	Analysis Ready Data *For Land*	**Product Family Specification:** **Polarimetric Radar**
CEOS — Committee on Earth Observation Satellites		

Document Status

For Adoption as: Product Family Specification, Polarimetric Radar

This Specification should next be reviewed on: March 2021, or no later than 2 weeks before LSI-VC-11 meeting.

Proposed revisions may be provided to: lsi@lists.ceos.org

Document History

Version	Date	Description of change	Author
1.0	31-07-2018	Draft based on CARD4L PFS Normalised RADAR Backscatter v3.1.1	Charbonneau
1.1	20-08-2018	Update Draft based on CARD4L PFS Normalised RADAR Backscatter v3.2, Polarimetric Decomposition v1.0 documents and discussion during "SAR ARD definition Team" telecons.	Charbonneau
1.2	28-01-2019	- New abstract - Add Notice and Limitation section - Update References section - Change threshold requirement on Faraday rotation, distortion matrix and multi-looking	Charbonneau
1.3	16-04-2019	- Update based on latest CARD4L PFS Normalised RADAR Backscatter v4.0 - Replace "procedural examples" section by "Note on Covariance Matrices" - Add a draft metadata example in .xml format	Charbonneau
1.4	03-06-2019	- Merge Normalise Covariance Matrix PFS with Polarimetric Decomposition PFS - Update description of element "3.1 Measurement" - Rename PFS to Coherent Radar - Rewrite abstract accordingly to new changes - Add general description of Polarimetric	Charbonneau
1.5	16-04-2019	- Rename PFS to Polarimetric Radar - Notice and Limitation: clarification of measurement layer structure - 1.7 Remove reference to DEM - 1.10 Add new acquisition parameters - 2.6 Change Ellips. Inc. Angle to Target - 2.7 Remove DEM from per-pixel metadata	Rosenqvist, Lavalle, Zhou

Version	Date	Description of change	Author
2.0	08-08-2019	- Restructure the document for better distinction between metadata related to source data against output product ones. - Specify default parameter name, units and type for each item of the metadata - Remove redundant information	Charbonneau
2.2	10-11-2019	- Move parameter name, units and type for each item of the metadata to separate metadata document - Add self-assessment columns - Clarify resampling and filtering recommendations	Rosenqvist, Charbonneau, Lavalle, Zhou
2.3	21.11.2019	- Integrated review at CEOS WGCV SAR meeting (Frascati, Italy Nov 18-22, 2019)	Rosenqvist, Small, Chapman, Meyer, Lavalle, Miranda, Thankappan, Tadono, Zhou
2.7	12-02-2020	- Quantum leap from 2.2 to 2.7 - Harmonization of the document with CARD4L NRBr PFS v4.5	Charbonneau, Rosenqvist, Small, Lavalle, Chapman
2.8	25-02-2020 03-03-2020 13-03-2020	- Keep 2.3 (Scattering Area) and 2.4 (Local Inc. Angle) as threshold. - Rephrase 4.4 (Gridding Convention) - Typo corrections	Charbonneau, Rosenqvist, Small, Lavalle, Chapman, Zhou
2.9	23.04.2020 10.05.2020	- Abstract and Definitions aligned with CARD4L Normalised Radar Backscatter PFS v4.8 - Item 1.7.4. Name change from "Speckle filtering" to "Filtering"	Rosenqvist Charbonneau, Rosenqvist
2.9.2	12.05.2020	- Items 1.2 & 2.1. Aligned Target requirements with the SR 4.2 PFS and added POL Metadata Specification as Target - Document history editorial	Rosenqvist, Labahn Rosenqvist, Chapman
3.0	12.05.2020	PFS endorsed at LSI-VC-9, meeting #3	LSI-VC-9

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Description

Product Family Title: **Polarimetric Radar (CARD4L-POL)**

Applies to*:*   Data collected by Synthetic Aperture Radar sensors.

Abstract

The CARD4L Product Family Specifications for Synthetic Aperture Radar (SAR) data are specifically aimed at users interested in exploring the potential of SAR, but who may lack the expertise or facilities for SAR processing. There are currently four CARD4L SAR products:

- *Normalised Radar Backscatter*
- *Polarimetric Radar*
- *Geocoded Single-Look Complex*
- *Interferometric Products*

The Polarimetric Radar (POL) analysis ready data (ARD) product format is an extension of the CARD4L-SAR Normalised Radar Backscatter format. This extension is required in order to better support Level-1 SLC polarimetric data, including full-polarimetric modes (RADARSAT-2, ALOS-2, SAOCOM and future missions), and hybrid or linear dual-polarimetric modes (i.e., Compact Polarimetric mode available on RCM, SAOCOM and the upcoming NISAR mission). The POL product can be defined in two processing levels:

- *The normalised covariance matrix (CovMat) representation (C2 or C3) which preserves the inter-channel polarimetric phase(s) and maximizes the available information for users. Interoperability within current CARD4L-SAR backscatter definition is preserved, since diagonal elements of the covariance matrix are backscatter intensities. Scattering information enhancement can be achieved by applying incoherent polarimetric decomposition techniques (e.g., Freeman-Durden, van Zyl, Cloude-Pottier, Yamaguchi-based) directly on the C2 or C3 matrix.*
- *Polarimetric Radar Decomposition (PRD) refers to ARD products where polarimetric information is broken down into simplified parameters to facilitate user interpretation of the data. They are derived from coherent or incoherent polarimetric decomposition techniques. Specific examples of polarimetric decomposition results derived from fully polarimetric and compact or linear dual polarimetric covariance matrix ARD products are shown.*

Notice and Limitations

Optimal incoherent polarimetric radar decomposition (PRD) should be performed under the slant range projection (Gens et al., 2013, Toutin et al., 2013). In order to minimise bias in the CARD4L-SAR Level-2a covariance matrix product, speckle filtering and averaging of the covariance matrix should be applied in slant range projection, and geocoding should be performed with nearest-neighbor resampling. Specifically, nearest-neighbor resampling ensures that the averaged covariance matrix elements in slant range and in geocoded ground projection are exactly the same. Consequently, the polarimetric-derived parameters are *exactly* equal in both approaches (assuming that no further averaging is performed on the ARD product for

decomposing the polarimetric information). Bilinear and average resampling methods are also suitable for resampling the covariance matrix, but some differences with polarimetric parameters generated in slant range and then resampled (bilinear) might be observed on slope terrains. Even if the Sinc method is more robust for spatial resampling, it doesn't preserve the covariance matrix integrity, consequently, it should not be used for this ARD product.

