ICEYE X2 Quality Assessment Summary

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AMENDMENT RECORD SHEET

The Amendment Record Sheet below records the history and issue status of this document.

ISSUE	DATE	REASON
1.0	Feb 2020	First version
2.0	July 2020	Revised after receiving comments from ESA and one new ICEYE document

ACRONYMS

AASR	Azimuth Ambiguity to Signal Ratio
ATBD	Algorithm Theoretical Basis Document
CR	Corner Reflector
DEM	Digital Elevation Model
ENL	Equivalent Number of Looks
FMI	Finnish Meteorological Institute
GIS	Geographic Information System
HDF	Hierarchical Data Format
IRF	Impulse Response Function
ISLR	Integrated Side Lobe Ratio
NESZ	Noise Equivalent Sigma Zero
NetCDF	Network Common Data Form
NLS	National Land Survey
PSLR	Peak Side Lobe Ration
RASR	Range Ambiguity to Signal Ratio
RCRA	Rosamond Corner Reflector Array
RD	Reference Document
SLC	Single Look Complex
SNAP	SeNtinel Application Platform

SQT	SAR Quality Toolbox
STD	STandard Deviation
UTM	Universal Transverse Mercator

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

Quality assessment was performed for ICEYE's X2 SAR satellite's Single Look Complex (SLC) images. The assessment is divided into two main parts: Documentation review and the assessment of the reference datasets. The document review in sections 2.1-2.4 includes the assessment of the documentation provided by ICEYE, and the correspondent grading is given in columns 1-4 of the maturity matrix shown in Figure 1. Section 2.5 deals with the validation performed by FMI using the test data acquired for the EDAP project, and the grading for this is given in the last column of the maturity matrix. Section 3 provides more detailed explanations on the results of the data analysis performed by FMI.

The product information provided through the openly available documentation (RD-1, RD-2) and the products themselves (metadata) is overall good. Data order and delivery to the customer was smooth due to well written and clear instructions regarding the FTP delivery procedures. The provided product details include most of the required information, data is easily accessed and processed with the SNAP toolbox and the data are in a standard file format, easily read and understood. Documentation describing the metrological traceability is not available.

All relevant characterisation of the SAR system and data is provided, and metadata includes all relevant ancillary information. Documentation about pre-flight calibration is minimal. The post launch radiometric calibration methods are well documented in RD-5; the radiometric calibration was performed using distributed targets (rainforests) and point targets (corner reflectors). No additional higher lever (L2) products are processed from the ICEYE SLC product.

All relevant uncertainty values for SAR provided, such as ISLR, PSLR, NESZ and Geolocation error. Single uncertainty values for the product are provided in the openly available documentation (RD-2), but a more detailed information is provided in the not openly available documents (RD-3, RD-4). Pixel-wise uncertainty is not provided. The methods for uncertainty characterization are partly documented. Methods describing e.g. the IRF and geolocation error analyses are well described well, while methods for assessing the radiometric accuracy, ENL and NESZ are not documented or documented only in a general manner.

An independent quality assessment of the essential quality parameters in SAR, such as spatial resolution, PSLR, ISLR, ENL and NESZ was performed by FMI, using a representative dataset collected by the ICEYE X2-satellite from various test sites, including distributed target test sites and point target test sites. The received quality parameters were compared with the corresponding values provided by ICEYE. The validation was mainly performed using a SAR Quality Toolbox (SQT) dedicated for the assessment of SAR data quality, developed by Aresys. Processing was also tested with the SNAP toolbox. The reference data quality analysis results are generally in a good agreement with the values provided by ICEYE, such as the spatial resolution, geolocation accuracy, PSLR and ISLR. The ENL in the homogenous targets sometimes showed values lower than 1, but this might be related to the areas being not ideally homogeneous in the assessed high spatial resolution data of ~0.5-3 m. The NESZ was higher (worse) than the values provided by ICEYE, however, this is most likely due to an overestimation by the SQT. The data was successfully processed in SNAP indicating that the SNAP plugin provided by ICEYE works well. Based on our evaluation results and the quality values provided by ICEYE we generally view the X2 SLC product as "fit for purpose".

1.1 Mission Quality Assessment Matrix

Product Information	Product Generation	Ancillary Information	Uncertainty Characterisation	Validation
Product Details	Sensor Calibration & Characterisation Pre-Flight	Product Flags	Uncertainty Characterisation Method	Reference Data Representativeness
Availability & Accessibility	Sensor Calibration & Characterisation Post-Launch	Ancillary Data	Uncertainty Sources Included	Reference Data Quality
Product Format			Uncertainty Values Provided	Validation Method
User Documentation			Geolocation Uncertainty	Validation Results
Metrological Traceability Documentation				

Key
Not Assessed
Not Assessable
Basic
Intermediate
Good
Excellent

Information Not Public

Figure 1 – Mission Product Quality Evaluation Matrix for ICEYE's X2 SLC product

2. MISSION ASSESSMENT OVERVIEW

2.1 Product Information

Product Details	
Product Name	*ICEYE_X2_SLC_SM_XXXX_YYYYMMDDTHHmmss*
Sensor Name	*X2*
Sensor Type	*X-Band SAR*
Mission Type	*Constellation – 4 satellites (2019)*
Mission Orbit	*Sun Synchronous Polar Orbit*
Product Version Number	*ICEYE_P_0.99*
Product ID	*A number with four to five digits individual for each product (see* Table 1*)*
Processing level of product	*Level 1 SLC*
Measured Quantity Name	*Radar Backscatter*
Measured Quantity Units	*dB*
Stated Measurement Quality	*Included, < 2 dB*
Spatial Resolution	*Range 0.5-1.5 m, Azimuth 2.5-3.0 m*
Spatial Coverage	*All relevant information included*
Temporal Resolution	17 days
Temporal Coverage	*Images on demand*
Point of Contact	*customer@iceye.com*
Product locator (DOI/URL)	NA
Conditions for access and use	*Data were provided under specific agreement for utilization within the EDAP framework.*
Limitations on public access	NA
Product Abstract	NA

Some recommended information missing: Product locator, Limitations on public access, Product Abstract.

