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A SIGNIFICANT POST-LAUNCH CALIBRATION EXPERIMENT FOR THE SEASAT-A SAR

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SUMMARY

This paper outlines a technique for periodically monitoring the impulse response function of the Seasat-A Synthetic Aperture Radar (SAR). The technique will directly yield most of the significant contributors to the overall instrument transfer function, and in addition will yield several diagnostic side benefits. The essential measurement involves exciting the total SAR system at L-band with a strong point source scatterer of radar cross section ~10^7 m^2, receiving via the normal S-band analog data link, and finally sampling and processing only a small subset of data in the immediate vicinity of the strong point source.

Depending upon the details of the data handling, a number of key system parameters can be extracted:

(1) Resolution of the entire system, or of the system devoid of optical processor contamination, as obtained by the effective width of the point source response.

(2) Optimum phase and amplitude compensation for minimizing either the width of the impulse response or the sidelobe energy.

(3) Real aperture antenna pattern, by collecting several successive passes of data, and employing range compression. Such information might be essential for post-launch analysis of the actual antenna deployment and for an evaluation of the sources of image contrast degradation resulting from excessive sidelobe energy.

(4) Long term radiometric calibration, relative and perhaps absolute, by using the stable S-band pilot tone in the data link as a reference throughout the life of the experiment.

(5) Absolute geometric calibration, by comparing the actual measured range and azimuth position of the strong scatterer with predicted location using Seasat Project-generated instrument predicts, again throughout the life of the mission. Such information might be essential for characterizing and removing positional biases.

(6) Data link contamination, by locating the strong scatterer in a region of overlapping station coverage, and comparing the quality of the impulse response at low station elevation angles.

1.0 THE CONCEPT OF AN IDEAL ACTIVE RADIOMETER

1.1 PERSPECTIVE

Even though practical microwave synthetic apertures have existed for about twenty years, our ability to extract quantitative, scientifically useful information has been substantially lagging. Perhaps part of this lag is understandable. Many of the early applications of SAR were of a reconniassance nature, and were successful merely because of the ability of the technique to pierce cloudcover and darkness. As more sophisticated applications are sought, however, such as the space-borne measurements of ocean wave spectra, ice thickness and structure, soil moisture, and vegetation classification, it becomes imperative that we expand our understanding of the total instrument transfer function, that is, the effect of the total instrument on the quantity to be measured. The Seasat-A SAR can provide the ideal opportunity from which to gain this understanding.

1.2 AN IDEAL SYSTEM DEFINITION

The Seasat-A SAR, from a radar measurement (as opposed to applications) point of view, has a purpose which is simply stated: it should produce an absolute radar backscatter map of certain areas of the earth's surface at an incidence angle of 20 degrees, wavelength of 23 cm, spatial resolution of 25 m, and radiometric resolution of 3 dB. If the instrument were "perfect", it would yield an image of a backscatter map uniquely related to the actual surface distribution of the radar backscatter at a known instant in time. In this perfect system, not only is the mapping function unique, it is also known. As a result, the image is error-free in position, magnitude, and time for any value of backscatter. Such a system, of course, cannot exist.

1.3 BASIC IMAGE DESCRIPTORS

There are literally dozens of significant contamination sources in a real system which prevent perfection. These sources manifest themselves, however, in a relatively small number of ways in the output imagery. It is therefore possible to specify and describe the measurement system with a relatively small number of basic image descriptors. The following set is offered as being more or less complete and orthogonal.

Spatial resolution, or the spatial width of the half intensity points resulting from an ideal impulse excitation. This definition, although convenient, does not account for sidelobe structure which also affects the ability of the system to discriminate between closely spaced targets.

Radiometric resolution, or the "just-detectable difference" in input backscatter, σ_o, sometimes referred to as "noise equivalent $\Delta\sigma_o$". For any real system, radiometric resolution can always be traded against spatial resolution by varying either the detection or the processing bandwidth.

Dynamic range, or the range of absolute input backscatter values which produce output changes. Usually only a small fraction of the total dynamic range is linear, and SAR systems with instantaneous dynamic ranges in excess of 20 dB are rare.