It is recommended for ARD providers who desire distributing PRD products to decompose the polarimetric information starting from Level-1 SLC data and then geocode the derived parameters instead of using the CovMat ARD product. Resampling can be performed using any of the supported methods (nearest-neighbor, bilinear, average, bi-cubic spline or Lanczos are recommended), which need to be indicated in the product metadata. Note that coherent decomposition techniques cannot be performed on CovMat ARD products.

Covariance matrix products contain a variable number of layers (or bands) with different data types depending on the polarimetric mode (full or dual) and decomposition technique. The CovMat products for the C2 matrix have 3 layers (2 real-valued diagonal elements and 1 complex-valued off-diagonal element). CovMat products for the C3 matrix have 6 layers (3 real-valued diagonal elements and 3 complex-valued off-diagonal elements). Layers that can be obtained as complex conjugation of other layers are not provided within the product. Polarimetric Decomposition products contain typically 2 to 4 (or more) real-valued layers depending on the particular decomposition algorithm. Within the CovMat product files, ARD layers are organized in order to minimise access time and maximize efficiency in extracting the desired information. In CovMat products, geographically contiguous samples for each layer may be stored next to each other and organized "layer by layer". Alternatively, samples belonging to the same covariance matrix might be stored next to each other and organized "matrix by matrix". PRD products are organized "layer by layer", i.e., with bands corresponding to the output of the polarimetric decomposition stored next to each other.

Definitions

CARD4L	CEOS Analysis Ready Data for Land
NRB	Normalised Radar Backscatter
POL	Polarimetric Radar
CovMat	Normalised Radar Covariance Matrix
PRD	Polarimetric Radar Decomposition
GSLC	Geocoded Single-Look Complex
InSAR	Interferometric Radar
Ancillary Data	Data other than instrument measurements, originating in the instrument itself or from the satellite, required to perform processing of the data. They include orbit data, attitude data, time information, spacecraft engineering data, calibration data, data quality information, and data from other instruments.
Auxiliary Data	The data required for instrument processing, which does not originate in the instrument itself or from the satellite. Some auxiliary data will be generated in the ground segment, whilst other data will be provided from external sources.
Metadata	Structured information that describes other information or information services. With well-defined metadata, users should be able to get basic information about data, without the need to have knowledge about its entire content.
Spatial Resolution	The highest magnification of the sensor at the ground surface.
Spatial Sampling Distance	Spatial sampling distance is the barycentre-to-barycentre distance between adjacent spatial samples on the Earth's surface.

Requirements

General Metadata

These are metadata records describing a distributed collection of pixels. The collection of pixels referred to must be contiguous in space and time. General metadata should allow the user to assess the overall suitability of the dataset, and must meet the following requirements, which are common to the Normalised Radar Backscatter ARD and to CovMat and PRD products:

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.1	**Traceability**	Not required.	Data must be traceable to SI reference standard. *Note 1: Relationship to 3.4. Traceability requires an estimate of measurement uncertainty. Note 2: Information on traceability should be available in the metadata as a single DOI landing page.*				
1.2	**Metadata Machine Readability**	Metadata is provided in a structure that enables a computer algorithm to be used to consistently and automatically identify and extract each component part for further use.	As threshold, but metadata is formatted in accordance with CARD4L POL Metadata Specifications, v.3.0, or a community endorsed standard that facilitates machine-readability, such ISO 19115-2.				
1.3	**Product Type**	CARD4L product type name and (if required by the data provider) Copyright.	As threshold.				
1.4	**Document Identifier**	Reference to CARD4L- Polarimetric Radar document as URL or DOI.	As threshold.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.5	Data Collection Time	Number of source data acquisitions of the data collection is identified. The start and stop time of data collection is identified in the metadata, expressed in date/time (UTC). In case of composite products, the dates/times of the first and last datatakes.	As threshold.				
1.6	Source Data Attributes	Subsection describing (detailing) each SAR acquisition used to generate the ARD product. *Note: Source data attribute information are described for each acquisition and sequentially identified as acqID= 1, 2, 3, …*					
1.6.1	Source Data Access	The metadata identifies the location from where the source data can be retrieved, expressed as a URL or DOI.	The metadata identifies an online location from where the data can be consistently and reliably retrieved by a computer algorithm without any manual intervention being required.				
1.6.2	Instrument	The instrument used to collect the data is identified in the metadata. - Satellite name - Instrument name	As threshold, but including a reference to the relevant CEOS Missions, Instruments and Measurements Database record.				
1.6.3	Source Data Acquisition Time	The start and stop date+time of source data is identified in the metadata, expressed in date/time, to the second, with the time offset from UTC unambiguously identified.	Acquisition time for each pixel is identified (or can be reliably determined) in the metadata, expressed in date/time at UTC, to the microsecond.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.6.4	**Source Data Acquisition Parameters**	Acquisition parameters related to the SAR antenna: - Radar band - Centre frequency Observation mode - Polarisation(s) - Antenna pointing [Right/Left] - Beam ID	As threshold.				
1.6.5	**Source Data Orbit Information**	Information related to the platform orbit used for data processing: - Pass direction [asc/desc] - Orbit data source [e.g., predicted/definite/ precise/ downlinked, etc.]	As threshold, including also: - Platform heading angle - Orbit data file containing state vectors (minimum of 5 state vectors, from 10% of scene length *before* start time to 10% of scene length *after* stop time) - Platform (mean) altitude				
1.6.6	**Source Data Processing Parameters**	Processing parameters details of the source data: - Processing facility - Processing date - Software version - Product level - Product ID (file name) - Azimuth number of Looks - Range number of Looks (separate values for each beam, as necessary)	As threshold, plus additional relevant processing parameters, e.g., Range- and Azimuth Look Bandwidth and LUT applied.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.6.7	**Source Data Image Attributes**	Image attributes related to the source data: - Product geometry (slant range/ground range) - Azimuth pixel spacing - Range pixel spacing - Azimuth resolution - Range resolution - Near range incident angle - Far range incident angle	As threshold.				
1.6.8	**Sensor Calibration**	Not required.	Sensor calibration parameters are identified in the metadata or can be accessed using details included in the metadata. Ideally this would support machine to machine access.				
1.6.9	**Performance Indicators**	Provide performance indicators on data intensity mean noise level ($NE\sigma^0$ or $NE\beta^0$ (noise equivalent beta naught)). Provided for each polarisation channel when available. Those are not to be estimated individually for each product, but estimated once for each acquisition mode, and annotated on all products.	Provide additional relevant performance indicators (e.g., ENL, PSLR, ISLR, etc.).				
1.6.10	**Source Data Polarimetric Calibration Matrices**	Not required.	The complex-valued polarimetric distortion matrices with the channel imbalance and the cross-talk applied for the polarimetric calibration.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.6.11	**Mean Faraday Rotation Angle**	Not required.	The mean Faraday rotation angle estimated from the polarimetric data and/or from models with reference to the method or paper used to derive the estimate.				
1.6.12	**Ionosphere Indicator**	Not required.	Flag indicating whether the backscatter imagery is "significantly impacted" by the ionosphere (0 – no, 1 – yes). Significant impact would imply that the ionospheric impact on the backscatter exceeds the radiometric calibration requirement or goal for the imagery.				
1.7	**Product Attributes**	Subsection containing information related to the CARD4L product generation procedure and geographic parameters.					
1.7.1	**Product Data Access**	Processing parameters details of the CARD4L product: - Processing facility - Processing date - Software version - Product level - Product ID (file name) The metadata also identifies the location from where the CARD4L product can be retrieved, expressed as a URL or DOI.	The metadata identifies an online location from where the data can be consistently and reliably retrieved by a computer algorithm without any manual intervention being required.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.7.2	Ancillary Data	Not required.	The metadata identifies the sources of ancillary data used in the generation process, ideally expressed as DOIs. *Note: Ancillary data includes DEMs, etc., and any additional data sources used in the generation of the product.*				
1.7.3	Product Sample Spacing	CARD4L product processing parameters details: - Pixel (column) spacing - Line (row) spacing	As threshold.				