Availability & Accessibility	
Compliant with FAIR principles	*Most of the Fair principles meet, except: Metadata and data include qualified references to other (meta)data.*
Data Management Plan	*RD-2*
Availability Status	*Possibility to use free software (SNAP) for data processing and analysis. SNAP plugin provided by ICEYE.*

Product Format	
Product File Format	*HDF5*
Metadata Conventions	*NetCDF v1*
Analysis Ready Data?	*No*

Format is well-documented, with naming standards. Some of the Analysis Ready Data threshold requirements missing.

User Documentation		
Document	*Reference*	*QA4ECV Compliant*
Product Format Specification	*RD-1*	*No*
Product User Guide	*RD-2*	*No*
Radiometric Calibration and Validation	*RD-5*	*No*

Metrological Traceability Documentation	
Document Reference	*No*
Traceability Chain / Uncertainty Tree Diagram Available	*No*

2.2 Product Generation

Sensor Calibration & Characterisation – Pre-Flight	
Summary	*All relevant characterisation of a SAR system stated. Documentation about pre-flight calibration is minimal.*
References	*RD-1* *RD-2*

Sensor Calibration & Characterisation – Post-Launch	
Summary	*Metadata includes all reasonable aspects. Post-launch calibration methods are well explained in the provided documentation (RD-5). The radiometric calibration was performed using homogeneous targets and point targets. It included e.g. antenna elevation beam calibration and calibration coefficient calculation. Calibration against homogeneous targets was initially performed over Amazon rainforest, and a validation of the calibration parameters was done using Congo rainforest data. The corner reflectors in Rosamond JPL site were used in the point target radiometric calibration. The calibration parameters were derived through an analysis of many images. Routine and ongoing validation activities are planned for the operational ICEYE satellites.*
References	*RD-1* *RD-2* *RD-5*

Additional Processing	
Description	*No additional processing done for ICEYE SLC product. Box removed from maturity matrix.*
Reference	*RD-1*

2.3 Ancillary Information

Product Flags	
Product Flag Documentation	*RD-1*
Comprehensiveness of Flags	*Only two flags, either 0 or 1, no documentation about them*

Ancillary Data	
Ancillary Data Documentation	*RD-1*
Comprehensiveness of Data	*All the necessary and relevant ancillary data for SAR systems exists. There is no additional ancillary data related to ground conditions at the time of imaging, such as meteorological data.*

Uncertainty Quantified	*No*

2.4 Uncertainty Characterisation

Uncertainty Characterisation Method	
Summary	*The methods for uncertainty characterization are partly documented. Methods describing e.g. the IRF and geolocation error analyses are described well in the documentation, however, methods for assessing the radiometric accuracy, ENL and NESZ are not documented or documented only in a general manner.*
Reference	*RD-2, RD-3, RD-4*

Uncertainty Sources Included	
Summary	*The products are corrected for any measured or characterized gain variation including the ones of the instrument and resulting from projected antenna pattern. The SAR processor compensates the effects of range spread loss, elevation antenna pattern, different azimuth and range bandwidths, and sensor settings variations (receiver gain, transmit power, duty cycle)*
Reference	*RD-2*

Uncertainty Values Provided	
Summary	*All the relevant uncertainty values for SAR are provided: ISLR, PSLR, AASR, RASR, NESZ, Geolocation error. The given uncertainty values are based on an analysis of several datasets. Single uncertainty values for the product are provided in the openly available documentation, but a more detailed analysis is provided in the additional documentation (not openly available). Pixel-wise uncertainty is not provided.*
Reference	*RD-2, RD-3, RD-4*

Geolocation Uncertainty	
Summary	*In the publicly available documentation, the geolocation uncertainty is given as a one single value for the SLC product. This would correspond to the "basic" grade. However, in the additional documentation (not publicly available) provided by ICEYE for the EDAP evaluation, the geolocation uncertainty is given in a more detailed manner (Absolute Location Error, Root Mean Square Error, Circular Error at the 90% percentile calculated with the three different methods). This would correspond more with the "Good" grade.*
Reference	*RD-2, RD-3, RD-4*

2.5 Validation

Validation Activity #1	
Independently Assessed?	Yes
Reference Data Representativeness	
Summary	*Reference measurements assessed are well representative of the satellite measurements, covering a reasonable range of X2 satellite's measurements. The total number of assessed images is 40, including corner reflector and urban sites for IRF and localization error analysis, low backscatter images from doldrums and lakes, as well as homogenous rainforest sites in Southern America and Central Africa for radiometric analysis. The reference datasets enable a proper validation of the most essential quality parameters in SAR, such as spatial resolution, PSLR, ISLR, ENL and NESZ.*
Reference	*NA*
Reference Data Quality & Suitability	
Summary	*The quality parameters of the reference data are given as single uncertainty values representing all datasets.*
Reference	*RD-1, RD-2*
Validation Method	
Summary	*The methodology assesses all relevant quality parameters in SAR for the reference datasets and compares them with the uncertainty/quality values provided by ICEYE. The validation was mainly performed using a dedicated SAR quality analysis toolbox, but processing was also tested with the SNAP toolbox.*
Reference	*RD-1, RD-2, RD-3, RD-4*
Validation Results	
Summary	*The reference data quality analysis results are generally in a good agreement with the values provided by ICEYE. The spatial resolution from the IRF analyses is very close to the values provided by ICEYE. Geolocation accuracy was better in Rosamond CR site, and less good in Sodankylä CR site. In Sodankylä the accuracy was thus slightly above the defined 10 m geolocation accuracy. The ENL in the homogenous targets sometimes showed values lower than 1 (the optimal ENL value for SLC data is one). The PSLR and ISLR were close to the values defined by ICEYE. The NESZ was higher (worse) than the values provided by ICEYE, however, this is most likely due to an overestimation by the SQT. The processing in SNAP was successful. Based on our evaluation results and the quality values provided by ICEYE we generally view the X2 SLC product as "fit for purpose".*
Reference	*NA*

3. DETAILED ASSESSMENT

This chapter provides more detailed explanations on the independent data analysis and assessment performed by FMI using the reference X2-satellite SLC SAR dataset. Table 1 shows the date and the ID number of the X2 images acquired by ICEYE and provided to FMI for evaluation purposes within the EDAP project. Data was collected from various sites enabling a comprehensive assessment of the most relevant SAR quality metrics, such as spatial resolution, peak side lobe ratio (PSLR), integrated side lobe ratio (ISLR), geolocation accuracy, equivalent number of looks (ENL) and noise equivalent sigma zero (NESZ).

