UNCLASSIFIED

[redacted]

AD 513725

33 pgs.

DTIC

45 pg

Technical Report

THIS DOCUMENT HAS BEEN DOWNGRADED

TO UNCLASSIFIED

Per Director DARPA, SEIO/TIO

NOV 10 1992

distributed by

Defense Technical Information Center

DEFENSE LOGISTICS AGENCY

CAMERON STATION, ALEXANDRIA, VIRGINIA 22304-6145

UNCLASSIFIED

[redacted]

DO NOT REMOVE

NOTICE

We are pleased to supply this document in response to your request.

The acquisition of technical reports, notes, memorandums, etc., is an active, ongoing program at the Defense Technical Information Center (DTIC) that depends, in part, on the efforts and interests of users and contributors.

Therefore, if you know of the existence of any significant reports, etc., that are not in the DTIC collection, we would appreciate receiving copies or information related to their sources and availability.

The appropriate regulations are Department of Defense Directive 3200.12, DoD Scientific and Technical Information Program; Department of Defense Directive 5200.20, Distribution Statements on Technical Documents (amended by Secretary of Defense Memorandum, 18 Oct 1983, subject: Control of Unclassified Technology with Military Application); Military Standard (MIL-STD) 847-B, Format Requirements for Scientific and Technical Reports Prepared by or for the Department of Defense; Department of Defense 5200.1R, Information Security Program Regulation.

Our Acquisition Section, DTIC-DDAB, will assist in resolving any questions you may have. Telephone numbers of that office are: (202)274-6847, 274-6874 or Autovon 284-6847, 284-6874.

FEBRUARY 1984

© U.S. Government Printing Office

SECURITY MARKING

The classified or limited status of this report applies to each page, unless otherwise marked. Separate page printouts MUST be marked accordingly.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U.S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

UNCLASSIFIED

[redacted]

UNCLASSIFIED

GTE SYLVANIA INCORPORATED
P. O. Box 205
Mountain View, California 94040

EDL-M1380

Project AQUARIUS Special Report (U)

Principal Investigator S. Richmond 415/966-3771
Project Engineer K. Snow 415/966-3186

ARPA Order No. 1459
Effective Date of Contract: 2 June 1969
Contract Expiration Date: 31 March 1971
Amount of Contract: $118,864

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Office of Naval Research under Contract No. N00014-69-C-0446

ABSTRACT

This report discusses an investigation of the feasibility of defending surface vessels against low-flying threats. Various models and techniques based on them for the estimation of threat trajectories are derived using a polystatic radar approach wherein targets are illuminated with skywave and surface-wave modes and reflections are received by a shipborne receiving system via the surface-wave mode. Two of the models were tested via simulation: a two-transmitter, one-receiver (double baseline) case and a one-transmitter, one-receiver (single baseline) case. The results of the investigation indicate that of the models tested only the double baseline approach may be a feasible method. However, further analysis is needed before a final conclusion can be reached.

Two configurations that might be feasible for the shipborne hardware required to perform the azimuthal and Doppler measurements are discussed: the multiple-baseline/pattern-recognition system and the switched linear array Doppler direction finding system. It is concluded that the relative advantages of the two systems should be investigated to select the one most appropriate to the specific application desired.

CONTENTS

ILLUSTRATIONS

TABLES

Section I

INTRODUCTION

1.1 (U) ~~(S)~~ BACKGROUND.

The detection of low-flying threats to surface vessels at a range sufficient to give useful warning time and tracking information is a problem which must be solved if the surface navy is to survive. In detecting these threats the enemy must not be given the opportunity to use simple direction finding techniques to locate fleet units. Thus, it is desirable that target detection not require radiation from the fleet and that the fleet operate under complete electromagnetic control (EMCON).

The feasibility of using a hybrid (skywave/surface-wave) system to help solve this problem has been demonstrated as part of the MAY BELL Program. In this concept, the target is illuminated by skywaves from transmitters (either shipborne or land-based) located at over-the-horizon (OTH) ranges. Surface waves which propagate from the target to a receiving system aboard a ship permit detections to be made even when the target is below the line-of-sight radar horizon.

Experiments performed at Cape Kennedy, Florida, with a shore-based receiving station simulating the shipboard environment, a Navy P3V aircraft as a controlled target, and illumination provided by the MADRE (pulse) and CHAPEL BELL (phase code) transmitters, located respectively in Maryland and Virginia, have shown the technique to be feasible. For most of the flights of the target its altitude was 200 feet, and detections were made at ranges as great as 104 kilometers (km) from the receiver.

1.2 (U) ~~(S)~~ FEASIBILITY STUDY.

As an application of the hybrid-system, fleet air-defense technique, a feasibility study under Project AQUARIUS has been conducted to determine the practicality of defending the Mediterranean Fleet against low flying aircraft and cruise missiles using over-the-horizon detection (OHD) skywave--surface-wave and surface-wave--surface-wave techniques. A parallel effort within this study was to determine if simple continuous wave (CW) rather than range code transmissions could be used which might then result in a simpler, more mobile system.

1.2 (U) (S) --CONTINUED.

It was determined that shore-based HF (CW) sources could be used for skywave and surface-wave target illumination and shipboard receivers used to detect the surface-wave Doppler shifted signal scattered by the target. Assuming reasonable powers (10,000 W), vertical antennas and 100 m^2 cross sections, a target detection range of approximately 100 km from the ship is typical.

Although the Doppler detection provides some information about the target velocity and direction, because of symmetry, targets flying near the transmitter may give the same Doppler shift as those flying near the ship. Thus a means of discriminating between threatening and non-threatening targets may be as important as detecting the targets themselves, at OTH ranges.

This report describes the derivation and presents simulation results for three straight-forward techniques which allow OTH target detection and tracking while maintaining EMCON.

1.3 (U) (S) SUMMARY.

Derivations have been made of techniques to provide location estimates of low-flying targets using a polystatic radar approach in which the targets are illuminated with skywave and/or surface-wave modes from a land-based HF CW transmitter and the reflections from the targets are received by a shipborne receiving system via surface wave mode. The models used have been examined for two configurations: a two-transmitter, one-receiver (double baseline) case and a one-transmitter, one-receiver (single baseline) case. For the double baseline case two models were developed, one to represent azimuthal and Doppler measurements made at two different time points for each baseline and a second to represent a single set of measurements for each baseline. For the single baseline case a third model requiring two sets of azimuthal and Doppler measurements was developed.

The second and third models were simulated for aircraft detection in the Mediterranean for two situations: one in which the aircraft flies directly at the ship and a second in which it flies at an angle of 30° from the ship. The influences of bearing error measurements on the trajectory estimation were examined.

1.3 (U) ~~(S)~~ --CONTINUED.

Implementation considerations indicate that Doppler resolutions of 0.1 Hz and azimuthal accuracies of 1.? degrees RMS are feasible.

Two configurations--the multiple-baseline/pattern-recognition system (MB/PR) and the switched linear array Doppler direction finding system (SLAD)--that might be feasible for the shipborne hardware required to perform the azimuthal and Doppler measurements are discussed.

1.4 (U) ~~(S)~~ CONCLUSIONS.

The results of the investigation indicate that the double baseline approach wherein a single set of measurements is made for each baseline is superior to the single baseline approach. The necessary assumption required by the single baseline method introduces large errors in practice and makes this formulation of the method unacceptable. An estimation accuracy of 1 km in range is achievable for the ideal double-baseline case where there are no measurement errors. Inaccurate azimuthal measurements result in greater errors in range estimates than do inaccurate Doppler measurements. A preliminary error analysis indicates that errors of ± 2° in bearing measurement result in range errors of 1 - 5 km.

From the foregoing results it is concluded that the double baseline approach appears to be a feasible method for estimating the location of low-flying aircraft using a polystatic HF system. However, additional analysis is required in

(a) detailed error analysis of the double baseline (single measurement) method,

(b) a simulation and error analysis of the double baseline (multiple measurement) method,

(c) location estimation of high flying aircraft/missiles (the case for which a flat earth and two dimensional model is no longer valid),

(d) system design for implementing the double baseline (single measurement) method, and

(e) analysis of other formulations of the single baseline approach.

1.4 (U) (S) --CONTINUED.

It is also concluded that the two possible shipborne hardware systems should be further investigated to select the one most appropriate to the specific application desired.

1.5 (U) REPORT ORGANIZATION.

This report consists of four sections. The first presents introductory background information concerning previous work done on the detection of low-flying threats to surface vessels. It also introduces the feasibility study described in this report and gives a summary of the study and the conclusions reached. The second section describes the models used and the derivations of the various techniques, based on the models, for estimation of missile/aircraft trajectories. Section 3 discusses the simulation and testing that was performed on two of the models and points out sources of error in each. Estimates of the effects of errors in the measured parameters on the results are also given. Finally, Section 4 discusses ways of designing and constructing the shipborne hardware required to provide the azimuth and Doppler measurement information necessary to the application of the derived techniques.

