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DESCRIPTION OF A COMPUTER SIMULATION
OF AN ORBITAL SAR SYSTEM

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SUMMARY

In order to predict the performance of a synthetic aperture radar (SAR) for
a wide variety of system and environmental parameters a computer simulation
of the SAR system has been developed. This model is a detailed description
of the SAR imaging process on a pulse-by-pulse basis. The simulation is im-
plemented as seven computer programs for a CDC Cyber 171 digital computer.
The first of these programs is the simulation controller. This program co-
ordinates communication between the other programs and between the user and
the simulation. It is also responsible for computing certain parameters,
like the map start time, that will be needed by the other programs. The
second program discussed in this paper specifies the model of the terrain to
be mapped. The terrain can consist of discrete scatterers or extended homo-
geneous areas. The homogeneous areas are represented by a collection of
many discrete targets. The density of the discrete targets per unit area
is under user control but the scatterers are placed so as to insure several
per SAR resolution cell. Representing homogeneous areas as collections of
point reflectors enables the simulation to support the phenomenon of co-
herent speckle which is characteristic of some monochromatic SAR imagery.
The third program discussed computes the range between each scatterer in the
terrain and the phase center of the antenna. These calculations are made on
a pulse-by-pulse basis for each pulse in the simulated time interval. The
range is a function of the location of the terrain on the planet surface,
the rotation and shape of the planet, the orbital parameters of the satellite
carrying the SAR and the location of the antenna phase center with respect
to the center of mass of the satellite. This program also weights the re-
ceived echo strength in accordance with the antenna gain pattern. The
fourth program computes the IPQ (In Phase and Quadrature) video signal by

convolving the radar impulse-response and the echo time histories. The fifth program handles motion compensation. It applies the Doppler phase corrections for each pulse to effect SAR beam steering and range focusing. The sixth program is the SAR processor. It weights the IPQ video and computes the fourier transform to produce the complex output image. The seventh and last program is the post processor. It computes the image log magnitude levels, assigns grey shade levels and displays the resultant image. The output of the simulation is a fully processed SAR image displayed on a high resolution CRT.

1.0 PURPOSE AND STATUS

In general the simulation is designed to permit investigators to assess the effect of various radar and geometric parameters on the quality of the SAR imagery produced. In particular it will be used to investigate the following:

1. To assess the effect of various antenna patterns on the SAR image,

2. To assess the effect of various SAR parameters on the system's ability to detect small differences in the radar cross section of adjacent homogeneous areas.

3. To assess the effect of mapping geometry on SAR image quality.

The first SAR simulation produced at ARL:UT modeled an airborne SAR scenario. This simulation has been completed and results obtained from this first simulation indicate that our approach was feasible. The simulation of the orbital case, on a faster computer, is nearing completion.

2.0 PROGRAM STRUCTURE

The structure of the simulation is shown in Figure 1. The simulation control program, SARTREK, is run first. It reads all the user input data, computes various system parameters based on these inputs and stores these data in an area which is accessible to the other programs. As the other programs in the simulation are executed they will produce other parameters necessary to subsequent programs. These data are also stored in the "control parameter" area. The user supplies input data which specifies the antenna pattern, terrain parameters, SAR radar and processor parameters, orbital parameters and a description of the planet being mapped. After SARTREK the data flow is from left to right in Figure 1. Each program is run in turn
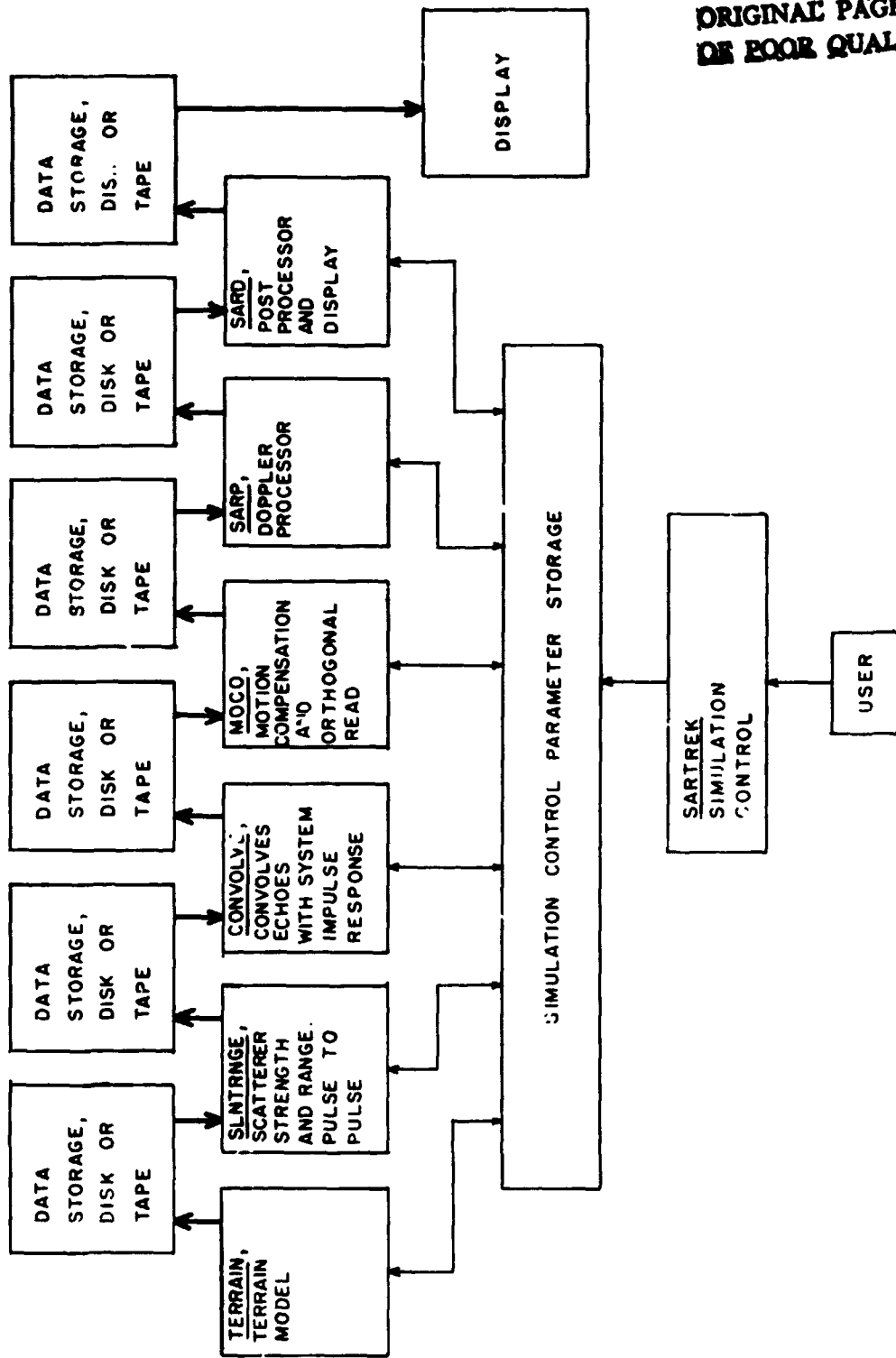
PROGRAM STRUCTURE FOR SAR SIMULATION

