A general method for calibration of the C-band Convair-580 SAR

R. Touzi
Canada Centre for Remote Sensing
Natural Resources Canada
588 Booth Street,
Ottawa, Ontario, Canada K1A 0Y7

C.E. Livingstone
Defence R&D Canada-Ottawa
National defence
3701 Carling Av.
Ottawa, Ontario, Canada K1A 0Z4

Abstract

A general polarimetric model which includes systems whose receiving configuration is independent of the transmitted polarization (one configuration), as well as systems with two distinct receiving configurations, was introduced in [9]. This model was used to develop a calibration method for early X-band polarimetric SAR developed at Canada Centre for Remote Sensing (CCRS) [9]. A simplified method was adapted for the C-band SAR system that is equipped with polarization switches with high isolation (better than 50 dB) [4], [2]. This method leads to an accuracy of 1 to 2 dB in radiometry and 5°in phase, for incidence angles within ±20°from the antenna boresight angle. Tests run on various data sets lead to the conclusion that the Convair-580 SAR system is quite stable in short-term, but is not over the long-term. This requires the deployment of reference point targets during each flight. On the other hand, several data sets demonstrated the existence from time to time of a significant cross-talk term. It is shown that the general calibration method of [9] can still be applied to retrieve pure polarizations from the distorted measurements, and provide an assessment of the system distortion matrix during data acquisition.

I. Introduction

In order to exploit the fully polarimetric capability of the Convair-580 SAR, pure HH, VV, HV, and VH data have to be retrieved from the distorted measurements. In contrast to most existing polarimeters, the Convair-580 SAR polarimeter uses two receiving configurations as a function of the transmitting polarization H or V [4]. A general polarimetric model which includes systems whose receiving configuration is independent of the transmitted polarization (one configuration), as well as systems with two distinct receiving configurations, was introduced in [9]. This model was used to develop a calibration method for early X-band polarimetric SAR developed at CCRS [9]. A simplified method was adapted for the C-band SAR system that is equipped with polarization switches with high isolation (better than 50 dB) [4], [2]. This method leads to an accuracy of 1 to 2 dB in radiometry and 5°in phase, for incidence angles within 20°from the antenna boresight angle. On the other hand, several data sets demonstrated the presence from time to time of a significant cross-talk term. It is shown that the general calibration method of [9] can still be applied to retrieve pure polarizations from the distorted C-band measurements.

In the following, the general polarimetric SAR model and calibration method derived in [9] are introduced. In Section 2, a simplified method is adapted for the C-band SAR system that is equipped with polarization switches with high isolation (better than 50 dB). The effect of time system stability on the calibration parameters is then discussed. The accuracy of calibration in phase and magnitude is studied, and an error budget is derived. The case of C-band data with poor isolation is discussed in Section 3. It is shown that the general method developed for early X-band polarimetric SAR can still be applied to calibrate the data, and provide an assessment of the system distortion matrix during data acquisition.

II. A general model for the X and C-band Convair 580 SAR system

A. System description

Figure 1 shows a simplified block diagram of the Convair-580 polarimetric system described in [4]. The system transmits pulses at twice the normal pulse repetition frequency of the radar through the antenna where horizontally and vertically polarized feeds are time multiplexed through a ferrite switching circulator to drive a single radiating aperture. The backscattered signal, received by the same antenna used in transmission, is passed through the finite ferrite polarimeter switch which has the configuration 1(or 2) if H (or V) is the transmitted polarization (Figures 2 and 3). Furthermore, the switch separates the co-polarized signals (HH-VV) from the cross-polarized ones (HV-VH) which permits separate amplification of the cross-polarized signals which are generally much weaker than the co-polarized signals. The co- and cross-polarized signals are then fed to two different, receivers (A and B, respectively) and routed through the video distribution interface to two dual channel Processor/Control Units where they are digitized. The two PCUs operate alternately so that each unit processes like- and cross-polarized data corresponding to a single transmit polarization.

