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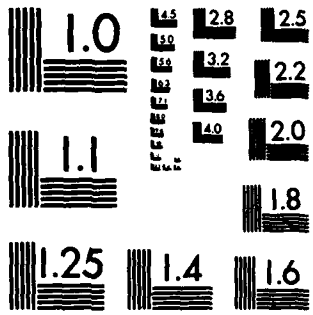

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer software model for a space based radar system is described. The model includes algorithms for estimating ship and aircraft radar cross sections, land and sea clutter, and effects caused by jamming. The model includes a resource scheduler which considers prime power and time availability to assign radar coverage of specific regions to a satellite.

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CONTENTS

A GENERIC SPACE BASED RADAR MODEL WITH RESOURCE SCHEDULER

1.0 INTRODUCTION

A computer simulation program that can be used to evaluate space radar configurations in a realistic environment is described in this report.

The Space Radar Model (SRM) is part of the Ocean Surveillance Integration Model (OSIM). OSIM permits simulation of various ocean surveillance systems for the purpose of studying Navy ocean surveillance problems. Key aspects of the operating environment such as sensor capabilities, threats, supporting systems, and background traffic can be modeled.

A statement of work for software development of SRM was released in the summer of 1981. Subsequently, a contract for the development of SRM was awarded to General Research Corporation of Santa Barbara California.

The resulting software was delivered in December 1981 and installed on a DEC VAX 11/780 computer at NRL. During January to March 1982, the delivered subroutines were integrated into OSIM and underwent a phase of validation during which various segments of the SRM were evaluated for proper operation.

The SRM can simulate the detection of aircraft and ships by space-based radars. This model provides a more detailed satellite radar sensor model for OSIM than did the previous model which had been based on a previous space radar concept.

1.1 General Description of the Space Radar Model

The operation of a large number of satellite radars may be simulated by the SRM. Input data define the characteristics of each radar, each radar

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antenna, and each satellite power supply system. In addition, several radar jammers may be defined in a simulation run.

SRM processes requests for radar coverage of specified regions which are known as Tactical Control Areas, or TCAs. These coverage requests may be "one-time looks" (e.g., an updated surveillance picture for a task group), or they may be routine requests for coverage of a barrier or choke point for which repeated coverage is desired. One-time looks take precedence over routine coverage and may "bump" lower priority radar operations if necessary for scheduling. Although radar requests are usually defined at the beginning of a simulation run, they are only made known to SRM as the simulation unfolds. A radar operation will be scheduled to satisfy a specific request provided that: (1) the region is visible to one or more radars; (2) there is no conflict with higher priority operations already scheduled; and (3) the new operation will not cause the satellite's battery charge to drop below a minimum value.

Requests for radar coverage may be made for the area of interest (AOI) being examined or for one or more background areas. Radar operations for both AOI and background requests are scheduled in the same way. However, only AOI operations are actually simulated. For background requests, system power and resource time is deducted from total power and time available as if the areas had been scanned by the radar.

The SRM begins its operation by scanning through a list of aircraft and ships currently "in view" of a satellite. It discards those that are not within the TCA and computes the detection probability on the ones remaining. The computed detection probability is used in a Monte Carlo random draw to simulate detection. If a target is detected, a perturbed location and associated error ellipse are reported. Running totals are maintained of targets in the AOI, targets in the TCA, targets detected, and targets missed during the course of the simulation run. Separate tallies are kept for each type of target. The four current target types are combatant and background ships and combatant and background aircraft.

Because the design of the SRM was constrained to meet an execution time objective, some approximations have been made in the SRM which may affect the fidelity of the simulation. However, these approximations are clearly marked in the SRM code, and are described in this report.

SRM and OSIM run on NRL's VAX-11/780 computer system. The SRM software is written in VAX-11 FORTRAN, and it uses the VAX virtual memory system to handle dynamic lists used for radar scheduling. Because it has been written so explicitly for the VAX, it would be difficult to transfer the SRM code to any other computer system lacking comparable features.

1.2 Approximations made to decrease execution time

The most significant approximation within SRM involves the calculations for jamming and clutter. Each of these calculations is made only once for an entire TCA (coverage region), rather than once for each target in the TCA. The satellite radar is assumed to be fixed at one point for an entire radar operation. This fixed point is the location of the satellite for the midpoint of radar operation. The radar antenna beam is then assumed to be pointed at the center of the TCA for calculations of land and sea clutter cross section and the total jamming interference.

2.0 SRM MODELS

2.1 Coordinate Systems And Units

SRM uses three different Cartesian coordinate systems. The basic coordinate system, shown in Fig. 1, is an earth-center system. The x-axis lies in the 0-degree longitude plane, the y-axis lies in the 90-degree-east longitude plane, and the z-axis passes through the north pole. This coordinate system rotates with the earth.

All transformations between this earth-centered system and a latitude-longitude-altitude system are based on a spherical earth with a

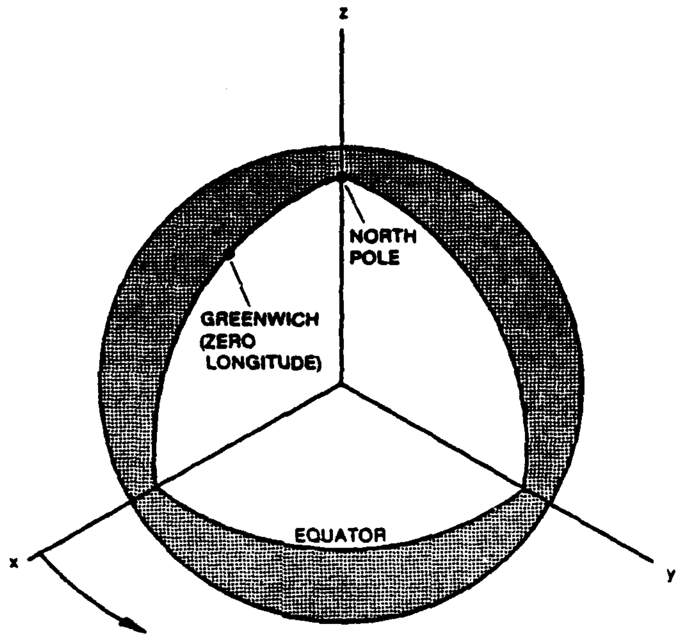

Fig. 1 — Earth-centered cartesian coordinate system

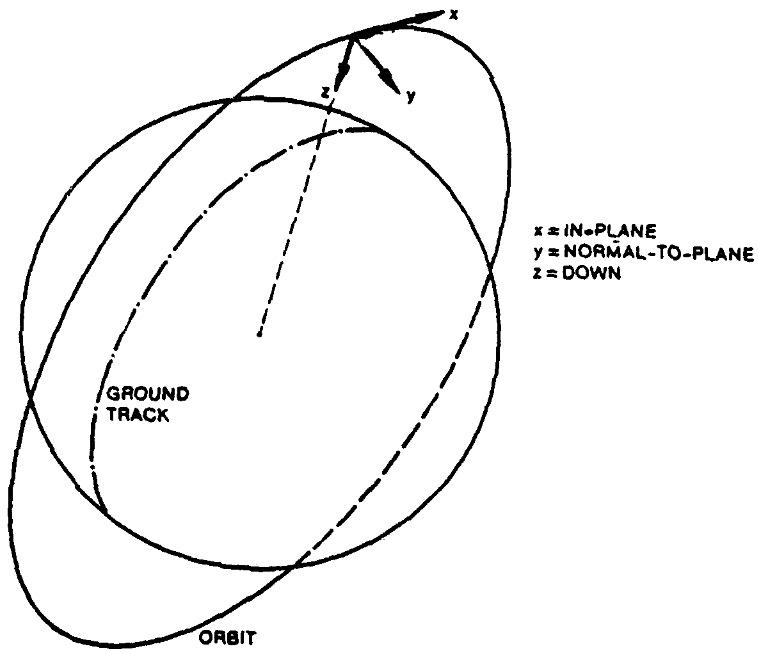

Fig. 2 — Satellite centered cartesian coordinate system

radius of 6,375,180 meters (3,443.931 nmi). The differences between geocentric and geodetic latitude are ignored.