FIGURE I

and its output is stored on tape or disk. The output of one program forms
the input to the next. This technique has two advantages. First, it re-
duces the amount of computer time one must use in a single block. Second,
it yields a considerable savings in computer time since the investigator can
change parameters in a given program and rerun the simulation without having
to rerun the program upstream from where the changes were made. For example,
the user can investigate the effect of changes in Doppler processor para-
meters (SARP) without rerunning the four programs which precede it. The
output of the program is a fully processed SAR map of the modeled terrain
displayed on a high resolution CRT.

3.0 SARTREK - THE SIMULATION CONTROLLER

Program SARTREK forms the communication link between the user and the simula-
tion and between the various programs within the simulation itself. SARTREK
performs four major functions; it reads the user specifications of the
simulation to be run, it computes the mapping start time for the conditions
specified; it computes the change in incident angle during the formation of
the SAR map and it computes the range of useable pulse repetition frequen-
cies (prf). Each of these functions will be discussed in turn.

Program SARTREK reads the specification of the simulation parameters su -
plied by the user. These specifications are listed below. The user speci-
fies certain parameters describing the planet about which the SAR is
orbiting. These parameters are;

1. Planet Name,
2. Planet Equatorial Radius,
3. Planet Eccentricity,
4. Planet Gravitational Constant,
5. Planet Rotational Rate and
6. Time of Prime Meridian Passage.

The planet name is used simply as an identifier for the set of data which
describes the planet. The equatorial radii , and the planet eccentricity
determine the shape of the planet. The length of the radius vector from
the center of the planet to a point on it's surface is a function of lati-
tude. The planet is assumed to be symmetric in longitude. By modeling the
planet in this manner one can investigate the degradation in a SAR map due

to assuming it to be a spherical planet. The planet gravitational constant is necessary to define the satellite orbit. The planet rotational rate and radius at the point being mapped are necessary ingredients in the computation of the distance between scatterers in the terrain and the antenna phase center on a pulse-to-pulse basis. Unlike the aircraft case, the terrain cannot be considered stationary in the orbital situation. Planet motion influences the Doppler shift observed from the terrain and introduces range gate positioning problems. The time of prime meridian passage is the time at which the planet's prime meridian crosses a fixed reference point in inertial space. For the earth this reference is the point at which the vernal equinox occurs.

The user specifies the orbital parameters to be used. They are listed below;

1. Orbit Identification,
2. The Semi-Major axis of the orbit,
3. The Orbit Eccentricity,
4. The Inclination of the Orbit,
5. The Argument of the Perigee,
6. The Longitude of the Ascending Node and
7. The Time of Perigee Passage.

Again the orbit identification is a serial number used to identify the set of parameters with which it is associated. The semi-major axis of the orbit ellipse determines the scale of the orbit. The orbit eccentricity determines the shape of the orbit. An eccentricity of 0 specifies a circular orbit and an eccentricity of one specifies a parabola. Eccentricities between zero and one yield an elleptical orbit. The inclination of the orbit specifies the angle between the plane of the orbit and the equatorial plane of the planet being orbited. The longitude of the ascending node specifies the orientation of the orbital plane about the north-south axis of the planet. The argument of the perigee specifies the orientation of the major axis of the orbit ellip in the plane of the orbit. Lastly, the time of perigee passage determines the location of the radar platform in the specified orbit at a given time.

The user specifies the parameters of the terrain model. These include;

1. The latitude of the terrain,

2. The number, cross section and location of discrete scatterers,

3. The number, size and location of each homogeneous fields and

4. The scatterer density and strength within each homogeneous field.

These parameters will be discussed in detail in the section which describes the terrain model.

The user also specifies the SAR radar and processor parameters. The parameters are listed below;

1. Radar configuration identification,

2. Radar wavelength,

3. Ground range sample interval,

4. Azimuth resolution,

5. Azimuth sampling interval,

6. Radar impulse response shape,

7. Doppler weighting functions,

8. Pulse repetition frequency and

9. Overlay ratio.

The radar configuration identifier is a serial number used to denote the set of parameters with which it is associated. Most of these parameters need no additional explanation. The user specifies the ground range sample interval desired. Once SARTREK has determined the mapping geometry it determines and reports to the user the slant range sample interval required to yield the desired results. The radar impulse response shape, which determines the system range resolution, is specified in terms of the slant range sample interval.

