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ABSOLUTE RADIOMETRIC

AND POLARIMETRIC CALIBRATION

OF

ALOS PALSAR PRODUCTS

GENERATED WITHIN ADEN

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1 INTRODUCTION

The aim of this document is to describe the steps to perform the absolute radiometric calibration and the relative polarimetric calibration of ALOS-PALSAR products [1] generated by the processor delivered by JAXA and installed in the ADEN environment [4].

The document is organized as follow:

- Section 2 lists the technical documents and the scientific literature cited in the text
- Section 3 lists the abbreviations and acronyms used in the text
- Section 4 provides an overview of the characteristics of PALSAR products
- Section 5 describes how to perform the absolute radiometric correction
- Section 6 describes how to correct for polarimetric distortions
- Annex A deals with the geometric calibration
- Annex B explains how to derive the incident angle used to calculate beta nought and gamma nought
- Annex C recommends a methodology to derive Faraday rotation angle from polarimetric data products.

2 REFERENCES

[1] ALOS User Handbook, Japan Aerospace Exploration Agency (JAXA), Nov. 2007, available at http://www.eorc.nasda.go.jp/ALOS/doc/handbk.htm.
[2] Information on ALOS PALSAR Products for ADEN Users, ALOS-GSEG-EOPG-TN-07-0001, Issue 1, Rev. 1, ESA Technical Note, 5 April 2007.
[3] B. Rosich, P.Meadows, “Absolute Calibration of ASAR Level 1 Products Generated with PF-ASAR”, ESA Technical Note, Issue 1, Rev. 5, 7 Oct. 2004.
[4] ALOS PALSAR Product Specifications Format, Japan Aerospace Exploration Agency (JAXA), available at http://www.eorc.jaxa.jp/ALOS/doc/format.htm.
[5] Masanobu Shimada, Osamu Isoguchi, Takeo Tadono, Riko Higuchi, Kazuo Isono, “PALSAR CALVAL Summary and Update 2007”, IEEE International Geoscience and Remote Sensing Symposium, 23-27 July 2007.
[6] PALSAR Quality Control Tools – Detailed Design Document of Advanced Tools, PS-ALG-DLR-DDD-002 developed under ESA Contract, 30 May 2007.
[7] T. Moriyama, M. Shimada and M. Watanabe, “Initial Polarimetric Calibration Results of ALOS-PALSAR”, Progress in Electromagnetic Research Symposium 2007, Beijing, China, March 26-30.
[8] A. Freeman, “Calibration of Linearly Polarized Polarimetric SAR Data Subject to Faraday Rotation,” IEEE Transactions on Geoscience and Remote Sensing, Vol. 42, No. 8, August 2004.

3 ABBREVIATIONS AND ACRONYMS

ADEN	ALOS Data European Node
ADF	Auxiliary Data file
ALOS	Advanced Land Observing Satellite
CR	Corner Reflector
DN	Digital Number

DSN	PALSAR Direct Downlink mode
FBD	PALSAR Fine Beam Dual polarization mode
FBS	PALSAR Fine Beam Single polarization mode
FR	Faraday Rotation
GR	Ground Range
IMG	CEOS Image File
IPF	Instrument Processing Facility
IRF	Impulse Response Function
JAXA	Japan Aerospace Exploration Agency
LED	CEOS Leader File
PALSAR	Phased Array L-band SAR
PLR	PALSAR Polarimetric mode
PT	Point Target
RCS	Radar Cross Section
SAR	Synthetic Aperture Radar
SLC	Slant Range Complex
TEC	Total Electron Content
TRL	CEOS Trailer File
VOL	CEOS Volume File
WB1	PALSAR ScanSAR short burst mode
WB2	PALSAR ScanSAR long burst mode

4 CHARACTERISTICS OF PALSAR PRODUCTS

This chapter provides an overview of the main characteristics of PALSAR products generated by the ADEN-IPF. In particular, section 4.1 shows the operational and experimental acquisition modes and section 4.2 the processing levels available. Last section introduces radiometric and polarimetric characteristics of PALSAR data.

