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APPLICATION OF SPATIAL DIVERSITY FOR JOG
DETECTION IN THE PRESENCE OF MULTIPATH EFFECTS

by

Keith R. Doucet, B.Eng.

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of

Master of Engineering

Ottawa-Carleton Institute of Electrical Engineering
Department of Electronics
Carleton University
Ottawa, Canada
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ABSTRACT

This thesis describes a new approach for achieving jog detection in the presence of maritime multipath effects. Propagation trials over the Ottawa River were performed, which involved flying a helicopter, equipped with a beacon source, towards a receiver located at DND's low angle tracking facility at Shirley's bay. The data collected was analyzed to determine the extent of the multipath/jog ambiguity problem, and to identify unique characteristics between the two phenomena which could be used to establish a jog detection criterion. An algorithm, based on spatial diversity, was developed and tested, and the results indicate that it is an effective means of distinguishing between 'smooth surface' multipath and jog fades. To test this technique against typical rough sea scattering, not obtainable from the river trials, a relatively detailed software model was developed. Simulation results indicate that the spatial diversity technique may also be effective against certain rough sea disturbances.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

$\langle \rangle$	Mean value
β	Angle of Facet for Diffuse Multipath
β_o	Maximum Angle for Diffuse Multipath Contributions
Γ_h	Horizontal Fresnel reflection coefficient
Γ_v	Vertical Fresnel reflection coefficient
$\gamma[i]$	Angle between mean surface perpendicular and R_{r2}
Δ	Difference Channel of monopulse antenna
ϵ	Permittivity of the medium
ϵ_0	Permittivity of free space
ϵ_c	Complex permittivity
ζ	Total phase of the reflected signal
ζ'_1	Angle between ship and reflection point at earth's center
ζ_2	Angle between reflection point and transmitter at earth's center
η	Angle between R_{r2} and perpendicular to mean surface
η_r	Angle between R_{r1} and perpendicular to mean surface
$\Im$	Imaginary part
θ	Angle between R_r and tangent plane
θ_p	Angle between R_{r1} and HR
θ_r	Angle between $R_d[1]$ and R_{r1}
θ_s	Angle between the i^{th} horn and first horn from the transmitter
λ	Signal wavelength
θ_r	Angle between receive antenna boresight and R_d
$\Re$	Real Part
ρ	Magnitude of Fresnel reflection coefficient
ρ_d	Diffuse scattering coefficient
ρ_s	Specular scattering coefficient
σ	rms height of the sea
Σ	Sum channel of monopulse antenna
σ^o	Scattering Coefficient

σ_s	rms slope of small surface facets over the sea
ϕ	Angle between tangent plane and perpendicular to mean surface
ϕ_r	Phase of the reflection coefficient
ψ	Grazing angle
μ	Permeability
A_e	Radius of the earth
$C(r)$	Autocorrelation function
D	Directivity
D_v	Divergence factor
d_c	Autocorrelation distance
e	Partial pressure of water vapor, mbar
F_d	Roughness factor
h	Difference in height of surface irregularities
H_e	Height of receiver antenna
$HE[i]$	Height of the i^{th} receive horn relative to the mean surface
H_r	Height of radar
H_t	Height of transmitter
I	In-phase
k	Propagation constant
n	Index of refraction
N	Refractivity
p	Barometric pressure, mbar
Q	Quadrature-phase
R	Range of transmitter relative to ship
R_d	Direct path between transmitter and receiver
R_N	Range of sampling window relative to ship
R_{r1}, R_1	Path between transmitter and reflection point
R_{r2}, R_2	Path between reflection point and receiver
R_t	Range between transmitter and receiver
Rx	Receiver
S	Siemens
$S(t)$	Signal level at time t
Sc	Shadowing coefficient
S_{decav}	Decay rate of signal due to a jog
T	Absolute temperature, Kelvin
T_s	Sample period of receiver

T_x	Transmitter
v_h	Instantaneous angular velocity
v_m	Radial velocity of the transmitter
V_t	Threshold voltage for the jog detector
$\perp A_c$	Perpendicular line to the mean surface

ABBREVIATIONS

A/D	Analog to Digital
AGC	Automatic Gain Control
AI	Air Intercept
CW	Continuous Wave
dB	decibels
DND	Department of National Defence
ECM	Electronic Countermeasures
ELAT	Experimental Low Angle Tracking
EM	Electromagnetic
GHz	Gigahertz
GTD	Geometrical Theory of Diffraction
HPBW	Half Power Beamwidth
Hz	Hertz
IF	Intermediate Frequency
MP	Multipath
LOS	Line of Sight
PRI	Pulse Repetition Interval
PW	Pulse Width
RF	Radio Frequency
rms	Root Mean Square

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Multipath can degrade the performance of shipborne Electronic Countermeasure (ECM) systems equipped with jog detection [1]. ECM is used to protect the ship against approaching missiles by transmitting electromagnetic jamming signals directly at the missile radar so that its range and angle tracking are disturbed sufficiently to prevent the missile from intercepting the ship. In general, the ECM system may sequentially apply various jamming techniques until it hits upon one which is effective in producing angle deflections (or jogs) in the radar antenna of the missile seeker. To detect these angle deflections or jogs, the ECM receiver looks for a sudden drop in the strength of the incoming radar signal.

Since maritime missiles typically fly at low altitudes, multipath effects will be present. Consequently, signals transmitted from the missile radar will propagate towards the ship via more than one path - a direct one as well as indirect ones through reflections off the surface of the water. The electric fields from the direct and indirect paths will combine vectorially at the ECM receiver to produce fluctuations or fades in the received radar signal as the missile approaches the ship. A key difficulty for the ECM system, as indicated in [1], is that multipath fades in certain cases can resemble the drop in signal power level expected for jogs, leading to possible false jog readings and hence a degradation in jamming performance.

To properly address the multipath-jog ambiguity problem, it is necessary to perform experimental trials over water, using a low-flying platform equipped with a microwave source, which can produce multipath disturbances that are similar to the

effects encountered by ECM systems. The Experimental Low Angle Tracking (ELAT) facility located along the Ottawa River provides the necessary receiver system to support this type of experiment. In addition to the trials, a detailed software model of propagation over the sea is required to represent various sea conditions, and geometries which cannot be obtained through the river trials. Existing propagation models suffer from various deficiencies in representing the actual phenomenon, hampering an investigation of the jog detection problem. The data compiled from both the trials and software model can be analyzed to determine what unique characteristics exist between jog and multipath effects, which can be used to establish a jog detection criterion.

1.2 THESIS OBJECTIVES

The primary objective of this thesis is to demonstrate and investigate the jog/multipath ambiguity problem and to establish a possible remedy. At this time, the open literature does not document a complete solution to the problem. The work is comprised of the following parts:

- (i) perform a mathematical analysis of the multipath phenomenon for the maritime case,
- (ii) conduct propagation trials over the Ottawa river to gather experimental data comprising both jog and multipath effects,
- (iii) demonstrate the extent of the jog-multipath ambiguity problem using the experimental results, and formulate a possible jog detection remedy, and,
- (iv) develop a detailed software model comprising the relevant propagation effects, including sea swells, to determine the performance of the proposed jog detector against rough surface scattering.

1.3 THESIS ORGANIZATION

Chapter 2 presents a general discussion of the theory of multipath pertaining to the maritime case. A mathematical analysis is provided which addresses the various propagation effects that are relevant to this study such as specular and diffuse scattering, reflection coefficients, refraction, etc. As well, an explanation of jogs and their associated effects on the received radar signal is given.

In Chapter 3, the trials procedure, as well as the results obtained from the measurements, are described. The data collected are derived from river scattering, and hence, represent the multipath phenomenon for the 'smooth sea' case. A discussion of relevant factors which affect the outcome of multipath, such as transmitter platform motion, antenna beamwidths, etc., is given.

Chapter 4 presents the analysis of the experimental data. An attempt is made to identify unique characteristics which may exist between jogs and multipath effects to facilitate discrimination between the two occurrences. Results indicate that detection through temporal or statistical means may not be possible. However, an approach using spatial diversity appears promising, and is presented in this chapter. An assessment of the performance of the proposed jog detector is given.

Chapter 5 provides a description of the software model implemented to evaluate the performance of the spatial jog detector against multipath effects created by rough seas, specifically sea swells. The model is based on a ray-tracing approach which includes a curved-earth geometry, shadowing, and a receiver with an eight-horn antenna array, as well as time-varying factors such as jog events, sea swells, ship motion and radar platform velocity.

Finally, in Chapter 6, conclusions are drawn and recommendations presented regarding possible future work in this area.

CHAPTER 2

THEORY OF MULTIPATH AND JOGS

2.1 INTRODUCTION

In this chapter, the theoretical and practical issues regarding the multipath phenomenon and jog effects are presented to provide insight into the nature of the ambiguity problem, to obtain a possible solution, and to form the basis for a detailed simulation model. The discussion begins with the flat earth geometry to illustrate the fundamentals of the scattering phenomenon. Following this, the two general classes of multipath reflections, specular and diffuse, are discussed in detail. A review of the reflection coefficient formula for flat surfaces, based on their electrical properties, is provided. Key propagation factors relevant to the multipath phenomenon are also examined, including refraction and diffraction effects. Finally, a presentation of the general characteristics of jogs and their effects on the received signal is given.

2.2 FLAT EARTH GEOMETRY

Multipath is the term used to describe the propagation of an electromagnetic signal from one point to another by means of more than one path. For the maritime case, which is the focus of this study, multipath arises through sea reflections off the surface of the water. Unlike land scattering, where the indirect fields can reflect in both the azimuth and elevation directions, multipath over water is primarily a height-dependent phenomenon. Figure 2.1 illustrates the problem for a flat earth geometry, in which an active radar-guided system flies low over the water to intercept a target

Figure 2.1 Flat Earth Geometry

ship. Although simplistic, the flat earth case is useful in providing insight into some of the fundamentals regarding surface reflection phenomena.

The missile radar or seeker, at a distance R_t from the ship, radiates a signal that travels directly to the shipborne receiver antenna via path R_d and indirectly through paths R_{r1} and R_{r2} . Angles θ_d and θ_r describe the elevation angle of the direct signal R_d and reflected signal R_{r1} respectively, referenced to the horizontal plane. The angle of the reflected signal R_{r2} is depicted by ψ and is referred to as the grazing angle. The grazing angle plays an important role in defining many of the factors included in propagation theory, and will be discussed in the following sections. If the radar antenna pattern is defined by $f(\theta)$, then the total signal received at the ship antenna is given by [2],

$$E = A_r f(\theta_s) e^{j0} + A_c \rho f(-\theta_r) e^{-j\zeta} \quad (2.1)$$

where A_c and A_r represent the field strengths of the radar signal at the ship receiver antenna and its image below the surface respectively. The term ρ is the magnitude of the reflection coefficient for the smooth flat surface at grazing angle ψ , and ζ is the total phase shift of the reflected signal relative to the direct wave, defined as

$$\zeta = \frac{2\pi\delta}{\lambda} + \phi_r \quad (2.2)$$

where δ is the path length difference between the direct and reflected signals: $\delta = (R_{r1} + R_{r2}) - R_d$. The term ϕ_r is the phase angle of the reflection coefficient, which is described later in this chapter. Using the Pythagorean Theorem to define the path lengths

$$R_d = \sqrt{R_t^2 + (H_c - H_r)^2} \quad (2.3)$$

and

$$(R_{r1} + R_{r2}) = \sqrt{R_t^2 + (H_c + H_r)^2} \quad (2.4)$$

The equations (2.3) and (2.4) can be represented by their binomial expansions

$$R_{r1} + R_{r2} = R_t + \frac{R_t^{-1}(H_r + H_c)^2}{2} - \frac{R_t^{-3}(H_r + H_c)^4}{8} + \frac{R_t^{-5}(H_r + H_c)^6}{16} - \dots \quad (2.5)$$

and

$$R_d = R_t + \frac{R_t^{-1}(H_c - H_r)^2}{2} - \frac{R_t^{-3}(H_c - H_r)^4}{8} + \frac{R_t^{-5}(H_c - H_r)^6}{16} - \dots \quad (2.6)$$

Subtracting (2.5) from (2.6) and performing further manipulation yields an approximate path length difference of

$$\delta \approx \frac{2H_r H_c}{R_t} \quad (2.7)$$

which is valid for $(H_r + H_c) \ll R_t$.

It is seen by equation (2.7) that the multipath effect for the sea is primarily dependent on the relative heights and range of the transmitter and receiver antennas. As the missile approaches the ship, δ increases which in turn causes ζ to rise. To observe the general behaviour of the total received signal E in equation (2.1), assume for now that the surface is a perfect conductor yielding a reflection coefficient of $\rho = 1$ and $\phi_r = 180$ degrees. Also, for illustrative purposes, let the field strengths $A_r = A_c = 1$, and the transmit and receiving antennas be represented by omnidirectional antennas (unity gain for all θ 's). Equation (2.1) then becomes,

$$E = 1 - \exp\left(-j \frac{2\pi \delta}{\lambda}\right) \quad (2.8)$$

It is observed from equation (2.8) that E is 0 when the ratio of the path length difference to wavelength is an integer ($\delta/\lambda = 1, 2, 3, 4$, etc.). Alternatively, when the ratio is an odd half multiple ($\delta/\lambda = 1/2, 3/2, 5/2$, etc.), then E is equal to twice the

magnitude of the incident field (6 dB). The total received signal, then, fluctuates between these two extreme values as the transmitter approaches the receiver, shown in Figure 2.2. The geometry for Figure 2.2 is based on a smooth earth with $H_t = 20$ m, $H_e = 10$ m, and $R_t = 10$ km.

At far ranges, the path length difference δ (Equation 2.7) varies minutely with changing R_t , causing the total received power level to fluctuate slowly as the missile approaches the ship. At close ranges, however, δ changes quickly with decreasing R_t , causing the received power level to fluctuate rapidly. When the fluctuations are intense and numerous, as shown in the figure, it becomes extremely difficult to distinguish between signal fades that are due to multipath and other occurrences such as jogs. Recall from Chapter 1 that a jog takes place when the antenna of a tracking radar deflects in angle due to intentional jamming. The ambiguity between jogs and multipath effects is examined more closely in Chapter 4.

Multipath not only affects the amplitude of the received signal, but also its apparent angle of arrival. For low angle tracking radars, multipath interference can cause the radar to track between the real target echo and its image below the water, resulting in erroneous elevation readings. The errors can be severe enough to cause the radar to lose track of the target. Many remedies have been proposed to improve low angle radar tracking over water surfaces and are presented in [2] and [3]. However, the solutions are, for the most part, not applicable to the jog-multipath ambiguity problem since they are aimed at improving active angle tracking systems while the jog detector is based on a passive receiver. This is discussed in more detail in Chapter 4.

The flat earth geometry provides useful insight into the basic effects of multipath and represents a good approximation of the phenomenon for radial distances (R_t) that are not too large compared to the earth's radius. However, when $R_t^2/8R$ (R is the earth's radius) is no longer negligible with respect to heights H_t and H_e , then it is necessary to include the effects of the earth surface curvature [4], which

Figure 2.2 Signal Fluctuations Due to Smooth Surface Multipath Effects

is discussed in Chapter 5. In the next section, a discussion of the different classes of multipath is given.

2.3 SCATTERING PARAMETERS

As discussed earlier, the reflection of electromagnetic waves by the sea can be specular or diffuse. Specular reflections arise from surfaces that are relatively smooth and large compared to the wavelength of the incident field. They tend to scatter 'in phase' and with high directivity, and hence are designated as coherent components of the multipath disturbance. Diffuse scatter, on the other hand, is generated by relatively rough surfaces which create 'out of phase' scattered fields propagating in all directions. Their contributions to the multipath phenomenon are incoherent. These two types of multipath effects are discussed, including a review of the Rayleigh criterion used to classify the roughness condition of the surface. Also, an examination of the Fresnel reflection coefficient is provided.

2.3.1 Specular Reflection

As discussed above, specular reflection is classified as coherent multipath and is produced by a relatively smooth surface. The phases of the individual specular scatterers on the flat surface are highly correlated so that, when combined at the receiver, they produce a strong total reflected signal. As explained in [5], the specular phenomenon is directional and obeys the laws of classical optics. An analogy to specular reflection is the scattering that takes place from a sunset over a smooth sea. The image of the sun can be clearly seen below the horizon of the water surface due to the coherent or specular reflections of the sun rays. The fluctuations of specularly scattered electromagnetic fields are relatively small in amplitude. Consequently, if the surface is a good conductor, it is possible for the

reflected EM signal to have the same magnitude as the direct one, causing a complete cancellation or nulling of the received power when the total path length difference is 180 degrees. The deep fades are evident in Figure 2.2.