The SAR Quality Toolbox provided by Aresys was used for assessing the above-mentioned metrics. Data was also processed in SNAP version 7.0 for testing the SNAP plugin provided by ICEYE. The measured quality values were evaluated by comparing them to the corresponding quality values provided by ICEYE, taking into consideration the product's "fit to purpose".

The data was first delivered to FMI starting from April 2019 until November 2019. Due to updates in the processing lines of the SAR product, all data was updated by ICEYE and delivered to FMI again in December 2019. Only the SNAP processing testing and the related geolocation accuracy assessment for Helsinki were performed with the first (old) version of the data. All the other data analyses were performed using the updated version of the datasets.

Table 1: All X2 data products provided by ICEYE to FMI and included in the data analysis and evaluation.

Test Area	Date	ID number
Sodankylä, Finland	20190413	4206
	20190428	4751
	20190818	8011
	20190904	8184
	20191008	10573
	20191025	12119
Rosamond, California	20190328	3709
	20190414	4251
	20190811	6591
	20190828	6592
Doldrums, Atlantic	20190628	6376
	20190629	6378
	20190626	6379
	20190817	8018
	20190818	8019
	20190820	8020
Doldrums, Pacific	20190629	6177
	20190702	6182
	20190816	7867
	20190816	7869
	20190817	7873
	20190909	6877
Lake Loka, Finland	20190525	5646
	20190609	5998
	20190627	6161
	20190627	6164
Rainforest, Amazon	20190306	2995
	20190409	4096
	20190420	4550
	20190609	5941
Rainforest, Central Africa	20190524	5638
	20190525	5639
	20190610	6002
	20190609	6005
	20190627	6155
	20190628	6156
Helsinki, Finland	20190227	2717
	20190331	3280
	20190401	3281
	20190402	3283

3.1 IRF Analysis

Several images were analysed over two different test areas with corner reflectors; the Rosamond Corner Reflector Array (RCRA) located in California (Table 2) and Sodankylä airfield, located in northern Finland (Table 3). Figure 2 present an overview of SQT software from Aresys. An option for manual IRF analysis is available along with an automated SQT that generated HTML Reports. The figures (Figure 3-Figure 6) present the results of the manual analysis of an arbitrary selected CR over Rosamond. The results for all installed corner reflectors were obtained through the automatized function, and therefore unreasonable results were discarded.

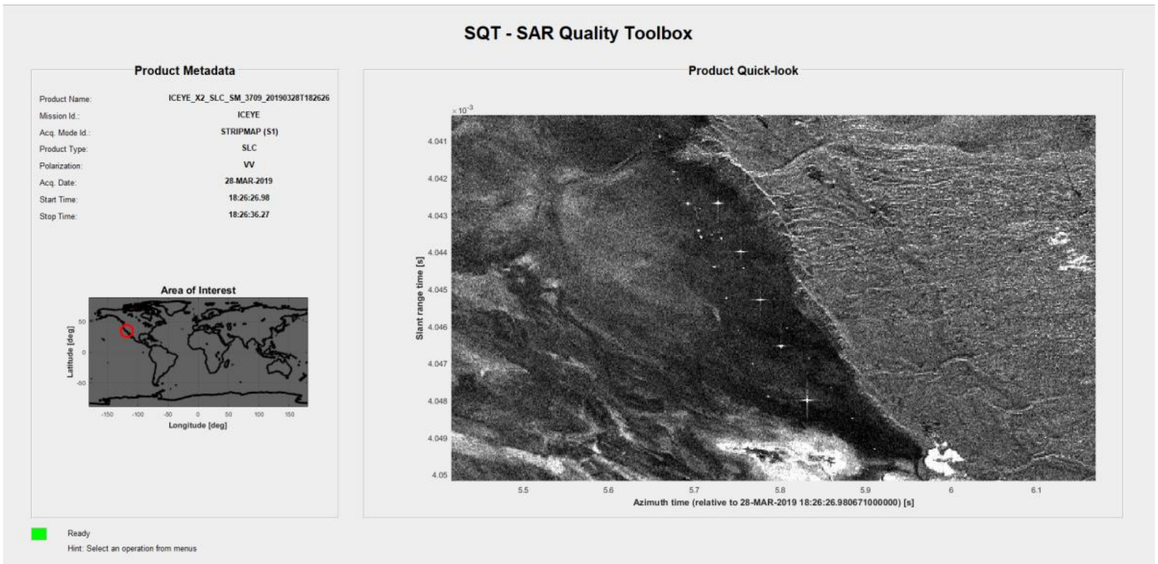

Figure 2. Overview of SQT software.

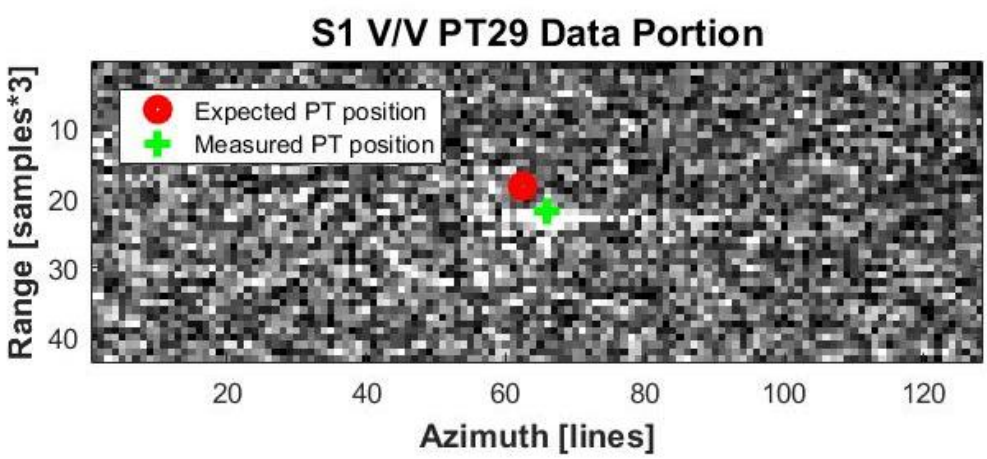

Figure 3. A quicklook image showing the geolocation accuracy of an observed corner reflector.