4.1 PALSAR modes

PALSAR sensor can operate in 5 different science data modes: FBS, FBD, DSN, WB and PLR. The characteristics of default acquisition modes defined by JAXA are summarized in Table 1. These modes are calibrated with higher priority by JAXA and this document refers to them.

DEFAULT PALSAR ACQUISITION MODES AS DEFINED BY JAXA (Calibrated with higher priority)					
	FINE BEAM SINGLE POLARISATION (FBS)	FINE BEAM DOUBLE POLARISATION (FBD)	DIRECT DOWNLINK (DSN)	ScanSAR (WB1)	POLARIMETRY (PLR)
Chirp bandwidth [Mhz]	28 MHz	14 MHz	14 MHz	14 MHz	14 MHz
Polarsation	HH	HH/HV	HH	HH	HH/HV + VV/VH
Off-nadir angle [deg]	34.3	34.3	34.3	20.1-36.5	21.5
Incidence angle [deg]	7.5-60.0	7.5-60.0	7.5-60.0	18.0-43.3	8-30
Swath Width [Km]	70	70	70	35	30
Bit quantization [bits]	5	5	5	5	5
Data rate [Mbps]	240	240	120	120	240

Table 1 *PALSAR default acquisition modes.*

4.2 PALSAR processing levels

PALSAR products provided by ADEN are generated using JAXA PALSAR processor. Release notes of the processing software, as well as anomalies encountered during the processing and bugs that have been fixed are timely reported by JAXA at https://auig.eoc.jaxa.jp/auigs/jsp/1004_syorisoft_en.html. Therefore, product format and processing levels are those defined by JAXA. JAXA delivers regularly new processor version that need to be integrated in the ADEN environment. The current processor version can be found in the PALSAR ESA cyclic reports http://earth.esrin.esa.it/pcs/alos/palsar/reports/cyclic/index.html or in the general information page http://earth.esrin.esa.it/pcs/alos/palsar/userinfo/.

PALSAR products are available to users in three Processing levels: L1.0, L1.1 and L1.5. All modes in Table 1, except for WB mode, support L1.0, L1.1 and L1.5 processing levels. Mode WB supports the level L1.0 and L1.5. Further details on the processing levels of PALSAR product can be found in [4].

Processing Level	Definition
1.0	• The data of 1 scene area is extracted from received data. • The number of SAR data files is the same as the number of polarizations in the case of dual polarization and polarimetry modes. • The data in SCAN SAR mode is not divided into individual scans. • This corresponds to raw data products ready to be processed into single look complex (L1.1) or precision images (L1.5). • Data type: 8 bit(I) + 8 bit(Q)
1.1	• Single Look Complex products. • Provided in slant range geometry • Phase preserving products. • Natural pixel spacing • Data type: 32 bit(I) + 32 bit(Q) (*1)
1.5	• Detected products. • Provided in ground range geometry • Multi-look in range and azimuth. • Pixel spacing can be selected for the Fine mode. • Latitudes and longitudes in the product are calculated without considering the terrain height but based on ellipsoid GRS80. • 16 bit unsigned integer (*2)

***Table 2** Processing levels definitions. (1*) I and Q are IEEE real data, byte order is Big Endian. (*2) byte order is Big Endian.*

4.3 Radiometric characteristics

The discussion in this section and in the following chapters is restricted to L1.1 and L1.5 products.

The radiometric characteristics of PALSAR products, as well as the calibration constant and the polarimetric parameters, are those defined by JAXA. Calibration and Validation Quality Control is reported by JAXA at http://www.eorc.jaxa.jp/ALOS/en/calval/calval_index.htm and by ESA at http://earth.esrin.esa.it/pcs/alos/palsar/reports/cyclic/index.html

PALSAR slant-range products (L1.1) are provided with the same radiometric correction as for detected ground-range products (L1.5). The following radiometric corrections are already applied in L1.1 and L1.5 products:

- the elevation antenna pattern. To date, the elevation antenna pattern is part of the JAXA processor and it is of JAXA responsibility to monitor and update patterns.
- the range spreading loss ,
- the area normalisation. Pixels are normalised using the cosine of the incidence angle.

