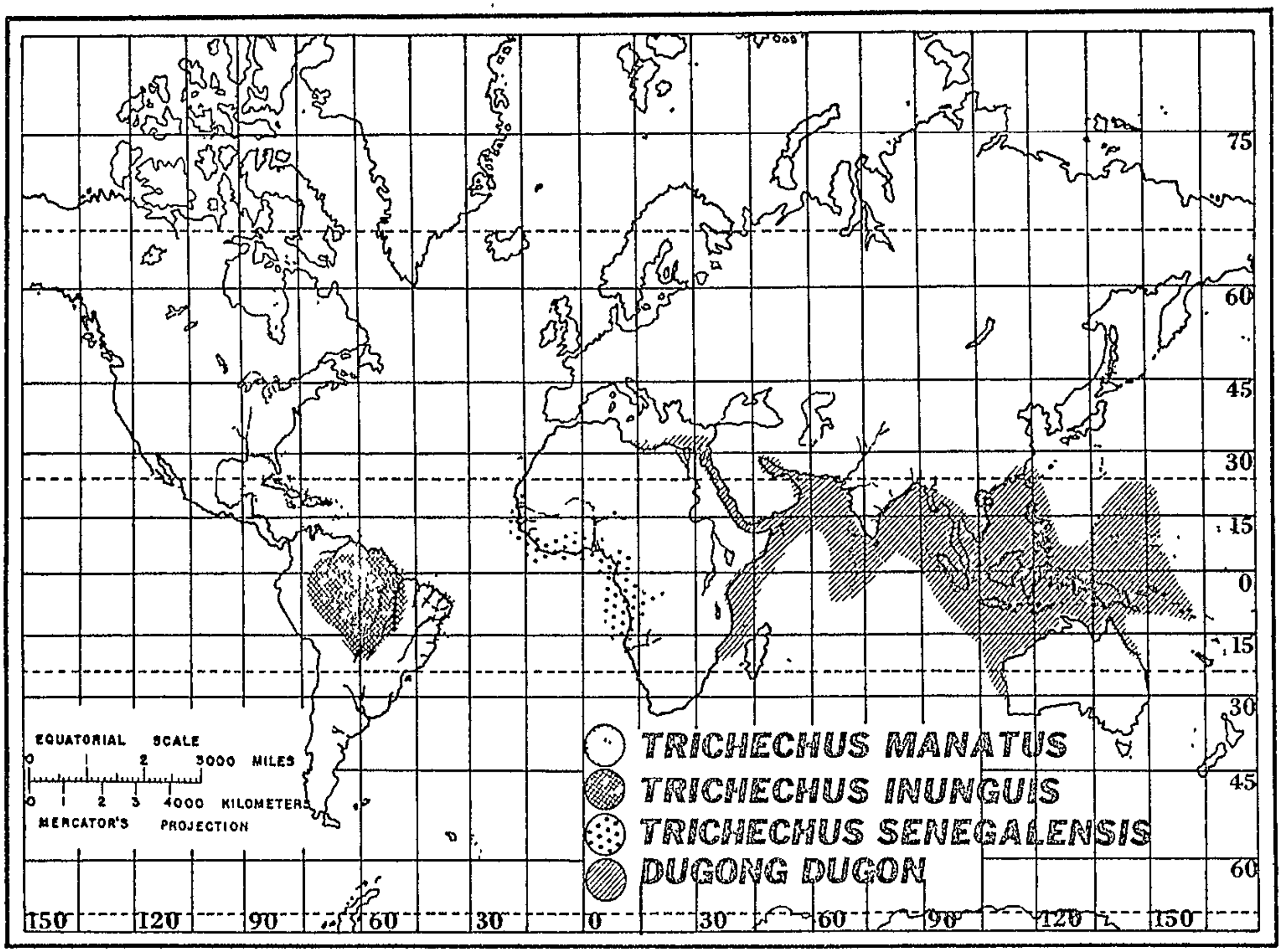
Sirenia inhabit most of the coastal and estuarine waters of the tropics and subtropics. More specifically (see Figure 2), the West Indian manatee (Trichechus manatus) inhabits the coastal waters around the Gulf of Mexico, Carribbean Sea and along the northern coast of South America; the Amazon manatee (Trichechus inunguis) is distributed solely in Brazil's Amazon River and its tributaries. The African manatee (Trichechus senegalensis) is found along the coastal waters of western Africa between latitudes 15° North and 18° South. The Dugong (Dugong dugon), a fork tailed cousin of the manatee, frequents the coastal waters of the Red Sea, the eastern coast of Africa around the Bay of Bengal and in the waters surrounding southeastern Asia, the Philippines, New Guinea, Indonesia and northern Australia. The now extinct Steller's sea cow (Hydrodamalis stelleri) was the only known cold water member of this family living in the Bering Sea.

The United States manatee population is concentrated in the coastal waters of central to southern Florida. Periodically, manatee sightings range as far northward as Georgia and west to Lousiana and Texas. Manatees are found in slow moving rivers, estuaries and salt water bays that are in excess of 1.5 to 2 meters deep. Four factors are dominant in the choice of habitat:

- Availability of aquatic vegetation
- Proximity of deep channels
- Warm water winter refuges
- A source of fresh water

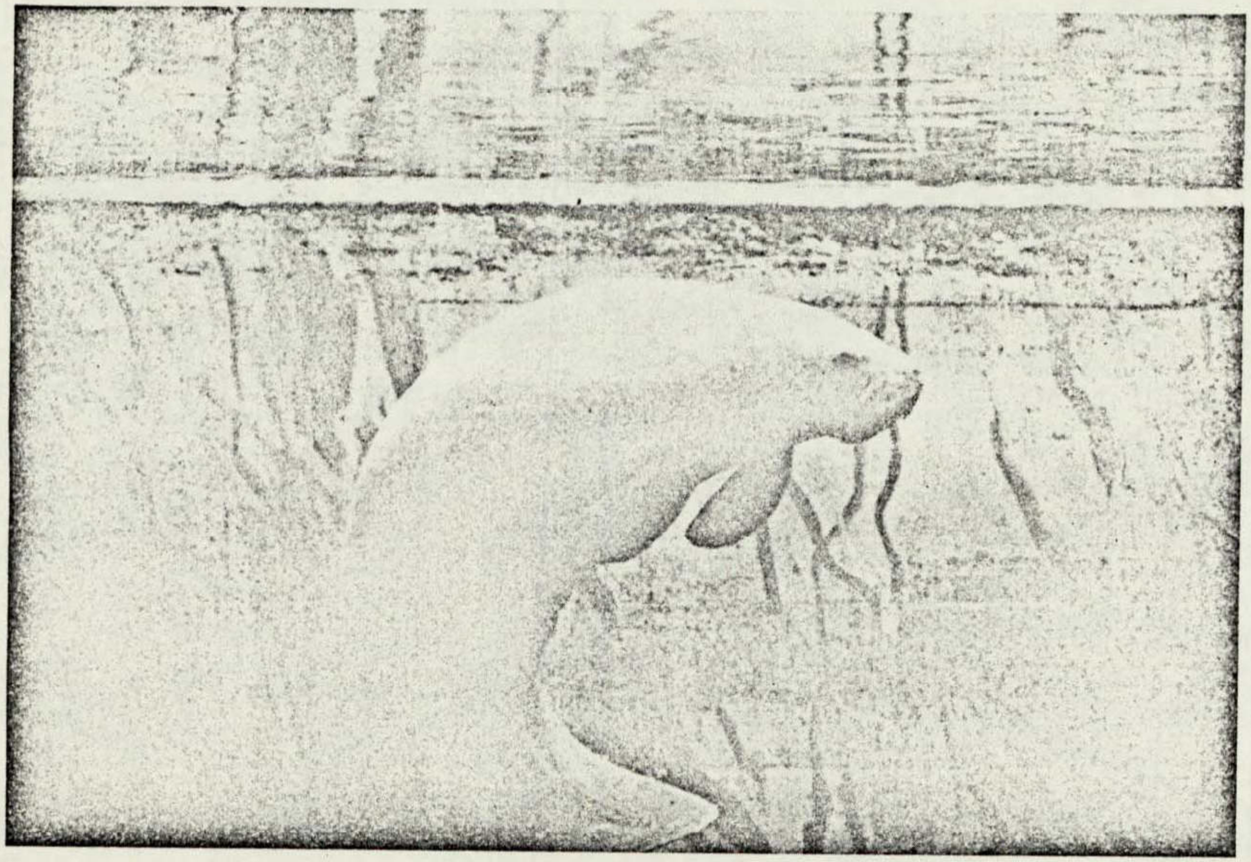
Physiology of the Manatee

The manatee, sometimes referred to as the "sea cow" is a large totally aquatic mammal that can achieve a length of as much as 3.8 meters and weigh approximately one metric ton though lengths usually range from 2.8 to 3.5 meters and weighs from 1/4 to 1/2 metric ton. The manatee is seal-shaped in appearance with gray or brown skin and a broad, spatulate tail (see Figure 3). The body is almost hairless except for bristly whiskers on the muzzle. The skin is quite thick changing from its darker outer color to a light pink, approximately 2 millimeters down from the surface. The blubber blanket under the skin may be several centimeters thick. The forelimbs are paddle-shaped with vestigial nails; the hind limbs are absent and the pelvis is represented



Global Sirenian Habitat

Figure 2



T. manatus in Captivity
Figure 3

by vestigial bones [37]. The nostrils are located on the upper surface of the snout and are tightly closed by valves when submerged and open when the manatee surfaces to breathe [1]. The upper lip is cleft and lobed which allows the manatee to maniuplate food into its mouth. Grinding molars, which form at the back of the jaw and wear down as they move forward are the only functional teeth in the Florida manatee. In contrast, the Steller's sea cow had no teeth at all. This replacement pattern may be an adaptation to eating plants mixed with sand [7]. The bones are massive and heavy and may function in buoyancy control [38,1]. One notable difference between the manatee and other mammals is the number of neck vertebrae. The genus Trichechus has six vertebrae while nearly all other mammals have seven [7].

Reasons for the Decline of the Manatee in the United States

The total number of manatees in the United States is estimated to be only about 850. This population figure is believed to be far below historical levels and is a direct result of man's encroachment in the manatee's natural habitat. This is exemplified no better than in the case of the Steller's sea cow (Hydrodamalis stelleri), a cold water member of the Dugong family, that was so avidly hunted by man that it was totally eradicated only 27 years after its discovery in 1742.

As European man began to colonize the New World, the previously secure existence of the manatee in the Americas was threatened as their hide was used for leather, their oil and blubber used for fuel while men cultivated a taste for their meat. The greatest pressure on the manatee population in the United States however, has come about in recent decades due to loss of grazing territory, motor boat inflicted injuries, poaching and the severe winters that have gripped the entire United States of late (including that last vestige of the manatee - Florida).

Perhaps the worst of these pressures is due to the loss of grazing territory. This results from coastal land development, water pollution and in some areas, the use of defoliants to keep boating channels clear of vegetation.

Motor boat inflicted injuries also take a heavy toll on the current population. Many manatees living in Florida have propeller scars on their backs where they have been run over by high speed motor boats; however, most do not survive such encounters with the whirling blades. Manatees will dive to avoid motorized craft when they hear them coming but unfortunately, numerous speedboat operators insist on racing at speeds of 40 to 60 mph in known manatee habitats. Under such circumstances, a manatee has little warning of the ensuing propeller. Another hazard is presented by barges which when moving through shallow water or docking, will often crush manatees.

Manatees are thought to be quite susceptible to the cold. Numerous manatee corpses are frequently found following a cold snap. During the winter, many manatees flee to more temperate southern Florida waters. A number of animals, however, congregate at some of Florida's natural spring fed rivers. At the head waters where fresh water wells up from the bottom of submerged sink holes, the water temperature remains a pleasant 74°F year round. In recent winters, manatees have been observed congregating in the hot water output flumes of Florida power generating stations. There is concern that manatees are being lured farther north during the winter by these man-made warm water refuges. In the event of an energy crisis in which power plants are forced to shut down, many manatees could be lost, thus increasing the likelihood of eventual extinction of the species in this range. Manatees have a slow reproductive rate and it would be difficult to restore initial population figures quickly since their gestation period may be as long as 13 months with a female typically producing only one calf every two or three years.

Legal Status of the Manatee

Currently, the Florida manatees are protected under both Federal and State law. Federal protection laws include the United States Marine Mammal Protection Act of 1972, which prohibits the taking, sale, possession, importation and transportation of specific marine mammals (including the manatee) within the United States. A Federal permit is required to capture manatees for any reason. Violators of this law can be imprisoned for one year and fined up to $20,000. In addition, the Federal Endangered Species Act of 1973 lists the manatees of Florida as an endangered species thus requiring a permit to handle dead of living manatees [3]. The state of Florida has enacted similar statutes establishing the manatee as an endangered species and the state itself as a sanctuary in which display of, or research on the mammal is strictly regulated. In fact, Florida was established as a manatee sanctuary by the English as early as the 16th century [3]. Unfortunately, the manatee continues to decline due in part to a lack of knowledge about what is conducive to manatee survival (thus hindering the legislation of effective positive action programs and laws) and the inability to adequately enforce the laws already enacted.

EXISTING REMOTE TRACKING AND POSITIONING SYSTEMS

Many remote tracking and positioning systems already exist and are currently in use on a world-wide basis. This section enumerates and briefly describes a number of these systems. Not all of those mentioned will be directly applicable to manatee tracking for various reasons. However, the principles of operation could be. The following is a list of acronyms for existing systems or system families. Items marked with an asterisk are briefly described in the body of this section.

- DECCA*
- OMEGA*
- CONSOL
- LORAN A, C, D*
- MLS (Microwave Landing Systems)
- VHF/UHF ILS (Instrument Landing Systems)
- ATCRBS (Air Traffic Control Radar Beacon Systems)
- LARIAT (MX Missile Facility Intruder Tracking System)
- TRANSIT*
- DME (Air Traffic Control Distance Measuring Equipment)
- EELS (U. S. Navy Electronic Emitter Locator System)
- AGTELIS (U. S. Army Automatic Ground Transportable Emitter Location and Identification System)
- TACELIS (U. S. Army Tactical Emitter Location and Identification System)
- GELLIS (U. S. Army Ground Emitter Location and Identification System)
- CIRIS (Completely Integrated Reference Instrumentation System)
- AROD*
- CR-100*
- TACAN (Tactical Air Navigation)*
- VOR (VHF Omnidirectional Range)
- ITNS (Inertical Tactical Navigation Systems)*
- DABS (Air Traffic Control Discrete-Address Beacon System)
- GPS/NAVSTAR (Satellite-Based Global Positioning System)*
- MISTRAM

- o AZUSA
- o PELSS (USAF Precision Emitter Location Strike System)
- o ELS (USAF Emitter Location System)
- o ALSS (USAF Advanced Location Strike System)
- o PLRS/SEEK BUS (USAF Position Locating and Reporting System)*
- o CAPER (Combined Active/Passive Emitter Rangings)
- o SHIRAN*
- o RMS-2/DCS*
- o RMS/SCORE*
- o ARIS*
- o PATS*
- o A-7E*
- o ACRS*
- o JTIDS-RELNAV*
- o TASK 4*
- o AFWET-WESTE*
- o MTTIS*
- o RAYDIST T*
- o PARTS*

DECCA, OMEGA, LORAN, LORAN/Inertial, TACAN and TRANSIT are all user orientated systems and, with the exception of TACAN, passive in the sense that the user does not transmit any signals to determine his position. The TACAN system requires the user to transmit pulses which are replied to by a ground station in order to determine range and bearing. None of the systems have a central location reporting capability.

DECCA, OMEGA and LORAN are hyperbolic position systems. The user determines position from the intersection of two known hyperbolic lines. These lines are determined by measuring the range difference between the user and land-based stations, properly spaced and normally operated in groups of three.

The LORAN/Inertial system is a hybrid configuration which combines the long term accuracy of LORAN with the short term accuracy of an inertial measuring unit (IMU). The synergistic use of LORAN and an IMU results in positionings that are far more accurate than those of LORAN or an IMU alone.

The LORAN/Inertial system can operate day or night and under all weather conditions. The frequencies used are noninterfering with Air Traffic Control signals and known threat equipment.

TACAN is a line-of-sight system with ground-based stations from which users obtain range and bearing. The user must transmit an RF signal to the TACAN station to obtain a range measurement. Bearing is obtained by phase measurement.

TRANSIT is a space-borne navigation system which uses satellites as reference stations. The user measures the doppler frequency of the satellite and translates this into hyperbolic lines of position on the surface of the earth.

DECCA Navigation System [4]

The DECCA navigation system consists of four ground stations, one master and three slaves. Low frequency radio emissions from all stations are phase-locked to and harmonic multiples of the master station signal. A user receiver multiplies the received signals from any two stations to obtain a common comparable frequency. The measured difference in phase between signals determines a hyperbolic line of position for the user.

Typical accuracy is ± 1 n.mi at 120 n.mi range from the master station and ± 5 n.mi. at 250 n.mi.

The system is continuous in operation and the user's position is plotted in rectilinear coordinates by a DECCA X-Y type plotter. The time constant associated with this equipment is approximately 0.6 sec.

OMEGA Navigation System [4]

OMEGA is an earth-referenced navigation system operating between 10.2 and 13.6 KHz. At present, four stations are operating although eight stations are planned to provide world-wide coverage. Each station transmits on synchronized frequencies of 10.2, 13.6 and 11.33 KHz in sequence. At each frequency a unique family of hyperbolic lines-of-position (LOP's) is generated by phase difference measurement between two stations of a synchronized pair.

Single frequency OMEGA is the standard configuration. The basic measurement is the phase of the 10.2 KHz signals from each of several stations.

Phase differences between two pairs of stations are measured and two LOP's are obtained. Position is then determined at the intersection of the LOP's.

Phase measurement results in multiple ambiguous position possibilities since a phase difference of X degrees cannot be distinguished from a phase difference of X $\pm$360n degrees. At 10.2 KHz, the position uncertainties, called lanes are spaced 16 n.mi in distance. The position uncertainties can be resolved by starting from a known geographical position and counting lanes or using difference frequency OMEGA. In this mode, the 10.2 and 13.6 KHz signals are used to create a 3.4 KHz difference frequency. The resulting lane width is 24 n.mi. thus decreasing the lane identification problems.

LORAN Navigation System [4].

LORAN is a hyperbolic system of navigation. A measurement of the difference in times of arrival of signals from two points by a receiver provides a measure of the difference in the distance of the propagation paths. Measurement of the time differences and hence the distance differences places the receiver on a hyperbolic line-of-position. Measurments from a minimum of three stations, taken in pairs, are required to obtain a navigation fix. The intersection of the two lines-of-position defines the receiver location.

A LORAN triad consists of one master and two slave stations. The master station initiates RF transmissions at time zero. Each slave station receives these transmissions and phase and frequency locks its receiver to the master station's transmissions. After a prescribed time delay, different for each slave station, each slave station transmits a pulse group. There is no overlap in transmissions from any of the stations.

The receiver synchronizes to the master and slave transmissions and determines the time differences. With knowledge of the slave station time delays, these differences are translated into lines-of-position.

LORAN-D/Inertial Navigation System [4]

LORAN-D/Inertial is a hybrid navigation system which integrates data from an inertial measuring unit with position information derived from LORAN/D signals. The inertial dead reckonner has high short term accuracy and is able to follow maneuvers of the user. Long term accuracy, however, is poor due to gyro drifts.

Position data obtained from LORAN-D signals has excellent long term accuracy, thus, the hybrid system which results from combining the two has better overall accuracy characteristics than either subsystem separately. In general, the greater the accuracy of the inertial equipment, the larger the reduction in position error over the unaided LORAN-D system.

Although several integration schemes are possible, the most accurate inertial platforms usually require Kalman filtering techniques to achieve their ultimate accuracy. For a state-of-the-art 0.25 knot inertial system, a reduction in positioning uncertainty from 300 ft. to 78 ft. or a factor of 3.85 times is possible neglecting errors due to geometrical dilution of precision and topographical distortion of the earth's magnetic field (warp).

Warp errors, however, may be large enough to make in unnecessary to incorporate an exceptionally precise inertial unit. Overall improvement in position accuracy accounting for warp errors may be typically 12% over an unaided system with little sensitivity to inertial unit accuracy.

TACAN Navigation System [4]

TACAN is a tactical air navigation system which provides an aircraft distance and bearing from a selected ground station within line-of-sight range.

The user sends pulses that are replied to by a ground station. The elapsed time between the user sending and receiving a reply is used to determine the distance to the station. The nominal system accuray is 0.17 n.mi. The distance-measuring replies from the ground station are amplitude modulated by a rotating directional antenna. This signal is compared with a reference signal sent by the ground station, the phase difference between the two giving the bearing to a nominal accuracy of one degree.

The available frequency band is between 960 and 1215 MHz and is split into 252 channels. Each ground station is assigned one receive and one transmit channel and can reply to about 100 aircraft simultaneously.

TRANSIT Navigation System [4]

The TRANSIT navigation system uses four orbiting satellites to enable users to calculate position fixes every 110 minutes.

With simple user equipment, position accuracy is 0.5 n.mi. Elaborate equipment will improve accuracy to 0.1 n.mi.

The satellite emits a stable radio frequency signal. The user receives the signal and infers its position with respect to the satellite by measuring the doppler shift in frequency due to the relative velocity between the user and satellite.

To provide the required doppler data, a satellite is equipped with a transmitter containing a very stable oscillator. As the satellite passes within receiving range, its signals provide a doppler curve as well as its orbital parameters and the precise time. The slope of the doppler curve determines the distance between user and satellite. The point of closest approach from satellite to user occurs when the Doppler shift is zero. Thus, knowledge of the time of signal transmission, the position of the satellite in space, the doppler curve and the velocity of the user can provide a navigator with his true position.

Four ground tracking stations monitor satellite emissions and make corrections for atmospheric refraction. One master station also controls satellite clock settings and regulation. All of the above correction information is relayed to a ground injection station. Once every twelve hours, the injection station transmits the correction data to each of the satellites, at which time it is entered into the satellite memory unit.

Table 1 gives a condensed comparison of the above systems.

Hastings-Raydist Radiolocation System [4]

The Hastings-Raydist system is a continuous wave navigation system operating in the 1.6 - 4.0 MHz frequency band. (X,Y) coordinate location is computed by each user based on the phase delay experienced by continuous wave signals propagating through free space. No elevation (Z axis) information is available, however.

In use, the Raydist T system has demonstrated position accuracy of 10 ft. RMS, with a resolution of 1.5 ft. Usable range is 200 n.mi. during the day and 150 n.mi. at night and is limited by skywave interference.

Since the system is user oriented, no central location reporting capability exists. The system has been designed primarily for marine navigation.

TABLE 1 : COMPARISON OF SOME EXISTING NAVIGATION SYSTEMS

	DECCA	OMEGA	LORAN	LORAN/INERTIAL	TACAN	TRANSIT
PRINCIPLE	Phase	Phase	Pulse and Phase	Pulse and Phase and Inertial	Pulse and Phase	Phase Doppler
FREQUENCY BAND	100 kHz	10.20, 11.33 & 13.60 kHz	100 kHz	100 kHz	960 to 1215 MHz	150 MHz 400 MHz
NUMBER OF USERS	Unlimited	Unlimited	Unlimited	Unlimited	100	Unlimited
RANGE	250 nmi Radius	Worldwide (1972)	200 nmi Radius	200 nmi Radius	400 nmi Radius	Worldwide
ACCURACY (X and Y)	0.25 nmi	1 to 2 nmi	300 to 3000 ft	± 64 ft	± 200 ft ± 1°	0.1 nmi
POSITION UPDATE INTERVAL	0.6 s	Near-real time	Near-real time	Near-real time	Near-real time	6 to 22 min every 108 min
RESOLUTION	50 ft	400 ft	60 to 300 ft	128 ft	±50 ft ±0.1°	50 ft

Inertial Tactical Navigation System (ITNS)-Singer Company [4]

The Singer ITNS is a cooperative ranging system which employs clocks and frequency sources at all user and ground station locations which are precisely synchronized in relative frequency and time with those of a master control station. One way RF transmissions from the master station are received by each range member. Since the master station and range member clocks are synchronized, the time difference from the ranging message initiation time to the time of receipt of the message is known by the range member and slant range can be computed. This range data together with information from an on-board dead reckoning inertial system is processed by the range member to obtain an optimal estimate of position.

All range members report their position, in a predetermined sequence, to all other range members and the master station. The additional information obtained by each range member in this procedure is used to further refine the position estimate to be reported during the next cycle.

Information reported to the master station can include estimated position, inertial parameter values and digital communications information on discrete events.

In addition to clock synchronization and identification, the ITNS system provides 1024 slots per second during each of which up to 300 bits of digital data may be transmitted from range members to the master station. This scheme provides more than adequate capacity to permit obtaining position, attitude and 100 bits of discrete event data on twelve aircraft ten times per second and four aircraft fifty times per second.

Since the reporting scheme is preset before the mission, a selection of four subset members would have to be made prior to an exercise and could not be changed at will.

The equipment carried by an ITNS range member consists of a ranging system, a computer system, an integrated inertial navigation system, appropriate interface electronic units and power supply equipment.

Task 4 - International Business Machines Corporation [4]

The Task 4 system was designed to provide guidance information for up to seven cooperative aircraft.

For the aircraft tracking and guidance function, a sequential interrogation, pulse type ranging technique enables computation of aircraft position in accordance with a multilateration algorithm.

An interrogation command signal is originated by the Ground Command Station (GCS). Digitally encoded identification information specifies the aircraft of interest and the GRS to be used for that interrogation. All aircraft carry a pod-mounted transponder which will transmit a ranging reply upon receiving a properly addressed interrogation signal. The ranging replay passes through the same GRS and is retransmitted to the GCS station. The transponder time delays are known and the GSC to GRS range is known either from a geodetic survey or by interrogation of a calibration transponder at a known location, therefore, slant range from the GRS to the subject aircraft can be computed. Calculating three ranges from the GRS stations to the subject aircraft in this manner, it is possible to uniquely determine the three axis position coordinates of the aircraft.

Since the Task 4 system does not incorporate an Inertial Measuring Unit (IMU), no aircraft attitude data is available. Also, since no IMU data is available to minimize errors due to aircraft maneuvering, the member aircraft are limited to level flying at slowly changing altitudes. There is no data available, however, on the dynamic limits of the system in its present form.

Three GRS stations are employed in addition to the GCS station. Position updates can be obtained at a 70/second rate on one aircraft or approximately 10/second on seven aircraft. Present range size is in excess of 80 n.mi. with good geography.

Air Force Weapons Effectiveness Testing - Weapons Effectiveness System Test Environment (AFWET-WESTE) - Raytheon Company [4]

The AFWET-WESTE system can obtain position, attitude and identification information on 15 cooperative aircraft and position and identification information on up to 11 ground units of which 10 are fixed and one is mobile. Both coarse and fine position locating subsystems are carried on-board each member.

Coarse position is obtained passively from a DECCA navigation set with an accuracy of approximately 400 ft. (1 σ). Fine position of the member with respect to the ground master station, other range members or any fixed, instrumented ground element is obtained from a precision Position Reference Radar/Transponder (PRRT). The aircraft is active during fine position measurement in that RF energy must be emitted. The fine position accuracy is $\pm$ 5 ft. in range and 2 milliradians in azimuth and elevation angles.

The DECCA navigation system is a CW-type operating on 100 KHz and employs one master and three slave stations each requiring a large (300 ft. high) tower. CW systems suffer degraded position accuracy at low aircraft operating altitudes. Attitude information is obtained from the aircraft's own instrumentation and a modification kit is necessary for each different type of aircraft using the range.

All range elements report their position to the master station. Time multiplex UHF radio transmission enables down-link reporting for airborne range members. Ground units report on individual UHF frequencies. Up-link communications from the master station to range members use the same techniques.

In addition to a transmitting and receiving antenna at the master station, a 1200-ft. tower located at one side of the range is employed to minimize data loss from antenna shadowing due to aircraft maneuvering. A second radar transponder is mounted through the top of the aircraft fuselage to further minimize this data loss.

The position and attitude update rate for all range members is 10 per second and is hardware controlled. Therefore, no higher data rate on a subset of aircraft can be obtained with present system components.

Data analysis and display is performed in essentially real-time. An IBM 360-65 handles data processing for the system. Alphanumeric read-out and major event annotation are provided in addition to the basic two dimensional display capability.

The AFWET-WESTE system can also provide trajectory simulation for bombs, bullets, rockets and missiles as well as kill/no kill assessment and miss distance calculations.

Multiple Target Tracking and Identification System (MITIS) - General Dynamics [4]

The General Dynamics MITIS is a proposed system for which the ranging system hardware has been built and tested. A three baseline interferometer is used to measure two angles (azimuth and elevation) plus range to uniquely determine the position coordinates of a cooperative aircraft.

A coded ranging interrogation signal is transmitted from the ground station. The aircraft whose identification code matches that of the ranging signal retransmits the signal to the ground. The difference in phase of the signal as received at two locations on the ground is proportional to the angle between the receiver baseline and a radial vector to the aircraft.

Slant range to the aircraft is determined by measuring the difference in phase between the ranging transmission and the reply signal as received at the master station ranging receiver. This phase difference is proportional to the two-way ranging distance to the aircraft, since the transmitter and ranging receiver antennas are colocated.

Simulation based on an error model of the three baseline interferometer predicted position errors of less than 50 ft. in X, Y and Z. Tests with a vertical baseline interferometer confirmed the value assumed for worst-case multipath errors which is the largest error term for a CW ranging system.

Phased Array Ranging Trilateration System (PARTS) - Radio Corporation of American [4]

PARTS is a RCA proposed system which would employ multiple phased array radar stations to obtain range and range rate data on aircraft. A multilateration algorithm would be used to compute aircraft position and velocity.

Each phased array radar would have a 60 degree electronic scan in elevation/azimuth and a 60 degree mechanical scan in azimuth/elevation.

The basic range would be an equilaterial triangle 43 n.mi. on a side. Adding a fourth station would produce a parallelogram-shaped range. The long diagonal of this range is 75 n.mi.

Each phased array radar can track a target having a 1 square meter cross section at a maximum range of 75 n.mi. Basic accuracy of the radar is predicted to be 1 ft. in range and .05 mil in azimuth and elevation. Using these figures, RCA predicted a position accuracy of 1.73 ft. in X and Y for aircraft between 1000 and 50,000 ft. altitude. Z accuracy was predicted to be 8.7 ft. for aircraft between 10,000 and 50,000 ft. AGL, 19 ft. for aircraft between 5,000 and 10,000 ft. AGL and 43 ft. for aircraft in the 2000-5000 ft. AGL region.

The GPS System

The GPS is a space-based radio navigation system currently being developed under management of the United States Air Force (USAF) Space and Missile Systems Organization (SAMSO) GPS Joint Program Office (JPO). The GPS consists of three segments: Space Segment, Control Segment, and User (UE) Segment. The operational Space Segment will consist of three planes of satellite vehicles (SV's) - eight SV's per plane - in circular 10,900 nautical mile 12-hour orbits. This deployment will insure that at least six SV's are continuously in view from any point on earth, thus providing global coverage. Each SV will broadcast L-band signals (thus achieving all-weather coverage) containing information as to its position. The Control Segment will consist of the ground stations necessary to track the SV's, monitor the system operation, and periodically provide corrections to the navigation and time signals. The UE Segment will consist of the hardware and software necessary to receive, process and convert the SV signals into useful navigation information. By receiving signals from four SV's, the user can calculate and display three dimensional position and velocity and system time under the operating coditions associated with the host vehicle. Signals of two precision levels are transmitted to provide the opportunity for user investments to match navigation requirements.

The space vehicle navigation system provides continuous earth coverage for a navigational signal comprised of both a clear/acquisition (C/A) signal and a precision (P) signal on one L-Band carrier and a precision (P) signal or a (C/A) signal on a second L-Band carrier. The navigation signal is composed of pseudo-random noise (PRN) ranging code signals. Superimposed data provides satellite system time for acquisition aiding, the space vehicle ephemerides and clock correction.

PRN phase modulated signals are generated and radiated in two bands, L_1 and L_2. The L_1 carrier components are bi-phase shift key (BPSK) modulated by separate PRN codes which contain the required navigation information. One carrier component is the precision (P) navigation signal and the other is the clear/acquisition (C/A) signal. The P and C/A carrier components are in phase quadrature and their relative RF power levels depend upon which of the two operating modes is utilized. The L_2 carrier signal is bi-phase modulated by the same P or C/A signals used to modulate L_1, selectable by ground command. The L_1 and L_2 carriers and all modulation rates are derived from a common frequency source.

Characteristics of the baseband P and C/A codes are as follows with the frequency and time tolerances being controlled by the SV frequency standard.

	P	C/A
Chipping Rate (Mbps)	10.23	1.023
Code Repetition Period	7 days	1 millisecond
Data Rate (bits/sec)	50	50
Frame Length (bits)	1500	same

The transmitted system data D(t) carries space vehicle ephemerides, system time, space vehicle clock behavior data, system status messages, and C/A to P signal handover information. The data stream D(t) is common to both the P and C/A signals on both L_1 and L_2.

GPS is expected to be partly operational, with two dimensional navigational service (9 SV's) in 1981. Full operational status (24 SV's) is projected for 1984.

To summarize, some of the capabilities afforded by GPS are:

- o Wide area, global coverage
- o Three dimensional position and velocity
- o Real-time, continuous access
- o Compatible with rapidly maneuvering aircraft
- o No user radiation required
- o No system saturation
- o Compatible with many user classes

Expected current GPS accuracies are:

- o Position (x, y, z): 10 meters
- o Velocity (x, y, z): 0.5 m/sec
- o Synchronized Time: 20 nsec

JTIDS-RELNAV

The Joint Tactical Information Distribution System (JTIDS) is an L-Band, synchronous, time-division multiple-access (TDMA) spread spectrum system which provides passive, high-accuracy (PN codes) relative navigation (RELNAV) with respect to other terminals within a net of users.

Multilateration ranging techniques are used; however, the basic observable is a TOA measurement used in conjunction with appropriate position estimators (Kalman filtering). Although RELNAV involves relative position-fixing between users, absolute position data can be obtained if some of the terminals have independent knowledge of geographic position.

Position-fixing algorithm, least-square estimation and coordinate conversion programs are resident in a tactically-expedient minicomputer.

JTIDS-RELNAV represents the operational state-of-the-art in tactical radio position-fixing from the viewpoint of technique, hardware and software.

The following outline is a condensation of the characteristics of a number of additional position locating systems. It includes systems with ranging only, as well as systems combining range and inertial measurement. One system is a laser radar which measures azimuth, elevation, and range to the target from a ground based site.

AROD, (RRS)

A. Data Source/References (all by Motorola)
   1. AROD Test and Feasibility Demonstration Program Definition
   2. AROD Vehicle Tracking Receiver Design
   3. AROD System Concept
   4. AROD System Test Model
   5. AROD Test Model Hardware
   6. AROD Flight Demonstration Proposal
   7. AROD Flight Demonstration Test Report

B. Operational Description
   1. Three or more ground-based, completely automatic transponders
   2. Space vehicle based interrogator
   3. Space vehicle based computer

B. Operational Description continued

4. Range modulation: $\pm$ 90° phase shift, PN code

5. Readout: 4/sec.

6. Acquisition: 2 sec.

7. PN code: Low clock rate for acquisition; high clock rate for tracking

   Length: 6.084 x 10^6 count equivalent

   Down Link: 2.214 GHz

   Up Link: 1.800 GHz

   Command: 137.5 MHz

   Transponders: 60

   S-Band: 20W

   VHF: 6W

   Threshold: -126 dBm

   Dynamic range: 27 dB

   N.F.: 8.3 dB

   Power Required:

   Interr: 143W

   Trans.: 220W

   Tracking BW: Range, 4-5 Hz; carrier, 200 Hz

   Signal: As strong as -70 dBm degrades the performance

C. Employment (Scenario)

Range and range-rate measurements from space vehicle to ground are transmitted on a turn-around S-band link. Range is determined from two-way time delay; range rate, from Doppler shift of S-band carrier frequency. PN code length assures no ambiguity within 3.042 x 10^6 m. Transponders are phase locked loop tracking type--not easily adapted to multiple interrogators.

Interrogation of three transponders is simultaneous, while fourth is being acquired. Pick-up and drop are automatic, controlled by range.