The second coordinate system is satellite-centered and is shown in Fig. 2. In this coordinate system the z-axis points down toward the center of the earth; the x-axis lies in the orbit plane, generally in the direction of the velocity vector but exactly orthogonal to the z-axis; the y-axis is normal to the orbit plane and orthogonal to both the x-axis and the z-axis. This coordinate system is centered on the satellite position at the midpoint of an observation interval. Strictly speaking, the origin of the coordinate system should shift incrementally to correspond with the exact satellite position for each measurement of a target. However, defining a single position is a simplification that makes the program run much faster, and it is not a bad approximation if the observation interval is not too long.

The third Cartesian coordinate system, shown in Fig. 3, is used when a target has been detected. This system is centered on the target with the x-axis pointing east, the y-axis pointing north, and the z-axis pointing up. Locating the satellite in this system allows the orientation of the error ellipse to be computed.

In the earth-center and target coordinate systems, bearings are measured clockwise from north. In the satellite coordinate system radar azimuths are measured from the x-axis with the azimuth of the positive y-axis being +90 degrees. In the satellite and target systems elevation is measured from the x,y-plane, and the z-axis lies at +90 degrees in both systems.

2.2 Tactical Control Areas

A Tactical Control Area (TCA) is a region on the earth's surface for which radar coverage is requested. A TCA is defined by a center point (latitude and longitude), inner and outer radii, and two azimuth limits. This is illustrated in Fig. 4.

Background areas, for which energy is expended but radar measurements

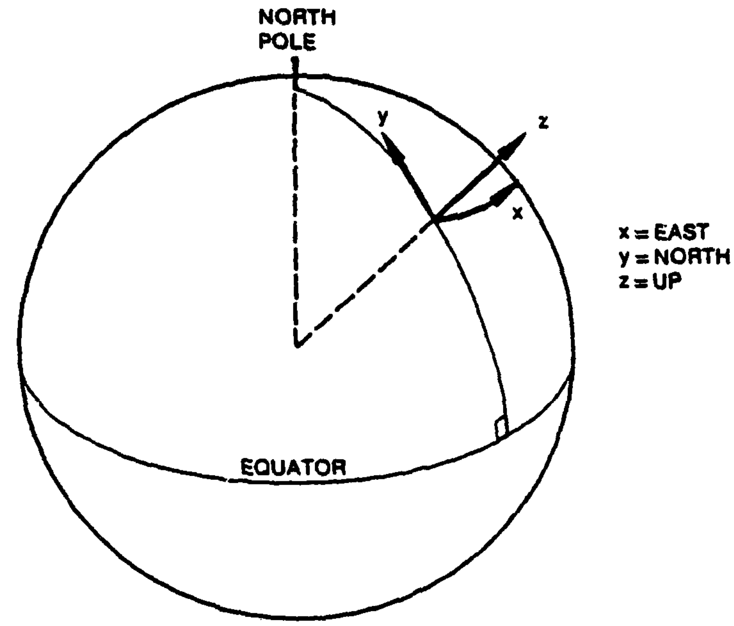

Fig. 3 — Target centered cartesian coordinate system

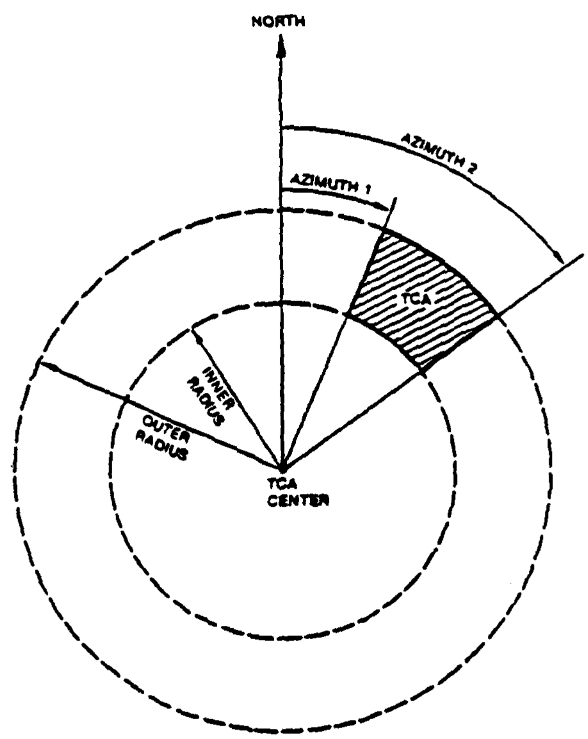

Fig. 4 — Diagram of a Tactical Control Area (TCA). A TCA is defined by a center point (latitude and longitude), an inner and outer radius, and two azimuth limits.

are not actually calculated, are similarly specified.

2.3 Targets

Data describing targets are obtained from two types of sources. First, there are files that contain data on periods of target visibility, from acquisition of target (AOT) to loss of target (LOT), by each satellite. Each record from these files provides the following data on a target:

Target Identification Number
Satellite Identification Number
Ground Station Identification Number
Time Target Comes into View of a Satellite (the AOT)
Target Latitude at AOT
Target Longitude at AOT
Azimuth to Target at AOT
Target Altitude at AOT
Target Heading at AOT
Target Speed at AOT
Time Target Leaves View of the Satellite (the LOT)
Target Latitude at LOT
Target Longitude at LOT
Azimuth to Target at LOT
Target Altitude at LOT

The second source of target data is arrays that are passed as arguments to SRM routines. These provide the length (in meters) of each target.

SRM radar observation events are specified by a turn-on time and a turn-off time. If a target is within the TCA, and if its possible viewing time overlaps the radar's observation interval, then the target is processed for possible radar detection. The first step is to pick a detection time centered in the radar's observation interval, and to interpolate to find the target's position vector in earth-centered coordinates at this time. The target is assigned a velocity vector defined by its speed and heading at the beginning of the viewing interval.

The sole parameter describing the target is its length. This is used to compute the radar cross section of ships and aircraft as shown below.

Ship RCS. The radar cross section (RCS) model for ships computes an average RCS as a function of frequency and the displacement of the ship[1]. This formula is:

$$\sigma = 5.2 \text{ X } 10^{-2} f^{1/2} D^{3/2}$$

where σ is the RCS is square meters, f is the radar frequency in hertz, and D is the displacement in kilotons. An approximation to a ship's displacement as a function of its length was derived by fitting a curve to [illegible] data from Jane's Fighting Ships. This approximation is:

$$D = 2.5 \text{ X } 10^{-6} L^{3}$$

where L is the ship's length in meters. Combining these two expressions yields the formula:

$$\sigma = 2 \text{ X } 10^{-10} f^{1/2} L^{9/2}$$

This formula is used for all ship RCS calculations in SRM. RCS versus radar frequency is plotted for several values of ship length in Figure 5.