1.7.4	Speckle Filtering	Flag if speckle filter has been applied (Y/N).
		
		Metadata should include:
		- Reference to algorithm
		- Input filtering parameters
		   - Type
		   - Window size
		   - Other filter parameters
			Advanced polarimetric filter preserving covariance matrix properties should be applied.				

1.7.5	Geographic Bounding Box	The four corners of the product file (bounding box) are identified, expressed in an accepted coordinate reference system.	As threshold.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
1.7.6	Geographic Image Extent	The 4 extreme points of the image expressed as 4 sets of geographic coordinates holding the points of minimum and maximum latitude, minimum and maximum longitude.	As threshold.				
1.7.7	Product Image Size	Image attributes of the CARD4L product: - Number of lines - Number of pixels/line - File header size (if applicable) - Number of border pixels (if applicable)	As threshold.				
1.7.8	Pixel Coordinate Convention	Pixel coordinate convention [pixel centre, pixel ULC or pixel LLC].	As threshold.				
1.7.9	Coordinate Reference System	The metadata lists the coordinate reference system that has been used.	As threshold, but expressed as an EPSG code.				
1.7.10	Map Projection	The metadata lists the map projection (or geographical coordinates if applicable) that has been used and any relevant parameters required in relation to use of data in that map projection.	As threshold, but expressed as a human readable (gdal WKT) code.				

Per-Pixel Metadata

The following minimum metadata specifications apply to each pixel. Whether the metadata are provided in a single record relevant to all pixels, or separately for each pixel, is at the discretion of the data provider. Per-pixel metadata should allow users to <u>discriminate between</u> (choose) observations on the basis of their individual suitability for application.

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
2.1	**Metadata Machine Readability**	Metadata is provided in a structure that enables a computer algorithm to be used to consistently and automatically identify and extract each component part for further use.	As threshold, but metadata is formatted in accordance with CARD4L POL Metadata Specifications, v.3.0.				
2.2	**Data Mask Image**	Mask image indicating: - Valid data - Invalid data - No-data File format specifications/ contents provided in metadata: - Sample Type [Mask] - Data Format [Raw/GeoTif, …] - Data Type [Byte/Int/Float, ...] - Bits per sample - Byte order - Bit value representation	As threshold, including in addition: - Layover (included as invalid data in Threshold) - Radar shadow (included as invalid data in Threshold) - Ocean water, etc.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
2.3	**Scattering Area Image**	DEM-based local contributing scattering area image used for normalisation is provided. File format specifications/ contents provided in metadata: - Sample Type [square_meters] - Data Format - Data Type - Byte Order - Bits per sample	As threshold.				
2.4	**Local Incident Angle Image**	DEM-based Local Incident angle image is provided. File format specifications/ contents provided in metadata: - Sample Type [Angle] - Data Format - Data Type - Byte Order - Bits per sample *Note: Users should be made aware that estimated "local incident angle" values are incorrect in regions where the scattering normalisation areas is integrated from irregular terrain, especially foreslopes.*	As threshold.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
2.5	**Ellipsoidal Incident Angle Image**	Not required.	Ellipsoidal incident angle is provided. Indicate which ellipsoidal height was used. File format specifications/ contents provided in metadata: - Sample Type [Angle] - Data Format - Data Type - Byte Order - Bits per sample				
2.6	**Noise Power Image**	Not required.	Estimated noise equivalent σ^o (or β^0, as applicable) used for Noise Removal, <u>if applied</u>, for each channel. File format specifications/ contents provided in metadata: - Sample Type [NESZ or NEBZ] - Polarisation - Data Format - Data Type - Byte Order - Bits per sample				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
2.7	**Gamma-to-Sigma Ratio Image**	Not required.	Ratio of the integrated area in the Gamma projection over the integrated area in the Sigma projection (ground). Multiplying RTC γ^o by this ratio results in an estimate of RTC σ^o. File format specifications/ contents provided in metadata: - Sample Type [Ratio] - Data Format - Data Type - Byte Order - Bits per sample				
2.8	**Acquisition Date Image**	Required for multi-source product. Acquisition date for each pixel is identified. Data are day offset to reference observation date [UTC]. Date used as reference ("Day 0") is provided in the metadata. Acquisition date image data type [Byte/INT16/Float/etc.] provided in metadata *Note: Not required for single source data.* Alternatively to "image", when offsets are in integer format, a shapefile (.shp) containing polygons delimiting each "day	As threshold.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
		offset class". In case of multi-temporal image stacks, use acquisition ID to list contributing images.					