The intensity of the final data product is thus proportional to sigma nought σ^0. The way to derive sigma nought from L1.1 and L1.5 products is described in section 5.

Full polarimetric products (i.e. PLR L1.1 and PLR L1.5 products) are provided with cross-talk and channel imbalance corrected. Faraday rotation compensation and symmetrisation are further steps that can be performed by the user in order to improve the polarimetric calibration. These last 2 corrections are described in section 6.

Table 1 summarizes the radiometric characteristics of PALSAR products and lists the radiometric and polarimetric corrections already applied to the data.

	ABSOLUTE RADIOMETRIC CALIBRATION		RELATIVE POLARIMETRIC CALIBRATION			
	Range Spreading Loss, Antenna Pattern, Incidence Angle	Calibrated σ^0	Cross-Talk	Channel Imbalance	Faraday Rotation	Symmetrisation
FBS, FBD, DSN, WB	YES	NO	N/A	N/A	N/A	N/A
PLR	YES	NO	YES	YES	NO	NO

Table 3 *Radiometric characteristics of PALSAR data. (YES = correction already performed; NO = correction not performed,* ***N/A=Not Applicable****)*

5 ABSOLUTE RADIOMETRIC CALIBRATION

This chapter gives the guidelines to properly calibrate PALSAR products L1.1 and L1.5. Necessary steps that allow to derive sigma nought, beta nought and gamma nought for distributed target, as well as sigma for point target are provided below.

5.1 General principles and assumptions

To perform a precise absolute calibration and derive the radar backscattering coefficient σ^0 for detected ground products, a detailed knowledge of the local slope (i.e. local incidence angle) is required. Since the information is usually not available at the processing time, a "flat terrain" is assumed during processing (based on the ellipsoid GRS80 - WGS84). The incident angle correction (area normalisation) has been included in the processing and therefore the final image intensity (i.e. the square of the digital number DN) is proportional to the normalized radar cross-section σ^0 of the illuminated scene.

The relationship between the digital number *DN* and the backscattering coefficient σ^0 can be written as:

$$DN^2 = \sigma^0 \cdot const$$

The Digital Number *DN* is the pixel value of L1.5 products. In the case of L1.1 products, *DN* is the magnitude of the complex pixel value, i.e. $DN = \sqrt{Q^2 + I^2}$, where *Q* and *I* are respectively the real part and the imaginary part of the pixel value in L1.1 products. The *const* factor is constant over the whole product and it is hereafter referred as "absolute calibration constant" (*K*), which is derived from measurements over precision transponders.

The value of K has been adjusted for PALSAR to be constant for the same product level among different modes, while it differs between L1.1 and L1.5 product. The calibration constant K is derived from the "calibration factor" *CF* and "calibration factor offset" *CF_offset* defined by JAXA. *CF* is written in the product header, LED.RadiometricDataRecord (bytes 21-36), as shown in Table 4.

Calibration constant	**L1.1**	**L1.5**
K [dB]	CF [dB] – CF_offset [dB]	CF [dB]

Table 4 *Relationship between Calibration Constant K and Calibration Factor fro L1.1 and L1.5 products.*

For data processed with v 5.04 of the ADEN processor (installed ,11/3/09), CF = –83 dB with accuracy 0.64 dB, and CF_offset[dB] = 32 dB. Note that L1.1 and L1.5 products contain the same value of CF = –83 dB. For data processed with version 5.02 or earlier versions (prior to 11/3/09), changes to the calibration factor are given in the table below. Note that only the products type and beams listed in the table have had a change of calibration factor.