D. Principal Sources and Magnitudes of Error

1. Range to position geometrical blow-up error (GDOP) 10 times the range error

D. Principal Sources and Magnitudes of Error continued

2. Survey error 1×10^{-5}

3. Altitude measurement error (negligible if calibrated during line crossing)

4. Equipment error 0.7 feet RMS

5. Atmospheric propagation velocity error, 6×10^{-6}

E. Accuracy Specifications (bench test)

Range

Resolution 0.25m
Accuracy $\pm$ 0.5m (0.75m, with 26 dB co-channel interference)
R max, 2×10^6m (unambiguous range)

Range Rate

Resolution 0.02 m/s
Accuracy $\pm$ 0.015 m/s
$\dot{R}$ max $\pm 1.2 \times 10^4$ m/s
$\ddot{R}$ max 450 m/s^2 (for 20 sec)

F. Cost Estimate

10's of thousands of dollars for transponders

G. Availability

No working system exists

<u>CIRIS, Litton/Cubic CR-100</u> (RRS, IMU, Kalman)

A. Data Source/References

1. CIRIS Design Evaluation Report [6]

2. Precision Ranging System, CR-100 brochure

3. Study of Instrumentation Methods for Precision Determination of Aircraft Position, Velocity and Attitude (Motorola)

4. Telephone conversations with:

   (a) Richard Pearson, Holloman AFB

   (b) Bard Crawford, TASC

   (c) Visit to Litton and Cubic

5. Post-Flight Filtering and Smoothing of CIRIS Inertial and Precision Ranging Data

B. Operational Description

1. Radio Reference System: Ground based transponder (R and $\dot{R}$), Cubic CR-100

2. Airborne interrogator

B. Operational Description continued

3. IMU: Litton AN/ASN-86, with Navigation Computer Unit, which uses barometric altimeter input to vertical channel

C. Employment

Sequential interrogation from airborne reference platform of the ground site transponders, at rate of 5 sec per transponder, 15 sec for three units. Range and range rate are obtained at same time in each interrogation. Dropout of one transponder and pickup of another, to get optimum location accuracy, is possible. The RRS may be viewed as reinitializing the IMU, or the IMU can be viewed as a smoothing filter to give continuity of data between RRS interrogations. A 10-state Kalman filter permits the hybrid system to be more accurate than either component (IMU or RRS) alone, provided the filter is properly designed. This implies good prior knowledge of the characteristics of the sources of error.

D. Principal Sources of Error

1. IMU sensors (gyros and accelerometers)
2. Attitude readout
3. Range measurement (scale factor and atmospheric disturbances)
4. Range rate measurement
5. Barometric measurement
6. Survey
7. Computer mechanizations

E. Accuracy Specifications

Position: 12.5 feet RMS (150 mile maximum spacing between transponders)

Velocity: 0.05 ft/sec RMS

Attitude: 15 sec/axis RMS

F. Cost Estimate

$100,000 for each transponder (space shuttle version)

$1,500,000 for airborne unit

G. Generic system

Is operational at Holloman AFB

AC Carousel/Cubic CR-100 (RRS, IMU, Kalman)

A. Data Sources/References: same as CIRIS (see above)

B. Operational Description

   1. RRS: Cubic CR-100, range only, ground based

   2. Airborne interrogator

   3. IMU: AC Carousel IV, with 32-speed resolver for azimuth readout

   4. Northrup NDC-1051A computer

C. Employment

Same as CIRIS system except that Kalman filter has 22 states (including 3 for survey errors when in "survey mode"). Every fifth measurement is the output of an altimeter and four transponders are interrogated cyclically rather than three. Every 10 seconds the system is updated by a single scalar measurement, so 50 seconds is the period of an interrogation cycle.

D. Principal Sources of Error

Same as CIRIS system but with bias tip rate in place of azimuth gyro scale factor error and certain other sensor errors. Absence of range rate information as an independent measurement affects error distributions and magnitudes.

E. Accuracy Specifications: Same as CIRIS system

F. Cost Estimate

$100,000 for each transponder (space shuttle version)

$1,500,000 for airborne unit

G. Generic System is operational at Holloman AFB

SHIRAN (RRS)

A. Data Source

   1. Study of instrumentation methods for precision determination of aircraft position, velocity and attitude (Motorola) .

   2. SHIRAN Geodetic Survey System, Electronic

B. Operational Description

   1. 3 GHz

   2. 4 of 6 transponders at a time

   3. 500 miles capability

B. Operational Description continued

4. Preflight calibration (pole beacon)
5. Interrogation: 12 millisec, each station, every 0.1 sec.
6. 4 sinewave frequencies, lowest gives least significant digit = 500 miles
7. ϕ modulation $\pm$ 12 rad
8. RF BW = 35 MHz
9. Continuous range tracker, 10 samples/sec input, 22 bits @ 5/sec (110 bits/sec) output
10. Receiver: -107 dBm sensitivity
11. Transmitter power: 20W, airborne and ground units
12. Antenna gain: A/C, 8 dB; ground, 18 dB
13. Transponder: 250 lb. 50 foot pole mounted, must be monitored
14. Dynamic range: not designed for short transmission paths

C. Employment Scenario

Aerial surveying. Calibration by pole beacon; line crossings for range and altitude calibration during flight. Adaptable to multiple users and to slaving.

D. Principal Sources of Error

1. Atmospheric effect of index of refraction along propagation path.
2. Accuracy of survey of benchmarks used for reference.
3. Calibration errors.

E. Accuracy (measured)

1. Position resolution: 9 inches
2. Position accuracy: 3 m (includes propagation and survey error)

F. Cost Estimate

- $25,000 for each six transponders
- $200,000 for airborne interrogator

G. Availability: Exists, has military designation, AN/ASQ-32

PLRS Hughes/Gen. Dynamics (RRS)

A. Data Source/References: personal notes

B. Operational Description

1. One master unit, one sub-master unit

B. Operational Description continued

2. Many man-packed, surface vehicular and airborne units
3. Range measurements
4. Trilateration computes three dimensional position
5. Unit display of position, navigation, related information
6. Time slot reporting
7. 100 message types
8. 1.875 second reporting cycle (frame)
9. 9 millisecond range/message time slot, 900 per frame
10. Aircraft reporting cycle: 2 seconds at 15 per second maximum rate for a mix of users

C. Employment

Tactical data support system for command and control of deployed amphibious assault forces. Capacity: 370 users.

D. Principal Error Sources

Probably equipment, since accuracy specifications are poor

E. Accuracy Specifications

Zone A	Az	El
slow, fixed wing a/c	50 m	50 m
high speed	200 m	200 m
Zone B		
slow	200 m	200 m
high speed	400 m	400 m

F. Cost Estimate: Several million dollars for a full system

G. Availability: Operating system at Navelex, Fleet Marines

RMS-2/DCS (Range Measuring System Data Collection System), General Dynamics

A. Data Source/References: Notes, brochure

B. Operational Description

1. Fixed and mobile interrogation (A units)
2. Relay (D units)
3. One centralized, computer interfaced (C unit)
4. Range [C/A or D:9km; A/B:64km(LOS)]. By command from C unit, A unit interrogates B unit by sending a ranging pulse, measuring time to response, sending 15-bit number to C unit

B. Operational Description continued

   5. Time Slot: 0.744 percent duty cycle/B unit

   6. WWV synchronization

C. Employment

   Cylinder 20 miles diameter, 20,000 ft. altitude. Men, vehicles, aircraft. Position and communication. C unit uses simi-trailer (10 tons) scaffold tower, parabola & omni antennas. Full computer/terminal equipment. Power required: 18 kW. A-station has erected tower & unmanned electronics.

D. Principal Sources of Error

   1. Survey errors for C and A units

   2. Propagation errors

   3. Equipment errors, A/B units, including A unit clocks

E. Accuracy Specifications

   1. Position, ±3 meters, with respect to known reference in x,y,z coordinates

   2. Precision of ranging: ± 2 meters

   3. Clock must thus have pulse jitter less than ± 7 nanoseconds

   4. ±20 meters reported as experienced Yuma Proving Ground

F. Cost Estimate: C unit: $350,000; A unit: $50,000; Micro B unit: $35,000 each

G. Availability: Operational at Yuma Proving Ground

RMS/SCORE, General Dynamics (RRS, IMU, Kalman)

A. Data Source/Reference

   1. Trip reports

   2. Brochures

B. Operational Description

   Same as RMS-2/DCS, with additions of SCORE (Simulated Combat Operations Equipment), large scale computer capability & large screen 3-D real time display. SCORE has an aircraft sub-system which includes:

   IMU (strapdown)
   Signal conditioner
   Micro B transducer
   Antenna and radome
   Air data unit

C. Employment

Extends RMS-2/DCS from primarily locating ground based equipment and low flying support aircraft to include high-flying aircraft.

D. Principal Sources of Error: IMU, and same as in item VI

E. Accuracy Specifications

Position: 25 feet any axis

Velocity: 15 feet/sec

IMU:

Accelerometer bias (3σ): 2×10^{-3}g
Accelerometer misalignment (3σ): 205 $\widehat{sec}$

Flight test errors (in good, transitional, and bad geometry regions)

X and Y: $\pm$ 4 meters
Z: $\pm$6, 8, 10 meters
Roll and pitch: $\pm$ 1 degree
Yaw: 1.5, 2.0, 2.5 degrees

F. Cost Estimates

SCORE pod: $100,000

Micro B unit: $35,000 each
C unit: 350,000 each
A unit: 50,000 each

G. Availability: Can be ordered

ARIS (Airborne Range Instrumentation System)-Litton (RRS, IMU, computer)

A. Data Source/Reference

1. Trip report
2. Brochure

B. Operational Description

SUU - 16, gun type pod, 22 inches diameter, 15 feet long, 800 lb.

IMU: AN-92 INU

Computer: ASN-92 ANCU

Pitot tube probe

Air pressure transducer

Interrogator

Recorder

Power supply and control

B. Operational Description continued

    1.6 GHz interrogator

    Cubic CR-100 ground sited transponders

C. Employment

    High precision bomb scoring

    Quick data turn-around

    One-day preparation

    Unmanned ground transponders

    Base maintenance

D. Principal Sources of Error: Same as CIRIS

E. Accuracy Specifications

    Position: 5 feet

    Velocity: 0.5 feet/sec

F. Cost Estimates

    Pod: $350,000
    Transponders: $12,000
    Ground data terminal: $50,000
    Support equipment: $30,000

G. Availability: Operating at Eglin AFB. Can be purchased.

PATS, Sylvania (laser radar; azimuth, elevation, range)

A. Data Source/References

    1. Trip report

    2. Brochure

B. Operational Description

    YAG, 1.06 micron wavelength

    Tracking laser

    Elevation over azimuth mount, ground based

    Retroreflector fastened to target

    Joystick acquisition

    Video camera co-mounted with laser for aid in acquisition

    Minicomputer

    Video recorder

    X-Y plotter

    Range counter

B. Operational Description continued

Logic control unit

Instrument van

C. Employment

Tracks mortar shell, helicopter, aircraft

Maximum range, 100,000 feet

Data rate: 10, 20, 50, 100/sec

Coverage: Azimuth, ± 170 degrees; elevation, -5 to +85 degrees

Slewing characteristics: 0.5 rad/sec, 0.08 rad/sec^2, azimuth and elevation

Display: Range, 1 foot increments; elevation and azimuth, 1 degree increments

Field of view: Video, 5 to 20 degrees (zoom); laser, acquisition 3 millirad

Set-up: 1 hour

D. Principal Sources of Error

Atmospheric refraction

Optics mechanical error

Servo and readout resolution

E. Accuracy Specified (up to 65,000 feet)

Range, ± 2 feet

Azimuth and elevation, 0.1 milliradian

F. Cost Estimate: $600,000, complete with instrument van

G. Availability: Operational at Yuma Proving Ground

<u>A-7E Navigation and Weapon Delivery System</u> (RRS, IMU)

A. Data Source/References

"A-7E-Simulation and Testing", 6th Guide Test Symposium

B. Operational Description

IMU: AN/ASN-90(V)

Doppler Radar Set (DRS): AN/APN-190(V)

Forward Looking Radar (FLR): AN/AFQ-126(V)

Air Data Computer (ADC): CP-953/AJQ

Heads Up Display: AN/AVQ-7(V)

B. Operational Description continued

Projected Map Display: AN/ASN-99

Tactical Computer Set (TC-2): AN/ASN-91(V)

C. Employment: Used on A-7E attack Naval aircraft

D. Principal Sources of Error: Not discussed in reference

E. Accuracy Specifications

1. Probably not stringent because missiles require only rough aiming if they are homing devices
2. Gun aiming probably uses feedback, miss distance error signal

F. Cost Estimate: Not given

G. Availability: All equipment in military arsenal

The systems described thus far have been oriented toward terrestrial and aerial tracking. In fact, the majority of existing tracking systems fall into this category. There are, however, sonar positioning systems such as ATNAV I and II which are designed for underwater use. Centered around a DEC PDP-11 minicomputer, the ATNAV system uses many of the same techniques as its land-locked counterparts to locate and track objects underwater. Currently, the Navy is using an ATNAV system to track their submersibles. This particular system not only has range/range/range locating capability, but also incorporates a range/bearing system which permits tracking of a submersible without deployment of transponders in operations where precise positioning is not required [42].

The Navy also has a number of systems used in antisubmarine warfare (ASW) to locate targets. Typically, these systems rely on the deployment of sonobuoys to form triangulation nets. These can be either active or passive in nature (sonar, hydrophones). The locating techniques employed are the acoustic analog of those mentioned in earlier sections.

One other class of remote locating and positioning systems is the small self-contained bearing-only triangulation sets used primarily by ships around harbors in times of poor visibility. Such systems are commercially available but are limited in range and degrade rapidly in accuracy as target distance increases. Falling into this category are most current animal tracking systems which typically employ bearing-only triangulation with manually scanned antennas.

Such systems are neither automatic nor are they accurate at target distances beyond several kilometers.

MEASUREMENT TECHNIQUES

Remote measurement of position is dependent on the ability to compare an apparent position with a known reference. "Remote" measurements implies that this comparison will be performed from some location or locations distant to the position being measured and that no physical contact with this position is required in performing the comparison.

Position locating systems interact with either cooperative or uncooperative targets. An uncooperative target plays no active role in the remote determination of its position. A cooperative target, on the other hand, is one that can give the interrogating system some type of additional information to aid in the determination of its location. Of course, an interrogating system must be configured to accept the particular type of information available from a cooperative target and for this reason, there are several general categories of cooperative target trackers while techniques of uncooperative target tracking are less varied.

Systems for locating position in one, two and three dimensions already exist. Each added dimension or degree of target freedom that is to be accounted for by a tracking system increases not only the complexity of the system, but also the uncertainty in determining the actual position of the target. Manatee tracking will involve two dimensional position location, being concerned with range and azimuth variables only.

The following discussion sets forth the principles of operation for numerous positioning schemes that could have application to manatee tracking. The discussion of sensing media has been left to subsequent sections as the techniques to be addressed are independent of the type of energy (acoustic, electromagnetic, nuclear, etc.) used for target interrogation.

Uncooperative Target Tracking: Single Site. To track uncooperative targets from a single station, range and azimuth information must be gathered from energy reflected off the target. The only reflected energy of use will be that which is reflected radially toward the receiver station. The source of the energy that is subsequently reflected off the target can be naturally occurring or artificially generated. Naturally occurring energy (for example sun light) is uncontrollable and unreliable, so most single site trackers rely on an internal energy source to "illuminate" the target.

The typical mode of operation used in single site trackers involves the comparison of the reflected energy image with a range and azimuth calibrated standard located at the receiver site. The mechanism necessary to achieve this is quite simple; however, both the range and azimuth resolution degrade as the target-receiver site separation is increased. An example of a system operating on this principle would be a device that was a cross between a range finder camera and a theodolite.

If the reflected energy originally eminates from the site, then it is possible to regulate its output such that it is emitted in short bursts. If the propagation speed of the energy through the medium separating the target and transmitter/receiver site is known, then the round trip energy propagation delay can be measured from the instant of transmission to the reception of the reflected energy back at the site. The relation

$$\text{distance} = \tfrac{1}{2}c(\Delta t)$$

(where c is the speed of propagation and Δt is the round trip propagation delay) can then be used to calculate target-site separation. The position of the target can then be determined when this is coupled with azimuth readings from a calibrated standard. As before, range and azimuth accuracy decreases with increasing range.

Azimuthal precision depends on how accurately the relative (measured) azimuth can be compared to the calibrated standard. Azimuthal resolution is a function of receiver beamwidth. Thus the narrower the beamwidth, the higher the resolution. Range precision, on the other hand, is limited by the accuracy with which the transmit/receiver interval can be measured. Typically with systems of this type, the range precision will be far greater than the range resolution obtainable. Range resolution is limited by the transmitted pulse-width; the shorter the pulse duration, the finer the range resolution. Examples of systems operating on this concept are pulsed radars, lidars and sonars.

Additional information can be obtained from the reflected energy if Doppler shift is monitored. The radial velocity component of the target motion vector is directly proportional to the frequency difference between the transmitted energy and that which is reradiated from the target. This information can be used to extrapolate future target positions or to estimate current target position if the reflected energy flow is temporarily obstructed.

Uncooperative Target Tracking: Multiple Site. Improved positioning can often be achieved by the use of multiple sites since a given target is less likely to become completely masked (e.g. by an island) from all monitoring sites. However, certain problems can arise when dealing with an uncooperative target. In order to interrogate the target, one or more of the sites must illuminate the target with energy. Depending on the site configuration, one or more of the sites may receive the radiated energy directly from another transmitting site without the energy having been reflected off the target. Thus, stations could interfere with one another, though intersite synchronization can be used to alleviate much of this problem.

When considering multiple sites, two major techniques are generally employed to fix the position of an uncooperative target, interferometry and multilateration. Interferometry derives ranging information from phase angle information contained within the received energy.

Interferometry. The use of interferometry with an uncooperative target relies on the following principles. If a source continuously emits radiation which is continuously reradiated from an object, then the wavefronts of the radiated and reradiated energy will interfere (provided the reflection of the energy preserves coherence and some component of the reflection is directed radially back toward the source). The amplitude and phase of the transmitted energy are known while that of the reradiated energy is unknown. When wavefronts of these propagating energies encounter one another, the intensity of the summed energy will depend on both the amplitude and the phase of the transmitted wavefront. Thus, if

$$\vec{A}(x,y,z) = A(x,y,z) \exp[-j\psi(x,y,z)]$$

represents the transmitted wavefront of the energy, and

$$\vec{a}(x,y,z) = a(x,y,z)\exp[-j\phi(x,y,z)]$$

represents the wavefront of the reradiated energy with which $\vec{A}$ interferes, the intensity of the sum is given by

$$I(x,y,z) = |\vec{A}(x,y,z)|^2 + |\vec{a}(x,y,z)|^2 + 2A(x,y,z)a(x,y,z)\cos[\psi(x,y,z)-\phi(x,y,z)]$$

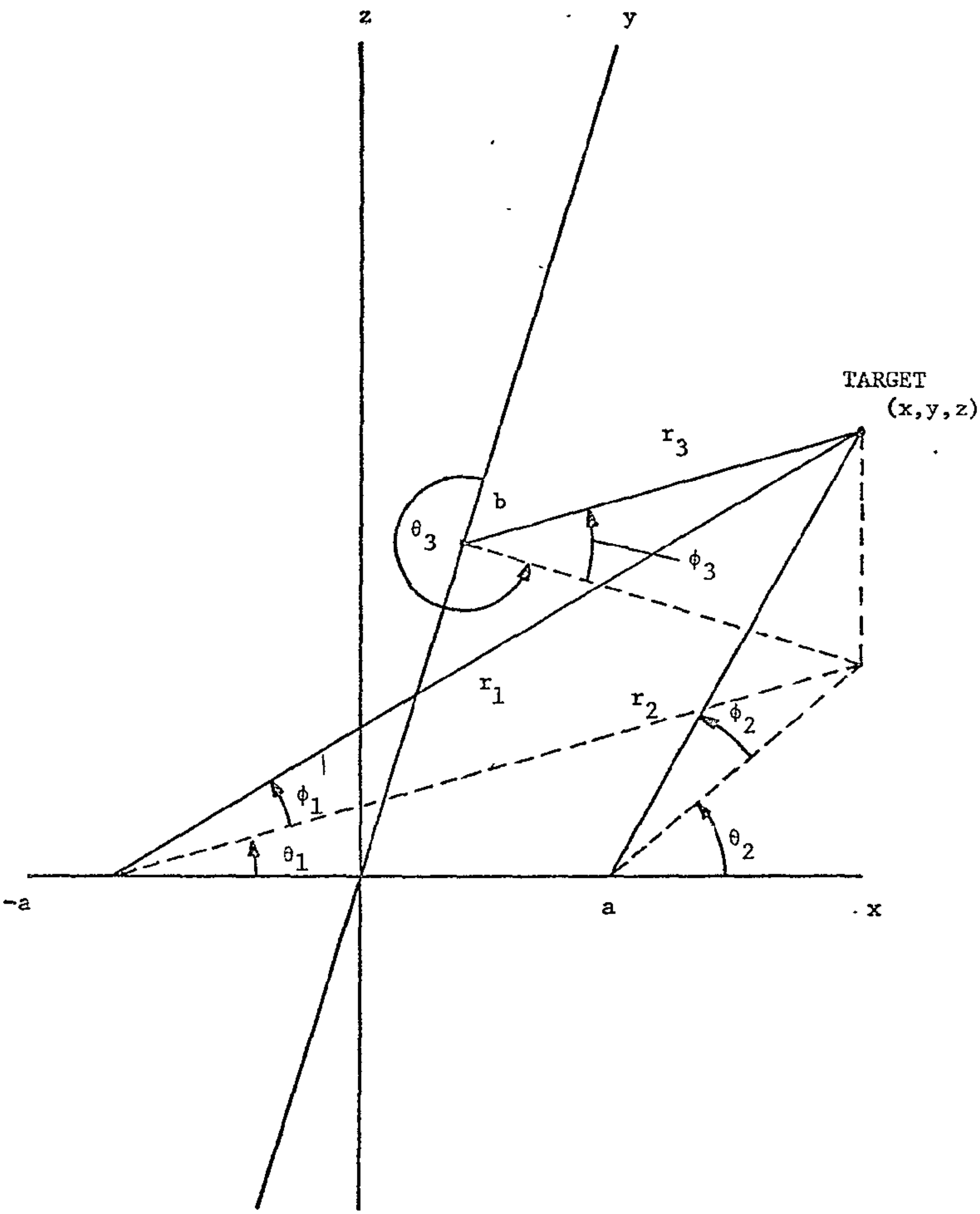
While the first two terms of this expression depend only on the intensities of of the two waves, the third depends on their relative phases. This information can then be used to calculate distance.

Multilateration. Since range measurements typically become more accurate than angular measurements as target distance increases, a method using multiple sites known as multilateration, can be used to fix uncooperative target positions based on range information only, or on various combinations of range and angular information. Consider the multilateration scheme in Figure 4 which involves three sites (trilateration) each of which is capable of radiating energy. Data collected from all sites must be brought together for processing. A minimum of three observations must be used. Assuming that each site can measure angles ϕ, θ, and r, Table 2 shows how various combinations of these measurement can be used to position fix the target at x, y, z. Note that not all combinations work; for instance, use of r_1, r_2 and ϕ_1 results in ambiguity.

The first seven entries in Table 2 pertain to two-site position-fixing. The remaining entries are three-site fixes. In practice, three or more sensor sites are necessary to remove ambiguities, reduce geometric dilution of precision (GDOP), eliminate flase targets in a multiple target situation, improve coverage and field of view (FOV) and reduce propagation/atmospheric errors.

Systems utilized in interferometry and multilateration to position-fix uncooperative targets are sonar, lidar and radar. The preceding general explanation of these techniques has been for the three-dimensional case; however, when applied to manatee tracking, the elevation components (ϕ) can be dropped from the analysis.

Cooperative Target Tracking. When a target is cooperative, a great deal more information about is position can be gathered with increased accuracy. In general, the same techniques used to position-fix uncooperative targets can be used with cooperative ones. However, techniques such as proximity location, inertial systems and transponder operation are only possible with cooperative targets. All cooperative systems used to track manatees will entail the placement of an electronics package on the tagged individual. This is a significant drawback logistically, but extremely beneficial from a systems standpoint. The systems decribed thus far require energy of some sort to be directed at the target, reradiated from the target and received. As will be seen in subsequent sections dealing with energy media, the air-water interface will greatly hamper the direct reflection of energy from a given manatee due to either attenuation or multipath propagation. Additional advantages of a cooperative target system are simplified identification of indi-



Multistatic Position Fixing Coordinate System [14]

Figure 4

Measure used	Location equations
$\theta_1, \theta_2, \phi_1$	(1) $x = \dfrac{a \sin(\theta_1 + \theta_2)}{\sin(\theta_2 - \theta_1)}$ (2) $y = \dfrac{2a \sin\theta_1 \sin\theta_2}{\sin(\theta_2 - \theta_1)}$ (3) $z = \dfrac{2a \sin\theta_2}{\sin(\theta_2 - \theta_1)} \tan\phi_1$ $\phi_1 = 90° \Rightarrow$ no solution
$\theta_1, \theta_2, \phi_1, \phi_2$	Eqs (1) to (3) (4) $z = \dfrac{2a \sin\theta_1}{\sin(\theta_2 - \theta_1)} \tan\phi_2$
$\theta_1, \theta_2, r_1 + r_2 = s$	Eqs (1) and (2) (5) $z = \pm \dfrac{1}{2s} \sqrt{(4a^2 - s^2)(4x^2 - s^2) - y^2}$
$\theta_1, \theta_2, \phi_1, r_1 + r_2 = s$	Eqs (1) to (3) and (5)
$\theta_1, \phi_1, r_1 + r_2 = s$	(6) $x = \dfrac{(s/2)(2a/s - \cos\phi_1 \cos\theta_1)}{(2a/s)\cos\phi_1 \cos\theta_1 - 1}$ (7) $y = \dfrac{(s/2)(4a^2/s^2 - 1)\cos\phi_1 \sin\theta_1}{(2a/s)\cos\phi_1 \cos\theta_1 - 1}$ (8) $z = \dfrac{(s/2)(4a^2/s^2 - 1)\sin\phi_1}{(2a/s)\cos\phi_1 \cos\theta_1 - 1}$
$\theta_1, \theta_2, r_1 - r_2 = \Delta$	Eqs (1), (2), and (5) with Δ replacing s $\Delta = 0 \Rightarrow$ no solution
$\theta_1, \theta_3, \phi_3$	(9) $x = \dfrac{b - a \tan\theta_1}{\tan\theta_1 + \cot\theta_3}$ (10) $y = b - x \cot\theta_3$ (11) $z = \sqrt{x^2 + (y - b)^2} \tan\phi_3$ $\phi_3 = 90° \Rightarrow$ no solution
$\theta_1, \theta_2, \theta_3, \phi_1, \phi_2, \phi_3$	Eqs (1) to (4) and (9) to (11) (12) $x = \dfrac{b + a \tan\theta_2}{\tan\theta_2 + \cot\theta_3}$
$\theta_1, \theta_2, r_1, r_2$	Eqs. (1) and (2) (13) $z = \pm \sqrt{\dfrac{1}{a^2} l(l - 2a)(l - r_1)(l - r_2) - y^2}$ where $l = \dfrac{r_1 + r_2 + 2a}{2}$
$\theta_1, \theta_2, \phi_1, \phi_2, r_1, r_2$	Eqs (1) to (8) and (13) (14) $z = r_1 \sin\phi_1$ (15) $z = r_2 \sin\phi_2$
r_1, r_2, r_3	(16) $x = \dfrac{r_1^2 - r_2^2}{4a}$ (17) $y = \dfrac{r_1^2 + r_2^2 - 2r_3^2 + 2(b^2 - a^2)}{4b}$ (18) $z = \pm \sqrt{r_1^2 - (x - a)^2 - y^2}$
$\Delta_1, \Delta_2, \Delta_3$	$(x_j, y_j, 0) =$ jth-site location, $j = 0, 1, 2, 3$ $(x_0, y_0, 0) = (0,0,0)$ $d_j^2 = x_j^2 + y_j^2$ $r_j = +\sqrt{(x - x_j)^2 + (y - y_j)^2 + z^2}$ $\Delta_j = \rho - r_j$, where $\rho = +\sqrt{x^2 + y^2 + z^2}$ (19) $x = \dfrac{(d_1^2 - \Delta_1^2)(y_3\Delta_2 - y_2\Delta_3) + (d_2^2 - \Delta_2^2)(y_1\Delta_3 - y_3\Delta_1) + (d_3^2 - \Delta_3^2)(y_2\Delta_1 - y_1\Delta_2)}{2[x_1(y_3\Delta_2 - y_2\Delta_3) + x_2(y_1\Delta_3 - y_3\Delta_1) + x_3(y_2\Delta_1 - \Delta_1 y_2)]}$ (20) $y = \dfrac{(d_1^2 - \Delta_1^2)(x_2\Delta_3 - x_3\Delta_2) + (d_2^2 - \Delta_2^2)(x_3\Delta_1 - x_1\Delta_3) + (d_3^2 - \Delta_3^2)(x_1\Delta_2 - x_2\Delta_1)}{2[y_1(x_2\Delta_3 - x_3\Delta_2) + y_2(x_3\Delta_1 - x_1\Delta_3) + y_3(x_1\Delta_2 - x_2\Delta_1)]}$ (21) $\rho = \dfrac{(d_1^2 - \Delta_1^2)(x_2y_3 - x_3y_2) + (d_2^2 - \Delta_2^2)(x_3y_1 - x_1y_3) + (d_3^2 - \Delta_3^2)(x_1y_2 - x_2y_1)}{-2[\Delta_1(x_2y_3 - x_3y_2) + \Delta_2(x_3y_1 - x_1y_3) + \Delta_3(x_1y_2 - x_2y_1)]}$ (22) $z = \pm\sqrt{\rho^2 - x^2 - y^2}$
s_1, s_2, s_3	Same coordinate system as previous case $S_j = \rho + r_j$ Eqs (19) to (22) with S_j replacing Δ_j

Table 2, Location Equations

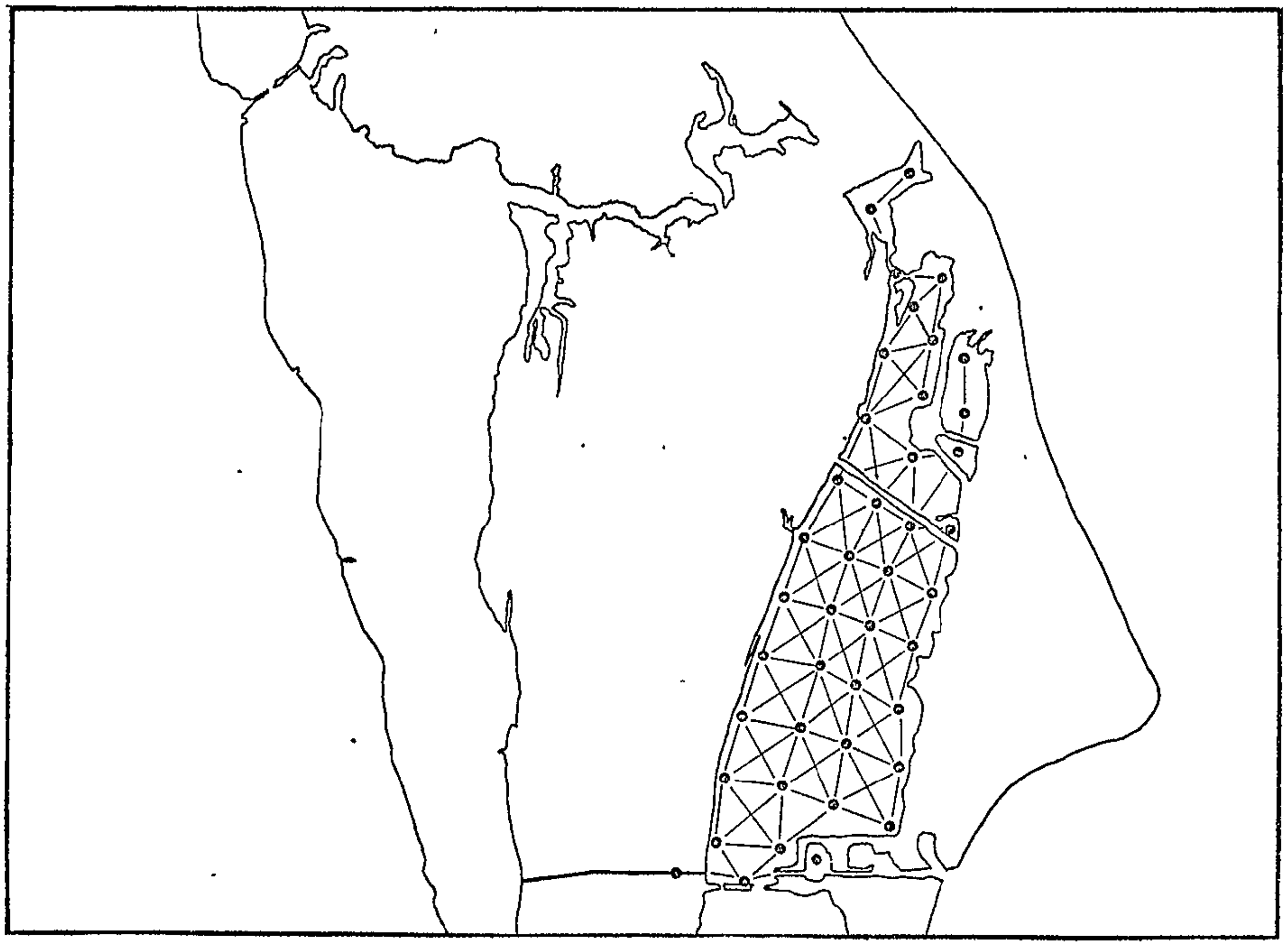
viduals and the omission of energy radiators at the sites (or at least diminished radiated power requirements in the case of a transponder system.

Proximity Systems. A proximity location system is one in which a large number of receiver sites are placed in a fixed array. The target, being cooperative, radiates energy either continuously or on a time sequenced basis. Signal strength is measured periodically by each site that is within sufficient range of the target to receive its signal. Assuming no ducting or shaddowing of the signal occurs (i.e., a homogeneous propagation medium), then the receiver sites can be ranked in terms of received signal amplitude. This will yield signal strength contours from which target position can be estimated. The denser the sensor array, the greater the position fixing accuracy. Figure 5 shows a network of such sensors as might be used in an acoustic proximity system.

Interial Systems. Inertial systems provide position or location information by electromechanical or electronic methods using completely self-contained equipment requiring no incident electromagnetic field. It is the only candidate system that does not depend upon a propagated energy field for position fixing. A one way telemetry link is necessary however to relay the inertial system output data to a remote receiving station.

An inertial unit calculates the target position relative to a known starting point (in x, y, z coordinates) by sensing and double integrating accelerations acting on the unit as measured in an inertial coordinate frame. Gimbaled inertial systems obtain the inertial frame accelerations by mounting accelerators upon a stable platform, while strapdown inertial units measure accelerations in a body fixed frame and electronically transform them to an inertial frame (using angle sensing devices such as rate gyroscopes). An additional benefit of the use of inertial systems is that target velocity vector information is available as a side product. In either case, the position of the target relative to its reference point is determined by double integration of translational accelerations expressed in an inertial frame. The accuracy of the resultant position information is primarily dependent upon drift in the gyros of the inertial platform or of the strapdown system and upon the accuracy of the electronic integration.

42 STATION PROXIMITY-SENSING SONOBUOY NET



Acoustic Proximity Sensing Example
Figure 5

Gimbaled systems represent the more mature technology, while the strapdown techniques have recently emerged from space vehicle technology. Performance of a gimbaled inertial system depends heavily upon precise machining and other mechanical characteristics of the inertial platform; this precision mechanical requirement is one of the key cost factors in gimbaled inertial systems. Strapdown systems, on the other hand, have significantly less stringent mechanical precision requirements, but do require significant additional computations to be made by an on-board computer or dedicated microprocessor system. The trend in the development of inexpensive computer systems and subsystems is in the favor of strapdown inertial systems.

Some of the important advantages of strapdown systems as compared to gimbaled systems are: (1) the nonexistence of a gimbaled platform eliminates errors associated with the platform stabilization; (2) being free from gimbal lock allows an all-attitude operation; (3) absence of mechanical platform gimbals makes the system smaller in size, lighter in weight, more rugged in mechanical structure and results in less power consumption; and (4) the potential of higher reliability. These advantages are achieved at the expense of a more complex electronic unit and a more stringent computer requirement. However, the progress of integrated circuit technology has made this tradeoff worthwhile.

In inertial systems, there exist a number of position error sources that are unique to inertial systems; these include electrical and mechanical as well as dynamic errors. Some specific error sources are:

1. inaccuracy of transducer
2. misalignment of baseplate
3. runout of gimbal bearings
4. nonorthogonality of gimbal axes
5. misalignment of sensor
6. servo error

It is well recognized that the environmental tolerance of present guidance inertial systems is dictated by the platform. Being a precision electromechanical device, the platform is affected at considerably lower tolerance levels than are electronic devices. Thermal conditioning of the inertial components is difficult in a platform system, since all signals and power are conventionally transported through the gimbaling structure by slip rings. Insulation to control heat flow is prohibited by the volumetric restrictions; a comparatively small change of volume on the inner element requires a large change in total volume, due to the multiplicative nature of the gimbaled structure. Inability to control heat flow results in slow warmup, large power dissipation and poorly regulated component temperatures. This is particularly true in relation to a manatee tracking system which would require the inertial system and its telemetry electronics to be enclosed in a water-tight container which would further restrict heat flow. In general, inertial systems are not good candidates for use in a manatee tracking system because they are typically heavy, bulky, and lack long term stability.