Section 2

DERIVATION FOR AIRCRAFT TRAJECTORY ESTIMATION

2.1 (U) ~~(S)~~ GENERAL.

As described in Section 1, protection of the fleet against low flying aircraft and/or cruise missiles may be accomplished using a bistatic radar with a shore-based transmitter for target illumination combined with passive shipboard reception. In fact, over-the-horizon warning may be accomplished without active shipboard radiation (i.e., with electromagnetic control, EMCON). The techniques considered in this study appear to eliminate two fundamental problems associated with CW-Doppler bistatic radar:

a. Target signal amplitude gives no indication of whether the target is near the transmitter or the receiving ship because the bistatic radar range equation is symmetric about the transmitter-target and receiver-target ranges.

b. Single Doppler measurements alone cannot provide unambiguous target location since single Doppler measurements have a four-fold location ambiguity caused by the geometric symmetry between the transmitter, receiver and target.

Three separate derivations will be given describing techniques which may be used to locate and track low flying targets which may threaten a surface fleet.

2.2 (U) MODELS USED.

For the two-dimensional (flat earth, low flying) situation being considered here, two geometries are worth investigating: a two-transmitter, one-receiver (double baseline) case and a one-transmitter, one-receiver (single baseline) case. For the double baseline case, two models were developed. One model requires that, for each baseline, azimuth and Doppler measurements be taken at two different time points. The other model requires only one azimuth and Doppler measurement for each baseline. The geometries for these two models are illustrated in Figures 1 and 2. The single baseline model requires azimuth and Doppler measurements at two different time points: the geometry for this model is shown in Figure 3.

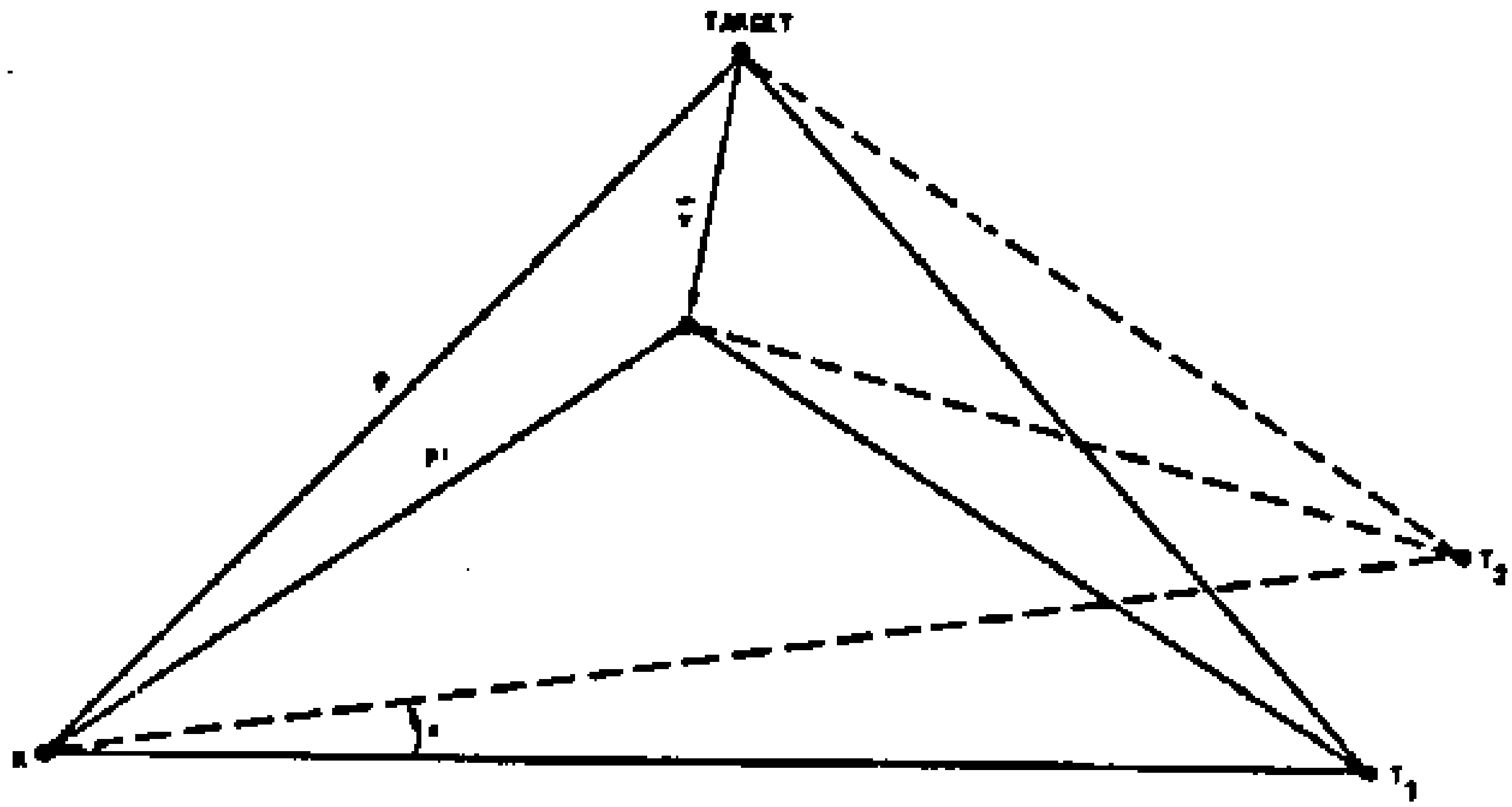

Figure 1. (U) Double-Baseline, Two-Measurements Model. (U)

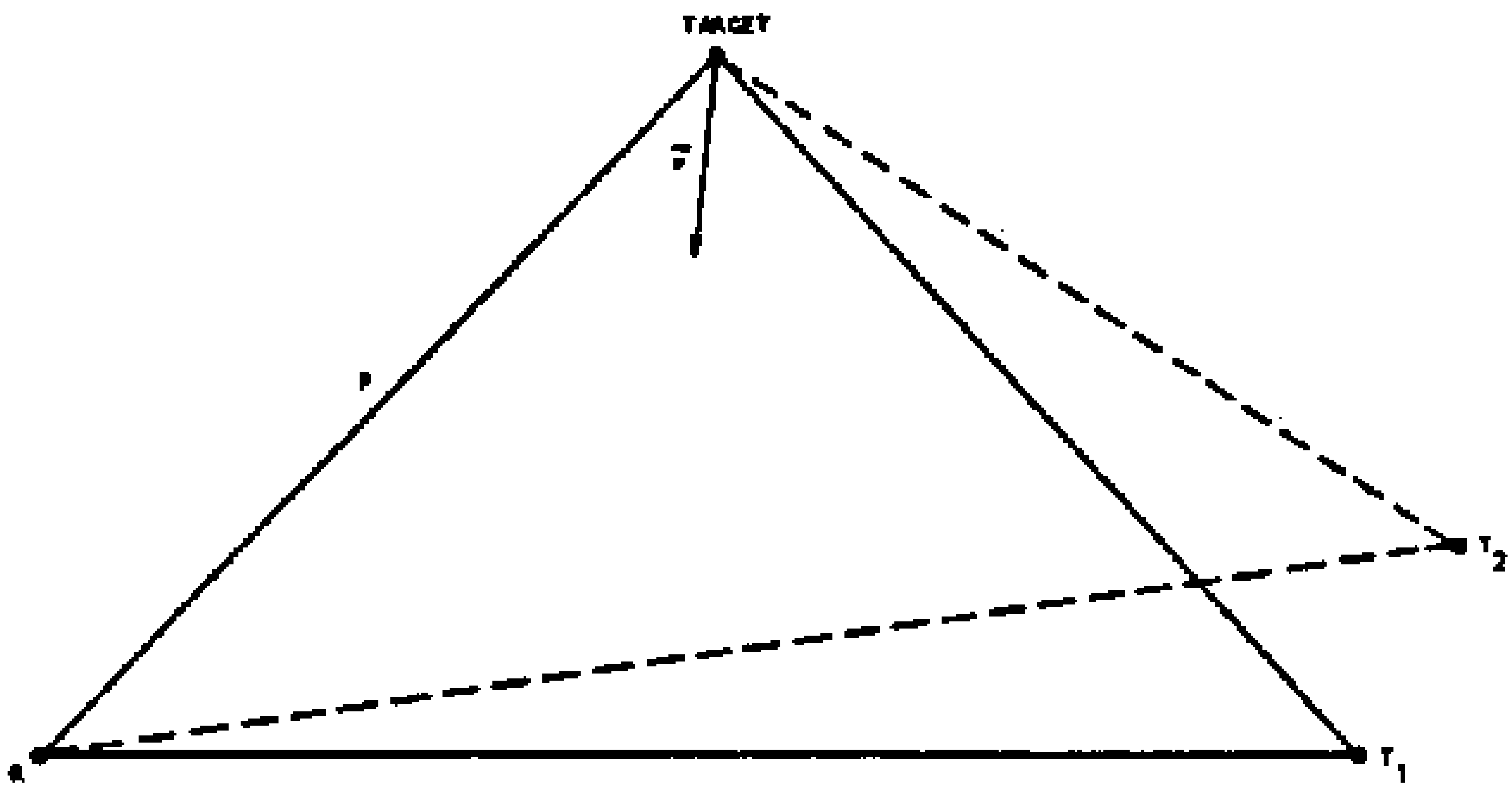

Figure 2. (U) Double-Baseline, One-Measurement Model. (U)

