Radiometric Correction and Calibration of SAR Images

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ABSTRACT: A technique for producing radiometrically calibrated SAR image products is described. The output imagery is corrected to represent a measurement of the ground reflectivity or radar cross section. The sources of calibration errors are discussed and the appropriate forms of the radar equation as applied to SAR image data are reviewed. A key result is the radar equation dependence on the azimuth reference function used in processing. A radiometric correction algorithm for use in an operational SAR correlator is presented. This algorithm has the characteristic that it is fully reversible. Additionally, it can be applied equally to detected or complex SAR images, and it allows for the subtraction of the estimated noise floor in the image but does not require this procedure.

INTRODUCTION

N EARLY 40 years have passed since Wiley (1965) made the observation that side-looking radar can achieve high azimuth resolution by utilizing the Doppler spread of the echo signal. This landmark observation, that signifies the birth of synthetic aperture radar (SAR), spurred a flurry of activity in system design and signal processing techniques in the ensuing years (Tomiyasu, 1978; Wehner, 1987). Although much of the early emphasis in SAR was directed toward military applications, the potential for utilizing SAR as an imaging sensor for scientific Earth resource applications was widely recognized and realized in several mapping campaigns. These airborne SAR programs eventually led to the SEASAT SAR spaceborne system in 1978. Although limited in duration to just 100 days, this mission opened the potential of SAR to a global scientific community (Jordan, 1980).

The SEASAT mission dramatically demonstrated the capabilities of SAR. Features such as all-weather, day-night imaging, wide-swath coverage, and spatial resolution independent of sensor altitude have led to a variety of both land and ocean applications as well as planetary mapping missions (Elachi, 1982; Johnson, 1985). However, in conjunction with all its unique features, a SAR also has several major drawbacks that have limited the operational utilization of this data set for Earth resource applications. The primary issues can be summarized as follows:

- Large data volume and extensive processing to form image products;
- Geometric distortion from terrain, platform, and processing effects; and
- Radiometric distortion from the atmosphere, sensor instability, and processor mismatch.

Substantial progress in correcting the systematic radiometric and geometric distortions has only occurred in recent years. This is primarily due to the fact that historically the large data volume and computational complexity necessitated that the bulk processing be performed optically with lasers and Fourier lenses using film as the input and output data media. Optical processing has a distinct advantage over digital in that high data throughput can be achieved; however, the film medium has a very poor dynamic range and its quality is inconsistent.

Only with the advent of low cost, high speed digital processing hardware has digital data processing become feasible. Most airborne SAR systems are now fully digital from the video output of the receiver system to the final data products. The first (and only) spaceborne SAR with a fully digital data handling system was SIR-B. Unfortunately, SIR-B experienced a failure in the antenna feed network, resulting in a major uncertainty in the overall system calibration. The unfortunate conclusion is that we have yet to build and operate a "calibrated" spaceborne SAR system. However, both the technology and expertise in the SAR field have now matured to a point where we believe an operationally calibrated system is realizable.

In this paper, we review the causes of radiometric calibration errors in SAR data. We show how the radar equation, which relates radar backscatter to image pixel value, can depend on the form of the SAR processing algorithm used, and we review some properties of the SAR radar equation which may not be familiar to the general reader. An algorithm designed to correct deterministic radiometric errors which vary across the imaged swath, such as range attenuation and antenna pattern, is developed. The novel features of the algorithm are that it can be applied to both complex and detected images, it allows the user to subtract an estimated mean level of system noise but does not require this procedure, and the user is supplied with sufficient information to invert the radiometric correction process, if necessary. The approach to radiometric correction and calibration put forward in this paper is designed to be compatible with the SAR processors and data product formats being developed for a number of NASA-sponsored facilities, including the Spaceborne Imaging Radar-C, Eos SAR, and the ERS-1 SAR processor at the Alaska SAR Facility.

DISCUSSION OF CALIBRATION ERROR SOURCES

When reference is made to radiometric calibration of an instrument, it typically refers to the various types of internal calibration signals available to measure transmitter power or receiver gain. The concept of system calibration extends far beyond the radar design engineer. Only when the end-to-end system is fully characterized can the final product be declared calibrated. Figure 1 illustrates the various factors to be considered in calibrating a SAR system. The goal of the SAR instrument is to provide sufficient information about the target characteristics (through the electromagnetic interaction of the radiated signal with the target) to derive geophysical data from the resulting images.