Transponder Systems. A transponder system differs from the single and multiple site radiating systems in that the targets are not cooperative, each carrying a receiver and transmitter to relay information on command such as identification and orientation. Ranging is typically performed by transmission-to-time-of-arrival. However, the weak reflected energy return is ignored. The mode of operation is thus: site transmitter transmits a coded signal (the code is the "name" of a single cooperative target); the appropriate target responds to the coded signal by transmitting back its own identifying code or any other information desired. Each receiver-transmitter carried by a target has a known receive-to-transmit propagation delay. Range information at each site is calculated by observing that the round trip propagation delay (Δtot) equals the site-to-target propagation delay (Δ1), plus the known receiver-to-transmit propagation delay of the target's transponder circuitry (Δ2), plus the target-to-site propagation delay (Δ3). Therefore, the one way distance from site to target is

$$\text{RANGE(m)} = ([(\Delta\text{tot}) - (\Delta 2)]/2) * (3 \times 10^8 \text{m/s})$$

If the target is interrogated by all of the sites that can establish a communications link, then triangulation techniques can be employed to establish the target's horizontal position. It should be noted that the interrogate and answer back energy type need not be the same. In addition, transponder operation is not limited to range only triangulation to find the target position. Direction of arrival and phase comparison techniques are also applicable though less popular.

When one target has been completely interrogated, the transmitted code name will be automatically changed and the next target interrogated. In this way, all targets will eventually be polled.

The speed with which this polling can take place is sufficient to handle a large number of targets. However, the degree of sufficiency is dependent on the speed of the targets. Adaptive polling can be incorporated to increase the frequency of interrogation of those targets whose velocity exceeds some threshold. Targets that are detected not to be moving after several interrogations might be dropped to a lower interrogation frequency in the polling cue to accommodate the stepped up interrogation activity associated with high velocity targets.

Intersite communications is an essential element to this type of tracking system since interrogation results from each peripheral site must be relayed to a main site for reduction and incorporation into the triangulation algorithms. Also, the main site must communicate polling sequences to each peripheral site. A high speed computing facility will be required at the main site in order to maintain real-time operation while controlling the polling sequences and applying the triangulation algorithms to the incoming data. For this reason, it would be advantageous to put some of the processing in the peripheral sites as well. For example, if Doppler shifts in the returned signals were analyzed to aid in the determination of target velocity (note that velocity can be determined from change in target position alone), this analysis could be performed at the peripheral site and digitized prior to transmission to the main site.

Another essential item to this system is the receiver/transmitter and decoders carried by each target. These units must be amenable to placement on a manatee and battery operated.

PAGE INTENTIONALLY BLANK

MEDIA

The energy medium chosen to remotely track manatees should satisfy the following:

- o Ease of generation and reception
- o Lack of natural or man-made interference
- o Non-hazardous to man, manatee or environment
- o Unobtrusive to man, manatee or environment
- o Reliable
- o Economic
- o Result in small physical size and weight of items that must be carried by the tagged manatee

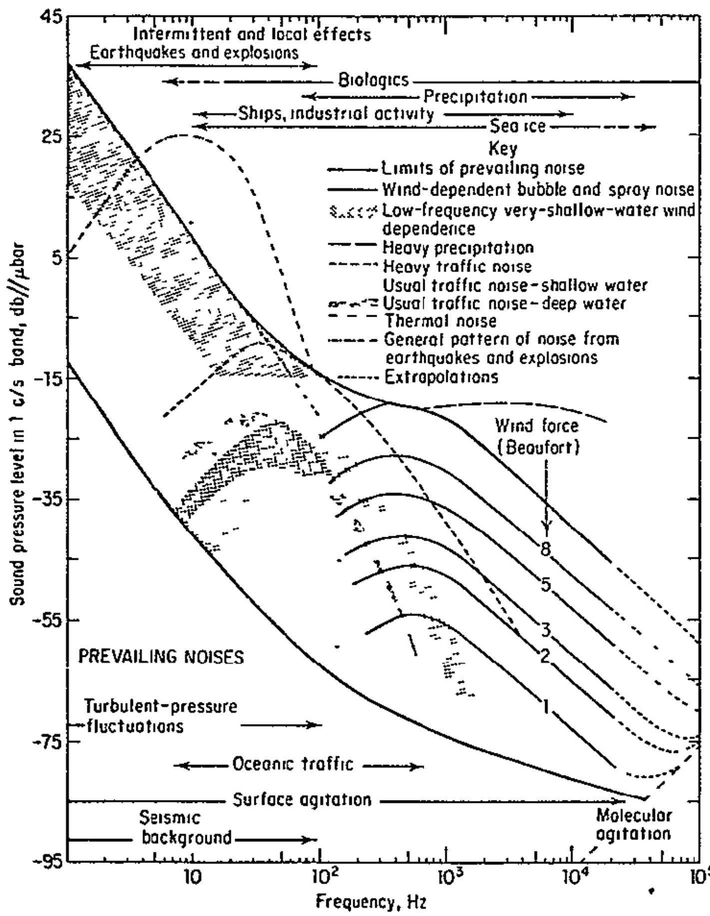
Certain energy media such as kinetic, nuclear, gravitational, etc. present a low probability of success and involve high risk technologies in comparison to those examined below. Therefore, they have been discounted at the onset.

The types of energy that appear to have the highest probability of return when applied to a manatee tracking system can be categorized as either electromagnetic or acoustic. Of course, within these categories are extensive spectra of frequencies each of which has properties that could make it a viable candidate for tracking. Certain limiting factors do enter into this analysis, however. First, the manatee is totally aquatic. This means that energy must propagate solely in the air, solely in the water or be able to traverse the air/water interface. Also, transducer technology limits the high frequency extremes over which operation can be considered.

Acoustic Medium

Acoustic energy is easily generated and sensed. Technology exists for producing acoustic energy at all frequencies from near static conditions (on the order of barometric changes), through audio and into the high kilohertz range (e.g. sonar) and beyond (surface acoustic wave (SAW) devices). Typically, the same device that generates the acoustic energy can be used to sense its presence (e.g. magnetostrictive devices or piezoelectric and ferroelectric crystalline structures such as barium titanate posses this capability). These devices can be quite compact and efficient.

As shown in Figure 6, both natural and man-made acoustic interference can be expected at all frequencies in open water. The same is true in air. The sould levels encountered typically decrease with increasing frequency. Due to



Ambient Sound Levels in the Ocean [16]

Figure 6

the higher density of water with respect to air, sound is more easily channeled in water and tends to travel faster and farther than in air. Though a seeming advantage, this characteristic of sound in water will actually cause more problems than it will solve in terms of the manatee tracking environment. Transmission of sound through the air/water interface is quite lossy due to the great mismatch resulting from the abrupt change in density. Since air is the less dense medium, acoustic energy will travel from air-to-water through the interface more readily than from water-to-air. For this reason, bodies of water tend to act as acoustic sinks.

Sound pressure below certain threshold levels is not believed to be physically harmful to life; however, even at low levels sound with various frequency contents can be a source of behavior modification in both man and animals (some would argue that plants are affected too). In the case of the manatee, sound interference could have a profound effect since manatees have exceptional acoustic sensitivity [1]. According to Hartman [1], "sound is doubtless the major directional determinant in social interactions. Guided apparently by vocal cues alone, lagging bulls tend to follow beelines in their efforts to catch up with estrus herds." Therefore, any system which produces frequencies within the audible range of the manatee could result in annoyance or, if it falls within the frequencies of vocalization (6-8 KHz vocalization for T. inunguis, and 2.5-5 KHz T. manatus; after Evans et. al [30]), could result in a jamming of the audio cues by which manatees locate one another.

Sound propagation in the atmosphere is extremely inefficient compared to that in water. An extreme example of this difference would be the detonation of a one pound bomb in air and in the deep sound channel of the ocean. In air, the explosion might be detected (acoustically) up to several miles away. Yet when the same one pound bomb is detonated within the deep sound channel, it can be heard easily above the background noise at a distance of 5,000 miles [8]. This is due primarily to the difference in density between air and water and the density stratification that is possible in large bodies of water.

The use of acoustic propagation through the atmosphere over links of more than 100 meters is not recommended. This precludes its use in the desired manatee tracking system as a means of remote location. Atmospheric acoustic propagation is not extensively used in existing automatic remote location systems with one noted exception being short range pulsed Doppler sensors as might be found in an acoustic burglar alarm system or in various industrial velocimeters and fluid level detectors.

Acoustic propagation in air is relatively uninteresting because air is so homogeneous and rarified. Water, on the other hand, is subject to temperature, salinity, pressure, etc. gradients which can drastically affect sound propagation. Being denser, the absorption coefficient is higher. It increases with (1) increasing frequency, (2) increasing salinity, (3) decreasing temperature and, (4) decreasing hydrostatic pressure. In sea water, the absorption is of a thermoviscous nature, owing to chemical relaxation, primarily of $MgSO_4$, and to viscosity. The relaxation process is the controlling loss mechanism for frequencies below 100 KHz and viscosity losses are dominant for frequencies above 1 MHz [16]. These density-changing mechanisms which influence sound speed ultimately affect its path as well. Sound is refracted toward the region of minimum propagation speed by density gradients. It can also be reflected by abrupt density changes such as those occurring at the water surface and bottom. Of course, any object in the path of sound propagation will cause diffraction and reflection. All of these mechanisms are potential sources of multipath interference. Multipath propagation occurs whenever energy can propagate from a source to a destination by different paths. Slight variations in path lengths or path propagation speeds result in spectra of received amplitudes, phases and sometimes frequencies. The smattering of received phases and amplitudes causes both constructive and destructive addition of the signals.

The manatee lives in "acoustically shallow" water. Urick's [8] acoustical definition of shallow water states that "shallow water exists whenever the propagation (of sound) is characterized by numerous encounters with <u>both</u> surface and bottom". There are a number of effects which are encountered in shallow water acoustic operations. First is the certain occurrence of multipath propagation as described earlier. This would hamper any long distance determination of target azimuth or range by echo ranging techniques (sonar). Another serious problem encountered in shallow water acoustics pertains to the dispersion and distortion of the typically short pulses transmitted by sonars in echo location. This is a result of the production of both a ground wave and a water wave. The received signal ends up being a composite of these two waves with the return from the ground wave being received prior and during the reception of the water wave. In addition, both the amplitude and frequency of the ground wave steadily increase while the amplitude of the water wave increases and its frequency decreases. Both waves terminate with the same amplitude at a common frequency. The superposition of these two waves represents the received signal which is typically drawn out in time and unrepresentative of the originally transmitted pulse. This condition is caused by mechanisms such as differing propagation speeds of the different frequency components contained within the transmitted pulse.

Attenuation is another area of concern when considering shallow water acoustic operations. Typically, the attenuation of sound in shallow water increases with increasing

(a) frequency beyond a fundamental mode which can no longer be supported in the given surface-bottom sound propagation duct.

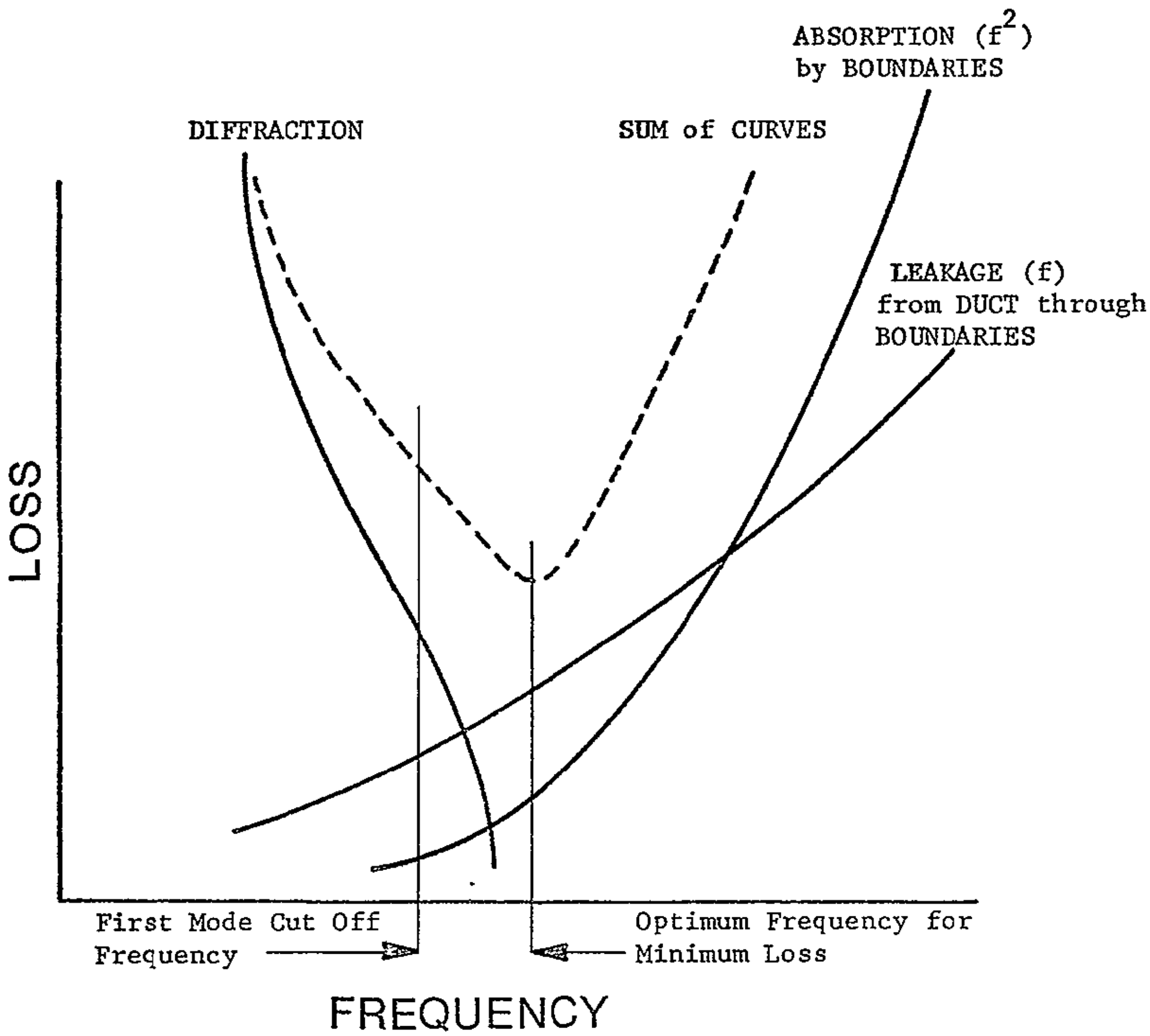
(b) bottom reflection loss being greater for a sand-mud bottom (e.g. the Banana River tracking area) than either sand or rock,

(c) negative thermal gradient (being greater in the summer than in the winter),

(d) transducer depth if a density gradient is present, and

(e) sea state.

The effect of water depth is not constant, and depends on the gradient and bottom type [8]. As can be seen, a number of variables affect the amount of attenuation that can be expected. Other than transducer depth, frequency is the only factor that can be optimized to achieve minimum signal loss due to attenuation. Figure 7 shows the relationship between acoustic operating frequency and signal attentuation for sound ducts in general. Note that the indicated first mode cut-off frequency depends solely on the width of the surface duct (in shallow water, this is the depth) and may actually occur to the right of the superposition curve minimum. Mode theory indicates that this cut-off condition exists whenever the wavelength exceeds four times the duct width. In the case of a surface-bottom duct, propagation can often occur in the bottom material. Hence, the transmitted wavelength-to-duct width (water depth) ratio must be modified by the velocity ratio of sound through the water and the bottom material [9].



Frequency-Loss Characteristics for Ducts
[after Urick, personal communication]

Figure 7

The Banana River tracking area, besides being acoustically shallow, contains more than 300 major obstacles including islands, submerged sandbars, bridge abutments, channel-dredging piles, channels, power distribution poles, pilings, etc. Each obstacle is a potential source of multipath propagation or signal blockage. The upper reaches of the Banana River are particularly cluttered with extreme shallows and circuitous inlets.

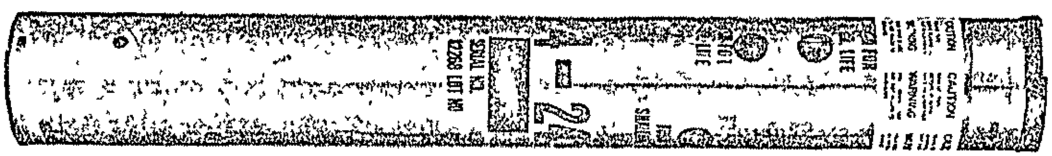
Recommendations for an Acoustic System

A sonar tracking approach is not recommended for use in the specified Banana River tracking range due primarily to the extent of the multipath signal blockage and attenuation expected. In addition, there is no existing sonar cross section data for manatees.

An acoustic triangulation system using a cooperative target electronics package carried by the manatee would increase detection range; however, multipath and signal blockage expected in the specified tracking range would make the system highly unreliable. Acoustic triangulation is not recommended.

The only acoustic technique that can be recommended for use in manatee tracking in the specified Banana River range would be a proximity system using cooperative targets. Multipath will not affect the sensing of proximity if the receiving net is dense and the acoustic propagation distance of the manatee tag is limited. A dense net will also overcome any signal blockage problems due to obstructions. Since signal propagation is intended to be limited in range, the effects of attenuation are less pronounced.

A disadvantage of this system lies in the number of receiver/transducers necessary to implement a "dense" net. Exactly how dense the net is in any given area would depend on the number of perceived obstructions in that area. When designing the net, the manatee-borne acoustic source must be matched in power to the open water grid spacing of the receiver net such that only the closest members of the net are able to receiver the signal. This will minimize error due to anomalous ducting. Modified sonobuoys like that shown in Figure 8 are an inexpensive way to relay signal strength information back to a main site for reduction. Care must be taken when designing the sonobuoy network because easily noticed or accessible sonobuoys are an invitation to vandalism. Avoidance of boating lanes must also be considered.



Sonobuoy AN/SSQ-41B

Typical Sonobuoy [Courtesy of Sparton Corporation]
Figure 8

Choice of acoustic operating frequency becomes more of a pragmatic problem (i.e., what is available off-the-shelf) than a design problem. This is because the importance of the effects of attenuation loss at a given frequency are diminished when working at the relatively short transmitter-receiver separations that would be involved in this system. Before this technique is actually employed, however, tests must be conducted on a manatee exposed to the proposed acoustic frequency and amplitude of operation to determine if there is any behavior modification or sensory interference. The literature [30, 1] indicates that operating frequencies in excess of 10 KHz will be suitable for use with the manatee.

The RF frequency used to relay information from each sonobuoy to the main site for processing can be at any frequency which will meet with FCC regulations. A particularly attractive frequency range extends from 130 MHz to approximately 420 MHz. This region is open for use with low power communications devices (with the exception of certain bands allocated to amateur, police, fire and VHF TV channels 7-13). In addition, most commercial sonobuoys operate in this range.

Simplification of the system will result if the sonobuoys are modified to operate in an RF transponder mode. This will extend the operational lifetime of each sonobuoy by restricting its activity to interrogation periods, thereby reducing battery demand. By using a single frequency coded interrogation signal issued by the main site, each member of the sonobuoy net can be identical in operating frequency and transponder receiver electronics. Individual units would vary only in their "code name" decoders (a minor difference).

The instrument package carried by the manatee would be nothing more than an acoustic pinger (keyed acoustic source), timing circuitry and a battery pack. Low duty cycle keyed operation of the source will conserve the battery. Each pinger must emit the same acoustic frequency with closely matched output powers. The timing circuitry is used to key up the pinger only during a given interval each hour. Prior knowledge of which device is to be activated at what time during the hour will allow the main site to identify individuals. This will also prevent confused receptions due to a congregations of tagged animals since operation times for each would be mutually exclusive. Accuracy of timing over the long term is essential; however, it is well within the current state-of-the-art (e.g., electronic digital watches accurate within minutes per year).

Electromagnetic Medium

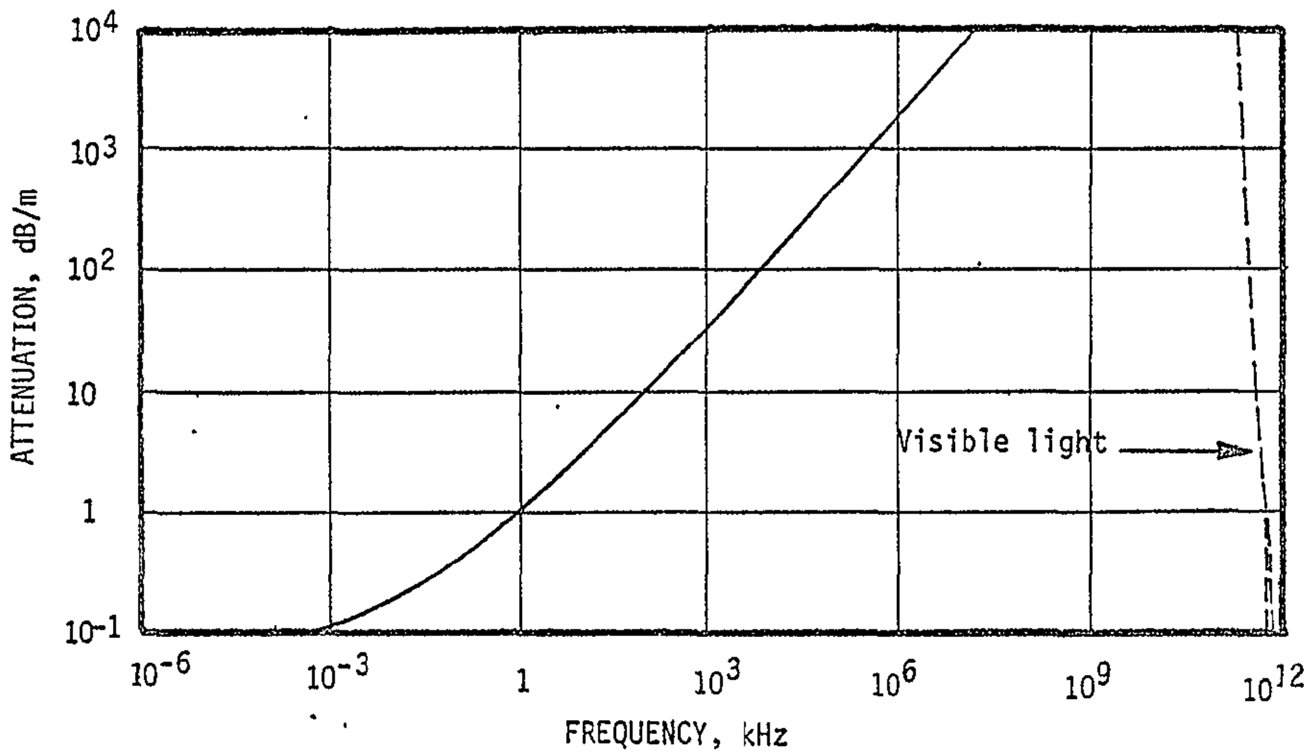
Electromagnetic energy, like acoustic energy, is easily generated and fairly simple to sense. Electromagnetic (EM) waves, however, can currently be produced over a much broader spectrum. Frequencies ranging from direct current (DC) to visible light (5×10^{14} Hz) and beyond (x-ray, etc.) are achievable with present technology. Typically EM energy cannot be sensed by the same transducer that is used to radiate that energy. A major exception is radio frequency (RF) radiation. This spans a large part of the spectrum, extending from DC to millimeter waves (around 100 GHz). Transducers and oscillators change markedly as frequencies exceed 10^{13} Hz (far infrared).

Electromagnetic Properties

Propagation of EM energy, unlike acoustic energy, is not dependent on a physical substance. EM waves are capable of propagating across a perfect vacuum. Physical substances do affect the velocities and directions of propagation, however. EM energy can be diffracted, refracted, reflected, attenuated or have its speed of propagation changed by modifying the composition of the material through which it travels. Since EM and acoustic energy are therefore subject to the same perturbations, one would expect to encounter many of the same maladies that plague acoustic systems, in an EM implementation. This is, in fact, the case. For example, multipath propagation with its associated phase and amplitude scrambling effects can be a serious problem in an EM tracking system.

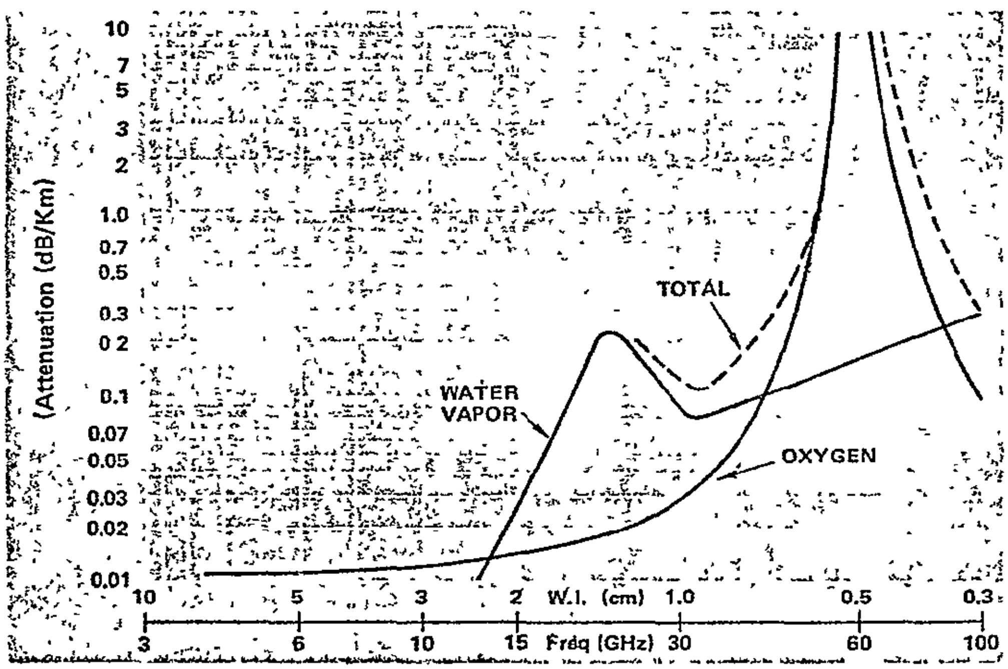
Frequency is the greatest factor contributing to the transmission properties of EM radiation through a substance. Of main concern here, is transmission through air, water and the air-water interface. Figure 9 shows how electromagnetic waves are attenuated in pure sea water. Note that the attenuation is small for very low frequencies and increases rapidly with frequency until a window is reached in the visible light region of the spectrum.

In the atmosphere, no appreciable attenuation is encountered until frequencies in excess of 10 GHz are encountered. Figure 10 shows that atmospheric water and oxygen excitation at these frequencies results in absorption of energy



Electromagnetic Wave Attenuation in Sea Water. ($\sigma \simeq 4$ mhos/m) [16]

Figure 9



Atmospheric Absorption vs Wavelength [44]

Figure 10

ORIGINAL PAGE IS
OF POOR QUALITY

from the electromagnetic wave. Only in the vicinity of 60 GHz does this absorption result in severe attenuation. Beyond several hundred gigahertz, the attenuation due to the atmosphere becomes more eratic. Numerous atmospheric windows occur in the transition from near and far infrared ($\lambda = 20\mu$ to $0.7\ \mu$), through the visible ($\lambda = 0.7\mu$ to 0.4μ), and into the ultraviolet regions of the electromagnetic spectrum. This progression is shown from right to left in Figure 11. Beyond ultraviolet, attenuation is high but so is the wave energy. Various rays such as x-ray, gamma-ray and cosmic rays are able to penetrate long distances through the atmosphere without being attenuated.

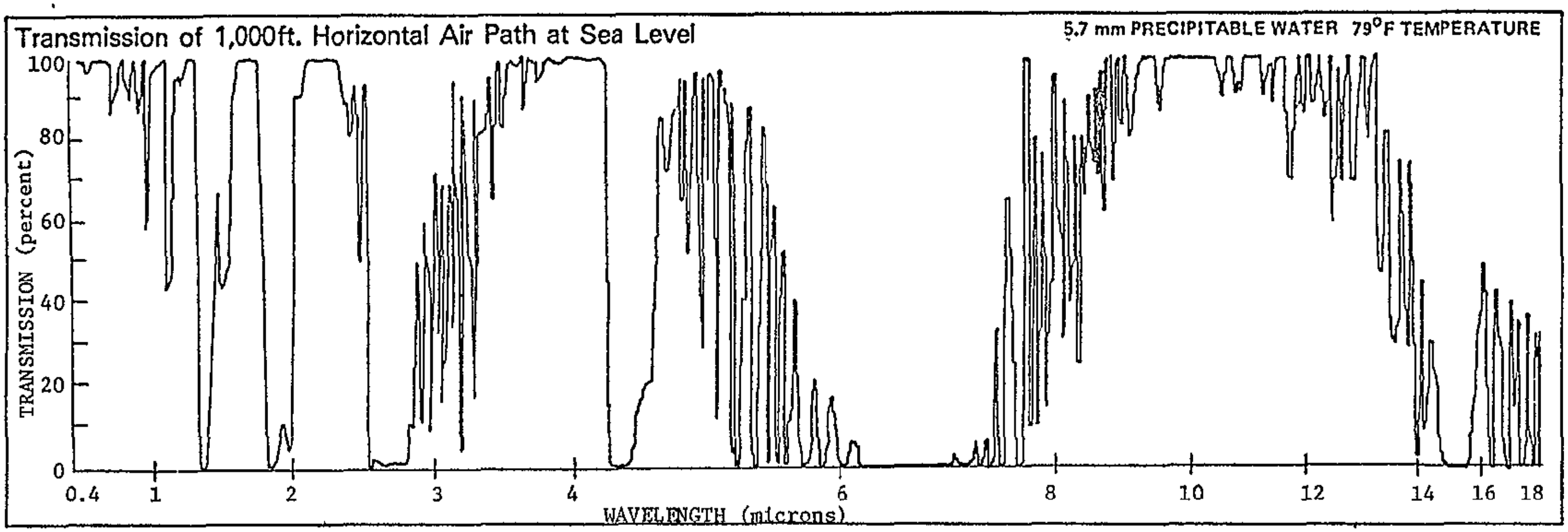
Any EM energy capable of significant transmission through the water will pass in both directions through the air-water interface provided it is beyond the critical angle for reflection. As is the case with acoustic energy, bodies of water tend to act as sinks for electromagnetic energy. This means that EM energy directed down at various angles above the surface of the water is more likely to pass through the interface than energy directed at the same angle plus 180° (i.e., directed up) from below the surface.

The safety of using electromagnetic energy depends on the radiated intensity and the frequency involved. Energy increases linearly with frequency ($E = h\nu$) and becomes hazardous when it can damage body tissue. Damage from RF radiation usually occurs as a result of internal heating. Sensitive organs such as the eyes are particularly susceptible. A level of 10 mW/cm^2 is considered to be the threshold of potentially dangerous RF radiation (this is the U. S. standard, Soviet standards are far stricter with more than 1 mW/cm^2 considered hazardous).

When the energy is sufficient to strip electrons from the outer shells of atoms ($E \simeq 1eV$), it is considered to be ionizing radiation. This can be very hazardous and difficult to contain. Hard x-rays, gamma rays and cosmic rays have sufficient energy to fall into this class.

From the standpoint of safety, ease of handling and transmission/reception qualities, frequencies of electromagnetic radiation falling below 7×10^{14} Hz are the most attractive candidates for use in a manatee tracking system. This range of frequencies spans from visible light to DC.

The configurations that an EM tracking system could assume will vary in accordance with the frequency chosen in this range. Basically, all frequencies



Atmospheric Transmission of Ultraviolet, Visible, Near and Far Infrared Portions of the Electromagnetic Spectrum [43]

Figure 11

from 0 to 7 x 10^{14} Hz will propagate through the atmosphere with minor attenuation (with the exception of the water vapor-oxygen absorption window near 60 GHz). As shown earlier, frequencies from 0 to nearly 1 MHz as well as approximately 4 x 10^{14} to 7 x 10^{14} Hz (visible light) will propagate through water fairly efficiently. It should be noted, however, that the statistics for transmission of visible light in sea water assume pure sea water [see Figure 9]. In actuality, the proposed Banana River tracking range maintains a heavy concentration of particulate matter which would easily attenuate energy within the visible spectrum through scattering and absorption. Therefore, use of light energy over links of greater than 100 meters is not recommended in this application. The band from 1 MHz to the visible light region must be relegated to atmospheric transmission only.

Recommendations for an Electromagnetic System

Systems relying on passive solar irradiance or artificial illumination of the manatee from the surface are not recommended. The manatee keeps its body totally submerged most of the time. Typically, only its nostrils and occasionally the crest of its back will break surface when breathing or resting. This is considered to be too low a profile for passive optical detection methods, especially in the presence of wave action. Any manatee-borne reflector large enough to make optical detection possible at even a moderate range (1 Km) would provide so much hydrodynamic drag as to guarantee eratic manatee behavior. Analysis shows that any passive or active manatee tracking system (laser, radar, etc.) will have a low probability of success as long as the target is uncooperative. As stated earlier, a cooperative target is one that aids the remote interrogating site by actively supplying it with information to be used in the determination of the target's position. This usually involves the transmission of energy from the target position.

There are three unobtrusive electromagnetic characteristics of the manatee in his natural habitat that would inherently qualify it as a cooperative target without the addition of any manatee-borne equipment. First, and perhaps the most obvious, is body heat. The infrared radiation emitted from a manatee due to its normal metabolic process could be monitored; however, being an aquatic mammal, most of this energy is absorbed by the surrounding water which acts as a heat sink. Often the surface waters of protected shallow bays such as the upper Banana River, will equal or surpass the infrared output of a manatee when irradiated by the sun. Under such conditions, the presence of the manatee would be totally obscured.

Another characteristic of a manatee's presence is agitation of microscopic sea life. Upon agitation, many of these creatures emit a momentary burst of light. Bioluminiscenece is not an uncommon plaktonic response to agitation and likely occurs in the Banana River. This key to manatee position would only be useful in darkness and even then it is highly doubtful that instrumentation could detect anything at a distance.

The manatee's primary means of locomotion stems from upward and downward thrusts of its tail. During this process, ions of predominantly sodium and chlorine are accelerated along with the water being pushed by the tail. Any time charged particles such as these ions are accelerated, an electromagnetic field is formed. This field will vary in accordance with the ionic acceleration and will radiate at an extremely low frequency (ELF). Referring once again to Figure 9, it is seen that sea water poses very little attenuation to signals in this frequency range. If enough ELF radiation is generated by a swimming manatee, it could be sensed and used to fix its position. No data is available concerning the ELF output of a manatee; however, it is expected to be down in the noise.

None of the above unobstrusive electromagnetic characteristics of the manatee are recommended for use in tracking the animal. Each characteristic suffers from three common flaws. First, many other sources also produce the same effects (e.g. a motorboat has infrared output, agitates bioluminescent sea life and accelerates sea water ions). Second, there is no provision for identification of individuals, and third, each is a very weak source of radiation. Thus, it can be seen that an electromagnetic approach to manatee tracking must involve active cooperative targets capable of a discernable coded output that is not mimicked by other naturally occurring or man-made systems. This requirement necessitates the placement of equipment on the manatee.

So far, the only viable electromagnetic frequency range that has not been discounted for use within the water is that lying between 0 and about 1 MHz. Those frequencies that remain uncontested for use in the air range from 0 to several gigahertz. The following sections will discuss methods of tracking using these frequencies and what subfrequency bands are expected to produce the best results in the noise and multipath environment particular to the proposed Banana River tracking range.