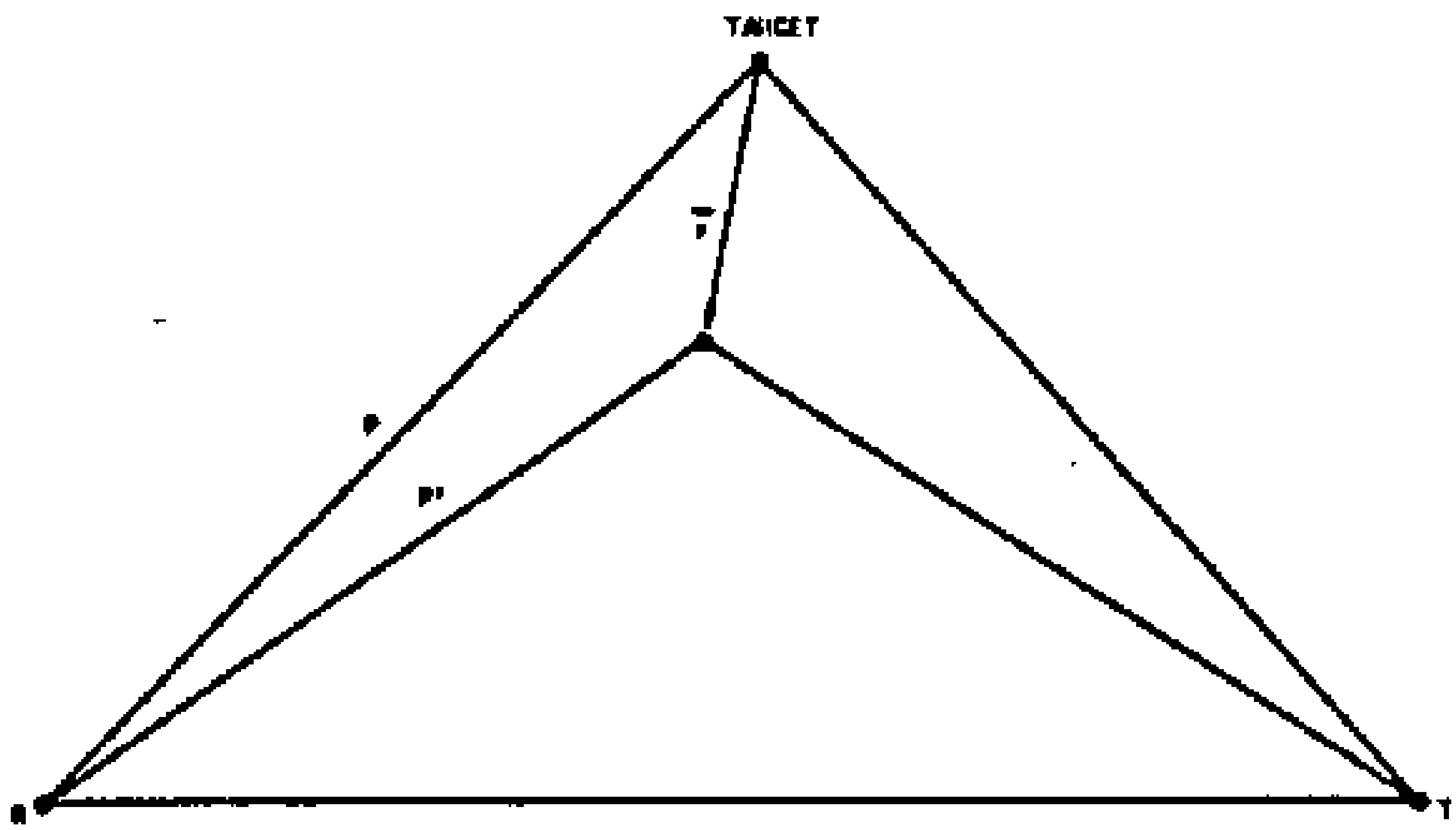

Figure 3. (U) Single Baseline Model. (U)

2.2 (U) --CONTINUED.

Of the three models, the single baseline case is the most desirable from an operational point of view because it requires monitoring only one transmitter. Of the double baseline models, the one-measurement case is the simplest and the easiest to implement. The following derivations describe how trajectory information may be obtained using each of these models. All models assume that the aircraft of interest has constant velocity and direction. Flat earth geometry is also assumed, a valid simplification for low flying targets.

2.2.1 (U) Double-Baseline, Two-Measurements Model.

Consider the single baseline, one time point situation shown in Figure 4, where a vehicle is moving at an unknown velocity $\hat{\upsilon}$, the distance between the transmitter and the receiver is assumed known to be D, and the transmitter is broadcasting on a known wavelength λ. The azimuth angle of the target at the receiver, σ, and the Doppler shift, Δf, are measured.

The received Doppler shift for this geometry may be written as

$$\Delta f = -\frac{\hat{\upsilon}}{\lambda}(\hat{r}_1 + \hat{r}_2)$$

$$= -\frac{\upsilon}{\lambda}(\cos\theta_1 + \cos\theta_2)$$

Angles θ_1 and θ_2 can also be written:

$$\theta_1 = 90 + \sigma + \delta$$

$$\theta_2 = 90 + \sigma - \delta$$

Therefore,

$$\Delta f = \frac{\upsilon}{\lambda}[\sin(\sigma + \delta) + \sin(\sigma - \delta)]$$

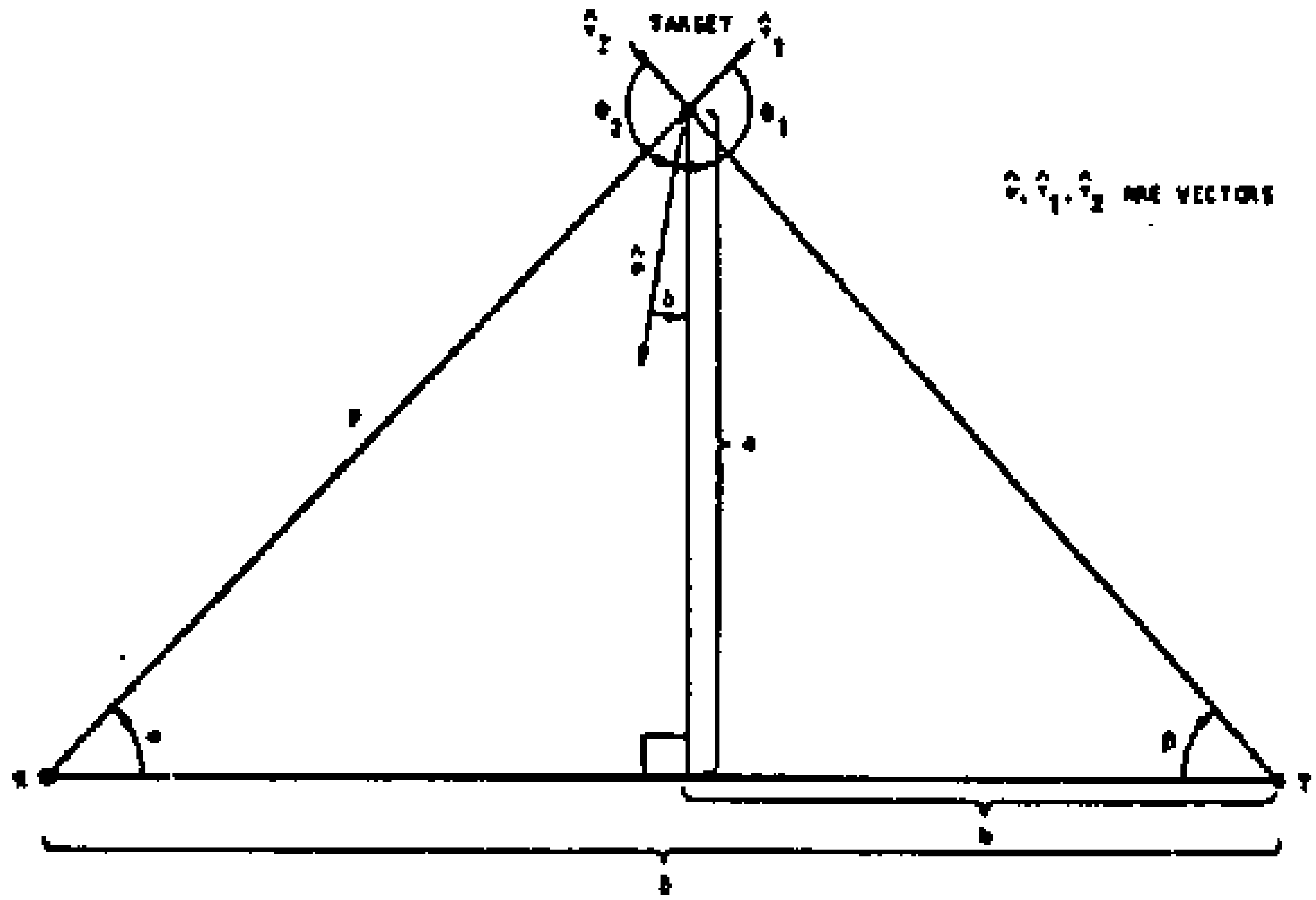

Figure 4. (U) Variables for Double-Baseline, Two-Measurements Model. (U)

2.2.1 (U) -Continued.