To determine the roughness condition of the surface, the Rayleigh criterion is applied, see Figure 2.3. A surface is considered smooth when

$$h < \frac{\lambda}{8\sin\psi} \quad (2.9)$$

where h is the difference in height of the irregularities within the first Fresnel zone, and ψ is the local grazing angle of the incident and reflected wave. The derivation of h is provided in the figure. Fresnel zones are used to define the significant scattering area of the surface and are discussed below. It must be noted that the Rayleigh criterion represents only a qualitative assessment of surface roughness, as it does not take into account diffraction effects which occur from surface irregularities that are comparable in size to the incident wavelength. Also, since the criterion is based on a single ray, it fails to account for complex surfaces that are described by their statistical behaviour, such as the sea with its varying waves, fetches, etc. Despite this, the criterion is considered adequate [6].

The geometry shown in Figure 2.1 is applicable to specular multipath, since the surface is flat. As well, the power fluctuations illustrated in Figure 2.2 are representative of specular scattering effects.

Fresnel zones provide a mathematical means of defining the significant area of the surface which contributes to forward scattering. Specular reflection is the result of the radiation of the points on the Fresnel zones, which transmit waves of approximately equal phases towards the receiver. As shown in Figure 2.4, the zones are designated by drawing lines on the surface, between the transmitter and receiver, which correspond to a constant phase difference of half a wavelength between the direct path and reflected path:

$$\Delta R = 2a = 2h \cos(90^\circ - \psi)$$

$$\Delta R = 2h \sin \psi$$

$$k\Delta R = \frac{4\pi h \sin \psi}{\lambda}$$

To divide rough from smooth, let

$$k\Delta R = \frac{\pi}{2}$$

therefore,

$$h < \lambda / (8 \sin \psi)$$

Figure 2.3 Geometry for Rayleigh Criterion

Figure 2.4 Family of Fresnel Ellipsoids [5].

$$R_1 + R_2 - R = \frac{\lambda}{2} \quad (2.10)$$

As depicted in the figure, a number of path lines exist which satisfy equation (2.10), resulting in a family of $\lambda/2$ ellipsoids. It is important to note that each zone is in opposite phase to the adjacent one, and hence, the fields created by the surface currents within each zone tend to cancel the neighbouring ones as the integral of the surface is performed over the entire surface. Since the amplitude of excitation is not constant from zone to zone, the fields do not cancel completely. This results in the total radiation field being produced by approximately half the area of the first zone [5] and [6]. As will be discussed later, the propagation model makes use of this fact in defining the effective aperture of the reflecting facet.

The concept of Fresnel zones also helps in the treatment of quasi-specular reflections, which are similar to specular reflections, except that the associated surface is not entirely smooth. For quasi-specular scattering, the surface contains undulations which are periodic or near periodic characterized by generally large wavelengths. Depending on the geometry, the specular points can occur anywhere along the surface. However, as will be discussed in Chapter 5, the reflections occur mostly near the peak of the undulations when the transmitter and receiver are low to the surface. Fresnel zones are drawn about the specular point to indicate local planes of reflections or facets. This is illustrated in Figure 2.5. Within each zone, the Rayleigh criterion is applied to determine if the facet is sufficiently smooth for specular reflection. The complete scattering phenomenon is the result of the summation of all local specular reflections created by each facet.

To account for quasi or 'rough surface' specular reflection, Beckmann [5] developed a model which modifies the Fresnel reflection coefficient of equation (2.1). A new factor called the specular scattering coefficient ρ_s is introduced, which, for a normally distributed surface, is defined as

a) Sea Swell Profile.

b) Local Facet Representation.

Figure 2.5 Fresnel Zones for Quasi-Rough Surface

$$\langle \rho_s^2 \rangle = \exp \left[- \left(\frac{4\pi\sigma \sin \psi}{\lambda} \right)^2 \right] \quad (2.11)$$

where $\langle \rangle$ denotes mean value.

The term σ is the rms height perturbation of the surface. The new specular reflection coefficient is given as the product of ρ and ρ_s . It can be seen that as the sea becomes rough, or as σ increases, the magnitude of the total reflected wave decreases. The rms wave height is determined by the sea state, and is presented in Table 2.1. Although the Gaussian distribution is described, there are various

Table 2.1 Sea State and Wave Height [10].

Sea State	Wave Height σ (m)	Description
0	0	Calm, Glassy
1	0-0.1	Calm, Rippled
2	0.1-0.5	Smooth, Wavelets
3	0.5-0.1.2	Slight
4	1.2-2.4	Moderate
5	2.4-4.0	Rough
6	4.0-6.0	Very Rough
7	6.0-9.0	High
8	9.0-14	Very High
9	over 14	Phenomenal

statistical models that can be employed to describe sea behaviour for the purpose of modifying the specular reflection term.

The results of equation (2.11) are in fair agreement with experimental data collected by Beard over rough seas [7]. However, it is important to note that the

rough scattering coefficient does not take into account shadowing effects, or the autocorrelation distance of the surface, i.e. the rapidity of sea fluctuations as a function of distance. As will be explained in Chapter 5, the propagation model developed for this study implements rough sea conditions, and allows several different sea parameters to be varied to determine their overall effect on the scattering phenomenon. Since ρ_s does not take into account the autocorrelation distance of the surface perturbations, which is required to describe the signal dispersions occurring at different heights of the receiver antenna array, ρ_s is not used in the propagation model.

When the proper sea conditions are present, quasi-specular reflections, combined with the direct signal, can produce numerous fluctuations in the received power level as the missile approaches the ship. The fluctuations can occur with varying rates and depths, making it extremely difficult to identify jog fades. Sea swells are a source of quasi-specular reflections, as they tend to have long gentle slopes (large autocorrelation distances) with 'locally flat' perturbations. As a result, sea swells are examined in this thesis and are included in the simulation model.

The next section addresses diffuse multipath.

2.3.2 Diffuse Reflection

Diffuse multipath is the non-coherent component of the scattering phenomena, and is associated with surfaces that are rough according to the Rayleigh criterion. The scattered signal has little directivity, propagating in all directions with varying intensity and phase. The amplitude fluctuations are large and usually follow a Rayleigh distribution [5]. When the individual scatterers combine, their random phases add up to produce a total reflected field strength that is small in comparison with the direct wave. As a result, diffuse scattering does not significantly alter the power level of the direct signal, except to introduce noise [6].

The region of the earth's surface that radiates diffuse energy towards the receiver is called the 'glistening surface' and is shown in Figure 2.6. The length of the region, denoted by r_1 and r_2 , is generally quite extensive, implying that the grazing angle ψ changes significantly from one end of the glistening surface to the other. Since the grazing angle is required to calculate the reflection coefficient, and hence, the radiated energy, it is necessary to divide the surface into smaller elements such that, i) each element of the surface is large compared with the horizontal dimensions of the irregularities (so that the local surface or facet can be described by statistics), and ii) each element of the surface is sufficiently small that the grazing angle does not change appreciably over the extent of the facet [5]. The total diffuse energy is then calculated by summing the individual scattered fields from each facet.

Different models have been used to describe the behavior of the surface. In [2], a Gaussian model is proposed, and the standard deviation of the heights of the irregularities is represented by σ . The autocorrelation function of the surface, at a given distance r , is defined by

$$C(r) = \exp \left(- \frac{r^2}{d_c^2} \right) \quad (2.12)$$

where d_c is the autocorrelation distance of the surface, which is identical for all directions. The rms slope of the irregularities is defined by [2]

$$\tan \beta_o = \frac{2\sigma}{d_c} \quad (2.13)$$

The glistening surface is defined as the region of facets having slopes $\beta < \beta_o$. The angles β and β_o are made by the bisector of the incident and reflected rays with the vertical axis. If the transmitter and receiver antennas are highly directional, then the size of the glistening surface may be limited by the antenna beams. For a Gaussian distributed surface, the scattering coefficient, σ^o , is defined as [2]:

$$\sigma^0 = \cot^2 \beta_o \exp \left(- \frac{\tan^2 \beta}{\tan^2 \beta_o} \right) \quad (2.14)$$

The above formula assumes that the surface is very rough ($\rho_s \approx 0$), and that all the scattered power comes from the glistening surface ($\beta \leq \beta_o$).

To determine the diffuse scattering coefficient, for the case when a fraction of the incident field is reflected specularly, Barton [2], derived the following formula

$$\rho_d^2 = \frac{R_d^2}{2\pi\beta_o^2} \int_{r_1}^{r_2} \frac{F_d^2 y}{(R_d - x)^2 x^2} dx \quad (2.15)$$

where y is the coordinate of the glistening region given by

$$y = \pm \frac{x_1 x_2}{x_1 + x_2} \left(\frac{H_r}{x_1} + \frac{H_d}{x_2} \right) \sqrt{\beta_o^2 - \frac{1}{4} \left(\frac{H_r}{x_1} - \frac{H_d}{x_2} \right)^2} \quad (2.16)$$

and $x_1 + x_2 = R_d$. F_d is the roughness factor defined as

$$F_d^2 = 1 - \rho_s^2 = 1 - \exp \left[- \left(\frac{4\pi\sigma \sin \psi}{\lambda} \right)^2 \right] \quad (2.17)$$

The roughness factor scales down the diffuse term, to account for surfaces which also produce specular reflections. Experimental results indicate that the value of ρ_d levels off to approximately 0.4 as the surface becomes very rough [2].

For the general case, the diffuse scattering coefficient is sufficiently small that it does not appear to play a significant role in the ambiguity problem that exists between multipath and jog fades. Diffuse scattering is representative of Rayleigh distributed noise which may be minimized through integration in the receiver prior to the jog detector.

The next section examines the Fresnel reflection coefficient, which is modified by both ρ_s and ρ_d .

2.3.3 Fresnel Reflection Coefficient

The Fresnel reflection coefficient is defined as the field strength ratio of the reflected wave to the incident wave over a smooth surface. The electrical properties of the surface, as well as the polarization and grazing angle of the incident wave, determine the magnitude of the reflection coefficient (which can range from 0 to 1), and its phase shift (which can be between -180 and 180 degrees). The complex Fresnel reflection coefficient, for horizontal polarization, is given as [9],

$$\Gamma_h = \rho e^{-j\phi} = \frac{\sin\psi - \sqrt{(k_1/k_0)^2 - \cos^2\psi}}{\sin\psi + \sqrt{(k_1/k_0)^2 - \cos^2\psi}} \quad (2.18)$$

where

- ρ is the Fresnel reflection coefficient,
- ψ is the grazing angle,
- k_1 is the propagation factor of the surface,
- k_0 is the propagation factor of air, and

$$(k_1/k_0)^2 = \epsilon/\epsilon_0 - j\sigma/\omega\epsilon_0 = \epsilon_1 - j\epsilon_2 = \epsilon_c \quad (2.19)$$

The term ϵ_c is the complex dielectric constant, while ϵ/ϵ_0 is the dielectric constant of the earth denoted by ϵ_1 ($\epsilon_0 = 8.8542 \times 10^{-12}$ F/m is the permittivity of free space). It is also given that $\epsilon_2 = \sigma/\omega\epsilon_0 = 60\lambda\sigma$, so that (2.19) can be expressed as

$$\epsilon_c = \epsilon_1 - j\epsilon_2 = \epsilon_1 - j60\lambda\sigma \quad (2.20)$$

The complex reflection coefficient for vertical polarization is

$$\Gamma_v = \rho e^{-j\phi} = \frac{(k_1/k_0)\sin\psi - \sqrt{(k_1/k_0)^2 - \cos^2\psi}}{(k_1/k_0)\sin\psi + \sqrt{(k_1/k_0)^2 - \cos^2\psi}} \quad (2.21)$$

ϵ_1 has a value of approximately 80 for both fresh and salt (sea) water. σ can range from 0.001 to 0.01 S/m for fresh water, and to 4 S/m for sea water.

For horizontal polarization, the magnitude of the reflection coefficient remains

near unity with a phase shift of 180 degrees for grazing angles up to 10 degrees. On the other hand, the magnitude of the reflection coefficient for vertical polarization can be as low as 0.1 within the same grazing angle. Despite the effects of multipath disturbances, most missile systems still employ horizontal polarization since backscattering or clutter represents a greater hindrance to vertically polarized radars operating low over the sea. To avoid complications from multipath disturbances, missile systems often use altimeters to provide guidance in elevation [10].

Once the Fresnel reflection coefficient has been obtained, it is necessary to modify it with the specular scattering coefficient ρ_s (for specular multipath), and the diffuse scattering coefficient ρ_d (for diffuse multipath), as discussed above. When the curved earth geometry can no longer be ignored, another factor must be introduced to modify the Fresnel reflection coefficient. It is called the divergence factor.

The curvature of the earth has the effect of weakening or diverging the reflected signal, so that the magnitude of the reflection coefficient becomes slightly lower than that associated with a flat earth. To modify the Fresnel reflection coefficient, the divergence factor D is utilized, and is expressed as [7]

$$D = \frac{1}{\sqrt{1 + \frac{2r_1 r_2}{A_e(r_1 + r_2) \sin \psi}}} \quad (2.22)$$

where A_e is the effective earth's radius, r_1 is the distance between the transmitter and point of reflection on the surface, and r_2 is the distance between the point of reflection and the receiver. As before, ψ is the grazing angle of the incident and reflected field to the surface. The divergence factor is unity at high grazing angles and decreases towards zero as the angle decreases. Divergence minimizes the extent of the amplitude fluctuations that are produced by multipath disturbances, such as those shown in Figure 2.2. In the propagation model, the Fresnel reflection coefficient is multiplied by D .

The next section reviews the effects of refraction and diffraction on the propagating wave.

2.4 REFRACTION AND DIFFRACTION EFFECTS

Electromagnetic waves do not propagate in a straight line within the earth's atmosphere, but rather bend or refract depending on the frequency. Refraction is caused by the variation of the velocity of propagation, or the index of refraction, with changing altitude. The index of refraction, called n , is defined as [10]

$$n = \frac{c}{v} \quad (2.23)$$

where c is the velocity of the electromagnetic wave in free space and v is the velocity of the wave in the medium of concern. A more convenient parameter to use is the refractivity, N , which is defined as [10]

$$N = (n-1) \times 10^6 \quad (2.24)$$

A typical value of n , near the surface of the earth, is 1.0003, which corresponds to a refractivity of 300. Refractivity normally decreases at a rate of 40 km^{-1} ($n=4 \times 10^{-8} \text{ m}^{-1}$), which causes the ray to bend downwards towards the earth's surface, but not as fast as the earth's curvature.

To take into account refraction effects in the propagation model, so that the curved rays effectively propagate in a straight line for ray tracing, the earth's radius is multiplied by a factor k specified as,

$$k = \frac{1}{1+a(\partial n/\partial h)} \quad (2.25)$$

where a is the radius of the actual earth, and $\partial n/\partial h$ is the rate of change of refractive index n with height h . For a normal gradient of approximately 40 km^{-1} , k

has a value of $4/3$, which produces an effective earth radius of approximately 8500 km.

It must be noted that the term k is only an approximation, and assumes that n decreases linearly with height, i.e. $\partial n / \partial h$ remains constant in altitude. This is generally not the case in reality, where k may vary widely over different altitudes, depending on local meteorological conditions. In this case, no single variable can effectively describe the phenomenon. However, in general, k is considered to be adequate for approximating the overall effects of refraction on the propagation of electromagnetic waves in the atmosphere. For the propagation model, k is given an initial value of $4/3$, which can be altered by the user to represent other desired conditions.

For certain atmospheric conditions, the refractivity can decrease at a rate greater than 157 km^{-1} , causing the ray to bend down faster than the curvature of the earth. This phenomenon is known as superrefraction or ducting, and occurs when the air mass changes rapidly from cool and moist (below the duct layer) to warm and dry (above the duct layer). The duct layer hangs low over the earth's surface, and is characterised by a 'skip zone' which causes the propagating wave to bounce between the duct layer and earth, when the incident angle is sufficiently small.