Radiometric accuracy, or the probable error in mapping a point in the output image back into an absolute value of backscatter. Reference to an absolute standard is necessary.

Geometric accuracy, or the probable error in mapping a point in the output image back to an absolute position.

Temporal invariance, or the extent to which all of the above descriptors remain invariant with time.

It is possible to express other common descriptors such as "signal-to-noise ratio" and "contrast" as variations of these six basic descriptors. Signal-to-noise ratio (for a particular input, σ_0) for example, is a function of both the "noise-equivalent σ_0" at the lower end of the absolute dynamic range, and the noise equivalent $\Delta\sigma_0$. Similarly, "contrast" can be related to both spatial resolution and instantaneous dynamic range. To first order, then, modifications of the above six descriptors can be defended as containing the necessary and sufficient information for a complete image quality description.

2.0 SOME POSSIBLE CONTAMINATION SOURCES IN SEASAT-A

As mentioned above, there are several potential contamination sources in the Seasat-A SAR which will determine the final image quality. Some of these sources are predictable and measurable with sufficient pre-launch testing. Others can only be anticipated, and require a precisely controlled set of post-launch measurements for their determination. Some of the more significant potential sources of contamination are discussed here.

2.1 RANGE AND AZIMUTH RESOLUTION

In the Seasat-A SAR, range resolution is fundamentally limited by a combination of geometry and bandwidth in the front end of the sensor. From then on, the information must be preserved with adequate bandwidth while preventing the introduction of additional noise. A resolution calculation : r the Seasat-A SAR based only on front-end parameters yields about 20 m at the near-range point. If no significant degradation occurs in the remainder of the system, the 25 m specification will be satisfied. In the optical processor, however, significant sources of degradation can easily occur. Similarly, either short term oscillator instabilities or an improperly deployed antenna can cause azimuth correlation difficulties with resulting resolution and contrast degradation.

2.2 RADIOMETRIC RESOLUTION

The least-detectable difference in σ_0 for a SAR is chiefly a by-product of its coherent radiation source. Rayleigh scattering produces multiplicative noise yielding a variance in output power proportional to its mean. This contamination source results in a variance of 6 dB for a single sample of dimension one resolution element. For the Seasat-A parameters, spatial integration in azimuth by a factor of four can result in a factor of two increase in radiometric resolution, to 3 dB, if the four samples (or "looks") are statistically independent. Spatial integration beyond 25 m can further increase the radiometric resolution. Normally the Rayleigh-produced variance is a sufficiently large contamination source that it alone determines the radiometric resolution, except at low scattering values where other sources, such as thermal noise, begin to predominate. Consider, for example, a SAR system having a linear operating range of 20 dB, with only four independent samples per resolution element (very close to the Seasat-A SAR situation). Such a system could resolve with respectable confidence only about seven "grey scales", or values of input backscatter. This example illustrates the challenge of SAR remote sensing, when compared with more common visible remote sensors, typically having a radiometric resolution of twenty to one hundred grey scales.

2.3 DYNAMIC RANGE

There are at least three separate and distinct values of dynamic range for most SAR systems. For extended sources, the lower end of the dynamic range is limited by thermal noise. For the Seasat-A SAR, this equivalent thermal noise corresponds to an area-normalized scattering coefficient, σ_0, of approximately -27 dB in the highest receiver gain setting. Conversely, the upper end of the extended source dynamic range is usually limited by saturation levels in electronic components. In Seasat, the data link saturation limits the extended source dynamic range to ~20 dB. The instantaneous dynamic range of the system, however, is much less, and is determined by the amount of energy which spills over from its intended position into adjacent elements. The most common cause of this contamination is random phase and amplitude noise preventing optimum correlation. In Seasat, the instantaneous dynamic range will probably be about 10 dB, unless these random contamination sources are much stronger than expected.