The user specifies the mapping geometry by indicating the desired nadir and squint angle and the swath width.

The radar platform is specified by the orientation of the platform body axis at the start of mapping and the platform roll, pitch and yaw rates.

The antenna is specified by the following;

1. Antenna identification,

2. Antenna gain pattern,

3. Location of the antenna phase center with respect to the platform body axis coordinate system, and

4. Orientation of the antenna coordinate system with respect to the platform body axis coordinate system.

Again, the antenna identification is just a number used to identify a particular set of antenna parameters. The antenna gain pattern is read as a table of values which specify antenna gain as a function of the boresight angle through which the energy passes to and from the antenna. By permitting the user to separate the phase center of the antenna and the center of mass of the platform, the simulation can be used to model the effects of improper stabilization of the radar platform on the image. Similarly, the orientation of the antenna coordinate system can be used to study the effects of antenna pointing errors.

Program SARTREK also c   es the map start time and the length of the SAR array. The user has specified the platform orbit, the planet, the latitude at which the terrain to be mapped is located and the mapping geometry. The programs takes these parameters and computes those times in the satellite orbit for which the specified conditions are met. SARTREK produces the plot shown in Figure 2. This plot is used to provide the user with a general view of the results of his specifications. The ground track of two orbits are shown. In the figure shown the orbit is circular and inclined at 45° to the equator. The user has set the terrain at 45° north latitude, the nadir angle at 60° and the squint angle at 90° to the left of the velocity vector. The program begins plotting the ground track at start of the first mapping time. For the case illustrated the ground track starts just over northwestern Turkey. The program also draws a line from the ground track to the center of the map. For this case the line is perpendicular to the satellite ground track reflecting the 90° squint angle specified. Note that the program locates three other mapping locations which satisfy the requirements during the two orbits. The simulation uses the first one found.

Program SARTREK also computes and reports to the user the change in incident angle which occurred during the time of map formation. The program computes
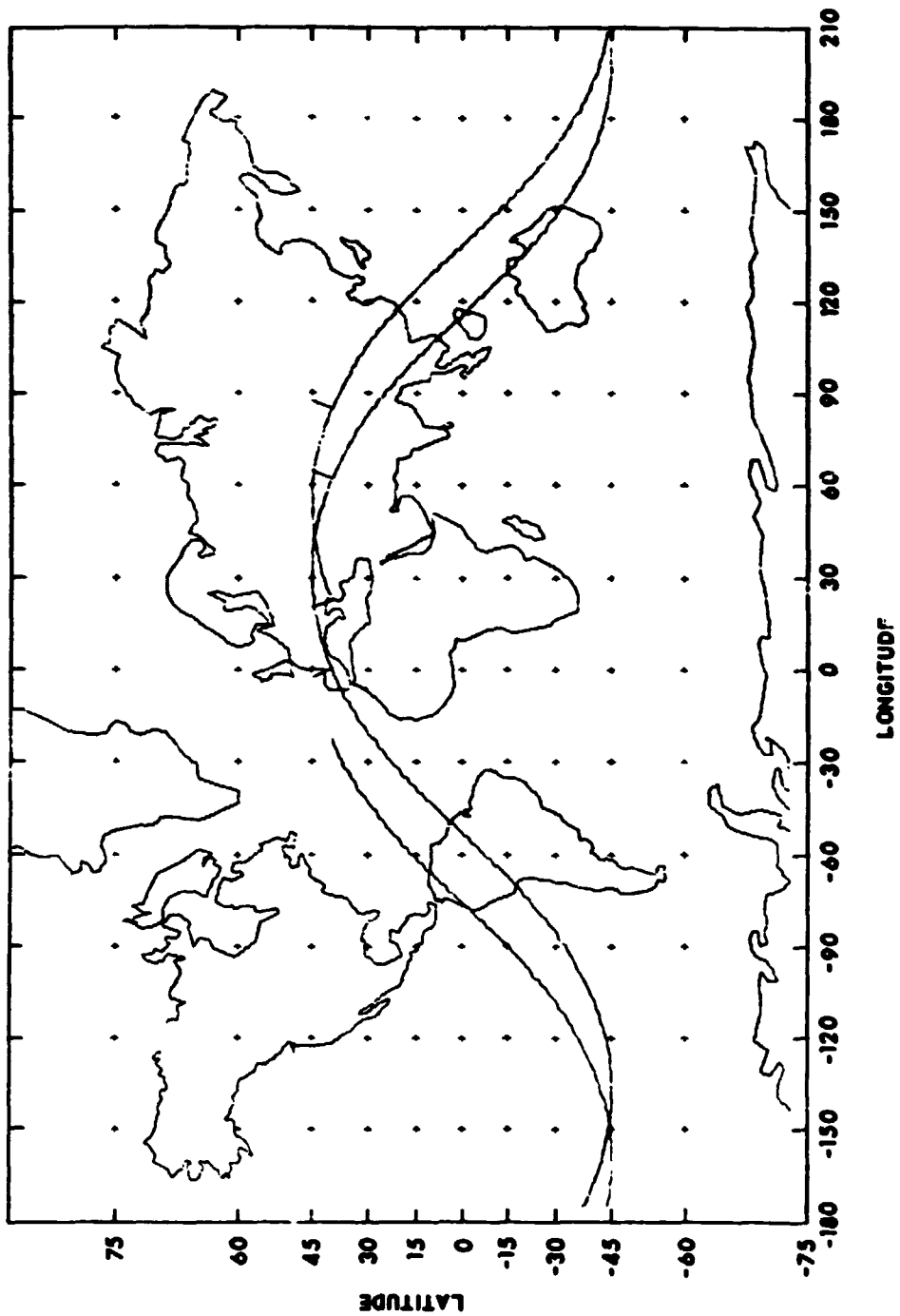
FIGURE 2
ORBIT No. 1
ECCENTRICITY = 0 INCLINATION = 45° TIME OF PERIGEE PASSAGE = 0
SEMI-MAJOR AXIS = 6678 km LONGITUDE OF ASCENDING NODE = -30°
ARGUMENT OF PERIGEE = 0 MAP START LATITUDE = 45°
NADIR ANGLE = 60° SQUINT ANGLE = -90°