Also,

$$\beta = \tan^{-1}\left(\frac{a}{b}\right)$$

$$= \tan^{-1}\left[\frac{a}{D - \frac{a}{\tan\sigma}}\right] = \tan^{-1}\left[\frac{a\tan\sigma}{D\tan\sigma - a}\right]$$

If there are two transmitter geometries, which shall be distinguished using subscripts, then the following three equations can be written:

$$\Delta f_1 = \frac{v}{\lambda_1}\left\{\sin(\sigma_1+\delta_1) + \sin\left[\tan^{-1}\left(\frac{a_1\tan\sigma_1}{D_1\tan\sigma_1 - a_1}\right) - \delta_1\right]\right\} \quad (1)$$

$$\Delta f_2 = \frac{v}{\lambda_2}\left\{\sin(\sigma_2+\delta_2) + \sin\left[\tan^{-1}\left(\frac{a_2\tan\sigma_2}{D_2\tan\sigma_2 - a_2}\right) - \delta_2\right]\right\} \quad (2)$$

and

$$\delta_2 = \delta_1 + \epsilon \quad (3)$$

where ϵ is the angle between the two baselines, as shown in Figure 1. The value of ϵ may be calculated because the coordinates of the two transmitters and the receivers are assumed known.

If additional azimuth and Doppler measurements are made for these same two geometries at some time Δt later, then four more equations can be written. This set of equations is distinguished by a superscript prime.

$$\Delta f_1' = \frac{v}{\lambda_1}\left\{\sin(\sigma_1'+\delta_1) + \sin\left[\tan^{-1}\left(\frac{a_1'\tan\sigma_1'}{D_1\tan\sigma_1' - a_1'}\right) - \delta_1\right]\right\} \quad (4)$$

$$\Delta f_2' = \frac{v}{\lambda_2}\left\{\sin(\sigma_2'+\delta_2) + \sin\left[\tan^{-1}\left(\frac{a_2'\tan\sigma_2'}{D_2\tan\sigma_2' - a_2'}\right) - \delta_2\right]\right\} \quad (5)$$

2.2.1 (U) --Continued.

$$a_1' = a_1 - \upsilon \Delta t \cos \delta_1 \qquad (6)$$

$$a_2' = a_2 - \upsilon \Delta t \cos \delta_2 \qquad (7)$$

The last two equations are a result of the constant velocity and direction assumption. All seven equations can be combined into a system of four equations in four unknowns by eliminating δ_2 from the equations. The results are:

$$\Delta f_1 = F_1(\upsilon, a_1, \delta_1)$$

$$\Delta f_2 = F_2(\upsilon, a_2, \delta_1)$$

$$\Delta f_1' = F_3(\upsilon, a_1, \delta_1)$$

$$\Delta f_2' = F_4(\upsilon, a_2, \delta_1)$$

where the $F_i(\cdot)$ are different functions of the argument parameters.

The unknowns are υ, a_1, a_2 and δ_1. The measured quantities are σ_1, σ_2', σ_1', σ_2, Δf_1, $\Delta f_1'$, Δf_2, and $\Delta f_2'$. The quantities known a priori are D_1, D_2, λ_1, λ_2, Δt, and c. The above set of simultaneous equations may be solved for the unknowns and the ground range from the receiver to the target could be calculated by

$$p = \frac{a_1}{\sin \sigma_1}$$

Although this procedure yields four independent equations which may be solved for the target position, a slight reformulation of the problem can reduce the number of equations by two as described below.

2.2.2 (U) Double-Baseline, One-Measurement Model.

The variables for the double-baseline, one-measurement model are defined in Figure 5. As in the previous case, the transmitter-receiver distances, D_1 and D_2, and the transmitter wavelengths, λ_1 and λ_2, are assumed known a priori. The azimuths, α_1, and α_2, and Doppler shifts, Δf_1 and Δf_2, are the only quantities requiring measurement.

From another form of the Doppler equation,

$$\Delta f_1 = \frac{-1}{\lambda_1}(\dot{p} + \dot{n}_1)$$

$$\Delta f_2 = \frac{-1}{\lambda_2}(\dot{p} + \dot{n}_2)$$

where $\dot{p} = dp/dt$ and $\dot{n}_i = dn/dt$

From the law of cosines,

$$n_1 = (p^2 + D_1^2 - 2pD_1 \cos \alpha_1)^{1/2}$$

so

$$\dot{n}_1 = \frac{(p\dot{p} - \dot{p}D_1 \cos \alpha_1 + pD_1 \dot{\alpha}_1 \sin \alpha_1)}{(p^2 + D_1^2 - 2pD_1 \cos \alpha_1)^{1/2}} \tag{8}$$

where $\dot{\alpha}_1 = d\alpha_1/dt$

Similarly

$$\dot{n}_2 = \frac{(p\dot{p} - \dot{p}D_2 \cos \alpha_2 + pD_2 \dot{\alpha}_2 \sin \alpha_2)}{(p^2 + D_2^2 - 2pD_2 \cos \alpha_2)^{1/2}} \tag{9}$$

Note that $\dot{\alpha}_1 = \dot{\alpha}_2 = \dot{\alpha}$. The quantity $\dot{\alpha}$ can be estimated using the previous azimuth measurements as follows:

$$\dot{\alpha} = \frac{[\alpha_1(t) - \alpha_1(t-\Delta t)] + [\alpha_2(t) - \alpha_2(t-\Delta t)]}{2\Delta t}$$

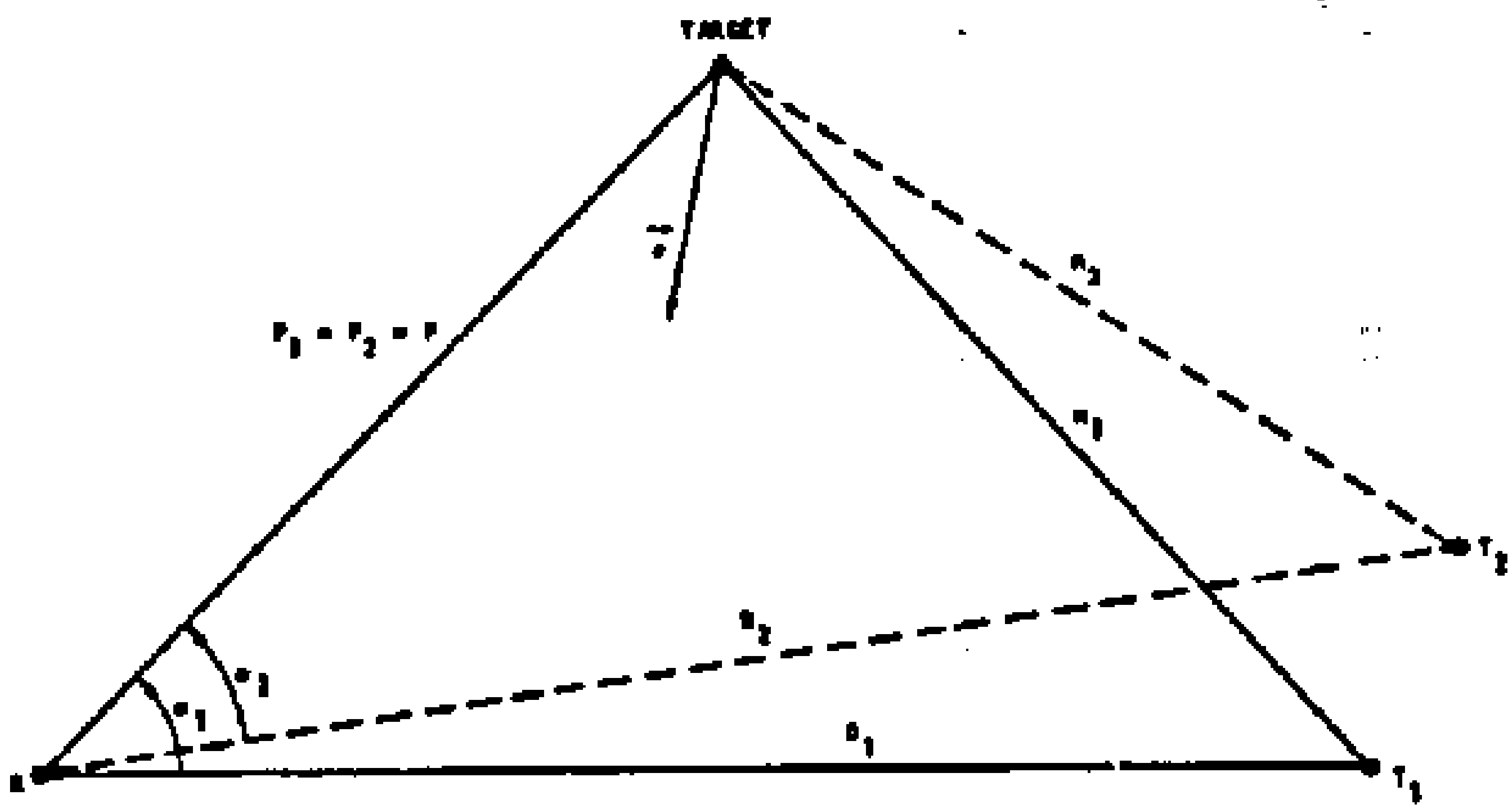

Figure 5. (U) Variables for Double-Baseline, One-Measurement Model. (U)

2.2.2 (U) --Continued.