Finally, there is a point source dynamic range. Radars which use pulse expansion (to reduce peak power) and doppler discrimination (to accomplish aperture synthesis) effectively spread the energy from the point source over many equivalent resolution elements until, in the act of processing, matched filtering compresses the energy close to its original spatial extent. The

Seasat-A SAR expands the range energy by a factor of 600, and the azimuth energy by a factor of 160 (when processing to 25 m resolution), for a total energy dispersion of 10^5. This energy dispersion quality of the SAR allows point sources of extremely large backscatter relative to the average to pass through the system unaffected. The dynamic range for point sources, therefore, is typically much larger than that for extended sources, 50 dB larger for the Seasat-A SAR.

2.4 RADIOMETRIC ACCURACY

As mentioned briefly at the beginning of this paper, imaging radar will not yield its full scientific potential until it can provide a calibrated map of radar backscatter. Moreover, within a single pass of the Seasat-A SAR, at least three separate contamination sources will act to impede absolute calibration:

(1) the ability to reference points in the image to an absolute standard,

(2) small scale local errors caused by, for example, strong sources contaminating adjacent regions containing weak sources,

(3) large scale systematic but unknown variations in the system transfer function, caused by, for example, antenna pattern uncertainties.

In addition to these three, the absolute measurement will be foiled by the Rayleigh scattering discussed in 2.2 and by temporal variations to be discussed in 2.6. Unfortunately, even if complete knowledge of each of the above contamination sources were available, an extremely sophisticated and non-linear algorithm would be required to map output amplitude back to input backscatter coefficient. In general, all but a fraction of the knowledge necessary to create this algorithm is lacking. In Seasat-A, for example, the SAR antenna pattern is sufficiently sharp that a spacecraft roll of one degree can result in a change of several dB in system gain at a particular range. In addition, the backscatter function itself (for a homogeneous partially specular target) is varying rapidly with angle, especially at angles near nadir. Consequently, even for attitude control systems accurate to 0.3 degrees, the steeply varying antenna pattern combined with the initial uncertainty in the measurement of that pattern can result in errors of several dB.

In spite of these inherently difficult problems, however, a number of major error sources can be reduced or even eliminated by formulating a proper calibration philosophy.

2.5 GEOMETRIC ACCURACY

Every imaging system forms its image with a unique perspective. If the mapping from object to image is one-to-one, with a known mapping function, then no information is lost, and it might be said that the geometry is absolutely accurate. The synthetic aperture radar also has its own perspective, making measurements of time delay and doppler frequency, from which geocentric latitude and longitude must be inferred. Any discussion of geometric accuracy, therefore, must be centered about the ability to make this inference.

Assume a spacecraft in a perfectly circular orbit around a perfectly homogeneous stationary spherical Earth. The spacecraft velocity and altitude are therefore constant. Finally, assume that the orbital parameters of the spacecraft are known, so that its position in terms of geocentric coordinates is a known function of time. In this ideal situation, the mapping between SAR parameters and geocentric coordinates is trivial. For vacuum, the radar time delay is uniquely related to range from the spacecraft. Therefore, a particular time delay defines a sphere of unique radius centered on the spacecraft. Similarly, a particular doppler frequency shift defines a unique angle with respect to the spacecraft velocity vector, the locus of which is a cone. The full universe of range and doppler frequencies measured by the radar, therefore, can be visualized as concentric families of spheres and cones centered on the spacecraft. The intersections of these spheres and cones with the spherical earth result in a corresponding family of circles and hyperbolae, and allow a unique mapping from "range-doppler" space to geocentric coordinates. In particular, if processing is performed about "zero-doppler", i.e., the position of a point is defined by the time at which it has no radial velocity component, then the only concern need be with the intersection of circles with a plane normal to the velocity vector (the degenerate form of the hyperbola).

In reality, the spacecraft is in a non-circular orbit, and the earth is neither stationary nor spherical. A non-circular orbit implies a rate of change of altitude and a zero-doppler plane which no longer passes through the sub-satellite point. In Seasat-A, for example, a 1-m/s altitude rate produces nearly a 100-m shift in the zero-doppler plane at the surface of the earth. It is, therefore, necessary to know and correct for altitude rates of 0.25 m/s to limit geometric errors caused by this source to 25 m.