Radiometric Terrain Corrected Measurements

The following requirements must be met for all pixels in a collection. The requirements indicate the necessary outcomes and, to some degree, the minimum steps necessary to be deemed to have achieved those outcomes. Radiometric corrections must lead to normalised measurement(s) of backscatter intensity and/or decomposed polarimetric parameters. As for the per-pixel metadata, information regarding data format specification need to be provided for each record.

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
3.1	Radiometric Measurements	Measurements can be: **Normalised Radar Covariance Matrix (CovMat)** Diagonal and upper diagonal elements of the Gamma-0 (γ^o) covariance matrix are provided for coherent dual (e.g., HH-HV, VV-VH, or …) and fully polarimetric (e.g., HH- HV-VH-VV) acquisitions. *And/Or* **Polarimetric Radar Decomposition (PRD)** The individual components of the polarimetric decomposition obtained from the terrain-corrected (Gamma-0 (γ^o)) covariance matrix. **File format** specifications/contents for each measurement provided in metadata: - Measurement Type [CovMat/PRD] - Measurement convention unit [linear amplitude, linear	As threshold.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
		power, angle] - Individual covariance matrix element or/and Individual component of the decomposition [C3m11, C3m12, … or H,A, alpha, or ..] - Data Format [Raw/GeoTif, etc] - Data Type [Byte/Int/Float, Complex, etc.] - Byte order - Bits per sample *Note: It is recommended to keep CovMat or PRD measurement files separated. Otherwise, specify the multi-channel format order [BIP,BIL,BSQ]*					
3.2	**Scaling Conversion**	If applicable, Indicate equation to convert compressed data (int8/int16/float16) to float32 and/or pixel linear amplitude/power to logarithmic decibel scale, including, if applicable, associated calibration (ex.: dB offset) factor.	As threshold, but use of float32.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
3.3	**Noise Removal**	Flag if noise removal* has been applied (Y/N). Metadata should include reference to algorithm as URL or DOI. *Note: Thermal noise removal and image border noise removal to remove overall scene noise and scene edge artefacts, respectively.*	As threshold.				
3.4	**Radiometric Terrain Correction Algorithms**	Adjustments are made for terrain by modelling the local illuminated reference area using the preferred choice of a published peer-reviewed algorithm to produce a radiometrically terrain corrected (RTC) γ^0. Metadata references: - a citable peer-reviewed algorithm - technical documentation regarding the implementation of that algorithm expressed as URLs or DOIs - the sources of ancillary data used to make corrections *Note: Examples of technical documentation include an Algorithm, Theoretical Basis Document, product user guide, etc.*	Require resolution of DEM better than the output product resolution when applying terrain corrections.				

#	Item	Threshold (Minimum) Requirements	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
3.5	**Radiometric Accuracy**	Not required.	Uncertainty (e.g., bounds on γ^0) information is provided as document referenced as URL or DOI. SI traceability is achieved.				

Geometric Terrain Corrections

Geometric corrections must place the measurement accurately on the surface of the Earth (that is, geolocate the measurement) allowing measurements taken through time to be compared.

#	Item	Threshold (Minimum Requirements)	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
4.1	**Geometric Correction Algorithms**	Not required.	Metadata references: - a Metadata citable peer-reviewed algorithm - technical documentation regarding the implementation of that algorithm expressed as URLs or DOIs - the sources of ancillary data used to make corrections *Note: Examples of technical documentation include an Algorithm, Theoretical Basis Document, product user guide, etc.*				
4.2	**Digital Elevation Model**	a) During ortho-rectification, the data provider shall use the same DEM that was used for the radiometric terrain flattening to ensure consistency of the data stack. Provide reference to Digital Elevation Model used for Geometric Terrain Correction.	a) A DEM with comparable or better resolution to the resolution of the output CARD4L product shall be used. As threshold.				

#	Item	Threshold (Minimum Requirements)	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
4.3	**Geometric Accuracy**	An estimate of the geometric accuracy (absolute localisation error) is provided (for example as slant range bias and standard deviation, as well as azimuth bias and standard deviation). Output product subpixel accuracy is taken to be less than or equal to 0.2-pixel radial root mean square error (rRMSE). *Note 1: Typically obtained from corner reflector measurements, and not estimated on a per-product basis* *Note 2: Accurate geolocation is a prerequisite to radar processing to correct for terrain. To enable interoperability between radar sensors, absolute accuracy is required.*	Output product subpixel accuracy is taken to be less than or equal to 0.1-pixel radial root mean square error (rRMSE). Provide documentation of estimate of absolute localisation error as DOI or URL.				
4.4	**Gridding Convention**	A consistent gridding/sampling frame is used. The origin is chosen to minimise any need for subsequent resampling between multiple products (be they from the same or different providers). This is typically accomplished via a "snap to grid" in relation to the most proximate grid tile in a global system.**	When multiple providers share a common map projection, providers are encouraged to standardise the origins of their products among each other. In the case of UTM/UPS coordinates, the upper left corner coordinates should be set to an integer multiple of sample intervals from a 100 km by 100 km grid tile of the				

#	Item	Threshold (Minimum Requirements)	Target (Desired) Requirements	Threshold Self-Assessment	Target Self-Assessment	Self-Assessment Explanation/ Justification	Recommended Requirement Modification
		**Note: If a product hierarchy of resolutions exists (or is planned), the multiple resolutions should nest within each other (e.g., 12.5m, 25m, 50m, 100m, etc.), and not be disjointed.	Military Grid Reference System's 100k coordinates ("snap to grid"). For products presented in geographic coordinates (latitude and longitude), the origin should be set to an integer multiple of samples in relation to the closest integer degree.				