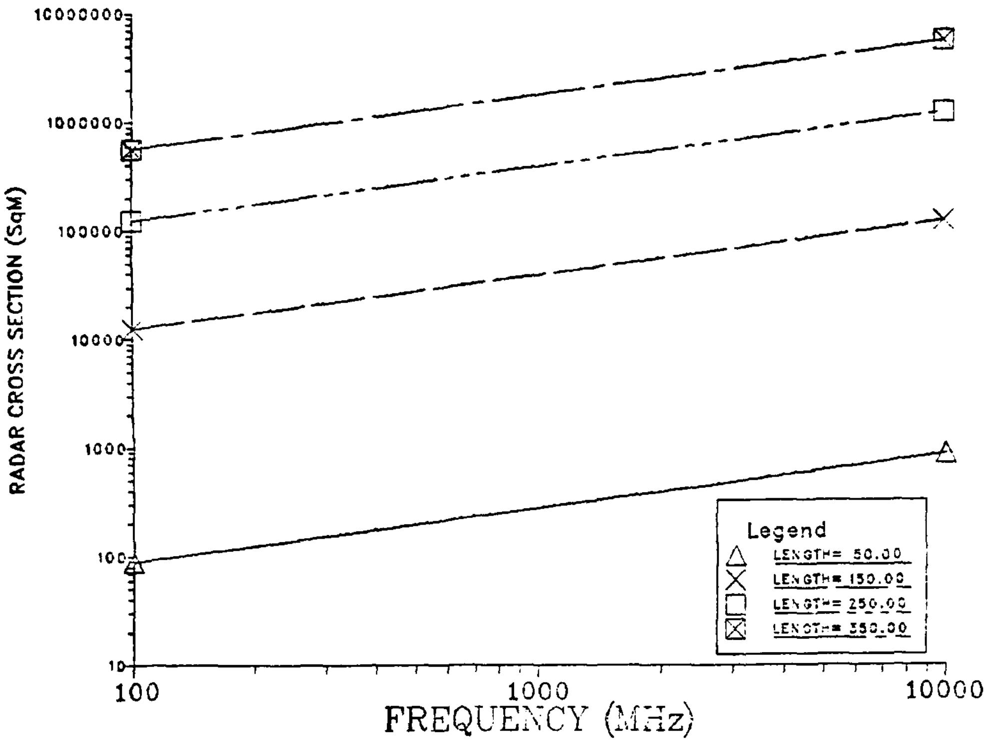

Fig. 5 — Plot of ships' radar cross section versus frequency for various ship lengths

Table 1 — SRM Aircraft Radar Cross Section Model Values of length and RCS for selected Soviet aircraft

AIRCRAFT TYPE	LENGTH (Meters)	CROSS SECTION (Meters ^{2})
Backfire	39	15.21
Badger	35	12.25
Bear	44	19.36
Blinder	39	15.21
Flagon	19	3.61
Flogger	16	2.56
Foxbat	20	4.00

Aircraft RCS. The formula used in SRM for aircraft RCS is:

$$\sigma = 0.01\ L^2$$

Table 1 lists the lengths and the computed RCS values for selected Soviet Aircraft.

2.4 Radar Characteristics

The radar model in SRM allows a variety of different types of satellite radars to be modeled by changing only the input data. This section describes the parameters used to model radars and some of the equations used in the radar calculations.

2.4.1 General Radar Parameters

A set of five parameters characterize the detection objectives of the entire set of radars; all are operated to meet these objectives. These parameters are: (1) the desired probability of detection (P_d); (2) the desired probability of false alarm (P_{fa}); (3) the nominal target radar cross section (σ_N); (4) the signal-to-noise ratio $(S/N)_N$ required to achieve the specified values of P_d and P_{fa}; and (5) the number of pulses integrated by the detection algorithm.

These parameters are used in the following way. The radar is operated such that when the received signal-to-noise ratio equals $(S/N)_N$ for an illuminated target of RCS equal to σ_N, the target will be detected with the desired P_d and P_{fa}. (The calculation of radar energy is discussed later.)

A maximum grazing angle value is also specified for the entire set of satellites. This grazing angle limit prevents the radar model from searching for targets in regions where detectability is known to be clutter limited. Scheduling of a request area is not permitted during those times when the grazing angle to the approximate center of the area is greater than the specified value.

The total radar energy required to achieve the nominal detection on targets within a given request area is calculated for each satellite and for each area. The exact calculation requires an integration, but some experiments have shown that a good fit to the exact calculation can be obtained by an expression involving only the area of the region and the altitude of the satellite, in addition to the parameters of the radar. It is instructive to consider the exact calculation.

Suppose that the coverage region is a circle on the earth's surface, and that the center of the circle is displaced from the satellite's nadir point as illustrated in Fig. 6. The radar energy, in joules, of a single beam of solid angle Ω required to achieve nominal detection of targets within the beam is given by the expression

$$E = \frac{4 \pi k T L n}{A \sigma_{N}} \left(\frac{S}{N} \right)_{N} R^4 \Omega$$

in which k is Boltzmann's constant, T is the system noise temperature, L is the system loss factor, A is the effective aperture of the radar, R is the range to the earth at the center of the beam and n is the number of pulses needed to achieve the nominal probability of detection. The range R depends on both the satellite altitude and the scan angle off the satellite nadir. All the other terms in the energy expression are constants. Consequently, the total energy to cover the region can be computed by integrating over the solid angle subtended by the region:

$$E_t = \frac{4 \pi k T L n P_t}{A \sigma_{N}} \left(\frac{S}{N} \right)_{N} \int R^4 d\Omega$$

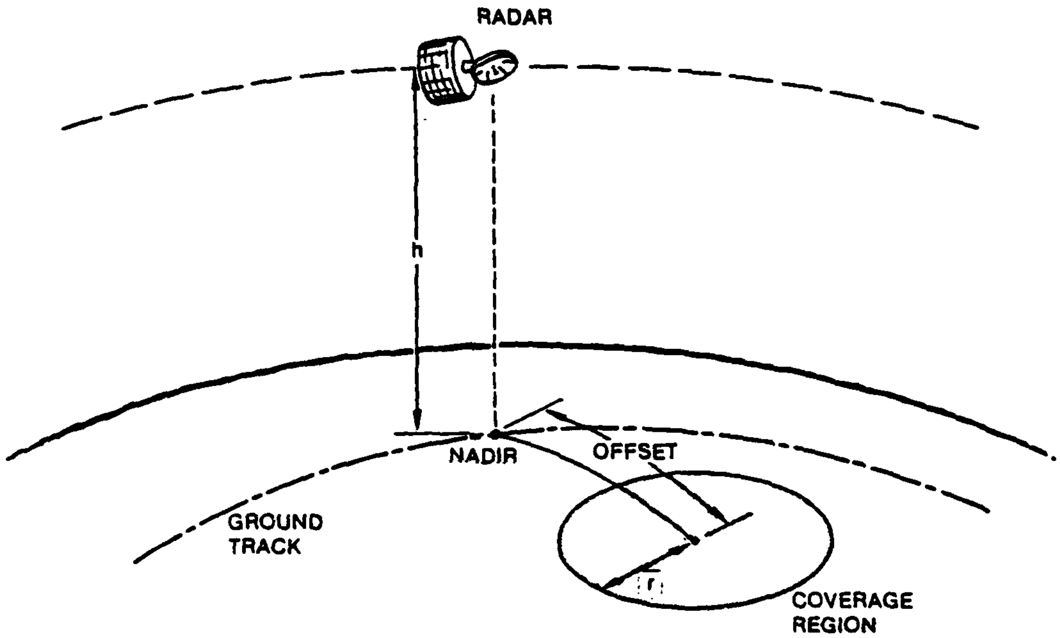

Fig. 6 — Illustration of offset radar coverage geometry for a request area

where P_f is an antenna pattern overlap factor which can take on fixed values of 1.0 or more. A pattern factor of 1.0 represents no overlap, while higher values represent the amount of overlap of the beam pattern.

Calculations of the integral were made for different combinations of satellite altitude, nadir offset distance, and radius of the region. Some of the computed results are shown in Fig. 7. In Fig. 7a the satellite altitude is fixed at 1,000 km (540 nmi). The integral is quite insensitive to the offset from nadir out to about 500 km (270 nmi), then increases by somewhat less than a factor of two up to 2,000 km (1080 nmi) offset, and then drops rapidly as the region approaches the horizon. The broken lines on the figure represent the values of $\pi r^2 h^2$, where πr^2 is approximately the area of the region, and h is the satellite altitude. The approximation is quite good for offsets up to 500 km, and not too bad for any offset. In Fig. 7b, the satellite altitude is 3,000 km (1620 nmi), and the $\pi r^2 h^2$ approximation is extremely good out to 3,000 km offset.

Because the $\pi r^2 h^2$ expression yields such a good approximation to the value of the integral, it is used in SRM to calculate the surveillance energy for any area. For non-circular TCAs, the actual area of the TCA is used in place of πr^2.