Depending on the altitude of the duct layer, and the heights of both the transmit radar and receive antennas, superrefraction may actually prevent reflections from arriving at the receiver, and hence improve the accuracy of jog detection. As an example, Figure 2.7 illustrates the case where the transmit radar and receive antennas are situated just above the duct layer. It is seen that the indirect wave enters the layer at the radar where the angle of incidence is sufficiently large. The reflected signal, on the other hand, produces an angle with the duct layer which is small enough that it bounces off the layer (similar to a small rock skipping over the sea surface when it is thrown at a slight angle). The reflected signal eventually becomes trapped between the duct layer and the earth's surface, resulting in just the

Figure 2.7 Ducting Effects to Counter Multipath Disturbance

direct signal entering the receiver. Ducting of this type is common for the maritime case, as the temperature, pressure and water vapour contents of the atmosphere above the water surface change significantly with height, causing the atmospheric index of refraction to decrease accordingly. The average worldwide duct height is 13 m, which is low enough to trap an X-band signal for the grazing angles that are relevant to this study [11]. Although refraction may minimize the effects of multipath for this particular example, it is obviously not feasible to rely on this precarious phenomenon as a means of improving jog detection performance.

Diffraction is another propagation phenomenon associated with electromagnetic waves that interact with the surface. The effect enables waves to propagate around obstacles on the surface and can be understood using Huygen's principle which states that 'each point on a primary wavefront can be considered to be a new source of a secondary spherical wave and that a secondary wavefront can be constructed as the envelope of these secondary spherical waves' [12].

When the incident electromagnetic field illuminates a surface that is comparable in size to its wavelength, not all of the signal is forward scattered in the specular direction (i.e. angle of reflection equal to angle of incidence). Some of the waves diffract due to electrical currents travelling along the edges of the reflecting plane, reradiating energy in other directions, including the shadowed region. The shadowed region is the area located behind the obstacle or surface irregularity which is physically blocked or 'out of sight' from the incident wave. Diffraction becomes more pronounced when the wavelength increases for a given irregularity or obstacle size. If the frequency is sufficiently low, electromagnetic waves can actually travel beyond the extent of earth's horizon as a result of the wave diffracting around the curved earth.

When the reflecting plane is extremely large compared to the wavelength, it may be assumed that most of the diffracted wave is forward scattered in the specular direction. In this case, physical optics based on the Kirchhoff approximation is

sufficient to determine the field strength of the reflected wave. If, on the other hand, the surface size is comparable to a wavelength, then diffraction effects may become predominant, requiring a more precise method than the Kirchhoff approach to calculate the fields. Various methods exist, one of which is called the Geometrical Theory of Diffraction (GTD), discussed in [13] and [14]. GTD extends the physical optics approximation to include the effects of diffraction, polarization and phase differences. For the propagation model, the reflecting facets are suitably large that diffraction effects are negligible. As well, in circumstances where the first Fresnel region is not fully illuminated, shadowing usually prevents the reflected signal from propagating towards the receiver. This is discussed in more detail in Chapter 5.

In the next section, a review of two other propagation effects, namely depolarization and atmospheric attenuation, is provided.

2.5 OTHER PROPAGATION EFFECTS

This section provides a discussion of additional factors which influence the propagation of multipath signals. One effect, which appears not to be too critical to the jog-multipath ambiguity problem, is the depolarization of the reflected signal. Depolarization occurs when the polarization of the reflected wave is different from that of the incident wave. It is created primarily by reflecting surfaces which are rough, i.e. local reflecting planes with varying slopes. To demonstrate the depolarization effect, Figure 2.8 presents a reflecting surface slanted at 45 degrees, upon which a vertically polarized wave E_1 is incident. It is assumed that the surface is a perfect conductor so that all of the incident field is reflected. Resolving the incident field into tangential and normal components, and using Maxwell's boundary conditions, a reflected wave E_2 is produced having the following, $E_{2n} = E_{1n}$, and $E_{2t} = -E_{1t}$. Consequently, the resultant field E_2 is horizontally polarized, or in other words, the incident field has been depolarized by an angle of 90 degrees.

Figure 2.8 Depolarization Effects from a Sloped Plane

The level of depolarization arising from a relatively smooth sea is negligible [5]. A rough sea, on the other hand, will consist of 'local' reflecting planes with varying slopes which will serve to depolarize the incident wave, resulting in diffuse multipath. However, as discussed earlier, diffuse multipath is not considered to be pronounced enough to conceal true jog fades. This is because the diffuse signals are sufficiently incoherent that they do not interfere destructively with the direct signal to cause significant multipath fades which are similar to jog fades.

Atmospheric attenuation is another propagation effect which takes place when an electromagnetic wave travels over the sea. The attenuation is caused by oxygen and water vapor in the air which absorb radar energy in the form of heat dissipation. Since the radar system of interest is flown low over the water, an attenuation on the order of 2 dB can take place [10]. Atmospheric attenuation is not included in the propagation model, as it has no significant bearing on the jog detection problem, except to introduce an average bias in both the direct and indirect field.

2.6 JOG DEFINITION

The term jog is used to describe the sudden movement of the tracking radar's antenna away from target boresight due to jamming. The type of angle deflections associated with jogs vary considerably in rate, direction, and swing limits depending on the type of electromagnetic interference being applied. Since there are so many different jamming techniques available [1], with each having a unique effect on the radar, it is not meaningful to describe general jogs by any specific 'repeatable' antenna behaviour. Within the context of this problem, antenna motion in response to angle deception jamming is assumed to be quasi-random, that is, a deflection may occur at any rate, in any direction and to any limits, within the physical constraints imposed by the servo characteristics of the tracking radar. As well, a jog may occur at any time. The constraints of the radar are now examined.

The maximum slew rate of the radar antenna determines how fast the antenna can track the deception signal in angle during a jog. An experiment using a threat radar simulator representing a typical fire control radar was conducted to determine the radar's maximum slew rate. As shown in Figure 2.9, a horn antenna was mounted on a rotating arm and placed 5 m away from the radar. The length of the arm is 1 m. The horn transmitted a CW signal which was tracked by the radar antenna, i.e. as the horn rotated, the radar pursued it in angle. To obtain the maximum slew rate of the radar, the rotational speed of the horn was slowly increased until the radar could no longer track the signal from the horn.

It was observed that the radar ceased to track the beacon antenna at a rotational speed of 9 rpm. This is equivalent to a linear velocity of $9 \times 2\pi \times 1\text{m} = 56.5\text{m/min} = 0.9\text{m/s}$. The instantaneous angular velocity V_h , seen 5 m away, is

$$V_h = \tan^{-1}\left(\frac{0.9}{5}\right) = 10.67^\circ/\text{s} \quad (2.26)$$

Therefore, the maximum slew rate of this radar is approximately $11^\circ/\text{s}$. To calculate a hypothetical power fluctuation (dB/s) which might be observed during a jog of this radar's antenna, it is necessary to incorporate the beamwidth of the radar antenna. A typical missile may employ a circular aperture having a diameter of 0.5 m, which produces a half power beamwidth of 5° . For a rectangular aperture antenna (which was used in the trials), an aperture width (A_w) of 10.15λ is required to produce a 5° beamwidth, where λ is the wavelength of the radar signal. The single plane antenna pattern for a rectangular aperture is given as [21]

$$f(\theta) = \frac{\sin\left(\frac{2\pi A_w}{\lambda} \sin(\theta)\right)}{\frac{2\pi A_w}{\lambda} \sin(\theta)} \quad (2.27)$$

The corresponding power response of the antenna is $20 \log f(\theta)^2$. If a jog is a full

Figure 2.9 Experiment to Obtain Maximum Slew Rate of Radar Simulator.

half power beamwidth (5°), then the corresponding power level, at this angle, is -18 dB with respect to the boresight level. The average decay rate is

$$S_{\text{decay}} = \frac{-18\text{dB}}{5^\circ} \times \frac{11^\circ}{1s} = -39.4\text{dB/s} \quad (2.28)$$

The term 'average' is used because the decay rate varies for different angles of the antenna pattern. For example, at boresight, the slope of the pattern is 0, therefore, any slight movement of the antenna about this angle will result in a signal decay that is close to 0 dB/s. As the antenna increases in angular swing, the measured signal decay rate becomes larger due to the drop in gain of the antenna pattern from boresight. If the receiver has an instantaneous AGC, then it can measure rates that are equivalent to the instantaneous derivative of the radar power antenna pattern multiplied by the angular velocity of the antenna. This is discussed in more detail in Chapter 4.

Most receivers are equipped with digital processors, in which case the measured decay rate is

$$S_{\text{decay}} = \frac{S(t) - S(t - T_s)}{T_s} \quad (2.29)$$

where S is the signal amplitude (defined in dB) and T_s is the digital sampling period, expressed in seconds. As will be discussed in the next chapter, the decay rate for a 0.5 Hz jog from a 12° antenna can reach -30 dB/s, as measured by the ELAT receiver sampling at an interval of 64 ms. The sampling rate of the receiver generally does not affect the measured signal decay rate, unless it is sampling well below the Nyquist rate of the power drop due to a jog, in which case, the measured signal decay rate can be erroneous, as is discussed in Chapter 4.

The absolute angular limits of jogs are not critical for the ambiguity study. It is only important that the radar antenna experience swings in the order of a HPBW so that jog fades can be measured at a distance. Similar to angular limits,

the direction in which the jog occurs is not critical to the jog-multipath ambiguity problem, providing the radar has reasonable HPBW in both planes. Direction only becomes important if the radar employs a non-circular aperture which produces a very broad HPBW in either azimuth or elevation. In this case, it is important that the antenna swings off into the direction with the smallest HPBW, to produce adequate signal fades. For non-circular antennas, various studies would have to be conducted to determine the radar antenna's precise jog response to specific jamming signals. This goes well beyond the scope of this thesis, which primarily addresses the general trends of jogs. To cover the various possibilities, different parameters of the jog phenomenon are implemented in the simulator and tested against the proposed jog detector.

CHAPTER 3

EXPERIMENTAL PROCEDURE AND RESULTS

3.1 INTRODUCTION

A description of the experimental measurements of multipath and jogs conducted over the Ottawa River is presented in this chapter, as well as the results of these measurements. The experiment took place over a two-day period, in which a total of nine valid runs was completed. For each run, power measurements were made on individual channels of an eight-horn antenna array used to intercept the direct and multipath signals. Since the signal was recorded at each of the eight antennas separately, a total of 72 different data sets was collected for subsequent analysis. The weather during the trials was calm, consequently the river surface appeared to be very smooth, approximating a zero sea state, as defined in Table 2.1.

A helicopter equipped with a low power microwave transmitter was used to represent the seeker radar. The DND Experimental Low Angle Tracking (ELAT) Facility, located at Shirley's Bay off the Ottawa River, provided the necessary radio frequency (RF) receiver and data acquisition systems for data collection. Two types of beacon horns were employed: a narrow-beam antenna to produce well defined jog effects, and a broad-beam antenna to isolate multipath scattering effects from movements of the helicopter or the operator holding the beacon horn. Care was also taken in selecting the appropriate initial range of the helicopter in accordance with the beamwidths of the beacon horns, so that contributions from scattering off land would be minimized, thus maintaining homogeneity of the total multipath signal. To properly meet this criterion, a distance of 6 km was selected as the initial range for

all runs.

3.2 EXPERIMENTAL PROCEDURE

The geometry of equipment used in the river trials is shown in Figure 3.1. A four seater helicopter, equipped with an 8.69 GHz continuous wave (CW) beacon source was flown along the Ottawa River at a nominal velocity of 117 km/hr towards an 8 horn antenna array receiver (ELAT system) located at Shirley's bay. The helicopter flew at an altitude of 167 m for all runs, which was chosen to comply with air regulations for that aircraft flying over water.

As mentioned earlier, two types of beacon antennas were used: a Narda standard gain horn with a 12-degree half power beamwidth (HPBW), to produce well defined jog effects, and a Scientific Atlanta standard gain horn with a 30-degree HPBW to produce multipath effects which would not be affected by helicopter movements or by the operator inadvertently moving the antenna. The radiation patterns for both horns are shown in Figure 3.2. The crosspolar purity of both beacon antennas is approximately -40 dB with respect to the co-polarization channel.

Three different types of runs were performed to provide the appropriate data required for investigating the jog-multipath ambiguity problem. The first type of runs were designed to demonstrate strictly multipath fades as the helicopter approached the ELAT system. The second set of runs involved 'jogging' the antenna while the helicopter hovered at a fixed range, for several ranges. This was intended to demonstrate the fluctuations of received power due to jogs alone. The third type of runs involved features of the first two sets combining jog events with multipath effects. A description of how all three sets of runs were performed is now presented.

- 1) Beginning at approximately 6 km, the helicopter flew directly towards the receiver, while the operator kept the beacon antenna pointed directly at the ELAT antenna array. The purpose of these runs was to measure and record the effects of

Figure 3.1 River Trials Configuration

a) 12° Horn

b) 30° Horn

Figure 3.2 Antenna Gain Patterns for 12° and 30° Beacon Horns

multipath only for the given platform velocity of 117 km/hr. Separate runs were performed for the 12° and 30° beacon horns. For safety reasons, the helicopter ended each run approximately 1 km from the facility.

2) In the second type of runs, the helicopter flew along the river until it reached a range of 5 km from the receiver, where it hovered over the river, while the operator introduced two or three separate jog events with the beacon horn. For the experiment, a jog event is defined as an antenna swing in azimuth of 15° (either left or right) from target boresight and back over a period of 2 seconds. This corresponds to a maximum slew rate of 15 °/s, which is considered typical for tracking systems relevant to this study, as discussed in Chapter 2. The helicopter pilot then proceeded to 3 km and 1.5 km, remaining stationary at each range while the operator introduced similar jog events. The above run was performed for the 12 degree beacon horn. The purpose of these trials was to measure and record the fades in the received power due to jog events only. The aim of keeping the helicopter stationary was to eliminate signal fluctuations due to changing geometry between the transmitter and receiver.

3) In the final type of runs, both jog and multipath effects were observed simultaneously. The procedure involved flying the helicopter toward the ELAT receiver, beginning at approximately 6 km, while introducing the same jog events at ranges 5, 3, and 1.5 km as described in (2).

Table 3.1 provides a summary of the experimental runs performed. The table indicates which horn was implemented for each run, and whether jogs were introduced. Because of technical difficulties with the ELAT data acquisition system, only the 12° HPBW horn was used for the type two run (jogs only).

The helicopter was equipped with a Loran-C navigation device allowing the pilot to accurately follow the desired radial flight path on inbound runs. A radar altimeter helped maintain constant altitude, and an airspeed indicator helped maintain constant velocity. There was radio communication between the operator

Table 3.1 Summary of Experimental Runs Performed

Run Number	Horn Type	Multipath only	Multipath and Jogs	Jogs only
1	30°	X		
2	30°	X		
3	30°		X	
4	30°		X	
5	12°	X		
6	12°	X		
7	12°		X	
8	12°		X	
9	12°			X

onboard the helicopter and the personnel in the ELAT facility, to positively identify jog events in specific runs, and to synchronize data acquisition with the beginning of inbound runs.

Figure 3.3 presents a plan view map of the propagation experiment. A silo, located upstream and on the opposite side of the river from the ELAT receiver, was used as the far end coordinate for the helicopter to establish the desired flight line to the ELAT receiver. As indicated, using this flight path served to keep the helicopter far enough away from either shore line to minimize scattering of the transmitted signal over land surfaces. This is an important consideration, since this study is concerned with propagation phenomena over water only. Superimposed on the map of Figure 3.3 are the individual HPBW radiation patterns of the two horns, placed at the 6 km mark, to illustrate that at this range reflections from the land are expected to be low. At longer ranges, the beam of either horn begins to illuminate the shore line, especially for the 30 degree horn.

Figure 3.3 Map of the Ottawa River for Propagation Experiment

The ELAT array is comprised of 8 horns, spaced 0.125 m apart, to establish a total vertical height of 0.875 m. The height of the first element is nominally 7.9 m above the river surface, as shown in Figure 3.1. The antennas can be configured for horizontal polarization (which was used for these trials), or for vertical polarization. The output of each horn produces in-phase and quadrature E-field signals (I and Q) that are sampled at a 1 KHz rate and digitized by a 12 bit A/D converter. The digital data are then stored on a floppy disk in floating point format. The operation of the 8 horn array system of the ELAT system is described in Appendix A.

Figure 3.4 provides a photo of both the interior and exterior of the ELAT facility housing the receiver and data-acquisition systems. The antenna array is located on the opposite side of the building, facing the river. The entire facility is transportable, so that it can be placed aboard a ship for sea trials.

Figure 3.5 provides a photo and close-up illustration of the beacon apparatus developed for the propagation experiment. The apparatus is designed to allow the operator to easily point the beacon horn directly at the ELAT array from the helicopter, and to introduce the required antenna deflections with sufficient accuracy. A description of the experimental apparatus is now given.