The rotating earth produces an angular offset to the zero-doppler plane of about four degrees at the equator, sinusoidally decreasing to zero as a function of latitude. For Seasat-A geometry, at twenty degrees from nadir, this rotation amounts to a lateral shift of about 150 m.

The non-spherical earth distorts the family of range and doppler curves according to the local figure and terrain (or tidal) properties. Much of this error can be eliminated by using the proper earth model. Local terrain variations, however, are generally unknown a priori, and will introduce significant displacements. A mountain whose peak is 1 km higher than the surface of the corresponding earth model will, in the Seasat-A geometry, be apparently displaced by 3 km.

In addition to these distortions caused by the geometry, additional errors result in the deduction of range from time delay unless electronic-system delays are calibrated frequently. In Seasat-A, this problem is compounded by the fact that the system time delay is a strong function of temperature, which in itself is varying at nearly a constant rate throughout a typical pass.

In summary, a number of significant error sources will drive the system geometric-location accuracy on Seasat-A to at least 100 m, and, more likely, several hundred meters. The final performance will depend largely on to what extent post-launch calibration can remove systematic contamination sources.

2.6 TEMPORAL INVARIANCE

For a meaningful calibration, each of the above image quality descriptors must be either invariant with time or a known function of time. In general, the spacecraft environment is relatively benign, and one might expect few problems in this regard. There are, however, two areas in which the SAR may be particularly succeptible. Short term temperature variations (within a pass) can affect radiometric accuracy (via electronic gain changes) and geometric accuracy (via electronic time delay changes). Attitude and altitude drifts and uncertainties can similarly result in radiometric and geometric errors. A good fraction of this contamination can be eliminated with proper ground testing, but post-launch calibration will be essential to determine the time variance of the total transfer function as well as the actual in-orbit antenna pattern.

3.0 A COMPREHENSIVE POST-LAUNCH CALIBRATION TECHNIQUE

3.1 RATIONALE AND CONCEPTUAL DESCRIPTION

In view of all the potential sources of contamination in the Seasat-A SAR, periodic post-launch calibration of the system transfer function is clearly imperative. Fortunately, because the system is linear to first order, its impulse response function is a very powerful and nearly complete descriptor.

This section outlines a technique for periodically monitoring the impulse response function of the Seasat-A SAR. The technique will directly yield quantitative measures of each of the six basic image quality descriptors discussed in Section 2.0. In addition, simple modifications of either the experiment strategy or the data analysis will allow the monitoring of

(1) possible resolution degradation resulting from the use of an optical processor,

(2) the optimum phase and amplitude compensation functions for range correlation

(3) the real aperture antenna pattern, and

(4) contamination effects of the data link versus elevation angle.

Figure 1 is a schematic representation of all of the major components of the Seasat-A SAR system in the proposed calibration mode. The information flow as well as the majority of the actual hardware is identical to that planned for a typical SAR receiving station. (See reference [1] for detailed system characteristics.) Note the following significant deviations, however:

(1) the receiving antenna is serving an additional function of a calibrated, constant amplitude, geometrically fixed point source reference,

(2) the demodulated video output is immediately range compressed and equalized, and only a small fraction of the inherent data is digitized and buffered at an easily manageable data rate for only about two seconds, and

(3) azimuth compression is accomplished via computer by using the actual phase and amplitude history of the point source, rather than relying on supplementary position and attitude information.

3.2 DESCRIPTION OF THE SYSTEM

Any large tracking antenna equipped with a wideband (1 GHz to 3 GHz) feed structure would be suitable for use simultaneously as both the strong point source and the data link receiving aperture. For example, [illegible] ng the feed of a 20 meter diameter antenna selectively at 1.275 GHz (Seasat-A SAR operating frequency), a point source reflector can be created of cross-section [2]

$$\sigma = \frac{4\pi A^2}{\lambda^2} \eta^2 \tag{1}$$

where

σ = radar cross section, m^2

A = antenna aperture = $(\pi/4)(20)^2$ m^2

λ = radar operating wavelength = 0.23 m

η = antenna efficiency ≈ 0.5

Substituting, $\sigma \approx 6 \times 10^6$ m^2 along the axis of the antenna.