B. General system model

In contrast to most existing polarimeters, the Convair-580 SAR polarimeter uses two receiving configurations as a function of the transmitting polarization, H or V. A general polarimetric model which includes systems whose receiving configuration is independent of the transmitted polarization (one configuration), as well as systems with two distinct receiving configurations according to the commanded transmitted polarization (H or V), was introduced in [9]. The model, which explicitly includes key radar architecture elements, separately considers parameters that are independent of target illumination angle and those with illumination angle dependence, thus allowing calibration approaches which are valid for targets at different illumination angles provided that the complex antenna elevation gains are known. This model, which was originally developed for the calibration of the X-band system, is adapted here to the C-band system. The notations of [9] are used in the following.

The transmitter (antenna not included) is characterized by its distortion matrix $[d^t]$ which is constructed from the switch distortion matrix and the complex gains a^t_i of the H-V signal paths[1] in the radar (i= H or V, generally $|a^t_i| \leq 1$):

$$[d^t] = \begin{bmatrix} sw^t_{HH} & sw^t_{VH} \\ sw^t_{HV} & sw^t_{VV} \end{bmatrix} \begin{bmatrix} a^t_H & 0 \\ 0 & a^t_V \end{bmatrix}. \tag{1}$$

For the switch parameters sw^t_{ij}, i designates the commanded polarization and j designates the antenna field actually driven. The diagonal terms are the switch complex efficiency coefficients (generally, $|sw^t_{ii}| \simeq 1$), and the off-diagonal terms are the leakage coefficients (or cross-talk, generally $|sw^t_{ij}| \ll 1$).

The antenna which can be assumed to be reciprocal is characterized by its distortion matrix:

$$[g] = \begin{bmatrix} g_{HH} & g_{HV} \\ g_{HV} & g_{VV} \end{bmatrix},$$

where the $[g]$ elements, g_{ij}, are the complex, far-field, antenna gains. The diagonal terms give the one way gains, and the off-diagonal terms correspond to the antenna cross-talks.

The receiver distortion matrix $[d^{r,k}]$ for the commanded transmit polarization k (H or V) is given by:

$$[d^{r,k}]^T = \begin{bmatrix} a^r_{kH} & 0 \\ 0 & a^r_{kV} \end{bmatrix} \begin{bmatrix} sw^{r,k}_{HH} & sw^{r,k}_{VH} \\ sw^{r,k}_{HV} & sw^{r,k}_{VV} \end{bmatrix}, \tag{2}$$

where k is the commanded transmitted polarization H or V. The complex gains a^r_{kj} (j is the expected received polarization H or V) account for the signal paths (switch-receivers) in the receiving system, as well as for the different gains eventually applied to the 4 received radar returns. The sw^r_{ij} are the elements of the receive switch distortion matrix, where i designates the active receiving antenna field and j designates the switch output polarization, and a^r_i are the complex gains of the H or V signal paths [2] in the receiver channels.

A general expression for the transmitter-receiver distortion matrix $[d^{t,r}]$ can be expressed in terms of the pseudo-Kronecker product ($\odot$) of the transmitter distortion matrix $[d^t]$ and the two receive distortion matrices ($[d^{r,H}]$, $[d^{r,V}]$),

[1] They only concern the transmitter paths up to the switch. The phase paths (switch output)-(antennas) are included in the switch distortion matrix elements

[2] (switch output)-(receivers) paths. The phase paths antenna-switch are included in the switch distortion matrix elements

defined in [9] as:

$$[d^{t,r}] = [d^t]^T \odot ([d^{r,H}]^T, [d^{r,V}]^T) = \begin{bmatrix} d^t_{HH} \cdot [d^{r,H}]^T & d^t_{HV} \cdot [d^{r,H}]^T \\ d^t_{VH} \cdot [d^{r,V}]^T & d^t_{VV} \cdot [d^{r,V}]^T \end{bmatrix}. \tag{3}$$