The transmitter horn was fitted with a sight and mounted on a monopod. The monopod was passed through a round hole in a board, which rested on the operator's lap. Surrounding this hole are much smaller ones placed every 10 degrees away from the center line, to serve as a graticule. A set of limit bolts are inserted into these marked holes, symmetrically placed about the 0 degree mark, to define the maximum angular swing that the antenna may undergo during a jog. Once the bolts are inserted, a suspension band with a special holder is placed between the two bolts, forming a guide for the boresight pointer. The metal pointer, which is attached to the monopod and physically aligned to the mechanical boresight of the horn, is inserted into the holder and positioned over the center line or 0 degree mark of the graticule.

a) Exterior

b) Interior

Figure 3.4 Photograph of the ELAT Facility

a) Implementation in Helicopter.

b) Close-up Diagram

Figure 3.5 Beacon Horn Apparatus for Experiment

At the beginning of the trials, the operator points the beacon horn antenna directly at the ELAT receiver antenna array, by using his eyes to align the two pins mounted on the top of the horn. When alignment is achieved, the operator positions the board so that its center line is directly below the pointer, thus aligning the antenna boresight with the board's 0 degree mark. The elastic band helps keep the antenna in the boresight position, allowing the operator to concentrate on keeping the horn pointed in elevation at the array receiver. To implement jogs, the operator rotates the monopod or horn until the boresight pointer approaches the limit bolts, indicating that the maximum swing of the jog has been reached. To return the antenna's boresight to the center line, the operator slowly releases his hold on the pole until the elastic band is back in its neutral position.

The microwave source for the beacon antenna was located in the back seat of the helicopter. It operated on a battery pack, transmitting an 8.69 GHz CW signal of approximately 100 mW. A three foot RG/59 coaxial cable was used to deliver the power from the source to the antenna. The operator holding the beacon horn had a wide field of view due to the full glass design of the front of the helicopter. Hence, it is believed that no significant reflections took place from the helicopter which could lead to inaccurate propagation measurements. The next section presents the results of the trials.

3.3 EXPERIMENTAL RESULTS

The results of these measurements over the river are presented in this section. A series of graphs are included which show the effects of multipath on the received signal, and ultimately the degree of ambiguity that appears to exist between jog and multipath fades. A detailed study into the jog/multipath ambiguity problem is provided in Chapter 4, based on the results presented in this chapter. As mentioned already, 9 valid runs were completed. In each run, 8 separate array channels

recorded unique power levels, yielding a total collection of 72 data sets.

For each channel, the received signal is down-converted into in-phase and quadrature (I and Q) components, which are sampled at a 1 KHz rate by a 12 bit A/D converter and then integrated over 64 samples. The dynamic range of the received signal, prior to being integrated, is 10.24 volts (+/- 5.12 v). The digital data is then stored on a floppy disk, in PDP 11/73 32-bit floating point format represented as real numbers. Refer to Appendix A for more information on the ELAT data acquisition system.

As discussed in the previous section, the first experiment involved measuring and recording multipath effects alone. This was achieved by flying the helicopter towards the ELAT facility while the beacon antenna remained stationary in angle and pointed directly at the antenna receiver. Referring to Table 3.1, this experiment was executed in runs 1 and 2 for the 30° horn. The power response from trial run 2, horn 2 is depicted in Figure 3.6. As shown in the figure, the fluctuations are slow at long range and become more rapid as the helicopter approaches the ELAT receiver. The spurious jumps in signal level at certain spots along the graph are artifacts introduced by the data acquisition system. Approximately 2000 data points were collected for this run, which lasted almost 3 minutes. The dynamic range of the received signal is approximately 40 dB.

A second graph is presented in Figure 3.7 to illustrate the power response of trial run 5, horn 5. This is equivalent to the experiment performed in run 2, except that a 12 degree beacon horn is employed instead of a 30 degree horn. The received signal is similar to that observed for the 30 degree horn, implying that any instability of the transmit antenna in angle due to the operator or helicopter motion was insignificant, or at least the same as for measurements with the 30 degree horn. This is important, since the measurements made with the 12 degree horn proved more suitable for testing the jog detector algorithm presented in the next chapter. The remaining results from all eight channels of runs 1, 2, 5, and 6 are similar to the ones

Figure 3.6 Power Response of Trial Run 2 with 30° Horn.

Figure 3.7 Power Response of Trial Run 5 with 12° Horn.

displayed above, and so are not presented. Some of these graphs are included in the following chapters, where the data is analyzed and compared to simulation results.

Experimental run numbers 3, 4, 7 and 8 include jogs in the presence of multipath fades (see Table 3.1). Since the results from each trial are quite similar, only one run is presented, which is representative of the others in expressing the relevant phenomena. Run 8 is arbitrarily chosen for this purpose, and is depicted in Figure 3.8a. There are a set of jogs at approximately 5, 3, and 1.5 km, as well as multipath fades throughout the run. Also, at 5.8 and 1.3 kna, three large antenna swings of over 40 degrees are introduced, which are also considered as jogs with different characteristics, to indicate the beginning and end of the experimental run. Most of the jogs cannot be seen over the full range scale, except at far ranges where the multipath fades do not fluctuate too rapidly. For example, the jogs at 5 km are easily seen close-up in Figure 3.8b. The jogs produce a signal drop of approximately 10 dB, which is expected, for the antenna pattern of the 12° horn (shown in Figure 3.2). It is not too difficult to identify the jogs in this instance, as there is prior knowledge of their location. However, it is much more difficult to locate the jogs that are present in Figure 3.9, when the transmitter is close to the receiver. Their positions are revealed in Figure 4.7 of Chapter 4.

Finally, Figure 3.10 depicts the power response of run 9, horn 2, which contains jog effects only. The figure shows a close-up of the jogs measured when the helicopter is 3 km away from the ELAT receiver. The power fluctuations surrounding the jogs are due to the data acquisition system collecting irrelevant data while the helicopter positioned itself for the next set of jog events. It is seen that the shapes of these jogs are similar to the ones presented in Figure 3.8, implying that jog effects are not influenced by the radial velocity of the transmitter for the smooth sea case. This feature forms part of the basis for the design of the proposed jog detector which is detailed in the next chapter.

a) Full Range View.

b) Expanded Range View.

Figure 3.8 Power Response of Trial Run 8 with Multipath and Jogs.

Figure 3.9 Jogs Hidden in Multipath Disturbance.

Figure 3.10 Power Response of Trial Run 9 with Jogs Only.

CHAPTER 4

A PROPOSED JOG DETECTION ALGORITHM

4.1 INTRODUCTION

The data collected from the propagation experiment is analyzed in this chapter, to determine the extent of the ambiguity problem that exists between jogs and multipath fades, and to establish a method for distinguishing between the two phenomena. Based on this work, a novel approach has been devised which uses spatial diversity as a means of discriminating jogs from multipath fades. The approach is based on the fact that multipath, for the maritime case, is primarily a height dependent phenomenon, i.e. the profile of received signal strength, with changing range between receiver and transmitter, is a sensitive function of the heights of the receiver and transmitter. An antenna jog, on the other hand, produces a fade that is essentially independent of the height of the receiver and transmitter. By taking advantage of this difference, an algorithm has been developed which uses the multiple signals from a vertical antenna array to facilitate jog detection. This technique was applied to experimental data, and successfully identified antenna jogs emulated during measurements, for the case of a "smooth" reflecting surface.

Before the spatial diversity technique is discussed, a review of the various methods that have been proposed to minimize multipath disturbances is given. Although the techniques are designed primarily to improve the performance of low angle tracking radars, they are examined in this thesis to determine their applicability to the jog detection problem.

4.2 PROPOSED MULTIPATH REDUCTION REMEDIES

To the author's knowledge, the open literature does not document a solution to the jog/multipath ambiguity problem. Several techniques have been proposed to improve the performance of low angle tracking radars in the presence of multipath [3], however, for the most part, they are not applicable to the jog detection problem. The primary reason is that the radar is an active system (transmitting and receiving), which has control over many parameters that can be altered or diversified in attempt to improve performance over multipath interference. Some of these parameters include frequency, polarization, pulse width, pulse repetition interval (PRI), and antenna scanning. The jog detection system, on the other hand, is a passive device which only receives the radar signal.

Sherman [3] and Barton [2] discuss several possible remedies which utilize the features of the active radar to minimize the effects of multipath. These include range and doppler resolution, frequency diversity, and offset and double offset null tracking. Neither of these techniques are applicable to the ambiguity problem, since the jog detector has no control over the parameters playing key roles in these approaches. Also discussed in [2] are other techniques which involve manipulating the antenna pattern of the radar to yield a symmetrical 'difference over sum channel' (Δ/Σ) error pattern that is on the midpoint between the target and image. These techniques, however, require range information which is assumed to be unavailable to the jog detection system in this analysis.

Conceptually, one way of eliminating multipath interference is for the receive antennas to have negligible gain in the directions of the sea surface. This requires extremely high resolution in elevation angle and reduced sidelobes of the antenna pattern, which is a difficult design constraint on the system. As noted in [2], the use of low edge illumination on the antenna aperture, to reduce sidelobes, broadens the mainlobe width and extends the region in which significant multipath signals can be

received. Consequently, a tradeoff is established (between low sidelobes and a narrow main beam) where multipath can be avoided at either close range or far range, but not both. For jog detection, it is important that the rejection of the multipath contributions to the signal occur over a large range (beyond 20 km), which necessitates a very narrow main beam, following the above line of reasoning. In addition to this limitation, the size of the antenna required to achieve the desired resolution is too large to be practical. For example, to track a 30 m high radar that is 20 km away, a beamwidth of less than 0.2 degrees is required to avoid illuminating the surface with the antenna's HPBW. At X-band frequencies, the aperture would have to be greater than 8 m, which is considered impractical because of space constraints on-board the ship. Finally, with high resolution, it is necessary for the jog detection system to angle track the incoming radar signal with extremely high precision so as to avoid introducing signal fades from its own antenna pattern. This is difficult to achieve, since multipath also acutely hinders angle tracking performance at low grazing angles (i.e. angle tracking may wander between the target and any of its images). Therefore, based on the above, a high resolution antenna does not seem feasible for jog detection.

Another approach to rejecting multipath signals is the use of radar fences on the ship, to electrically block the line of sight between the multipath sources and the receiver, without affecting the direct path. This is impractical, however, as the ship rolls and pitches with the waves, assuming typical rough sea conditions, possibly causing the fence to block the view between the receiver and the radar source. Furthermore, when the fence is not blocking the path, a new source of scattered signal is created by diffraction, from the top edge of the fence [15], introducing new signal fades that may be ambiguous to jog fades.

Another potential approach to the jog/multipath ambiguity problem involves the application of techniques to maximize the detection of signals from noise, known as matched filtering. In this case, the power fade from a jog represents the signal

that is to be detected, while fluctuations from multipath interference represents the noise. The key difficulty with this method, in terms of its relevance to jog detection, is that the output of the matched filter must be tailored to the signal waveform to achieve the maximum signal-to-noise ratio [16]. Unfortunately, as discussed in Chapter 2, the antenna response to a jog is quasi-random, hence, *a priori* knowledge of the signal is unknown. The precise swing rate, period and direction of the jog, as well as the beamwidth of the radar antenna, must be known before the jog fade can be characterised. Therefore, predicting jogs through matched filtering does not appear to be feasible.

The above survey of possible solutions of the jog/multipath ambiguity problem underlines the level of difficulty in minimizing multipath disturbances without adversely affecting the performance of the system of interest. As discussed, the majority of approaches are aimed at improving the performance of tracking radars and are generally not applicable to the problem of jog detection. For certain approaches, which exhibit technical merit, such as high resolution antenna patterns, practical limitations preclude them from being implemented. Hence, a new approach for discrimination of jogs and multipath, to facilitate jog detection, is required.

The next section provides an analysis of the experimental data, examining possible unique differences between jog fades and multipath fluctuations, which can serve as the basis for a jog detection algorithm.

4.3 ANALYSIS OF EXPERIMENTAL DATA

Various graphs are presented in this section which illustrate the apparent ambiguity problem that exists between jogs and multipath fades. The complete set of graphs presented in this chapter is based on the results of experiment run number 8, which are representative of the other runs of the same type (see Table 3.1 for information regarding the different runs). A summary of the relevant parameters

pertaining to the trials is given in Table 4.1.

Table 4.1 Key Parameters Relevant to the Experiment

Helicopter Speed	117 km/h
Helicopter Height	167 m
Height of 1 st Receiving Antenna	7.9 m
Antenna Separation (8 horns)	0.125 m
Transmit Horn (HPBW)	12°
Receive Array Horns (HPBW)	12°
Initial Range	6 km
Jogs	15° (Rate = 15°/s)
Effective Sampling Period of ELAT Receiver	64 ms

As indicated in the table, jogs are implemented for runs using the 12° transmit horn antenna. Recall, from Chapter 2, that a jog occurs when the tracking radar's antenna is suddenly deflected in angle due to jamming. In the experiment, a jog is simulated by swinging the antenna 15° in one direction and back over a period of 2 seconds. This equates to an angular swing rate of 15°/s, which is taken to be typical for the maximum tracking slew rate of radars relevant to this study. Although the experiment only includes jog rates of 15°/s, other rates are analyzed in this and the next chapter, to formulate a more complete study of the problem.

Figure 4.1 depicts the power response and derivative of the signal received from horn 5 of run 8. In the power response graph, asterisks are drawn to indicate the location of each set of jogs, which occur at approximately 5.8, 5, 3.1, 1.6 and 1.3 km. As indicated in the figure, the depth of the signal fade due to a jog is approximately 10 dB, except for the jogs at 5.8 and 1.3 km, which have signal fades of approximately 20 dB. As explained in Chapter 3, these jogs were made larger to

Figure 4.1 Power and Derivative Response of Run 8, Horn 5

serve as indicators of the beginning and end of the experimental run. The rate of fall of the signal is approximately 15-20 dB/s for each jog, as indicated by the derivative response. As discussed in Chapter 2, the apparent signal decay rate is a function of the receiver's sampling rate, as well as the transmitter's antenna HPBW and swing rate during a jog. The derivative is required for the detector, as will be discussed shortly.

It is relatively easy to identify the jogs at the 5.8 and 5 km range, since the signal drops abruptly from the 'normal' multipath profile. At these ranges, multipath interference from a smooth surface causes the power level of the received signal to fluctuate slowly, with deep fades occurring at large intervals. As a result, it is straightforward to visually detect the sudden deviation in amplitude due to a jog, providing it does not occur during a multipath fade, such as is the case when the transmitter is approximately 3.1 km away from the receiver, as seen close-up in Figure 4.2.

Although it is relatively easy to visually detect the jogs at long range, it is extremely difficult to incorporate this capability in a passive receiver, such as the jog detector, which has no information regarding the height or range of the transmitter to predict the multipath fades. Recall from Chapter 2, that a multipath fade, from a smooth surface, occurs when the path length difference

$$\delta = \frac{2H_t H_c}{R_t} \quad \text{is an integer} \quad (4.1)$$

where

H_t = transmitter (radar) height

H_c = receiver height, and

R_t = range between transmitter and receiver.

Without prior knowledge of R_t or H_c , a passive detector is unable to predict the location of the multipath fades so as to recognize unexpected fluctuations brought on by an independent event, such as a jog.

It is important to note that the power response from the experiment does not

Figure 4.2 Close-up View of Jog Fade Coincident With MP Fade

exactly replicate the classical 'smooth surface' multipath profile, where the fades occur at regular intervals and progressively narrow as the transmitter approaches the receiver, as shown in Figure 2.2 of Chapter 2. This is evident beginning at 5.8 km where the fades are separated by 140 m, 400 m, 240 m, 214 m, 400 m, etc. It is likely that additional multipath signals are being introduced from either land scattering or extra reflections off the water surface due to slight perturbations on the river surface.

The profile of the received signal is examined to determine if multipath effects imply unique statistical characteristics which may be filtered out to reveal jog events. The mean and standard deviation of the received power is calculated, using numerous sampling window sizes. The window moves in range, one data point at a time, processing the specified number of data values each time, to derive the mean and deviation of the input signal. A window size of more than 50 points caused the jog fades to disappear completely, while a window size of less than 50 points yielded mild filtering of the power response, providing little improvement in potential for jog discrimination.