Now define h_1, q_1, r_1, and s_1 as follows:

$$h_1 = (p^2 + D^2 - 2pD_1 \cos \alpha_1)^{1/2}$$

$$q_1 = \Delta f_1 \lambda_1$$

$$r_1 = D_1 \cos \alpha_1$$

$$s_1 = D_1 \dot{\alpha} \sin \alpha_1$$

The quantities h_2, q_2, r_2, and s_2 are similarly defined. Equations (8) and (9) can then be written as

$$\dot{h}_1 = \frac{p\dot{p} - \dot{p} r_1 + ps_1}{h_1}$$

$$\dot{h}_2 = \frac{p\dot{p} - \dot{p} r_2 + ps_2}{h_2}$$

So Δf_1 can be written

$$\Delta f_1 = \frac{-1}{\lambda_1} \left[\dot{p} + \frac{\dot{p}(p-r_1) + ps_1}{h_1}\right]$$

Similarly

$$\Delta f_2 = \frac{-1}{\lambda_2} \left[\dot{p} + \frac{\dot{p}(p-r_2) + ps_2}{h_2}\right]$$

Solving for $\dot{p}$,

$$\dot{p} = -\frac{(q_2 h_2 + ps_2)}{(h_2 + p - r_2)} \qquad (10)$$

2.2.2 (U) --Continued.

Also,

$$-q_1 \dot{h}_1 = \dot{p}\, h_1 + \dot{p}\,(p - r_1) + p\, s_1$$

and so

$$p = \frac{-\{q_1 \dot{h}_1 + \dot{h}\,(h_1 - r_2)\}}{s_1 + \dot{p}} \qquad (11)$$

Equations (10) and (11) form a system of two equations in two unknowns (p and $\dot{p}$) that may be solved using standard iterative techniques. Note also that, for this formulation, the assumption of constant velocity and direction are not necessary.

2.2.3 (U) Single Baseline Model.

The final derivation to be considered is that involving the model using only one transmitter. The variables for the single baseline model are defined in Figure 6. As before, the transmitter-receivcr distance, D, and the transmitter wavelength, λ, are assumed known. The azimuths, α and α', and Doppler shifts Δf and $\Delta f'$, are measured quantities where the primes signify measurement at some time Δt after the first (unprimed) measurements. The velocity, υ, of the vehicle is not known.

From the Doppler equation,

$$f = \frac{-1}{\lambda}\,(\dot{p} + \dot{n})$$

$$f' = \frac{-1}{\lambda}\,(\dot{p}' + \dot{n}')$$

From the law of cosines,

$$n = (p^2 + D^2 - 2pD\cos\alpha)^{1/2}$$

$$\dot{n} = \frac{(p\,\dot{p} - \dot{p}\,D\cos\alpha + pD\,\dot{\alpha}\sin\alpha)}{(p^2 + D^2 - 2pD\cos\alpha)^{1/2}}$$

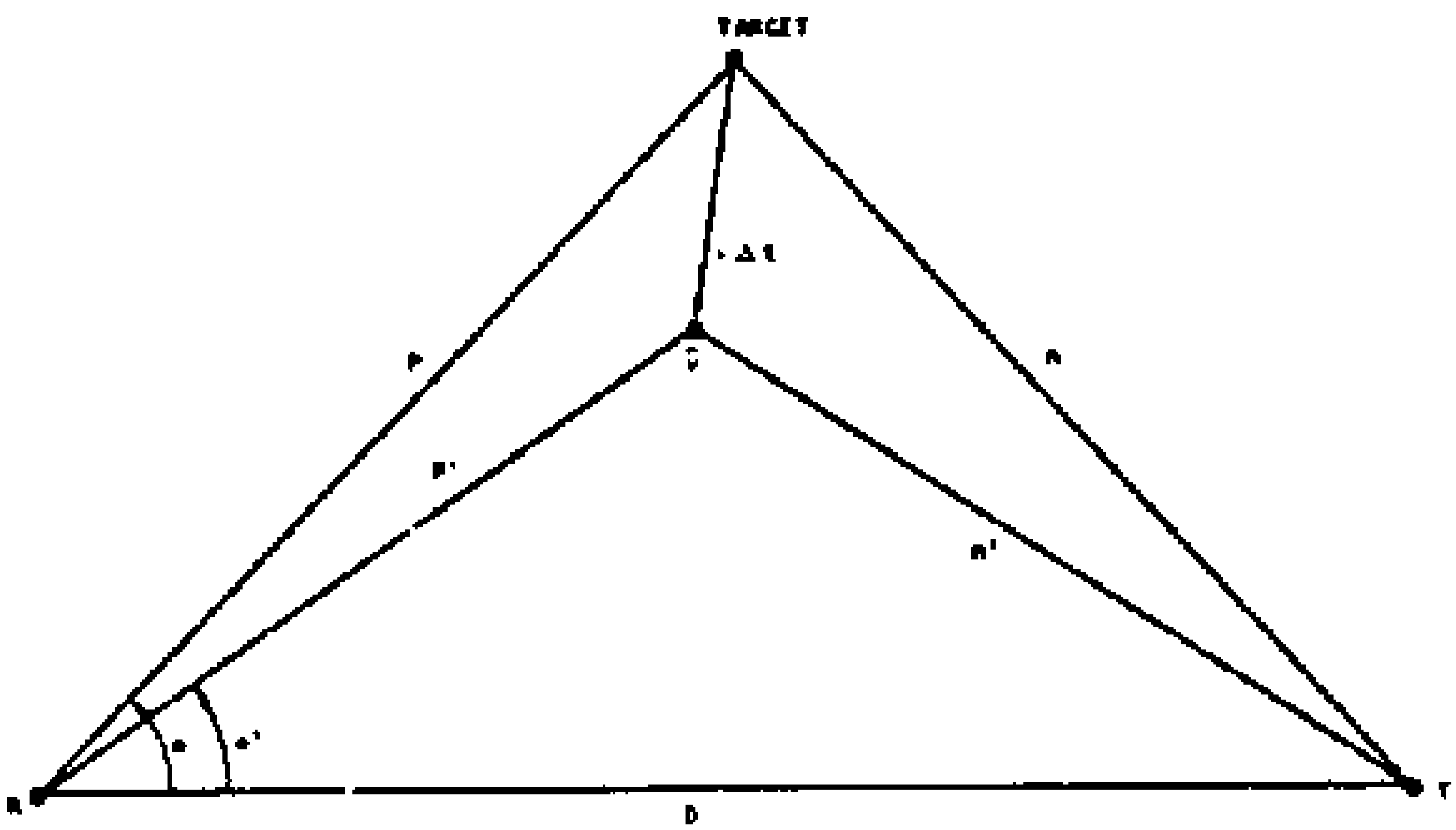

Figure 6. (U) Variables for Single Baseline Model. (U)

2.2.3 (U) --Continued.

Similarly,

$$h' = \frac{(p'\dot{p}' - \dot{p}' D \cos \alpha' + p' D \dot{\alpha}' \sin \alpha')}{(p'^2 + D^2 - 2p' D \cos \alpha')^{1/2}}$$

In order to find a solution using only one baseline, two approximations have to be made

(a) $\dot{p}$ is constant; i.e., $\dot{p}' = \dot{p}$ and, furthermore,

$$p = p' - \dot{p}\,\Delta t$$

(b) $\dot{\alpha}$ is constant: i.e., $\dot{\alpha}' = \dot{\alpha}$

Over short time intervals (small Δt) these assumptions are reasonable. The angular velocity $\dot{\alpha}$ can be estimated as follows:

$$\dot{\alpha} = \frac{\alpha' - \alpha}{\Delta t}$$

These approximations are strictly true if the target is flying on a radial path, toward or away from the ship.