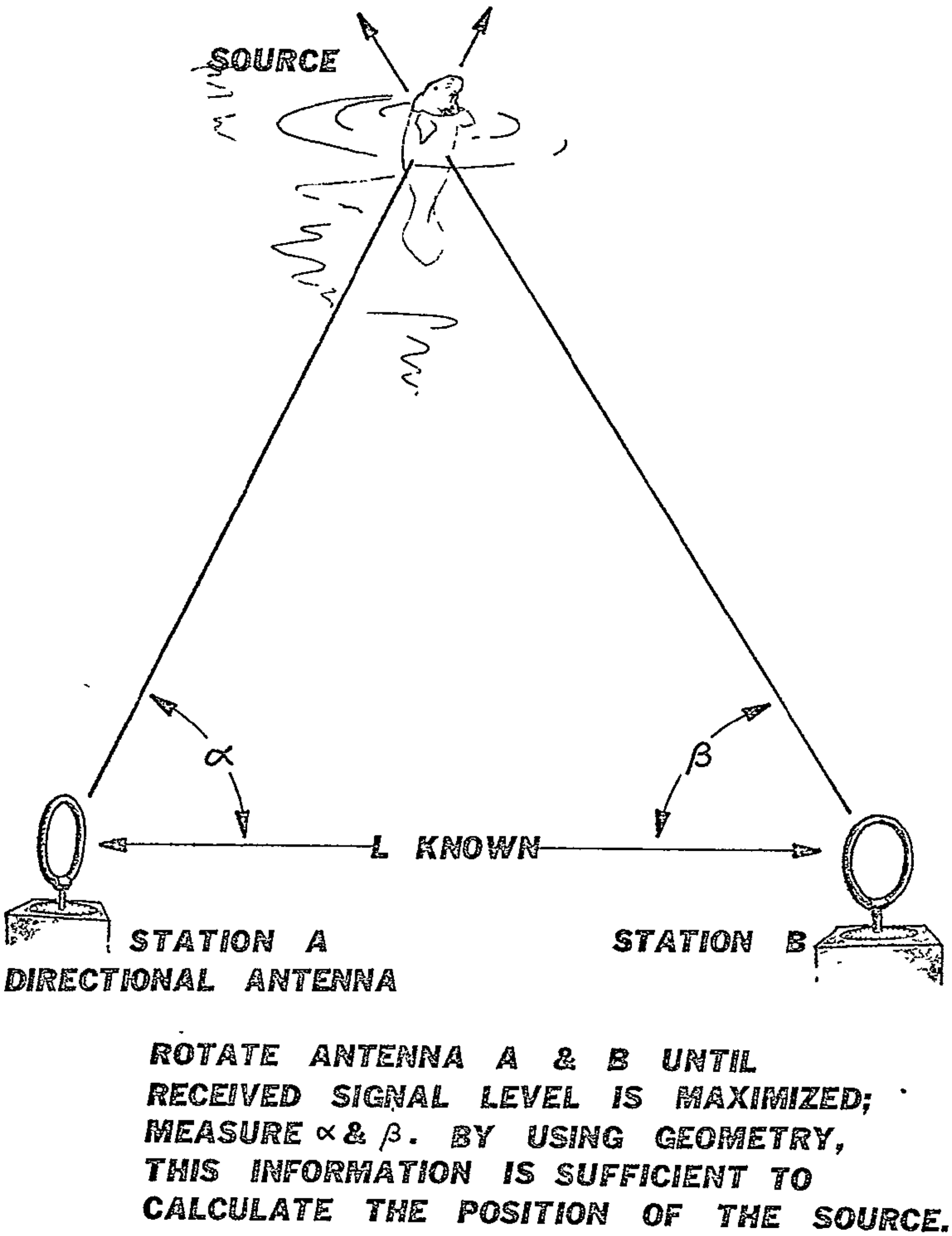
RF APPLICATION OF SPECIFIC DIRECTION FINDING TECHNIQUES

RF direction finding techniques can be broken down into two major classes, direction-of-arrival (DOA) and time-of-arrival (TOA). An example of a DOA sensor is pictured in Figure 12. Commonly termed "bearing triangulation", this techniques employs two or more receivers separated by a known baseline distance. Highly directional rotating antennas are used to "home in" on a signal source of unknown position (i.e., the target) and record the azimuthal bearing of greatest signal amplitude. Electronically scanned array antennas such as the Watson-Watt configuration can be employed instead of mechanically rotated antennas to achieve the same effect. The bearing measured at each receiver site is then compared to the angle of the intersite baseline to calculate the angular offset of the received maximum (assumed direction of the target) from the normal to the baseline. By using geometry, this information is sufficient to calculate the position of the source. This, and other DOA techniques using amplitude or interferometric comparison fall into one of the following categories:

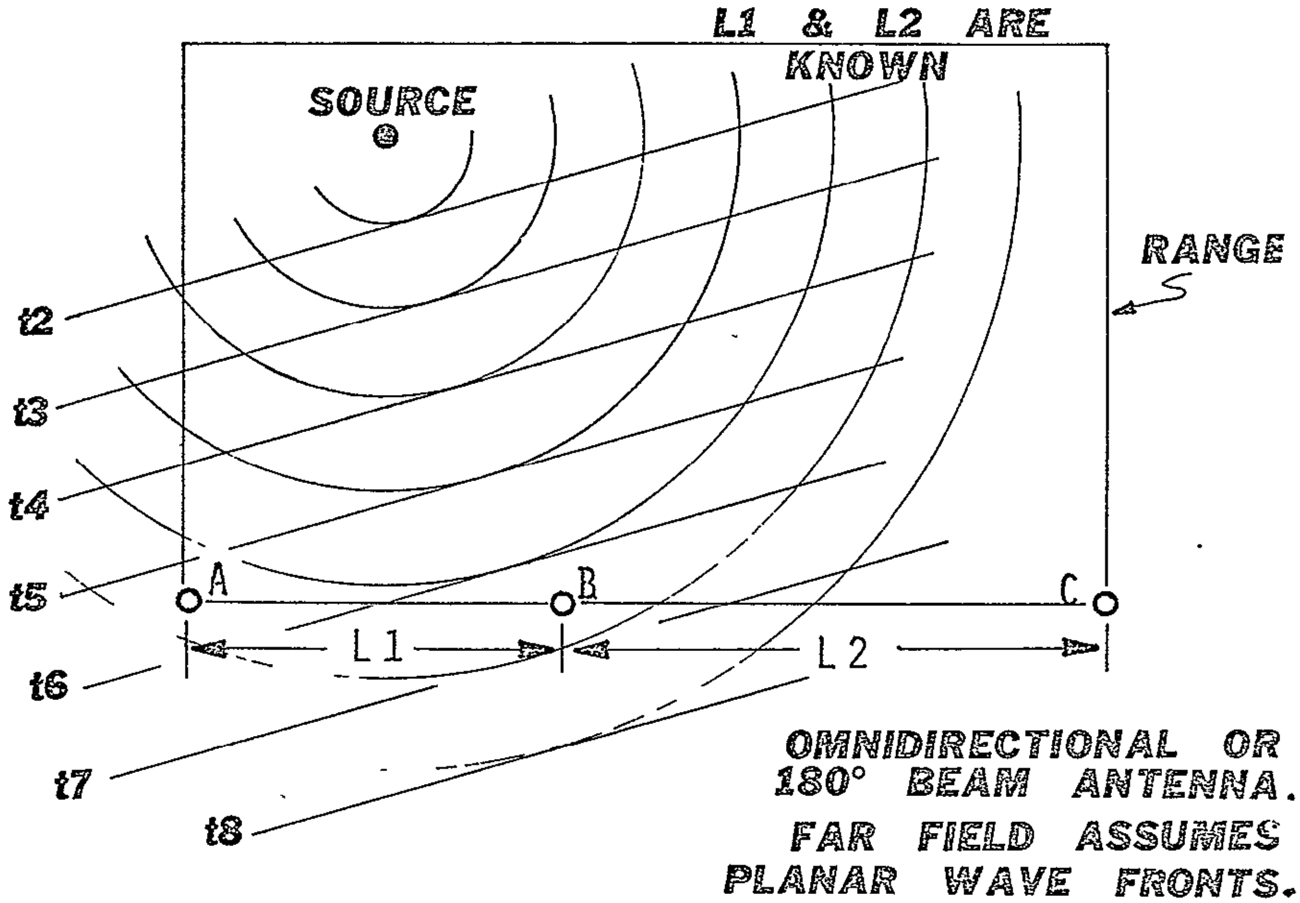
- Amplitude monopulse (Watson-Watt)
- Phase monopulse (two element interferometer)
- Sum/difference antenna response
- Multimode antenna response (Chubb-Honey Antenna, 2 port biconical)
- Short and long baseline interferometers

In the time-of-arrival systems, angular measurements are based on absolute arrival times, or differences of arrival times of the RF signal at two or more locations. TOA systems usually operate against pulsed sources; however, operation on non-pulsed signals is possible using cross correlation or modulated carrier phase comparison methods to measure time difference. Pseudonoise (PN) codes can be employed as the modulation along with side tone modulation to provide both coarse and fine time difference measures. At the expense of complexity, this approach offers several advantages such as considerable reduction in susceptibility to interference, the ability to discriminate between targets based on the PN coding, reduced transmitter peak power requirements and the capability to use the basic system for a data link.

Time-of-arrival techniques in their most basic form, can be understood by considering Figures 13 and 14. In this example, three receiver sites are located along one boundary of a tracking range (Figure 13). The baseline



Bearing Triangulation
Figure 12



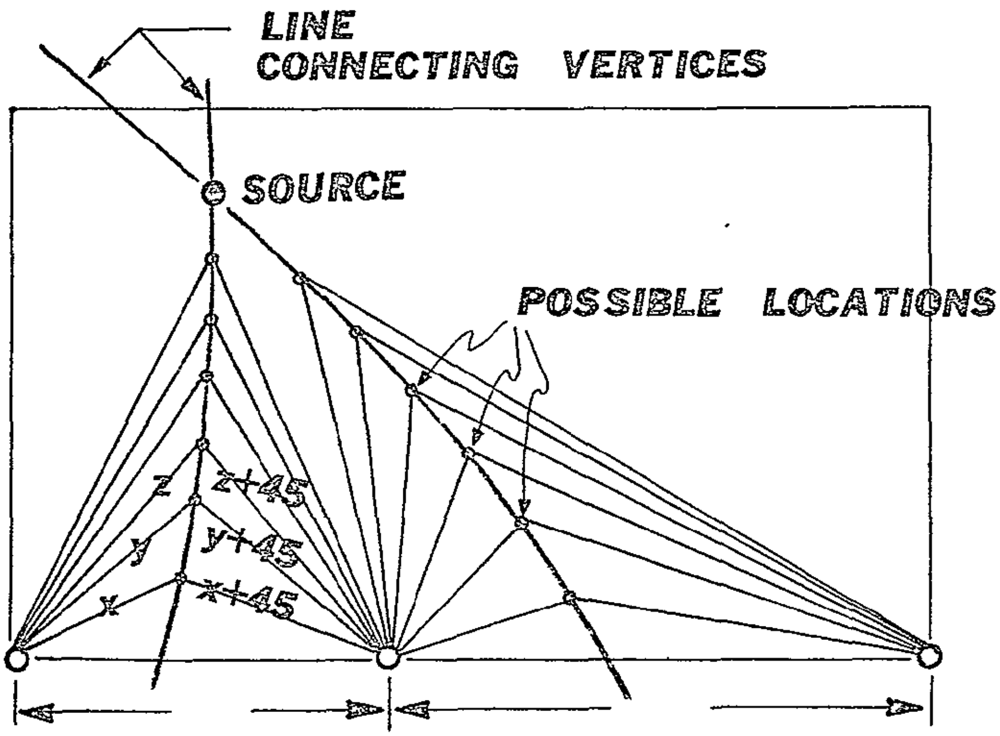
MEASUREMENT OF PHASE FRONT PASSAGE MIGHT YIELD :

STATION A (REFERENCE) MEASURES t5

STATION B MEASURES t6

STATION C " t7

Time-of-Arrival Triangulation
Figure 13



t7–t6=150 ns ⇒ 45 meters PATH DIFFERENCE

t6–t5=210 ns ⇒ 63 meters "

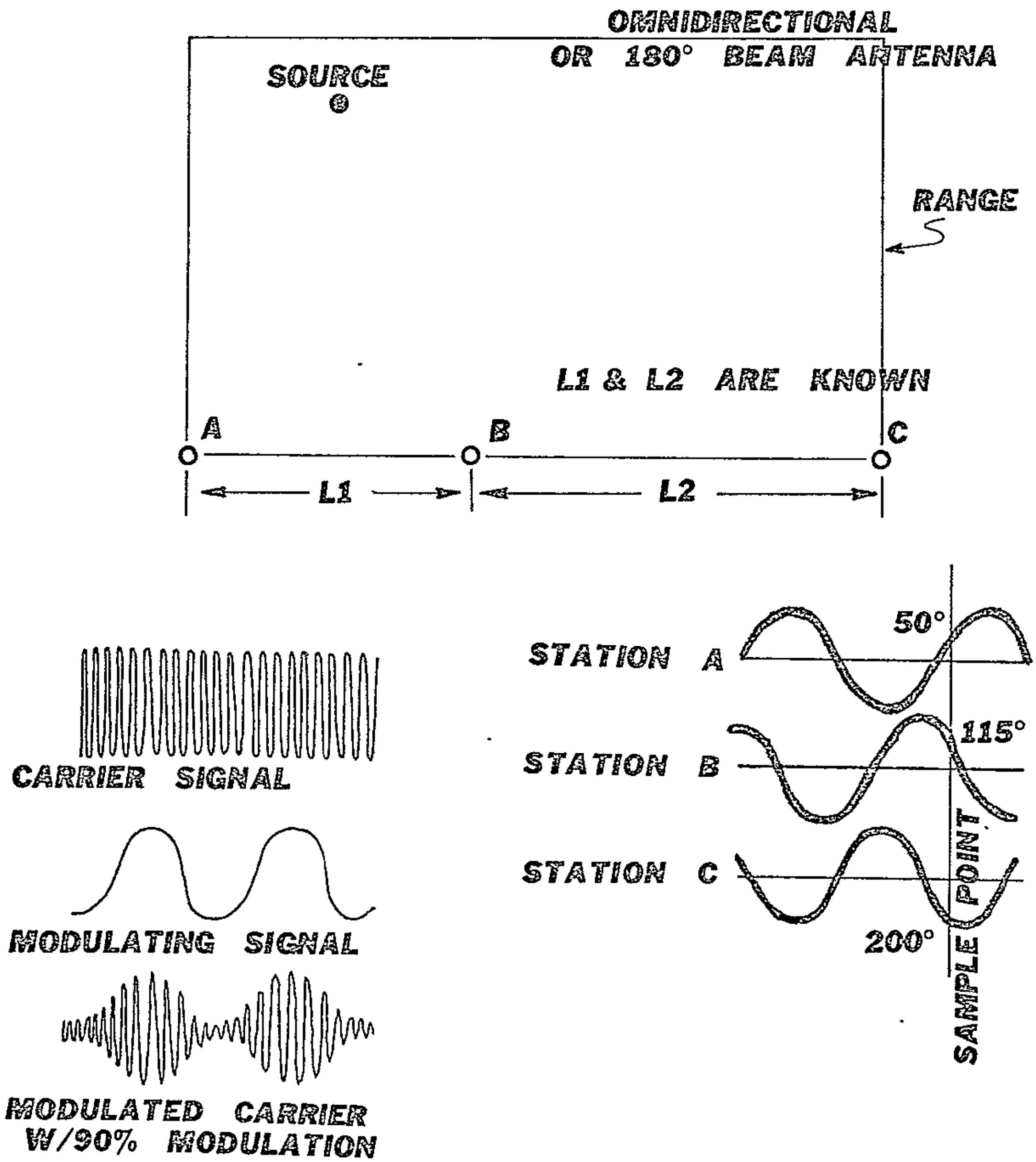
t7–t5=360 ns ⇒ 180 meters "

Time-of-Arrival Triangulation Example
Figure 14

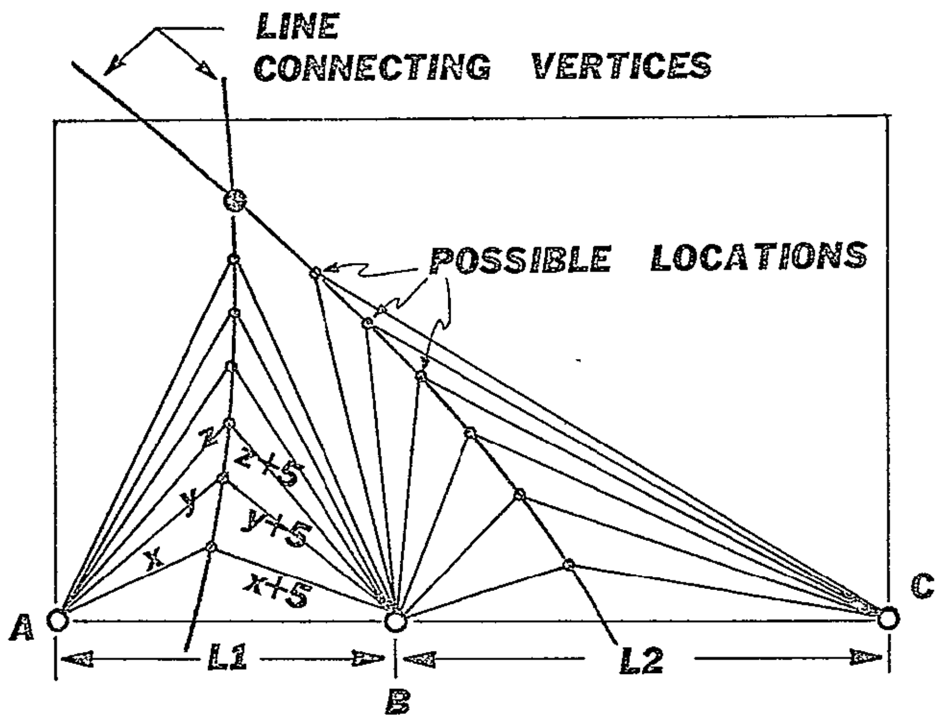
distance between the sites, L1 and L2, are known quantities. Unlike the highly directional antennas required by each site of the bearing triangulation system described previously, TOA sites require fixed omnidirectional antennas.

The source, being a cooperative target, transmits an RF energy pulse. In the far field, the phase front of this pulse can be considered planar. In Figure 14, the time intervals t_2 through t_8 represent various sequential "looks" at the planar wavefront as it propagates. T_2 and t_8 can also be thought of as sequential units of time since the transmission of the RF pulse at t_0. If each site notes the time unit corresponding to the passage of the wavefront, one might find that site A sensed the wave front passage at $t = t_5$, B sensed it at $t = t_6$ and C sensed it at $t = t_7$. Referring to Figure 14, it is seen that with knowledge of the wavefront propagation speed, the differences in each site's time unit measurement can be translated into units of path difference, that is, the different in distance that the wavefront had to travel from the source to each of the respective receiver sites. Triangles can then be formed as shown in Figure 14 using the known baselines as their bases. Each triangle vertex represents a possible location of the source based on the path length differences measured by pairs of sites. Three two-site nets are possible in this figure though only two are shown. By connecting the vertices of the respective families of triangles, a total of three lines may be formed (two are shown) all of which are found to intersect at the location of the source.

A variation of this scheme involving a modulated carrier is shown in Figures 15 and 16. If the source transmits a modulated RF signal, a simultaneous sampling of this signal by each receiver site will yield measurements of modulation phase that vary in accordance with the source location and which result from overall signal propagation delays. As shown in Figure 16, these phase differences as measured from site to site can be converted into source-to-site propagation distance differences, given the frequency of modulation and the speed of propagation. As before, three nets are possible in this example. However, only two are shown for clarity in Figure 16. Triangles are again constructed, vertices connected, and in a similar fashion, the source location is identified by the intersection of the hyperbolic lines. One advantage of sensing modulation phase rather than carrier wavefront lies in the fact that samples can be taken at any time whereas the latter requires memory



Phase Angle Triangulation
Figure 15



Δ AB=65° PHASE DIFFERENCE

Δ BC=85° "

Δ AC=150° "

FOR SOME GIVEN MODULATION FREQUENCY THESE PHASE DIFFERENCES MIGHT CORRESPOND TO

Δ AB $\Rrightarrow$ 5 meters PATH DIFFERENCE

Δ BC $\Rrightarrow$ 10 meters "

Δ AC $\Rrightarrow$ 15 meters "

CHOOSING Δ AB & Δ AC ,

Phase Angle Triangulation Example
Figure 16

of past events. TOA schemes will require some sort of intersite reference, be it digital timing pulse, a phase reference or a synchronized psuedo-noise code. As a result, all multinet TOA configurations will require interreceiver communications.

Care must be taken to match source pulse rate, modulation frequency or code repetition rate to the TOA direction finding (DF) net size to avoid ambiguities. If, for example, the frequency of the source modulation were too high, numerous 360° phase reversals could occur in the short time of signal propagation from one site to the next. Of course, the resulting position fix would be ambiguous to the extent of the number of cycles of phase reversal that had occurred.

Factors Affecting Direction Finding

DOA and TOA techniques differ significantly in the manner in which the basic angular and range data are derived; however, many basic error sources are essentially common to both. Such error sources have a direct and significant effect on performance (through required precision and accuracy), system complexity and cost. These sources can be labeled either "signal induced errors" or "system induced errors".

Signal induced errors include errors such as those resulting from:

- Multipath
- Depolarization (electromagnetic only)
- Interleaved-pulses
- Signal time-frequency dispersion
- Nonuniform noise background
- Multiple signal effects
- Refraction

System induced errors include errors such as those resulting from:

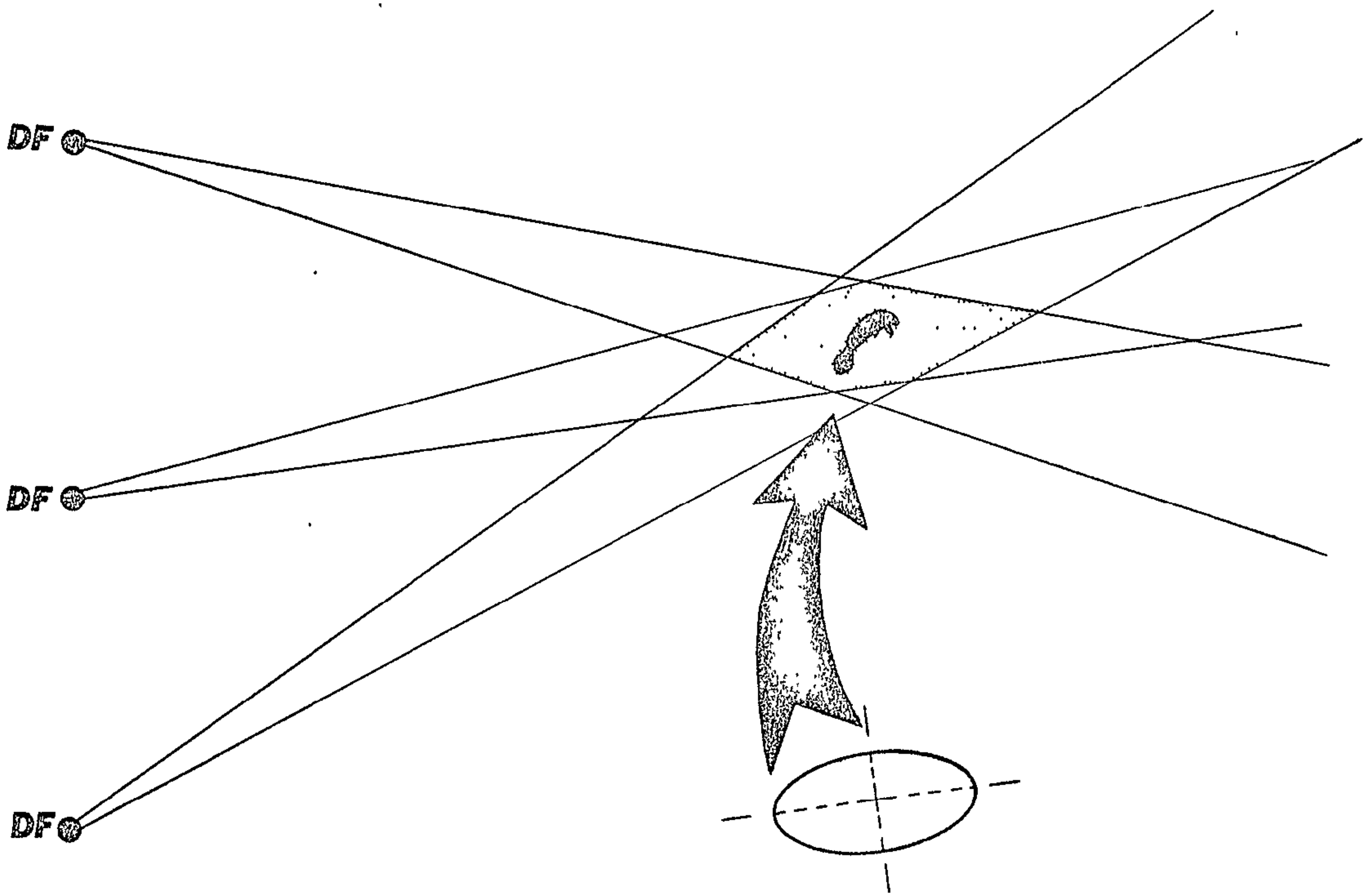
- Polarization and antenna pattern effects (electromagnetic only)
- Radiator beam-forming network unbalance
- Thermal noise (signal-to-noise ratio)
- Receiver amplitude/phase unbalance
- Transducer scattering and coupling
- Platform (reradiation effects and misorientation)
- Time measurement errors
- Timing inaccuracies
- Platform/position location inaccuracy
- Netting/synchronization factors
- Quantization error
- Round-off error
- Clock rate error
- Bit count error

All of these error sources lend uncertainty to each individual DF site fix. Figure 17 shows how the uncertainty in each measurement results in an area of uncertainty around the actual position of a target. It can be said that the target lies within this region; however, the precise position of the target within the region can only be extrapolated. Such regions usually assume an elliptical shape (in two dimensions) and are referred to as EPE's or elliptical probable errors. For uniformity of comparison, these elliptical uncertainty regions are frequency mapped into circles of equal area and are known as circular error probabilities (CEP). The location of each DF site within a net has a major influence on the size of the EPE. Obviously, the smaller the EPE the better. Typically, nets that surround a tracking region will result in significantly smaller EPE's than a colinear array of sites off to one side of the tracking range. Computer programs have been developed to optimize net configurations so as to minimize EPE uncertainties. Such an error analysis is presented in subsequent sections.

Of those errors listed above, multipath propagation is one of the most detrimental. Large reradiators will not only appear as "ghost" targets, but can obliterate actual targets through destructive addition of signals resulting in confused amplitude and phase returns. If any receiver site is not in line-of-site (LOS) contact with the target source (e.g., over the horizon) then tall reradiators can reflect normally non-radial energy from the source back to the receiver site on a radial path. This multipath signal may in fact be of greater amplitude than that received directly from the source. Under such circumstances, the DF system is likely to identify the location of the tall reradiator as the position of the target source. It is therefore desirable to maintain LOS coverage of an entire tracking range by at least two sites within a net at all times. An analysis of two-site LOS coverage for the proposed Banana River tracking area is presented in subsequent sections. Appendix I also discusses the various factors affecting direction finding systems as they relate to computer modeling of the optimum DF net configuration.

RF Operating Frequency

Since it has been established that the manatee must be a cooperative target, several factors must be considered when choosing the operating frequency



EPE Definition
Figure 17

of an electromagnetic system to be carried by the manatee. Of prime importance is antenna size, weight and shape. Typically, the larger the antenna or the more elements contained within it, the more efficient the antenna will be as a radiating/receiving transducer. These qualities, however, are incompatible with manatee hydrodynamics. Multielement and dish antennas must therefore be discounted at the onset. In fact, any antenna that can easily snag on vegetation, provides water resistance, or is unable to penetrate the surface of the water (except ELF antennas which will radiate through the water) must be avoided. Practically, this limits the manatee-borne antenna configuration to that of a whip type for frequencies above ELF. Further, a manatee-borne whip will become untractable for frequencies below approximately 30 MHz (HF range) because the length of a 1/4 λ stub at 30 MHz would be:

$$1/4\ \lambda = 1/4\ (\frac{c}{f}) = 1/4\ (3 \times 10^8\ \text{m/s})/(30 \times 10^6\ \text{Hz}) = 2.5\ \text{m}$$

Two and a half meters is beyond the perceived limits of tractability as well, but two additional factors must be included. First, whip antennas can be designed with loading coils which make them electrically longer than their actual physical length. Also, a monopole antenna normal to its ground plane (e.g., a whip extending above the water surface) has an electrically reflected image in the ground plane which serves to increase the electrical length of the antenna. Therefore, whips extending no more than approximately one meter above the water surface are adequate to radiate/receive frequencies in the HF, VHF, UHF and regions beyond. Of course, as the frequency increases, 1/4 λ decreases as does the necessary antenna length, making the antenna placement less of a problem.

ELF antennas, unlike those mentioned above, increase in size, weight and water penetrating efficiency as the frequency approaches DC. It is an absolute necessity that any manatee-borne ELF antenna be physically orders of magnitude shorter than its usable electrical length. This is evident when 1/4 λ is computed for f = 500 Hz, for example. A "whip" antenna at this frequency would be 150 Km long.

Frequencies commonly used by U. S. biologists and the Bureau of Sport Fisheries and Wildlife for animal studies, fall in the ranges of 150.85 to 151.15 MHz and 164.425 to 164.725 MHz, respectively. These are not FCC assigned (protected) frequencies though certain bands have been specified by the FCC for particular purposes. Examples of interest are 30.005-30.01 MHz for space research (likely to be available for use in and around the Cape Canaveral - Banana River area), 37.75-38.25 MHz for radio astronomy, 138-144 MHz for radiolocation and 400.05-401.0 MHz for space research. When considering operation in the upper HF (30 MHz), VHF (140 MHz - 300 MHz), UHF (300 MHz - 3 GHz) and beyond, care must be taken to choose a frequency band that will not interfere with any of the numerous assigned facilities occurring within this range. All VHF television channels as well as the FM broadcast band fall between 30 and 300 MHz. CB radio, police, fire radio service and amateur radio also occupy this band. From 300 MHz to 3 GHz, UHF television channels, police, fire and amateur radio will be encountered. Above 3 GHz, most systems such as radar and communication links become quite directional and are not likely to present the same interference problems as might be expected in the VHF band, for example. At ELF frequencies, interference will be from submarine communications, thunderstorms, commercial power generation, explosions, missile plumes and various other high powered, low frequency sources.

Comparison of HF, VHF, UHF

Table 3 compares HF, VHF and UHF over a range of parameters. This table is based in part on empirical near-surface HF/VHF/UHF propagation data gathered by EES during field tests at Boca Raton, Florida. For the most part, however, the table reflects three years of experience at Cape Canaveral monitoring 30, 140 and 400 MHz during EES's field operation in conjunction with the "Thunderstorm Research Instrumentation Program". Therefore, the table is quite specific about the spectral characteristics of the Kennedy Space Center (KSC) - Banana River area.

From the table, it can be seen that UHF (and beyond) is plagued by high path losses and fading while being most susceptible to meteorological effects (rain attenuation, etc.) and multipath reradiation in the KSC area. All of these effects are inherent in very high frequency atmospheric operation and should be expected; however, the multipath reradiation is particularly acute at KSC where so many of the man-made structures have antennas (ideal reradiators) mounted on top. In spite of the low noise, low interference UHF environ-

Table 3: Frequency Comparison

PARAMETER	HF	VHF	UHF
PATH LOSS	LOW	MEDIUM	HIGH
NOISE	HIGH	LOW-MED.	LOW
INTERFERENCE	HIGH	LOW	LOW
FADING	LOW	LOW	HIGH
ANTENNA EFFICIENCY	VERY LOW	NOMINAL	NOMINAL
METEOROLOGICAL EFFECTS	NEGLIGIBLE	NEGLIGIBLE	SIGNIFICANT
RERADIATION (MULTIPATH)	LOW	MED.-LOW	HIGH

ment at KSC, UHF operation or higher is not recommended for use in the proposed Banana River tracking area due to the other numerous problems outlined above.

Use of HF or VHF for manatee tracking does appear viable in the proposed tracking range. Though slightly more susceptible to multipath reradiation than HF, the use of VHF is recommended over HF due to the quietness of the band in the KSC area, reduced antenna length requirement (antenna efficiency) and the presence of FCC designated radio location frequencies.

ELF Frequency Considerations

The choice of a useful ELF frequency is much more difficult. For best water transmission qualities as low a frequency as possible should be employed. This, however, severely limits the data rate of any encoding or frequency modulation. Transmitter and antenna efficiency also decrease with frequency. For a battery operated manatee-borne system, it is imperative that high efficiency of power consumption be maintained at all times in order to obtain a reasonable system lifetime. This favors use of higher frequencies, perhaps in the VLF, LF or MF range (e.g., as high as 3 MHz). Insufficient data exists in the literature for submerged antenna efficiency at frequencies below MF. It is recommended that a brief measurement program be initiated to tabulate radiated power efficiency vs. frequency from ELF to MF before embarking on a low frequency implementation of the tracking system. If an optimum low frequency can be identified, further experiments are recommended to find an antenna configuration that is adaptible to a manatee without loss of efficiency. Following the designs of Mackay [18], it has been suggested that a loop antenna be used with 10 to 20 turns around the smallest diameter of the manatee's body, just forward of the tail.

MANATEE-BORNE ELECTRONICS PLACEMENT

Manatees are difficult creatures upon which to place telemetry. The ideal location for a strap-on instrument package would be just behind the front flippers. Since the manatee is very articulate with these appendages when feeding and manuevering, it is felt that anything placed over or around the flipper would be a constant source of annoyance to the animal. A strap around the narrow stock of the tail is the next best choice since the spatulate tail flair would restrict forward slippage. Strap-on equipment at any other body location is highly likely to migrate fore or aft, ultimately falling off the animal. Any equipment strapped to the tail stock should be located dorsally, as ventral placement will expose the equipment to excess abuse as the manatee skims along the bottom during grazing. It should be noted that manatees are "habitual scratchers" because much of their time is spend rubbing against submerged objects with the result that any ectophoretic equipment (regardless of location) is likely to be periodically abraded.

Hartman [1] describes his attempts to tag manatees with a miniature acoustic pinger embedded in a buoyant material and tied around one of the manatee's flippers with a two meter long string. Five trials were made all ending in failure.

> Within half an hour into each trial, all of the animals reacted to the sensation of the string and tried to unleash themselves by rubbing the noose against logs and poles or by scratching at the string with the free flipper. In her third trial, one manatee tangled the string around her trunk, grew agitated and swam to the base of an iron signpost where she rubbed frantically until I was obliged to free her. In every instance, routine behavior was so disrupted that further experiments with the buoy were discontinued.
>
> In a final effort to tag an animal, the transmitter was sheathed in a latex "armband" which was slipped over the distal end of the flipper and secured in its axil. The manatee rubbed at the sheath with its free flipper and managed to roll it down and off within an hour.

Other experiments involving balloons and floats were also unsuccessful.

There are methods currently in existence which would undoubtedly meet with success such as those used to tag other marine mammals (e.g. the walrus and sea lions). These methods employ grappling barbes which catch in the thick hide like miniature fish hooks. Surgical implantation is also extremely promising because the entire instrument package could be placed under or within the dermal layer. This would lessen the chance of infection that might be encountered with foreign objects (e.g. grappling barbes) protruding through the surface of the dermis. These methods all have merit; however, little research of this kind has been attempted on the manatee principly because it is so difficult to obtain the necessary federal and state authorization for experimentation that is potentially hazardous to the health of an endangered species. This problem is currently under study by the biologists at the Gainesville (Florida) Field Station, NFWL-FWS, who have been able to suture a metal plate at the rear of the cranium. Various suture materials were employed with stainless steel being the most promising. No infection has been observed (even under fresh water conditions) and at the time of this writing, the plate has remained in place for a period of months. At this point, the folloiwng observations can be made:

(a) Implantable electronics (the most desirable from a systems standpoint are out of the question for political reasons that could arise due to the death of a tagged manatee--even it death were determined to be unrelated to the tagging.

(b) Epidermal grappling devices (such as are in use on sea lions) must be rejected for the same reasons as stated above as well as the increased chance of infection.

(c) Adhesives (such as the cyanoacrylates or "super glues") would apparently be ineffective due to the high rate of dermal sloughing of the manatee.

(d) Ectophoretic attachments such as harnesses seem to be the most acaceptable methods.

(e) Thin sutures show promise, however, final results of experimentation in this area are not yet available.

Certain questions related to harnessing need to be addressed in further detail. It is recommended that a brief experimental program be initiated to investigate the following areas:

- Life-time of harness material in a marine environment.
- Harness material that allows skin to breath, slough, etc. yet prevents organisms or detritus from becoming lodged at the dermal-harness interface.

- o Points of the manatee which can be used to hold a harness in place.
- o Possible behavior modification or motor restriction due to harness.