To illustrate the difficulty in achieving jog detection through statistics, Figure 4.3 depicts the standard deviation and mean response of the signal measured by horn 5 of experiment run number 8. A sampling window size of 50 points is used, which corresponds to a range cell of approximately 100 m for the given helicopter speed. The signal deviates from its mean with varying rates and amplitudes, many of which resemble jog fades. The statistics of the time derivative of the received signal are shown in Figure 4.4, for a sampling window size of 50 points. Again, no noticeable or significant changes in the two responses appear when a jog fade takes place. Based on this, the above statistical analysis does not seem to offer useful information regarding jog detection.

As indicated by equation 4.1, the power response of the received signal is directly proportional to the heights of the transmitter and receiver. It follows then, that a receiver equipped with a vertical antenna array measures different responses

Figure 4.3 Statistics of Power Response of Trial Run 8

Figure 4.4 Statistics of the Derivative Response of Run 8.

in each receiving antenna for the same transmitter height H_t , and radial range R_t . To verify this, data from all eight channels of the ELAT antenna array were collected during the experiment, as discussed in Chapter 3. The individual antennas are separated by 0.125 m, with the first one located approximately 8 m above the river surface (see Appendix A).

Figure 4.5 depicts the power response and its derivative, received by antennas 1 and 5 of experiment run number 8. The graph is plotted over a range of 4.0 to 4.5 km, where only multipath effects exist (no jogs). The deep multipath fades (30-40 dB) occur at different ranges for each antenna. As predicted by the equation, horn 5 (top graph) encounters the fades at slightly longer range than horn 1 (bottom graph), because of its greater height. Additionally, horn 5 measures a few smaller fluctuations (10-20 dB), which are not shown in the graph of horn 1. This is attributed to extra reflections, discussed above, which happen to be prevalent at this range for horn 5, but not for horn 1. These effects of the extra reflections are found at other ranges for horn 1. The derivative responses indicate that the multipath fades can produce a rate of fluctuation as high as 200 dB/s, for the given helicopter speed and geometry. The fluctuations in derivative, due to multipath, do not occur simultaneously between the two channels, as discussed above for the power response. Hence, a basis is established for rejecting multipath effects using spatial diversity through a vertically aligned antenna array. It is necessary now to examine the effects of jogs for this vertical configuration of receiving elements, to determine if a unique response exists.

Figure 4.6 depicts the power and derivative responses of the signal received by horns 5 and 1. In this case, the abscissa is set to between 4.7 and 5.2 km, to include two jog events which were introduced at the 5 km range during the trials. As shown, the two jogs occur simultaneously in both channels, as expected, since jogs are not geometry dependent. The jog fades are approximately 10-12 dB deep, which corresponds to the first null of the 12° horn antenna pattern, illustrated in Chapter

Figure 4.5 Power Response of Horns 1 and 5 of Run 8 (No Jogs)

Figure 4.6 Power Response of Horns 1 and 5 of Run 8 (With Jogs)

3. The resultant maximum derivatives are approximately 20 dB/s for each jog, and occur simultaneously in each channel, which meets the requirement for the spatial diversity technique.

The extent of the ambiguity problem between jogs and multipath fades is clearly demonstrated in the power response of horn 1 (bottom left graph). A fade occurs just before the true jog, at approximately 5.05 km, which itself strongly resembles a jog. The depth and width of the fade is so close to an actual jog, that it is easy to make a false reading using a visual inspection of the received power of this single antenna. Through spatial diversity, however, the fade is identified as a multipath occurrence, since it does not appear simultaneously in the power response of horn 5 (top left graph).

Figure 4.7 further illustrates the extent in which jogs can blend in with multipath fades. Asterisks are drawn in the power response graph to indicate the known locations of the jogs. This graph is a reproduction of the one shown in Figure 3.9 (Chapter 3), where the positions of the jog fades were purposely concealed to demonstrate the extent of the ambiguity problem.

The above analysis has established the basis for utilizing spatial diversity as a means of discriminating between jogs and multipath fades. The next section presents the design and performance evaluation of the spatial diversity technique, as applied to the experimental data.

4.4 SPATIAL DIVERSITY TECHNIQUE FOR JOG DETECTION

As already mentioned, the proposed technique for improving jog detection in the presence of multipath is based on discrimination through spatial diversity. The technique exploits the fact that maritime multipath is primarily a height-dependent phenomenon, and as such, produces different responses for varying heights of the transmit and receive antennas. Consequently, if a series of horns at different heights

Figure 4.7 Hidden Jogs in Figure 3.9 Revealed.

is employed, such as is the case for a vertical antenna array, then each channel measures slightly different instantaneous power levels of the MP response, due to their differing heights relative to the radar wavelength. Jogs, on the other hand, affect the signal power in all receiving antennas simultaneously, because all the elements lie in the same bearing.

A block diagram of the proposed jog detector is shown in Figure 4.8. Note that the algorithm portion of the detector, which includes the circuitry beyond the A/D converters, is implemented in software for this study. The system accepts X-band signals from three channels of an antenna array, which are frequency down-converted and then digitized. As will be discussed, three antennas provided the ideal number of input signals for the detection algorithm operating against 'smooth sea' multipath effects. Although all of the experimental data were tested against the jog detection algorithm, only the results of the detector against data obtained from horns 1, 5, and 8 of run 8 are presented. The outcome is representative of the remaining runs. For proper operation of the detector, it is imperative that all channels of the receiver have similar RF dynamic responses, although it is not essential that they be perfectly balanced, as will be explained shortly.

As shown in the figure, each channel is down converted to a baseband signal and then digitized. The digital signal is applied to a first-order differentiator, which measures the time rate of change of the input signal. The output of the differentiator is fed to a threshold detector, which determines if the derivative of the signal has exceeded a pre-specified value called V_T . If so, then a +1 logic value is created and applied to the input of an AND gate. The output of the AND gate remains low until all channels produce a logical 1 simultaneously, at which time, it toggles to a +1, indicating the presence of a jog.

As discussed earlier, when a signal fade takes place due to multipath interference only, each channel registers the fade at different ranges of the transmitter, based on equation 4.1. The corresponding derivatives, in turn, exceed

Figure 4.8 Block Diagram of the Proposed Jog Detector

V_t at different times, resulting in a logical 0 at the output of the AND gate (no jogs). When the signal decreases as a result of a jog, each receive channel responds similarly (as discussed above). The derivatives, in turn, simultaneously exceed V_t , producing coincidental pulses at the AND gate, which then registers a logical 1 to indicate a jog event. The key to an effective performance of the algorithm is in selecting the appropriate threshold value. If it is too low, then the first derivative of erroneous effects will trigger false jog readings, such as inconsequential reflections, slight antenna movements which are not intentional jogs, and receiver noise. On the other hand, if the threshold is too high, then the jogs themselves will be missed. The effects of different V_t 's are examined later in this section.

Figure 4.9 illustrates the power response of the signal received by horn 5 over the entire range of the experiment run (top graph), and the corresponding output of the jog detector (bottom graph). Asterisks are included in the bottom graph to indicate the known locations of the jogs. As already mentioned, jogs are introduced at the 5.8, 5, 3.1, 1.6, and 1.3 km range. From the graph of the derivative response shown in Figure 4.6, the maximum rate of decay of the signal due to a jog is approximately -20 dB/s. Therefore, the threshold value V_t is set to this number. The detector identified almost all of the jogs except for one at 1.6 km. The reason it failed to locate one at this range is because the signal is scintillating very rapidly due to multipath, and thus altered the derivative response of one or more of the channels sufficiently to prevent the signal from exceeding V_t simultaneously with the remaining channels.

At ranges less than 1.5 km, a few false jogs are read, due to the ambiguous heights of the receiving antennas with respect to the signal wavelength. Recall from Chapter 2, the total received signal is proportional to

$$E = 1 - \exp\left(-j \frac{4\pi H_t H_c}{R\lambda}\right) \quad (4.2)$$

Figure 4.9 Power Response and Detector Output of Run 8

Since the exponent is a phase term, any path length difference ($H_t H_c / R$) that is greater than a radar wavelength becomes ambiguous. Consequently, a number of range values exist where the same phase information is simultaneously measured by the three receiving antennas of the array. This in turn causes similar amplitude fluctuations to be measured, leading to possible false jog readings. Adding more antennas in the array reduces the number of range positions which could produce ambiguous signal phase readings. However, as will be discussed in Chapter 5, extra antennas for rough sea scattering degrade the performance of the jog detection algorithm, using spatial diversity.

The derivative of the power response is used for the jog detector, rather than the absolute power level, for the following reason. With absolute power levels, it is necessary to have prior knowledge of the transmitter's output power level, as well as the radial range between the transmitter and receiver, in order to select the proper threshold value for detection. As already discussed, the jog detection system does not have access to this information. Derivatives, on the other hand, remove all dependencies on absolute power levels. They describe the jog phenomenon strictly on the basis of antenna motion, no matter how close the transmitter is or how much power is being radiated.

To determine the sensitivity of the threshold setting, four different values of V_t are assessed. The results are shown in Figure 4.10 for $V_t = 0, -10, -15$, and -20 dB/s. The probability of false jog detection increases as V_t rises to 0. At $V_t = 0$, the false jog readings are almost constant, due to a number of factors discussed above, such as i) slight movements of the transmit antenna which are not true jogs, ii) diffuse scattering effects that cause the signal to fluctuate simultaneously in each antenna, and iii) noise in the receiver system. At $V_t = -20$ to -15 dB/s, the number of false jog readings are few for ranges greater than 1.5 km, making the detector operationally useful. An important fact to recall is that a 12" beacon horn was used during the trials, which is much broader than the HPBW of typical missile tracking

Figure 4.10 Detection Output for Different Threshold Values

systems, as discussed in Chapter 2. As will be shown in the next section, a narrower beamwidth can provide a larger signal decay rate, which can enhance the performance of the jog detection algorithm.

The next section examines the effects of different characteristics of jogs on the derivative response of the received signal.

4.5 EFFECTS OF DIFFERENT JOG CHARACTERISTICS

In the previous section, the jog detection algorithm was tested against a 12" horn antenna, in which jogs were represented by swinging the antenna at a rate of 15°/s over a 15° limit. The maximum signal decay rate, produced by this jog, was approximately -20 dB/s. By setting $V'_t = -20$ dB/s, the detector was successful in identifying most of the jogs that appeared ambiguous with the 'smooth surface' multipath fades. Since the detector is dependent primarily on the characteristics of a jog, it is useful to examine different antenna half power beamwidths and jog behaviours to gain insight into the type of signal decays that can be measured by the receiver. Additionally, the dynamic range and bandwidth (or sampling period) of the receiver must be quantified to determine the impact on the measured values.

As discussed in Chapter 2, the signal decay rate of a jog is a function of, among other things, the instantaneous decay rate (first order derivative with respect to scan angle) of the transmitter's antenna pattern multiplied its slew rate. Figure 4-1 depicts the power response and instantaneous decay rate of a 12" HPBW antenna, represented by a sinc pattern ($\sin x/x$). The decay rate is 0 dB/deg at 0° scan angle (the antenna's boresight position is in line with the receiver), and gradually decreases to a theoretical value of minus infinity when the first null is reached. In general, the nulls of the antenna pattern are quite shallow, as is evident in the antenna patterns of Figure 3.2 (Chapter 3), yielding a much smaller decay rate. Since the decay rate of the signal is not constant throughout the antenna swing, no

Figure 4.11 Theoretical Power Response and Decay Rate of 12 Degree Antenna.

single value can be used to describe the power response of a given jog. To simplify the analysis, the maximum decay rate is used, which implies that the jog detection threshold value cannot exceed this rate for proper jog detection.

To gain an understanding of the types of decay rates that can be measured, two antennas are simulated, a 5° and 12° HPBW antenna, which are represented by sinc functions. For the receiver, two sampling rates are simulated, 15 Hz (which replicates the effective sampling rate of the ELAT receiver) and 1 kHz. Jogs are represented by an antenna swing of 15° in one direction and back, with rates ranging from 0 to 60°/s. The formula for calculating the power decay is given as

$$S_{\text{decay}} = \frac{\Delta S}{T_s} = \frac{S(t) - S(t - T_s)}{T_s} \quad (4.3)$$

where T_s is the sampling period of the data acquisition receiver (measured in seconds) and S is the power level of the received signal expressed in dB's. Figure 4.12 depicts the maximum decay rate for both antennas measured by a receiver sampling at 15 Hz and 1 kHz. The first (top) line of the figure represents the signal decay produced by the 12° horn, measured by the receiver sampling at 64 ms intervals, or at a rate of 15 Hz. The second line is for the same horn, except that the sampling rate is increased to 1 kHz. The third line represents the signal response of the 5° horn, for a sampling rate of 15 Hz, and the fourth line is the same horn measured at a 1 kHz rate.

For the 12° antenna, measured by the receiver operating at 15 Hz, shallow fades are recorded, reaching only 100 dB/s when the jog rate exceeds 55°/s. With reference to the trials, the expected maximum signal decay from a 12° horn, swinging at a rate of 15°/s, is approximately -20 dB/s, which is what was measured. The effects of increasing the sampling rate is seen in the second line, where the fades become slightly larger beyond jog rates of 20°/s. The reason is that the receiver (operating at 15 Hz) under-sampled the jog event, producing an inaccurate

representation of the fade. When the sampling rate is too low, the receiver will, for the most part, sample about the null, where small differences in power levels are measured, as illustrated in Figure 4.13. Slope 1 represents a receiver that has a sufficient sampling rate, while slope 2 represents an under-sampling system. Increasing the sampling rate, beyond 1 kHz does not change the response, implying that the Nyquist rate of the power drop, during a jog, has been met.

The 5° antenna produces much higher signal fade rates than the 12° antenna, for the same set of jog rates. The sampling rate of 15 Hz is much too low to sufficiently describe the event, as discussed above. In this case, a maximum signal decay rate of only -300 dB/s is measured. For the 1 kHz sampling rate, however, the maximum signal decay rate is seen to be as great as -1000 dB/s for jog rates reaching 55°/s. For a typical jog rate of 15°/s, which was used in the trials, the signal decay rate is approximately 300 dB/s. Based on this, the jog detection system should have no difficulty in identifying jogs in the presence of 'smooth sea' multipath disturbances for a 5° transmit antenna.

Different angular limits for the antenna jog were tested to determine the impact on the received signal. The signal decay response did not change as long as the antenna swing was equal to or greater than a half-power beamwidth. At less than a HPBW, the signal decay rate remained close to 0 dB/s, which is expected since the instantaneous decay rate of the pattern is also nearly 0 dB/s, as shown in Figure 4.12. Therefore, based on this, it appears that the jog swing has to be greater than a HPBW in order for the jog detection algorithm to be effective. Finally, the dynamic range of the receiver, in terms of amplitude response, is not critical, providing that it is larger than the power difference between the transmitter's antenna response at boresight and its first null. For typical antennas, the difference is anywhere from 10 dB to 35 dB, which is well within the dynamic range of most R.F. receivers.

Figure 4.12 Derivative Response of Received Signal for Different Jogs

Figure 4.13 The Effects of Under-Sampling.

CHAPTER 5

SIMULATION MODEL

5.1 INTRODUCTION

This chapter presents the propagation model developed for the study of possible ambiguity between jogs and multipath. The model is an implementation of mathematical descriptions of quasi-rough sea conditions as described and derived in the literature. As reported, sea swells are long, slow, wavelike undulations of the ocean surface, producing multiple coherent scatterings of the incident field. When combined with the direct signal at the receiver, these multiple reflections can result in rapidly fluctuating power levels in the received signal. As will be discussed, these fluctuations can resemble jogs in antenna pointing direction, hence, it is desirable to evaluate the performance of the proposed jog detection algorithm against this form of multipath disturbance. The model was developed due to a lack of experimental data comprising the necessary ocean-surface and jog effects relevant to this study.

It is important to note that the fidelity of the propagation model is fundamentally limited by the quality of the mathematical descriptions of scattering over the ocean surface, presented in the open literature. Improvement on these descriptions is beyond the scope of this thesis. Sufficient detail, however, is introduced to evaluate the general trends that are associated with quasi-rough sea disturbances, as they pertain to the spatial diversity technique of the proposed jog detector. Final proof of performance of the jog detection algorithm requires actual sea trials.

The simulation represents a low flying platform transmitting a radar signal

towards a ship equipped with an eight-horn antenna array receiver. The electromagnetic signal transmitted by the radar propagates in a direct path to the ship as well as through indirect ones, via reflections off the surface of the water. The model characterizes the propagation of these signals by means of geometrical optics or 'ray optics', and incorporates Snell's law to define the angle of reflection of the scattered wave with respect to a tangent plane at the sea surface. The propagating fields are treated as a continuous microwave signals, represented by a single spectral component. It also assumes perfect polarization alignment between the radar and receiver, and depolarization of the signal incident on the ocean is not considered. A curved earth geometry is employed, with a modification to the earth's radius to account for first order refraction effects, as discussed in Chapter 2. The program also represents such effects as transmitter platform motion (radial trajectory to the ship), antenna jogs, sea swell propagation, and ship movements about the surface. The simulation produces as output, a series of ASCII data files containing the total power received by each antenna during the simulation run, as the transmitter flies radially from a given range to the ship.