Combining the equations and approximations above gives

$$-\Delta f\lambda = -q = \dot{p} + \frac{\dot{p}(p-r) + ps}{h}$$

where

$$q = \Delta f\lambda$$

$$r = D \cos \alpha$$

$$s = D \dot{\alpha} \sin \alpha$$

$$h = (p^2 + D^2 - 2pD \cos \alpha)^{1/2}$$

2.2.3 (U) --Continued.

Substituting $p = p' - \dot{p}\Delta t$, squaring to eliminate square roots and algebraic manipulation of the results yields the cubic equation

$$A\dot{p}^3 + B\dot{p}^2 - C\dot{p} + D = 0 \tag{12}$$

where

$$A = 2\Delta t^2 (q-s)$$

$$B = \Delta t^2 (q^2-s^2) + \Delta t (4qr-4qp') + 2s\Delta t (2p'-r) + D^2 - r^2$$

$$C = \Delta t (2q^2r-2q^2 p'+2p's^2) + 2p'^2 (q-s) + 2p'r (s-2q) + 2qD^2$$

$$D = p'^2 (q^2-s^2) + q^2 (D^2-2p'r)$$

This cubic equation can be solved for $\dot{p}$ and the correct root chosen. Also note that $\dot{p}$ is still a function of the single unknown p'.

In similar fashion,

$$\Delta f' = \frac{-1}{\lambda} (\dot{p}' + \dot{h}')$$

or

$$-\Delta f\lambda = -q' = \dot{p} + \frac{\dot{p}(p'-r') + p's'}{h'}$$

Where h', q', r' and s' are defined similarly to h, q, r and s.

Now

$$-q'h' - \dot{p}(h'-r') = p'(\dot{p} + s')$$

or

$$p' = \frac{-q'h' - \dot{p}(h'-r')}{\dot{p} s'} \tag{13}$$

Equations (12) and (13) form a set of simultaneous equations in the two unknowns p' and $\dot{p}$ which may be solved for the target position.

Software simulations have been written to estimate the target location accuracy to be expected by using these techniques. The results of these simulations are discussed in the next section.

Section 3

SIMULATION AND MODEL TESTING

3.1 (U) MODELS SIMULATED.

The results of simulations of realistic trajectory estimation situations are detailed below for the double-baseline, one-measurement model and the single baseline model. The double-baseline, two-measurement model was not simulated.

3.2 (U) DOUBLE-BASELINE, ONE-MEASUREMENT MODEL.

An algorithm was developed for solving sets of nonlinear simultaneous equations such as equations (10) and (11) in Section 2. The algorithm is based on a standard iterative procedure for solving equations of the form $p = f(p)$ (see, for example, Introductory Computer Methods and Numerical Analysis, by Ralph H. Pennington, The MacMillan Co., 1965). This procedure consists of estimating a solution p_0 and using this estimate to get a new estimate p_1, where $p_1 = f(p_0)$. A new estimate p_2 is obtained from $p_2 = f(p_1)$, and so on until $|p_n - p_{n-1}| < \epsilon$, where ϵ is some small number. At this point the process is judged to have converged with a solution $p = p_n$. In practice, each successive p_i is transformed slightly so as to guarantee convergence.

Graphically, this technique amounts to finding the intersection of the plots of $y_1 = f(p)$ and $y_2 = p$. The point of intersection is where the algorithm converges. In actual practice, there may be more than one intersection. However, the correct root may be determined by examining the sign of $\dot{p}$ and the trend of the previous values of p.

3.2.1 (U) The Simulation.

The situation simulated is that of a ship in the Mediterrenean sea at 37°N., 25°E, and an aircraft at a range of 180 kilometers, due north, flying at 720 km/hour (about Mach 0.66). Two cases are considered as shown in Figure 7. In the first case the aircraft is merely flying at a 30° angle by the ship, whereas in the second case it is on an attack course, heading straight for the ship. In both cases, the speed and direction of the aircraft are constant. The transmitters are assumed to be located at Rhodes and Athens.

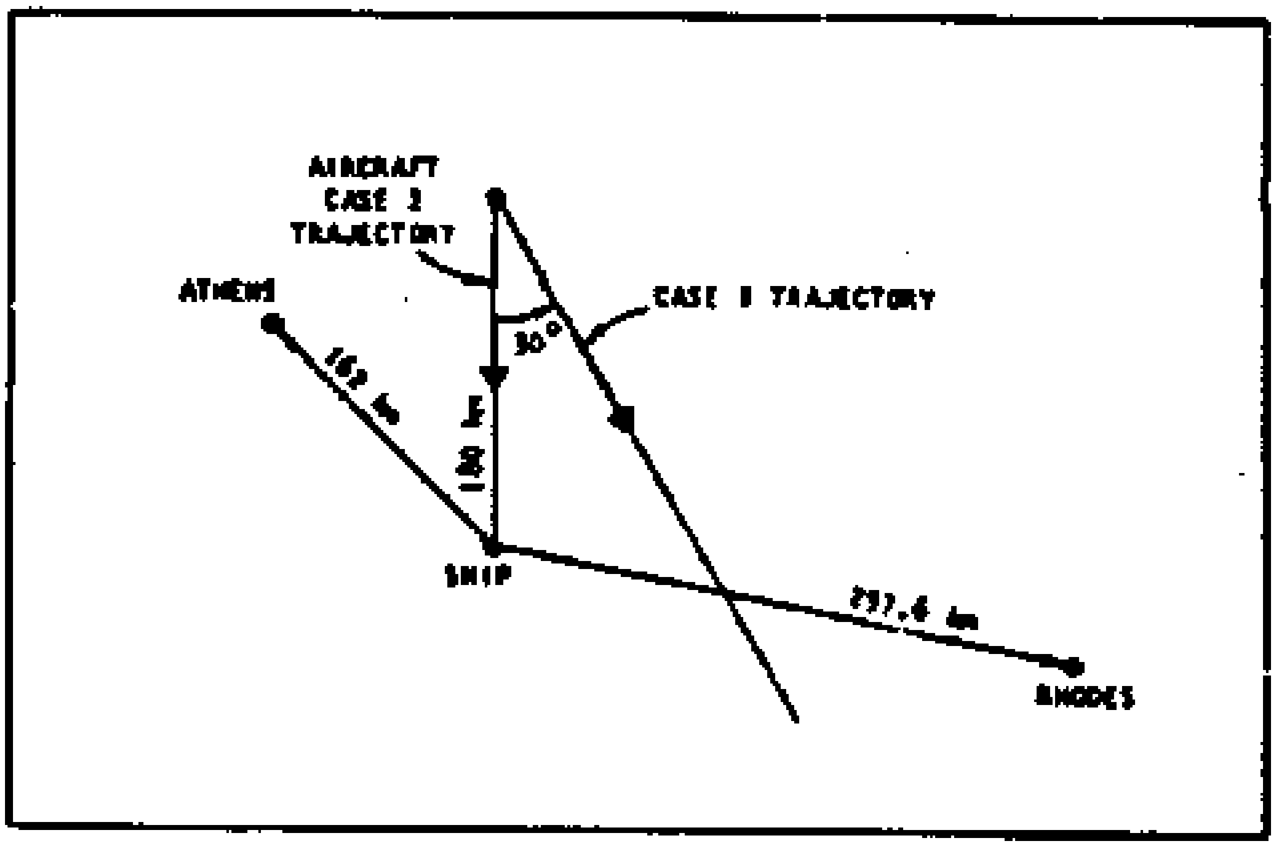

Figure 7. (U) Geometry of Situation Being Simulated. (U)

3.2.2 (U) Simulation Results for Double Baseline Model.

The results of the two simulations are presented in Tables 1 and 2. These tables give the actual and estimated range, ρ, and the actual and estimated derivative of range, $\dot{\rho}$, at intervals of 60 seconds for the two cases.