2.4.2 Individual Radar Parameters

Each satellite radar in SRM is defined by input data in MKS units. The parameters that describe each radar are the following:

Parameter	Input Units
Radar Frequency	MHz
Radar Bandwidth	MHz
Radar Range Resolution	m
Radar Noise Temperature	kelvin
Radar Loss Factor	dB
Radar Peak Power	W

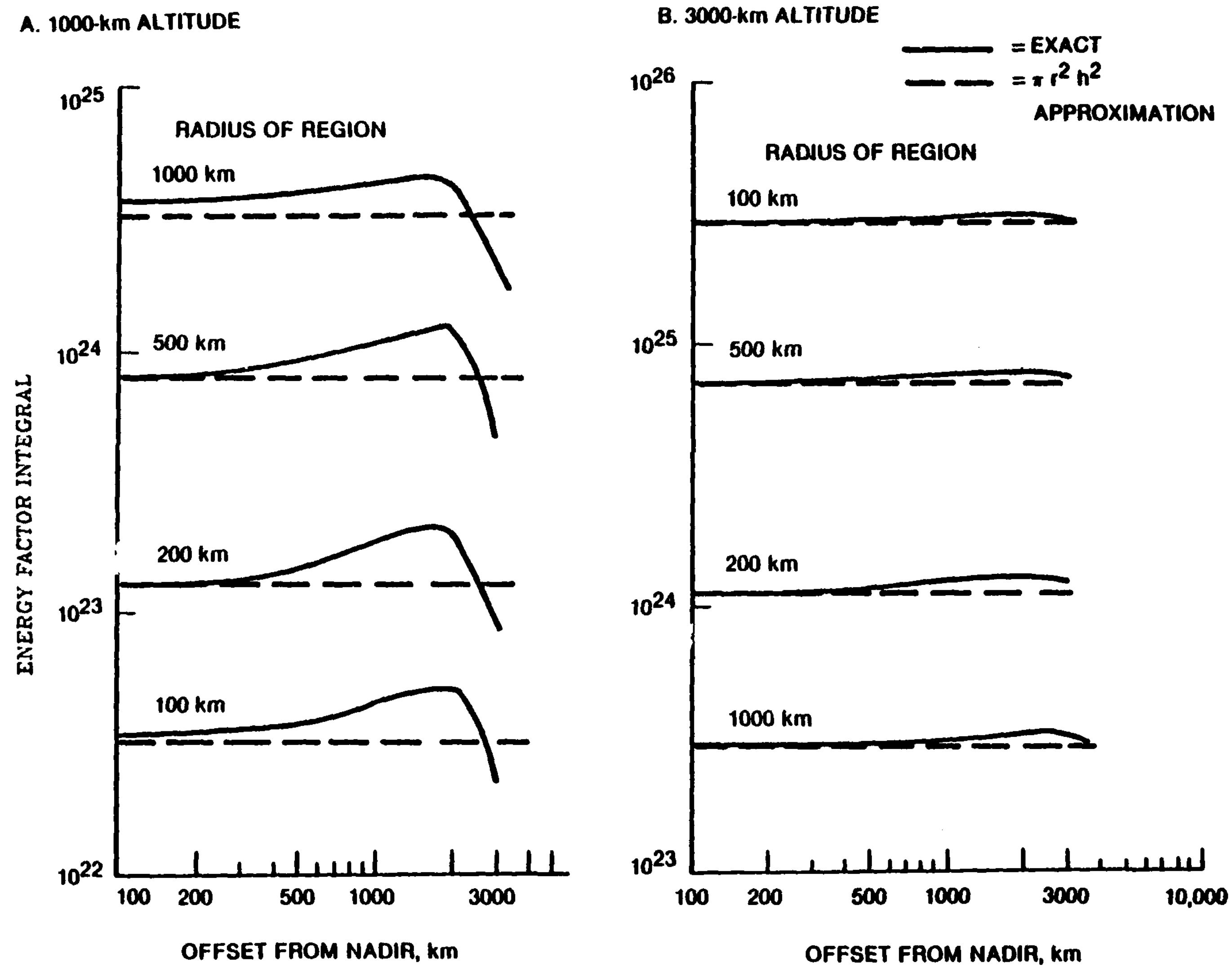

Fig. 7 — Plots of energy required for a radar to cover an area of radius r from a satellite at 1000 and 3000 Km altitude for various values of r. The solid curve is a plot of the theoretical value while the dotted curve represents energy as approximated by the SRM.

Radar Average Power	W
Radar Effective Pulse Length	s
Clutter Rejection	dB
Clutter Rejection Speed	m/s

2.4.3 Radar Antenna

The type and characteristics of each radar's antenna are defined by input data. These inputs are:

Parameter	Input Units
Antenna Type	--
Peak Antenna Gain	dB
Azimuth Beamwidth	deg
Elevation Beamwidth	deg
Azimuth RMS Sidelobe Level	dB
Elevation RMS Sidelobe Level	dB
Mechanical Azimuth Scan Limit	deg
Mechanical Elevation Scan Limit	deg
Electronic Azimuth Scan Limit	deg
Electronic Elevation Scan Limit	deg
Mechanical Slew Acceleration	deg/s^2
Mechanical Slew Speed	deg/s

The one-dimensional antenna pattern model used for SRM is illustrated in Fig. 8. The parameters of the model are the peak gain, the 3-dB beamwidth, and the RMS sidelobe level (measured relative to the peak gain.) The total antenna pattern is the product of two such patterns, one in the azimuth plane and one in the elevation plane; the beamwidth and the sidelobe level may differ between the two, but the peak gain applies tc the composite pattern. Within the mainlobe the power pattern has a $[\sin(x)/x]^2$ shape. The calculation is actually made with the two patterns normalized to unit gain, and then the result is multiplied by the peak gain.

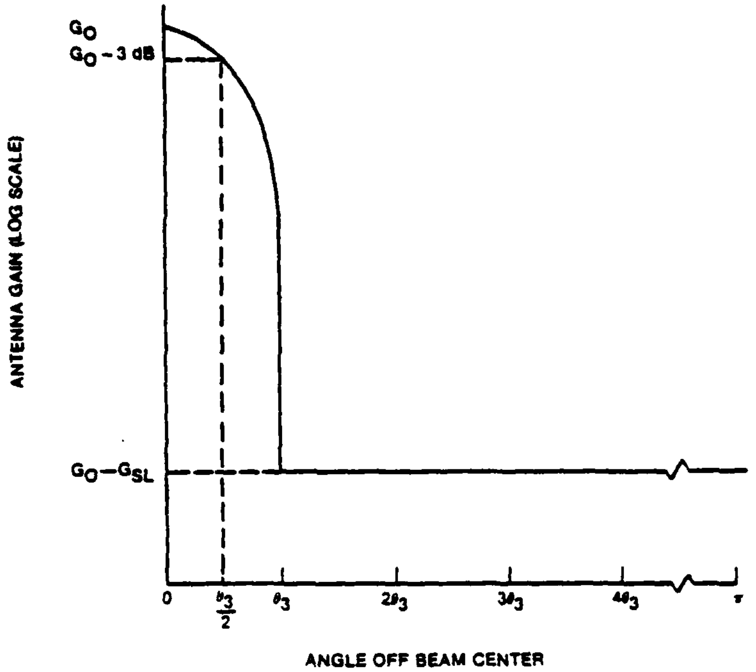

Fig. 8 — One-dimensional antenna pattern as modelled by SRM

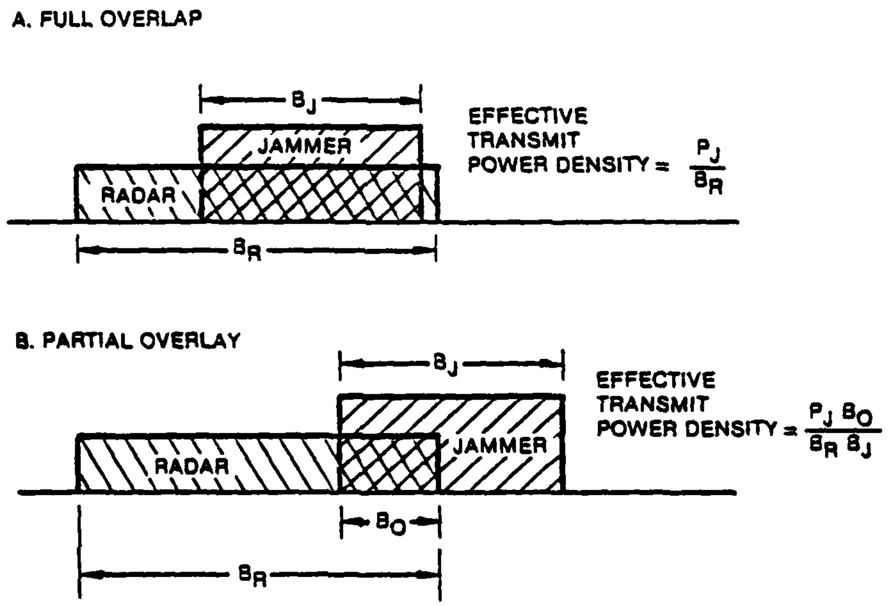

Fig. 9 — Illustration of jammer effective transmit power density for cases of full and partial overlap of jammer bandwidth where $B_O = B_R - B_J$