Product	Beam	CF [dB]
FBS9.9HH	0	-83.16
FBS21.5HH	3	-83.55
FBS34.3HH	7	-83.4
FBD34.3HH	7	-83.2
FBD34.3HV	7	-80.2
FBS41.5HH	10	-83.65
FBD41.5HH	10	-83.19
FBD41.5HV	10	-80.19
FBS50.8HH	17	-83.3
PLR215 (HH,VV,HV,VH)	ALL	-83.4

Table 5 *New calibration factors for products processed with v 5.02 and earlier.*

Some results on the calibration activities run by JAXA are stored in the LED.DataQualitySummary record. The date of the last calibration update is stored at LED.DataQualitySummary (bytes 21-26) and the calibration constant accuracy is stored at LED.DataQualitySummary (bytes 191-206).

5.2 Derivation of Sigma, Beta and Gamma Nought over distributed target

Calibrated sigma nought σ^0, beta nought β^0, and gamma nought γ^0 images for all modes and product levels can be derived as:

$$\boxed{\sigma^0_{i,j} = K \cdot DN^2_{i,j}\,; \qquad \beta^0_{i,j} = \frac{\sigma_{i,j}}{\sin(\alpha_{i,j})}\,; \qquad \gamma^0_{i,j} = \frac{\sigma_{i,j}}{\cos(\alpha_{i,j})}\,; \qquad i = 1,2\ldots L,\;\; j = 1,2,\ldots M}$$

where

K	=	absolute calibration constant
$DN^2_{i,j}$	=	pixel intensity value at image line *i* and column *j*
$\sigma^0_{i,j}$	=	sigma nought (backscattering coefficient) at image line *i* and column *j*
$\beta^0_{i,j}$	=	beta nought (brightness) at image line *i* and column *j*
$\gamma^0_{i,j}$	=	gamma nought at image line *i* and column *j*
$\alpha_{i,j}$	=	incident angle at image line *i* and column *j*

L, M = number of lines and columns in the product

Note that in the previous expression the absolute calibration factor *K* is not at denominator because the value of the calibration factor *CF* stored in the product header is negative.

The average backscattering coefficient for an area of interest can be derived as an average of $\sigma^0_{i,j}$ over $N = N_a \times N_r$ pixels within the distributed target as:

$$\sigma^0_{avg} = \frac{1}{N} \sum_{i=1}^{i=N_r} \sum_{j=1}^{j=N_a} \sigma^0_{i,j}$$

To obtain sigma nought to dB:

$$\sigma^0[dB] = 10 \log_{10}\left(\sigma^0\right) = 20 \log_{10}\left(DN\right) + K[dB]$$

5.3 Derivation of Sigma over point target

For ground-range and slant-range products, as well as for all PALSAR modes, the radar cross section (RCS) σ of a point target (target of opportunity, corner reflector or transponder) in a level 1.5 product can be derived from its interpolated and background corrected impulse response as [3]:

$$\sigma = I_p \, P_{Ag} \cdot K$$

where
σ = radar cross section of the point target
I_p = background corrected integrated power of the target IRF (see below)
K = absolute calibration constant
P_{Ag} = ground range pixel area

In order to measure the Radar Cross Section of a point target in the image, it is necessary to remove the background backscattering contribution from the image under analysis – around the target impulse response function (IRF) – and to convert the pixel values to intensity. The following pre-processing steps shall therefore be carried out:

- extraction of a sub-image of 128 by 128 pixels around the point target IRF;
- conversion of pixel values to intensity (I_{int});
- derivation of the background intensity (I_{backg}) by summing the pixel intensities over four square areas of M=10 resolution cells, positioned around the target in such a way that they do not include samples on the range or azimuth IRF cuts or other PTs responses but mainly the clutter intensity (see Fig. 1);
- subtraction of the mean background intensity (I_{backg}) from the intensity image (I_{int})

$$I_c = I_{\text{int}} - \frac{1}{4M^2} I_{back}$$

- interpolation of the intensity background corrected sub-image (I_c) by a factor of 8 ($I_{c,int}$). IRF analysis is performed on this interpolated image.
- integration of the interpolated and background corrected intensity over 20 x 20 resolution cells. The resulting background corrected integrated power I_p is used to derive the RCS as described above in this section.