The target characterization is best performed by multi-parameter imaging where parameters such as the radar wavelength, polarization, and imaging geometry are varied to produce a complete description of the target. Interpretation of the data relies on relating the amplitude and phase of the resulting image pixels to specific target characteristics (complex reflectivity, radar cross-section, σ or σ°) considering each element in the data system, although we shall only consider amplitude calibration in this paper. Following is a general description of the calibration error sources for each of these elements.

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Fig. 1. Sources of radiometric calibration errors.

ATMOSPHERIC PROPAGATION

Propagation of both the radiated and reflected waves through the atmosphere and the ionosphere can result in significant modification in the wave parameters.

Effects such as Faraday rotation, group wave delay, and attenuation of the signal are localized phenomena in terms of both time and space and are therefore extremely difficult to operationally calibrate. The ionospheric effects will depend not only on latitude but also on time of day and season of the year. The effect is especially severe for high altitude (above 500 km) low frequency (below 1 GHz) polar orbiting sensors. Attenuation resulting from water vapor in the atmosphere could also affect measurements from SAR data.

SENSOR PLATFORM

A stable platform with precise attitude and orbit determination capability is a necessity for a coherent imaging system. The absolute location accuracy and relative geometric fidelity are highly dependent on knowledge of the platform position (and the target height), with the radial or cross-track component being most important. Precise attitude knowledge is necessarily required for system calibration. Although these parameters can be derived from the SAR echo data, the techniques are target dependent; therefore, the accuracy will vary with target type. It is preferable to have precise attitude determination from instrument measurements. Similarly, the attitude rate (if not properly compensated) will degrade the image quality by blurring the image focus. Again, these parameters can be derived from the data by processing techniques, but error in the estimate will degrade the calibration accuracy.

ANTENNA

Characterization of the antenna typically requires external calibration sources. Especially in the spaceborne (zero-gravity) environment, the thermal and mechanically induced distortions can cause significant degradation in the pattern. For an active array or an electronically steerable beam, additional uncertainties will result from element degradation and/or failure. Precise characterization of the gain and phase, both across the main beam in azimuth and elevation and across the system bandwidth, is required. Additionally, good cross-polarization isolation (better than 30dB) is critical for polarization synthesis. This is true not only in the main-lobe of the azimuth pattern but also in the sidelobes as well due to the finite sampling of the azimuth spectra (Blanchard 1985).

RADAR SENSOR

This element, which includes both the RF and digital electronics, is typically well characterized by internal calibration signals such as coherent tones and attenuated replicas of the transmitted pulse. The system performance will be degraded by random amplitude and phase errors caused by component aging or temperature variation. A second area of consideration is system nonlinearity. The dynamic range of the system should always be limited by the analog-to-digital converter (i.e., no amplifier saturation before ADC saturation and the video amplifier should be the first to saturate). Additionally, the dynamic range of the ADC should be sufficient to span the two- to three-sigma variance of the echo for the type of targets under consideration. An all purpose imaging SAR typically requires at least 25 to 30 dB dynamic range or an equivalent of six bits of quantization.

SIGNAL PROCESSOR

The signal processor forms the image product from the raw signal data by convolving these data with the appropriate reference functions (i.e., two-dimensional matched filter). These reference functions, in general, must be derived from the signal data and then their accuracy will be target dependent. Errors result in increased azimuth ambiguities, loss of signal-to-noise ratio (SNR), defocussing, and geometric distortion. This is especially critical for external calibration sources using point targets because processor errors cannot be distinguished from radar system errors.

IMAGE PROCESSOR

The image processing, which may be incorporated into the signal processing, is the processing stage that converts the complex image data into a geocoded target backscatter or Stokes matrix map. This process requires compilation of all the ancillary data (system gains/losses, orbit, attitude, imaging parameters) into a model of the radar system to relate the image pixel data number to the backscattered power. The accuracy of this estimate is dependent on the accuracy of the measured parameters as well as the adequacy of the spatial and temporal sampling intervals. These factors are necessarily affected by conditions such as the space environment, the available telemetry bandwidth, and limitations of the measurement sensors. Additionally, the models make some approximations regarding system stability and consistency which will degrade the estimate of the backscattered energy.

GEOPHYSICAL PROCESSOR

This is the final processing stage whereby geophysical characteristics of the imaged target are measured. This can be done by inversion of a scattering model (e.g., Bragg) which gives the target type or by image processing, utilizing the statistics of the image (e.g., mean-to-standard deviation ratio). Both techniques are dependent on the availability of accurate ground truth data to train/test the processing algorithms, subject to the adequacy of the derived models or image processing techniques.