2.4.4 Radar Factor

For all calculations of target detection within SRM, each radar is characterized by a radar factor F, defined by the expression

$$F = \frac{P_{pk} \tau \lambda^2}{(4\pi)^3 L}$$

where P_{pk} is the peak radar power, τ is the effective radar pulse length, λ is the radar wavelength, and L is the system loss factor. The product $P_{pk}\tau$ is the total radar energy (E) transmitted in the radar beam. The radar factor is used in the following expression to calculate the total energy (S) received from a target:

$$S = \frac{F \sigma G^2}{R^4}$$

where σ is the target radar cross section, G is the antenna gain in the direction of the target, and R is the range to the target.

2.4.5 Interference

Thermal Noise. The energy from a target always competes with the receiver noise. The radar noise power spectral density N_n is given by the product kT, where k is Boltzmann's constant (1.38×10^{-23} J/°K) and T is the system noise temperature in degrees kelvin.

Jamming. SRM allows several noise jammers to be defined. Pulse or deception jammers are not currently modeled by SRM.

A noise jammer in SRM is defined by a location (longitude and latitude), an effective radiated power (the product of antenna gain and jammer power), a center frequency, a bandwidth, and turn-on and turn-off times. The effective jammer transmitted power spectral density against each radar is calculated by comparing each jammer's center frequency and bandwidth with those of each radar. The effective jammer power spectral density (PSD) is the ratio of the jammer power (P_J) to the radar bandwidth (B_R), but with the ratio scaled by the fractional overlap of the jammer bandwidth by the radar bandwidth. If the radar bandwidth completely overlaps that of the jammer, then PSD is given by P_J/B_R; if the overlap is only partial (amounting to B_O), then PSD is given by $(P_J B_O)/(B_R B_J)$. These cases are illustrated in Fig. 9.

In the calculation of the jammer effect on the radar, the approximation is made that exactly the same jammer power is received for all radar beams in the TCA. This is obviously not exactly correct, but it makes the model run faster since the calculation is made once for the TCA, instead of once for each target. The received jammer power spectral density N_j is given by the sum

$$N_j = \sum \frac{\lambda^2 \sigma \, P S D_i \, G_i}{4 \pi R_i^2}$$

where i denotes the index of an active jammer, G_i is the antenna gain in the direction of the jammer when the radar beam points to the center of the TCA, and R_i is the range to the jammer. Of course, any jammer not within the radar horizon is skipped in the summation. The exact calculation would use the antenna gain in the direction of the jammer when the antenna beam points to the target.

Clutter. Clutter can compete with the radar return from a target. SRM computes a "clutter noise" term N_c for each target; the clutter noise is added to the thermal noise and jammer noise to yield a total interference energy or power spectral density. In general, radar clutter may result from

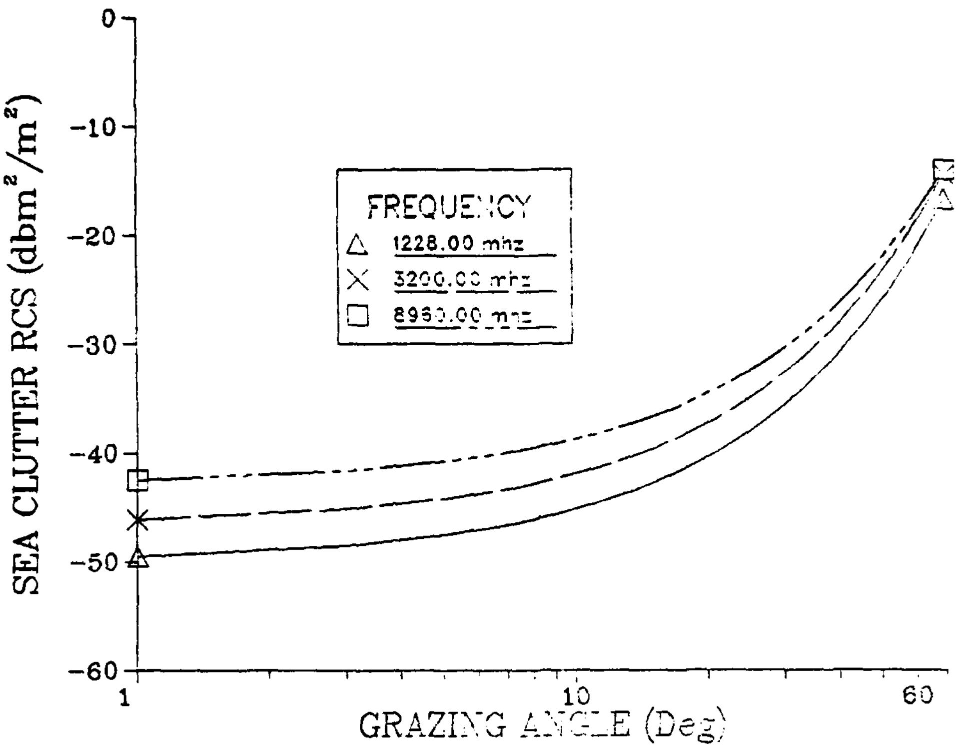

Fig. 10 — Space Radar Model sea clutter RCS model for horizontal polarization and sea state = 3

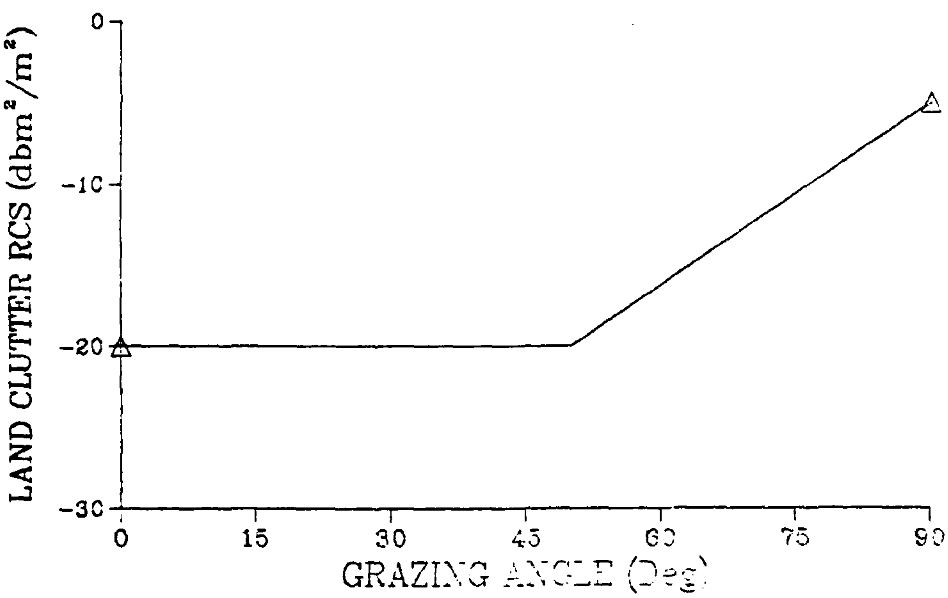

Fig. 11 — Space Radar Model land clutter RCS model

either land or sea or both.