Summary Self-Assessment Table

		Threshold	Target
1	**General Metadata**		
1.1	Traceability		
1.2	Metadata Machine Readability		
1.3	Product Type		
1.4	Document Identifier		
1.5	Data Collection Time		
1.6	**Source Data Attributes**		
1.6.1	Source Data Access		
1.6.2	Instrument		
1.6.3	Source Data Acquisition Time		
1.6.4	Source Data Acquisition Parameters		
1.6.5	Source Data Orbit Information		
1.6.6	Source Data Processing Parameters		
1.6.7	Source Data Image Attributes		
1.6.8	Sensor Calibration		
1.6.9	Performance Indicators		
1.6.10	Source Data Polarimetric Calibration Matrices		
1.6.11	Mean Faraday Rotation Angle		
1.6.12	Ionosphere Indicator		
1.7	**Product Attributes**		
1.7.1	Product Data Access		
1.7.2	Ancillary Data		
1.7.3	Product Sample Spacing		
1.7.4	Speckle Filtering		
1.7.5	Geographic Bounding Box		
1.7.6	Geographic Image Extent		
1.7.7	Product Image Size		
1.7.8	Pixel Coordinate Convention		
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1.7.10	Map Projection		
2	**Per-Pixel Metadata**		
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2.4	Local Incident Angle Image		
2.5	Ellipsoid Incident Angle Image		
2.6	Noise Power Image		
2.7	Gamma-to-Sigma Ratio Image		
2.8	Acquisition Date Image		
3	**Radiometric Corrections**		
3.1	Radiometric Measurements		
3.2	Scaling Conversion		
3.3	Noise Removal		
3.4	Radiometric Terrain Correction Algorithms		
3.5	Radiometric Accuracy		
4	**Geometric Corrections**		
4.1	Geometric Correction Algorithms		
4.2	Digital Elevation Model		
4.3	Geometric Accuracy		
4.4	Gridding Convention		

Guidance

This section aims to provide background on analysis ready data. This guidance material does not replace or over-ride the specifications. Specific information on the processing steps that can be used to achieve ARD is described in annexes 1, 2 and 3.

Introduction to CARD4L

What are CEOS Analysis Ready Data for Land (CARD4L) products?

CARD4L products have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort. These products would be resampled onto a common geometric grid (for a given product) and would provide baseline data for further interoperability both through time and with other datasets.

CARD4L products are intended to be flexible and accessible products suitable for a wide range of users for a wide variety of applications, including particularly time series analysis and multi-sensor application development. They are also intended to support rapid ingestion and exploitation via high-performance computing, cloud computing, and other future data architectures. They may not be suitable for all purposes and are not intended as a 'replacement' for other types of satellite products.

When can a product be called CARD4L?

The CARD4L branding is applied to a particular product once:

- the product has been assessed as meeting CARD4L requirements by the agency responsible for production and distribution of the product, and
- the assessment has been peer reviewed by the CEOS Land Surface Imaging Virtual Constellation in consultation with the CEOS Working Group on Calibration and Validation.

Agencies or other entities considering undertaking an assessment process should contact the co-leads of the [CEOS Land Surface Imaging Virtual Constellation](#).

A product can continue to use CARD4L branding as long as its generation and distribution remain consistent with the peer-reviewed assessment.

What is the difference between Threshold and Target?

Products that meet all threshold requirements should be immediately useful for scientific analysis or decision-making.

Products that meet target requirements will reduce the overall product uncertainties and enhance broad-scale applications. For example, the products may enhance interoperability or provide increased accuracy through additional corrections that are not reasonable at the *threshold* level.

Target requirements anticipate continuous improvement of methods and evolution of community expectations, which are both normal and inevitable in a developing field. Over time, *target* specifications may (as subject to due process) become accepted as *threshold* requirements.

Reference Papers

The following papers provide scientific and technical guidance:

Cameron, W.L., N.N. Youssef, and L.K. Leung (1996) Simulated polarimetric signatures of primitive geometrical shapes, IEEE Transactions on Geoscience and Remote Sensing, vol. 34, no. 3, pp. 793–803.

Cloude, S.R. and E. Pottier (1996) A review of target decomposition theorems in radar polarimetry, IEEE Transactions on Geoscience and Remote Sensing, vol. 34, no. 2, pp. 498–518.

Freeman, A. and S.L. Durden (1998) A three-component scattering model for polarimetric SAR data, IEEE Transactions on Geoscience and Remote Sensing, vol. 36, no. 3, pp. 964–973.

Gens, R., D.K. Atwood and E. Pottier (2013) Geocoding of polarimetric processing results: Alternative processing strategies, Remote Sensing Letters, vol. 4, no. 1, pp. 38-44.

ISO 19115-2 (2009) Geographic information -- Metadata -- Part 2: Extensions for imagery and gridded data, www.iso.org/standard/39229.html

Krogager, E. (1993) Aspects of polarimetric radar imaging, Ph.D. dissertation, Tech. Univ. Denmark, Electromagn. Inst., Lyngby, Denmark

Lee, J.-S., J.-H. Wen, T.L. Ainsworth, K.-S. Chen, and A.J. Chen (2009) Improved Sigma Filter for Speckle Filtering of SAR Imagery, IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 1, pp. 202-213.

Raney, R.K., J.T.S. Cahill, G.W. Patterson and D.B.J. Bussey (2012) The m-chi decomposition of hybrid dual-polarimetric radar data with application to lunar craters Journal of Geophysical Research: Planets 117(E5)

Small, D. (2011) Flattening Gamma: Radiometric Terrain Correction for SAR Imagery, IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 8, pp. 3081-3093.

Toutin, T., H. Wang, P. Chomaz and E. Pottier (2013) Orthorectification of Full-Polarimetric Radarsat-2 Data Using Accurate LIDAR DSM, IEEE Transactions on Geoscience and Remote Sensing, vol. 51, no. 12, pp. 5252-5258.

Yamaguchi, Y., A. Sato, W.M. Boerner, R. Sato and H. Yamada (2011) Four-Component Scattering Power Decomposition with Rotation of Coherency Matrix, IEEE Transactions on Geoscience and Remote Sensing vol. 49, no. 6, pp. 2251-2258.

Annex 1: Normalised Covariance Matrices (CovMat)

In order to preserve the inter-channel polarimetric phase and thus the full information content of coherent dual-pol and fully polarimetric data, the covariance matrix is proposed as the data storage format. Covariance matrices are generated from the complex cross product of polarimetric channels, as shown in Equation 1 for fully polarimetric data (C3) and in Equation 2 for dual polarisation data (C2). Since these matrices are complex symmetrical, only the upper diagonal elements (bold elements) need to be stored in the ARD database.