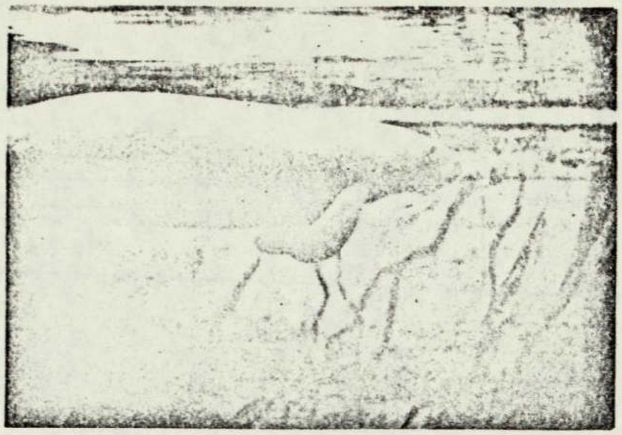
It is also important to consider the impact of the manatee-borne electronics as it approaches the end of its useful life. The system should be retrieved while the tagged individual is still able to be tracked. This would allow reuse of the system and prevent the manatee from having to carry around functionless equipment for the rest of its life. Duration of tracking operations could purposely end one month prior to the estimated battery failure date. This would allow biologists 30 days to locate and remove the tag with the aid of the tracking system. This is not a complete answer, however. Premature tag failures or migration of a tagged individual from the tracking range would likely result in the individual being tagged for life unless a time-release mechanism (perhaps nothing more than a seawater corrodible link) is employed to automatically jettison the electronics after some period of time exceeding the expected battery life of the tag. In fact, internal battery impedance could be electronically monitored and result in tag jettison upon battery discharge. If the system is surgically implanted into the manatee, it must be either benign after battery failure or must be removed surgically. No recommendation for system jettison or retrieval should be made until a choice of placement techniques is specified and tested.

An additional restriction is imposed when considering the use of an HF or VHF antenna. To operate reliably, the entire radiating length of the antenna must extend above the surface of the water. Since the manatee is totally aquatic, this is only assured during periods of inhalation when the animal is guaranteed to be at the surface. Manatees also spend time at the surface when resting or traveling but the frequency of these activities, unlike breathing, is irregular. Manatees typically spend from approximately 2-1/2 to 4 seconds (depending on age and state of activity) at the surface during a breathing interval (note that a TOA DF system can acquire a signal and fix position in well under one second). Typically, manatees will return to the surface to breathe every 1 to 2 minutes when cruising or as infrequently as once every 10 minutes when resting [1]. This implies that an antenna must be deployed reliably at every opportunity since opportunities will be relatively infrequent.

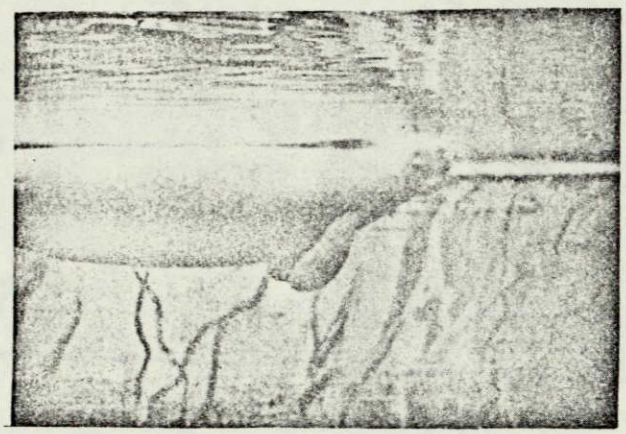
Figure 18 shows an actual manatee breathing sequence. Note that an antenna could be positioned anywhere from the tip of the nostrils to the mid-dorsal section. Placing anything forward of the eyes or in the field of view is not recommended. However, Figure 19 shows that manatees often approach the surface at nearly a 30° angle when breathing. This behavior limits reliable antenna deployment to the region above and just behind the cranium.

Use of an acoustic or ELF system has its greatest advantage in being able to be placed anywhere on the manatee. As stated previously, tail stock placement would be advisable from a harnessing standpoint. Acoustic transmissions are likely to be blocked by the animals' body in certain orientations if transducers are placed too near the body surface. This will result in an undesirable directionality of the signal.

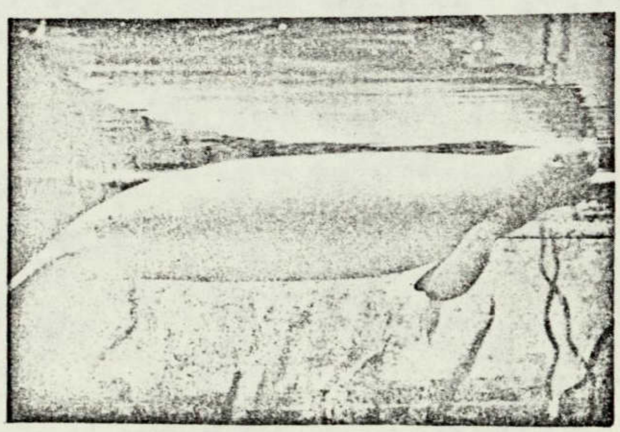
Again, insufficient information is available concerning placement of objects on manatees. The sutured headplate under test will yield some answers to the viability of head-mount whip antennas. It is recommended that a brief experimental program be initiated to investigate the placement of a simulated whip antenna on a substrate attached just behind the head of a manatee in a fashion similar to that used with the sutured plate. This simulated antenna and small associated electronics module would monitor the frequency of successful antenna deployment above the water (a salt water switch might be employed as a sensor on the antenna). Various parameters such as antenna angle, position and length could be varied to empirically determine the optimum position. Also, the manatee's response to the antenna (if any) would be evident.



(a)

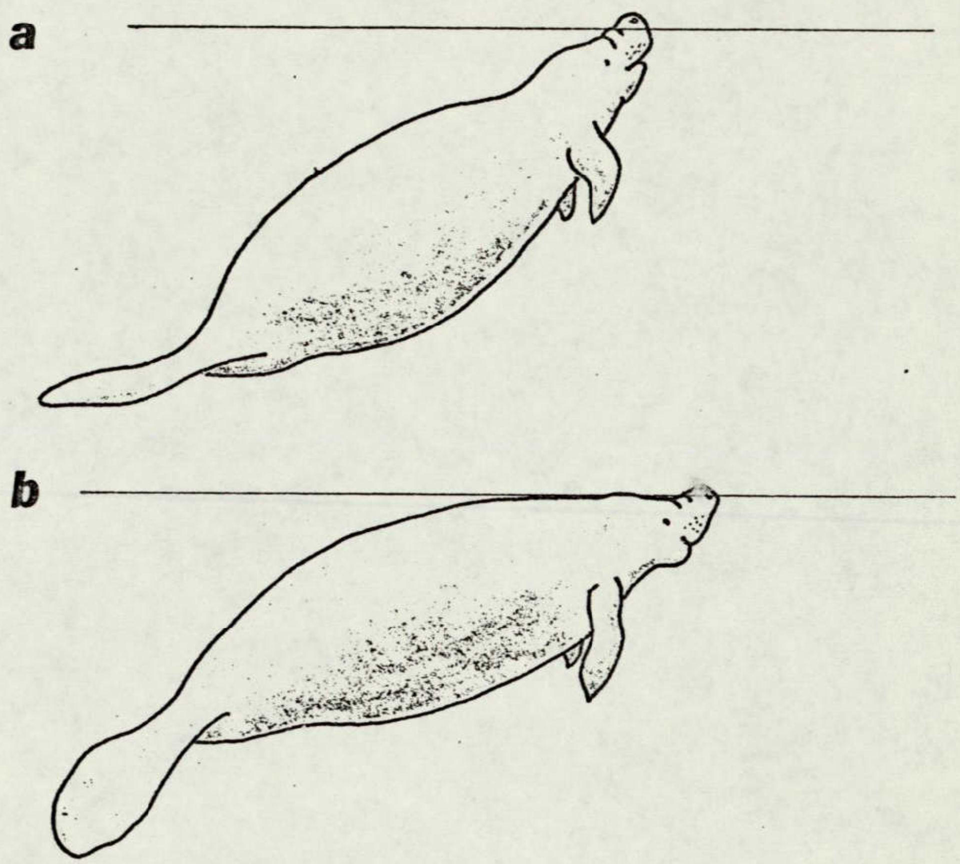


(b)



(c)

Breathing Sequence of T. manatus
Figure 18



Typical Breathing Postures
Figure 19

ENCAPSULATION OF MANATEE-BORNE ELECTRONICS

There are three basic methods of embedding electrical circuits: molding, casting and dipping. Molding involves the use of a container, usually metal, to house the electronic assembly. The container is slowly filled with the potting material and then cured. The thermal coefficient of expansion of the container, electronics and the embedment medium must match or the medium will separate from the walls of the container and/or circuit resulting in poor thermal contact. This can lead to possible overheating of the circuit. Another problem which may arise is electrical shorts to the container. A sheet of insulating material is often needed between the electronic assembly and the container.

Casting involves the use of a mold. The electrical circuitry is placed inside the mold and the embedding material is slowly poured in. After this material hardens, the mold is removed. If a large number of circuits are to be embedded, casting can be less expensive than molding. Molds for casting typically cost more than several containers for molding.

The third method of embedment is dipping. The electronic assembly is simply dipped into the encapsulating material, pulled out and cured. It has the advantage of being less expensive than either casting or molding. The curing time is usually reduced as well since the encapsulating layer is frequently quite thin. However, this method provides little protection from mechanical shock and abrasion. Also, voids in the circuit being dipped often make total coverage difficult.

Cyanoacrylates exhibit the shortest curing times; typically less than one second at room temperature. This is an excellent characteristic if curing time is a prime concern; however, it makes the handling of the cyanoacrylates extremely difficult. Since the surface layer cures so rapidly, only a thin coat, such as that achieved by dipping, can be used.

Cyanoacrylates will form a strong bond with a wide variety of materials. However, its thermal expansion coefficient must be compared to that of the material which is to be encapsulated. This is important when encapsulating electronics since mismatching may occur when the circuit is brought up to operating temperature during use. Mismatching will result in strains which can cause leaks in the cyanoacrylate coating or even damage the circuit components. The cyanoacrylates have good resistance to mechanical shock and abrasion but poor resistance to moisture. None of the compounds are flexible. They are useful in the temperature range of 0°C to 100°C. Cyanoacrylates currently cost about $60 per kilogram.

A second group of potting materials, the polyesters, cure at room temperature within a few hours depending on the depth of the layer. During curing, they exhibit very little exothermic reaction but have high shrinkage which might damage very delicate electrical components. Since the polyesters will expand and compress somewhat, matching of thermal expansion coefficients need only be considered if circuit components are highly fragile. Polyesters are flexible and have good resistance to both mechanical shock and abrasion; however, they have only fair humidity resistance and very poor moisture resistance when immersed. The cost is around $8.00 per kilogram.

The silicones form one of the most useful groups of embedding materials. A variety of silicone potting compounds are available from a number of commercial sources. The silicones fall into three categories:

1. RTV (room temperature vulcanized) silicone resins. As the name indicates, they cure at room temperature. However, many of the RTV compounds can be placed at moderately elevated temperatures (up to 60°C) to decrease curing time. Curing time varies from half an hour to 48 hours depending on curing temperatures, the depth of the layer, and the particular compound used. RTV compounds cure in either thin or deep layers and exhibit very little shrinkage, internal stress, or exothermic reaction during curing. Thermal expansion of the encapsulated circuit is not a problem with RTV silicones since they will stretch or compress. They respond well to mechnical shock and exhibit fair to good abrasion resistance depending on the particular compound. RTV silicones display good resistance to atmospheric moisture but performance is degraded with extended immersion. Once cured, RTV silicones can be used anywhere from -65°C to 260°C. These compounds are the easiest of all of the encapsulating materials to work with. A high quality RTV silicone costs around $10.00 per kilogram.

2. Silicone gels. They are very tough and are able to withstand con-

C2

siderable shear force and heal themselves when punctured. They lack some of the flexibility and compressibility of the RTV silicone compounds but other characteristics are comparable.

3. Rigid, solventless silicones. These are used infrequently because they require high temperatures for curing and crack easily under thermal and mechanical shock.

Polyurethanes have many properties similar to those of silicones. They cure at room temperature or in a moderate (to 60°C) oven with curing times depending on temperature, the thickness of the layer and the particular compound used. While all polyurethanes will cure in thick layers, some compounds will not cure properly in thin layers. During curing, polyurethanes tend to shrink somewhat. However, the resulting stresses are insufficient to effect most electronic circuits. Very little exothermal heat is generated during curing. The adherence of polyurethanes is fair to good, depending on the particular compound and the material to which it is bonded. Thermal expansion of polyurethane encapsulated electronics typically does not cause adherence problems since polyurethanes will stretch and compress with circuit components. Polyurethanes have good mechanical shock resistance and their abrasion resistance is very good (even better than that of some epoxy compounds). They have good resistance to atmospheric moisture but vary widely in moisture resistance upon extended immersion (though most do poorly in this regard, certain compounds are able to outperform any of the silicones). The flexibility and compressibility of polyurethanes are comparable to those of silicones. Though polyurethanes will not perform at the elevated temperatures tolerated by silicones, they can be used from -60°C to 180°C. Most polyurethanes contain toluene and proper precautions must be taken during handling. The average cost is about $11.00 per kilogram.

Epoxy-based materials are the most widely varied group of encapsulants. They are available as one component and two component types. Curing temperatures range from room temperature to 130°C with curing times ranging anywhere from two hours to two weeks. Most epoxies will cure in either thin or thick layers and exhibit very high exothermal reaction temperatures in the process. Epoxies also shrink during curing, therefore fragile components should first be coated with a compressible material such as silicone or polyurethane to prevent breakage. Coefficients of thermal expansion must be carefully matched between epoxy and the circuit assembly to prevent leaks or broken components if this potting agent is to be in direct contact.

Epoxies form strong bonds to most materials and are particularly effective in sealing around terminals. Resistance to mechanical shock and abrasion range from good to very good depending on the particular compounds.

Epoxies are highly resistant to both water vapor and liquid water. In fact, one particular group of resins are supposedly inpenetrable to water molecules [41]. However, the cost is high - $50.00 per kilogram as compared with $10.00 per kilogram for a more typical epoxy. When the cost of epoxy is compared to that of silicone or polyurethane, several additional factors must be evaluated. Epoxies are very dense in comparison to silicones and polyurethanes. This means that one kilogram of epoxy will not encapsulate as many circuits as one kilogram of either the silicones or polyurethanes. Also, the cost of using two component epoxies is driven up by the necessity for precise mixing and dispensing equipment.

Fillers such as sand or silica can be added to epoxies. The advantages are lower cost, increased thermal conductivity, and reduced exothermal reaction temperature and shrinkage during curing. Fillers can also make the normally rigid epoxies somewhat flexible. There are disadvantages to fillers, however; mechanical shock resistance and machinability are reduced while the adherence and electrical properties may be affected.

Flexibilizers are also available for epoxies. They lessen the basic hardness of epoxies, reduce strains during curing and improve adherence, low temperature performance and crack resistance during temperature cycling. Offsetting these mechanical advantages however are losses in some of the desired electrical properties. As the rubber like qualities increase, dielectric loss factor and dielectric constant increase while resistivity decreases. Moreover, the material loses strength and softens at elevated temperatures. Because of the negative effects of the flexibilizers, most manufacturers recommend that designers use the most rigid epoxy resin that will provide the needed mechanical properties when cured.

In general, all of the encapsulants mentioned (with the exception of several epoxies) are impervious to the corrosive effects of salt water.

Table 4 is a summary of the major characteristics of the silicones, epoxies and polyurethanes.

Recommended Encapsulation Technique

Three basic factors enter into the choice of encapsulants and methods of application when considering the manatee-borne electronics. First, the circuitry will be immersed for very long periods of time. This means that the encapsulant must exhibit excellent water tight integrity. In addition, some sort of transducer terminals must pass from the circuitry through the encapsulant, to the transducer. Therefore, the encapsulant must exhibit strong bonding tendencies to prvent moisture from seeping along the interface.

Though anticipated hydrostatic pressures are not expected to exceed more than 0.5 Kg cm^2, the encapsulant must be very strong to withstand the high impacts and regular abrasion to be encountered on the manatee. The delicate electronic circuitry must be "shock mounted" within the encapsulating material to prevent transmission of surface impact shock to the interior.

The shape of the encapsulated circuitry will be hydrodynamically uniform to reduce drag and the likelihood of vegetative fouling. Therefore, casting techniques can be used without much difficulty. Casting will allow for thicker walled encapsulations than dipping, thereby affording greater strength.

Based on these requirement, it is recommended that the circuitry of the manatee-borne electronics be dipped in a silicone bath, cured and then cast in a high grade pure epoxy. The epoxy will afford the strength, water resistance and feed through bonding required while the silicone will provide protection from harmful curing effects of the epoxy as well as providing additional shock resistance.

It will be cost effective to include the batteries within the potted enclosure (taking necessary precautions for battery expansion, gassing and the effects of salting on the encapsulant) to minimize feed through connections. A magnetic reedswitch can be used to deactivate the circuitry (and conserve battery life) once encapsulated. This means that the manatee-borne electronics would be considered expendable and disposable (see discussion of system release/retrieval). In the event that the batteries required replacement, removal and replacement could be achieved by cutting away one end of the battery section, replacing the batteries and recasting the cut away end.

TABLE 4. COMPARISON OF ENCAPSULATING COMPOUNDS

TYPE		SILICONES	EPOXIES	POLYURETHANES
CURING TEMP., °C		25 - 60	25 - 130	25 - 60
CURING TIME		1/2 - 48 HRS.	2 HRS.- 14 DAYS	1/2 - 72 HRS.
CURING CHARACTER.	SHRINK	VL	M	M
	EXO. HEAT	VL	H	H
DURABILITY		G	VG	E
FLEXIBILITY		FLEX	RIGID TO SEMI-FLEX	FLEX TO SEMI-FLEX
COMPRESSIBILITY		YES	NO	YES
ADHERENCE		F-G	G-E	F-G
THERMAL EXPANSION		N/A	MATCHED	N/A
MOISTURE RESISTANCE	ATMOS.	G	G	G
	IMMER.	F	G	P-G
ABRASION RESISTANCE		F-G	G-VG	G-E
MECHANICAL SHOCK RESISTANCE		G	F-VG	G-E
USEFUL TEMP. RANGE, °C		-65 - 260	-20 - 300+	-60 - 180
EASE OF HANDLING		VERY EASY	CAREFUL MIXING REQ'D	CAUTION W/ ORGANIC SOLVENTS
COST PER KILOGRAM		$10.00	$10.00-$50.00	$11.00

VL--VERY LOW M--MEDIUM H--HIGH P--POOR F--FAIR G--GOOD VG--VERY GOOD E--EXCELLENT

ENERGY SOURCES

The energy requirement for a manatee tracking system can be divided into two major categories, the receiver site energy source and the manatee-borne energy source, the general characteristics of which are given below:

Receiver Site (Fixed Station):	110 VAC Operation with Battery/ inverter backup
	Continuous Operation
	Multiple DC Output Voltage Taps
	Regulated, Over-voltage Protect, Over-Current Foldback
	Deliverable Power 500 W
Receiver Site (Mobile Station):	110 VAC Operation - Battery/Inverter
	Intermittant Operation
	Multiple Output Voltage Taps
	Regulated, Over-voltage Protect, Over-Current Foldback
	Deliverable Power 500 W

Note that the receiver site requirements listed above are solely for the operation of system electronics. Enclosure lighting, air conditioning, etc. for each site (if desired at all) will not be included as part of the tracking system analysis.

Manatee-Borne Electronics:	Low Voltage DC
	Compact
	Lightweight
	Intermittant Operation
	Deliverable Power Approximately 3 Watts (Peak)
	Nontoxic
	Long Life Remote Operation

The selection of 110 VAC as the operating voltage at the receiver sites is prompted by the availability of commercial equipment which requires this input voltage. Much of the equipment necessary to the operation of each receiver site is available off-the-shelf and will typically provide for its own internal voltage, current and regulation requirements. Obviously, the most accessible source of 110 VAC is directly from the local power company's facilities and therefore, it will be economically advantageous to locate receiver sites near such commercial power distribution points. For reasons of unavailability, power system backup, or mobile use, the regular 110 VAC operation must be assisted or supplanted by auxillary means of power generation. This auxillary (or primary, in the case of mobile operation) power supply can be implemented in a number of forms of which several are listed below:

- o Battery (any chemical source)
- o Solar Cells
- o Mechanical Generator
- o Nuclear
- o Fuel Cells

Note that identifying the best primary source of electrical energy is of central importance here as the transformation of that energy into the proper state (voltage, current, frequency, etc.) presents no particular design problem. This list of primary sources is also applicable (though not all are viable) to the manatee-borne electronics.

Many energy sources with obvious shortcomings have been omitted from this analysis (e.g. geothermal, peizoelectric, etc.). Fuel cells and nuclear generators will also be discounted due to their complexity, cost and potential risk. In this regard, batteries, solar cells and mechanical generators in either stand-alone or synergistic combinations come far closer to fulfilling the requirement of a manatee tracking system power source than do any others.

Battery Considerations

Since it is desirable that the manatee-borne electronics operate for as long as possible (6 months to 1 year), a high service capacity battery would be needed. However, the size of the electronics package must be kept to a minimum thus requiring batteries with a high volumetric energy density per cell. The weight of the electronics package must be buoyancy compensated (a requirement usually resulting in greater volume), hence for this application a higher gravimetric energy density per cell would also serve to minimize the package size.

From an electrical standpoint, a flat voltage discharge curve is a particularly important battery characteristic because a gradual decrease in voltage could result in a gradual shift of the modulation or carrier frequency of transmission. Since battery operation is the direct result of a chemical reaction, it is not surprising to learn that discharge efficiency is closely related to temperature . Normally, manatees do not encounter water temperatures below about 5°C with a typical low being around 10°C. For certain battery types, this is a region of high inefficiency, hence temperature efficiency ratings must be considered.

Other considerations concern leakage and the amount of gas produced as a result of electrical discharge. Leakage of corrosives can harm circuitry, reduce the integrity of encapsulating materials or irritate the subject manatee while excess gassing can cause water-tight battery containers to explode.

Battery Analysis

Since hundreds of batteries are commercially available, their analysis is simplified by grouping them according to their electrochemical systems, then examining the general characteristics of each group.

The most commonly used battery is the carbon-zinc type. Because of its commonality, it is available in many styles varying in shape, size, voltage and terminal arrangements.

Carbon Zinc

A carbon zinc cell has a nominal voltage of 1.5 V. At a cost of $0.57, the best "D" size battery has a service capacity of 6A-H operating with a 200 mA constant drain. It maintains 80% of that capacity at 10°C. As Table 5 indicates, the working voltage of a carbon zinc cell falls off gradually as the battery is discharged. Its gravimetric and volumetric energy densities are 44.44 W-hrs per Kg and 0.14 W-hrs per cu. cm, respectively.

Encapsulating a carbon zinc cell should be avoided since its venting mechanism would be hindered. Total blockage of the vent could result in sufficient hydrogen gas build-up to cause explosion of the battery.

A zinc chloride version of the carbon zinc battery is available. Though it lacks the wide variety of shapes and sizes available in the standard carbon

TABLE 5. DRY CELL CHARACTERISTICS

Usual Name		Carbon-zinc	Carbon-zinc (Zinc Chloride)	Alkaline-Manganese Dioxide	Mercuric Oxide	Silver Oxide	Nickel-cadmium	Lithium
Voltage Per Cell		1.5	1.5	1.5	1.35	1.5	1.2	2.95
Type		Primary	Primary	Primary & Secondary	Primary	Primary	Secondary	Primary
Typical Service Capacity (A-H @ 200 mA Drain)		6	6	Primary - 10 Secondary - 2.5	19	0.2	4	10
Energy Density W-Hr/Kg.		44.44	88.89	Primary - 88.89 Secondary - 22.22	111.11	111.11	31.11	333.33
Energy Density W-Hr/Cu. cm		0.14	0.18	Primary - 0.15 Secondary - 0.07	0.37	0.49	0.08	0.53
Operating Temp. Range (°C)		-6.7/54.4	-17.8/71.1	-28.9/54.4	0/54.4	0/54.4	-20/45	-40/70
Temperature Performance W.R.T. Service Capacity	Hi	M	M	G	G	M	VP	VG
	Low	P	F	M	P	P	P	VG
Discharge Curve								
Leakage		Medium	Low	Rare	Some Salting	Some Salting	None	None
Gassing		Medium	Higher than Carbon-zinc	Low	Very Low	Very Low	Low	None
Reliability @ 2 yrs		99%	99%	99%	99%	99%	99%	99%
Shock Resistance		F - G	G	F - G	G	G	G	G
Initial Cost		$.57	$.62	Primary $.65 3-Cell Sec. $6.12	$4.87	$1.20	$6.98	$8.50
Features		Low cost; variety of shapes & sizes	Service capacity at moderate to high drains better than carbon-zinc. Good leakage resistance; low temp. performance better than carbon-zinc	High efficiency under moderate & high continuous drain. Good low temp. performance, low impedance	High service capacity to volume ratio, flat voltage discharge curve, good high temp. performance	Moderately flat voltage discharge curve high service capacity to volume ratio	Flat voltage discharge curve, good high & low temp. performance high resistance to shock & vibration, can be stored in any charge state	Flat volt-discharge curve, very good high & low temp. performance, no gassing problem, very high energy density to weight ratio
Limitations		Efficiency decreases at high current drains; poor low temp. performance		Primary type expensive for low drains, limited cycle on secondary, secondary not available in "D" size	Poor low temp. performance	Available only in small sizes low capacities	High initial cost only fair charge retention	

VP--Very Poor P--Poor F--Fair M--Medium G--Good VG--Very Good zinc cell, it has other advantages. For example, under normal operating conditions, the zinc chloride cell has the same nominal voltage and service capacity as the standard cell. However, at an operating temperature of 10°C, it maintains 90% of its service capacity (a 10% increase over an ordinary carbon zinc cell). Its gravimetric energy density (88.89 W-hrs per Kg) is twice that of the standard carbon zinc cell and its volumetric energy density (0.18 W-hrs/cu. cm) is 23% higher. It has the same sloping voltage discharge curve as the standard cell though production of hydrogen gas is greater. Nominal cost is $0.62 per battery.

Alkaline-Manganese Dioxide

Alkaline-manganese dioxide batteries are available in both primary and secondary cells. Both types have a nominal voltage of 1.5 V characterized by a sloping discharge curve (see Table 5). For the secondary cell, the slope of the discharge curve varies directly with the number of charge/discharge cycles. The service capacities of "D" size primary and secondary cells are 10 A-H and 2.5 A-H, respectively, based on a constant drain of 200 mA. The service capacity of the secondary cell decreases with an increasing number of charge/discharge cycles. Both have approximately 85% of their rated capacities at 10°C. In comparison to the secondary cell, the primary cell has both a higher gravimetric energy density (88.89 vs. 22.22 W-hrs/Kg) and a higher volumetric energy density (2.15 vs 0.07 W-hrs/cu. cm). The cost is also much higher for the secondary cell, $6.12 compared with $0.65 for the primary. In both types of alkaline-manganese dioxide cells, gassing is lower than it is in a carbon zinc cell. However, complete potting should be avoided for the same reasons presented for carbon zinc.

The chief advantage of the alkaline manganese battery lies in its high efficiency under continuous or heavy duty, high drain conditions where the standard carbon zinc cell is unsatisfactory. At light drains, however, or under intermittant duty conditions, the alkaline-manganese cells have little advantage over the standard carbon zinc cell.

Mercuric Oxide

The mercuric oxide battery is a primary cell with a nominal voltage of 1.35 V. The "D" size cell costs around $4.87 and has a service capacity of

19 A-H under a 200 mA constant drain. This service capacity is lessened by pulsed use. Below room temperature, it is very inefficient maintaining only 15% of its rated capacity at 10°C. During discharge, voltage declines about 14% initially and then remains constant until the end of the cell's useful life (see Table 5). Mercury cells have high gravimetric and volumetric energy densities (111.11 W-hr per Kg and 0.37 W-hr per cu. cm, respectively).

Mercury cells must be permitted to vent to the atmosphere to allow the escape of hydrogen gases. This is particularly true in case of operating abnormalities such as reverse currents or short circuits which produce excessive gas. Though the rate of hydrogen gas production in mercuric oxide cells is lower than in either carbon zinc or alkaline-manganese dioxide cells, complete potting is still not recommended. There are also some salting effects with mercury batteries.

Silver Oxide

The silver oxide cell has a nominal voltage of 1.5 V with a maximum service capacity of 200 mA-H. Eighty percent of this capacity is available at 10°C. A silver oxide battery maintains a stable voltage level until the end of the cell's useful life when the voltage drops sharply. Gassing is very low in silver oxide cells, but there are some salting effects.

Silver oxide batteries have best efficiency at very low, intermittent usage. A major drawback of silver oxide cells stems from the fact that they are only commercially available in very samll sizes and with low capacities. The largest capacity cell costs approximately $1.20.

Nickel Cadmium

The nickel-cadmium cell is a hermetically sealed secondary cell with a nominal voltage of 1.2 V. It has gravimetric and volumetric energy densities of 31.11 W-hrs. per Kg and 0.08 W-hrs per cu. cm, respectively. A "D" size cell costing about $6.98 has a service capacity of 4 A-H with a 200 mA continuous drain and maintains 95% of that capacity at 10°C. Nickel cadmium cells have a relatively flat discharge characteristic which remains flat through multiple charge/discharge cycles. However, the service capacity decreases with each cell recharge.

A nickel cadmium cell emits very little gas; however, it does undergo expansion and contraction due to normal internal pressures. Because of this, it should not be entirely potted in a material which would restrict its expansion.

Lithium

Lithium cells are primary cells with a nominal voltage of 2.95 V - twice that of the other cells examined. The gravimetric energy density of lithium cells is three times that of mercuric oxide and the volumetric energy density is nearly 50% greater. At a nominal cost of $8.50, the service capacity of the best "D" size lithium cell is 10 A-H rated at a 200 mA constant current drain while maintaining essentially 100% of that capacity at 10°C. The cell operates most efficiently in a pulsed current mode. As indicated in Table 5, the operating voltage of a lithium battery remains stable until the end of the useful life of the cell at which time it drops abruptly.

Since the electrolyte in a lithium cell is non-aqueous, no hydrogen gas evolves during discharge. However, misuse (i.e., short circuit and reverse currents) or any continuous high current drain can result in internal heat that causes a pressure build up which must be released through a vent. If the batteries are to be encapsulated, protective devices should be included to handle short circuits or reverse currents and care must be taken to see that the batteries are under only moderate or intermittent current drains.

Seawater Batteries

Seawater batteries have some unusual characteristics. They are essentially dry charge primary cells which are activated by seawater. The electrodes consist of magnesium for the anode and either silver or copper chloride for the cathode. Seawater batteries cannot be recharged since the electrodes are consumed during the electrochemical process. The nominal voltage is 1.6 V and the gravimetric energy density is approximately 66.67 W-hrs. per Kg. The voltage rises somewhat during operation until it reaches a maximum occuring near the middle of its useful life and then gradually declines. Seawater batteries are activated immediately upon immersion in salt water and are deenergized upon removal. However, degradation of the electrodes continues at a reduced rate that is sufficiently high to destroy the battery at a rate equal to about 1% of design life in 24 hours for a 6 V battery and 5% in 24 hours for a 24 V battery (degradation is approximately linear with design voltage and equal to about 1.5% in 24 hours per 6 V of battery potential) [16].

Seawater batteries are generally available in service capacities up to 60 A-H with a variety of voltages. These batteries are normally designed to last for five hours but they may be designed to last as long as 75 hours with light current drains which adds to the already high cost ($0.60-1.25/A-H at 1.5 V) [16].

Seawater batteries seem attractive for use with the manatee-borne electronics because the battery becomes less of a weight burden as the electrodes are consumed and the manatees are in a saline (electrolyte) environment while in the Banana River tracking range. The following negative points are more than sufficient to eliminate the seawater battery from further consideration:

- o Unstable Output Voltage
- o Short Lifetime
- o Offensive Reaction Products Will Likely Affect Manatee Behavior
- o Expense
- o Will Not Function in Freshwater Manatee Habitats

Other Battery Types

Thus far only batteries conducive for use with the manatee-borne electronics have been considered. Other bulkier batteries are available for use at the receiver sites if necessary. Certain "wet cell" varieties (nickel cadmium, lead acid, etc.) which would be totally unacceptable for use with the manatee-borne electronics from a size, weight or restricted orientational standpoint are in fact better suited for use at receiver sites than those types analyzed so far. Size, weight, gassing, leakage and expansion will typically not be critical factors at the receiver sites. Tables 6 and 7 give some data on typical secondary wet cells. (The following discussion of secondary wet cells has been taken from selected sections of [16]).

The lead-acid cell is the lowest cost secondary cell. It also has good capacity, life, high voltage per cell and can be discharged at high rates for short periods of time. It is quite heavy and bulky and cannot be sealed because it gasses on charge and on discharge.

TABLE 6. CELL CHARACTERISTICS FOR TYPICAL SECONDARY WET CELLS [16]

Battery Type	Composition, Charged State			Cell Potential, V		Life in Operation	
	Pos.	Neg.	Electrolyte	Open Circ.	Discharging	Cycles	Float
Lead-acid	PbO_2	Pb	H_2SO_4	2.14	2.1-1.46	to 500	to 14 yr
Nickel-iron	NiO_2	Fe	KOH	1.34	1.3-0.75	100 - 3,000	to 30 yr
Nickel-cadmium	NiO_2	Cd	KOH	1.34	1.3-0.75	100 - 2,000 25 - 500	8-14 yr 4-8 yr
Silver-zinc	AgO	Zn	KOH	1.86	1.55-1.1	100 - 300 low dis. 5 - 100 high dis.	1-2 yr
Silver-cadmium	AgO	Cd	KOH	1.34	1.3-0.8	500 - 1,000	2-3 yr

TABLE 7. RELATIONSHIP OF TEMPERATURE, DISCHARGE RATE, AND PERFORMANCE [16]

Battery Type	Cell Rated Capacity A-hr	Discharge Rate, A	Potential at Midpoint V			Capacity, A-Hr % Rated			Energy Density W-Hr/Kg			Energy Density W-Hr/cm^3		
			27°C	-18°C	-40°C	27°C	-18°C	-40°C	27°C	-18°C	-40°C	27°C	-18°C	-40°C
Lead-acid	5	0.5	1.95	1.89	1.85	100	54	30	24.0	12.4	6.9	0.05	0.02	0.01
		1.0	1.92	1.84	1.80	88	50	21	20.7	11.3	4.7	0.04	0.02	0.01
		10.0	1.81	1.60	1.40	46	16	3	10.4	3.1	0.5	0.02	0.01	.001
	60	10.0	1 92	1.89	1.82	100	54	26	27.1	14.4	6 9	0 06	0 03	0.01
		25.0	1.90	1.80	1.65	87	31	10	23.3	7.8	2.2	0 05	0.02	.004
		50.0	1.87	1.70	-	63	18	-	16.7	4.4	-	0.03	0.01	-
		100 0	1.70	-	-	39	-	-	9.1	-	-	0.02	-	-
Nickel-iron	10	2.0	1.20	0 98	-	100	67	-	23.6	15.8	-	0.06	0.04	-
	75	15.0	1.20	0 98	-	100	67	-	22.9	16.0	-	0.04	0.03	-
Nickel-cadmium	5	1.0	1.22	-	-	100	-	-	23.6	-	-	0.05	-	-
		10.0	1.11	1.05	1.05	94	67	21	20 2	13.8	4.4	0.04	0.03	0.01
	75	10.0	1.23	1.16	1.14	100	86	64	25.3	20.4	14.9	0.05	0.04	0.03
		25.0	1.20	1.14	1.06	97	82	48	24 0	19.3	10.4	0 05	0.04	0.02
		50.0	1.18	1 07	1.00	94	72	34	22 9	15.6	6 9	0 05	0.03	0.01
		100.0	1.17	-	-	82	-	-	18.7	-	-	0.04	-	-
Silver-zinc	5	0.5	1.52	1.45	-	100	75	-	95 6	68 9	-	0.13	0 10	-
		1.0	1.50	1.42	-	96	70	-	90.4	66.7	-	0.13	0 10	-
		10.0	1.40	1.26	-	85	63	-	74.9	60.0	-	0.10	0.09	-
	60	10.0	1.52	1.46	-	100	92	-	103.0	86.7	-	0.19	0.16	-
		25.0	1.49	1.42	-	97	79	-	99.3	86.7	-	0.18	0 16	-
		50.0	1.48	1.42	-	92	75	-	93.8	86.7	-	0.17	0.16	-
		100.0	1.42	1.30	-	84	69	-	82.0	77.8	-	0.15	0.15	-
Silver-cadmium	5	0.5	1.08	1.03	0.9	100	85	44	59 6	47.8	22.2	0.11	0.09	0.04
		5.0	1.05	0.99	0.7	95	80	40	46 7	35.6	12.4	0.09	0.06	0.02
	60	6.0	1.10	1.08	-	100	96	-	70.4	68.0	-	0.18	0.17	-
		60.0	1.00	0.94	0.9	95	80	40	54 4	50.2	28.9	0 13	0 12	0.07

NOTE. These performance data are taken at random from a variety of cells. They show pronounced effects of temperature and discharge rate on performance Dashes indicate that heaters are needed to warm cell in cold ambients. Nickel-iron cells, however, are not usually used at temperatures below 0°F.