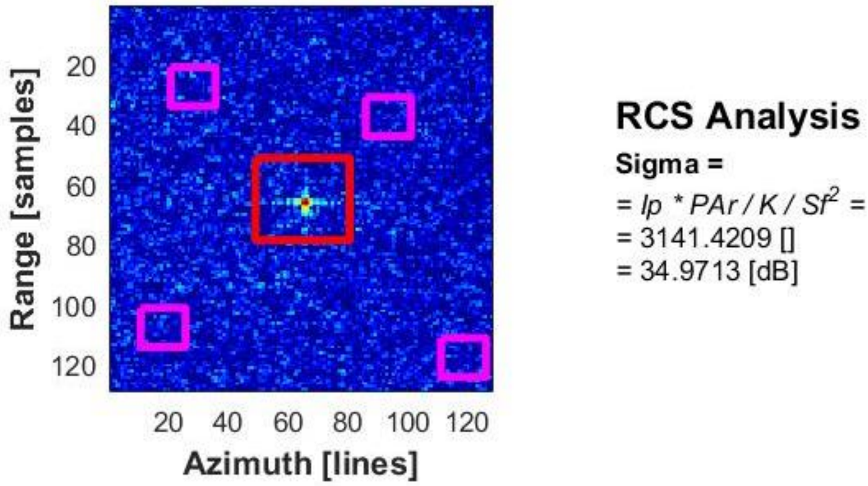

Figure 4. RCS Analysis from SQT.

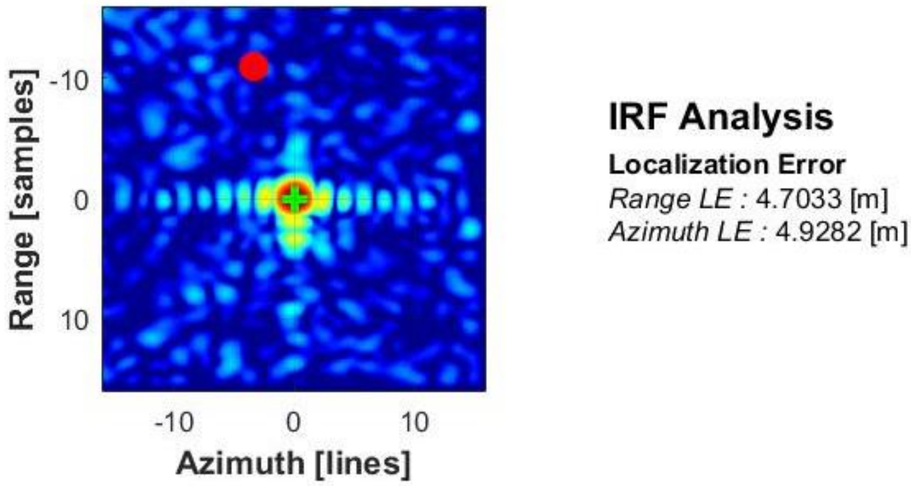

Figure 5. The geolocation error for one corner reflector calculated by the SQT.

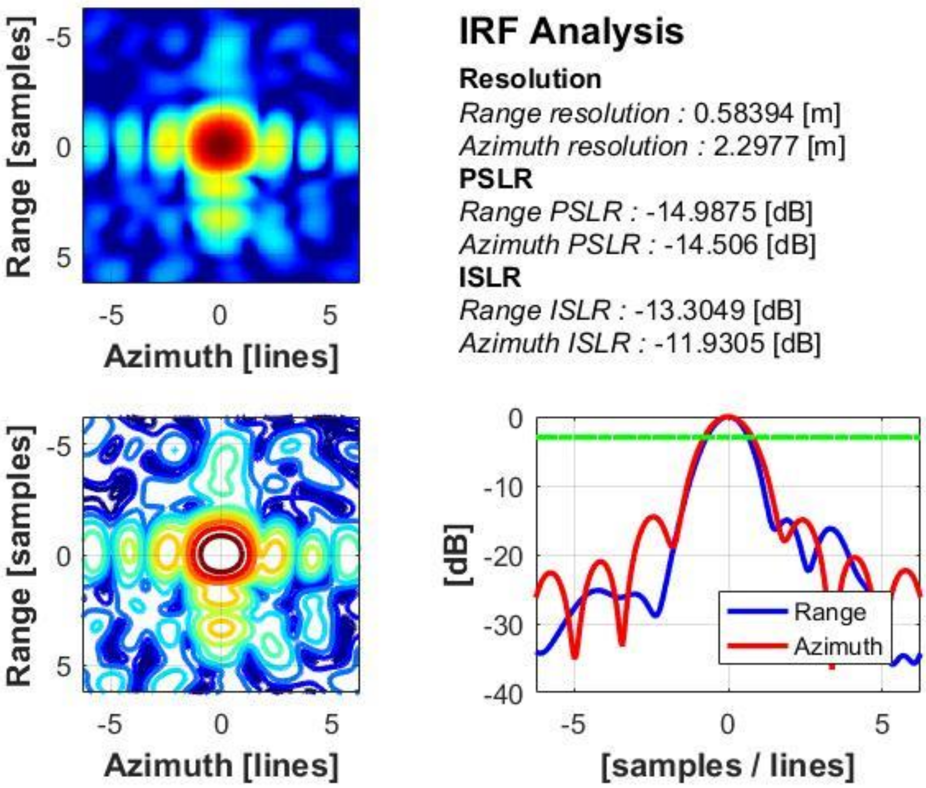

Figure 6: IRF Analysis from SQT

Table 2. IRF analysis for Rosamond.