The voltage vector $\vec{V}$ ($\vec{V} = (V_{HH}, V_{HV}, V_{VH}, V_{VV})^T$) received from an area (range resolution cell) characterized by its scattering vector, $\vec{S}$, ($\vec{S} = (S_{HH}, S_{HV}, S_{VH}, S_{VV})$, S_{ij}: i is the the transmitted polarization, and j the received one) can be expressed (for each pixel) as a function of $\vec{S}$, the distortion matrices, and the target illumination angle, θ, by using the the Kronecker product ($\otimes$) and the pseudo-Kronecker product ($\odot$):

$$\vec{V} = K \cdot \frac{n_{az}\rho_{az}}{R^2} \cdot ([d^t]^T \odot \left[[d^{r,H}]^T, [d^{r,V}]^T\right])([g(\theta)]^T \otimes [g(\theta)]^T)\vec{S}, \tag{4}$$

where K is a constant depending on system losses, the peak transmitter power, the length of the transmitted pulses and the number of samples integrated in range. All terms are assumed to be temporally stable, or at worst, have known time histories. n_{az} is the number of pulses integrated in azimuth and ρ_{az} is an optional azimuth compression term. Without any normalization (i.e $\rho_{az} = 1$), the voltage is inversely proportional to the slant range distance R, since n_{az} is proportional to R ($n_{az} = PRF \cdot R \cdot \beta / V$, where β is the antenna beamwidth, and V the beam footprint velocity). If the azimuthal matched filter is defined as an ortho-normal function, its impulse response function should be multiplied by the normalization compression term $\rho_{az} = \sqrt{B/T_{az}}$ (where B is the Doppler bandwidth, and T_{az} is the azimuth integration time). The product $n_{az}\rho_{az}$ is then proportional to the square root of the azimuth SAR Time Bandwidth Product (TBP) given by: TBP=$(V_{S/C}/V)(2R\beta^2/\lambda)$, where $V_{S/C}$ is the SAR platform velocity, and the ratio of the two velocities is generally a function of the slant range R and the local incidence angle θ_{inc} [6]. For an aircraft, the two velocities are the same and the voltage expression above varies as $1/R^{3/2}$. Such normalization is used by the CCRS processor but is not generally employed at all institutions.

Equation (4) includes the product of two distortion matrices: the pseudo- Kronecker matrix $[A] = [d^{t,r}]$ which will be called receiver-transmitter distortion matrix, and the 4x4 diagonal matrix $[G^c] = [g(\theta)^T] \otimes [g(\theta)^T]$ which will be called the antenna Kronecker distortion matrix.

C. Simplification of the model for the Convair-580 system with co-located antenna phase centers

The dual array feed, shared aperture horn antenna designed by Com Dev Ltd. has measured cross polarization couplings (including radome contributions) less than -35 dB [3]. Therefore, only the one way antenna gains $g_{HH} = G_H \exp j\phi_H$ and $g_{VV} = G_V \exp j\phi_V$ need to be considered, and the antenna distortion matrix $[\tilde{G^c}]$ is a diagonal matrix (whose diagonal is $(g^2_{HH}, g_{HH}g_{VV}, g_{HH}g_{VV}, g^2_{VV})$).

The antenna gain pattern G_H and G_V were measured on an antenna range, in a fixture that included the antenna drive mechanism, the aircraft radome, and a mock-up of the immediately adjacent aircraft hull by MPB of Montreal. Antenna range results were compared to calibration flight results [1], [11] and were shown to be compatible to within ± 0.5 dB over a look angle range of $\pm 20°$ from the antenna boresight.