Secondary cells, except lead-acid, have alkaline electrolytes and can be stored with or without electrical charge. Lead-acid cells must be kept charged because lead sulfate, formed during discharge, will convert slowly to a form that interferes with recharging. Lead-acid, Ni-Fe and Ni-Cd cells inherently self-discharge if used at very low rates and therefore cannot be operated for long periods of time without recharging. Silver cells self-discharge at a slower rate.

For very low capacity operations, Ni-Cd, Ag-Ce and Ag-Zn cells may be sealed; however, they cannot be discharged excessively or overcharged without venting. Generally sealed batteries should be used only when they are equipped with pop-off vents to minimize the chances of explosion. While all batteries except lead-acid can be stored in a discharged condition, discharged batteries should not be stored in a sealed condition because of potential gas buildup.

Normal orientation for wet cells is upright. Most are equipped with spill-proof vents for protection against inversion but wet batteries are not generally designed for operation in any position other than upright. For example, if Ag-Zn batteries with an unabsorbed electrolyte are inverted for any length of time, they will soon destroy themselves because of zinc migration around the separator.

Sealed batteries should be purged with dry nitrogen because release of hydrogen within the battery could cause an explosion during heavy load or a short circuit. Under certain conditions of overcharge and discharge, oxygen can also be released which will negate this safety precaution.

A single cell that is able to handle the full ampere-hour capacity is always preferable to smaller cells in parallel. Paralleling cells to increase ampere-hour capacity is not advisable because of the possibility of differences in cell potential. If some cells discharge sooner than others, the active cells become unbalanced. This may happen near the end of a full discharge cycle or sooner if one group of cells did not have a full initial charge.

Normal operation temperatures of most secondary batteries are in the range 65 to 90°. At these temperatures, chemical activity is good and optimum performance is obtained. At elevated temperatures, the voltage will rise slightly. High temperatures are a problem only if they are excessive enough to boil off the electrolyte, deteriorate the separators or distort the battery case. Special designs can permit higher or lower operating temperatures. At low temperatures, the voltage and the ampere-hour capacity are reduced because the initial voltage is lower, causing the battery to reach the fixed cutoff value sooner.

Secondary battery systems are subject to aging after the introduction of electrolyte. From the moment the battery has been wetted (activated), its life is measured in terms of wet life and cycle life (see Tables 6 and 7), These data will vary with the design of the battery and the individual application requirements. High rate batteries, which can deliver large current drains for short periods of a few minutes to an hour, offer fewer cycles and a shorter wet life than the medium- or low-rate batteries which are designed to discharge at rates of 1 to 10 hr. or longer.

Wet charge batteries should never be drained of electrolyte and allowed to dry because rapid degradation of plates and separators will take place.

Among the alkaline batteries (Ag-Zn, Ag-Cd and Ni-Cd), it is mainly the separator system which is affected by aging. In the lead-acid battery, the electrodes mainly are subject to aging. In wet life alone (stored in the charged condition), high rate lead acid cells may lose up to 50 percent of their charge in a few days. Normal lead-acid cells lose up to 50 percent capacity in 6 months. Low-rate lead-acid cells lose 15 to 20 percent of their charge per year, Ni-Cd (sintered) cells lose 10 to 20 percent per month and Ag-Zn and Ag-Cd cells lose 15 to 20 percent per year.

It is desirable to take the maximum specified number of cycles from a given battery within its specified wet life. It is possible to continue operating the battery beyond this point, but the capacity will decrease. Should the indicated number of cycles be taken from a battery well before the end of its wet life, it may continue to function but its ability to accept a full charge and also deliver the output cannot be assured.

Solar Cells

Solar cells can be used either as a power source or as a charging device for a secondary cell. The output of a solar cell varies considerably depending on the size and composition of the cell and on light conditions. The most common solar cells are made of silicon, cadmium, or gallium with a variety of impurities. A 20 x 30 mm cadmium cell with copper impurities can produce a few tenths of a volt with a current of as much as 130 mA.

Solar cells have limited usefulness as a primary power source when light intensity or duration cannot be guaranteed. If the light source is the sun, the cell will have practically no output at night or on a cloudy day. On a sunny day, the output will vary according to the cell's orientation to the sun.

Solar cells are more useful in conjunction with a secondary battery. A single cell or a plurality of cells can be used to charge the secondary cell when light conditions are favorable. In arrangements of this type, the solar cells must be isolated from the battery at times when they are not charging it lest they act as a load and discharge the battery.

The various shortcomings of solar cells preclude them from use as a primary source in any part of the tracking system. Inefficiency and relatively high cost also make them unattractive for use as a supplementary power source at the receiver sites; however, some advantage might be gained by using them in conjunction with secondary cells in the manatee-borne electronics package. There, the current drain requirements are much lower as are the required charging voltages. Since manatees are typically exposed to direct sun light numerous times during the day, it would be expected that a solar cell assist to a secondary cell battery pack could extend to operational life of the system. It is doubtful, however, that such an intermittent diurnal solar assist could extend the battery life of nickel cadmium cells (for example) to the point of surpassing that of (unassisted primary) lithium cells.

Mechanical Generators

Mechanical generators are a popular means of generating power. At the receiver sites, they would be useful as a backup source to commercial power or as a primary power plant for mobile operation. Several modes of operation are possible when employing generators. First is the classic "dynamotor" which was used extensively during World War II as a DC-to-DC transformer. The Dynamotor configuration is a motor-generator set where the motor is typically battery operated. The driven generator in turn delivers a DC current at a potential other than that of the motor - energizing battery.

Since the advent of high power semiconductors, a new device has emerged which has all but replaced the Dynamotor. The device, known as an inverter, performs the same basic function of DC-to-DC conversion yet it contains no moving parts and is totally solid state.

Another mode of operation is where the generator is driven by a mechanical motor such as a steam turbine, windmill or internal combustion engine. Frequently other forms of energy are more prevalent than electricity in certain locations. If these can be harnessed and transformed into rotational motion, a mechanical generator can be employed to generate electricity. This is precisely the application that one would encounter when operating a mobile tracking site in the field.

Mechanical generators even have application in providing energy to the manatee-borne electronics. A miniature permanent magnet (PM) generator connected to a small propeller would provide charging current to a secondary cell battery pack whenever the manatee moved through the water. Though conceptually feasible, such a "charger-secondary cell" power scheme suffers from the same difficulties as does the solar assisted system described earlier with the added disadvantage that the rotating propeller shaft must have a magnetic or watertight bearing and be free from fouling in the manatee environment.

Power Source Recommendations

Fixed Receiver Site. It is recommended that commercially available 110 VAC power be used as a primary energy source. This source will also be used to trickle charge a lead-acid battery pack as a backup. The choice of lead acid secondary cells for this application is based on their low cost, availability and respectible service capacity. In the event of a power outage, the secondary cell pack would automatically be switched into service allowing 110 VAC operation to be maintained through the use of a solid state inverter. Note that a backup power system is not a necessity if infrequent shutdowns can be tolerated. In any event, it would be desirable to maintain main receiver site computer operation throughout a power outage to assure an orderly automatic restart of all computer-controlled systems and algorithms when power is restored.

Mobile Receiver Site. If mobile receiver sites are employed, then it is recommended that a lead-acid battery pack and inverter be used as a primary energy source. Provisions should also be made to allow 110 VAC commercial current operation when a mobile site is operating near a distribution point. Backup power should not be necessary since mobile units by definition are tolerant of intermittent operation (i.e., direction finding will not be possible using the recommended techniques when one or more of the receiver sites is in motion). For extended field operations, it would be desirable to have the battery pack charge off the propulsion unit of the carrier (truck engine, boat motor, etc.).

Manatee-borne Electronics. Analysis has shown lithium primary cells to be far superior to any other energy source available in terms of service capacity, discharge characteristic and cost. Assisted secondary cell arrangements promise an extended operational life but are actually rendered less effective in this application by the habits and habitat of the manatee.

PAGE INTENTIONALLY BLANK

DF SITE SELECTION

When selecting DF receiver sites in the proposed Banana River tracking area, eight major points were considered. First, low noise regions were sought. These are areas free of excessive power lines and population. Ignition noise, RF interference (RFI) from neon signs, heavy equipment and many other noise sources associated with urban areas are to be avoided.

High terrain is at a premium in the Banana River area. However, high areas will result in improved line-of-sight (LOS) coverage and lessened antenna tower expense. Any site chosen must be suitable for tower erection as well. Physically, a swamp area would be unsuitable and logistically, a tower placed in the middle of a highway would be unacceptable.

It is desirable to have sites that are readily accessible to authorized personnel for purposes of installation, data monitoring, maintenance or upgrading of the system. Accessibility to conventional 110 VAC power and telephone lines is also desirable.

DF net spacing and configuration is of primary importance since this is critical to the accuracy and resolution of the system. Conveniences like accessibility and high terrain would be forfeited to improve EPE and probability of intercept (discussed subsequently) over the entire tracking range.

Site placement must be such that two-site LOS coverage is possible in all regions of the tracking area. As mentioned in other sections, two site LOS coverage will diminish the effect of "on the horizon" reradiators.

Along these lines, a site must be located only in areas with minimum chance for multipath interference. For example, placing a receiver site in the middle of the antenna farm located at the southern end of Cape Canaveral would be a very poor choice. The tops of most buildings in the KSC-Cape Canaveral area, though high, easily accessible, and amenable to the tower erection, are typically poor site choices since most are inherently noisy environment (elevators, air conditioning plants, etc.) and contain numerous roof-mounted antennas already. These close proximity antennas will provide not only an additional noise source but extreme multipath reradiation. For example, due to its immense stature, the vehicle assembly building (VAB) located at the northern end of the proposed tracking range has been suggested by many as a seemingly excellent site for a DF receiving station (located on top). On the contrary, the VAB is a poor HF/VHF DF site for the following reasons:

1. Presence of resonant reradiators, e.g., the array of lightning rods on top of the VAB. This array consists of 1 meter rods ($\lambda/4$ resonant at 75 MHz and $\lambda/2$ at 150 MHz) located on a square matrix about 10 m on a side. These rods must be elevated above any object on the top of the VAB, meaning that any DF antenna will be located in the immediate proximity of a major reradiator, hence bearing errors will occur.

2. High RF noise level. The VAB is electrically noisy. Compressors, elevator control, internal machinery, etc., create a high RF noise environment. The optical LOS may be improved but the actual electromagnetic coverage area may not be greatly improved by this siting.

3. Shadowing. The extreme height of the VAB means that the dead zone surrounding the base of a horizontally directed antenna will be extensive. Antenna alignment and/or design will be necessary to make the receive pattern "look down" into the dead zone in order to "see" manatees in the northern reaches of the Banana River and Banana Creek.

NET CONFIGURATION CRITERIA

The major criteria used in the determination of the desired net configuration are (a) complete coverage of Banana River from Bennett Causeway to NASA Crawlerway (cf. statement of work, Contract NAS10-9097) with secondary emphasis on incidental coverage of the Indian River north of Bennett Causeway; (b) at least two-site coverage at any point of interest within this area; and (c) maximize probability of signal intercept (P(I)) and EPE. Figure 20 shows a candidate three-station net that satisfies many of the DF site selection criteria presented in the last section. The northern site is at the location of a 5 meter camera mound that is near an access road but several kilometers from the nearest urban area of the space center. The southeastern site is located at the end of the old skid strip in a region relatively free of reradiators and several kilometers from the main urban sections of the Cape Canaveral Air Force Station. Site number three, located in the southwest quadrant of Figure 20, is in an open area that was an old optical tracking site. This area is accessible and away from urban RFI.

A LOS coverage computer algorithm (see Appendix I) was applied to this three station net to calculate the two-site coverage overlap for DF receivers elevated to 15 meters.† The shaded region of Figure 21 shows that these three stations will cover all but the northernmost regions of the proposed Banana River tracking range.

More coverage is necessary to the north so an additional station, shown in Figure 22, was added to the net three kilometers southwest of the Merritt Island/Banana River side of the NASA causeway. Figure 23 shows the two-site LOS coverage for this four-site net using receivers at a height of 15 m. Note that all regions of interest within the proposed tracking area are covered along with much of the Banana Creek and a large portion of the Atlantic coastline parallel to the proposed tracking range.

As a matter of interest, two more sites were added to see if two-site LOS coverage of the Indian River would be possible with 15 m towers. The lo-

†Note that all LOS coverage analyses in this report are worst case conditions in that they purposely do not include any boosting of tower-mounted DF receiver height by terrain features.

THREE STATION NET

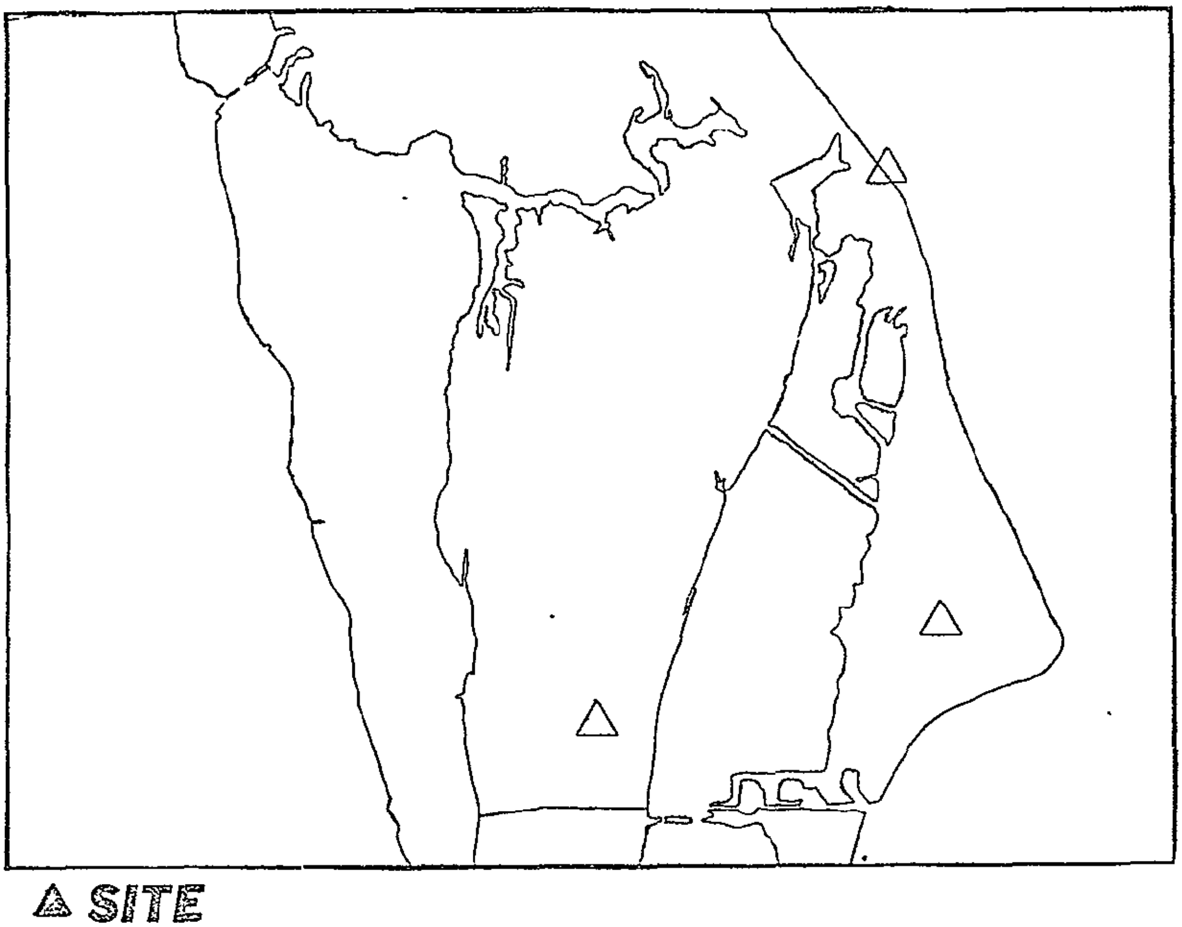
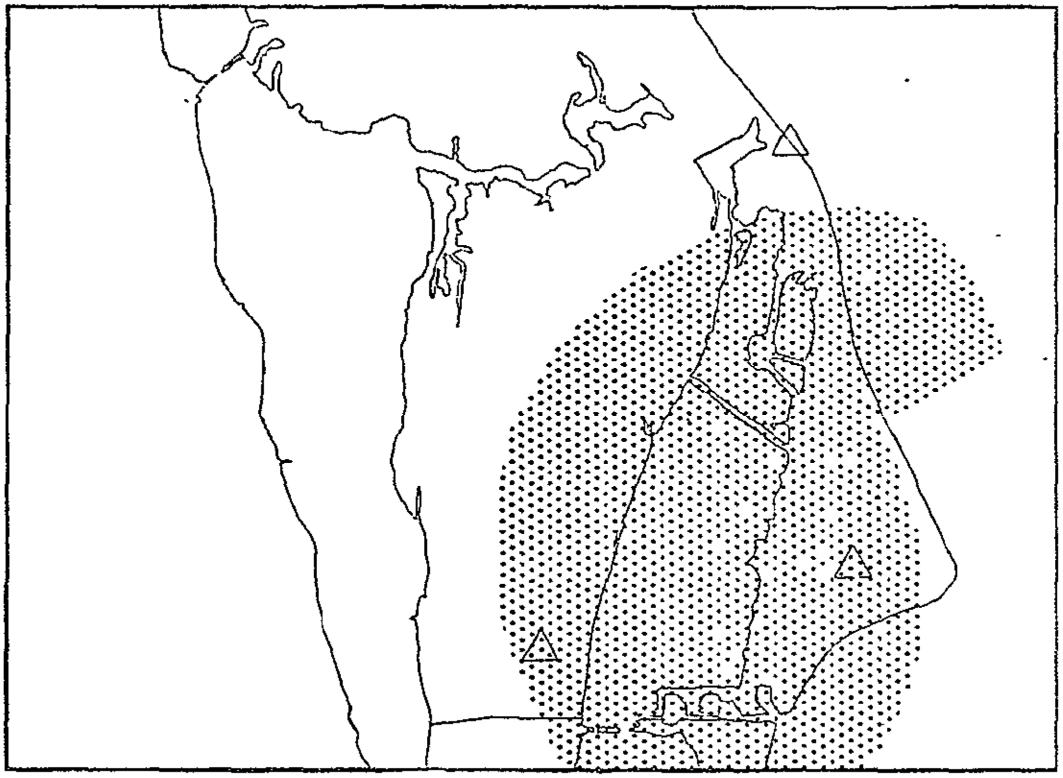


Figure 20

THREE STATION NET



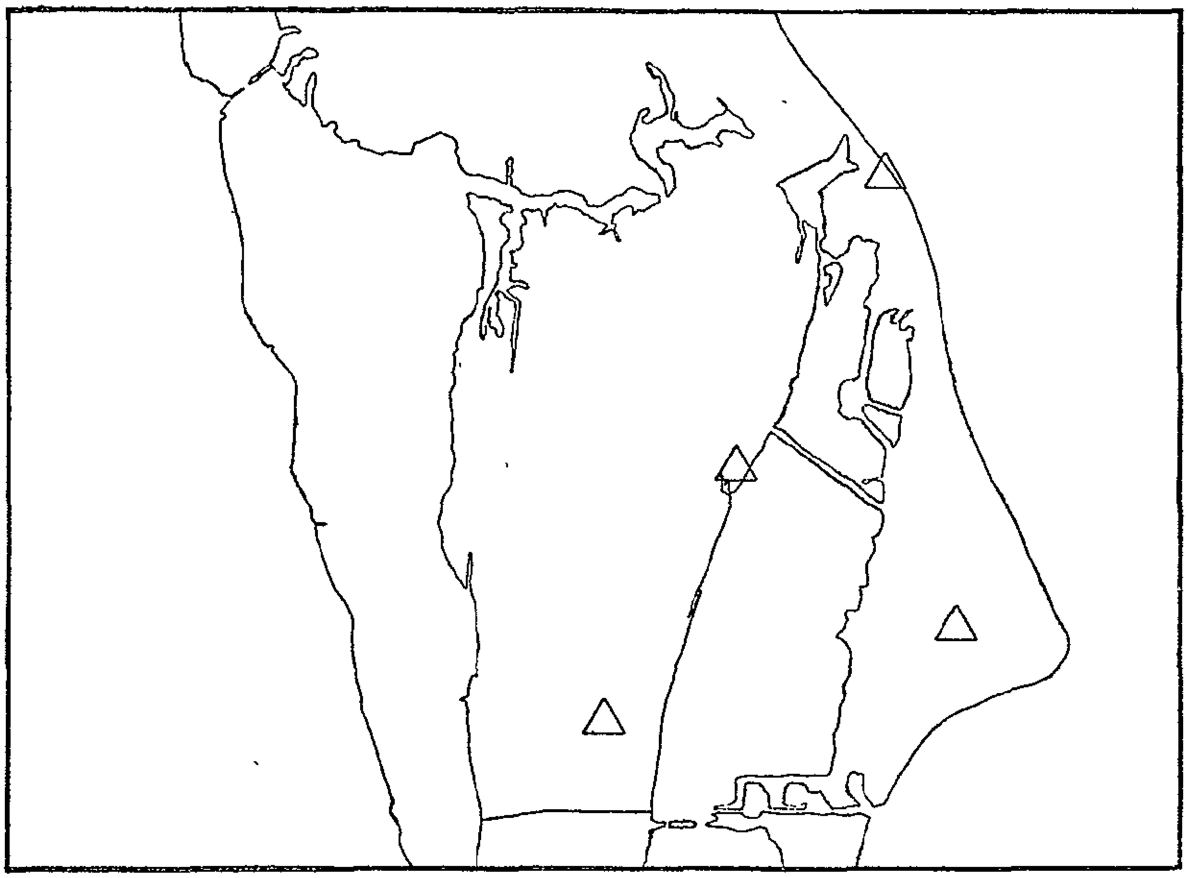
▲ SITE

LOS COVERAGE FOR 15m TOWERS—

TWO SITE COVERAGE OVERLAP

Figure 21

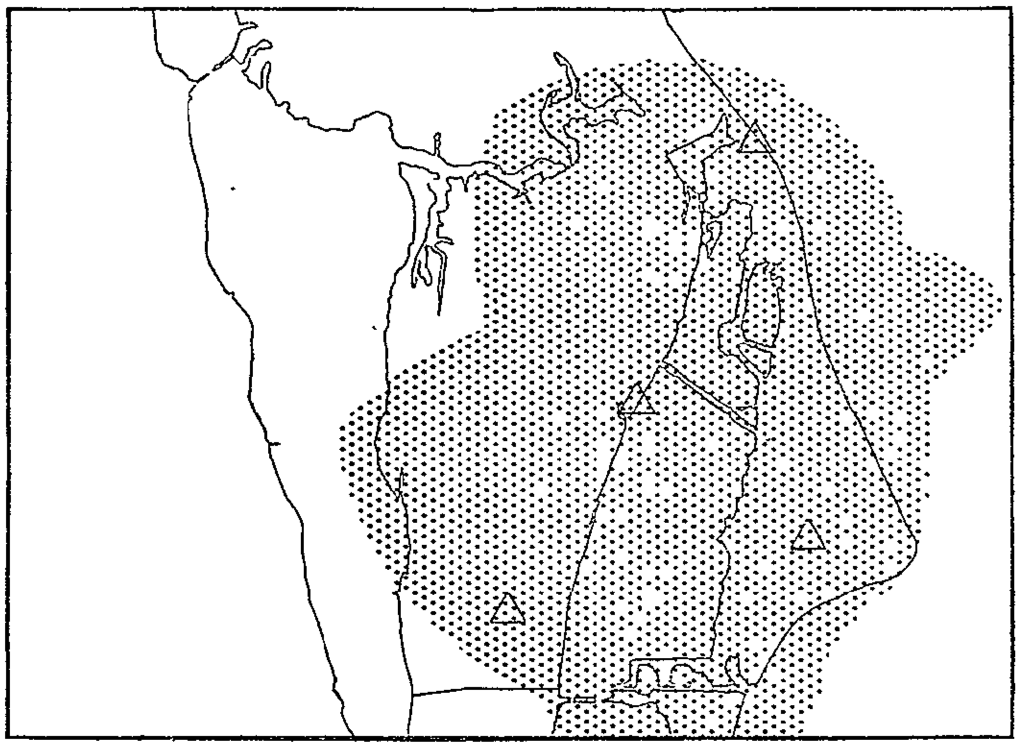
FOUR STATION NET



▲ SITE

Figure 22

FOUR STATION NET



▲ SITE

LOS COVERAGE FOR 15m TOWERS—

TWO SITE COVERAGE OVERLAP

Figure 23

cation of these sites and the resulting coverage is shown in Figure 24. Here, all of the proposed Banana River tracking range is covered, all of the Banana Creek area, a large portion of the Indian River (including Indian River Power generating station, a winter congregation point for some manatees) as well as a large portion of the Atlantic coastline and adjacent waters.

Various tower heights were analyzed to find the lowest usable receiver antenna height. It was found that towers resulting in a receiver antenna height of 15 m provide adequate coverage with minimum cost. Figure 25 shows the drastic change in two-site LOS coverage that results when the same net configuration as that of Figure 24 is used but with only 3 m receiver antenna height.

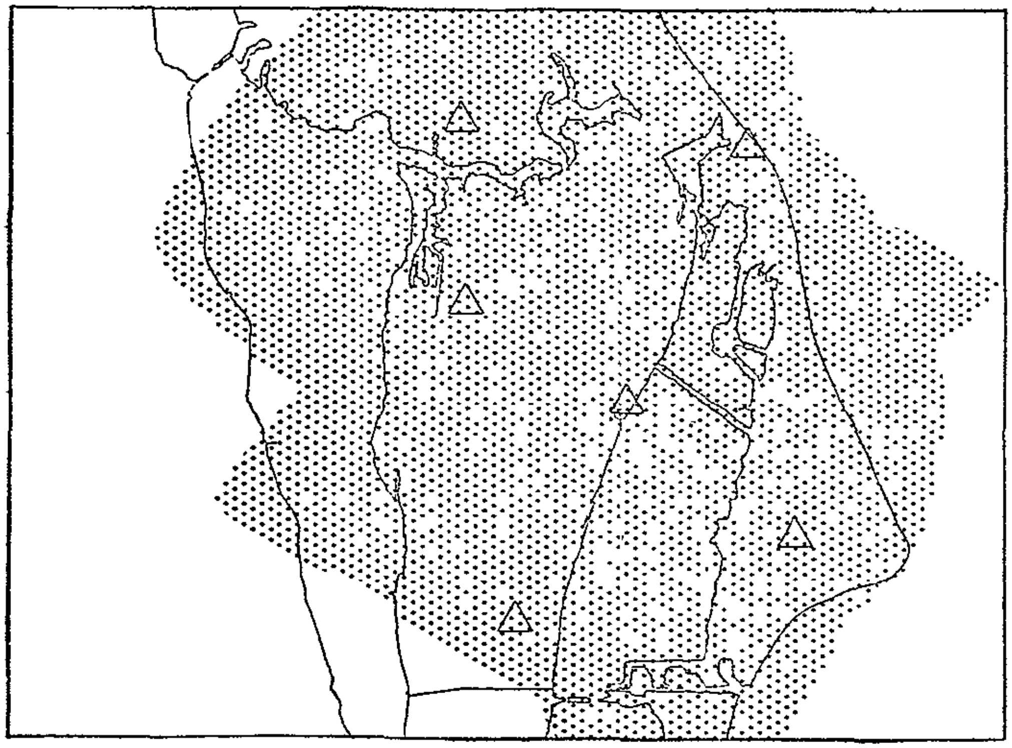
Based on this computer analysis of LOS coverage in the proposed Banana River tracking area, it is recommended that a four-station net be used for Banana River coverage, or a six-station net for both Banana and Indian River coverage. Thus far, each of the actual site locations has been intuitively derived, based on knowledge of the KSC-Cape Canaveral terrain, points of RFI concentration and areas of likely multipath interference. The next section presents a computer analysis of these site choices in terms of EPE and P(I); two parameters that will serve as measures of merit to verify or refute the value of this first siting attempt.

Net Parameter Values

Many computer permutations were run to study the effects of various parameters on EPE and the probability that a given transmitted signal is received by at least two sites (since a DF fix requires signal intercept by a minimum of two sites). The following is a list of the parameters and the range over which they were varied.

- o Net Configuration (number of stations)
  3, 4, 5 and 6 stations
- o Bearing Error, (θ_e)
  1°, 2°, 3° (it is felt that 1° is nominally attainable while $\theta_e > 3°$ is considered sloppy performance)
- o Observation Time (T_f)
  10, 10^2, 10^4 (this parameter refers to the number of samples averaged during a processing period to fix position)

SIX STATION NET



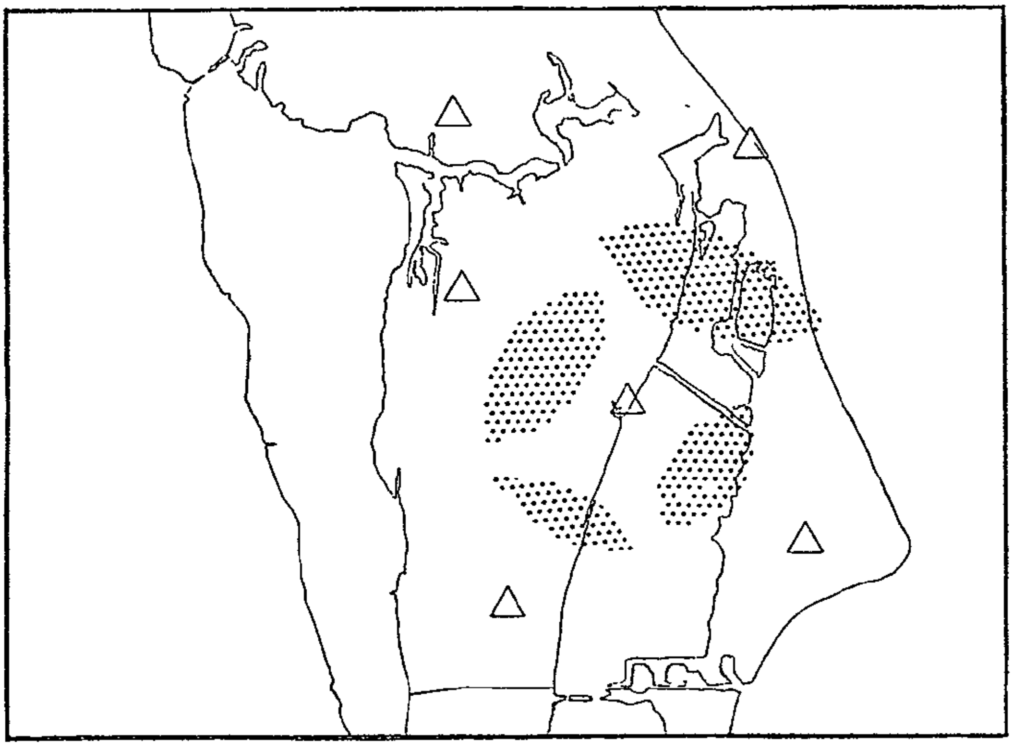
▲ SITE

LOS COVERAGE FOR 15m TOWERS—

TWO SITE COVERAGE OVERLAP

Figure 24

SIX STATION NET



▲ SITE

LOS COVERAGE FOR 3m TOWERS—

TWO SITE COVERAGE OVERLAP

Figure 25

- o Transmit-Antenna Gain, (G_t)

  HF: -2 dB_i, -10 dB_i (Transmit antenna figures are expected values for electrically short HF antennas or resonant VHF antennas, both over a poor ground plane)

  VHF: 0 dB_i (The range of G_t values for HF depends on tuning and matching characteristics)

  HF/VHF Height (h_t): 0.5 m (h_t is the "effective antenna height" due to ground plane imaging)

- o Receive-Antenna Gain, (G_r)

  HF: 2 dB_i
  VHF: 6 dB_i
  HF/VHF Height (h_r): 3 m, 15 m

- o Frequency

  30 MHz (upper HF)
  140 MHz (VHF)

- o Noise

  Low (VHF only; suburban/rural noise levels)
  Medium (VHF: High suburban levels; HF: winter levels)
  High [VHF: urban; HF: summer (especially P.M.)]

- o Receiver Bandwidth

  40 KHz (This is a worst case figure and could be improved in practice. This value was used in all runs)

- o Environmental Factors

  Terrain: Plains (see Appendix I for further explanation of this parameter)

  Surface Constants: $\sigma = 4.8$ mhos-m/m^2, $\varepsilon_r = 81$ (These are typical values for the entire Banana River area)

- o Transmit Polarization

  Vertical (This parameter was not varied since any manatee-borne whip antenna would be vertically polarized in order to break the surface of the water in its entirety)

- o Transmit Power, (P_t)

  0.01, 0.1, 1.0, 10.0 Watts

From this list of parameters, probabilities of intercept as a function of computed signal-to-noise ratio (SNR) were computed with values ranging from 100% to 0%. In addition, areas describing the positional uncertainty (EPE's) resulting from the cummulative errors of two or more sites were also computed.

"Best" Case Analysis

In order to obtain a benchmark by which various DF parameter variations could be compared, a computer net analysis was performed using the most favorable parameter extremes (as listed above) to yield "best" case EPE's and P(I)'s. The following parameters were used: high radiated power, P_t = 10 watts; large number of samples, $T_f = 10^4$; low noise; six station net; and low bearing error, $\theta_e = 1°$. Obviously even more favorable parameter values could be used (e.g., no noise, no bearing error, an infinite number of samples). However, the degree of improvement would be misleading and not realistically useful as a benchmark. Figure 26 shows the results of this "best" case analysis. Note that the small elliptical areas in the Banana and Indian Rivers, as well as the Banana Creek, represent possible sampled manatee positions. That is, a DF system with the stated parameters could identify the presence of a tagged manatee within the boundary of a given ellipse; however, beyond that resolution, the system could only extrapolate the animal's actual position within the ellipse. These are the EPE's or CEP's (circular error probabilities; terminology used interchangeably throughout the figures). The smaller the area of the CEP, the higher the position fixing resolution of the system. Note also that the probability of receiving a transmitted signal by two or more sites (P(I)) throughout the system is 100% for all points within the LOS coverage of both the Banana and Indian Rivers.

Representative Cases

Many computer runs were performed to find an optimum realizable set of system parameters. Certain parameters were not varied because of logistical constraints. These were P_t which was restricted to 0.1 W at VHF and 0.01 W at HF, as well as h_t of 0.5 m and G_r, limited to 6 dB_i for VHF and 2 dB_i for HF. These restrictions were imposed on all computer trails for battery life and manatee-borne antenna-type considerations, respectively. Certain other parameters were also fixed in order that the computer trails yield realistic worst case analyses. These parameters were receiver bandwidth of 40 KHz, θ_e of 3° and T_f of only ten samples. A receiver antenna height of 15 m was consistently used throughout all trials since the LOS coverage calculations had been based on this figure.

Because a four-station net was found to provide adequate LOS coverage over the proposed Banana River tracking range, the vast majority of computer runs concerned this configuration. Figures 27 through 33 are representative cases based on data compiled during the computer analysis. In each of the seven representative cases presented, a parameter of significance is varied to show its general effect on EPE (CEP) and P(I).