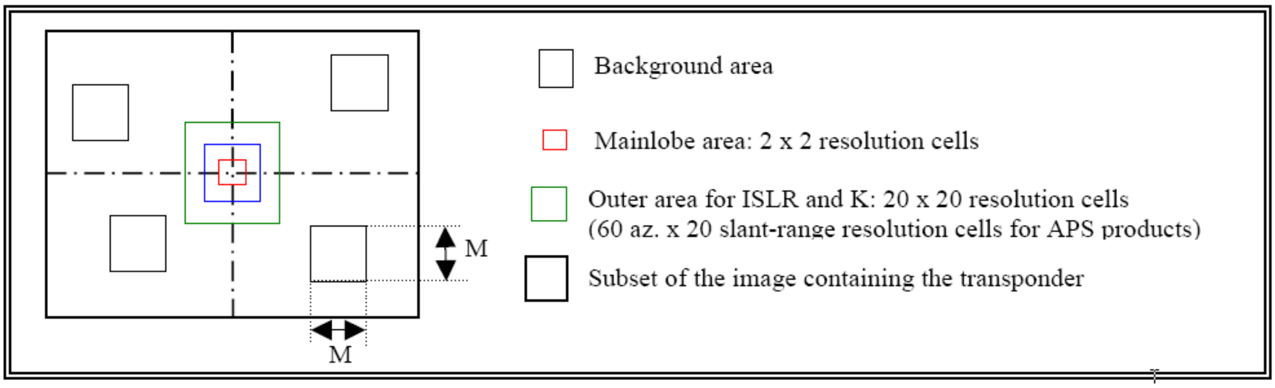

Figure 1 *Definition of point target response area and background areas for IRF analysis and calibration.*

6 RELATIVE POLARIMETRIC CALIBRATION

This chapter describes the necessary steps to derive the scattering matrix from full polarimetric data and to obtain a polarimetric calibrated PALSAR product. It applies only to PLR products L1.1 (SLC product), since polarimetric correction involves both magnitude and phase of the four polarimetric channels. The term “relative” refers to the fact the absolute radiometric calibration is not included in the following procedures, therefore it needs to be performed apart as described in section 5.

6.1 General principles and assumptions

When full polarimetric information are available, the user may need to correct for the relative distortions induced on different polarimetric channel of the same PLR product in order to derive the 2-by-2 complex scattering matrix of the observed scene.

Depending on their origin, polarimetric distortions can be classified into three effects:

- cross-talk,
- channel imbalance,
- Faraday rotation (FR).

The relationship between the polarimetric system measurements [O] and the calibrated scattering matrix [S] is expressed by the following model [7]:

$$[O]=[R][F][S][F][T]$$

where $[O]=\begin{pmatrix} O_{hh} & O_{hv} \\ O_{vh} & O_{vv} \end{pmatrix}$ is the measured (uncalibrated) scattering matrix that includes polarimetric distortions;

$[S]=\begin{pmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{pmatrix}$ is the true scattering matrix. After detection and absolute radiometric calibration described in section 5, the scattering matrix becomes $[\sigma^0]=\begin{pmatrix} \sigma^0_{hh} & \sigma^0_{hv} \\ \sigma^0_{vh} & \sigma^0_{vv} \end{pmatrix}$;

$[F]=\begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix}$ is the FR matrix;

Ω is the FR angle;

$[R]=\begin{pmatrix} R_{hh} & R_{hv} \\ R_{vh} & R_{vv} \end{pmatrix}$ is the reception distortion matrix which includes the effects of x-talk and channel imbalance;

$[T]=\begin{pmatrix} T_{hh} & T_{hv} \\ T_{vh} & T_{vv} \end{pmatrix}$ is the transmission distortion matrix which includes the effects of x-talk and channel imbalance;

The polarimetric channel HV (or VH) in the expressions above and in the scientific literature indicates H polarization on reception and V polarization on transmission (respectively V on reception and H on transmission). Due to the opposite naming convention adopted by JAXA, the PALSAR file that corresponds to HV (or VH) is IMG-VH-ALSPSL.. (or IMG-HV-ALSPSL..).