END-TO-END SYSTEM CALIBRATION

The calibration of all these elements, taken as a group, in the radar system presents a formidable challenge to both radar design engineers and science analysts. However, with proper system design, each element can be quantitatively characterized to establish an end-to-end radiometric performance specification for the system. This internal calibration procedure can be externally confirmed or verified by using appropriately equipped ground calibration sites. The following section will establish a basic set of calibration parameters that are necessary and sufficient to specify the radar performance.

The parameters defined above are random variables. With

each parameter value a probability of occurrence should be specified. For example, if the probability distribution is Gaussian, the parameter could be specified in terms of the number of standard deviations (e.g., 3 σ). A second point is that the radiometric and geometric calibration errors are both time and space dependent random variables. The errors are a function of the cross-track and along-track position within the image. Typically, a specification is given in terms of a single value for an image product, and it is not always clear to which portion of the image it is referenced.

THE SAR RADAR EQUATION

In this section we develop forms of the SAR radar equation which are appropriate for images of both point and distributed targets, explicitly incorporating the effects of the SAR correlator. The forms of the equation are particularly suitable for implementation of the correction of systematic cross-track radiometric variations during SAR processing. In this formulation, we ignore the effects of propagation errors and the possible effects of target dependent errors such as ambiguities or speckle. We also assume that the radar system is approximately linear. It is well known (e.g., Cutrona, 1970) that the expected power

It is well known (e.g., Cutrona, 1970) that the expected power in a single pulse received from a point target of RCS, σ , at the "raw" data stage, i.e., after digitization but before any signal processing (e.g., azimuth or range compression), is

$$P_r = P_s + \overline{P}_n$$

or $P_r = \frac{P_t G^2(\theta_t) \lambda^2 G_r \sigma}{(4\pi)^3 R^4} + \overline{P}_n$ (1)

where P_t = transmitter power,

- $G(\theta_i) =$ gain of antenna at local incidence angle θ_i ,
 - λ = radar wavelength,
 - G_r = receiver gain,
 - R =slant range, and
 - \overline{P}_n = additive noise.

At the raw data stage, the signals received may be contaminated by additive noise from several sources: thermal noise in the receivers, quantization noise, thermal radiation from the Earth, and propagation noise. We assume here only that the noise is a white, stationary Gaussian process, with zero-mean voltage and average power, \overline{P}_n . Note a $1/R^4$ dependence appears in both the received power due to the signal alone, P_s , and the SNR, which is defined as P_s/\overline{P}_n , or peak signal power over average noise power.

The image formation process, which consists primarily of azimuth and range compression operations applied to the digitized video signal, can be considered as a phase-compensated coherent integration. This produces an expected signal strength, for the case of a point target (Ulaby *et al.*, 1982), given by

$$P'_{r} = P'_{s} + P'_{n}$$

$$= \frac{C(\theta_{i}) \sigma n^{2} L_{w} L_{\phi} N_{L}}{R^{4}} + n \overline{P}_{n} L_{w} N_{L}$$
(2)

where, for convenience, $C(\theta_i) = \frac{P_t G^2(\theta_i) \lambda^2 G_r}{(4\pi)^3}$, and $n = n_R n_{AZ}$ is the number of samples integrated. (This formulation assumes that no normalization factors used during the data set.)

that no normalization factors were used during processing). n_R = number of samples integrated in range compression (i.e., $\tau_n f_s$)

 τ_p = pulse length

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- f_s = range sampling frequency
- $n_{AZ} = T_s / \Delta t$, number of samples integrated in azimuth
- T_s = azimuth integration time (= $\lambda R/2V\rho_a$)
- V = platform speed
- $\Delta t = 1/\text{PRF} = \text{sampling interval in azimuth}$

- ρ_a = the theoretical azimuth resolution used in constructing the azimuth reference function (> d_a / 2 = half the azimuth antenna length)
- $L_w = L_{w_a} \cdot L_{w_r}$ loss in peak signal strength due to azimuth and range reference function weighting (e.g., Hamming)
- L_{ϕ} = any losses in peak signal strength due to phase mismatch in the reference function.