Rosamond Image ID	Range resolution [m]	Azimuth resolution [m]	Range PSLR [dB]	Azimuth PSLR [dB]	Range ISLR [dB]	Azimuth ISLR [dB]	Range Location Error [m]	Azimuth Location Error [m]
6519	0.69 ± 0.045	2.25 ± 0.021	-15.30 ± 4.395	-12.96 ± 2.056	-12.79 ± 5.030	-9.53 ± 2.918	3.37 ± 0.279	6.53 ± 0.156
4251	0.56 ± 0.032	2.25 ± 0.036	-8.67 ± 0.721	-13.84 ± 0.609	-7.07 ± 0.735	-10.85 ± 0.695	4.34 ± 0.031	5.47 ± 0.061
6592	0.66 ± 0.034	2.28 ± 0.022	-11.99 ± 0.977	-13.97 ± 0.339	-8.60 ± 0.743	-11.01 ± 0.561	4.44 ± 0.031	9.19 ± 0.152
3709	0.59 ± 0.014	2.28 ± 0.228	-14.24 ± 1.131	-14.03 ± 0.677	-12.19 ± 1.691	-10.95 ± 1.001	4.74 ± 0.031	4.90 ± 0.048

Table 3. IRF analysis for Sodankylä.

Sodankylä Image ID	Range resolution [m]	Azimuth resolution [m]	Range PSLR [dB]	Azimuth PSLR [dB]	Range ISLR [dB]	Azimuth ISLR [dB]	Range Location Error [m]	Azimuth Location Error [m]
8011	1.52 ± 0.847	3.13 ± 1.637	-9.14 ± 6.738	-10.11 ± 6.105	-8.91 ± 7.705	-7.83 ± 6.788	11.13 ± 1.737	6.87 ± 0.105
8184	1.09 ± 0.006	2.24 ± 0.017	-13.54 ± 0.184	-14.43 ± 0.059	-11.04 ± 0.130	-11.52 ± 0.382	11.81 ± 0.020	6.30 ± 0.002
10573	1.10 ± 0.04	3.37 ± 1.875	-13.49 ± 1.011	-9.71 ± 8.606	-9.80 ± 1.554	-6.99 ± 7.711	13.23 ± 1.742	6.76 ± 0.103
12119	1.24 ± 0.115	2.73 ± 0.847	-11.17 ± 6.086	-6.91 ± 5.792	-6.60 ± 8.414	-2.68 ± 6.383	12.53 ± 0.023	4.19 ± 0.053

The publicly available documentation of ICEYE (RD-1 and RD-2) provides single values for the spatial resolution and the geolocation error, and the additional documentation provided to FMI gives more detailed information regarding IRF analysis done by ICEYE and the retrieved quality values in terms of e.g. spatial resolution, side lobe ratios and geolocation error (RD-3 and RD-4). The results from the Rosamond test area show somewhat better quality of the data than the results from Sodankylä, but generally the values shown in the tables above (Table 2 and Table 3) are in agreement with the values provided by ICEYE.

3.2 Equivalent Number of Looks (ENL)

For the data assessed in this report the ENL should be close to one, as multi-looking is not done in the SLC products. The ENL is typically tested for homogeneous rainforests areas. Images from the Amazon and Africa rainforests were therefore primarily used for assessing the ENL. However, due to the relatively high spatial resolution of the assessed data, it was challenging to find homogeneous enough areas, especially in the rainforest images from Africa (Gabon). The ENL was therefore checked also in other potentially homogeneous areas, such as waterbodies. ENL values closer to one were indeed found in the Doldrums test areas. Table 4, Table 5 and Table 6 show the ENL in three images over the Pacific Doldrums, three images over Gabon's rainforest and two images over the Amazon Rainforest, respectively. For each image, the ENL has been calculated over a total of four different sub-areas. The measured ENL was clearly less than the optimal value in Gabon, most likely due to relatively non-homogeneous target with respect to the spatial resolution of the data. In Amazon the values are closer to one compared to Central Africa rainforest, and also in Pacific Doldrums the ENL is very close to one.

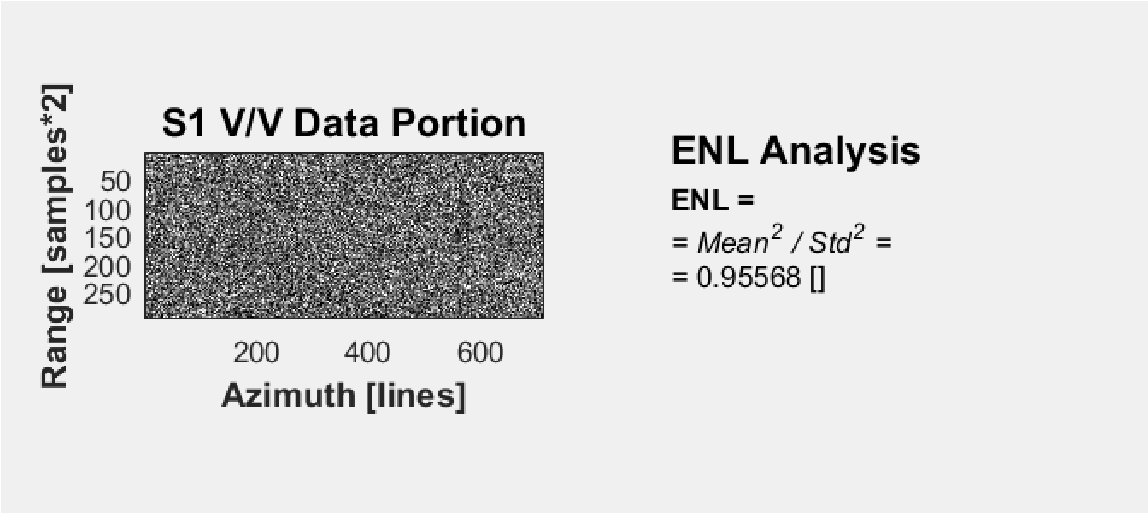

Figure 7. ENL Analysis example for Amazon Forest (image ID 2955).

Table 4. ENL for the Pacific Doldrums.

Pacific Doldrums	ENL
7869	0.996 ± 0.001
6005	0.993 ± 0.001
5638	0.997 ± 0.002

Table 5. ENL for Central Africa (Gabon) Rainforest.

Gabon Rainforest	ENL
5369	0.538 ± 0.028
6005	0.697 ± 0.014
5638	0.536 ± 0.016

Table 6. ENL for the Amazon Rainforest.