As specified in section 4.3, each PLR product sample contains the values of the 2-by-2 matrix $\left[\hat{O}\right]=[R]^{-1}[O][T]^{-1}=[F][S][F]$ because the effects of cross-talk and channel imbalance have been already removed during the data processing. The distortion matrices [R] and [T] applied to products have been estimated using CRs and are stored in the product header at LED.RadiometricDataRecord (bytes 37-292).

Currently, the JAXA processor installed at ADEN uses the following distortion matrices, available since the end of commissioning phase:

$$[R]=\begin{pmatrix} 1 & 2.4270e-3 + i*1.29302e-2 \\ -1.14724e-2 - i*6.2282e-3 & 9.572169e-1 + i*3.829563e-1 \end{pmatrix}$$

$$[T]=\begin{pmatrix} 1 & -6.2634e-3 + i*7.0829e-3 \\ -6.2971e-3 + i*8.0267e-3 & 7.217117e-1 - i*2.36768e-3 \end{pmatrix}$$

However, the distortion matrices have been updated by JAXA [5] in 2007, but the ADEN?? processor is still using the previous matrices. The new distortion matrices are:

$$[R]_{new}=\begin{pmatrix} 1 & -7.426688e-4 + i*4.024918e-3 \\ -9.462905e-3 + i*7.531153e-3 & 7.235826e-1 - i*9.659156e-3 \end{pmatrix}$$

$$[T]_{new}=\begin{pmatrix} 1 & 8.747163e-3 + i*1.435490e-2 \\ -1.438816e-2 - i*8.398601e-3 & 9.636059e-1 + i*4.023897e-1 \end{pmatrix}$$

It is recommended the user to check the date of the last polarimetric calibration update in the product header at LED.DataQualitySummary (bytes 21-26). section 6.4 describes how to remove the old distortion matrices and how to apply the new distortion matrices.

For a complete polarimetric calibration, the compensation for FR can be applied as further step (see section 6.2). In order to obtain equal cross-polarized channel (i.e. HV=VH), symmetrisation can be also performed as final step (see section 6.3).

Note that L1.5 PLR products are obtained from the detection of L1.1 PLR products after the application of the inverse of [R] and [T]. Therefore, it is not possible to remove the polarimetric calibration from L1.5 products or to perform Faraday rotation compensation.

6.2 Procedure for Faraday Rotation compensation

Faraday rotation is expressed using a single value, the angle Ω of which the polarization plane results rotated in the one-way travel path from the sensor to the target.

For each product sample, the correction for FR allows to derive the scattering matrix [S]:

$$[S]=[F]^{-1}[\hat{O}][F]^{-1}=\begin{pmatrix}\cos\Omega & -\sin\Omega\\ \sin\Omega & \cos\Omega\end{pmatrix}\begin{pmatrix}\hat{O}_{hh} & \hat{O}_{hv}\\ \hat{O}_{vh} & \hat{O}_{vv}\end{pmatrix}\begin{pmatrix}\cos\Omega & -\sin\Omega\\ \sin\Omega & \cos\Omega\end{pmatrix}$$

where $[S]=\begin{pmatrix}S_{hh} & S_{hv}\\ S_{vh} & S_{vv}\end{pmatrix}$ is the true scattering matrix. After detection and absolute radiometric calibration described in section 5, the scattering matrix becomes $[\sigma^0]=\begin{pmatrix}\sigma^0_{hh} & \sigma^0_{hv}\\ \sigma^0_{vh} & \sigma^0_{vv}\end{pmatrix}$;

$[F]^{-1}=\begin{pmatrix}\cos\Omega & -\sin\Omega\\ \sin\Omega & \cos\Omega\end{pmatrix}$ is the inverse of FR matrix;

Ω is the FR angle;

$[\hat{O}]=\begin{pmatrix}\hat{O}_{hh} & \hat{O}_{hv}\\ \hat{O}_{vh} & \hat{O}_{vv}\end{pmatrix}$ is the measured matrix with x-talk and channel imbalance corrected; it corresponds to the complex pixel values of PLR data product.