 N_L = number of (effective) looks used in processing. The difference in the behavior of noise and signal after coherent integration arises from the fact that the echo signals received from a point target add coherently in voltage, while the noise terms, which are mutually incoherent, add only in power (e.g., Ulaby *et al.*, 1982). Any loss due to weighting applied in the correlator, L_w , should apply equally to signal and noise terms. A non-coherent integration, such as multi-looking, increases both signal and noise terms by a factor N_L , the number of looks or samples integrated (again assuming no processor normalization).

Note that the power from a point target in the above expression demonstrates a $1/R^2$ dependence, because $n \alpha R$, while the peak SAR falls off as $1/R^3$.

For a large, distributed target, it is usual to discuss mean power, averaged over all scatterers in the target, instead of peak power (Develet, 1964). For a target of uniform normalized cross section, σ_{a} , this can be written

$$\overline{P}_{r} = \overline{P}_{s} + \overline{P}_{n}$$

$$= \frac{C(\theta_{i})}{R^{4}} \sigma_{o} \frac{c\tau_{p}}{2sin\theta_{i}} \beta_{a}R + \overline{P}_{n}$$
(3)

where $c\tau_p/2\sin\theta_i$ and $\beta_a R$ are the dimensions of the precompression "resolution cell," i.e., the resolution due to a pulse of duration τ_p in range and the width of the physical antenna footprint in azimuth, respectively. Note the $1/R^3$ dependence of the expected video signal power and the SNR. This is the relationship that should be used when designing the radar receive chain including the ADC.

The expression in Equation 6 for the signal power in an image due to a point target with additive noise can be directly extended to the distributed target case. Assuming that the average signal level for a homogeneous SAR image is independent of scene coherence (Raney, 1980), a uniform target can be modeled as a discrete set of scatterers with amplitude cross section

$$s(x,y) = A(x,y) \exp\{j \phi(x,y)\}$$
 (4)

spaced at intervals equal to the image resolution cell size, i.e., ρ_a and ρ_r . The amplitude A(x,y) is modeled as a Rayleigh distributed process in space but constant in time and the phase $\phi(x,y)$ as uniformly distributed in space and constant in time. Because the expected "RCS" of a resolution cell is given by

$$E[|A|^{2}_{x,y}] = \sigma_{o}\rho_{a}\rho_{r}/\sin\theta_{i}$$
(5)

the mean power in a homogeneous image is

$$\overline{P}_{r}' = \overline{P}_{s}' + \overline{P}_{n}' \\
= \frac{C(\theta_{i})n^{2}L_{w}N_{L}}{R^{4}} \sigma_{o}\rho_{a}\rho_{r}/\sin\theta_{i} + n\overline{P}_{n}L_{w}N_{L}.$$
(6)

The most important difference between Equation 6 for a distributed target and Equation 2 for a point target is the factor, L_{ϕ} , which does not affect the distributed target case because any energy loss due to lack of coherence is distributed equally over the target area. Otherwise, the signal intensity again falls off as $1/R^2$ while the noise power increases linearly with range. Assuming the azimuth reference function length, n_{AZ} , is adjusted as a function of range to keep ρ_a constant, the SNR varies as $1/R^3$. We can compare the mean signal power before processing with that after processing, so that, from Equations 3 and 6,

$$\frac{\overline{P}_{s}'}{\overline{P}_{s}} = n^{2} L_{w} N_{L} \rho_{a} \rho_{r} \frac{2}{c \tau_{p}} \cdot \frac{1}{\beta_{a} R}$$
(7)

The factor

$$\kappa = \frac{1}{\rho_a \rho_r} \cdot \frac{c\tau_\rho}{2} \cdot \beta_a R \tag{8}$$

is the ratio of the product of the range and azimuth spatial resolution before and after processing. It is sometimes referred to as the compression ratio of the system. For some SAR system realizations $\kappa \sim n$, so that the overall increase in signal level due to processing (Equation 7) would just be a factor of (nL_wN_L) .

Taking the ratio of the SNR after compression in Equation 6 to that before compression in Equation 3 for a uniform distributed target, we have

$$\frac{\mathrm{SNR}'}{\mathrm{SNR}} = \frac{\overline{P}_{s}'}{n\overline{P}_{n}L_{\omega}N_{L}}\frac{\overline{P}_{n}}{\overline{P}_{s}}$$
$$= \frac{2n\rho_{a}\rho_{r}}{c\tau_{v}\beta_{a}R} \qquad (9)$$

But
$$n = \tau_p f_s \frac{\lambda}{2} \frac{R}{V \rho_a} \text{ PRF}$$
,

so
$$\frac{\text{SNR}'}{\text{SNR}} = \frac{\text{PRF}}{\beta_a 2 V/\lambda} \frac{f_s}{B_p}$$
 (10)

where B_p is the pulse bandwidth.