Amazon Rainforest	ENL
2995	0.941 ± 0.018
4096	0.843 ± 0.015

3.3 Noise Equivalent Sigma Zero

The analysis was performed in areas with low backscatter; Doldrums over the Atlantic and Pacific oceans and in the Loka lake in Northern Finland. The results are shown in Table 7 for the Pacific Doldrums, Table 8 for the Atlantic Doldrums and Table 9 for Loka lake. ICEYE documentation provides a single value of -17 dB for the NESZ, which is lower (better) than the observed here. An overestimation of NESZ is probably caused by the SQT due to the inclusion of all pixels in the averaging of the sub-sections of the image, rather than choosing only the low backscatter pixels in the averaging. Another possible reason for the relatively high observed NESZ is the difficulty in finding areas with very low backscatter, as the shallowest possible incidence angle offered by ICEYE is only 30 degrees. The measured NESZ is of course affected by the water surface roughness. We assume that the higher NESZ values for Loka lake are due to higher water surface roughness compared to Doldrums. An example of a radiometric profile used to calculate the NESZ for a Pacific Doldrums image is shown in Figure 10. The values in the tables are in fact the lowest calculated average values of the radiometric profiles. The main aspect of the processing is properly selecting input and output quantities. In this case the input is in Beta Nought and the output Sigma Nought. Then selecting an area from the image and the range profile is calculated.

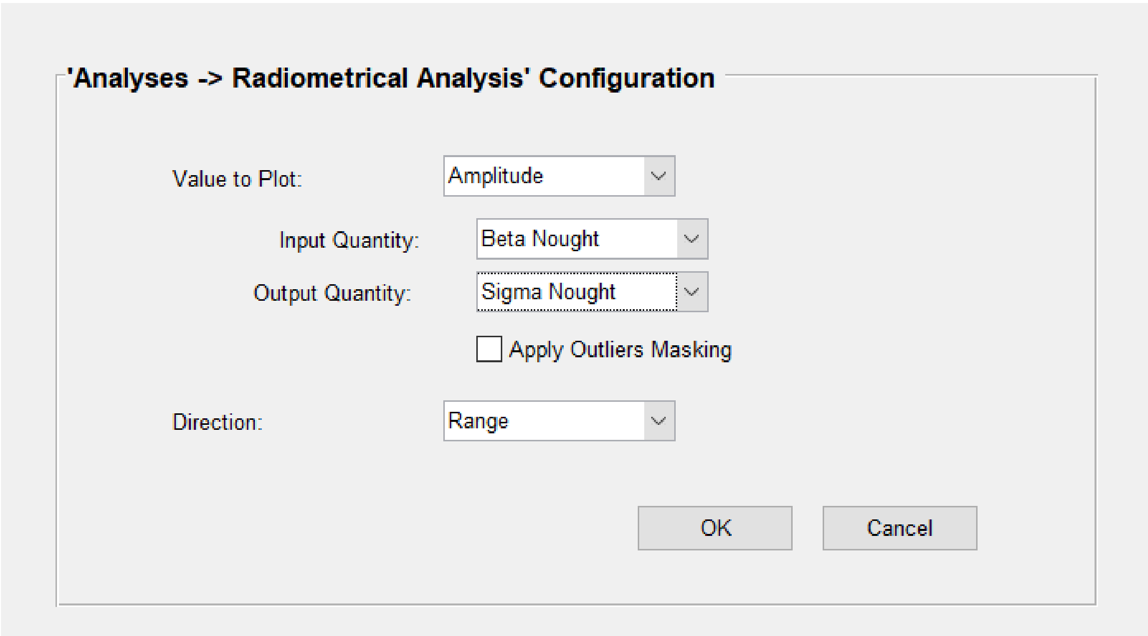

Figure 8. Radiometrical Analysis tool parameters.