Fully polarimetric

$$C3 = \begin{bmatrix} |\mathbf{HH}|^2 & \sqrt{2} \cdot \mathbf{HH} \cdot \mathbf{HV}^* & \mathbf{HH} \cdot \mathbf{VV}^* \\ \sqrt{2} \cdot HV \cdot HH^* & 2 \cdot |\mathbf{HV}|^2 & \sqrt{2} \cdot \mathbf{HV} \cdot \mathbf{VV}^* \\ VV \cdot HH^* & \sqrt{2} \cdot VV \cdot HV^* & |\mathbf{VV}|^2 \end{bmatrix} \qquad \textbf{Eq. 1}$$

Where HV = VH, under the reciprocity assumption. | | and * mean respectively complex modulus and the complex conjugate.

Dual polarisation

    HH-HV

$$C2 = \begin{bmatrix} |\mathbf{HH}|^2 & \mathbf{HH} \cdot \mathbf{HV}^* \\ HV \cdot HH^* & |\mathbf{HV}|^2 \end{bmatrix} \quad or$$

    VV-VH

$$C2 = \begin{bmatrix} |\mathbf{VH}|^2 & \mathbf{VH} \cdot \mathbf{VH}^* \\ VH \cdot VH^* & |\mathbf{VV}|^2 \end{bmatrix} \quad or$$

    Eq. 2

    CH-CV

$$C2 = \begin{bmatrix} |\mathbf{CH}|^2 & \mathbf{CH} \cdot \mathbf{CV}^* \\ CV \cdot CH^* & |\mathbf{CV}|^2 \end{bmatrix}$$

Where CH and CV refer to dual polarisation transmitting a circular polarised signal. [CH, CV] can be replaced by [LH, LV] or [RH, RV] for left (L) or right (R) hand circular transmission respectively, although RCM will offer only right-hand circular transmission. The coherent HH-VV configuration available on TerraSAR-X could also be represented as C2 format.

Polarimetric decomposition methods like Yamaguchi et al. (2011) for fully polarimetric, or m-chi (Raney et al., 2012) for compact polarimetric data, can be applied directly on averaged (speckle filtered) C3 and C2 matrices respectively. These decompositions enhance scattering information, bring it to a more comprehensible level to end users, and raise the performance of thematic classification methodologies.

For SAR products that were acquired with single polarisation the use of the covariance matrix does not result in superfluous storage requirements, since only the matrix elements that are populated are kept and the diagonal matrix elements are the backscatter intensities. Thus, a single channel intensity product would yield only one matrix element and the storage needs would not change.

In order to ease the data structure and the metadata in between C3 and C2, Equation 1 should be redefined as Equation 3. Users will have to take care of this non-standard representation when applying their polarimetric analytic tools. "< >" means that ARD matrix elements are speckle filtered. Equation 3 is valid both for dual-linear and quad polarisation.

$$C3\ modified\ \ C3m = \begin{bmatrix} \langle |HH|^2 \rangle & \langle HH \cdot HV^* \rangle & \langle HH \cdot VV^* \rangle \\ \langle HV \cdot HH^* \rangle & \langle |HV|^2 \rangle & \langle HV \cdot VV^* \rangle \\ \langle VV \cdot HH^* \rangle & \langle VV \cdot HV^* \rangle & \langle |VV|^2 \rangle \end{bmatrix} \qquad \textbf{Eq. 3}$$

Furthermore, for compact polarimetric data, it is recommended to store them, by simple transformation, under the circular-circular basis, since RR and RL polarisations (Equation 4) permit faster and more intuitive RGB visualizations (R=RR, G=RR/(RR+RL), B= RL).

$$\textbf{CH-CV} \qquad \textbf{C2 circular}\ \ C2c = \begin{bmatrix} \langle |RR|^2 \rangle & \langle RR \cdot RL^* \rangle \\ \langle RL \cdot RR^* \rangle & \langle |RL|^2 \rangle \end{bmatrix} \qquad \textbf{Eq. 4}$$

In order for the covariance matrix format to be accessible the metadata must specify which matrix elements have been stored. Table A1.1 lists the proposed format for quick reference. Polarisation search in the metadata could be done by "layer ID", "Matrix element" or by "Layer description".

Table A1.1. SAR ARD covariance matrix storage structure (RADARSAT-2 & RCM).
(Note: For dual-pol data the SAR ARD layers are only partially populated.)

SAR ARD layer ID	Matrix element	Layer description
1	C3m11	HH backscatter [intensity]
2	C3m12	HH × conj(HV) [complex]
3	C3m13	HH × conj(VV) [complex]
4	C3m22	HV backscatter [intensity]
5	C3m23	HV × conj(VV) [complex]
6	C3m33	VV backscatter [intensity]
7	C2c11	RR backscatter [intensity] *
8	C2c12	RR × conj(RL) [complex] *
9	C2c22	RL backscatter [intensity] *

* Examples of compact pol values. Can be e.g., LL, 45 deg etc.

Annex 2: Polarimetric Radar Decomposition (PRD)

Based on the literature, different methodologies allow decomposition of coherent dual-polarisation data or fully polarimetric data to meaningful components summarizing the scattering processing with the interacting media. Decomposition techniques are divided in two categories: Coherent and incoherent.

1. **Coherent decompositions** express the scattering matrix by the summation of elementary objects of known signature (ex.: a sphere, a diplane, a cylinder, a helix, …). They are used mainly to describe point targets which are coherent. As for examples, coherent PRD could be (but not limited to):

    a. Pauli decomposition (3 layers)

    $|\alpha|^2$: sphere (odd-bounce interaction) [Intensity]
    $|\beta|^2$: 0° diplane (even-bounce interaction) [Intensity]
    $|\gamma|^2$: 45° diplane (volumetric interaction) [Intensity]

    b. Krogager decomposition (5 layers) [Krogager, 1993]

    $|\kappa_\sigma|^2$: sphere (odd-bounce interaction) [Intensity]
    $|\kappa_\delta|^2$: diplane (odd-bounce interaction) [Intensity]
    $|\kappa_\eta|^2$: helix [Intensity]
    θ: orientation angle [degrees]
    ϕ_s: sphere to diplane angle [degrees]

    c. Cameron (nine classes) –non-dimensional layers [Cameron et al., 1996]

Table A2.1.