A detailed description of the propagation model and the relevant parameters of the simulation package are provided in this chapter. As well, the results from the simulation runs are presented and statistically compared with the trials data to validate the model representing the zero sea state case. Also, the jog detector algorithm that is proposed in the previous chapter is assessed against the model of signal fluctuations due to multipath from sea swells. The overall effectiveness of the jog detector against this form of quasi-rough sea condition, as modeled, is then determined by varying sea conditions and platform geometry.

5.2 SOFTWARE MODEL DESIGN

The program is menu driven, containing various parameters that can be

defined by the user prior to the simulation run (refer to Appendix B). The program was written in Turbo C and consists of over 2000 lines of code. Refer to Appendix C for a functional hierarchy of the simulation model.

5.2.1 Ray Optics Approach

The model represents the propagation of the electromagnetic waves using ray optics. This enables the total field on the reflecting surface to be described in scalar form by means of local reflections rather than through direct application of Maxwell's equations using boundary conditions. The ray optics method is considered valid only if the surface is relatively smooth and large compared to the wavelength of the incident field, so that diffraction effects are not predominant.

As discussed in Chapter 2, the Rayleigh criterion determines whether the surface is sufficiently smooth within the first Fresnel zone of the illuminated area. For all simulation runs, care is taken to select the appropriate geometry and surface conditions which will avoid diffraction errors. The only surface perturbations considered are sea swells, which have long periods and gentle slopes, and are relatively smooth. Wave breaks or other sharp edges in the sea surface are not considered.

5.2.2 Curved Earth Geometry

The geometry used for the propagation model is based on a curved earth model and is depicted in Figure 5.1. The simulation includes a low flying missile transmitting radar signals towards a ship equipped with an 8-horn-antenna array receiver. The radar transmits a microwave signal in a direct path $R_d[i]$ and an indirect path comprised of R_{r1} and $R_{r2}[i]$, where i represents the individual paths to each receive horn. The radar and receiver antennas have gain patterns that are

Figure 5.1 Curved Earth Geometry

Resolution test chart showing patterns of vertical and horizontal lines with numerical values: 1.0, 1.1, 1.25, 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, 2.8, 3.2, 3.6, 4.0, 4.5, 5.0, 5.6, 6.3, 7.1, 8.0, 9.0, 10.

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Figure 5.9 Simulation Results Compared With Experimental Results

$$\zeta_2 = \frac{R - R_N}{A_e} \quad (5.5)$$

Measuring from the center of the earth:

$HE_{\text{new}}[i]$ = height of the i^{th} horn onboard the ship,

HW_{total} = height of the surface at the reflection point,

YSS_o = height of the ship, and

HR_{total} = height of the radar.

$A_e = 8500$ km is the effective earth's radius, which is $4/3^{\text{rd}}$ of the true earth radius to compensate for refraction effects. The term $\Delta\zeta$ defines the angular swing of the ship with respect to the tangent of the surface at $R_N = 0$. A damping factor, which is not shown in the equation, is also included to define the extent of ship roll with the waves. A factor of 1 indicates that the ship will not rock at all (it will still continue to move up and down with varying sea heights), while 0 implies that the ship will be perpendicular to the local tangent of the waves. Now that the relevant paths are defined, an explanation of the search procedure used to find the proper reflection points is given.

At a given search range R_N , the simulation calculates the incident angle θ using

$$\theta = \sin^{-1} \left[\frac{HR_{\text{total}} \sin \zeta_2}{R_{r1}} \right] - \frac{\pi}{2} + \phi \quad (5.6)$$

On the reflection side of the specular point, θ is added to ϕ to produce η , which is referenced to the perpendicular of the mean earth surface. η is then compared with angle $\gamma[i]$, which defines the direction required for the reflected signal to hit the i^{th} horn. $\gamma[i]$ is given by,

$$\gamma[i] = \frac{\pi}{2} - \arccos \left[\frac{R_{r2}^2[i] + HE_{\text{new}}^2 - HW_{\text{total}}^2}{2R_{r2}[i]HE_{\text{new}}} \right] - \zeta_1' \quad (5.7)$$

When a range R_N is reached where $\gamma[i]$ and η are equal, then a specular point

has been located and the program proceeds to determine if shadowing exists. Before shadowing is addressed, a discussion on sea swells is given.

5.2.3 Sea Swells

Sea swells are ocean waves that have travelled out of their generating area or fetch. A fetch is an area of the sea surface over which waves are created by a wind having a constant direction and speed. Within the fetch, wind or sea waves are produced which are characterized by short periods and rapid fluctuations. They prevail for only as long as the wind is present, diminishing very quickly outside the fetch due to the molecular viscosity and turbulence of the sea surface [17]. Sea swells, on the other hand, exhibit a more regular and longer period and have flatter crests than waves within their fetch.

The amplitude of the swell is generally small in comparison to its wavelength, and the surface configuration in the direction of wave travel approximates a sine function [18]. From hydrodynamical theory, the height of the wave cannot exceed about one-seventh of its length before the wave breaks, resulting in 'white caps'. The maximum height to length ratio represented by the model never exceeds one-twentieth. Hence, for the geometries considered, the crest profile is relatively flat with respect to the incident electromagnetic wave.

The equation used to represent the sea swell in the propagation model is [20]

$$H_{RN} = H_p \cos \left(\frac{2\pi t}{T} - \frac{2\pi R_N}{L} \right) \quad (5.8)$$

where

- H_{RN} = wave height at range R_N
- H_p = amplitude of the sea swell
- T = period of the sea swell over time, and,
- L = wavelength of the sea swell from crest to crest.

Refer to Figure 5.2 for an illustration of the above variables. The crest height H_p follows a Rayleigh distribution given as [19];

$$p(H_p) = \frac{H_p}{\sigma_w^2} \exp\left(-\frac{H_p^2}{2\sigma_w^2}\right) \quad (5.9)$$

where σ_w is the rms deviation of the crests with respect to the mean surface. Little information is available regarding the correlation factor between sea swell peaks. To follow the same approach used by [19], the swells are considered independent for the propagation model. The slope or tangent plane of the surface in equation 5.8 is the range derivative of the wave, defined as

$$H'_{RN} = \frac{\partial H_{RN}}{\partial R_N} = \frac{2\pi H_p}{L} \sin\left(\frac{2\pi t}{T} - \frac{2\pi R_N}{L}\right) \quad (5.10)$$

The tangent plane angle, with respect to the surface mean, is

$$\phi = -\tan^{-1}(H'_{RN}) \quad (5.11)$$

The minus sign is included to account for range increasing from right to left, as shown in the figure, which is opposite to convention.

Sea swell wavelengths can be as large as 500 m with periods in the range from 5 to 30 sec [18]. The width of the swells, perpendicular to the direction of propagation, is at least 6 or 7 wavelengths long [18], well beyond the first few Fresnel zones, as will be discussed shortly. Typical sea swell rms heights implemented in the model range from 0.5 to 4.0 m (sea state 2 to 5 respectively).

5.2.4 Shadowing

The number of specular points present on the ocean surface, for a given geometry, is also affected by shadowing from nearby waves [19] and [20]. Shadowing

Figure 5.2 Sea Swell Profile

occurs when nearby sea crests prevent the propagation of the signal from either the radar to the reflection point on the surface of the water, or from the reflection point to the receive antennas on board the ship. Shadowing effects are most significant when the surface is extremely rough and/or when the missile is very low and distant from the ship. In the propagation model, shadowing acts as a gating function, turning the reflected signal completely off when it is present [19].

Figure 5.3 presents the relevant geometry for determining shadowing on both sides of the reflection point. Beginning with the radar side, shadowing will exist if $\eta_{\text{rad}} < \alpha$. The angle α is defined as [19]

$$\alpha = \frac{\pi}{2} - \sin^{-1} \left[\frac{HW_{\text{total}} \sin \left(\frac{R_{\text{cl}} - R_N}{A_e} \right)}{\Delta d} \right] - \frac{R_{\text{cl}} - R_N}{A_e} \quad (5.12)$$

where

$$\Delta d = \sqrt{H_{\text{left}}^2 + HW_{\text{total}}^2 - 2(H_{\text{left}})(HW_{\text{total}})\cos(\zeta_{\text{sr}})} \quad (5.13)$$

Following a similar procedure for the ship side, shadowing will exist if $\gamma[i] < \beta$. Note that shadowing is checked for each horn i , where $i=1$ to 8. The angle β is defined as

$$\beta = \frac{\pi}{2} - \sin^{-1} \left[\frac{HW_{\text{total}} \sin \left(\frac{R_N - R_{\text{cr}}}{A_e} \right)}{\Delta d} \right] - \frac{(R_N - R_{\text{cr}})}{A_e} \quad (5.14)$$

where

$$\Delta d = \sqrt{H_{\text{right}}^2[i] + HW_{\text{total}}^2 - 2(H_{\text{right}}[i])(HW_{\text{total}})\cos(\zeta_{\text{se}})} \quad (5.15)$$

If shadowing occurs, then there is no multipath contribution for the given search range R_N .

Figure 5.3 Shadowing Geometry

5.2.5 Antenna Patterns

In this section, the transmit and receive antenna patterns for the propagation model are described. The antennas are represented by rectangular apertures corresponding to the antennas employed in the river trials. Referring to Figure 5.4, the far field pattern $f(\theta)$ for a rectangular aperture is described by sinc functions for both the azimuth and elevation planes, given as [21]

$$f(\theta) = \frac{\sin\left[\frac{kA}{2}\sin\theta\right]}{\frac{kA}{2}\sin\theta} \cdot \frac{\sin\left[\frac{kB}{2}\sin\phi\right]}{\frac{kB}{2}\sin\phi} \quad (5.16)$$

where θ is the elevation angle and ϕ the azimuth angle referenced to boresight. A and B are the height and width of the aperture respectively, and $k=2\pi/\lambda$ is the propagation constant. In the simulation, the missile or transmit antenna remains laterally aligned with the receive antenna, so that the second term in equation (5.16) is set to unity, except when jogs are introduced, as will be discussed in Section 5.2.6. The aperture length A is derived by setting $f(\theta_b)^2 = 0.5$, yielding,

$$A = \frac{1.393\lambda}{\pi \sin(\theta_b/2)} \quad (5.17)$$

where θ_b defines the angle at which the power level of the pattern is 3 dB down from its boresight peak. The radar antenna power gain for the direct signal travelling in path $R_d[i]$ is

$$G_R(\theta_s) = D f^2(\theta_s) = \frac{4\pi AB}{\lambda^2} \frac{\sin^2\left[\frac{\pi A}{\lambda}\sin(\theta_s)\right]}{\left[\frac{\pi A}{\lambda}\sin(\theta_s)\right]^2} \quad (5.18)$$

where D is the maximum directivity of the rectangular aperture antenna [21] and θ_s is the angle created between $R_d[1]$ and $R_d[i]$. The gain factor G_R is applied to the

Figure 5.4 Radar Antenna Pattern

equation describing the total received power at the receiver antennas, given in section 5.2.8. The same calculation is used to to define the radar gain of the reflected signal in path R_{r1} , using angle θ_r . Likewise, the above formula is also used to find the array antenna gain factor $G_A(\theta_0)$ for the direct signal travelling along path R_d and $G_A(\theta_r)$ for the reflected signal travelling along path R_{r2} . For the receive antenna, the term A represents the aperture height of the array horn.

5.2.6 Jog Implementation

As discussed in Chapter 2, a jog is defined as an abrupt disturbance in the pointing direction of the tracking radar's antenna due to intentional electromagnetic interference or jamming. For the purpose of this investigation, antenna jogs are assumed to occur in an arbitrary direction away from the line of sight of the ship, and are limited to angular rates of approximately 10-15°/s, reflecting the maximum tracking slew rate imposed by the antenna servos. The actual jog behavior of the radar antenna, in a realistic scenario, depends on the type of jamming used against the tracking radar.

In the software simulation, a jog is represented by displacing the radar antenna in azimuth according to a cosine function described as,

$$\phi_{\text{jog}} = \phi_{\text{max}} \cos\left(\frac{2\pi t'}{T_{\text{scan}}}\right) \quad (5.19)$$

where

- ϕ_{max} = maximum azimuthal swing of the antenna,
- t' = absolute time synchronized to the beginning of the jog, and,
- T_{scan} = period of the jog.

The user can define the swing rate, extent of the angular swing, and number of jogs desired at a specified range or set of ranges.

As noted in Chapter 2, the rate of fall of the received signal from an antenna

experiencing a jog is also dependent on the HPBW of the radar. The narrower the beamwidth, the greater the rate and extent the signal will fade as the antenna swings away from the LOS to the ship. To derive the amount of signal drop on both the direct and indirect waves, the second sinc term of equation (5.16) is incorporated, where $\phi = \phi_{\text{jog}}$. The radar antenna power gain is then a function of both elevation and azimuth angles, $G_R(\theta_s, \phi_{\text{jog}})$.

As discussed in Chapter 2, the measured rate of fall of the transmitted signal, due to a jog, is also dependent on the characteristics of the receiver. Factors such as the AGC response and sampling rate of the A/D converter determines what signal decay will be measured by the receiver. The dynamic range of the receiver also determines the maximum decay rate that can be measured. For the software model, the sampling rate of 64 ms is used, to replicate the trials data acquisition system.

The next section discusses Fresnel zones, which are used to define the approximate amount of energy radiated from the sea surface.

5.2.7 Fresnel Zone Aperture Definition

Once a tangent plane has been located at a specular reflection point, it is necessary to calculate the amount of energy scattered or reradiated towards the receiver based on the size of the effective surface being illuminated. This is achieved by identifying the area of the surface which is encompassed by the first or dominant Fresnel zone intersecting the surface about the specular point. These Fresnel zones, as described in Chapter 2, are contours impressed on the sea surface, representing a constant path length difference of $\lambda/2$ between the direct and reflected signal. The strength of the reflected EM wave at the receiver is determined by integrating the amplitude of excitation over the entire illuminated surface about the specular point. Since adjacent zones are oppositely phased, the energy scattered from adjacent pairs of Fresnel zones tend to cancel, leaving the area of the first zone as the dominant

scattering region [5].

The concept of Fresnel zones is applied to the propagation model for approximating the size of the 'local' reflecting surface contributing to (quasi) specular multipath. As will be discussed below, the Fresnel zone is treated as an aperture, with the appropriate weighting function applied to determine the proper amount of energy reradiated towards the receiver.

The width of the first Fresnel zone W_f , shown in Figure 5.5, is given as

$$W_f = 2(R_{r1})(\tan(\gamma_r)) \quad (5.20)$$

where γ_r is found from solving the following transcendental equation

$$R_{r1}' + R_{r2}' = \frac{R_{r1}}{\cos \gamma_r} + \frac{R_{r2}}{\cos \left(\tan^{-1} \left(\frac{R_{r1} \tan \gamma_r}{R_{r2}} \right) \right)} = \frac{\lambda}{2} + R_{r1} + R_{r2} \quad (5.21)$$

The length of the aperture L_f is obtained by measuring the distance on each side of the specular point where $R_{r1}' + R_{r2}' = R_{r1} + R_{r2} + \lambda/2$. The length coordinate and width of the first Fresnel zone for the river trials configuration are shown in Figure 5.6. As discussed in Chapter 3, the transmit and receive antennas are 167 m and 7.9 m above the mean or datum surface respectively. For a radar distance of 6 km from the receiver, the first zone has a length of 200 m and a width of 6 m. Lowering either the transmitter or receiver antennas has the effect of significantly increasing zone length while only altering the width slightly. As an example, for a new transmitter height of 20 m, the length of the first zone increases to 2000 m, while the width only changes to 12 m.