The Sea Clutter model was derived from experimental data [2]. This data is tabulated in the Appendix. Sea clutter radar cross section, σ_s, depends upon the radar frequency, the grazing angle, and the sea state and is modeled in SRM by a mathematical expression of the form

$$\sigma_s = \frac{10^{(m\gamma + b)}}{\lambda^x}, \quad \gamma < 30$$

where γ is the grazing angle and λ is the radar wavelength. A good fit to the experimental data was obtained with x, the exponent of λ, equal to 0.82. The slope of the curve, m, is computed from

$$m = 2.4 - .075(K_b - 3) - .42(1 - \lambda'/\lambda)$$

in which K_b is the Beaufort sea state number and λ' is the wavelength corresponding to a frequency of 8960 mhz.

The intercept value, b, of the general equation is computed from the expression

$$b = .2(K_b - 3) - 5.5$$

Values of sea clutter RCS versus radio frequency are plotted in Fig. 10 for various grazing angles and sea state = 3.

The land clutter model is provided by an expression graphed in Fig. 11. If the grazing angle is less than 50 degrees, the land clutter density is given by the constant value σ_L = 0.01. For grazing angles greater than 50 degrees, the clutter density increases as the specular point is approached.

The expression for the clutter density in this region is

$$\sigma_L = 10^{(-2 + 1.5 (\gamma - 60) / 40)}$$

where γ is the grazing angle to the center of the TCA.

Since clutter return is a function of grazing angle, the exact calculation of total clutter would require adding the clutter contributions from all the range cells over land and sea areas along the radar-target line. However, the approximation is made in SRM that all clutter in the TCA has the same radar cross section density (square meters RCS per square meter of ground). Each TCA is assigned a ratio, ρ_s, which gives the fraction of sea area in the TCA. The sea clutter and land clutter RCS densities (σ_s and σ_L) are computed for the center of the TCA for the given radar location. Then the total RCS density for the TCA is given by the expression

$$\sigma_c = \rho_s \sigma_s + (1 - \rho_s) \sigma_L$$

The clutter noise N_c that competes with a target is then given by

$$N_c = \frac{\sigma F G_0 \sigma_c \Delta R \theta_3}{R^4}$$

where σ expresses the clutter rejection of the radar. In SRM, the clutter rejection depends upon the radial velocity of the target. If the radial velocity is less in magnitude than an input cutoff velocity, there is no clutter rejection and σ is set to 1; but if the radial velocity is greater than the cutoff value, σ is set to the value defined as an input parameter.

2.4.6 Target Detection

The process of detecting targets within a TCA during radar operation consists of the following steps. First, as described earlier, the location of the satellite is fixed at the midpoint of its operating interval for all of its observations of the TCA. Then the target's position is determined for the moment that the satellite is at that point. Next, the location of the target relative to the center of the TCA is computed. If the target does not lie between the inner and outer TCA radii and within the TCA's azimuth limits, it is skipped. (However, a target that is skipped is counted as lying within the AOI for the final detection summary.) Once the target is determined to lie within the TCA, its location in earth-center coordinates is computed.

SRM next computes the target's range, azimuth, and elevation from the radar and its radar cross section. If the target is an aircraft, the model computes the target's radial velocity relative to the radar. If the magnitude of this velocity exceeds the clutter rejection threshold, the clutter rejection factor is applied to the clutter "noise" N_c.

SRM computes the target signal energy from the radar factor, the antenna gain, the radar cross section, and the radar range as described in Sec. 2.4.4. The total interference N is the sum of thermal noise, jamming, and clutter noise ($N_n + N_j + N_c$). The signal-to-interference ratio S/N is then used in a Marcum-Swerling detection probability model to compute the detection probability P_d' for the nominal false alarm probability and number of pulses integrated.

To determine whether or not the target is detected, SRM generates a random number distributed uniformly in the interval [0,1]. If the random number is larger than P_d', failure is reported for this target. If the random number is smaller than P_d', the target is detected, and a perturbed target position and error ellipse are reported for the target. In addition, detection statistics are maintained for: (1) all targets detected; (2) those targets missed whose expected probability of detection is greater than P_d;

(the desired value) and (3) those targets missed whose expected probability of detection is less than P_d.

The error ellipse is computed for the target based on the range and azimuth measurement accuracy for the radar.

The two semiaxes of the error ellipse are computed to be:

$$\sigma_x = \rho_1 R \theta_{3az}$$

$$\sigma_y = \rho_2 \Delta R$$

where R is the radar range, ΔR is the range resolution, θ_3 is the 3 dB azimuth beamwidth and ρ_1 and ρ_2 are the "split factors" which relate accuracy to resolution in beamwidth and range respectively. The split factor has the form

$$\rho = [\beta + 1/(E/N)]^{1/2}$$

where β is the reciprocal of the practical limit to the number of splits permitted in range or beamwidth. SRM currently uses a value of β equal to 0.001. Since a target is extremely unlikely to be detected for E/N less than 10, the split factor will fall approximately in the range [0.03, 0.3], with the small values (better accuracy) corresponding to very large values of E/N.

The orientation of the error ellipse is found using the target-centered coordinate system described in Section 2.1. The azimuth location of the radar in this coordinate system (measuring clockwise from north) is then found. To this azimuth angle is added $\pi/2$ radians to define the orientation of the major axis of the error ellipse. The major axis is rotated 90 degrees from the target-to-radar line of sight because the azimuth error is normal to the radar line of sight. The geometry is illustrated in Fig. 12.

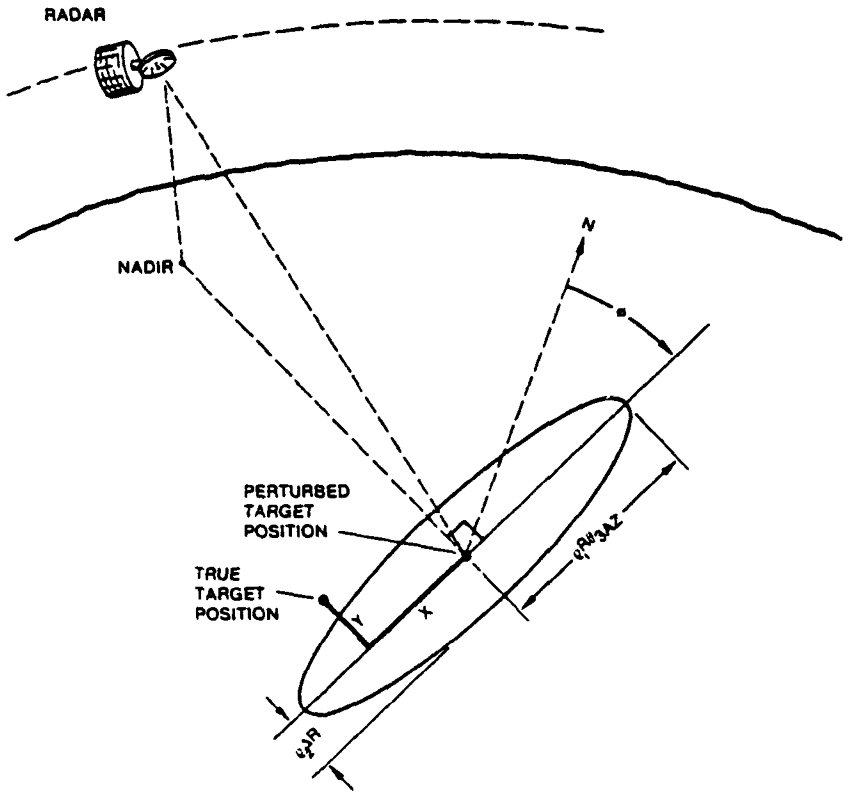

Fig. 12 — Detection error ellipse geometry showing semi-major and semi-minor axis lengths and ellipse orientation

After the ellipse and its orientation are found, SRM computes a perturbed target position. Two zero-mean normal random numbers x and y are generated. The standard deviations of the distributions are respectively σ_x and σ_y. These represent the respective displacements from the true target position along the major and minor axes of the ellipse. These displacements are converted to earth-center angles (by dividing by the earth's radius) and then translated into latitude and longitude increments. If the true target latitude is η and its longitude is ζ, and if the orientation angle is ϕ, the perturbed positon is given by

$$\eta_p = \frac{\eta + (x \cos \phi + y \sin \phi)}{R_e}$$

$$\zeta_p = \frac{\zeta + (x \sin \phi - y \cos \phi)}{R_e \cos \eta}$$

2.5 Satellite Power

SRM maintains a close watch on the power budget of each satellite. Each satellite has a battery that is continually being charged or discharged throughout the satellite orbit. SRM's radar scheduler, discussed in Sec. 4.7, assures that the battery charge always lies within prescribed bounds.