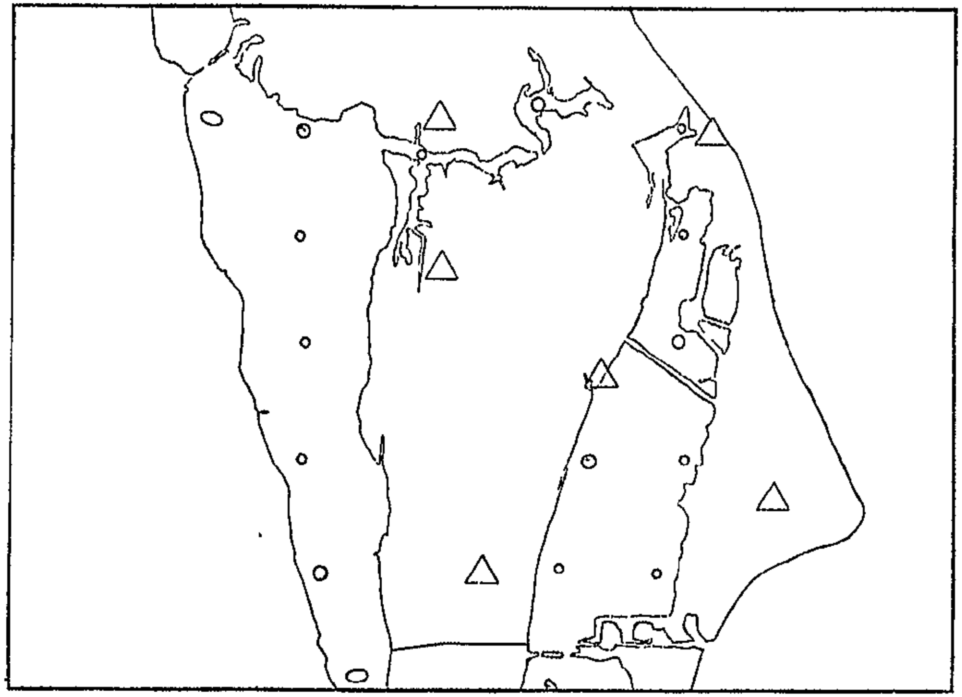
Figure 27 is an example of HF operation in a high noise environment. Here, probabilities of signal intercept range from 100% in the lower and mid-Banana River tracking area to a minimum of 44% up in the Banana Creek area. Note that there is a correlation between the probability of intercept and the area of uncertainty for a given region within the area shown. DF operation in the Indian River is quite poor with this net configuration and parameters. In general, DF operation will be optimum in regions surrounded by DF sites. Note that all DF measurements of the Indian River using the depicted four-station net are made from one side (east).

Figure 28 shows how increasing the gain of the manatee-borne antenna at HF could be used to improve the overall performance of the DF system in the high noise environment encountered at these frequencies in the KSC-Cape Canaveral area (see Table 3). Figure 29 shows that operation in a medium noise environment at HF would have a comparable effect on the overall DF system performance.

From the standpoint of DF system measurement realiability, it would be highly desirable to have 100% probability of intercept at all points within the proposed tracking range. So far, neither increasing antenna gain nor decreasing environmental noise along can guarantee 100% P(I) at all points of interest. Figure 30 shows that a combination of medium noise levels and increased radiating efficienty (G_t = -2 dB_i) can achieve 100% P(I) at all points. Unfortunately, medium noise levels can only be expected for HF during the winter months in this area. Therefore, even if antenna gain could be improved, it is unlikely that 100% P(I) could be guaranteed year round.

Figure 31 reveals that jumping in frequency from HF to VHF yields unaided DF operation in a high noise environment that is comparable to that of HF operating in either a medium noise winter environment or with an improved antenna gain. Still P(I) appears to be somewhat less than 100% under the stated conditions. In actuality, however, VHF noise levels in the KSC-Cape Canaveral area range from low to medium throughout the year. Figures 32 and 33 are based

BEST CASE ANALYSIS: SIX STATION NET



FREQ=30 OR 140MHz

Pt=10W $\theta e=1°$

$Tf=10^4$ hr=15m

Gt=0dBi ht=0.5m

Gr=6dB(30MHz),
2dB(140MHz)

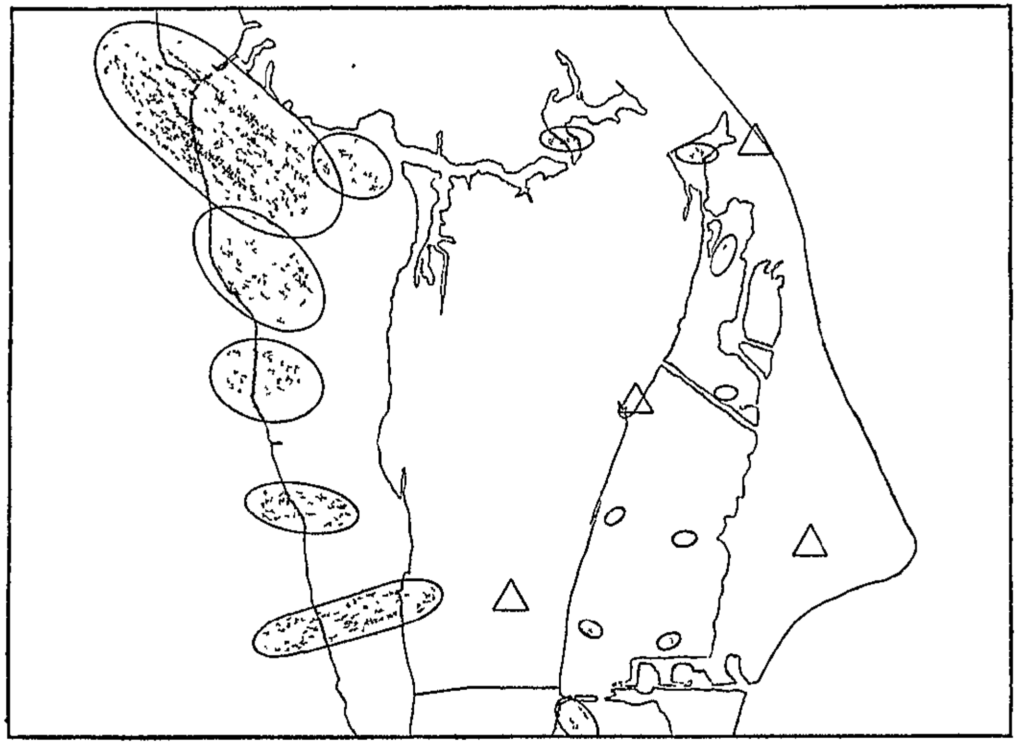
LOW NOISE

▲ SITE ⬬ CEP AREAS

INDIAN RIVER	MAX CEP: 0.17×0.09km MIN CEP: 0.10×0.06km	P(I) 100% ALL POINTS
BANANA RIVER	MAX CEP: 0.08×0.09km MIN CEP: 0.06×0.01km	P(I) 100% ALL POINTS

Figure 26

REPRESENTATIVE CASE--FOUR STATION NET



FREQ=30MHz

Pt=0.01W hr=15m

θe=3° Gr=2dBi

Gt=−10dBi ht=0.5m

Tf=10 SAMPLES

HIGH NOISE

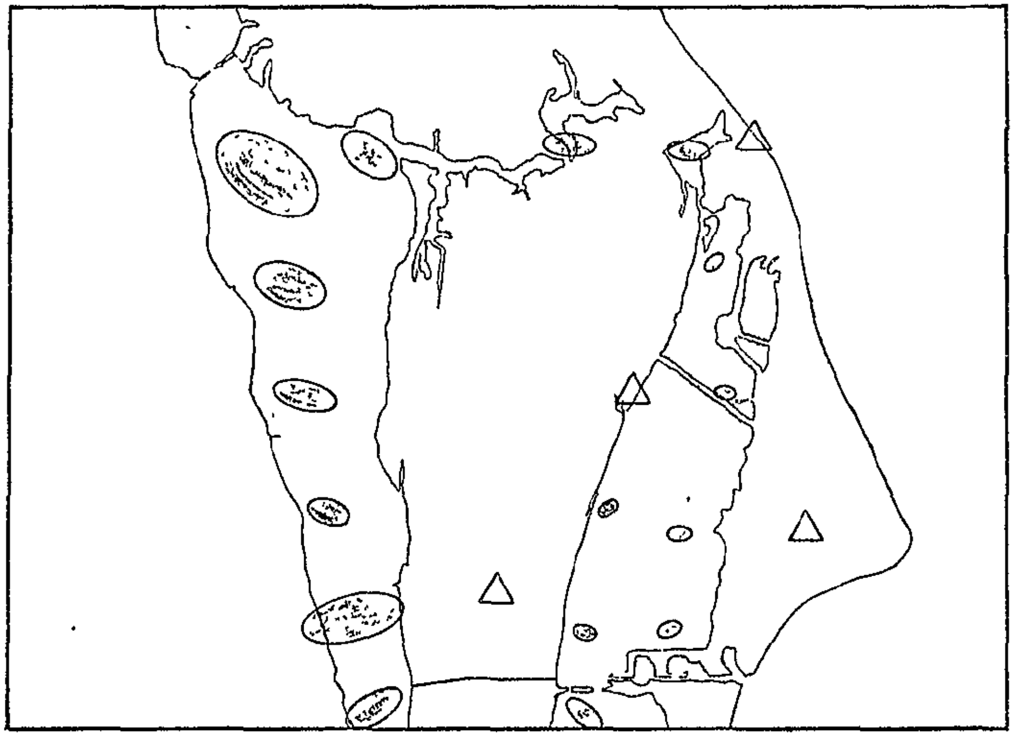
▲ SITE CEP AREAS

P(I) BANANA RIVER: 44–100%

P(I) INDIAN RIVER: 0–35%

Figure 27

REPRESENTATIVE CASE--FOUR STATION NET



FREQ=30MHz

Pt=0.01W   hr=15m

θe=3°   ht=0.5m

Gt=−2dBi   Gr=2dBi

Tf=10 SAMPLES

HIGH NOISE

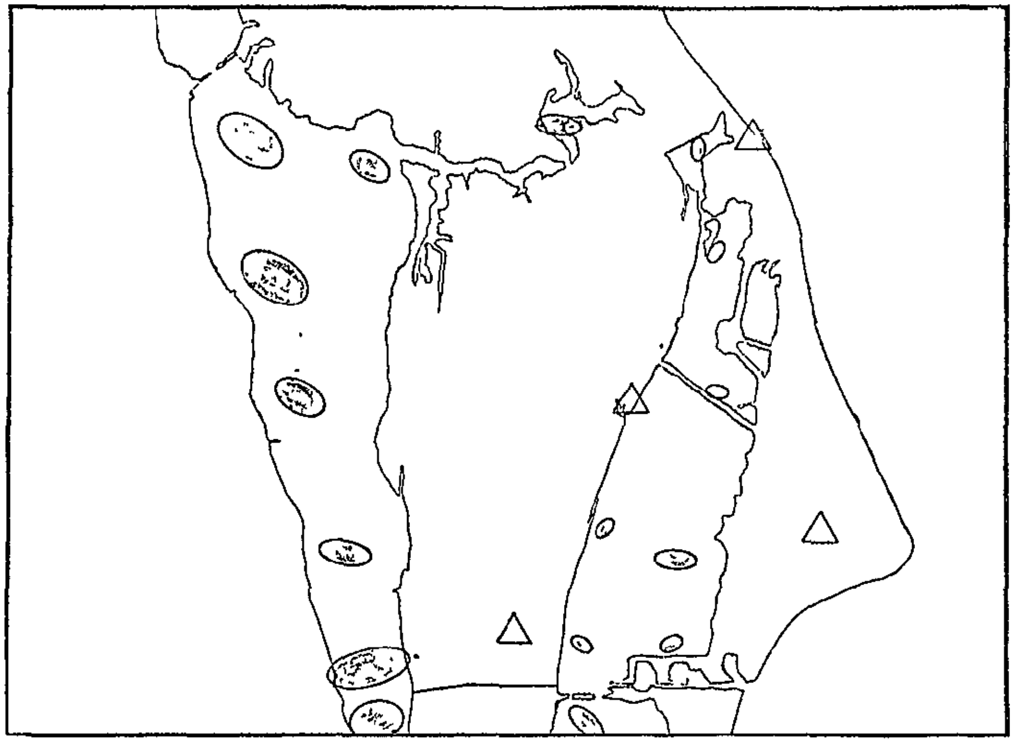
▲ SITE   CEP AREAS

P(I) BANANA RIVER: 76–100%

P(I) INDIAN RIVER: 15–67%

Figure 28

REPRESENTATIVE CASE--FOUR STATION NET



▲ SITE   ● CEP AREAS

TYPICAL TRANSMIT ANTENNA EFFICIENCY

FREQ=30MHz

Pt=0.01W   hr=15m

θe=3°   ht=0.5m

Gt=-10dBi   Gr=2dBi

Tf=10 SAMPLES

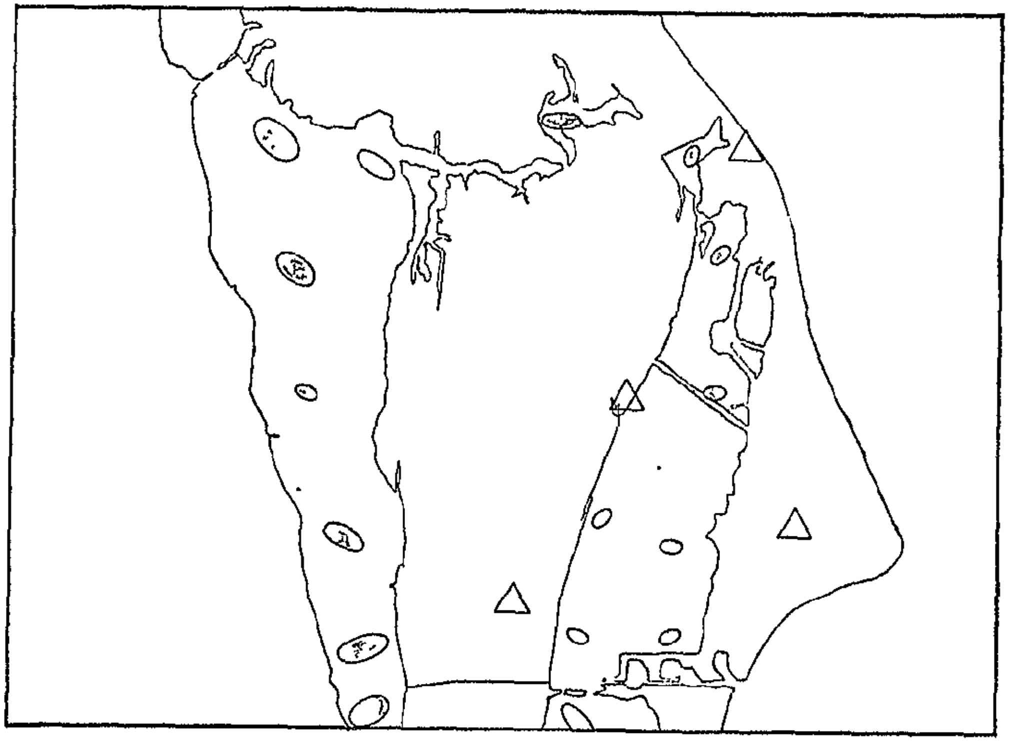
MEDIUM NOISE

P(I) BANANA RIVER: 56–100%

P(I) INDIAN RIVER: 30–80%

Figure 29

REPRESENTATIVE CASE--FOUR STATION NET



▲ SITE ⬬ CEP AREAS

GOOD TRANSMIT ANTENNA EFFICIENCY

FREQ=30MHz

Pt=0.01W hr=15m

θe=3° ht=0.5m

Gt=−2dBi Gr=2dBi

Tf=10 SAMPLES

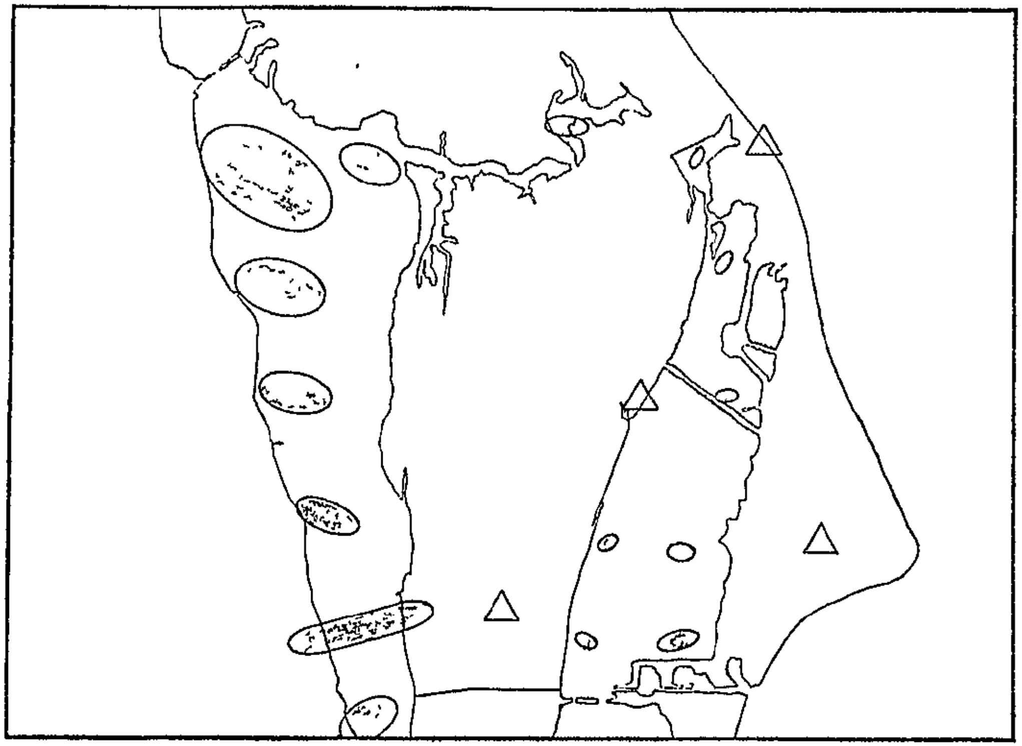
MEDIUM NOISE

P(I) BANANA RIVER: 100% ALL POINTS

P(I) INDIAN RIVER: GREATER THAN 50% ALL POINTS

Figure 30

REPRESENTATIVE CASE--FOUR STATION NET



FREQ=140MHz

P_t=0.1W h_r=15m

θ_e=3° h_t=0.5m

G_t=0dBi G^r=6dBi

T_f=10 SAMPLES

HIGH NOISE

▲ SITE ⬬ CEP AREAS

P(I) BANANA RIVER: 60–100%

P(I) INDIAN RIVER: 0–51%

Figure 31

on the same VHF data as Figure 31 but reflect the DF system's response to medium and low noise levels, respectively. In both cases, note that 100% P(I) is guaranteed at all points, all year, throughout the proposed tracking area.

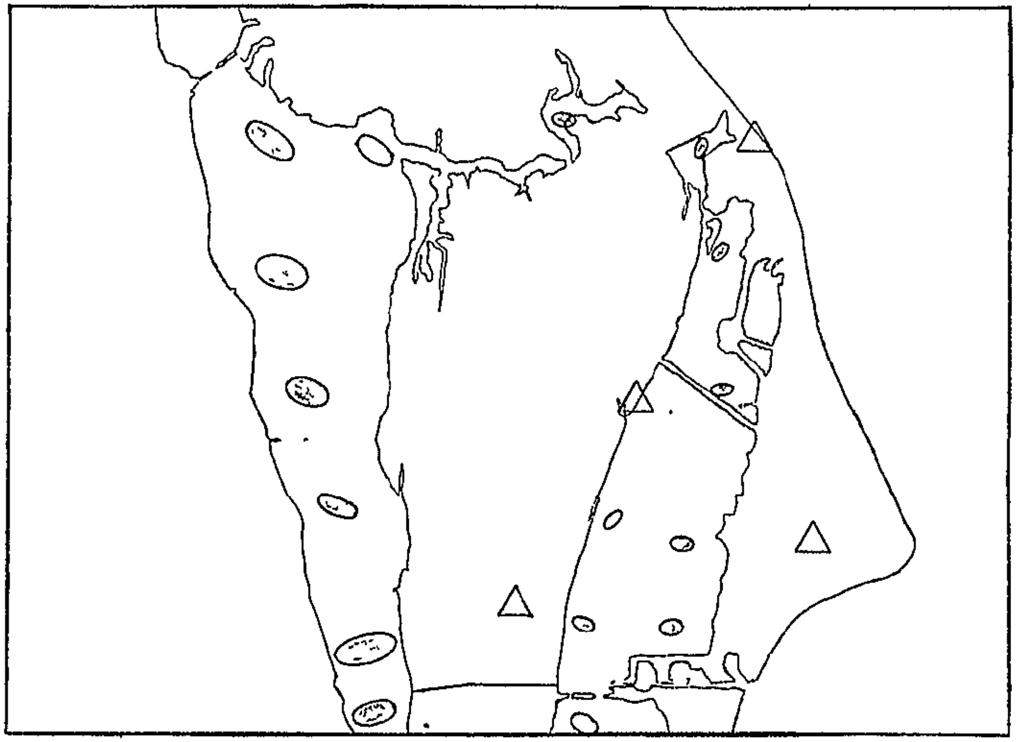
Referring back to the "best" case analysis of Figure 26, it may be noted that the CEP areas are typically smaller than those of Figure 33 thus implying greater accuracy. The questions arises "what degree of inaccuracy can be tolerated?" The largest CEP areas within the Banana River (as shown in Figure 26) have diameters of approximately 96 m. The diameters of the largest Banana River CEP areas of Figure 32, on the other hand, are approximately 330 m. Table 8 lists the pertinent data used to generate the CEP's and P(I)'s of Figures 27 through 33.

Discussions with NFWL-FWS biologists indicate that a maximum CEP of 1 km diameter would be suitable for NFWL-FWS needs as it is only important to know the "vicinity" that a given animal is occupying at a given time (see R & D status report No. 8, Contract NAS10-9097, November, 1977). Therefore, the medium noise VHF case as shown in Figure 32 provides nearly three times the performance of the maximum suitable 1 Km diameter CEP. Of course, even better performance is expected under the low noise VHF conditions that are prevalent in the proposed tracking area.

It should be noted that maximum HF CEP's are not vastly different in area and hence diameter, than the maximum VHF CEP's. The major difference results from the lower P(I)'s achievable at HF. This causes the <u>average</u> HF CEP area to be larger than the corresponding VHF CEP's which are associated with P(I)'s of 100%. As a consequence, the <u>maximum</u> CEP's of HF and VHF DF systems are similar but overall the VHF system outperforms the HF.

Further conversations with NFWL-FWS indicated that they felt that the constricted upper Banana River area (from the Titan launch complexes, north to the NASA Crawlerway) does not need specific DF fixes (other than information that an animal is in this area), as any animal in this region will be restricted to certain well defined channels. An additional computer analysis was performed to investigate the possibility of a reduced net configuration wherein only three sites were employed (northern site dropped) with emphasis on positioning accuracy being limited to the middle and lower reaches of the proposed

REPRESENTATIVE CASE--FOUR STATION NET



FREQ=140MHz

Pt=0.1W   hr=15m

θe=3°   Gr=6dBi

Gt=0dBi   ht=0.5m

Tf=10 SAMPLES

MEDIUM NOISE

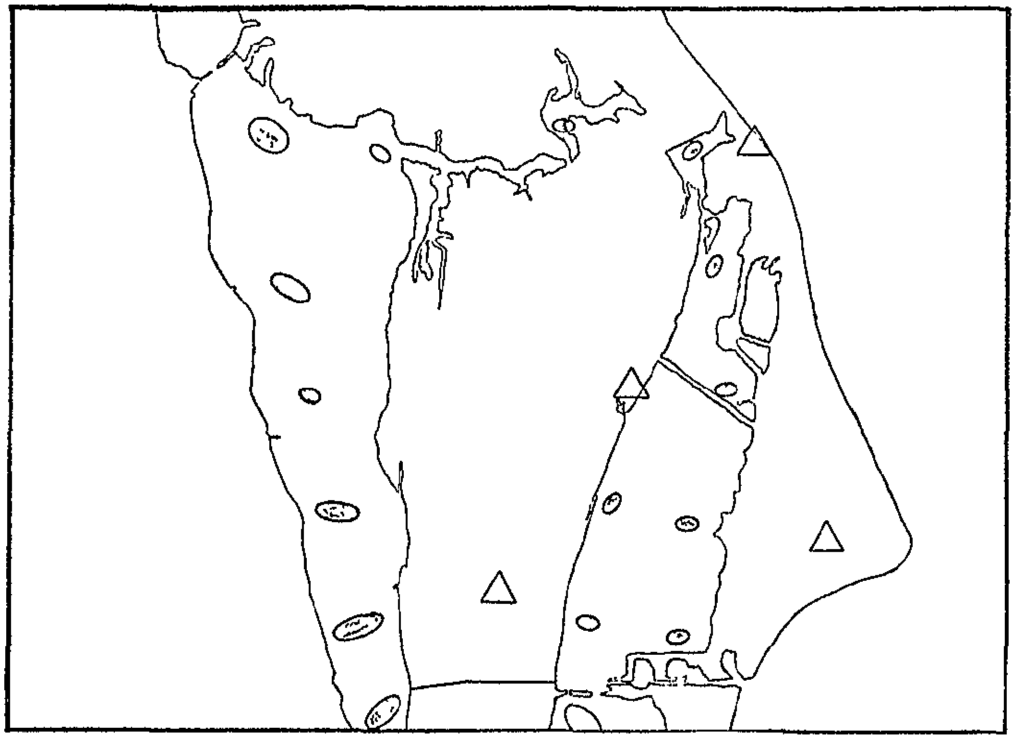
▲ SITE   CEP AREAS

P(I) BANANA RIVER: 100% ALL POINTS

P(I) INDIAN RIVER: 40–95%

Figure 32

REPRESENTATIVE CASE--FOUR STATION NET



FREQ=140MHz

Pt=0.1W   hr=15m

θe=3°   Gr=6dBi

Gt=0dBi   ht=0.5m

Tf=10 SAMPLES

LOW NOISE

▲ SITE   CEP AREAS

P(I) INDIAN RIVER: 100% ALL POINTS

P(I) BANANA RIVER: 100% ALL POINTS

Figure 33

TABLE 8. COMPARISON OF REPRESENTATIVE CASES

FREQUENCY (MHz)	G_I (dBi)	NOISE	BANANA RIVER P(I)* (%)	BANANA RIVER MAX CEP (KM x KM)	INDIAN RIVER P(I) (%)	INDIAN RIVER MAX CEP (KM x KM)
30	- 2	MEDIUM	100/100	0.17 x 0.49	59/100	1.08 x 0.30
(1) 30	-10	MEDIUM	88/100	0.18 x 0.53	27/73	1.65 x 0.93
30	- 2	HIGH	76/100	0.18 x 0.55	15/67	2.19 x 1.23
(2) 30	-10	HIGH	44/100	0.22 x 0.74	0/35	6.4 x 3.0
140	0	HIGH	60/100	0.20 x 0.62	0/51	3.4 x 1.9
140	0	MEDIUM	100/100	0.17 x 0.50	43/95	1.25 x 0.31
(3) 140	0	LOW	100/100	0.17 x 0.48	100/100	0.75 x 0.47

(1) ANTICIPATED CONDITION. WINTER AT KSC
(2) ANTICIPATED CONDITION. SUMMER AT KSC
(3) ANTICIPATED CONDITION. ALL YEAR AT KSC

LOCAL CONDITIONS MAY ALTER NOISE LEVELS

*P(I) RANGE: LOW TO HIGH

tracking area. The conclusions drawn from this analysis indicated that there was no appreciable effect on DF accuracy between the Bennett Causeway and the NASA Causeway while operations north of the NASA Causeway were significantly degraded as expected. The only advantage of this reduced net configuration lies in the reduced overall cost of the system.

ELF Net Analysis

Severe problems arise when trying to apply standard techniques to an ELF net analysis in the same manner as that performed for the HF and VHF systems above. This is due to a number of factors related directly to the extraordinarily low frequency of operation. In particular, the following unknowns become evident when considering direction finding using a submerged ELF source:

a. The optimum frequency ELF signal generator and antenna that is feasible to be placed on a manatee,

b. The design characteristics and placement of the antenna on the manatee in order to produce an omnidirectional signal,

c. The power radiation efficiency for ELF signals,

d. The possible bandwidth of frequency modulation that could be supported by an ELF carrier to make assessments of link transmission bandwidth. Will bandwidth support an ID code: electrically short antennas have high Q (e.g., 10^3) and hence low bandwidth. Also high Q implies slow rise time. Can a high Q ELF antenna support "on-off" encoding pulses?

e. Sea-air interface refraction loss magnitudes as a function of ELF frequency and antenna depth,

f. Received signal-to-noise ratio at representative distances from a submerged transmitter to a receiver site using typical atmospheric noise levels, and receiver noise and bandwidth figures.

g. Polarization and depolarization effects: are there significant differences between refraction losses for horizontal and vertical polarization,

h. The effects of ELF receivers being within the near field,

i. The ducting effects of the lower atmosphere on ELF signals,

j. The viability of a transponder system for signal radiation.

These questions have been briefly investigated with very little specific support by the literature. Nearly fifty journals, texts, reports, etc., have been reviewed with little empirical data fitting this particular application. Few applications of ELF direction finding have ever been employed. Most emphasis on ELF has been in the realm of passive monitoring with recent interest focused on worldwide submarine communications (Navy project "sanguine" later redesignated "seafarer").

Certain conclusions are likely, however. It is anticipated that grave difficulties will be experienced when network direction finding techniques are employed from within the near field of the ELF transmitter. H-field sensors (ferrite core loop antennas) require highly planar wavefronts for accurate direction finding. Planar wavefronts cannot be guaranteed and in fact, will probably not be present at all within the proposed tracking area because a distance of 5 λ or greater is recommended to achieve plane wave propagation, therefore requiring the DF site locations to be 30 to 50 km from the source. Even if 1 to 2 λ is assumed adequate for reliable DF operation, the site-to-source distance is still 10-20 km. Estimates vary as to the relative efficiency of a submerged ELF radiator, the average being somewhere around 0.1% efficient. This implies that if 1 watt effective radiated power (ERP) at ELF is suitable to get above the KSC-Cape Canaveral noise level, then up to 1000 watts of drive power would be necessary on the manatee. As a result, the success of a manatee-borne ELF tracking system is doubtful and certain basic experiments in the area of short antenna subsurface ELF transmission should be tried to verify expected radiation efficiencies before any development of an ELF DF system is begun.

PAGE INTENTIONALLY BLANK

RECOMMENDATIONS BASED ON COMPUTER NET ANALYSIS

The following recommendations are based on the HF/VHF computer net analysis:

- o Four-station net
- o Receive-Antenna Height: $h_r = 15$ m
- o Minimum ERP at HF: $P_t(HF) = 10$ mW
  $P_t(VHF) = 100$ mW
- o Transmit-Antenna Gain: $G_t(HF) \geq -2$ dB_i
  $G_t(VHF) \geq 0$ dB_i
- o Maximum Tolerable Bearing Error: $\theta_e \leq 3°$
- o Receive-Antenna Gain: $G_r(HF) \approx 2$ dB_i
  $G_r(VHF) \approx 6$ dB_i
- o Receive-Antenna Pattern: Omnidirectional in azimuth, directive toward horizon in elevation (i.e., stacked, verticle colinear array)

Preferred System

From the recommendations derived by the computer net analysis, a preferred RF system can be specified having the following general specifications:

(a) Frequency: ≈ 140 MHz
(b) Transmit-Antenna Gain: ≥ 0 dB_i
(c) Receive-Antenna Gain: ≥ 6 dB_i
(d) Receive-Bandwidth: ≤ 40 KHz
(e) Receive-Antenna Height: ≈ 15 m
(f) ERP: ≥ 100 mW
(g) Maximum tolerable bearing error: $\leq 3°$
(h) Net configuration: four-station, at specified sites (immobile)

The manatee-borne transmitter would have a keyed (pulsed) modulation for use in a phase angle TOA direction finding scheme as this will provide the most flexibility in terms of sampling times. The only critical parameter involved in this type of transmission is the short-term stability of the modulation frequency. By consistently sampling only the rising (or falling) edge of the modulation, the system can be made immune to minor modulation pulsewidth variations. Carrier frequency should also have good short-term stability. Both carrier and modulation frequencies can be crystal controlled to achieve this necessary short-term stability. Rapid temperature changes which might affect short-term oscillator frequency stability are not anticipated in the manatee habitat.

Identification of individuals is best performed using time segmented transmissions similar to the ID technique explained earlier in the section dealing with acoustic tracking recommendations. This would mean that all of the manatee-borne transmitters could operate on the same frequency thus simplifying transmitter construction and tuning while allowing the use of identical fixed frequency, narrow bandwidth receivers at each site. In this part of the system, long-term stability is important since it would be undesirable to have the transmission from a tagged individual drift outside of its appointed transmission time slot. The required degree of long-term stability is easily achievable using current timing circuit technology (similar to solid state watch circuits). ID overlap resulting from minor long-term drift can be avoided by placing dead zones between contiguous time slots. According to NFWL-FWS biologists, due to the difficulty in finding and capturing subjects for tagging, it should not be expected to have more than a maximum of four manatees for initial tracking experiments (see R & D status report No. 8, Contract NAS10-9097, November, 1977). This will mean that initially, transmission time slots for tagged individuals could range up to 14 minutes each, with a full minute dead time between adjacent interrogations.

Each site will have access to a reference frequency for use in measuring the phase of the received signals. This reference must have excellent frequency and phase stability. Since the sites are to be separated by large distances, distribution of the reference signal is best achieved by RF transmission from the main site to each peripheral site. Because intersite distances will have been accurately measured, constant phase shift due to propagation from the main site to each peripheral site can be accounted for. Use of a high ERP to transmit the reference will guarantee its accurate reception at each peripheral site. Upon reception, the reference will be used to injection-lock oscillators having excellent short-term stability. The reference could be transmitted continuously (at some frequency other than that used by the tagged individuals) to assure reliability.

Digitized data from each peripheral site could be transmitted back to the main site for processing via an RF communications link, however, serial transmission of data over existing telephone lines would be more economical. In such a configuration, peripheral-site data would be stored for periods of hours or even days prior to automated phone-dialing and subsequent relaying of the information to the main site for processing. In doing so, leased-line operation could be avoided and standard phone operation used. In fact, this would also allow direct data transmission to some large central computing facility for reduction. Main site computing and I/O equipment would then be unnecessary thereby reducing the overall system cost and complexity. The use of serial phone line transmission is not applicable if any site is to be mobile or if phone service is unavailable. In this event, RF links will be necessary, though one other possibility would be to transmit site data via RF links to some distant receiver point that had access to standard telephone service. The data could then be relayed from this point to the computing facility via phone lines.

In many cases, real time operation would be desired. This requires immediate peripheral site data transmission and on-site computing capability. Any modern minicomputer is capable of handling real-time processing and display at the required data rate of this system.

PAGE INTENTIONALLY BLANK

EXPANDIBILITY OF RECOMMENDED SYSTEMS

Both the acoustic proximity network and the VHF phase angle TOA network are practically expandable in two ways. First, either network type could be constructed at other locations and operated simultaneously with the Banana River net so long as telemetry from the adjacent nets did not interfere with one another. Such interference could be avoided by assuring that adjacent nets used telemetry links on different channels. Any broadcast reference signals would need to be spaced at harmonic intervals, with injection-locking occurring on a uniquely filtered version of the harmonic. For example, if two nets are adjacent and one net uses a 16 KHz reference, then the other net might use 8 KHz as its reference. Each peripheral site of the first net would receiver its 16 KHz reference through a 16 KHz bandpass filter. This would reject any 8 KHz that might be present from the adjacent net. Injection-locking of a 16 KHz oscillator would then take place using this filtered 16 KHz signal. The second net would operate similarly except each peripheral site would have an 8 KHz bandpass filter on its receiver to reject any stray 16 KHz signals coming from the first net. Injection-locking of a 16 KHz oscillator would then be accomplished on alternate cycles of the filtered 8 KHz reference. Of course, the frequency of the manatee tag modulation, being 16 KHz (in this example), would be usable by either network thereby expanding the system to handle net-to-net migrations.

The second way to expand the system is to make it mobile. Accurate position fixes could not be easily obtained while any part of the network was in motion; however, periodically repositioning the network to follow a gradual migration, for example, would synthetically increase the size and coverage of the network. Determination of the network configuration for a given area requires a degree of analysis and preplanning in order to achieve reliable operation with either an acoustic proximity network or especially an RF phase angle TOA network. It would therefore be necessary to have planned an itinerary and chosen network configurations (based on each given area on the itinerary) before attempting to move the system and make measurements at different locations.

PAGE INTENTIONALLY BLANK

APPENDIX I

CEP/P(I) PERFORMANCE ANALYSIS MODEL

Introduction and Approach

One of the major objectives of this study has been to assess the system performance of a net of DF systems in the VHF frequency region. This assessment required that consideration be given to the probability of intercept and the elliptical probable error (EPE). The probability of intercept provides a measure of the likelihood that a signal will be received at a remote point and the EPE quantifies the radiolocation error when two or more DF sites obtain bearings. It should be apparent that both of these performance measures involve a number of parameters which characterize any given situation. Typical of these parameters are: transmitter power, antenna heights, DF angular accuracy, frequency and soil and terrain characteristics. Fortunately, Georgia Tech has existing models which provided a starting point for the required performance analysis. The purpose of this Appendix is to provide a summary of the performance model and to show major mathematical results. For brevity, many details are omitted but key results are shown.

The general analysis model was constructed by adapting previous Georgia Tech models to the scope of this investigation. Basically, the analysis model consists of VHF propagation models, radio noise models, soil and terrain features, DF performance parameters and EPE plot routines. Inputs to the model included results from the literature and results derived from numerous radio wave propagation studies conducted at Cape Canaveral by Georgia Tech. To the maximum extent possible, the model was constructed so that parameter values could be inserted by the analyst during the course of performance evaluation.