Although the Fresnel zone is ellipsoidal in shape, it is treated as a rectangle, for simplicity, so that the total area (A_f) of the zone is the product of the width W_f and length L_f . The difference is considered to be negligible, as is discussed later in this section. To determine the amount of energy radiated from a Fresnel zone, a

a) Width

b) Length

Figure 5.5 Aperture Size of First Fresnel Zone

Figure 5.6 First Fresnel Zone Coordinate

scaling factor W_{ap} is used, which is derived from the smooth sea case, using image theory. The model i) simulates a smooth sea, ii) calculates the area of the first Fresnel zone generated by the given geometry, and then iii) determines the amount of incident energy re-radiated towards the receiver (by setting W_{ap}), using image theory, as discussed in Chapter 2. When surface perturbations are introduced, W_{ap} scales the reflected power according to the size of each dominant Fresnel zone. As the Fresnel zones become smaller, less energy is radiated from the surface accordingly. Various heights and ranges of the transmitter and receiver are tested to ensure that the effective aperture produces the proper reflected field strengths in each case. To illustrate this, the top graph in Figure 5.7 depicts the reflected field strength, both simulated and theoretical, for a transmitter height of 167 m and a receiver height of 8 m. In the second graph, the transmitter is 30 m above the surface, while the receiver is 8 m. In both instances, the required field strength for the reflected wave agrees with that predicted by image theory, serving as a validation for the propagation model representing the ideal smooth sea case.

As mentioned, when perturbations on the surface are present, local Fresnel zones are produced about the specular points, as shown in Figure 5.8a. Each of the zones represent a portion of the first Fresnel zone corresponding to the flat sea case, depicted in Figure 5.8b. The width of the individual zones from the rough sea is equivalent to that of the smooth sea. The lengths, however, vary according to the formula given above. Since the area of each zone represents a subset of the area of the 'smooth sea' Fresnel zone, then the maximum amount of power radiated for each quasi-specular point is also a subset of the energy radiated from the 'ideal' smooth surface. To test the sensitivity of W_{ap} on the overall scattering profile, several different values were implemented in the model. It appears that the amount of energy reflected from each crest is not critical, whereas, the relative phase of each scattered signal is important. Based on this, the Fresnel zone approach is considered to be a reasonable approximation.

Figure 5.7 Simulated and Theoretical Reflected Voltages

a) Fresnel Zones for Rough Sea.

b) Fresnel Zones for Smooth Sea.

Figure 5.8 Fresnel Zones for a Rough and Smooth Sea.

To provide insight into how small the zones can become when sea swells are present, consider a transmitter antenna height of 167 m and a receiver height of 10 m, separated by a distance of 10 km. The length of the first zone for a swell crest that is located 5 km from the receiver, having a wave height of 1 m and a wavelength of 500 m, is 120 m. For the equivalent smooth sea case, the total length of the zone is 500 m. The difference between these two values becomes larger as the heights of the transmitter and receiver decrease. Hence, a slight perturbation in the surface significantly reduces the effective length of the zones. The amount of energy radiated by each local perturbation is reduced accordingly.

The above is an approximation for calculating the reflected field strength from a specular point. It is not a rigorous representation of electromagnetic scattering effects over the sea surface, but it does help to introduce, in a qualitative sense, the effects of quasi-specular reflections which are known to exist through sea swells. The ultimate goal of the model is to gain insight into the performance of the jog detection algorithm against this type of rough sea condition. Once a general understanding has been gained, sea trials can be performed to determine the ability of the algorithm to discriminate jog fades from actual sea scattering effects.

5.2.8 Total Received Signal

For a given transmit power P_t , the power density P_{dr1} of the indirect field at the reflecting surface or facet is [10]

$$P_{dr1} = \frac{P_t G_R(\theta_r, \phi_{jog})}{4\pi R_{r1}^2} \quad (5.22)$$

where G_R is the power gain of the radar antenna. The effective facet area, as seen by the transmit antenna, is $A_r = W_r L_r \sin(\theta)$, yielding a total received power of

$$P_{\text{facet}} = A_t P_{\text{dr1}} = \frac{A_t P_t G_R(\theta_r, \phi_{\text{jog}})}{4\pi R_{r1}^2} \quad (5.23)$$

The total power reradiated by the facet is $P_{\text{rr}} = P_{\text{facet}} \rho^2$, where ρ is the magnitude of the Fresnel reflection coefficient from $\Gamma = \rho \exp[-j\phi_{\text{rc}}]$. To determine the portion of the power that is reradiated from the facet to the receive antenna, a scaling factor W_{ap} is used, which is derived by image theory. The power density P_{dr2} , at the receiver antenna, is given as [10]

$$P_{\text{dr2}} = \frac{\rho^2 P_{\text{facet}} W_{\text{ap}} S_c D_v}{4\pi R_{r2}^2} \quad (5.24)$$

where S_c is the shadowing coefficient and D_v is the divergence factor to account for curved earth effects. The total power that is collected by the antenna is the product of the incident power density P_{dr2} and the effective area in the direction of arrival [10],

$$P_{\text{tr}} = \frac{\lambda^2}{4\pi} P_{\text{dr2}} G_A(\theta_r) \quad (5.25)$$

where $G_A(\theta_r)$ is the power gain for the receive antenna in the direction of θ_r . Assuming that the receive antennas are matched to a 1 ohm load, the voltage received is given as [19]

$$V_r = \left(\frac{\lambda \rho}{4\pi R_{r1} R_{r2}} \right) \sqrt{\frac{G_A(\theta_r) W_{\text{ap}} W_{\text{r}} L_{\text{r}} \sin(\theta) P_t G_R(\theta_r, \phi_{\text{jog}}) S_c D_v}{4\pi}} \quad (5.26)$$

The total phase of the reflected signal with respect to the transmitter position is

$$\phi_r = \frac{2\pi}{\lambda} (R_{r1} + R_{r2}) + \phi_{\text{rc}} \quad (5.27)$$

where ϕ_{rc} is the phase of the reflection coefficient of the sea surface. Since there are N specular reflections for a given missile range R , the total reflected voltage is

$$V_{\pi} = \sum_{n=1}^N V_r e^{j\phi_r} = \sum_{n=1}^N V_r (\cos\phi_r + j\sin\phi_r) \quad (5.28)$$

The voltage contribution from the direct signal is

$$V_d = \sqrt{P_d} = \frac{\lambda}{4\pi R_d} \sqrt{P_t G_R(\theta_s, \phi_{log}) G_A(\theta)} \quad (5.29)$$

where the above variables have been previously described. Adding phase information to the direct signal yields

$$V_{dt} = V_d e^{j\phi_d} = V_d (\cos\phi_d + j\sin\phi_d) \quad (5.30)$$

where $\phi_d = 2\pi R_d/\lambda$ is the phase of the direct signal measured from the transmitter antenna. The total power received is given as

$$P_{total} = 10 \log \left[(\Re \{V_{dt} + V_{\pi}\})^2 + (\Im \{V_{dt} + V_{\pi}\})^2 \right] \quad (5.31)$$

A bias of 60 dB is added to the simulated data, so that the power levels from both the simulation and trials are equivalent. The discrepancy is due to the model not including the amplifiers in the ELAT receiver. Since absolute power levels are not important to this study, all power levels are expressed in dB. In the next section, the results from the propagation model are presented and compared to the trials data.

5.3 SIMULATION RESULTS AND VALIDATION

In this section, the results from the propagation model are presented and compared with the experimental data. The known parameters of the experiment, such as the transmitter height, speed and range, antenna characteristics, sampling rate of the digital receiver, etc., are incorporated into the model so that a one-to-one comparison of both sets of results can be made. Refer to Table 4.1 for a listing of

the parameters implemented in the trials.

For a proper comparison of the data, graphs are presented which depict the mean and standard deviation of the measured power and its first order time derivative. As discussed in the previous chapter, the jog detection algorithm utilizes the derivative of the received signal for processing. For the mean and standard deviation graphs, a sampling window of 100 points is used, which corresponds to a range cell of approximately 200 m for the given helicopter speed of 32 m/s. The window moves in range, one point at a time, processing 100 data values each time.

Figure 5.9 depicts the received power and derivative of received power from the model replicating the trials configuration (the top left and top right graphs respectively). The bottom graphs are the responses of the corresponding trials data, obtained from run 2, horn 2 (see table 3.1 for more information on the various experimental runs). As already discussed in Chapter 4, the power response from the experiment does not exhibit a multipath profile that is indicative of a perfectly smooth surface. Multipath fades from a flat surface occur very regularly, gradually increasing in rate as the relative range between the transmitter and receiver decreases (see top left graph in Figure 5.13).

The trials response, on the other hand, contains a few fades that are irregularly spaced, such as that found at 5.4 km. Although this difference is minor, it does imply that another scattering component, in addition to the specular one, has entered the receiver. One possibility is that a slight portion of the land was illuminated, which generated an extra reflecting field. Another possibility is that the surface of the river may have had a peculiar undulation, and hence, was not perfectly smooth. To account for this, a slight height perturbation of 0.1 m was introduced on the water surface in the software model. The perturbation was represented by a sea swell undulation, with a wavelength of 1500 m. The general characteristics of the two sets of results are quite comparable. As discussed already in Chapter 3, the ELAT data acquisition system introduced noise and intermittent drop outs in the

Figure 5.9 Simulation Results Compared With Experimental Results

data, resulting in a profile of signal fades that is not as smooth as that generated by the simulation. Nevertheless, the rate of change of the signal levels are quite similar.

For both cases, fades occurring beyond 4 km are separated by relatively great distances and are deep, averaging approximately 40 dB. At closer ranges, the power fluctuations steadily increase in rate, while the fades become more shallow. Their respective derivatives are also similar, with nominal fluctuations of 150 dB/s within a range of 3 km from the receiver. At a range of less than approximately 1.5 km, similar derivative responses are measured by several of the array antennas at the same time. As discussed in Chapter 4, this is due to the extreme geometry, in which more than one antenna observes the same path length difference, measured in signal wavelengths, for a given transmitter range. Consequently, similar multipath effects are observed. As shown in section 5.5, this ambiguity causes a degradation in the performance of the jog detection algorithm.

A further comparison is made based on the standard deviation and mean of the power responses of both data sets, shown in Figure 5.10. The power levels from the simulation and trials exhibit a standard deviation of approximately 9 dB over the entire range, using a window size of 100 points as discussed earlier. The standard deviation is a measure of how much the signal varies from its mean. The mean response of the received power is depicted in the adjacent graph. As indicated, the mean value steadily increases with decreasing range, reflecting the square law relationship between power and range. A slight mean signal drop in the trials data occurs at the 2.5 km range, which does not appear in the simulation data. This may be due to certain factors prevailing in the trials, which are not accounted for by the model, such as land scattering, or peculiar river perturbations not fully simulated. The last set of graphs, shown in Figure 5.11, are the standard deviation and mean responses of the derivative of the measured power. As indicated, the responses are quite comparable, giving further confidence in the propagation model.

For rough sea conditions, simulation results are compared with actual sea

Figure 5.10 Standard Deviation and Mean of Received Power

Figure 5.11 Standard Deviation and Mean of Power Derivative.

scattering effects obtained from low angle tracking radar experiments conducted at sea [22]. In the trials, the aircraft, carrying the radar, flew at an altitude of 133 m and at a velocity of 410 km/hr, towards a ship equipped with a single receiving antenna, placed 10 m above the water. The sea swell peaks were estimated to be 0.5 m above the datum, with a wavelength of approximately 300 m. The results from the simulation and experimental runs are shown in Figure 5.12. As seen, the multipath effects are comparable in both cases, indicating that the model is a reasonable approximation for this type of rough sea state. Of course, additional sea trials are needed, where precise measurements of sea conditions are carried out, so that a one-to-one comparison between simulated and sea trials results can be performed.

Collectively, the above comparisons of statistical data and sea trials results represent additional forms of validation of the simulation model, as the first involved comparing the model with theoretical results for the smooth sea case. In the next section, the general effects of sea swells are introduced in the model.

5.4 SEA SWELL EFFECTS

In Figure 5.13, the effects of sea swells on the received signal, as simulated by the model, are shown for varying sea swell wavelengths. The simulation is configured to represent the trials set-up, with the transmitter approaching the receiver at a speed of 32 m/s (117 km/hr). For each run, the sea swell is characterised by an rms wave height of 2 m and a period of 18 s. The top left graph, labelled 'Wavelength=0 m', represents the perfectly smooth sea case. As well, sea swell wavelengths of 500 m, 250 m, and 50 m are simulated. Also included are jog events, which occur at 8, 6, 4, and 2 km. The jogs are represented by a single 15° antenna swing in one direction and back over a period of 2 seconds, yielding an angle rate of 15°/s. Since the wave heights of the sea are generated from statistics, many repeated runs were performed to ensure that the general characteristics of the

a) Power Response From the Sea Trials.

b) Power Response From the Propagation Model.

Figure 5.12 Comparison of Experimental and Simulated Rough Sea MP.

Figure 5.13 Sea Swell Wavelength Effects

multipath phenomenon are observed for a given scenario. To avoid overwhelming the reader with numerous diagrams, only one sample graph from each run is shown.

The extent of the nulls or interference pattern, associated with smooth sea multipath, significantly decreases as the swell wavelengths are reduced. This is due to additional quasi-specular reflections being generated which have relatively equal magnitudes but different phases. The phase variations arise from the different heights of the sea while the time rate of change of the phase is dependent primarily on the velocity of the transmitter for a given sea state. The sea swell wavelength does not appear to be a significant factor in the multipath profile, except to introduce additional specular points, as discussed. To verify this, various simulations were performed in which the heights of the sea crests were set equal while different wavelengths were implemented. It was observed that the resultant reflected field did not change appreciably for varying wavelengths. This confirms the findings of Gerry and White [19], who developed a sea reflection model to investigate the low angle radar tracking problem.

As shown in the top left graph, the response from the smooth sea multipath profile exhibits a sudden drop in signal strength at approximately 1.2 km. This is due to the direct signal and specular reflection entering the nulls of the receiver antenna pattern simultaneously. Since all channels of the array observe relatively the same signal fade, due to the antenna pattern, the jog detection algorithm may incorrectly interpret the dip in signal as a jog event. However, as mentioned already, the jog detector may not be required at this range. When sea swells are present, additional specular reflections are produced, which arrive at the receiver at different angles, intercepting different portions of the pattern to provide continuous power. The result is, that the signal null observed at approximately 1.3 km begins to fill in as the sea swell wavelength decreases.

Figure 5.14 illustrates the derivative response for various sea swell wavelengths. The derivative of the received power reduces in magnitude as the sea

Figure 5.14 Derivative Response of Sea Swell Wavelength Effects.

swell wavelengths decrease, due to the averaging effect described above. For a swell wavelength of 500 m, the derivative fluctuates rapidly, extending beyond 100 dB/s for most of the time. For a wavelength of 50 m, the derivative exhibits average fluctuations of 50 dB/s, except at ranges below 2 km where the geometry is changing quickly relative to the radar's wavelength. Based on simulation results, it appears that more undulations between the transmitter and receiver produces 'noise-like' or diffuse multipath effects, which results in the direct signal becoming the dominant field. This may actually help the jog detector to perform more effectively, as is discussed in the next section.

The effects of different rms heights of the sea swell are shown in Figure 5.15, in the absence of jogs. Both the power response and derivative of the received signal are depicted for sea swell heights of 1 and 4 meters (with 500 m wavelengths). The sporadic deep nulls associated with the 1 m swells are not present with the 4 m swells. As well, the average depth of fluctuation is slightly lower for the 4 m sea swells. This is due to a greater number of height variations in the 4 m swells, which produce reflected signals having large phase dispersions. The result is an averaging effect, as discussed earlier. The deep nulls occur when the combination of sea heights are such that the individual scatterers add coherently, producing a total phase that is approximately opposite to the direct signal. The 1 m and 4 m sea heights correspond to a sea state of 3 (slight) and 5 (very rough) respectively.

In the next section, the jog detection algorithm is applied to the data obtained from the model simulating various sea swell effects.

5.5 JOG DETECTION VERSUS SEA SWELL MULTIPATH EFFECTS

Various sea swell scattering effects are tested on the jog detection algorithm, to determine if spatial diversity is a viable technique for discriminating jogs from multipath fades in quasi-rough sea conditions. For the perfectly smooth sea case

Figure 5.15 Sea Swell Effects for 1 m and 4 m rms Heights.

(Figure 5.13), visual detection of jogs is not difficult, providing they do not occur during a multipath fade. The observer can follow the 'normal' multipath profile and recognize precisely when a sudden null or drop in signal strength appears out of place. As noted earlier, the jogs occur at 2,4,6, and 8 km in range. For passive receivers, it is extremely difficult to reconstruct the multipath profile so as to determine the presence of these irregularities, since no information is available regarding the height or range of the transmitter relative to the receiver. Refer to section 4.2 for a more complete discussion on the prediction of multipath fades. The spatial diversity technique, for the proposed jog detector, works well in this case, since it does not need the additional target information. Several simulation tests were performed for different geometries over the smooth sea, and in all cases, the jog detection algorithm successfully identified the jogs. At shorter ranges (< 1.5 km), false jogs were read due to the ambiguous signal path lengths measured by the receiving antennas. Recall, from Chapter 4, that similar phase readings of the reflected signal, by each antenna, results in ambiguous jog measurements.