Classes	ID
Triedral	1
Dihedral	2
Narrow Dihedral	3
Dipole	4
Cylinder	5
¼ wave	6
Right Helix	7
Left Helix	8
Asymmetrical	9

2. **Incoherent decompositions** describe distributed targets in terms of scattering mechanisms and their diversity. They are generated from averaged Covariance, Coherence or Kennaugh matrices. As for examples, incoherent PRD could be (but not limited to):

   a. Based and saved on intensity of scattering mechanisms can be [Freeman and Durden, 1998; Yamaguchi et al., 2011; Raney et al., 2012]

Table A2.2.

Level2b- Layers [Intensity]	Incoherent Decompositions		
	Freeman-Durden	Yamaguchi	m-chi
Odd-bounce (surface/triedral)	X	X	X
Even-bounce (dihedral)	X	X	X
Random (volumetric)	X	X	X
Helix		X	

   b. Or based on eigenvector-eigenvalue decomposition expressing the diversity of scattering mechanisms [Cloude and Pottier, 1996] and types

> H : Entropy [ ] is the polarisation diversity
> A : Anisotropy [ ] is weighted difference between the 2nd and 3rd eigenvalues
> α : Odd-even bounce angle [Degrees]
> β : orientation angle [Degrees]

Annex 3: General Processing Roadmap

While the covariance matrix is the suggested fundamental storage structure, several other data processing steps are required to fully form the ARD specification and these are consistent with the CEOS CARD4L specification:

- Apply the best possible orbit parameters to give the most accurate product possible. These will have been projected to an ellipsoidal model such as WGS84. In order to achieve the threshold levels of geometric accuracy required of CARD4L precise orbit determination will be required.

- Apply instrument calibration to produce beta-naught values with high fidelity.

- Generate the covariance matrix from the complex cross-product of polarimetric channels as shown in Annex 1. For single channel intensity data, this process yields directly the appropriate ARD-SAR-CM layer.

- Perform radiometric normalisation (gamma flattening) on the covariance matrix by applying the local surface normalisation factor to each matrix element (Small, 2011).

- Perform polarimetric speckle filtering, before geocoding, in order to optimally preserve the polarimetric information. Most popular polarimetric decomposition methodologies are incoherent in nature, which requires averaging the covariance matrix for stationarity. Depending on the application, a polarimetric filter that preserves local point targets and locally average extended targets may be used, e.g., Sigma Lee filter with 7x7 window and 3 point target (Lee et al., 2009).

- Geometric terrain correction is applied to the filtered and normalised covariance matrix. The resampling methodology should be nearest-neighbor, bilinear or average in order to preserve integrity of the covariance matrix as other resampling functions can introduce artefacts due to the mix of intensity and complex number elements in the matrix. Geocoding can be either to a common grid structure with specified pixel spacings for true data cube format, or simply left in native resolution, but reprojected to a common reference system as is used in other instances.

- Generate CEOS format metadata to accompany product layers.

The pre-processed data are then stored in an ARD cloud data cube and are available for quick download to a local computer or for direct spatial analysis and/or multi-temporal analysis with other ARD products in the cloud, from a Graphical User Interface (GUI).

The processing chain will require multiple steps. Table A3.1 lists the logic, existing software tools (mostly Gamma software (GAMMA, 2018)) and scripting tasks that would form the SAR ARD Polarimetric Radar processing roadmap.

Table A3.1. SAR ARD PR processing roadmap and software options. RADARSAT-2 Example

Step	Implementation option
1. Orbit data refinement	Check xml date and delivered format. RADARSAT-2, pre EDOT (July 2015) replace. Post July 2015, check if 'DEF', otherwise replace. (Gamma - RSAT2_vec)
2. Apply radiometric correction to Beta-naught	Specification of LUT on ingest. (Gamma - par_RSAT2_SLC/SG)
3. Generate covariance matrix elements	Gamma – COV_MATRIX
4. Radiometric terrain normalisation	Gamma - geo_radcal2
5. Speckle filtering (Boxcar or Sigma Lee)	Custom scripting
6. Geometric terrain correction/Geocoding	Gamma – gc_map and geocode_back
7. Create metadata	Custom scripting

Annex 4: Polarimetric Radar Decomposition Product Examples

From fully polarimetric covariance matrix ARD format (Level-2a), it is possible to apply any version of the popular Yamaguchi methodology, which decomposes the polarimetric information under relative intensities of 4 scattering types: Odd bounce, Even bounce, Random (volume) and helix. Figure 1b) shows HH intensity of a RADARSAT fully polarimetric acquired over a Spanish area. Decomposition using Yamaguchi methodology [Yamaguchi et al., 2011] can be expressed in RGB color composite (Figure 1c) where Red channel refers to even bounce scattering like urban area; Green channel is random scattering like vegetation; and Blue channel is odd bounce scattering like bare soil. Figure 1d) is equivalent to 1c) where radiometric normalisation (terrain flattening) has been applied with the help of the DEM of the scene (Figure A4.1a).
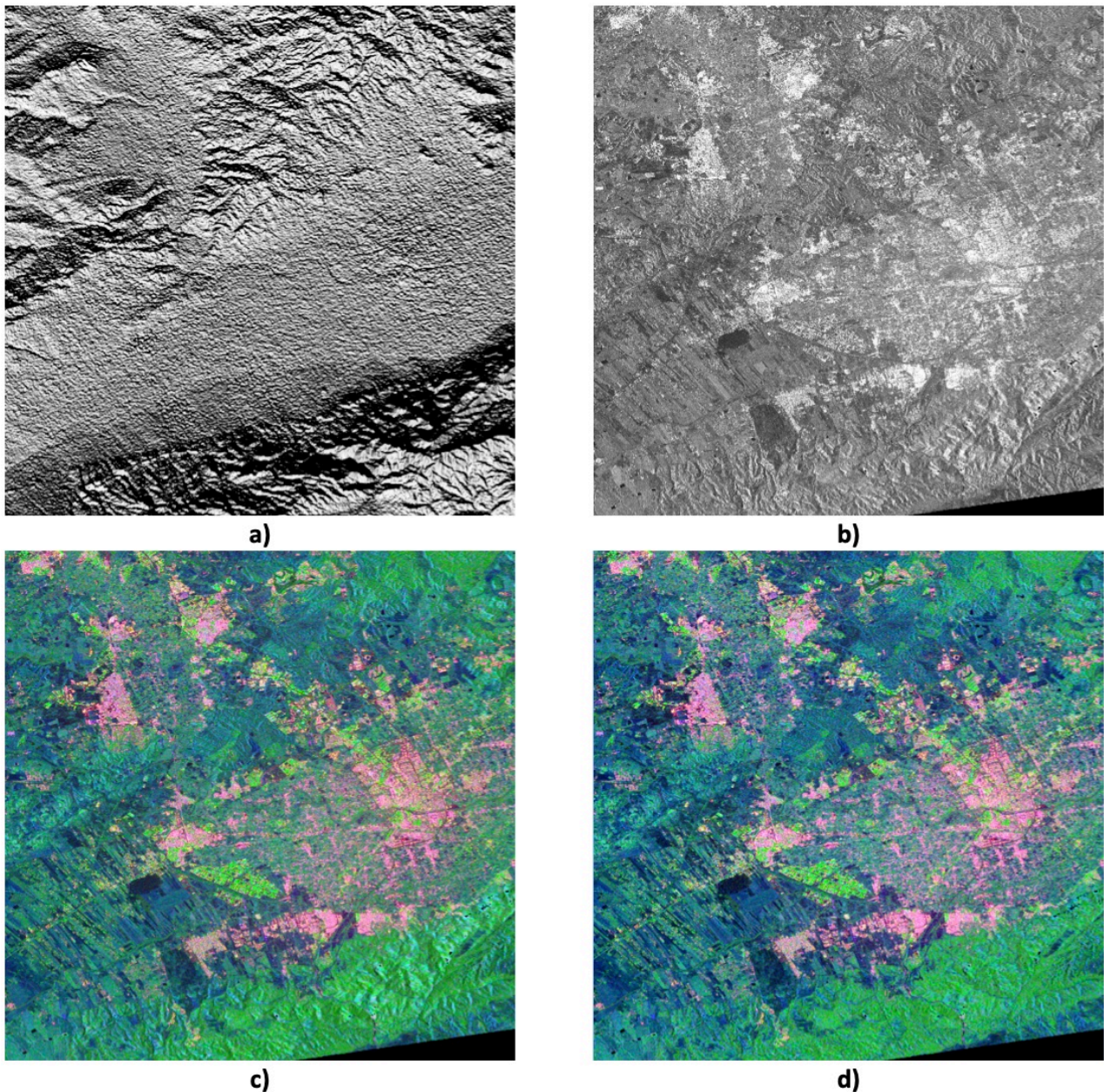