Thus, there is no increase in the perceived SNR for the returns from a uniform target due to compression, except by the product of two oversampling factors. These oversampling factors are the ratio of the PRF to the azimuth doppler bandwidth ($\beta_a 2V/\lambda$) and the ratio of the complex sampling frequency to the range pulse bandwidth. No further SNR increase, e.g., by using smaller processing bandwidths, is possible. [In practice, if ambiguity noise is considered, by adjusting the PRF and the processing bandwidth, the overall SNR can be improved.]

It is important to note that, although target coherence over time was assumed to obtain Equation 6, that is not mandatory for the result to be valid. Partial coherence is a common feature of many radar returns. Imaging of ocean waves is a well-studied example (Raney, 1980). The coherence of the target does not alter the total signal power in the image; rather, it degrades the final image resolution.

From the above, it follows that the form of the correction factor to be used in calibrating the range dependence of the SAR image intensity will depend on the form of the applied azimuth reference function. We have shown that, without any normalization factors, the image intensity for a given σ_o will drop off as $1/R^2$; therefore, the appropriate normalization factor to eliminate the range dependence in signal power is proportional to R^2 . The noise power, however, increases linearly with *R* before correction. If a normalization factor of 1/n is used during azimuth compression, the image correction factor is proportional to R^4 , and the noise power varies as 1/R. Only if a correction factor of $1/\sqrt{n}$ is used, will the signal correction factor be the traditional R^3 and the noise level constant as a function of range. Misunderstandings in these relationships may explain the range dependent variation in many SAR images found in the literature.

For example, in most operational SEASAT correlators it is convenient to fix the (non-zero) azimuth reference function length at 1024 samples per look. Typically, reference function coefficients are updated to account for their range dependence, but the reference length is not adjusted to maintain a constant azimuth resolution. This was a consequence of the fact that standard frequency domain (FFT) matched filtering algorithm is most efficient for reference functions that are a power of 2. Fixing the azimuth reference function length means that the theoretical azimuth resolution will degrade with range, so that it degrades slightly across the swath. Consequently, the average signal level varies as $1/R^3$ in most SEASAT SAR images, while the noise level is constant across the swath. This gives a variation of $1/R^3$ in SNR for SEASAT. [In fact, the range dependence in the SNR is invariant under linear operations.] The azimuth resolution broadens with increasing range by approximately 4.5 percent for a typical image that varies in slant range from near to far edge of the swath by nearly 40 km.

A second example is the SIR-B production image correlator (Curlander, 1986). This system used an azimuth reference function of a fixed length, 2048 samples, but varied the number of non-zero terms, *n*, to keep the azimuth resolution constant across the swath, according to the formula

$$n = \frac{0.4 \operatorname{PRF}^2 \lambda R}{V_g^2}$$
 (11)

The reference functions generated in the correlator were zero padded to the right. A normalization factor of $1/n_{\text{FFT}}$ (where n_{FFT} = 2048 is the length of the FFT used in processing) was applied to the reference. Because this correction does not vary with the actual (nonzero) reference function length, it does not affect the range dependence of either the expected signal power or SNR. Hence, for SIR-B images, the average signal level should vary as $1/R^2$, while the noise power will increase linearly with R, resulting in an SNR variation proportional to $1/R^3$. A summary of the range dependence of the mean signal power and SNR for different azimuth reference options is given in Table 1.

RADIOMETRIC CORRECTION IN THE SIGNAL PROCESSOR

Most of the deterministic or slowly varying random errors present in the end-to-end SAR system can theoretically be corrected during the SAR image formation process. The assumption is that the system is approximately linear and that sufficient measurements are performed during (or prior to) the radar operation to accurately characterize the overall transfer function of the system. This implies that the system dynamic range is large relative to the dynamic range of the input signal to be measured, i.e., a low signal-to-distortion noise ratio. Additionally, the radar must be stable related to the sampling frequency of the instrument calibration subsystem (i.e., the collection of current, temperature, voltage and power meters, injected calibration tones, stable noise sources, and leakage pulse replicas built into the radar system).