2.5.1 Battery

Each satellite's battery has a peak energy capacity. The battery can never be charged above its peak capacity; after the battery is fully charged, the excess charging power is switched off. A battery also has two thresholds for minimum energy capacity. The routine discharge threshold is the lowest state of charge allowed when the radar is servicing routine or urgent radar requests; the emergency discharge threshold is the lowest state of battery charge allowed to service an emergency radar request.

2.5.2 Battery Charging

Solar Array. Each satellite is assumed to have a solar array to charge its battery. The amount of power supplied by the solar array is assumed to be constant when the satellite is in sunlight and zero when the satellite is in the earth's shadow. The assumption of constant charging rate approximates the case of sun-seeking solar paddles that maintain a constant area exposed to solar flux. Strictly speaking, a body-fixed solar array would have a varying rate of charge throughout its orbit unless it were sunbathing (which would require a suspension of radar operations). In this case of a fixed solar array (not sunbathing), the calculation of total charge would require a numerical integration. The present SRM model replaces the integration by the product of time in the sun and a constant charging rate. This approach was chosen to save compute time because the entire charge history must be computed many times during the radar scheduling process.

The amount of solar power charging in sunlight is the product of the solar cell area, the solar flux, the cell efficiency, and the charging efficiency. The solar flux and cell efficiency are combined into a single input parameter that is defined for each satellite. This factor corresponds to the electrical output of a one-square-meter cell in sunlight. The charging efficiency accounts for losses in transferring the energy to the battery. SRM has input provisions for two values of solar cell area. Area 1 is the maximum cell area and Area 2 is the minimum cell area illuminated by the sun. The present SRM version uses only Area 1. If the effect of the varying solar angle on the solar cell charging rate is modeled in detail, the maximum and minimum areas would be used in the numerical integration.

Eclipses. In the model, solar cell charging of the battery takes place only when the satellite is exposed to sunlight. Therefore, SRM computes and maintains a table of times when each satellite enters and leaves the earth's shadow.

Alternate Power Source. A satellite may have a nuclear power supply that would provide a constant amount of power independent of solar illumination. This type power source can also be modelled in SRM.

Power Drain

There are four sources of satellite power drain:

1. Radar Operation
2. Housekeeping
3. Downlink Data Transmission
4. Antenna Slewing

Radar operation power drain consists of the average prime power used during intervals when the radar is transmitting and receiving.

The housekeeping power drain includes all power used in routine operation when the radar and communication downlink are not being operated. Examples of housekeeping activities are stationkeeping, attitude control, and maintaining electronics in standby mode.

Downlink data transmission uses prime power to report to a ground station. The downlink prime power is combined with that of the radar for SRM power calculations. The assumption is that the downlink transmitter operates exactly as long as the radar does.

Antenna slewing uses power to start the antenna moving and to stop it. The amount of energy expended during antenna acceleration is computed as part of the scheduling process.

2.6 Radar Scheduler

The radar scheduler is the most complex model in SRM. The function of the radar scheduler is to process requests for radar measurements in a specified coverage region, to fit radar operations into the radar's timeline, and to assure that the satellite battery charge never falls below the minimum thresholds.

2.6.1 Radar Requests

Requests for radar coverage specify the following information:

Type of request (TCA or background)

Priority of request (routine, urgent, or emergency)

Area to be covered

- Latitude and longitude of center
- Inner and outer radii
- Azimuth limits

Land/sea conditions

- Fraction area that is sea
- Sea state

Time that request is to become known to SRM

Earliest time to schedule radar operation

Latest time to schedule radar operation

Time between successive observations of area (applies only to routine request)

A TCA request defines a specific region in the AOI for the simulation run. If the request is scheduled, the radar is operated to detect targets. A background request simulates radar activity in one or more areas different from the AOI. These requests are scheduled in order to account for the battery discharge during operations outside the AOI. However, no radar operations are actually simulated for these background areas.

The priority of the requests defines their relative importance. The most important is the emergency request; the next most important is the urgent request; the least important is the routine request. If necessary, an emergency request will be scheduled by "bumping" any routine or urgent operation that had been scheduled previously. Similarily, an urgent request can "bump" a routine operation. An emergency or urgent request is satisfied by scheduling only one observation of the region. On the other hand, routine requests usually involve many observations.

The land/sea conditions for the region define parameters used in the clutter calculations as discussed in Sec. 2.4.5.

Although all requests are usually defined at the beginning of a simulation run, they are placed on a list that is time-ordered by request time. As the simulation progresses, the requests are made known to the radar scheduler as the simulation time equals or exceeds the request time. In this way, the model simulates the effects of new requests occurring over time. However, new requests may also be added to the list during the course of a run in order to model the cueing of the radar by other sensors that are being concurrently simulated.

Each request specifies a time window in which a radar observation is desired. If at least one observation is scheduled within the time window, the request is satisfied; otherwise, the request is flagged as being unfullfilled. In the case of a routine request, the scheduler attempts to schedule as many observations in the time window as it can, subject to the requested time between observations.

2.6.2 Radar Event List

A time-ordered list of radar operations is maintained for each satellite radar. Entries on the event list contain the following information for each radar operation:

Type coverage (TCA or background)
Priority (routine, urgent, or emergency)
Request identifier
Antenna slew beginning time
Radar turn-on time
Radar turn-off time
Battery charge at turn-on
Battery charge at turn-off

The event list is ordered on the time of radar turn-off.

Not every radar requires time for antenna slewing - only those with a mechanically steered antenna. The slew time is long enough for the antenna to slew from horizon-to-horizon. Ideally, a time should be computed for the antenna to slew from one scheduled area to the next. However, this scheme, would require a more complex scheduling algorithm and would increase simulation run time. Horizon-to-horizon slewing represents the worst case situation by simulating the maximum possible slew time for any radar operation.

2.6.3 Viewing Opportunities

The first step in scheduling a radar request is to compile a list of all occasions within the requested time window when the region is in view of a satellite and below the maximum grazing angle specified. This list is built by stepping through the orbit of each satellite and recording the times when the satellite is in-view and out-of-view of the region. If the request area encompasses more than 1/2 of a circle, the entire region must be seen on a satellite pass to be considered inview. The smaller the request area and the higher the satellite altitude the less severe this restriction will be. For regions defined as less than 1/2 of a circle, the scheduler will select a point approximately in the center of the region; this point must be in view for the region to be considered inview.

The viewing opportunity list also contains the calculated energy required from the satellite power supply to perform the requested radar observation. The calculation of transmitted energy is described in Sec. 2.4.1. The battery energy is computed as the product of operating time (the ratio of transmitted energy to average radar power) and the radar prime power. If the antenna was slewed, the slew motor's energy consumption is added to that of the radar.

2.6.4 Microscheduling

The previous sections have discussed scheduling in a general way. This section describes the details of how a radar operation is actually added to the event list of a radar.

For each request a time window is defined within which that event is to be scheduled. The extent of the window depends upon the priority of the request. Since routine requests are to be scheduled repetitively at specified intervals, the longest possible time window will be the duration of the interval. For example, if a request is to be scheduled for every 10 minutes, each time window can be no longer than 10 minutes. The window is then further restricted to lie within a viewing opportunity of the request area. Urgent and emergency request time windows, on the other hand, may be scheduled at any point within the first available viewing opportunity of the area.