Figure A4.1 Example of polarimetric decomposition generated from ARD covariance format. *a)* Shaded DEM of the area; *b)* RADARSAT-2 HH intensity; *c)* Yamaguchi decomposition color composite (Red: even bounce, Green: random, Blue: odd bounce); *d)* Same as c) with terrain flattening option. Generated from Radarsat-2 FQ18W acquired over Murcia, Spain on 18 June 2014 ©MDA 2014

Figure A4.2 is a compact polarimetric m-chi decomposition [Raney et al., 2012] simulated from two

Canadian prairies Radarsat-2 fully polarimetric scenes acquired in May and June 2012. In May, before the growing season (Figure 2a), m-chi shows mainly surface scattering from bare soil (blue channel) and vegetation interaction from forested areas (green channel), while in June (Figure 2b) growth of vegetation modifies the radar signal with interacting media function of the vegetation density and geometry which increase the amount of even bounce (red channel) and random scattering.
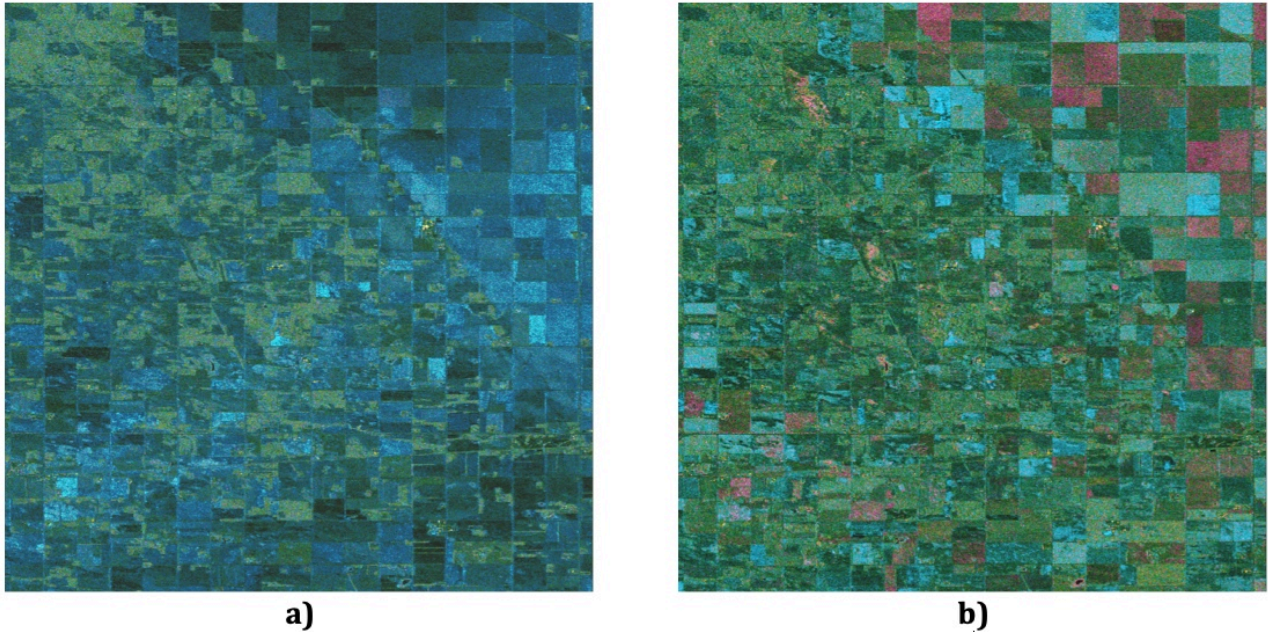

a)   b)

Figure A4.2 m-chi decomposition color composite of simulated compact polarimetry from Radarsat-2 over an agriculture area. RGB representation: Red: even bounce, Green: random, Blue: odd bounce. *a)* 3 May 2012; and *b)* 18 June 2012. Generated from Radarsat-2 FQ6W acquired over SMAPVEX12 campaign Manitoba, Canada on 3 May and 20 June 2012 ©MDA 2012