The calibration data can generally be categorized under three main headings:

- (1) Preflight Test Data (System Characterization)
- (2) Inflight Calibration Subsystem Measurements (Internal Calibration)
- (3) Ground Calibration Site Imagery (External Calibration)

An example of the type of data in category 1 is the antenna system characterization (i.e., the antenna gain and phase characteristics as a function of frequency and off-boresight angle). Measurements made in category 1 are often used to relate a critical parameter which is difficult to measure directly to an easily measured parameter (e.g., radiated power to transmitter temperature). The category 2 measurements are used (in conjunction with the preflight test data) to perform the relative system calibration, while the external ground site calibration data (category 3) is necessary for absolute calibration.

The processor's task is to utilize this calibration data to produce image products which are

· Relatively Calibrated. For any pixel in the output image, a given

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RADIOMETRIC CORRECTION AND CALIBRATION OF SAR IMAGES

TABLE 1. EXAMPLES OF AZIMUTH CORRELATION RANGE DEPENDENCE AND NORMALIZATION

Normalization	Length	Signal Power	Noise Power	SNR
1. None	Variable, αR	$\alpha 1/R^2$	αR	$1/R^{3}$
2. $1/n_{AZ}$	Variable, αR	$\alpha 1/R^4$	$\alpha 1/R$	$1/R^{3}$
3. $1/\sqrt{n_{AZ}}$	Variable, αR	$\alpha 1/R^3$	Constant	$1/R^{3}$
4. None	Fixed	$\alpha 1/R^3$	Constant	$1/R^{3}$

data number (or gray value) always represents the same backscatter coefficient (to within an allowable error tolerance) independent of its cross-track position or time of acquisition: and

• Absolutely Calibrated. For each data number in the output image, there is given a corresponding backscatter coefficient value (within the given error tolerance) as related by a proportionality constant or set of constants such that

$$\sigma_{\rm o} = K_1 / A^2 + K_o \tag{12}$$

where A is the pixel complex voltage, and K_1 , K_o are constant scale factors.

We will show later that in the practice it is advantageous to allow for relative variation in the cross-track direction with K_1 replaced by a range dependent variable, $K_i(R)$.

RADIOMETRIC CALIBRATION ALGORITHM

As previously discussed, the azimuth matched filter function necessary to maintain a constant azimuth resolution independent of target range position requires the filter length to vary in proportion to the change in range across the swath. Because as the reference increases, the scattered power returns from a larger area, a relative calibration correction of the form

$$K_a = (n_{az} L_w N_L)^{-1/2}$$
(13)

is required to normalize the reference function, where n_{az} is the number of (non-zero) azimuth samples, N_L is the number of looks incoherently added to form the final image and L_{w} is the effective range and azimuth weighting factor due to the pulse shaping and sidelobe weighting functions. This correction maintains a constant mean noise level P_n in the output image, equal to the input noise level in the raw data. Therefore, the mean noise power in noise-only raw data (radar transmitter turned off) divided by the mean noise power in the noise-only image data yields the term L_w . This is one aspect of processor calibration. We assume here that only the azimuth and range compressions, the azimuth presum, and multi-looking operations contribute to an increase in signal level through the processor. All other fundamental operations, such as forward and inverse FFTs, interpolation to correct range cell migration, etc., are assumed to be properly scaled. This can be verified by checking the overall gain of the processor, again by using noiseonly raw data as input over all operating modes. Another processing attribute which should be properly calibrated is L_{dr} the loss in peak signal strength of a point target signature due to phase mismatch in the reference functions. This should be calibrated using simulated point target raw data as input to the processor, and checked at intervals using both simulated data and data obtained over large arrays of known point targets.

From Equation 10, given the above normalization of the azimuth reference function, the appropriate form of the radar equation for a distributed target (after substituting for n in Equation 6 from Equation 2 is

$$\overline{P'}_{r} = \frac{P_{t}G^{2}(\theta_{i}) \lambda^{3} G_{r} \sigma_{o} \rho_{r} \tau_{p} f_{s} PRF}{(4\pi)^{3} R^{3} \sin\theta_{i} 2V} + \overline{P}_{n}$$
$$= K(R) \sigma_{o} + \overline{P}_{n}$$
(14)

where
$$K(R) = \frac{P_t G^2(\theta_i) \lambda^3 G_r \sigma_o \rho_r \tau_p f_s PRF}{(4\pi)^3 R^3 \sin\theta_i 2V}$$