the length oi the array necessary to provide the desired resolution and
from this and the geometry of the given mapping situation computes the
change of incident angle during the map. This information is passed to the
terrain simulation to be used there to change the reflectivity of the ter-
rain if the change in incident angle is large enough to warrant such a
change.

SARTREK also computes a suggested range of prf's to the user. These prf
ranges are based on the following criteria. First, the prf must be high
enough to permit at least two pulses per resolution cell. Second, the prf
should be low enough to preclude range ambiguities within the range extent
of the antenna main lobe footprint on the ground. Thirdly, the prf should
be high enough to preclude azimuth ambiguities within the cross range extent
of the antenna mainlobe footprint. Fourthly, the prf must preclude eclip-
sing, that is, the system must not emit a pulse during the time echoes are
being received from the desired swath. Prf ranges which satisfy these
requirements are reported to the user. However, the user is free to select
whatever prf he desires.

4.0 TERRAIN - THE TERRAIN MODEL

Program TERRAIN produces a set of data which represent the terrain. In
general terrain can be divided into two types of scatterers, discrete and
extended. Discrete or point scatterers were usually relatively small ob-
jects, often man-made such as automobiles, buildings, etc., any object that
is characterized by strong, specular, localized reflection. The extended
or homogeneous scatterer is a larger target such as a forest or wheat field.
The cross section of an extended target is fairly uniform within a given
area. For many purposes the cross section of an extended target is speci-
fied as cross section per unit area. This leads to simulating such a target
as a bounded area, the interior of which is set to some cross section per
unit area. This representation is not sufficient for representing homo-
geneous targets in the SAR application. As a result of coherent processing,
homogeneous areas of a SAR image can exhibit an effect known as coherent
speckle. Coheren speckle appears in the SAR image as dark winding trails
of various lengths. The origin of coherent speckle lies in the fact that
backscatter from a "homogeneous" area is really due to reflection from many

scatter points within each resolution cell. For a coherent processor the received power from each cell depends on the complex sum of the echoes from the many discrete scatterers in each resolution cell. Thus two resolution cells containing the same number of identical scatterers would yield different received power due to differences in the spacing of the scatterers within the resolution cell. The degree to which coherent speckle affects the image is a function of the width of the mainlobe response with respect to spacing of the scatterers within the resolution cell, the sampling interval and the amount and type of incoherent integration. The presence of coherent speckle increases the variance in the measurement of cross section in a homogeneous field and thus increases the error in the estimate of cross section. Since one purpose of the simulation is to assess the effect of various SAR parameters on the system's ability to detect small differences in cross section of adjacent homogeneous areas, it is necessary that the simulation support the origin and propagation of coherent speckle. For this reason the terrain program models homogeneous areas as a collection of many point scatterers. The user specifies each homogeneous field as a rectangular area. The center and extent of the area is specified with respect to the center of the terrain. The user also specifies the strength of the scatterers and the number per resolution cell. Program TERRAIN then computes the required number of scatterers and places them at random within the extent of the field. The user may specify up to nine such homogeneous areas. Up to fifty discretes may also be specified. Note that the location of each scatter is specified with respect to the center of the terrain being modeled. Placement of the terrain on the planet surface is accomplished by the next program in the chain. This permits the terrain to be placed at any desired latitude without rerunning program TERRAIN. At the user's option TERRAIN produces a plot of the terrain for inspection. Such a plot, showing a single homogeneous field and four discrete scatterers is shown in Figure 3.