In the matrix $[G^c]$, the antenna gain term magnitudes are tabulated functions but the phases (ϕ_H and ϕ_V) are a-priori unknown functions each of which can be expressed as the sum of a constant term, related to the feed geometry, and a term which varies as a function of the illumination angle θ, as follows:

$$\phi_H(\theta) = \phi_{H0} + \Phi_H(\theta) \text{ and } \phi_V(\theta) = \phi_{V0} + \Phi_V(\theta). \tag{5}$$

In general, the antenna phase difference pattern $\phi_H(\theta) - \phi_V(\theta)$ should be measured to calibrate a scene at the different illumination angles. The Convair-580 SAR antenna has been designed so that the H and V antenna phase centers are co-located, at least for illumination angles of $\pm 20°$ from the antenna boresight. The phase parts which vary as a function of the illumination angle are then practically the same, namely

$$\Phi_H(\theta) \simeq \Phi_V(\theta) = \Phi(\theta)$$

and the phase difference $\phi_H(\theta) - \phi_V(\theta)$, which is due to the H-V feed-horn path length difference, is constant.

As a consequence of this phase behavior, the antenna phase pattern does not need to be measured. The constant phase terms are included in the matrix $[A] = [d^{t,r}]$, and $[G^c]$ is replaced by its diagonal amplitude. As the illumination angle variations of the phase term $\Phi(\theta)$ are not known, the calibration will determine the vector $\exp[2j\Phi(\theta)]\vec{S}$, instead of $\vec{S}$. This does not present a problem since, in practice, the absolute phase is not required and only relative phases $arg(S_{HH}) - arg(S_{HV})$ and $arg(S_{HH}) - arg(S_{HV})$, which do not depend on $\Phi(\theta)$, are used.

III. Calibration of the C-band Convair 580 SAR with highly isolated switches

A. Simplification of the system distortion matrix

Since the switches are designed so that the cross-talk terms are small, the products of any two cross-talk terms can be ignored. This leads to the consequence that the off-diagonal elements of the matrix $[A] = [d^{t,r}]$, which are a product of cross-talk terms, are negligible. In contrast to the X-band switches, which had significant cross-channel leakage terms, the C-band switches are supposed to have cross-channel isolations in excess of 50 dB. Consequently, the leakage terms can be ignored with the result that the distortion matrix is diagonal.

Many data set were analysed to assess switches cross talk. Most of them demonstrate a weak HV and VH return (at the level of the clutter) from corner reflectors. This leads to the conclusion that the system is generally well isolated and that the scattering matrix elements can be extracted from the measured voltages using the following equation:

$$\vec{V} = K \cdot \frac{1}{R^{3/2}} \cdot [A][G^c]\vec{S}. \tag{6}$$

$[G^c]$ in equation (6) above is a 4x4 diagonal matrix whose elements are $|g_{HH}^2|$, $|g_{HH}g_{VV}|$, $|g_{HH}g_{VV}|$, and $|g_{VV}^2|$. $[A]$ is also 4x4 diagonal with elements which are combinations of the transmit and receive system complex gains (including the switches and the components up to the antenna). Each diagonal element includes the phase difference of the H and V antennas stable within $\pm 20°$ of the boresight angle. The constant K includes all the system gains of equation (4) which are stable within one flight pass.

B. Calibration strategy

The calibration method based on the system model of equation (6) should include the following steps:

1. Calculate the 4 unknown system elements of the diagonal matrix $[A]$ and the absolute calibration constant K.
2. Integrate the measured system elements a_{ij} in (6), and use the antenna gain measurements to retrieve the scattering matrix estimate for each pixel, at any incidence angle within ± 20 degrees from the boresight angle.
3. Deduce from the slant-range image the ground projected image and remove the additive thermal noise.

Step 1 is equivalent to solving a linear system of 4 equations in 5 unknowns. A 45°-45° PARC is used for channel relative calibration and a corner reflector is used for absolute calibration. Step 2 can be realized by using the antenna gain database, and the slant range variations with the illumination angle θ. The correction for the thermal noise in step 3 can be performed by using an internal measurement of system noise, a process which is implemented at the end of data acquisition for each pass.