Note that this differs from the point target formulation only by the factors, L_{ϕ} , and sin θ_i . Equation 14 suggests that an appropriate form of the radiometric correction algorithm to be applied to the output image voltage is to weight each range line by a factor $1/\sqrt{K(R)}$ in amplitude, so that

$$\overline{P}_{r}^{*} = \sigma_{o} + \frac{\overline{P}_{n}}{K(R)}$$
(15)

If the SNR is small, say <3dB, then the radiometric correction given in Equation 19 can cause a radiometric imbalance in the image, due to the scaling of noise by the factor *K*(*R*). This effect is illustrated in Figure 2 for a SIR-B image with very low SNR (\approx 0dB). One approach to correct for this effect is to subtract the mean noise level. Alternatively, it is possible to apply a form of correction which takes into account the SNR, as estimated from the range spectra of the raw data, such that

$$\hat{\sigma}_o = P'_r / [K(R) \cdot (1 + \text{SNR}^{-1})].$$
 (16)

Again, this correction could be done either in amplitude or power and recorded in a look-up table in the image header. However, if the SNR should change significantly within an image frame, e.g., at a land/water boundary, then more than one SNR estimate and hence more than one look-up table would be required. This may result in a radiometric discontinuity at the location in the image where the scale factor was adjusted.

Typically, when generating the final image product a twoparameter stretch (gain and bias) is applied to optimize the image representation utilizing the full dynamic range of the output medium, whether it be an 8- or 16-bits per pixel data file or photographic film. Thus, the final form of Equation 15 becomes

$$\overline{P}_{r} = K_{\text{GAIN}} \left[\sigma_{o} + \frac{\overline{P}_{n}}{K(R)} \right] + K_{\text{BIAS}}$$
(17)

To derive the correction factor, K(R), each of the parameters in Equation 14 must be determined. The parameters λ , τ_{ν} , and fs are assumed constant and determined from preflight measurements. The parameters, ρ_r and ρ_a , are the theoretical resolutions of the images and can be derived from processor inputs. The thermal noise \overline{P}_{μ} is estimated from the segment of recorded signal data after the radar begins transmitting and before the first echo is received. Alternatively, a less accurate estimate can be derived from the out-of-band power level in the range spectra. The accuracy of this technique is dependent on the oversampling factor (f_s / B_p) and the chirp spectral slope. The peak power, P_t , is estimated from inflight measurements after accounting for antenna system losses. The PRF is known and the swath velocity can be derived from the platform position and velocity vectors. The slant range, R, requires preflight measurement of the system electronic delays and any processor induced offsets. The incidence angle θ_i is easily derived if the slant range, platform position, and Earth radius are known.

The effective antenna pattern, including platform effects, is

ILLUMINATION



FIG. 2. SIR-B Image with low SNR, showing effect of radiometric correction on noise at edges.

typically the most difficult measurement to make. The gain and phase of the antenna should be characterized as a function of off-boresight angle at a set of frequencies across the radar bandwidth during preflight testing. Ideally, these measurements are made at operational temperatures in a vacuum (for spaceborne systems) with similar structural interferences to that which may occur during operations. Because this is not always practical, preflight measurements are updated by inflight measurements using external targets such as corner reflectors, transponders, and receivers. To determine the antenna gain at each incidence angle, the platform roll angle must be known because the range gate is independent of the attitude variations. The receiver gain is most easily determined by inflight measurement, by injecting a tone, noise source, or chirp replica of known signal level into the front end of the receiver (i.e., before the low-noise amplifier) and measuring its level in the raw signal data.

IMPLEMENTATION OF THE RADIOMETRIC CORRECTION ALGORITHM

The relative calibration is performed by selecting a reference value for each parameter in the radar equation (Equation 14) and normalizing each pixel in the image (across all images) by the ratio of the reference value to the estimated parameter value for that pixel. The absolute calibration is then given by Equation 15 where the parameters in K(R) are simply the reference values chosen in the relative calibration processes.

All corrections can be incorporated into the normal processing chain without adding any stages that would require an additional pass over the data. Figure 3 illustrates a typical flow chart for the SAR correlator illustrating how the calibration corrections are derived and where they are inserted in the processing chain. The caltone scan or pulse replica analysis (for deriving the range reference function) and the receive-only noise (RON) estimate (for deriving the mean noise power) are performed only occasionally (the frequency depends on the radar stability). The proposed correction scheme assumes all inflight system measurements are inserted into the telemetry data stream in conjunction with the platform attitude and position data. Additionally, all relevant radiometric correction factors are included in the image header for access by data product users. The factors supplied should be K_{GAIN} , K_{BIAS} , \overline{P}_n , and K(R) (as a look-up table). Because the corrections are all linear transformations (assuming no ADC nonlinearity corrections have been applied and the complex image is preserved), the user then has enough information to invert the correction process if desired. In addition, because the thermal noise level (and its variation across the swath) is also supplied in the header, the user can subtract the estimated noise power from the image after detection.