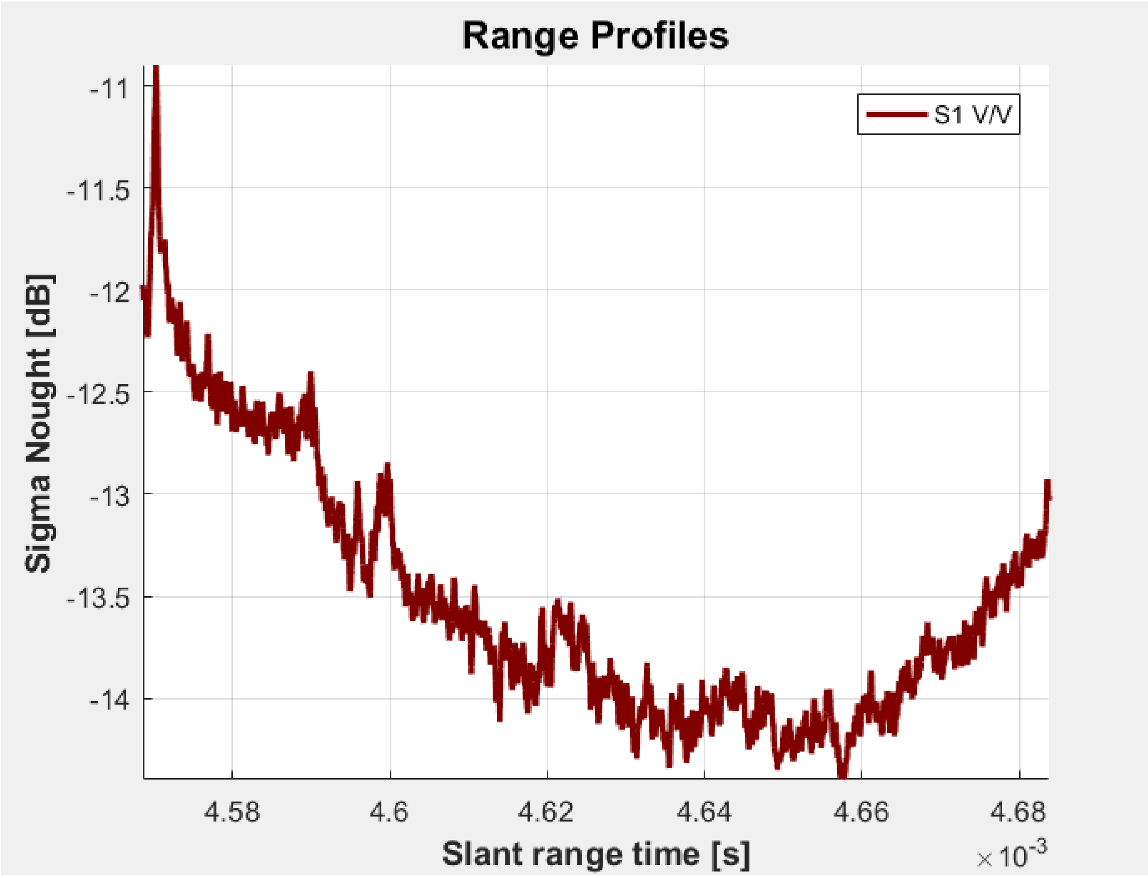

Figure 9. Range Profiles for Pacific Doldrums (Image ID: 6877).

Table 7: NESZ for Pacific Doldrums.

Pacific Doldrums	NESZ (dB)
6571	-13.3
6877	-14.4
7869	-14.5
7873	-14.4
7867	-14.6

Table 8. NESZ for Atlantic Doldrums.

Pacific Doldrums	NESZ (dB)
6378	-14.2
6379	-14.2
8018	-14.1
8019	-15.4

Table 9. NESZ for Loka Lake.

Loka Lake	NESZ (dB)
5645	-13.8
5998	-13.3
6161	-12.9
6164	-12.9

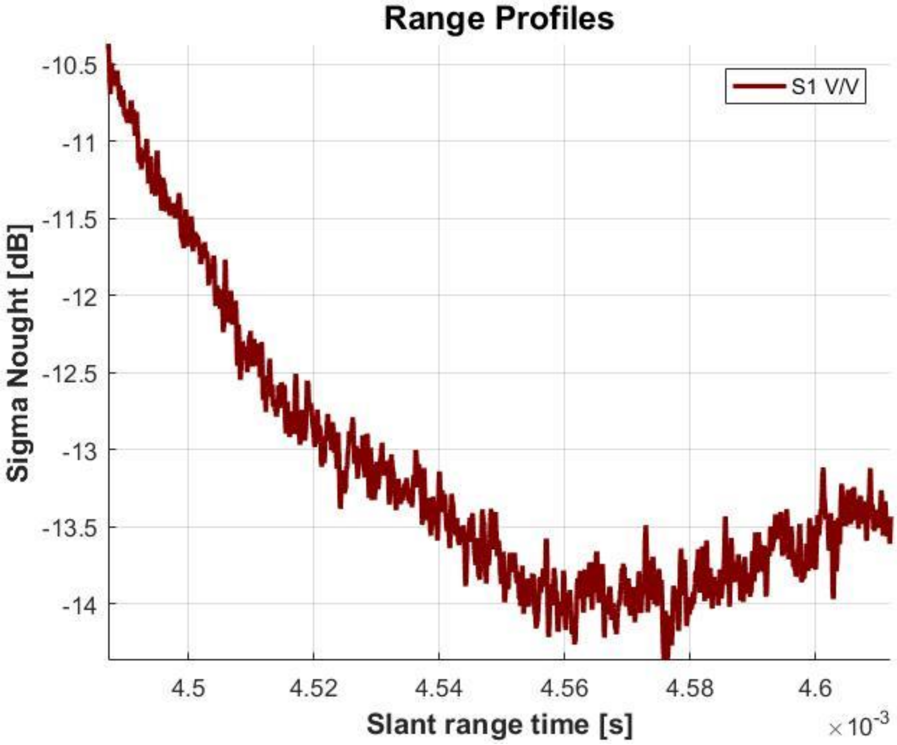

Figure 10: Example of Radiometric Analysis over the Pacific Ocean, expressed in Sigma Nought (dB). Product name: ICEYE_X2_SLC_SM_7873_20190817T235839

3.4 Data processing in SNAP

The ICEYE images were processed in SNAP version 7.0, in order to confirm the compatibility of the ICEYE data with SNAP, and to assess the SNAP plugin provided by

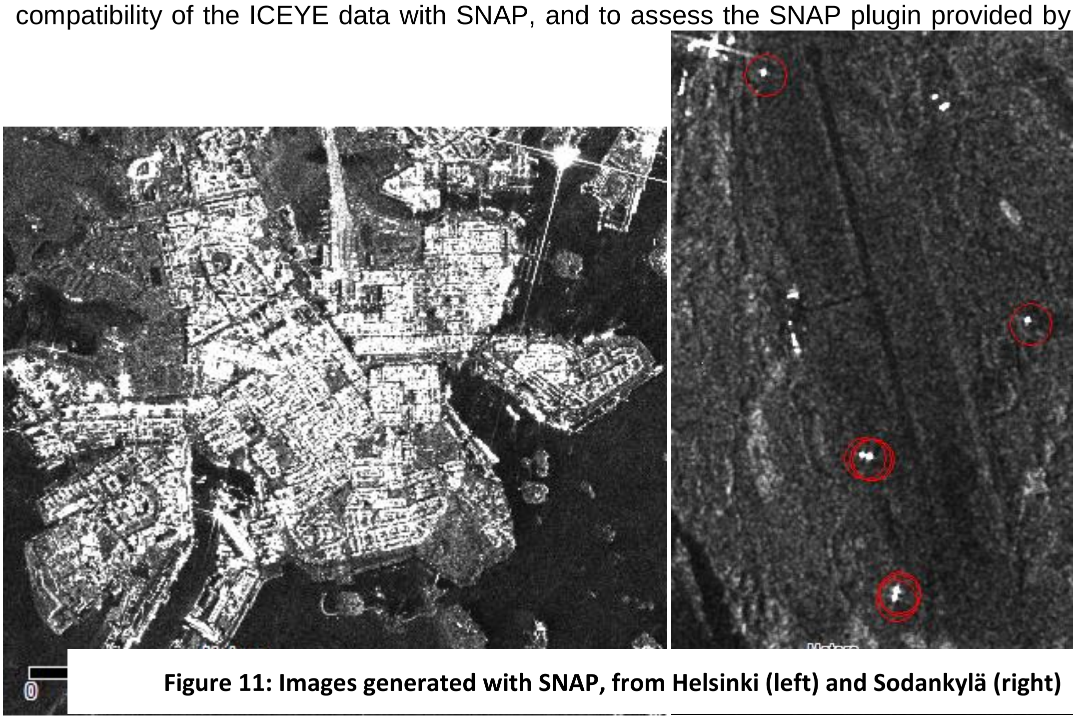

Figure 11: Images generated with SNAP, from Helsinki (left) and Sodankylä (right)