TABLE 1. (U) ACTUAL AND ESTIMATED QUANTITIES FOR CASE 1. (U)

Time (seconds)	α_1 (degrees)	α_2 (degrees)	Range, ρ (km)	Estimated (km)	$\dot{\rho}$ (km/sec)	Estimated (km/sec)
0	100.9	44.6	180.0			
60	98.9	42.6	169.7	170.2	-.169	-.171
120	96.6	40.3	159.7	160.2	-.165	-.166
180	94.0	37.7	149.9	150.4	-.160	-.161
240	91.1	34.8	140.5	141.0	-.154	-.155
300	87.7	31.4	131.5	132.1	-.146	-.147
360	83.9	37.6	123.0	123.6	-.136	-.138
420	79.5	23.2	115.2	115.7	-.125	-.127
480	74.5	18.2	108.1	108.7	-.111	-.112
540	68.9	12.6	101.9	102.5	-.094	-.096
600	62.6	6.3	96.9	97.4	-.074	-.083
660	55.8	-0.5	93.1	92.6	-.051	-.025
720	48.4	-7.9	90.8	91.1	-.026	-.056
780	40.8	-15.5	90.0	90.0	+.000	-.001
840	33.2	-23.1	90.8	90.5	+.027	+.026
900	25.9	-30.4	93.2	92.5	+.052	+.052
960	19.0	-37.3	97.0	96.0	+.074	+.075
1020	12.8	-43.5	102.0	100.7	+.094	+.095
1080	7.2	-49.1	108.2	106.7	+.111	+.111
1140	2.2	-54.1	115.3	113.8	+.125	+.125
1200	-2.2	-58.5	123.2	121.6	+.137	+.136
1260	-6.0	-62.3	131.7	130.2	+.146	+.146
1320	-9.3	-65.6	140.7	139.3	+.154	+.153
1380	-12.2	-68.6	150.1	148.9	+.160	+.160
1440	-14.8	-71.1	160.0	158.7	+.165	+.165
1550	-17.1	-73.4	170.0	169.0	+.170	+.169

TABLE 2. (U) ACTUAL AND ESTIMATED QUANTITIES FOR CASE 2. (U)

Time (seconds)	α_1 (degrees)	α_2 (degrees)	Range, ρ (km)	Estimated (km)	$\dot{\rho}$ (km/sec)	Estimated $\dot{\rho}$ (km/sec)
0	100.9	44.6	180.0			
60	100.9	44.6	168.0	168.0	-0.200	-0.200
120	100.9	44.6	156.0	156.0	-0.200	-0.200
180	100.9	44.6	144.0	144.0	-0.200	-0.200
240	100.9	44.6	132.0	132.0	-0.200	-0.200
300	100.9	44.6	120.0	120.0	-0.200	-0.200
360	100.9	44.6	108.0	108.0	-0.200	-0.200
420	100.9	44.6	96.0	96.0	-0.200	-0.200
480	100.9	44.6	84.0	84.0	-0.200	-0.200
540	100.9	44.6	72.0	72.0	-0.200	-0.200
600	100.9	44.6	60.0	60.0	-0.200	-0.201
660	100.9	44.6	48.0	48.0	-0.200	-0.201
720	100.9	44.6	36.0	36.0	-0.200	-0.201
780	100.9	44.6	24.0	24.0	-0.200	-0.202
840	100.9	44.6	12.0	12.0	-0.200	-0.202
900	100.0	44.6	0.0	0.0	-0.200	-0.202

3.2.2 (U) --Continued.

The most accurate results were obtained for case 2, the attack case. For case 1, the fly-by, errors in the range estimate are on the order of 0.5 to 1.0 kilometers. The reasons for these differences are discussed below.

3.2.3 (U) Sources of Error.

The sources of error include the linear estimate of rate of change of azimuth ($\dot{\alpha}$) and measurements of azimuth and Doppler frequency. Of these, the main source of error in determining the range is that due to $\dot{\alpha}$, given in Section 2. For example, in case 1 at 400 seconds the estimated value of $\dot{\alpha}$ is 1.271×10^{-2} radians/second, while the actual value is 1.300×10^{-3} radians/second. Using the estimated value of $\dot{\alpha}$, a solution of ρ = 118.28 km was obtained. Using the correct value of $\dot{\alpha}$, however, yielded a solution ρ = 117.51 km. The actual solution is ρ = 117.72 km.

3.2.3 (U) --Continued.

For some situations, a plot of $y = f(P)$ shows that it is very close to the function $y=p$ for a wide range of p. In this range, the small errors in $f(p)$ caused by the small errors in estimating $\dot{\alpha}$ produce drastic differences in where the two curves intersect, and hence produce errors in the range estimate. Normally, however, the set of conditions that would produce this problem occurs only for targets outside the detection range and would not affect a practical trajectory determination scheme.

It is now apparent why the trajectory estimation for case 2 was more accurate than for case 1; in case 2 the azimuth is constant, hence $\dot{\alpha} = 0$ and errors due to estimating $\dot{\alpha}$ disappear. It follows that it is during the most critical situations that the greatest accuracy can be expected.

3.2.4 (U) Sensitivity to Measurement Error.

During the simulations discussed above, it was assumed that the azimuth and Doppler measurements were exact. During normal operation in a shipboard environment great accuracy is not possible. To test the sensitivity of the model to measurement errors, range estimates were obtained for various combinations of errors in measuring azimuth angles α_1, and α_2, and Doppler shifts Δf_1 and Δf_2. The measurement errors and the corresponding range estimate are tabulated in Table 3. The estimates were made at time = 400 seconds in case 1.

The errors in measuring Δf_1 and Δf_2 have the least effect on the range estimate. The percentage error in the range estimate is about the same as the percentage error in these measurements. However, the errors in measuring azimuth have much greater effect. Here the errors in the range estimates are considerable. This is mainly due to the azimuth errors yielding very inaccurate $\dot{\alpha}$ estimates, which has the effect noted in the previous section. The subject of measurement error and error sensitivity needs further investigation.

3.2.5 (U) Single Baseline Model.

Simulations of the two cases described in 3.2.1 were also done using the single baseline model. The model failed to give good range estimates in nearly every situation. The probable reason for this is error introduced by the assumption of constant $\dot{\beta}$ and $\dot{\alpha}$ over the interval Δt. At the present time it is not clear whether or not the single baseline model is practical. However, further simulations using this technique will be investigated.

TABLE 3. (U) ESTIMATED RANGE WITH MEASUREMENT ERROR (CASE 1). (U)

Error in α_1 (degrees)	Error in α_2 (degrees)	Error in Δf_1 (Hertz)	Error in Δf_2 (Hertz)	Actual ρ (km)	Estimated ρ (km)
0.0	0.0	0.0	0.0	117.2	118.3
0.0	0.0	0.0	0.2	117.2	122.2
0.0	0.0	0.0	-0.2	117.2	114.7
0.0	0.0	-0.2	0.0	117.2	120.2
0.0	0.0	0.2	0.0	117.2	116.6
0.0	0.0	-0.2	0.2	117.2	124.1
0.0	0.0	0.2	-0.2	117.2	112.8
2.0	0.0	0.0	0.0	117.2	136.5
-2.0	0.0	0.0	0.0	117.2	102.3
0.0	-2.0	0.0	0.0	117.2	106.2
0.0	2.0	0.0	0.0	117.2	131.9
2.0	-2.0	0.0	0.0	117.2	122.6
-2.0	2.0	0.0	0.0	117.2	113.8
2.0	-2.0	-0.2	0.2	117.2	127.9
-2.0	2.0	0.2	-0.2	117.2	107.9

NOTE:

Exact α_1 = 82.49°

Exact α_2 = 26.19°

Exact Δf_1 = 6.174 Hz

Exact Δf_2 = 4.636 Hz

Time = 400 seconds

3.2.6 (U) Summary and Conclusions.

In summary, the double-baseline, one-measurement model yielded reasonably accurate trajectory estimates for two different simulations. The model was found to be more accurate when the azimuth was not changing ($\dot{\alpha} = 0$). It is much more sensitive to azimuth measurement error than it is to Doppler-shift measurement error. Since azimuth measurement is likely to be a difficult task in a practical implementation of this technique, investigation of ways to minimize the effect of azimuth errors should be initiated. This model should be tested further to uncover any undetected difficulties.

3.2.6 (U) --Continued.

At the present time the single baseline model has not been shown to be feasible. The double-baseline, two-measurement model has not been tested.

Section 4

DETECTION SYSTEM

4.1 (U) ~~(S)~~ GENERAL SYSTEM CONSIDERATIONS.

The analysis and simulation results discussed in Sections 2 and 3 were developed with the implicit assumption that the hardware to provide the necessary azimuth and Doppler measurements could be made available. In fact, an HF prototype system for tracking low-flying targets at distances beyond radar line of sight can be built with available hardware. The item of greatest concern in implementing such a system is the difficulty of building an accurate shipboard HF direction finding system. The following subsections describe the techniques and hardware that could be used to implement the system.

4.2 (U) ~~(S)~~ DOPPLER MEASUREMENT.

Precise target Doppler measurements (within 0.1 Hz) have long been made by both R&D and operational over-the-horizon (OTH) radar systems. A block diagram of a typical single channel receiving and data processing system is illustrated in Figure 8. Digitally tuned, synthesizer controlled receivers are preferred for their frequency stability. Each receiver output would be digitally spectrum analyzed with 0.1 Hz resolution with approximately a 50 Hz bandwidth to cover the maximum expected target Doppler shift. The Doppler shift would be displayed on a hard copy fax in the standard time-frequency-intensity format. The Doppler shift as measured from the direct path carrier could be scaled manually by the operator or scaled digitally for direct computer input using a x-y digitizing arm.

4.3 (U) SHIPBORNE DF CONSIDERATIONS.