The goals for radiometric calibration of SIR-C image products are given in Table 2. Absolute calibration is defined with reference to some target of known RCS, long-term relative calibration compares results from more than one pass over the same site, while short-term relative calibration refers to comparisons between identical scatterers within the same imaged scene. With a properly implemented radiometric correction and calibration scheme, incorporating all the elements put forward in this paper, we feel that these goals can be met.

CONCLUSION

We have addressed the problem of radiometric calibration of SAR imagery and introduced a form of the radar equation which explicitly includes the SAR image formation process. We have presented key factors which need to be considered for radiometric calibration and how they could be measured and included in the radiometric correction process. We have presented a particular form of radiometric correction algorithm which may be applied equally to complex or square-law detected (power) SAR images. This algorithm allows the subtraction of noise from the image power. We recommended, in implementing this algorithm, that the processing system append the necessary information to the image data in a look-up table, to enable the user to convert easily from the pixel numbers in his/her image to σ_0 values. In addition, all information relating to the correct

RADIOMETRIC CORRECTION AND CALIBRATION OF SAR IMAGES



FIG. 3. Calibration processing flowchart.

TABLE 2. RADIOMETRIC CALIBRATION GOALS FOR SIR-C (FREEMAN ET AL., 1988)

Absolute calibration	$\pm 3 dB$
Long-term relative calibration	$\pm 1 dB$
Short-term relative calibration	$\pm 1 dB$

tion factors applied to the image in the radiometric correction operation should be appended so that the user could invert this process, if desired.

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REFERENCES

- Blanchard, A., and D. Lukert, 1985. SAR Depolarization Ambiguity Effects, *Proc. IGARSS*, pp. 478–483.
- Curlander, J. C., 1986. Performance of the SIR-B Digital Image Processing Subsystem, *IEEE Trans. Geoscience & R.S.*, Vol. GE-24, No. 4, pp. 649–652.

- Cutrona, L. J., 1970. Synthetic Aperture Radar, Chapter 23 in Radar Handbook (M. I. Skolnick, ed.) McGraw-Hill.
- Develet, J. A., Jr., 1964. Performance of a Synthetic Aperture Mapping Radar System, *IEEE Trans. Aerospace and Navigational Electronics*, Vol. ANE-11, No. 3, pp. 173–179.
- Elachi, C., T. Bicknell, R. Jordan, and C. Wu, 1982. Spaceborne Synthetic Aperture Imaging Radars: Applications, Techniques and Technology, *IEEE Proceedings*, Vol 70, No. 10, pp. 1174–1209.
- Freeman, A., J. C. Curlander, P. C. Dubois, J. D. Klein, 1988. SIR-C Calibration Workshop Report, JPL Technical Report #D-6165, November, 1988.
- Johnson, W. T. K., and A. Edgerton, 1985. Venus Radar Mapper (VRM): Multi-mode Radar Systems Design, SPIE, Vol. 589, pp. 158–164.
- Jordan, Rolando L., 1980. The SEASAT A Synthetic Aperture Radar System, IEEE J. Oceanic Eng., Vol. OE-5, pp. 154–163.
- Raney, R. K., 1980. SAR Response to Partially Coherent Phenomena, IEEE Transactions on Antennas and Propagation, Vol. AP-28, No. 6, November 1980, pp. 777–787.
- Tomiyasu, Kiyo, 1978. Turotial review of Synthetic-Aperture Radar (SAR) with Applications to Imaging of the Ocean Surface, *Proceedings of* the IEEE, Vol. 66, No. 5, pp. 563–584.
- Ulaby, F. T., R. K. Moore, and A. K. Fung, 1982. Microwave Remote Sensing, Vol. II, Addison-Wesley.
- Wehner, D., 1987. High Resolution Radar. Artech House.
- Wiley, Carl A., 1985. Pulsed Doppler Radar Methods and Apparatus, U.S. Patent 3,196,436, Filed 13 August 1954, Patented 20 July 1965.