C. Accuracy of the calibration: Error Budget

C.1 Accuracy of $\sigma°$:

The radiometric calibration method applied here to each channel is very similar to the work done in [1], [11], [4], [2]. The same error budget in radiometry presented in [11] for the C-band system can be used here. The $\sigma°$ dispersion for each channel is within ±1 dB at the same incidence angle as the reference point targets. The error budget incorporates:

- The time variation of the system parameters (transmitter power,Receiver/ Processor linearity, receiver noise variation within one pass, altitude variations, data quantization, ...etc).
- The error on the integrated complex energy of corner reflector signals: The complex integration method introduced in [8] is used. The clutter error is better than ±0.4 dB.
- Corner reflectors RCS uncertainty,
- Error due to aircraft motion,
- Speckle error as a function of the number of independent samples contained in the target of interest: The method introduced in [5] is used. Since more than 1000 independent samples are generally used, the speckle error is within $\pm 0.3dB$.

The extension of the method to other illumination angles depends on the antenna gain patterns and pointing angle accuracy. This corresponds to an error of ±0.5 dB for illumination angles within ±20° from the boresight angle as shown in [11], [1], [10].

C.2 Accuracy of the phase

As can be noted by using the results of table [III], the phase dispersion is within 5 degrees at the illumination angles of the reference point targets. Accuracy should remain stable with illumination angles within ±20° from the boresight angle provided that the phase centers of the H and V antennas are co-located as discussed in [9], [4]. This assumption was validated within ±20°from the antenna boresight angle [10].

D. Effect of system stability on the calibration accuracy

D.1 Introduction

During one pass which covers the site of application interest as well as the calibration site, the system is quite stable and the method described above is reliable. In the following, calibration performance is discussed as a function of the system stability from one pass to another during the same flight, and from one flight to another. If the system demonstrates good long-term stability, the calibration parameters from one flight can be used to calibrate other flights.

Long-term calibration stability might be affected by the temperature noise variations of the two separate receivers used for the cross- and like-polarization. The method proposed in [1], [4], which uses the noise measurement of the block noise for the two receivers, might correct for the gain variation in radiometry. Unfortunately, it cannot correct for phase variations which may be significant.

Indeed, the method may not be effective even for radiometric calibration: one problem is that the amplifier which is used in the cross-polarization receiver to amplify the cross-polarized signals, generally much weaker than the co-polarized signals, is not taken into account within the loop measurement. The noise temperature variations of this amplifier might introduce significant radiometric errors, as shown below.

D.2 Assessment of short and long-term system stability

Tests were carried out in [10] by using reference point targets to ascertain whether the calibration parameters were stable from one pass to another (within the same day flight i.e. short-term stability), and from one flight to another (i.e. long-term stability). The stability tests were performed at three levels:

1. absolute radiometric calibration,
2. channel relative radiometric calibration, and
3. channel relative phase calibration

In each flight, there were radar reflectors deployed in more than a single pass so pass comparisons could be made to assess the system stability. The variation of the absolute radiometric calibration constant K was assessed using corner reflectors of known radar cross section (RCS). The relative calibration deviation (i.e. variation of the diagonal elements of the $[A]$ matrix in (6)) was measured using active calibrator ARC. Examination was made using 3 sets of flight data which were collected on the 6th and 12th of March, 1998, and on December 1st, 1995.

D.3 Assessment of short-term stability

The calibration constants determined from the data of 6th March, 1998, pass 8, were applied to calibrate the data of 6th March, 1998, pass 4. The following results were obtained:

Channel	**dB**
HH-HV	0.37
HH-VH	0.21
HH-VV	0.2

TABLE I

Relative error for pass 4 using parameters from pass 8

Channel	**dB**
HH	0.5
VV	0.3

TABLE II

Absolute error for pass 4 using parameters from pass 8

Channels	Degrees
HH-HV	-2.2
HH-VH	0.6
HH-VV	0.1

TABLE III

Relative phase error: pass 4 and pass 8 of March 6 1998

According to the results obtained above, the system demonstrates short-term stability. The pass to pass relative and absolute radiometric errors obtained for various passes are within 0.5 dB, and the relative phase errors recorded do not exceed 3 degrees.