Direction finding (DF) from a shipborne platform involves many of the problems encountered by shore based DF systems such as dense signal environment, multimode effects, and reradiation from nearby obstacles. It is also constrained by the practical size of HF DF antenna arrays that can be employed. The signal environment varies according to radio frequency (RF) band of operation and geographical location of the platform. For operations in the middle of the Atlantic and Pacific oceans

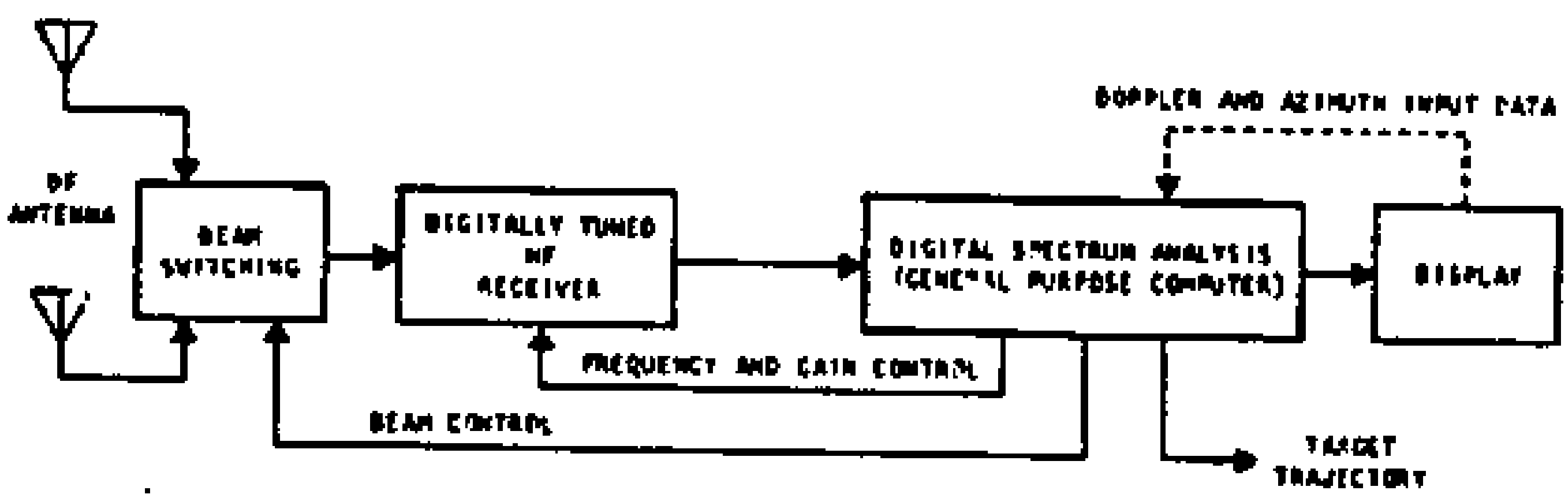

Figure 8. (U) A Typical Single-Channel Receiving and Processing System. (U)

4.3 (U) -- Continued.

a dense signal environment may not exist. However, for DF operation in the Mediterranean and near urban regions this problem area can become severe. Narrow bandwidths (e.g., 300-3000 Hz) can be used on DF receivers to minimize this problem. In addition, azimuth and elevation discrimination can be employed in the antenna system design to extract the DF information from the signal of interest in a dense environment.

The multimode effect can become a problem when a skywave as well as surface wave of approximately equal amplitude impinges on the DF system. Because of the phase shift due to the difference in path lengths, reinforcement and cancellation of signals occur that will make DF measurements difficult for any HF DF array. Because the signal reflected from the target is expected to be principally a surface wave, its greater amplitude will help to minimize any multimode effects.

The most severe problem of shipborne DF systems is that due to the reradiation of an incoming wave from the various superstructure elements. Many solutions have been attempted but most seem to be unsatisfactory because of the constraints and requirements placed on a shipborne DF system. These constraints are concerned with --

(a) the size of the antenna array and

(b) the location/space for DF system components

The size of the HF DF array is limited by the dimensions of the ship. Because the principal dimension (length) is on the order of 400 feet (destroyer class ship) and much of this length is not available for a DF system, a wide aperture HF DF antenna array (greater than 200 feet) is not generally feasible. The conventional wide-aperture antenna system has the dual advantage of achieving a high signal-to-noise ratio (from the gain of the antenna array) and high DF resolution (from the directivity of the array). Such a system has the additional advantage that a certain amount of reradiation rejection is possible from the directivity of the array. The size constraint of shipborne arrays prevents these advantages from being realized. One alternative is to employ a narrow aperture system. For this approach, which is very susceptible to reradiation effects, a location on the top of a mast away from superstructure elements is required. However, the premium for mast and topside space make this alternative infeasible in most cases.

4.3 (U) --Continued.

The requirements that must be met for shipborne HF DF systems vary according to application but generally may be stated as shown in Table 4. Many of the existing and proposed systems meet the majority of these requirements. The principal requirements that are difficult to completely satisfy are the DF accuracy and the azimuth and elevation coverages. This is due to the reradiation effects that cause DF errors as described above for both amplitude and phase comparison systems.

To date only two approaches appear promising for satisfying the shipborne DF requirements. These are:

(a) the multiple-baseline/pattern-recognition (MB/PR) system and

(b) the switched linear array Doppler (SLAD) direction finding system.

The characteristics of these two systems and their applicability to the early warning (EW) problem are described below. The references in footnotes 1 and 2 below contain more detailed descriptions of the systems.

4.3.1 (U) Multiple Baseline/Pattern Recognition System.

The multiple baseline/pattern recognition (MB/PR) system was initially suggested by D. Marx at Naval Electronic Laboratory Center (NELC) and employs an array of antenna elements distributed around the ship. The phase difference between pairs of elements is measured to form an input or signal vector. This vector is compared against a calibration matrix to determine the direction of arrival of the incoming signal. Model measurements were made by NELC for an HF system consisting of 15 antenna elements.[3] These measurements have been analyzed using the MB/PR approach. The results indicate that, for low angle (85.5° from zenith) signals, root-mean-square (RMS) accuracies of better than 3.3° are obtainable. For skywave signals unacceptable accuracies (greater than 10°) resulted. For the surface-wave mode, for which the polarization is essentially vertical, the RMS accuracy improves to 1.8° (or less). For low-flying target detection applications

1 K. E. Spencer, S. N. Watkins, J. Greisser, A Study of the Switched Linear Array Doppler Direction-Finding System, SES-WD M1372, November 1970. (UNCLASSIFIED publication).

2 C. Cornwell, Shipboard HF DF Final Report, SES-WD G-942, January 1971. (UNCLASSIFIED publication).

3 NELC Technical Document No. 72.

Table 4. (U) GENERAL REQUIREMENTS FOR A SHIPBORNE HF DF SYSTEM. (U)

Parameter	Specification
Maximum dimension	150 feet
System location	on deck
DF accuracy	4 degrees RMS or better
System sensitivity	8-10 μV/m
Azimuth coverage	360°
Elevation coverage	70° (above horizon)
Dependence on signal characteristics	independent of modulation and multiple signals

4.3.1 (U) -- Continued.

where the primary propagation mode is a surface wave the MB/PR approach appears to be promising in terms of satisfying the DF accuracy requirement and overcoming the reradiation problem aboard ships.

4.3.2 (U) Switched Linear Array Doppler (SLAD) Direction Finding System.

The switched linear array Doppler (SLAD) direction finding system is a method of determining the direction of arrival of a signal by processing the outputs of two simulated orthogonal moving antennas and a reference antenna. The simulated movement in each direction is accomplished by rapid switching between elements of a linear array. The azimuthal and elevation angles of arrival can be determined from the Doppler frequencies measured along the two orthogonal axes. This approach provides a method of overcoming the reradiation problems aboard ships as well as providing elevation angle-of-arrival information. A worst-case analysis of the DF accuracy was de by Spencer, Watkins and Greiser[4] by considering the reradiation due .o a resonant mast. The azimuthal angle errors were determined to be 16.3 degrees RMS at 4 MHz and 4.3 degrees RMS at 8 MHz for a CW signal.

To employ this approach for a target Doppler signal (i.e., a signal source whose frequency changes with time) the frequency of the target signal at the times the Doppler measurements are made must be separately obtained (e.g., from the reference antenna). These measurements then can be processed in a manner similar to that for a CW source.

4.4 (U) COMPARISON OF MB/PR AND SLAD SYSTEMS.

The MB/PR technique has the potential to provide much better DF accuracy than the SLAD approach for surface waves. However, the MB/PR method does not perform well against skywave si.:als and does not provide elevation angle-of-arrival information. The storage requirements of MB/PR processing are more severe than the SLAD technique because of the size of the calibration matrix. In contrast, the SLAD approach provides the capability to use skywave information and does determine elevation angle of arrival. However, because of its comparatively poor DF accuracy it does not meet the general DF requirements.

4 Op. cit.

4.4 (U) -- Continued.

Both approaches should be investigated in more detail before one method is selected over the other for a specific application. The MB/PR technique is expected to be tested using data from an experimental shipborne DF antenna array. A demonstration of this technique is expected to occur sooner than one for the SLAD technique.

END

DATE FILMED

3-71

[redacted]

PLEASE DO NOT RETURN THIS DOCUMENT TO DTIC

EACH ACTIVITY IS RESPONSIBLE FOR DESTRUCTION OF THIS DOCUMENT ACCORDING TO APPLICABLE REGULATIONS.

[redacted]