The detector was evaluated against rough sea multipath effects, using the same geometry as the trials set-up with an initial range of 10 km. The power response is shown in Figure 5.16 for a sea swell rms height of 4 m, a wavelength of 500 m, and a period of 18 s. The jog is represented by a 15° antenna swing in one direction and back over a period of 2 seconds. In the bottom graph, the output of the jog detection algorithm is shown. The asterisks indicate the known locations of the jogs computed by the program. The detector successfully located each jog, using the data obtained from receive channels 1, 5, and 8, and a criterion or threshold value of -45 dB/s. A false jog was read at approximately 4.3 km, due most likely to the path length ambiguity problem discussed above. The performance of the detector is impressive, considering the extent in which the jog fades blend in with the multipath fluctuations.

When the threshold value is increased towards zero, false jogs begin to

Figure 5.16 Jog Detection Performance Against Rough Sea Multipath

appear. To illustrate this, Figure 5.17 depicts the response of the jog detection algorithm for threshold values of -45, -25, -10, and 0 dB/s. The false jogs begin to appear at around the -30 dB/s mark, increasing significantly towards $V_t = 0$ dB/s.

The -30 dB/s criterion indicates the minimum jog rate that can be detected by the algorithm for this given scenario and sea state. Consequently, the radar antenna has to undergo the necessary swing rate and angular extent to cause the measured signal to decay at a rate faster than -30 dB/s. As discussed in Chapter 4, for typical radar systems employing half power beamwidths on the order of 5 degrees, a jog rate of 15°/s can produce a signal decay rate as large as 200 to 300 dB/s. Based on this, the jog detection system should be very effective against this type of antenna.

Unfortunately, a 5° antenna could not be employed in the trials, because of the difficulty there would be in holding an antenna perfectly steady towards the ELAT receiver from the helicopter. Any slight movement by the operator or helicopter, would have caused the signal to fluctuate considerably at the receiver due to the relatively narrow 5° beamwidth. As a result, a 12° horn was chosen to avoid this problem.

Jogs that result in a signal decay of less than 30 dB/s are unlikely to be detected for this type of rough sea condition. This can occur if the antenna moves less than a HPBW in one direction or if the swing rates are low (less than 15°/s for the 12° horn, or less than 3-4°/s for the 5° horn). Refer to Chapter 4 for a discussion on the effects of different jog rates and angular limits on the received signal.

To determine the ideal number of receiving antennas required for the detector to operate effectively against various sea states, 1 to 8 antennas (equally spaced apart) were tested in the model. Three antennas provided the best performance. Additional antennas decreased the probability of all channels observing the same jog profile simultaneously. When a jog takes place, some channels may coincidentally experience the same fluctuation in received power level due to multipath effects. If

Figure 5.17 Detection Status for Different Threshold Values.

the fluctuation is sufficiently acute, it may mask the jog effect, preventing proper detection, i.e. the decrease in received signal strength may be compensated by a coincidental increase in the total received power resulting from multipath effects. Thus, for simulated rough sea conditions, increasing the number of antennas does not appear to improve the performance of jog detection. Different separation heights of the antenna array were also implemented to determine the optimum configuration for various sea states and geometries. The performance of the jog detector remained relatively unchanged for the various separations. For the simulation, a nominal separation of 0.125 m was chosen, to match the antenna array design of the ELAT system.

Different radial velocities of the transmitter were also tested to determine the subsequent impact on jog detection. For the trials configuration, it was observed that the rate of fluctuations of the received power increased when the transmitter speed changed from 32 m/s (117 km/hr) to 330 m/s (Mach 1). This caused some true jogs to be missed and some false jogs to be read, as shown in Figure 5.18. This implies that the speed of the transmitter platform should be considered when selecting the appropriate threshold value. When the speed is increased, the rate of fluctuation of the multipath fades also increases. Consequently, the threshold value may have to be raised.

Figure 5.18 False Jog Readings Due To Increased Transmitter Velocity

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY OF RESULTS

A jog detection algorithm has been developed which is effective in discriminating generated jogs from multipath fades in the power response of microwave signals originating from a transmitter, flown low over the water surface. The technique is based on spatial diversity, and uses the first-order time derivative of the input signal to extract jog information from multipath. The algorithm makes use of the property that multipath fades vary with changing height of the receiver, while jogs produce fades that are independent of height. To properly test the jog detection algorithm, river trials were performed with a helicopter, equipped with a beacon source, transmitting microwave signals towards DND's Experimental Low Angle Tracking (ELAT) receiver located at Shirley's Bay. Jogs were simulated at various ranges along the river, which combined with the multipath effects to produce a mixed signal response at the receiver.

The jog detection algorithm identified most of the jog fades introduced in the trials, while rejecting 'smooth surface' multipath fluctuations closely resembling jog fades. At near ranges between the transmitter and receiver (less than 1.5 km), periodic false jogs were read as the helicopter flew inwards. This is due to each receiving antenna measuring the same integral number of wavelengths of the reflected radar signal, resulting in similar power fades being recorded in each channel of the detector. When the detector observes the same power drop in each channel, it assumes that a jog has taken place.

Based on the jogs introduced in the experiment, the optimum jog detection threshold value was found to be between -15 to -20 dB/s, for a 12° transmit antenna. Each jog was generated by an antenna swing of 15° in one direction and back at a rate of 15°/s, to produce a signal fluctuation, at the receiver, of approximately -20 dB/s. For lower detection threshold values, the algorithm triggered on erroneous effects such as i) slight movements of the transmit antenna which were not intentional jogs, ii) diffuse reflections originating possibly from land scattering or undulations in the river surface, and iii) noise in the receiver. For a typical missile antenna employing a smaller beamwidth, say 5°, the signal decay can be greater than 200 dB/s for the same antenna swing rate and extent. Therefore, the jog detection algorithm is expected to be very effective in identifying jogs produced by this type of antenna, against smooth sea multipath disturbances. To produce adequate signal fades, which are deeper than the fades generated by the erroneous effects, the antenna must experience angle swings on the order of a beamwidth during a jog.

To test the jog detection algorithm against typical rough sea multipath effects, which are not obtainable from the river, a relatively detailed software model was developed which simulates, among other things, the general effects of sea swells. Sea swells, as reported in the literature, are ocean waves that are smooth and regular, characterized by relatively large wavelengths, to produce quasi-coherent specular reflections. The resultant multipath effects cause the received signal to fade rapidly and deeply, completely concealing the jog fades. As a form of validation of the model, three types of comparisons were performed: i) ideal smooth surface simulation results versus image theory results, ii) simulation results of the propagation trials over the river versus measured experimental data and iii) simulation results for the rough-sea condition versus actual sea scattering data. In all cases, the simulation produced results which were highly comparable, giving confidence in the propagation model.

Using the propagation model, various sea states were simulated to determine

the effects of rough sea on the power response of the received signal. It was observed that as the wavelength of the sea swell decreases, the rate of fluctuations of the received signal increases, while the fades become more shallow. For sea swell wavelengths of 50 m or so, the multipath effects resemble diffuse scattering, in which the fades appear 'noise-like'. In this 'noise-like' environment, the jog fades are easy to visually detect. When the rms height of the sea swell increased, the depth of the multipath fades decreased. For example, a 1 m sea swell height produced multipath fades that are approximately 40 dB deep, while a 4 m sea swell height created fades that are only 10-15 dB deep. Also, as the wavelength of the sea swells increased, the resultant multipath fades became deeper, while the rate of fluctuations decreased significantly.

The jog detection algorithm was effective against most of the rough sea multipath effects simulated in the propagation model. To provide a critical test of the detector, the worst sea state condition was simulated, in which a sea swell rms height of 4 m and wavelength of 500 m, statistically characterized by a Rayleigh distribution with zero autocorrelation distance between sea swell peaks, was implemented. It was observed that the detector effectively recognized each of the jogs buried in the multipath fades. One or two false jogs were registered, which are believed to be due to path length ambiguity measurements of the reflected signal at each receiving horn. With rough seas, ambiguities are more prevalent due to the different heights of the quasi-reflecting surfaces.

Three antennas, equally spaced about the height of the array, provided the best configuration for the jog detection algorithm operating against simulated rough sea multipath. Additional antennas decreased the probability of all channels measuring identical jog fades, due to the uncorrelated scintillation introduced in each channel from the rough sea reflections.

Different transmitter velocities were tested to determine the subsequent impact on jog detection. For the rough sea, the transmitter speed did not appear to

significantly alter the outcome of detection performance. Using the same detection criterion for the river trials, the speed of the transmitter was increased from 32 m/s to 330 m/s in the simulation. It was observed that only a couple of jogs were missed by the detector, while a few more false jogs were measured. At higher speeds, the multipath signals fluctuate more rapidly, which tends to alter the characteristics of the jog, reducing the chance of each jog fade looking similar at the inputs of the detector. For smooth sea multipath effects, the speed of the transmitter did not affect the overall performance of the spatial diversity technique.

6.2 FUTURE WORK

In the future, it is recommended that trials be conducted at sea, to test the detector against actual rough surface multipath effects, particularly those produced by sea swells. Through sea trials, optimal detection threshold settings can be defined for various sea states. To provide a more complete study, several configurations of the transmitter should be implemented to assess the effects of transmitter speed and height on the performance of the detector. It is also recommended that the receiver, acquiring the data, sample the received signal at a much higher rate than 15 Hz (which is the effective sampling rate of the ELAT system), in order to measure accurately the signal decay rate produced by the jog. If the sampling rate is too low, the receiver measures erroneous signal decay rates which may hamper the performance of the jog detection algorithm.

Also, in the future, it is recommended that the jog detection algorithm be evaluated against true jog events, using an active tracking radar system, and applying electromagnetic jamming signals against it to obtain the corresponding antenna perturbations. This will permit the evaluation of the detector against various jog effects, since the antenna generally does not respond in the same manner under different jamming conditions. Also, the effects of multipath on the angle tracking

processing of the radar can be assessed, in terms of its impact on the jog detection algorithm. The antenna will track erroneously, due to multipath, which may cause the received signal to fade sufficiently to produce false jog readings. As well, it is important that the radar antenna have a half-power beamwidth (HPBW) on the order of 5° , rather than the 12° as provided by the beacon antenna used in the trials, so that typical seeker systems are more closely represented.

Also, results from future sea trials can be used to determine how well the software propagation model approximates the general effects of rough sea scattering, specifically sea swells. Close measurements of sea conditions, as well as the trials set-up, must be made in future trials, and the findings incorporated in the propagation model, so that a one-to-one comparison of results can be performed. Changes can be implemented, where necessary, so that the model may be used to estimate the effects of rough surface multipath on the spatial diversity technique for different experimental configurations. In this way, the evaluation process can be performed in a cost-effective and time saving manner.

The most obvious change to the model would be in redefining the formula for calculating the amount of energy re-radiated off the sea surface. In the present model, Fresnel zones are used to approximate the maximum amount of energy that can be reflected from a facet representing a sea swell. This is suitable for this thesis in understanding the general trends of multipath originating from sea swells. However, if it is deemed necessary to model the precise scattering effects of an electromagnetic signal off water surfaces, then a more detailed and mathematically intensive approach is recommended. As well, an extensive description of the sea is required. Other propagation effects, which were not included in the present model, but should be implemented in the future, are ducting effects, diffuse scattering, and depolarization of the reflected signal. Including these phenomena will constitute a more complete study of the effects of multipath disturbance on the performance of the spatial diversity technique for jog detection.

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APPENDICES

APPENDIX A

EXPERIMENTAL LOW ANGLE TRACKING FACILITY

The Experimental Low Angle Tracking (ELAT) Facility located at Shirley's Bay is described in this appendix. As shown in the block diagram of Figure A-1, the ELAT receiver comprises an eight horn vertical antenna array used to intercept incoming signals operating at 8.69 GHz and 9.6 GHz. For now, only the 8.69 GHz portion of the receiver will be discussed. An additional horn is placed adjacent to the array to provide a reference signal for the in-phase and quadrature phase (I and Q) demodulators in the receiver. The array utilizes standard gain horns which have a half power beamwidth of 12 degrees. The first antenna is situated at an optimal height of 8 m above the river surface. The horns are separated by 0.125 m, producing a total vertical height of 0.875 m.

Signals from the eight receiving channels, as well as the reference channel are down-converted to an intermediate frequency (IF) of 30 MHz, using a local oscillator of 8.66 GHz. They are then passed through a low pass filter to remove the intermodulation frequencies created by the mixing process. Each of the eight signals are divided into two channels which are applied to separate comparators. The first comparator mixes the received signal with the reference signal directly (I channel), while the second comparator mixes the received signal with the reference signal shifted by 90 degrees (Q channel).

The eight I and Q channels, which are now at baseband, are applied to a low pass filter to eliminate the higher spurious frequency components. The 16 'clean' signals are sampled at a 1 kHz rate by a 12 bit A/D converter and then digitally integrated over 64 samples before being recorded onto magnetic disk. This results

Figure A.1 Block Diagram of the ELAT Receiver

in an effective sampling rate of 64 ms. Prior to being sampled and integrated, the dynamic range of the I and Q signals is 10.24 volts (+/- 5.12 v). The digital data is then stored as 32 bit real numbers on a floppy disk using PDP 11/73 floating point format.

Although not shown in the figure, the ELAT receiver can process simultaneously two microwave signals, the other one operating at a frequency of 9.6 GHz. The same array is used. However, prior to being downconverted, the eight higher-frequency signals are separated from the lower ones. They are then demodulated and digitized in the same manner as described above, using similar circuitry. Hence, the total number of individual signals received, digitized, and stored on disk by the ELAT receiver is 32 (8 horns x 2 frequencies x 2 I/Q channels).

The ELAT system can be configured to operate in one of two modes: radar or beacon. In radar mode, the ELAT system operates as a radar, transmitting a microwave signal and receiving the subsequent target echo returns. In beacon mode, the ELAT system receives and processes signals emanating from an external source. The beacon mode was implemented for the propagation experiment, in which an 8.69 GHz CW transmitter was fitted on board the helicopter and flown radially towards the ELAT facility.

APPENDIX B

PROGRAM PARAMETER LISTING

The following is a list of parameters included in the propagation model. The numbers in the brackets () are the default values generated by the program.

1)	Loop Time(10 ms):	Time step of the simulation.
2)	Radar Frequency (9 GHz):	Radar operating frequency.
3)	Radar Beamwidth(12°):	Transmit antenna beamwidth.
4)	Include jogs? (yes):	Do you wish to include jogs.
5)	Scan Angle of jogs (15°):	Maximum jog perturbation.
6)	Scan Period of jogs (2s):	Period of jogs.
7)	Ranges of jogs (every 1 km):	Range where jogs occur.
8)	Number of jogs (1):	Number of jogs at each specified range.
9)	Height of the missile (20 m):	-
10)	Speed of the missile (330 m/s):	Typical missile speed is mach 1.
11)	Height of 1 st array antenna (8 m):	Height of receive antenna above mean water level.
12)	Separation between Rx antennas (.2 m):	Separation between each array antenna.
13)	Beamwidth of array antenna (12°):	BW for each array antenna.

14)	Initial range of missile (20 km):	-
15)	Include sea swells (SS)? (yes):	-
16)	SS rms height (1m):	Height of sea swell above mean surface.
17)	Rayleigh/Constant SS (R):	Rayleigh distributed or constant sea heights.
18)	SS period (18 s):	Time period of sea swell.
19)	SS wavelength (500 m):	Sea swell propagation wavelength.
20)	Include ship motion? (yes):	-
21)	Damping factor of ship (60%):	Defines the extent of ship roll due to the waves.
22)	Tolerance of search angle (.0001%):	Precision for finding specular points.
23)	Range step size RN (1 m):	Search range step size for finding θ .
24)	Electrical properties of water:	To define ϵ_r .
25)	Divergence Factor:	A function of grazing angle.
26)	Flat or Curved Earth?:	-
27)	Refraction Effects ($k=4/3$):	Changes Earth's effective radius.
28)	Fresnel Zone Weighting (386):	Scaling factor for effective aperture size.

APPENDIX C

FUNCTIONAL HIERARCHY OF THE PROPAGATION MODEL

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