5.0 SLNTRNGE - THE SLANT RANGE COMPUTATION

The program SLNTRNGE has three functions. The first of these is to compute, for each pulse, the slant range between each scatterer in the terrain and the phase center of the antenna. Figure 4 indicates the geometry involved.
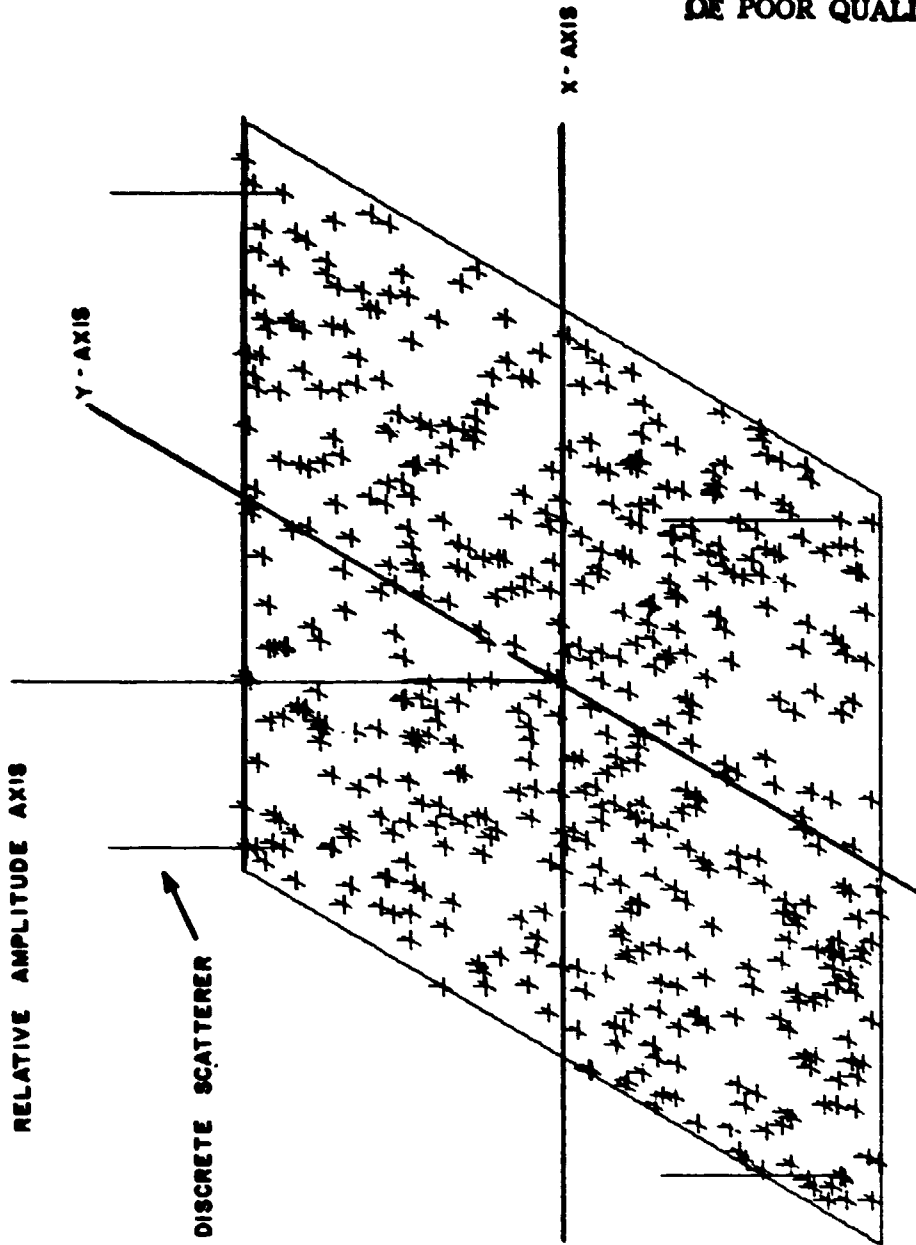
FIGURE 3