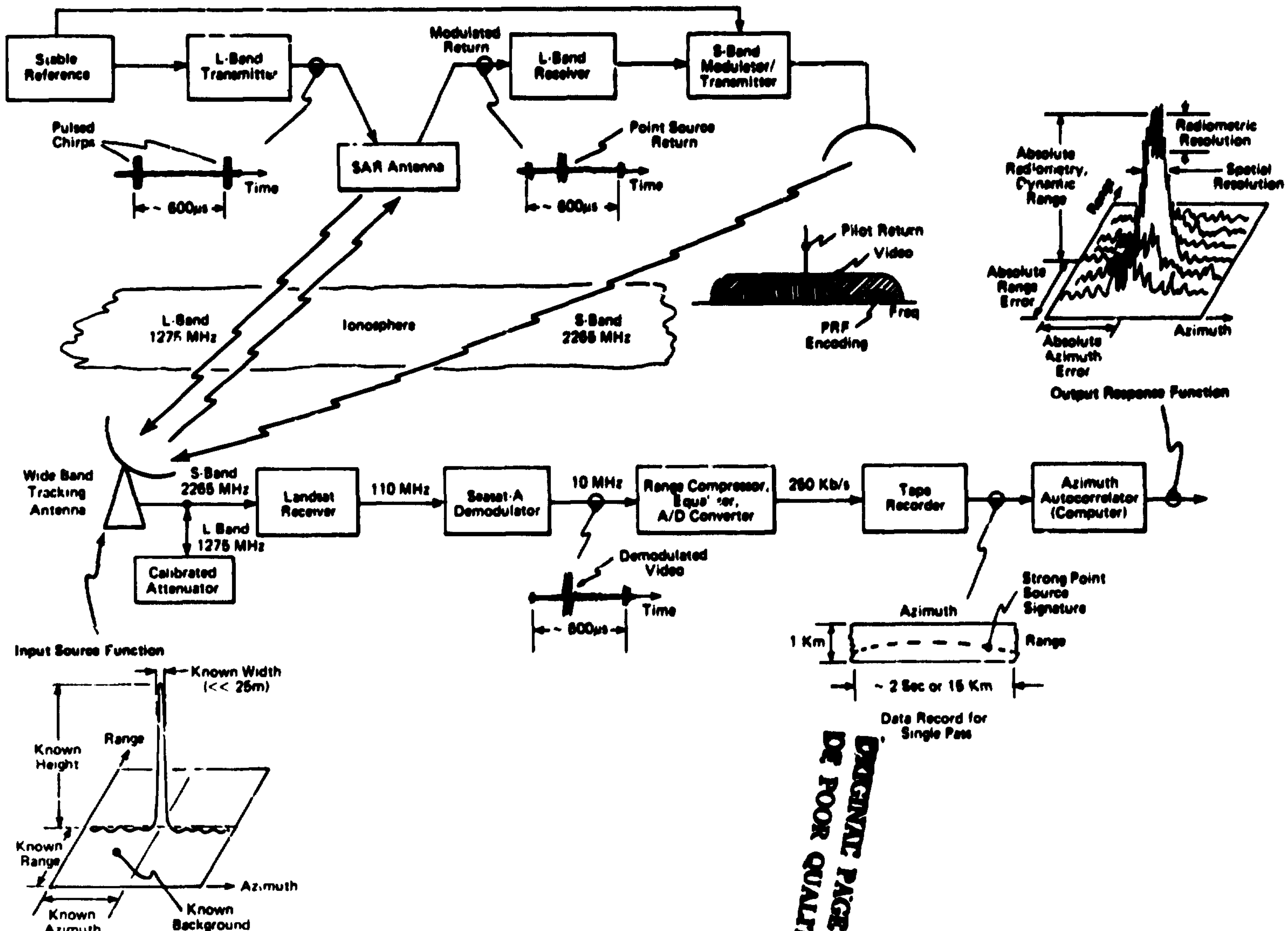

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Fig. 1 SEASAT-A SAR POST-LAUNCH CALIBRATION CONCEPT

This extremely bright target should still be slightly below saturation for the Seasat-A SAR. The expected minimum detectable cross-section is approximately 2 m^2 for the SAR in its highest receiver gain setting (i.e., when the noise is front-end limited). Assuming a range compression of 600, an azimuth compression of 160, and a linear dynamic range (for extended targets prior to compression) of 20 dB, the system should saturate for point sources of approximately 2×10^7 m^2.