D.4 Assessment of long-term stability

Flight data were analysed for 3 flights. The results are presented in the tables below. The following points can

Channel	dB
HH-HV	3.2
HH-VH	3
HH-VV	0.3

TABLE IV

Relative radiometric error (in dB): Dec. 1995- March6 1998

Channel	dB
HH-HV	0.5
HH-VH	0.1
HH-VV	0.2

TABLE V

Relative radiometric error (in dB): March6-March12 1998

be made:

- The system is not stable for various flights, and the noise temperature variations of the like polarization receiver (which is not taken into account) can lead to 3 dB offset between the two receivers, as is noted in table [IV].
- Important phase errors (25°) due to the separate receivers are noted even with one 1 week-apart flight (see table [VI]).
- It is worth noting that each separate receiver remains quite stable in radiometry and phase. Radiometric offset between like components (receiver 1) or cross-pol components (receiver 2) remain within 0.5 dB in radiometry and 5 degrees in phase.

Channels	Degrees
HH-HV	21.18
HH-VV	4.71
HH-VH	24.32

TABLE VI

Relative phase error: March6-March 12 1998

E. Implications for calibration

In conclusion, the system is short-term stable, and the calibration parameters obtained from one pass over the site of calibration can be used to calibrate in phase and magnitude other passes of the same flight. The system instability from one flight to another is mainly due to variations between the two receiver characteristics, variations which are currently not measured. To correct for the 2 receiver offsets in magnitude and phase which result from long-term system instability, two solutions might be considered:

1. Temporary solution: Reference point targets (ARC) should be deployed during each flight. The reltive complex gains between the four channels can be deduced from the image signal mesurements.
2. Hardware solution: In order to end up with a stable calibration which does not rely on the deployment of reference targets in each flight, the relative complex gains between the two receivers should be measured (in magnitude and phase) at the end of each pass. This might be performed by generating internally a continuous waveform which is injected into the two receivers with the transmission off (the signal does not have to go through the antennas as they are quite stable according to the stability tests above concerning each separate receiver).

IV. Calibration of the C-band Convair-580 system at the presence of significant cross-talk

A. Demonstration of significant cross-talk in several data sets

Several data sets analyzed demonstrated the presence of significant cross-talk. The analysis of the data set collected over Prince Edward Island in March 2001 demonstrated significant return in HV and VH component (about 13 dB signal to clutter ratio) from corner reflectors [7]. The analysis of data sets collected over Shirley's Bay (Ottawa) in November 1997, and November 1999, lead to similar conclusions. In these cases, the simplified model of Section 3 is not valid, and the general calibration method developed for the X-band system with significant cross-talk should be used to calibrate the system.

B. Calibration strategy

Under reciprocity assumption (HV=VH), the three pure components HH, HV, and VV can be retreived from the distorted measurements using a corner reflector, an ARC, and a natural target with azimuthal symmetry [9]. The calibration method of [9] is applied to the 1999 Shirley's Bay data set. Samples from forested areas were used as the azimuthally symmetrical reference targets. Like for the X-band data, the calibration method was successful. The method leads to a measurement of the system distortion matrix $[A]$ (during the data acquistion) which is presented in Table 7. As seen in row 2, the HV is affected by a cross-talk of about 13 dB from the VV component. Such significant cross talk cannot be ignored mainly for natural targets which generally demonstrate a cross polarization return about 6 dB lower than the like polarization components HH and VV.

19.49	11.13	0
5.80	22.81	9.59
0	5.98	20.23

TABLE VII

Distortion matrix [A] of Shirley's Bay November-9 1999 pass

V. Conclusion

In order to exploit the fully polarimetric capability of the Convair-580 SAR, pure HH, VV, HV, and VH data have to be retrieved from the distorted measurements. The general calibration method developed in [9] for early X-band polarimetric SAR, can be applied to the C-band data set suffering from significant cross-talk. This general method provides in addition a measurement of the system distortion matrix during the data acquisition. The Convair-580 SAR system is not stable from one flight to another, and an ARC needs to be deployed at each flight for system calibration. An upgrade of the hardware for the measurement of the relative complex gain between the two receivers at the end of each pass should permit the system calibration without the requirement for deployment of reference point targets. This attractive solution should in addition eliminate the eventual calibration errors related to ARC deployment.