The SRM will always try to schedule a requested radar operation without bumping any operations already scheduled. First an attempt is made to schedule the new radar operation in the middle of the scheduling time window. Figure 13a shows how the new radar operation, C, (which is T seconds in length) would ideally be placed if there were no conflicts with the existing schedule.

However, the existing schedule (shown in Figure 13b) already contains radar operation A that overlaps the preferred position. The scheduler must therefore compile a list of available openings within the time window. In the example, there are two openings $[T1, T1_A]$ and $[T2_A, T1_B]$. Either of these slots is large enough to fit radar operation C. The scheduling alogrithm will place operation C in the center of the slot closest to the preferred location, as shown in Figure 13C.

The next step is to test the energy budget for the satellite being scheduled. This is done by computing the battery charge for that satellite at the beginning and end of each radar operation on the event list. If the energy test is successful, the event is scheduled.

At this point, there is a difference between the "no-bump" scheduler and the "bump" scheduler. The "no-bump" scheduler is used on the first attempt to schedule a request of any priority. For routine requests, an attempt is

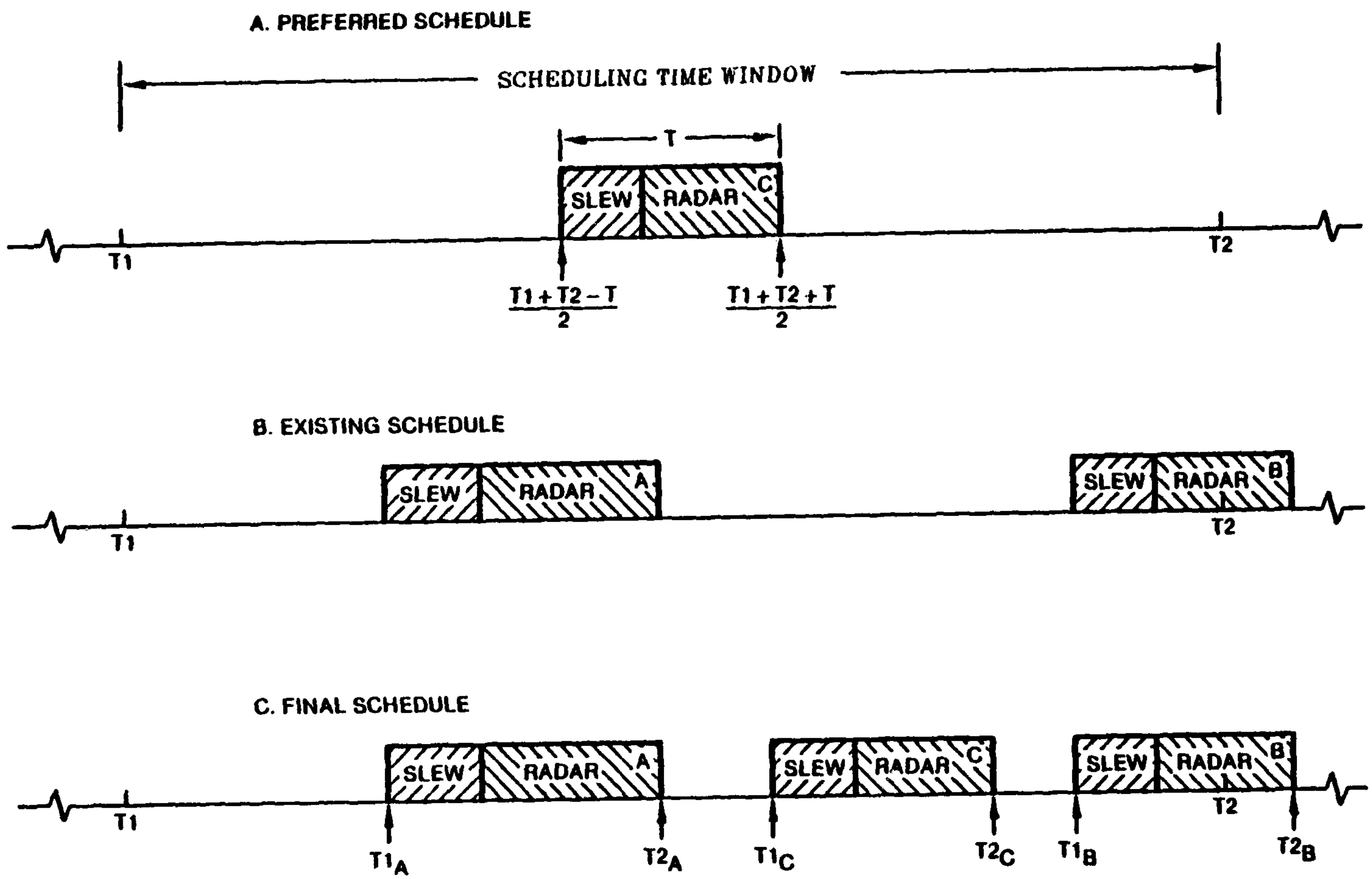

Fig. 13 — Illustration of resolution of a scheduling conflict. Event C is scheduled in the center of the available slot closest to the preferred time within the scheduling window T_1, T_2.

made to fit a radar observation into every scheduling time window. Success or failure in satisfying these routine requests for any specific time window are treated alike in the "no-bump" scheduler; the scheduler simply moves on to the next time window.

Urgent and emergency requests, however, are handled differently. Viewing opportunities are considered in time order within the "no-bump" scheduler. Success in scheduling a radar operation will terminate the scheduling process. If no viewing opportunity can be found to satisfy the urgent or emergency request using the "no-bump" scheduler, the "bump" scheduler will be invoked. In the "bump" scheduler, the first viewing opportunity is considered again. If the operation can now be fitted into the timeline, we know that the energy test must have failed, or else the "no-bump" scheduler would have been successful. The "bump" scheduler then deletes one lower-priority operation from the event list, and re-evaluates the energy budget for the satellite being considered. This process is repeated until the energy test is successful, or until there are no more lower-priority operations to bump. If the energy test is finally successful, the event is scheduled. If the final energy test was not successful, the "bump" scheduler goes on to the next viewing opportunity on the list.

The other reason that the "no-bump" scheduler may have failed is because there was no slot on the radar event list large enough for the requested operation. In this case, lower-priority events within the viewing opportunity window will be bumped until a large-enough slot is found. If such a slot is found, the process of energy tests and bumping proceeds as described above. If no slot is found, the "bump" scheduler goes on to the next viewing opportunity.

Upon completion of the "bump" scheduler operation, any bumped requests that did not result in the new request being scheduled are rescheduled in their original positions.

3. SUMMARY

A computer program that simulates a generic space radar system has been described. Some of the sub-models contained within SRM represent first order approximations of more sophisticated algorithms. However, any of these sub-models can be readily replaced with more rigorous versions, without impacting the rest of the software, because of the modular construction of SRM.

4. ACKNOWLEDGEMENTS

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5. APPENDIX: Experimental Data for Radar Cross Section of Sea Clutter

The following tables give the experimental values used to derive the mathematical model for sea clutter radar cross section.

Sea State = 5

GRAZING ANGLE (deg)	X BAND dB	S BAND dB	L BAND dB
1	−36.5	−46	−51.5
3	−36.5	−44.5	−48
5	−35.5	−42.5	−45.5
10	−34	−39	−41
20	−30.5	−34	−36
30	−27	−30.5	−32.5
45	−21.5	−24.5	−25.5
60	−15	−17	−18
70	−9	−9	−9

Sea State = 3

GRAZING ANGLE (deg)	X BAND dB	S BAND dB	L BAND dB
1	−41.5	−52.5	−60
3	−41	−48.5	−53
5	−40	−46	−49
10	−38.5	−43	−45.5
20	−35	−38	−39.5
30	−31.5	−33.5	−35
45	−25.5	−27	−27.5
60	−17.5	−19	−19.5
70	−9	−9.5	−10

References

1. M.I. Skolnik, "An Empirical Formula for the Radar Cross Section of Ships at Grazing Incidence", IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-10, No. 2, March 1974.

2. John C. Daley, "Target and Clutter RCS Model", NRL Internal Memo 7946-0750-5:JCD:dgw, 13 August 1980.

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