TERRAIN OUTPUT

HOMOGENEOUS FIELD AND FOUR DISCRETE SCATTERERS

INERTIAL
REFERENCE

TERRAIN
COORDINATES

PLANETOCENTRIC
COORDINATES

ANTENNA POINTING
DIRECTION

ANTENNA
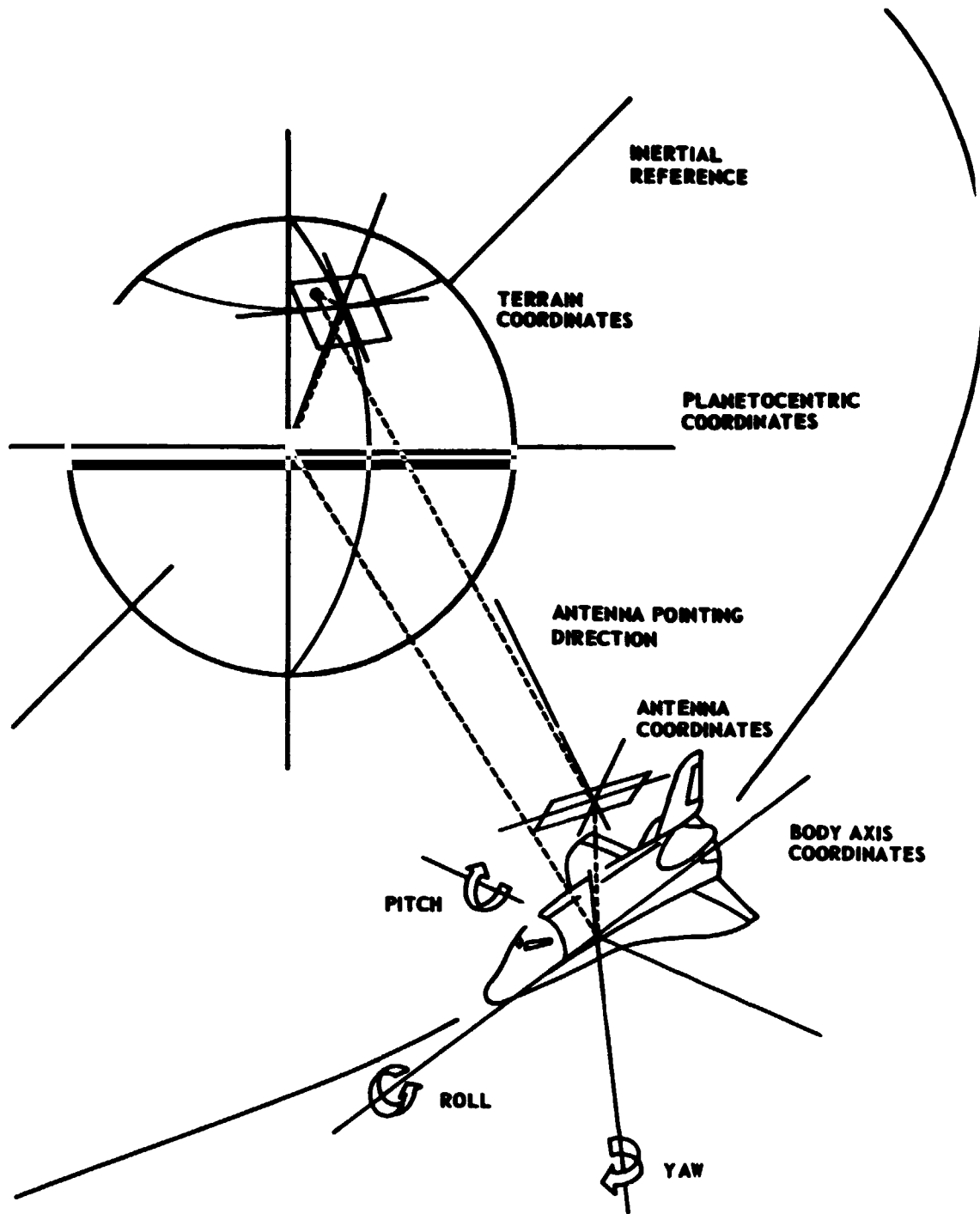COORDINATES

BODY AXIS
COORDINATES

PITCH

ROLL

YAW

FIGURE 4
SLANT RANGE GEOMETRY

The location of each scatterer is known with respect to the terrain co-ordinate system. The location of the center of the terrain is known relative to the planet center since the user has specified the latitude of the terrain and SARTREK has computed the longitude at which it must be placed to be mapped from the given orbit and geometry. The latitude and longitude yield the direction of the vector from the planet center to the terrain center. The radius of the planet at the latitude indicated gives the length of the vector. The orbital parameters yield the vector from the planet center to the center of mass of the SAR platform. The vector from the platform mass center to the phase center of the antenna is dependent on the location of the antenna with respect to the mass center and the orientation of the platform body axis. The vector between the scatterer and the antenna phase center can be found once the other four vectors are known. This computation involves several coordinate transformations repeated for each scatterer and each pulse. Much attention has been given to making the code that accomplishes this as efficient as possible.

Another function of SLNTRNGE is to compute the angle between line-of-sight to each scatterer and the antenna boresight. The gain to be associated with this angle is looked up in the antenna gain pattern table. This gain is then applied to the scatterer strength. This also is a potentially time consuming task. Time has been saved in this area by computing the antenna angles subtended by the terrain patch for each pulse and restricting the gain pattern search within these bounds.

The final function of SLNTRNGE is to reduce the echo strength in accordance with the space loss over the slant range.

The output of SLNTRNGE is a set of slant ranges and their associated echo strengths for each scatterer on each pulse. Note that for each pulse SLNTRNGE computes the range to all the scatterers. These ranges change on a pulse-to-pulse basis as the satellite moves. It is this range change with time that appears as a Doppler frequency in the SAR processor. Program SLNTRNGE will plot the range profiles for a given pulse at the user's option. Figure 5 shows two examples of these plots. The upper plot was produced from a terrain model which contained seven discrete targets. The lower plot was produced from a terrain model consisting of a single homogeneous
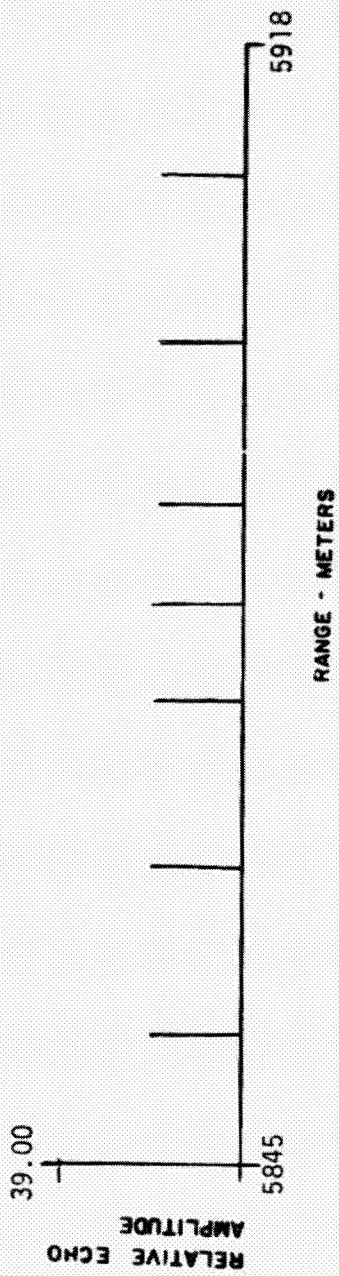
FIGURE 5

SLANT RANGE OUTPUT

field. The reduction is density of the scatterers at the near and far edge
of the terrain is caused by mapping the field from a diagonal aspect. Both
of these plots were produced by the airborne SAR simulation.

6.0 CONVOLVE - THE PRODUCTION OF THE IPQ VIDEO.

The objective of Program CONVOLVE is to compute the interaction between the
radar signal, the terrain and the radar receiver to produce the IPQ video
signal to be processed by the SAR processing portion of the simulation. The
overall simulation can be divided into two parts. The first part starts
with the terrain and progresses to the IPQ video (Programs TERRAIN, SLNTRNGE
and CONVOLVE). The second part begins with the IPQ video and moves back to
a representation of the terrain which is the SAR map (Programs MOCO, SARP
and SARD).

The antenna and radar are assumed to be linear networks. Under this assump-
tion the output of the radar receiver is the convolution of the received
signal and the radar impulse response,

$$H(x) = F(x) * G(x), \tag{1}$$

where

$F(x)$ is the input signal in the time domain,

$G(x)$ is the radar impulse response function,

$H(x)$ is the IPQ video and

$*$ is the convolution operator.