Acknowledgment The author would like to thank DRDC for having partially financed the present study. The following individuals are thanked for their interest in this work, and for their contribution of time and ideas: M. Yeremy and M. Rey from DRDC, Dr. B. Hawkins from CCRS, F. Charbonneau under CCRS contract with TGIS for having processed and calibrated the data set of November 1999, and S. Nedelcu and I. Sikaneta for their contribution when they were under CCRS contract with Intermap. The support of Environment Canada which owns and operates the system is also acknowledged.

References

[1] R.H. Hawkins. Determination of antenna elevation pattern for airborne SAR using the rough target approach. *IEEE Trans. Geoscience Rem. Sens.*, 28(5):896–905, 1990.

[2] R.K. Hawkins, R. Touzi, A. Wind, K. Murnaghan, and C.E. Livingstone. Polarimetric calibration results and error budget for SAR-580 systems. In *Proc. of the CEOS SAR workshop, ESA SP-450, http://www.estec.esa.nl/CONFANNOUN/99b02*, October 1999.

[3] Com. Dev. Limited. X-band sar antenna. Technical report, EIP/SAR/2399/001, March 1986.

[4] C. E. Livingstone, A. L. Gray, R. K. Hawkins, P. W. Vachon, T. I. Lukowski, and M. LaLonde. The CCRS airborne SAR systems: Radar for remote sensing research. *Can. J. Rem. Sens.*, 21(4):468–491, 1995.

[5] A. Lopes and R. Touzi. Extraction of the backscattering coefficient of agriculture fields from an airborne SAR image. In *Proc. 1986 International Geoscience and Remote Sensing Symposium (IGARSS'86), Zurich, Switerland*, pages 621–628, 1986.

[6] R.K. Raney. Considerations for SAR image quantification unique to orbital systems. *IEEE Trans. Geoscience Rem. Sens.*, 29(4):754–760, 1991.

[7] B. Scheuchl. Analysis of cv-580 fully polarimetric data of sea-ice: Data calibration test technical note. Technical report, MDA, Sep. 2002.

[8] R. Touzi. Extraction of point target response characteristics from complex SAR data. *IEEE Trans. Geoscience Rem. Sens.*, 30(6):1158–1161, 1992.

[9] R. Touzi, C. E. Livingstone, J. R. C. Lafontaine, and T. I. Lukowski. Consideration of antenna gain and phase patterns for calibration of polarimetric SAR data. *IEEE Trans. Geoscience Rem. Sens.*, 31(6):1132–1145, 1993.

[10] R. Touzi and S. Nedelcu. Calibration of the polarimetric convair-580 c-band sar. Technical Report 1, Progress Report provided to the Defense Research Establishment of Ottawa (DREO) under the CCRS/DREO agreement FY97/98-98/99, June 1998.

[11] L.M.H. Ulander, R.H. Hawkins, C.E. Livingstone, and T.I. Lukowski. Absolute radiometric calibration of the CCRS SAR. *IEEE Trans. Geoscience Rem. Sens.*, 29(6):922–933, 1991.