Performance Measures

Intercept and Signal Acquisition. Normally DF is preceded by signal reception and identification usually called signal intercept. The DF system can operate in several intercept modes: (1) it can operate in an autonomous, non-netted mode and, for example, provide bearings to a central control on all signals appearing on a specified frequency or, (2) it can operate in a netting mode with alerting and cuing from a central control where the primary inter-

PRECEDING PAGE BLANK NOT FILMED

cept is performed. In any mode of operation, a signal must be acquired and, possibly, pertinent characteristics identified before the DF mode is activated.

The probability-of-intercept and signal acquisition are a function of several system parameters such as the following:

- o Antenna Gain and Spatial Coverage
- o Antenna Height
- o Receiver Sensitivity
- o Receiver Selectivity
- o Frequency Coverage
- o Tuning Rates and Frequency Agility
- o Modulation Tolerance
- o Transmitter Power
- o Transmission Duration
- o Noise Levels
- o Terrain Features

All of these parameters including the characteristics of the incident signal must be considered in the probability-of-intercept computations.

DF Accuracy Considerations. DF accuracy is a function of many varied error sources. In general, these errors can be subdivided into four general classes:

- o System Instrumental Errors
- o Siting Errors
- o Path/Propagation Errors
- o Observational Errors

System instrumental errors are, in general, either (1) fixed, deterministic errors caused by departure of the subsystems, components, etc. from the ideal, e.g., the octantal errors of a goniometer and amplitude and phase mismatch in multichannel receivers; or (2) random, statistical errors induced primarily by the time-variable nature of the incident signal, e.g., the effects created by abnormal polarization pick-up on RF transmission lines and antenna intra-element scattering and coupling errors which vary as a function of incident signal angle-of-arrival and polarization.

Siting errors are created by irregularities of, and reradiating objects on, the terrain surrounding a DF system. These errors are, in general, random even though they can be regarded as systematic when a particular frequency, signal polarization and direction-or-arrival are considered. At VHF, it is possible to configure sites in which the only important siting errors arise from very local effects which can possibly be minimized and controlled.

The effects of path and propagation errors on bearing errors has been the subject of considerable research and mechanisms have been clearly delineated. For groundwave propagation, the major effects are terrain refraction and diffraction and signal wavefront distortion by terrain irregularities along the propagation path. At VHF, the errors are, in general, the result of scattering by a large variety of reradiators and, as a result, are very random in character exhibiting erratic variation with changes in frequency, azimuth, distance and ground properties.

Observational errors refer to those errors which occur at the interface between the bearing display and the operator. Operator proficiency, experience and motivation play a major role. Also, observational errors are highly time and modulation dependent; the longer the observational period, the better the bearing estimation. In general observational errors tend to decrease when augmented display techniques such as long-persistence or storage displays are used. Of course, operator effects are greatly reduced if digital bearing readouts are used.

Probability of Intercept. In order for a DF system to perform its function of emitter location, it is necessary that an adequate signal be intercepted. A definition of what is meant by "adequate" is subject to wide interpretation and, in fact, depends largely on the performance of the interceptor DF and the signal energy received. For example, many non-averaging DF's require approximately a 6 dB signal-to-noise ratio before a usable angular measurement can be obtained. In contrast, correlation and averaging DF's have demonstrated the capability to work with SNR's as low as -15 dB. In the first instance, a SNR significantly less than 6 dB will result in no usable information while in the latter case, a SNR of -15 dB or greater will not only produce useful data but angular accuracy will be improved by time averaging. The significant difference in "adequate" signal levels can be attributed to the different DF designs and to the exploitation of the signal energy (signal power times signal duration) for time averaging.

Notwithstanding these differences in required signal levels for DF operation, a useful definition of adequate signal is that level of signal-to-noise ratio which allows the signal to be discriminated from noise and interference. In most cases, the discrimination of the signal is on the basis of aural intercept. This definition is consistent with the requirement that the signal be detected before the DF operation (net or single station) can commence. Previous intercept models have used signal intercept SNR's in the range of 0 to 6 DB. For the model applied in this investigation, the criterion of 6 dB SNR was applied. Therefore, the intercept probability involves determination of the statistical distribution of SNR at the DF sites and calculation of the probability that the received SNR will be equal to or greater than the minimum intercept level of 6 dB SNR. This, therefore, becomes a worst case analysis when applied to correlation or averaging DF systems.

EPE Analysis. The Elliptical Probable Error (EPE)† is a performance measure which provides basic data about DF net performance. This performance measure, which is in the form of a contour (generally elliptical) about the most probable emitter location, provides an indication of the ability of the DF system to locate an emitter.

The CEP analysis in the performance evaluation model is based on Stansfield's method which requires calculating [45]

$$\lambda = \sum_{1}^{n} \frac{\sin^2 \theta_j}{\sigma_j^2 D_j^2} ,$$

$$\mu = \sum_{1}^{n} \frac{\cos^2 \theta_j}{\sigma_j^2 D_j^2} , \text{ and}$$

$$\nu = \sum_{1}^{n} \frac{\sin \theta_j \cos \theta_j}{\sigma_j^2 D_j^2}$$

†In this report and other sources, the term "Circular Error Probable"(CEP) is used interchangeably with EPE. Unless otherwise noted, all results stated deal with ellipses of statistical locational ability.

where,

θ_j = bearing angle of the target from station j,

σ_j = standard (angular) deviation of the j^{th} bearing,

D_j = distance from j^{th} station to the target, and

n = number of DF sites

Next the parameters a and b are determined from

$$a^2, b^2 = \frac{2}{\lambda + \mu \pm \sqrt{(\lambda-\mu)^2 + 4\nu^2}}$$

The semi-axes (A and B) of the elliptical contour of equal probability can then be obtained from

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = -2 \log_e (1 - P)$$

where P is the total probability that the target will lie within the area bounded by the contour.

DF Angular Variance. Aside from geographical parameters, the major parameter required for CEP analysis is the DF angular variance (square of DF standard deviation). This angular variance is composed of three components given by

$$\phi^2 = \phi_i^2 + \phi_p^2 + \phi_s^2$$

where,

ϕ_i^2 = DF instrumental variance,

ϕ_p^2 = variance due to propagation effects,

ϕ_s^2 = variance due to received SNR.

The instrumental variance is a measure of the DF accuracy under no limitations other than the basic accuracy of the DF equipment under best case conditions. Frequently, this variance is inappropriately called "DF accuracy" and, if used as such, can lead to abnormally good performance. The propagation variance is a measure of DF inaccuracy caused by propagation factors such as multipath, lateral deviation and diffraction paths. Although not necessarily determined by DF design, this error source exists and may place bounds on system performance. The variance due to received SNR reflects the fact that DF accuracy under operational conditions is dependent on the received signal level relative to noise perturbations.

In the performance analysis model, instrumental variance is treated as a variable which can be inserted by the analyst. Variance due to propagation is a function of terrain type and frequency as well as DF design and is handled in the model by selection of values for the particular propagation mode and the terrain type.

Variance due to SNR displays a much more complicated dependence and will be unique for each DF and each target point. This uniqueness is due to the existence of a different propagation path from each DF to the emitter point in question. In addition, the variance will also be a function of observational error.

In the performance evaluation model, it was recognized that the received SNR would be subject to statistical variation due to such factors as time variable propogatation loss, terrain variations, noise level variation, etc. Consequently, the DF angular variance due to SNR should assume a statistical distribution. The density function for this distribution is given by

$$p(\phi) = \int_S p(\phi|S)p(S)dS$$

where $p(\phi|S)$ is the error density function given the SNR and $p(S)$ is the density function for the SNR. The DF angular variance is then found from

$$\phi^2 = \int_\phi \phi^2 \; p(\phi)d\phi$$

For the analysis here, the reasonable assumption was applied that the DF error was normally distributed. In addition, it was assumed that the SNR was uniformly distributed over a specified region.

Application of the above equations along with the stated assumptions results in

$$\phi_s^{\,2} = \frac{4\phi_o^{\,2}\, e^{-0.2303X_o}}{\frac{kT}{T_m}(0.2303)\sqrt{3}\, S_v}\left[e^{0.2303\sqrt{3}\, S_v} - e^{-0.2303\sqrt{3}\, S_v}\right].$$

where,

ϕ_s^2 = DF variance due to SNR,

ϕ_o^2 = DF variance at a 6 dB SNR and a single DF scan ($T/T_m = 1$),

k = modulation factor ($0 \leq k \leq 1$) to account for reduced signal availability,

T/T_m = number of DF scans while signal is active,

S_v^2 = variance of SNR (dB^2)

X_o = mean value of SNR in dB

This expression allows the received SNR to be related to the resulting DF angular variance. Note that suitable factors are included to account for the effects of multiple DF scans (time averaging), modulation dependence and observation errors. Note also that the DF variance due to SNR will become zero for large values of SNR as it should.

The instrumental variance, ϕ_i^2, and the normalized DF error, ϕ_o^2, must be specified for each particular direction finder. The variance due to propagation will be a function of frequency and terrain type and is given by:

<u>VHF (f > 30 MHz)</u>

LOS: $\phi_p = 0°$

Non-LOS: $\phi_p =$ 0° plains; 2° hills; 4° mountains

The DF error due to VHF propogation is based on judgement as well as previous measured results [46].

To determine if a particular path is line-of-sight or not, the tests are applied:

$$\text{if } 1.33 \times 10^{-5} f_{MHz} \frac{h_1 h_2}{d_{km}} > 1,$$

or

$$\text{if } \frac{h_1 + h_2}{d_{km} \times 10^3} > 0.04$$

where h_1 = DF antenna height (m), and H_2 = transmitter antenna height (m). If either test is met, LOS is assumed. The first criteria is derived from first Fresnel zone clearance and the second test allows high angle line-of-sight paths [47].

Surface wave is discriminated from skywave by calculating the SNR for both and choosing the path which yields the largest SNR. If the LOS criteria is met, an LOS condition is assumed.

SNR vs. System Parameters

VHF SNR. VHF SNR ($f \geq$ 30 MHz) is calculated from the expression,

$$
\begin{aligned}
\text{SNR} - 10 \log (P_w \times 1{,}000) + G_T + G_D \\
- \left\{ \begin{array}{ll}
\text{non-LOS} & \left[120 + 40 \log d_{km} - 20 \log h_1 h_2 + 20 \log \frac{f}{40} + \left\{ \begin{array}{l} -10 \text{ plains} \\ 0 \text{ hills} \\ 15 \text{ mountains} \end{array} \right. \right] \\
\text{LOS} & \left[32.4 + 20 \log d_{km} + 20 \log f \right]
\end{array} \right. \\
- \left\{ \begin{array}{ll}
\text{high noise} & \left[-94 - 23 \log \frac{f}{30} \right] \\
\text{medium noise} & \left[-105 - 23 \log \frac{f}{30} \right] \\
\text{low noise} & \left[-122 - 23 \log \frac{f}{30} \right]
\end{array} \right. \\
-10 \log B_{kHz}
\end{aligned}
$$

where,

P_w = transmitter power (watts),

f = frequency (MHz),

G_T = transmitter antenna gain (dB/isotropic),

G_D = DF antenna gain (dB/isotropic),

d_{km} = distance between transmitter and DF site (km),

B_{kHz} = DF receiver bandwidth (kHz)

h_1 = transmitter antenna height above average terrain (m),

h_2 = DF antenna height above average terrain (m).

The constant loss factors which represent terrain effects are based on measured propagation loss data for Ohio hills, Colorado plains and Colorado mountains [48]. Statistical results for these cases were plotted from the raw data and then averaged to obtain a measure of terrain effects. It should be noted that these factors have statistical significance only, i.e., they represent the average effect of many measured cases.

Low, medium and high noise factors for VHF and HF bands are based on measured results reported in the literature [49].

Notice in the above equation that selection must be made (1) between LOS and non-LOS, (2) between plains, hills or mountains, and (3) between low, medium or high noise. Since effective antenna height may exceed actual height, it is necessary to use the maximum of either the actual or effective height. In terms of soil characteristics, this selection is made from the following table:

	Effective Height h_o in Meters	
Soil Characteristics	Vertical Polarization	Horizontal Polarization
Excellent $\varepsilon = 80, \sigma = 4.0$	$\frac{1220}{f}$	0
Good $\varepsilon = 30, \sigma = 0.02$	$\frac{305}{f}$	0
Poor $\varepsilon = 4, \sigma = 0.001$	$\frac{122}{f}$	$\frac{30.5}{f}$

f = frequency in MHz

The VHF SNR will have a variance due to noise level and propagation. This variance is given by

$$S_v^2 = L_v^2 + N_v^2$$

where,

L_v^2 = propagation loss variance,

and

N_v^2 = noise level variance.

The standard deviations used in the model are

$$N_v = 4 \text{ dB}$$

$$L_v = \begin{cases} 2 \text{ dB for LOS} \\ 10 \text{ dB for mountains} \\ 8 \text{ dB for hills} \\ 6 \text{ dB for plains} \end{cases}$$

The noise variance is based on measured results [49] and the loss variance is based on the propagation data referenced above [48].

The intercept probability is defined as the probability that the received SNR is greater than or equal to 6 dB. Under the assumption of a uniform distribution whose variance is equal to a Gaussian distribution, the intercept probability is given by

$$P(I) = \begin{cases} 0 \text{ if } X_o + \varepsilon < 6 \text{ dB} \\ 1 \text{ if } X_o - \varepsilon > 6 \text{ dB} \\ \dfrac{X_o + \varepsilon - 6}{2\varepsilon} \text{ otherwise} \end{cases}$$

where,

X_o = mean value of SNR (dB),

and

$\varepsilon = \sqrt{3}\, S_v$.

Structure of the Model

The performance evaluation model was implemented in FORTRAN IV on an HP 2100 minicomputer system which includes software for automatic CRT plotting of all major outputs.

As an aid for evaluating and generating graphical output, the model includes self-scaling features and scaling parameters. For example, if the region of analysis as specified by the analyst does not utilize the full plotting screen, the system will automatically extend the plotting region. In addition, the ellipses of error probability may be scaled by a scaling parameter. This feature is useful for resolving plots of closely spaced and overlapping contours. Figure A.1 shows a simplified flow chart of the model.

Example of Results

An example of results produced by the performance analysis model is shown in Figures A.2, A.3 and A.4. The first sheet as shown in Figure A.2 provides a tabulation of the input numerical data and the resulting output numerical data. The output data consists of the X-Y coordinates of each target point, the axes of the elliptical probability contour, the maximum intercepted SNR, and the maximum probability of intercept. The environmental parameters assumed for the problem are also tabulated (time-of-day, season, etc.). Specific DF parameters assumed for the problem are tabulated under "DF SCENARIO" and signal characteristics are tabulated under "TARGET DATA". The data shown in Figure A.2 are automatically listed on a teletype listing device.

Figure A.3 is the resulting graphical display of the CEP data. This plot is obtained automatically and directly from a CRT display. The plot is labeled in km, and the DF sites are identified by circles and a "cross". The ellipses are centered about the target points and show the 50% contour of radiolocation ability.

Figure A.4 is additional graphical data showing the probability of intercept. DF sites are shown as before. The size of the "square" about each target point is proportional to the intercept probability. The grid marks at each intercept point are 50% marks. Thus, for 50% probability of intercept the diagonal of the square will coincide with the target grid mark length.

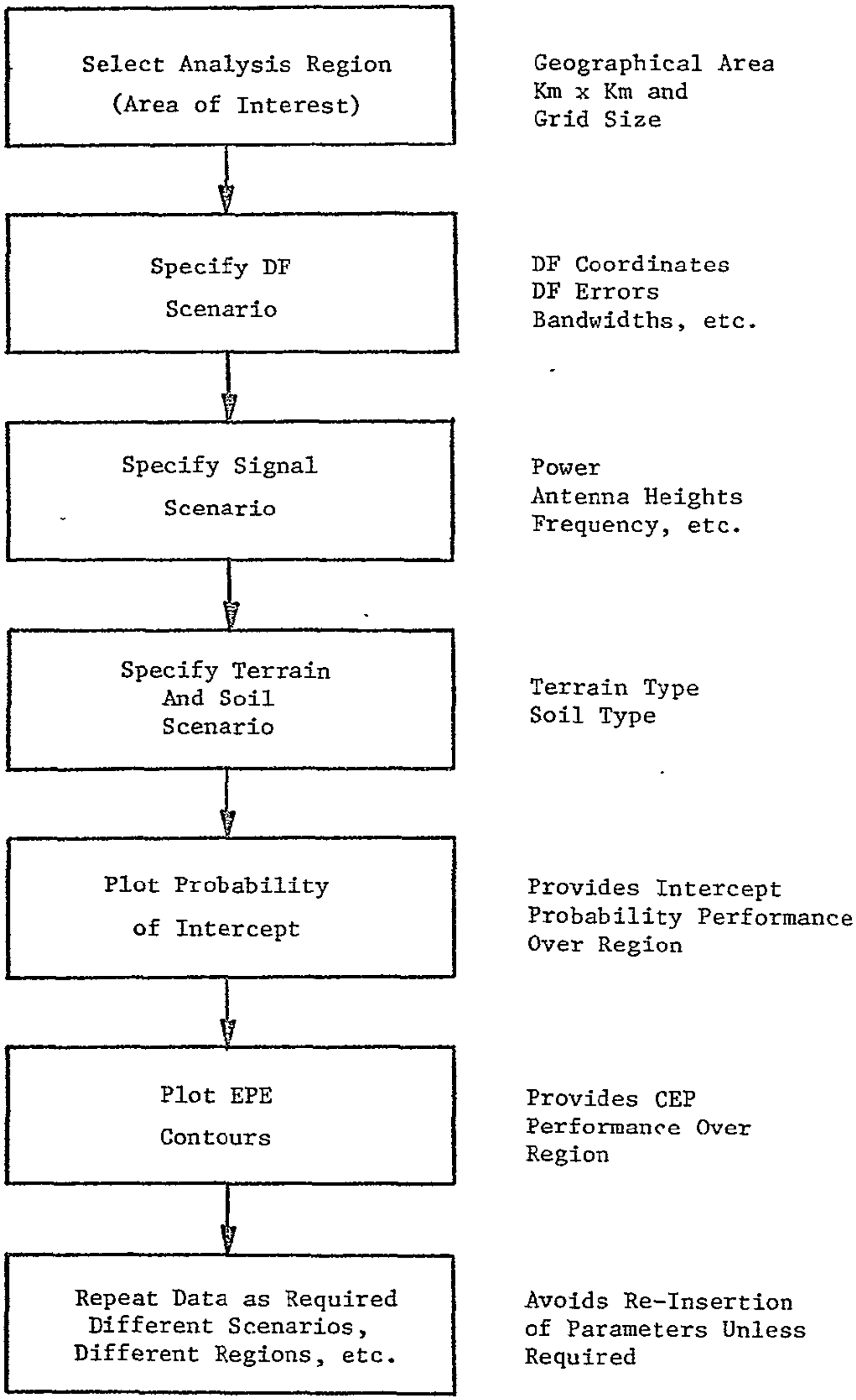


Figure A.1 Performance Model Characteristics.

DATA TABULATION

X	Y	CEP-A	CEP-B	MAX SNR	MAX P(I)
15.Ø	5.Ø	.18	.42	21.38	100
15.Ø	10.Ø	.76	2.26	9.34	61
15.Ø	15.Ø	2.21	8.81	2.29	38
15.Ø	20.Ø	4.95	25.32	-2.7Ø	22

TIME OF DAY	SEASON	NOISE FACTOR	TERRAIN TYPE	SOIL TYPE
12ØØ	TRANS	MED	HILLS	GOOD

```
XXXXXXXXXXXXXXXXX
X               X
X  DF SCENARIO  X
X               X
XXXXXXXXXXXXXXXXX
```

X	Y	NORM ERROR	INST ERROR	TIME FACTOR	RCVR BW	ANT HEIGHT	ANT GAIN
10.Ø	.Ø	10.Ø	1.Ø	10.Ø	10.Ø	10.Ø	.Ø
15.Ø	.Ø	10.Ø	1.Ø	10.Ø	10.Ø	10.Ø	.Ø
20.Ø	.Ø	10.Ø	1.Ø	10.Ø	10.Ø	10.Ø	.Ø

```
XXXXXXXXXXXXXXXXX
X               X
X  TARGET DATA  X
X               X
XXXXXXXXXXXXXXXXX
```

X	Y	X-MITTER POWER	FRFQ	ANTENNA POLARITY	ANT HEIGHT	ANT GAIN
15.Ø	5.Ø	2.Ø	47.Ø	VERT	1.Ø	2.Ø
15.Ø	10.Ø	2.Ø	47.Ø	VERT	1.Ø	2.Ø
15.Ø	15.Ø	2.Ø	47.Ø	VERT	1.Ø	2.Ø
15.Ø	20.Ø	2.Ø	47.Ø	VERT	1.Ø	2.Ø

Figure A.2 Data Tabulation.

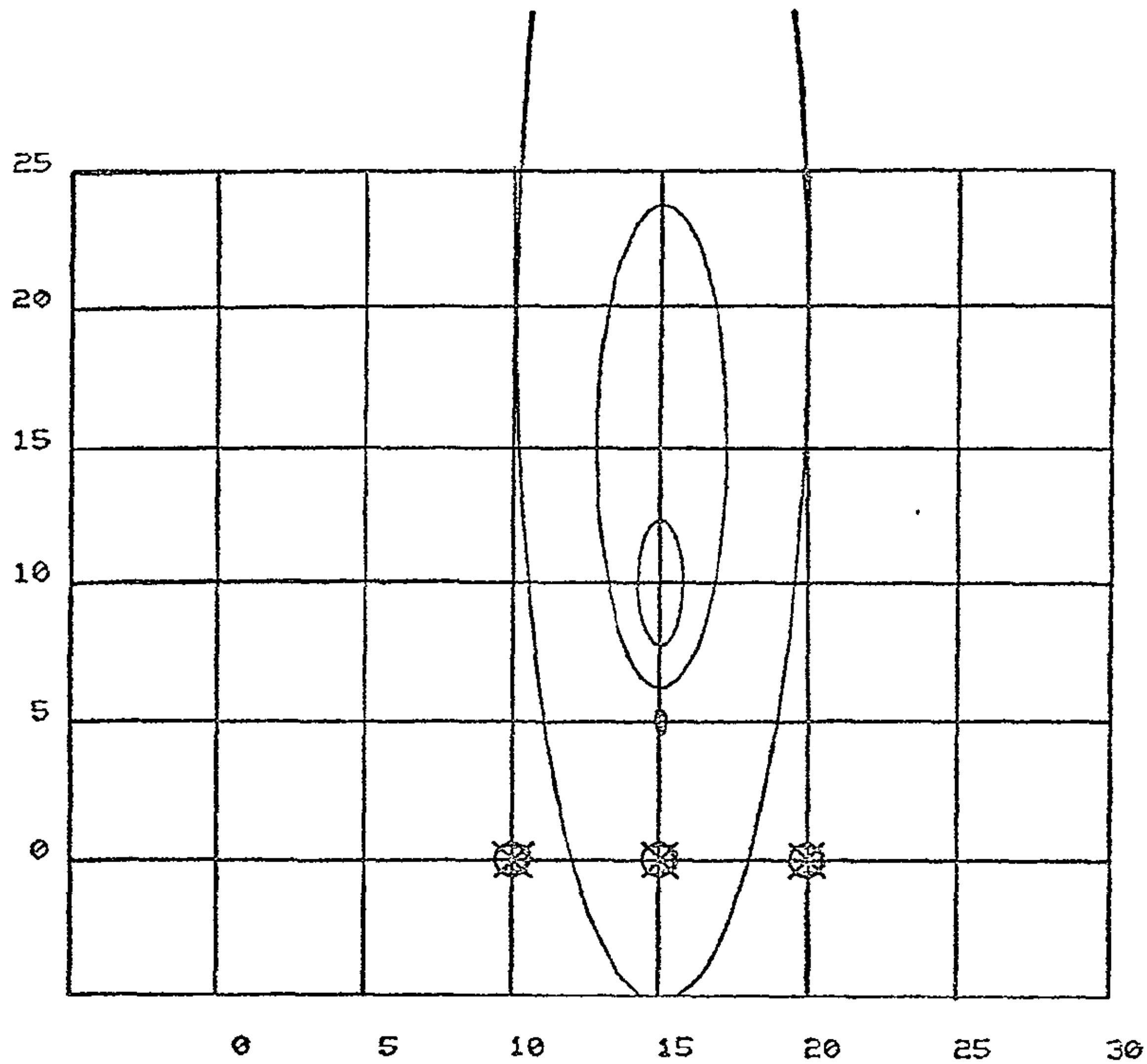


Figure A.3 CEP Plots.

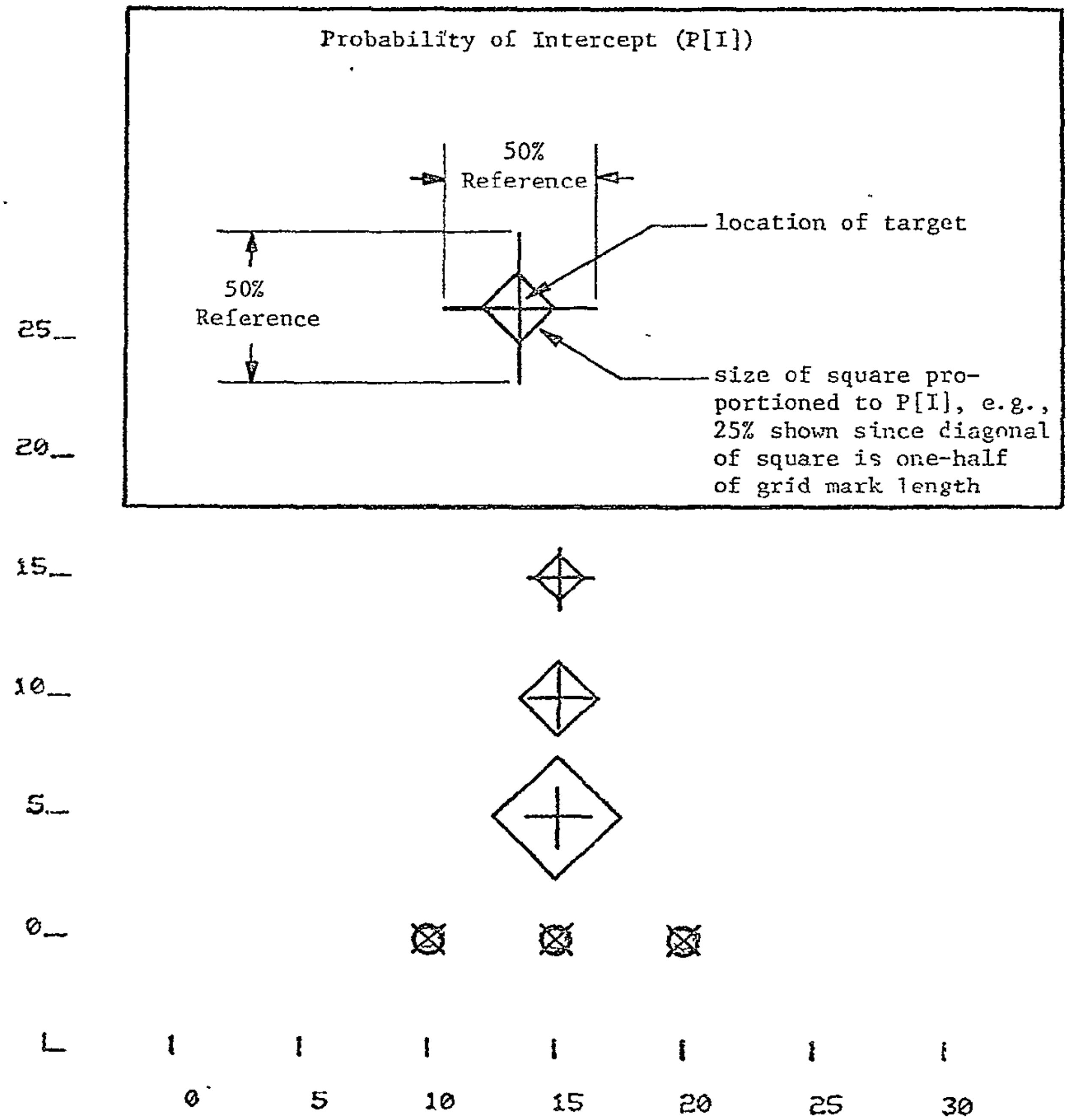


Figure A.4 Probability of Intercept Plot.

PAGE INTENTIONALLY BLANK

REFERENCES

1. Behavior and Ecology of the Florida Manatee, Trichechus Manatus Latirostris (Harlan), at Crystal River, Citrus County, Cornell University, Ph.D. Thesis, 1971, Zoology, Hartman, Danial Stanwood.

2. "The Florida Manatee Myth vs. Truth", Sea Frontiers, Vol. 22, No. 4, July-August, 1976, John E. Reynolds III, pp. 208-214.

3. Review of the Ecology and Life History of the Florida Manatee, Prepared for Florida Power and Light Company, Miami, Florida by Applied Biology, Inc., Atlanta, Georgia, March, 1977, Van Meter, Victoria.

4. Time, Space Position, Information (TSPI) Study, Prepared for the Rome Air Development Center, Air Force Systems Command, Griffiss AFB, N.Y. by the Calspan Corporation, Buffalo, N.Y., Final Technical Report RADC-TR-73-243, October, 1973, Mellenger, T., et. al.

5. CR-100 Implementation Study for Space Shuttle, Final Technical Report Prepared for Intermetrics, Inc., Cambridge, Ma. by the Cubic Corporation, San Diego, Ca., Subcontract Purchase Order 71-101 for Prime Contract NAS9-11593, June, 1971, Krenz, D., et. al.

6. Ciris Design Evaluation, Report No. TR-213-1, Prepared under Contract No. F29600-70-C-0022 for 6585th Test Group (GDD) Holloman AFB, N.M. by the Analytic Sciences Corporation, Reading, Ma., Sept., 1970, Crawford, B., et. al.

7. Mammals of the World, Vol. II, The John Hopkins Press, Baltimore, Md., 1964 pp. 1331-1337, Walker, E.

8. Notes on Topics in Propagation of Sound in the Sea, Compiled for use in Technology Service Corp. Underwater Acoustic Propagation Short Course, April, 1977. Urick., R. and Palmer, L.

9. Principles of Underwater Sound for Engineers, McGraw-Hill Book Company, N.Y., 1967, Urick., R.

10. Physics of Sound in the Sea, Part I: Transmission, Originally Issued as Division 6, Volume 8, NDRC Summary Technical Reports, Reprinted by the The Research Analysis Group, Committee on Undersea Warfare, National Research Council.

11. Physics of Sound in the Sea, Part II: Reverberation, Originally Issued as Division 6, Volume 8, NDRC Summary Technical Reports, Reprinted by the Research Analysis Group, Committee on Undersea Warfare, National Research Council.

12. Physics of Sound in the Sea, Part III: Reflection of Sound from Submarines and Surface Vessels, Originally Issued as Division 6, Volume 8, NDRC Summary Technical Reports, Reprinted by the Research Analysis Group, Committe of Undersea Warefare, National Research Council.

13. Physics of Sound in the Sea, Part IV: Acoustic Properties of Wakes, Originally Issued as Division 6, Volume 8, NDRC Summary Technical Reports, Reprinted by The Research Analysis Group, Committee of Undersea Warfare, National Research Council.

14. Radar Handbook, McGraw-Hill Book Company, N. Y., 1970, Skolnik, M., (Editor-in-Chief)

15. George M. Lowery, Jr., The Mammals of Louisiana and its Adjacent Waters, Louisiana State University Press, 1974, pp. 475-482.

16. John J. Myers, Handbook of Ocean and Underwater Engineering, McGraw-Hill Book Co., 1969, pp. 3-37, 38.

17. Forrest G. Wood, Marine Mammals and Man, The Navy's Porpoises and Sea Lions, Robert B. Luce, Inc., 1973.

18. R. Stuart Mackay, Bio-Medical Telemetry, John Wiley & Sons, Inc., 1968, pp. 296-330.

19. Medical and Biological Applications of Space Telemetry, Technology Utilization Report prepared under contract for NASA by Biosciences & Technology, Space & Life Systems Department, Hamilton Standard Division of United Aircraft Corp., NASA SP-5023, U. S. Government Printing Office, 1965, pp. 23-32.

20. William K. Brockelsby, "Microwave Techniques in Animal Radiotelēmetry," Biotelemetry II., 2nd International Symposium, Davos 1974, F. Reinhardt A.G., Basel, Switzerland, 1974, pp. 220-222.

21. Lloyd E. Slater, Interdisciplinary Conference on the Use of Telemetry in Animal Behavior and Physiology in Relation to Ecological Problems, New York, 1962, The Macmillan Company, 1963.

22. Thomas B. Fryer, Implantable Biotelemetry Systems, NASA Technology Utilization Report, NASA SP-5094, U. S. Government Printing Office, 1970.

23. Chapman, H. C., 1875, Observations on the Structure of the Manatee. Proc. Acad. Natur. Sci., Phila.

24. Coates, C. W., 1940. Manatees at the Aquarium, Bull., New York Zool. Soc. 43:99-100.

25. Jones, J. K., Jr. & R. R. Johnson, 1967. Sirenians, pp. 366-373 in Recent Mammals of the World: A Synopsis of Families (S. Anderson and J. K. Jones, Jr. eds), Ronald Press Co., New York, 453.

26. Kromholz, L. A., 1943., "Notes Concerning Manatees in Florida Waters", Journal of Mammalogy, 24:272-273.

27. Barrett, O. W., 1935, "Notes Concerning Manatees and Dugongs", Journal of Mammalogy, 16:216-220.

28. Brimley, H. H., 1931. "The Manatee in North Carolina", Journal of Mammalogy, 12:320-321.

29. Cahn, A. R., 1940. "Manatees and the Florida Freeze", Journal of Mammalogy, 21:222-223.

30. Evans, W. E. & E. S. Herald, 1970. "Underwater Calls of a Captive Amazon Manatee, Trichechus inunguis." Journal of Mammalogy, 51:820-823.

31. Gunter, G., 1941. "Occurrence of the Manatee in the United States with Records from Texas", Journal of Mammalogy, 22:60-64.

32. Gunter, G., 1942. "Further Miscellaneous Notes on American Manatees", Journal of Mammalogy, 23:89-90.

33. Moore, J. C., 1951a. "The Status of the Manatee in the Everglades National Park, with notes on its Natural History", Journal of Mammalogy, 32:22-36

34. Parker, G. H., 1922. "The Breathing of the Florida Manatee (Trichechus Latirostris)", Journal of Mammalogy, 3:127-135.

35. Tomkins, I. R., 1956. "The Manatee Along the Georgia Coast", Journal of Mammology, 37:288-289.

36. Hartman, D. S., "Florida Manatees, Mermaids in Peril", National Geographic Magazine, pp. 342-353, September 1969.

37. Beddard, F. E., 1897. "Notes upon the Anatomy of a Manatee (Manatus inunguis) Lately Living in the Society's Gardents", Proc. Zool. Soc. London, pp. 47-53.

38. Brown, A. E., 1878. "The Sirenia", Amer. Natur., 12:291-298.

39. Eveready Battery Engineering Data, Union Carbide Corporation, 1976.

40. Mallory Technical Data Sheets, Mallory Battery Company, 1974.

41. "Today's Resins Provide a Cure for Almost Every Embedding Ill", Electronic Design, Vol. 22, No. 25, December 6, 1974, pp. 28-34, Grossman, M.

42. "Navigation and Positioning Systems Come of Age", Sea Technology, Vol. 18, No. 3, March, 1977, pp.11-21, Nagy, A.

43. Infrared and Electro Optic Characteristics, Sanders Associates Inc., 25th Anniversary Brochure, Nashua, N. H., 1976.

44. Radio Frequency and ECM Characteristics, Sanders Associates Inc., 25th Anniversary Brochure, Nashua, N. H., 1976.

45. R. G. Stansfield, "Statistical Theory of DF Fixing," Journal of IEE, Vol. 94, Part IIIA, 1947, pp. 762-770.

46. H. H. Jenkins, R. W. Moss and R. S. Smith, "Miniature Manpack HD/VHF DF System," Contract DAAB07-73-C-0049, Final Report, Georgia Tech, April, 1974.

47. Edward C. Jordan, Electromagnetic Waves and Radiating Systems, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1950.

48. G. A. Hufford and J. L. Montgomery, "On the Statistics of VHF Field Strength Measurements Using Low Antenna Heights", U. W. Department of Commerce, National Bureau of Standards, 1966.

49. "Spectrum Engineering - The Key to Progress," The Joint Technical Advisory Committee (IEEE and EIA), 1968, p. 59-65.

50. Kenneth Davies, Ionospheric Radio Propagation, U. S. Deparment of Commerce National Bureau of Standards, 1965.