The value of Ω depends on the time of acquisition and can be estimated from data product, or calculated using appropriate models or derived from Total Electron Content (TEC) data. TEC maps and TEC data are available at http://www.aiub-download.unibe.ch/CODE/ or at http://www.kn.nz.dlr.de/. The procedure for estimating the FR angle from PLR data products is described in ANNEX C.

Before compensating for FR, the x-talk and channel imbalance must be already corrected according the model of section 6.1.

6.3 Procedure for cross-polarisation symmetrisation

Symmetrisation is an optional step that forces to be equal the cross-polarized channels in presence of system noise. It can be performed directly on the original PLR product if FR correction is not applied. Alternatively, symmetrisation can be applied after FR correction.

To calculate the cross polarized channel S_{xx} that replaces S_{hv} and S_{vh} into scattering matrix, it is necessary to derive the "ratio of receive to transmit channel imbalance" *a* [6] from the distortion matrices [R] and [T],

$$a=\frac{T_{hh}}{T_{vv}}\frac{R_{vv}}{R_{hh}}$$

where
a is the ratio of receive to transmit channel imbalance;
T_{hh} is the element (1,1) of the matrix [T];
T_{vv} is the element (2,2) of the matrix [T];

R_{hh} is the element (1,1) of the matrix [R];
R_{vv} is the element (2,2) of the matrix [R]

Using the distortion matrices [R] and [T] of section 6.1, it follows a = 9.572169e-1 + i*5.333578e-1 (|a| = 1.09578). Deriving the ratio of receive to transmit channel imbalance from the new distortion matrices $[R]_{new}$ and $[T]_{new}$ (Sec.6.1), it results a_{new} = 6.358e-1 – i*2.755e-1 (|a| = 0.6929).

The least-square estimate of the cross polarized channel is:

$$S_{xx} = \frac{S_{hv} + a^* S_{vh}}{1+|a|^2}$$

where S_{xx} is the cross-polarized channel after symmetrisation;
a is the ratio of receive to transmit channel imbalance calculated above;
S_{hv}, S_{vh} are the cross polarized channel before the symmetrisation.

Note that the previous expression reduces to a simple average between cross-polarized channels when a = 1.

For each product sample, the final calibrated and symmetric scattering matrix is

$$[S] = \begin{pmatrix} S_{hh} & S_{xx} \\ S_{xx} & S_{vv} \end{pmatrix}$$

where S_{hv} and S_{vh} have been replaced by S_{xx} calculated above.

6.4 Procedure of polarimetric retro calibration

The user might need to remove the polarimetric calibration already applied to L1.1 PLR products in order to apply new polarimetric calibration matrices (as mentioned in section 6.1) or to apply calibration matrices calculated by his own. This operation is referred as polarimetric retro calibration.

The polarimetric retro calibration procedure consists first in applying the “old” distortion matrices [R] and [T] to obtain the original un-calibrated data product:

$$[O] = [R][\hat{O}][T]$$

where $[O] = \begin{pmatrix} O_{hh} & O_{hv} \\ O_{vh} & O_{vv} \end{pmatrix}$ is the measured (uncalibrated) scattering matrix that includes polarimetric distortions;

$[\hat{O}] = \begin{pmatrix} \hat{O}_{hh} & \hat{O}_{hv} \\ \hat{O}_{vh} & \hat{O}_{vv} \end{pmatrix}$ is the measured matrix with x-talk and channel imbalance corrected, it corresponds to the complex pixel values of PLR data product;

[R] and [T] are the reception and transmission distortion matrix written in the product header.