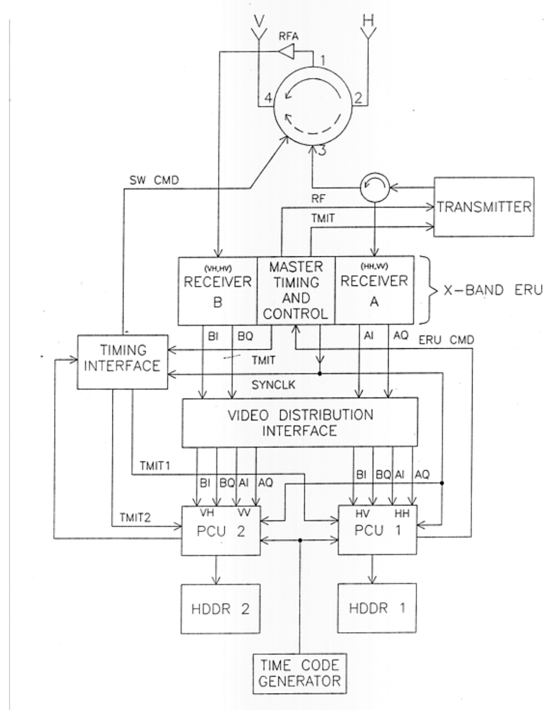

Fig. 1. *SAR data acquisition scheme*

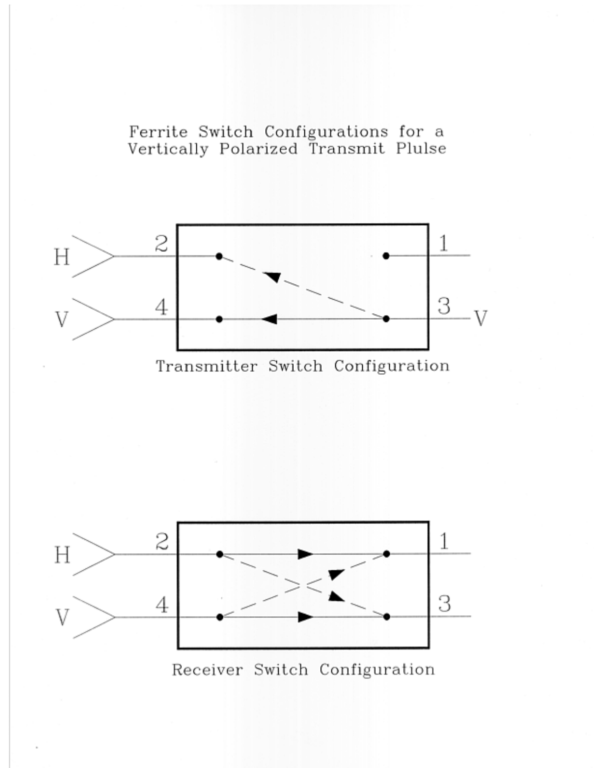

Fig. 2. *Ferrite switch positions for a vertically polarized transmit pulse*

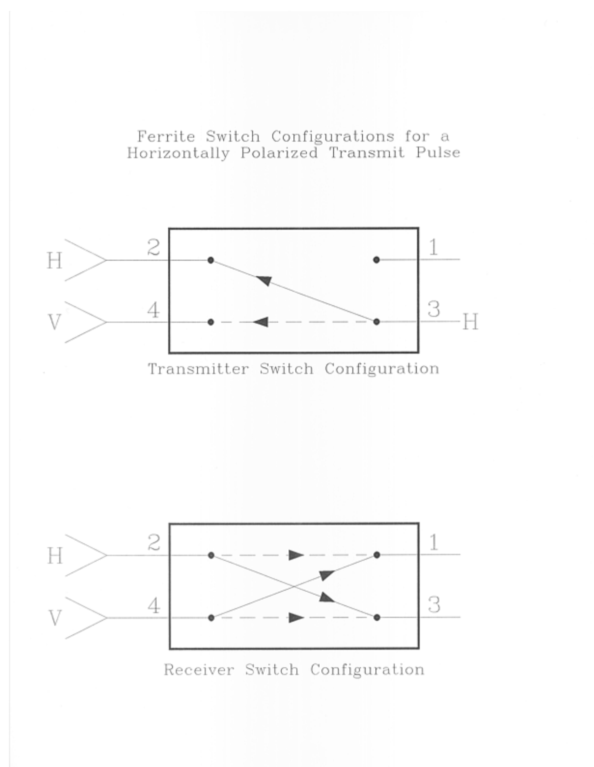

Fig. 3. *Ferrite switch positions for a horizontally polarized transmit pulse*