A particularly intriguing idea for precisely adjusting the amplitude of the point source involves the simple substitution of a calibrated attenuator for the short at 1.275 GHz. The total dynamic range possible (i.e., ratio of "on" to "off" scattering cross-section) is unclear, but depends largely upon the perfection of the feed assembly. It is possible, however, that switching the scatterer "off" for alternate looks (every 0.5 second) during the two second SAR integration time would provide an effective method of reducing background emanating from sources such as buildings and trees, by differencing sequential single-look images.

By shorting or attenuating the tracking antenna feed selectively only at 1.275 GHz, the antenna can simultaneously be used as a receiver for the S-band analog data. Thus, all the normal data link hardware is utilized through the demodulator. The output of the demodulator, however, is followed by modifications to existing hardware in order to contain the data rate and total data per pass to only a very small fraction of that obtained in the actual system. Since the total information of interest is almost surely confined to an area of ~1 km^2 about the point source, the information rate can be held to only about 1% of that inherent at the instrument output by performing range compression, and then sampling only in the immediate vicinity of the point source. The complete azimuth phase history of the 1 km^2 region will require only about 1.6 M bits of storage. If azimuth processing to only 25 m is desired, the total storage requirement is a factor of four less.

The only remaining step required to produce the two-dimensional point spread function is a cross-correlation in azimuth. For the limited data set described above, an attractive alternative procedure which eliminates the dependence on supplementary position and attitude information involves a simple autocorrelation of the strong point source phase history.

3.3 SOME FINAL CONSIDERATIONS

The power of the impulse response function to totally describe the SAR system is a direct result of our need to build quantitative remote sensing systems. In this sense, the degree to which the impulse response function is not a complete descriptor is a measure of the design shortcomings. The one-to-one mapping from image space back into radar backscatter space, so essential for scientific deduction, is possible only if the response function is reasonably unique, amplitude-independent, and time-invariant. A well designed calibration experiment should at a minimum, therefore,

(1) utilize a calibration source with well-known and dependable characteristics,

(2) verify the extent to which the impulse response function is both unique and amplitude-independent, and

(3) provide frequent opportunities for calibration to confirm the time invariance of the impulse response function.

For Seasat-A, the optimum geographic location of the calibrated source is tied to several factors, perhaps the most significant of which are the particular characteristics of the orbit. As observed from a fixed location on the earth, the baseline orbit will appear to precess toward the east at a rate of about 18 km at the equator every three days [3]. For either ascending or descending passes, therefore, a particular fixed target will present opportunities for calibration every three days until it passes out of the SAR swath of 100 km, yielding a total of five or six opportunities over a 15 day period. The cycle repeats approximately five months later. Moreover, by positioning the point source at particularly favorable latitudes, sets of ascending and descending passes can be phased to yield sets of 15 day opportunities spaced at 2.5 month intervals. Such favorable locations exist, for example, at latitudes of approximately 32°N, 39°N, and 46°N.

4.0 REFERENCES

1. Jordan, R. L. and D. H. Rodgers, "Seasat-A Synthetic Aperture Imaging Radar System", paper presented at 1976 Wescon, September 1976.

2. Inferred from Skolnik, M. I., Radar Handbook, 1970, McGraw Hill, p. 27-16, eq. (10).

3. Private communication with W. T. K. Johnson, Jet Propulsion Laboratory, Pasadena, California.

WEDNESDAY, MARCH 8, 1978

III. IMAGE SIMULATION AND INTERPRETABILITY (1:30 - 5:20), Chairman: R.K. Moore, Remote Sensing Laboratory, University of Kansas