Finally, to calibrate using the new polarimetric distortion matrices $[R]_{new}$ and $[T]_{new}$:

$$\left[\hat{O}\right]_{new} = [R]_{new}^{-1}[O][T]_{new}^{-1}$$

where $[O]$ is the measured (uncalibrated) scattering matrix that includes polarimetric distortions;
$\left[\hat{O}\right]_{new}$ is the new PLR matrix with x-talk and channel imbalance corrected;
$[R]_{new}$ and $[T]_{new}$ are the new reception and transmission distortion matrices.

ANNEX A DERIVATION OF SLANT RANGE DISTANCE

In order to derive beta nought β^0 and gamma nought γ^0 for standard PALSAR products, it is necessary to derive the slant-range distance and the incident angle for each product sample (see Annex B). The following procedures are recommended.

PALSAR L1.1 products

The slant-range distance $R_{i,j}$ for each product sample (*i*,*j*) can be derived from the slant-range distance of the first product sample (near range):

$$R_{i,j} = R_{i,0} + \frac{c}{2}\frac{j}{f_{sampl}} \quad i = 1,2,...,L, \quad j = 1,2,...,M$$

where $R_{i,0}$ is the slant range distance of the first product sample for the *i*-th line;
c is the speed of light (c = 299792458 m/s)
f_{sampl} is the A/D sampling rate stored at LED.DataSetSummayRecord (bytes 711-726).

PALSAR L1.5 products

In L1.5 products, slant-range distance $R_{i,j}$ for each product sample (*i*,*j*) can be derived by fitting a quadratic polynomial versus line sample number *j*. The IMG.ProcessedDataRecord (bytes 117-120) provides, for each product line, three values of slant range distance respectively at near-range, middle-range and far-range. These three values can be used to obtain, for *i*-th line, the coefficients r_{i0}, r_{i1}, r_{i2} of the quadratic polynomial:

$$R_{i,j} = r_{i0} + r_{i1}j + r_{i2}j^2 \qquad i = 1,2,...,L, \quad j = 1,2,...,M$$

In geocoded L1.5 product the above mentioned fields are blank filled.

ANNEX B DERIVATION OF INCIDENCE ANGLE

The incidence angle $\alpha_{i,j}$ for each pixel (*i*,*j*) is derived as:

$$\alpha_{i,j}[rad] = a_0 + a_1 R_{i,j} + a_2 R_{i,j}^2 + a_3 R_{i,j}^3 + a_4 R_{i,j}^4 + a_5 R_{i,j}^5 \qquad i = 1,2,...,L, \quad j = 1,2,...,M$$

where $a_0, a_1, a_2, a_3, a_4, a_5$ are the coefficients stored in LED.DataSetSummary (bytes 1887-2006),
$R_{i,j}$ [km] is the slant range distance between the sensor platform and the pixel (*i*,*j*).

Processing level L1.1 and L1.5 contains the same value of coefficients $a_0, a_1, a_2, a_3, a_4, a_5$.

ANNEX C ESTIMATION OF FARADAY ROTATION ANGLE FROM PLR DATA PRODUCTS

The amount of FR rotation can be estimated from the data products using the circular basis transformation. For each pixel of the data product the circular polarization is calculated by the following operation [8]:

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} \hat{O}_{hh} & \hat{O}_{hv} \\ \hat{O}_{vh} & \hat{O}_{vv} \end{pmatrix} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$

where i indicates the complex notation, $i^2 = -1$;

$\left[\hat{O}\right] = \begin{pmatrix} \hat{O}_{hh} & \hat{O}_{hv} \\ \hat{O}_{vh} & \hat{O}_{vv} \end{pmatrix}$ is the measured matrix with x-talk and channel imbalance corrected, it corresponds to the complex pixel values of PLR data product;

$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$ is the complex matrix that represent the PLR data in circular basis.

For any reciprocal scatterer the FR angle Ω can be estimated for each pixel using the following expression:

$$\Omega = \frac{1}{4}\arg(M_{12} M_{21}^{*})$$

The procedure to remove the effects of Faraday rotation is described in section 6.2.