The input signal, $F(x)$, has been computed by SLNTRNGE and the radar impulse
response function has been specified by the user. The convolution can be
computed directly or by using Fourier transform theory. Recall that the
convolution of two functions is the transform of the product of their trans-
forms. Using bars to denote Fourier transforms,

$$H(x) = \overline{\overline{F(x)} \cdot \overline{G(x)}} \tag{2}$$

This formulation greatly speeds the convolution process. The convolution
must be computed once for each pulse. The impulse response function does
not vary with time so $\overline{G(x)}$ need only be computed once. Figure 6 shows the
result of this process. Diagram a shows the impulse response and diagram b
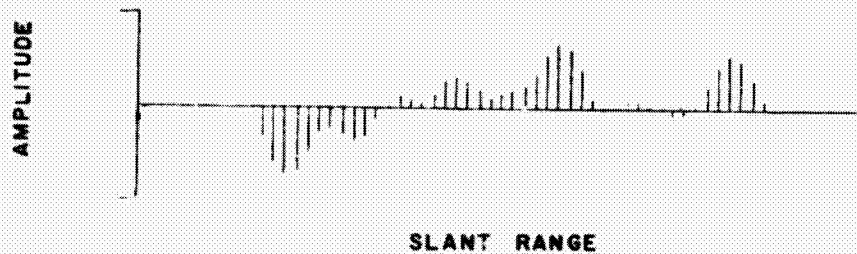shows the output of SLNTRNGE. Diagrams c and d are the I and Q components

RADAR
IMPULSE
RESPONSE
A

AMPLITUDE

1.0

0.5

0.0

RANGE SAMPLE INTERVALS

PROGRAM
SLNTRNGE
OUTPUT
B

AMPLITUDE
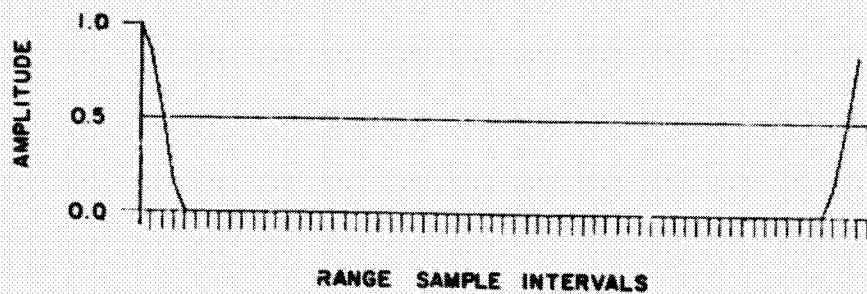
SLANT RANGE
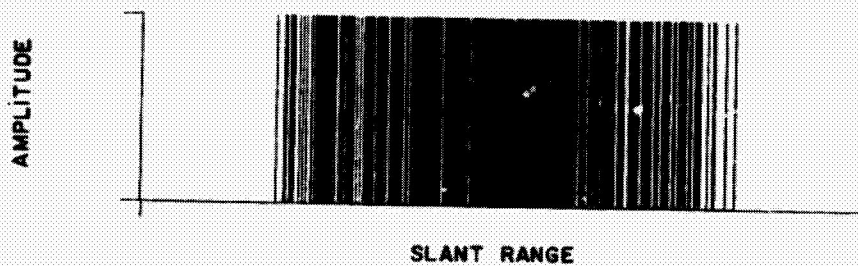
IN-PHASE VIDEO
AFTER
CONVOLUTION
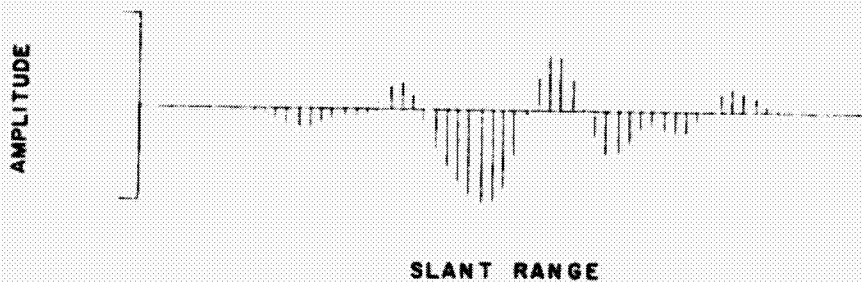C

AMPLITUDE

SLANT RANGE

QUADRATURE
VIDEO AFTER
CONVOLUTION
D

AMPLITUDE

SLANT RANGE

FIGURE b

PROGRAM CONVOLVE OUTPUT
THE MODELED TERRAIN CONSISTS
OF A HOMOGENEOUS FIELD

of the IPQ video obtained from the convolution.

7.0 MOCO - MOTION COMPENSATION

Program MOCO has two objectives. The first is to introduce the effects of
motion compensation or focusing on the IPQ video waveform. The second ob-
jective is to accomplish the orthogonal read or "memory corner turning"
necessary to further processing of the SAR signal. Focusing the synthetic
array on a point in space is accomplished by adjusting the phase of the IPQ
signal for each pulse so that the total time required for a signal to travel
from the focus point to the phase center of the antenna is the same for all
pulses. In the simulation the location of the scatterer with respect to
the antenna phase center is known exactly. Thus perfect motion compensation
or focusing is possible. In real systems this is .. + the case. Errors in
the location of the antenna phase center with respect to the map center can
be introduced into MOCO to study the effects of errors in motion compensa-
tion.

The second function of MOCO is the orthogonal reordering of the data. SAR
data are accumulated on a pulse-to-pulse basis. Each pulse contains a
sample at each range interval. The Doppler processor needs the data pre-
sented in range bin order. That is, the processor needs the time histories
of each range bin.