ICEYE. The processing steps included image subsetting, calibration, terrain correction and speckle filtering. The images were geocoded to UTM grid in GeoTIFF file format. A DEM of 10 m cell size acquired from the National Land Survey of Finland (NLS) was used in the terrain correction. Both the installation of the ICEYE plugin and the processing in SNAP were successful. Example images from Helsinki and Sodankylä are shown in Figure 11.

3.5 Geolocation accuracy in Helsinki

Geolocation accuracy was evaluated also in Helsinki test site, Finland. There were no corner reflectors installed in this area, so IRF analysis was not possible. Instead, georeferenced and calibrated images were produced in SNAP, as explained in section 3.4. The SAR images were compered against known reference targets on the ground. The distances between the known location of the targets and the location of the targets on the SAR images were measured manually in a GIS software. The targets included rail tracks, rivers and roads, which locations were derived from a 1:5000 scale (0.5 m resolution) map generated by NLS of Finland. It should be noted that the geolocation accuracy here is also dependent on the used DEM in the terrain correction. The geolocation error was found to be larger compared to the values of the IRF analyses and the uncertainty values provided by ICEYE (10 m). The larger error can be due to manual measurement and DEM inaccuracies. Table 10 presents the geolocation accuracy in x-axis (East-West) and y-axis (South-North) directions, the total error in 2D (Euclidian distance), RMSE and STD of the deviations. The low number of target points does not allow calculating additional geolocation error parameters, such as the circular error (CE90). Nevertheless, the purpose of the analysis performed over Helsinki was more to test the data processing in SNAP using the plugin provided by ICEYE. The more robust and meaningful geolocation accuracy assessment is done using the corner reflector test sites of Rosamond and Sodankylä.

Table 10: Observed geolocation error for the Helsinki images processed in SNAP. dx and dy refer to the error in x-axis (East-West) and y-axis (South-North). dl refers to the total distance in 2D space.

Target	20190227			20190331			20190401			20190402		
	dx	dy	dl	dx	dy	dl	dx	dy	dl	dx	dy	dl
Malmi airfield				16	7	17				-11	17	20
Pihlajisto river-tracks	-4	16	16	11	5	12	10	4	11	-5	15	16
Pohjois-Haaga tracks	-4	12	13	15	6	16	8	4	9	-8	14	16
Itakeskus metro tracks	-8	12	14	14	5	15	13	3	13	-8	11	14
RMSE	5.7	13.5	14.4	14.1	5.8	15.1	10.5	3.7	11.1	8.3	14.4	16.6
STD	1.9	1.9	1.2	1.9	0.8	1.9	2.1	0.5	1.6	2.1	2.2	2.2

4. CONCLUSIONS

An assessment of the ICEYE documentation and X2 SLC data was performed by FMI. The documentation was found to be overall in a good level. The openly available "Level 1 Product Format Specification Document" (RD-1) and "SAR Product Guide" (RD-2) provided the necessary basic information regarding the data products and properties. Documents which are not publicly available, describing the more detailed analyses performed by ICEYE, were also provided. These documents include an IRF analysis for assessing the spatial resolution, data focusing and energy distribution in space (RD-3), a geolocation accuracy analysis (RD-4), as well as the performed radiometric calibration of the sensor (RD-5). These documents provided a good theoretical background and explanation of the methods used, and they presented the results in a clear manner. There was no document addressing the metrological traceability, and some aspects of the radiometric accuracy were not fully addressed, such as the methods of calculating the NESZ and the radiometric accuracy.

An independent data analysis of reference datasets was performed by FMI using mainly the SQT software. The relevant parameters describing the SAR data quality were retrieved and compared with the corresponding values provided by ICEYE. The quality metrics were found to be in line with the values provided by ICEYE. These values include the spatial resolution, PSLR, ISLR and the geolocation accuracy. NESZ was found to be slightly higher (worse) than the value provided by ICEYE. However, this can be related to the difficulty of finding very low backscatter areas due to the relatively steep incidence angles offered (maximum 30 degrees). The retrieved ENL in rainforests was typically less than the expected value of ENL=1 in SLC data. This might be related to difficulty in finding entirely homogeneous regions in the relatively high-resolution data examined. Instead, the ENL in the Doldrums was very close to one.

Based on the assessment described in this document, the X2 ICEYE SAR data can be considered fit for purpose considering common SAR applications such as target detection, land, water and vegetation monitoring, as well as sea ice mapping. In this work we evaluated only the Stripmap mode, and therefore the capability of detecting smaller targets requiring very high spatial resolution (Spotlight mode) should be further tested. Interferometry could not be tested because of the low revisit times offered by the ICEYE constellation at the time of data procurement. The data quality regarding applications requiring interferometry such as displacement analyses and topography mapping should be assessed in the future, after the increase in the number of satellites in the ICEYE constellation, offering shorter temporal baselines.

REFERENCES

RD-1 LEVEL 1 PRODUCT FORMAT SPECIFICATION DOCUMENT, Version 1.0 Released: 05.07.2019, https://www.iceye.com/hubfs/Downloadables/ICEYE-Level-1-Product-Specs-2019.pdf

RD-2 SAR PRODUCT GUIDE, Version 2.0 Released: 14.08.2019, https://www.iceye.com/hubfs/Downloadables/ICEYE-SAR-Product-Guide-2019.pdf

RD-3 ICEYE IRF QUALITY PARAMETERS ASSESSMENT, Not public

RD-4 ICEYE SAR DATA GEOLOCATION, Not public

RD-5 ICEYE_calibration_and_validation_brochure_June_2020