8.0 SARP - THE SAR PROCESSOR

In one sense of the word, this portion of the SAR model is not a simulation
at all. The digital Doppler processor in this simulation differ from an
operational SAR processor mainly in the machine on which it is implemented.
Program SARP is a basic Fourier transform processor. The IPQ video from
MOCO is weighted by the function of the user choice. These data are then
transformed range bin by range bin and resultant spectrum is passed to the
next program in the simulation. If the user desires, program SARP will
produce a perspective plot of the filter magnitudes for each range bin.
Figure 7 shows such a plot for a terrain model consisting of seven discrete
targets.
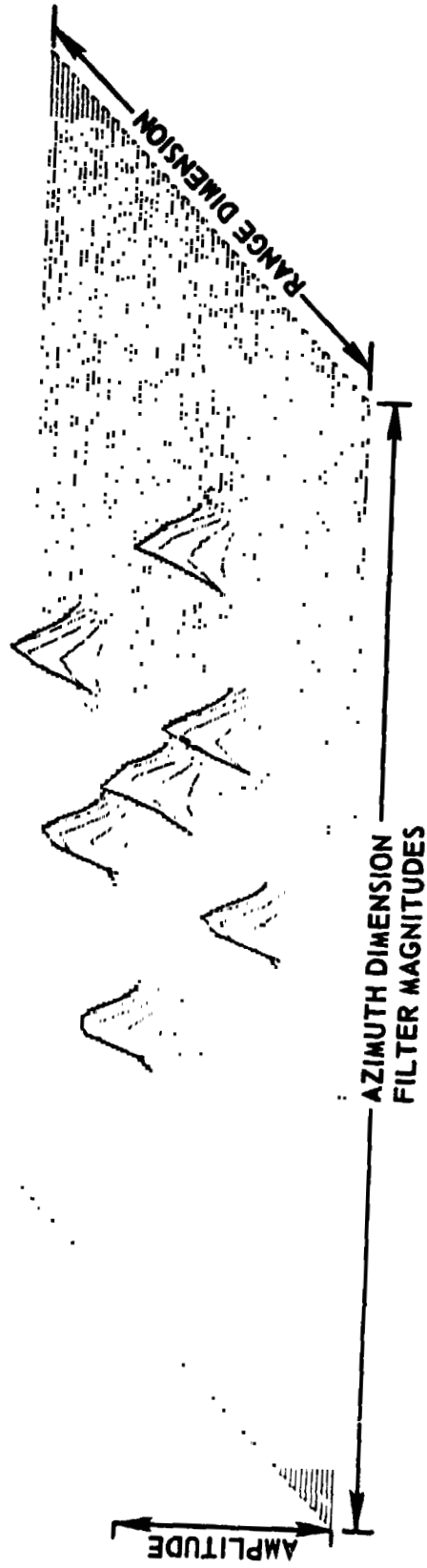
THE TERRAIN MODEL CONSISTS OF SEVEN DISCRETE TARGETS

FIGURE 7
PERSPECTIVE VIEW OF FILTER BANK MAGNITUDES
THIS IS AN OPTION OUTPUT OF PROGRAM SARD

III-3-18

9.0 SARD - THE SAR DISPLAY

The purpose of program SARD is to display the filter magnitude data as the final SAR map. The program has three basic functions. The first is to overlay the filter magnitudes if the overlay option is selected by the user. If overlay is selected the corresponding filter magnitudes from the maps involved are averaged and the result becomes the filter magnitudes displayed. The purpose of this noncoherent integration is to reduce coherent speckle and the effect of sampling grid placement.

The second function is to convert the filter magnitudes to grey shade levels. The high resolution has 16 grey shades. The grey shade assignments involve mapping the filter magnitude values into grey shades in accordance with the user's specifications.

The final function of SARD is to communicate the grey shade data from the computer to the display memory where it is transferred to the CRT. Figure 8 shows photographs of various modeled terrains. These images were produced by the airborne SAR simulation. The radar was illuminating the terrain from a near diagonal aspect. Detail "a" shows the SAR image for a terrain model consisting of seven discrete scatterers arranged along the front and back sides of a square with one scatterer in the center. For these images the resolution cell was not square, this led to the deformation of the image that can be observed in the figure. Detail "b" is the image from a single, square homogeneous field. Detail "c" is the image for a homogeneous field with large discretes at each corner.
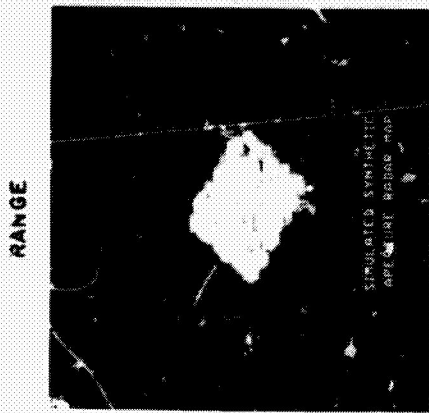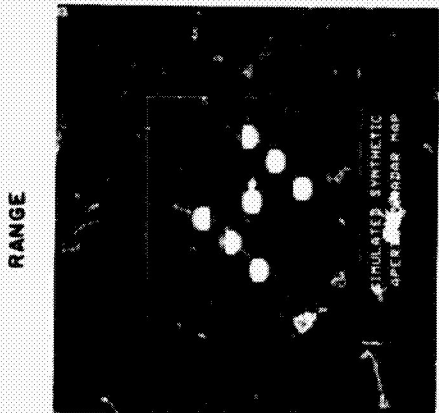
10.0 ACKNOWLEDGEMENTS

11.0 REFERENCES

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RANGE

AZIMUTH

DETAIL - C
HOMOGENEOUS FIELD AND
FOUR DISCRETE SCATTERERS

RANGE

AZIMUTH

DETAIL - B
HOMOGENEOUS FIELD

RANGE

AZIMUTH

DETAIL - A
SEVEN DISCRETE
TARGETS

FIGURE 8

IMAGES PRODUCED BY THE SAR SIMULATION