

SMOS L1 Processor L1a to L1b Data Processing Model

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Document Status Log

Issue	Change description	Date	Approved		
L1PP document					
1.0	First version for CDR	2005-06-30			
1.1	Update for CDR RIDs	2005-08-31			
1.2	Update after L1PP FAT	2006-04-10			
1.3	Final release for end of Phase 2	2006-06-07			
1.4	Release after Phase 2 OSAT. Updated Equations 16, 20 and 24	2006-07-20			
2.0	Updated Sun and backlobes visibilities algorithms in foreign sources correction (Sections 3.3.1.1 and 3.3.1.4).	2006-11-17			
	Updated Applicable and Reference documents				
2.1	Updates for V2R	2006-11-24			
2.2	Updates for V3R Delivery:	2007-04-09			
	- G-matrix Polar grid discontinued;				
	- Updated Sun Self estimation strategy.				
2.3	Updates for V3.5 delivery:	2007-07-16			
	- Flat Target Transformation scaling factor;				
	- Implementation of baseline weights;				
	- Updated Sun Self estimation strategy.				
2.4	Updates for V4.0 delivery:	2007-11-26			
	- Clarified Galaxy BT computation strategy				
	- Clarified FTT generation process				
	-Corrected Eq.24 and following ones for missing w				
	- Introduced Nominal/redundant correlator layer flag in G/J matrices				
	- Clarified sun self estimation algorithm				
	- Updated Sections 5.4 and 8.				
2.5	Updates for V5R delivery:	2008-03-31			
	- Corrected Fpixel area in page 34				
	- Corrected Sun Solid Angle in page 32				
	- Corrected unit circle limit in page 20				



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Issue	Change description	Date	Approved
2.6	Updates for V6R delivery:	2008-08-05	
	- Major revision of whole document for L1PP v1.6		
	- Updated Eq. 26 and subsequent description in Section 3.3.1.1.1		
2.7	Updates for L1PP v2.0 delivery:	2009-01-12	
	- Introduced Fresnel coefficients in section 2.2.2.1.4		
	- Corrected T_HV expression in Eq. 10 (SPR 420)		
	- Corrected typo in Fig. 7		
	- Clarified rotation for extended sources computed from ground polarisation frame to instrument frame (2.2.2.1.4 and 2.2.2.1.6)		
	- Introduced geometric rotation from Galaxy B1950 polarisation frame to instrument frame in section 2.2.2.1.2		
2.8	Updated for L1PP v2.2 delivery;	2009-07-24	
	- Added latest baseline for Sunglint correction in section 2.2.2.1.6 and Annex 1		
	- Added failure and baseline weight information to J+ generation in section 2.4		
	- Added Table of Baselines to be removed in Section 2.4.2		
	- Added reference to Baselines Avoidance TN		
2.9	Update on contents;	2009-09-24	
	- Added Annex 8 with clarifications on reference frames used in SMOS/L1PP		
2.10	Updated for L1PP v3.2.1 delivery;	2009-10-28	
	- Added correct precession equations in section 2.2.2.1.2		
2.11	Updated for L1PP v3.3 delivery;	2010-03-26	
	Update on L1PP Unit Circle value		
	Correction of FTT's scaling factor on section 2.2.2.2.1		
2.12	Updated for L1PP v3.4 delivery:	2010-05-31	
	Added clarification on baseline weights for NIR-LICEF baselines in section 4.6.4		
2.13	Updated for L1PP v3.5 delivery:	2010-10-29	
	Added RFI Detection and Mitigation Algorithms		
2.14	Updated for L1PP v5.0.0 delivery:	2011-05-06	
	 Updated RFI flagging and expanded details on algorithm involved in sections 2.2.2.1.8 and 4.4.4 		
	- Updated configuration values for Foreign Sources from CNFL1P		



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Issue	Change description	Date	Approved
2.15	Updated for L1PP v5.5.0 delivery:	2011-11-29	
	- Added description for new Sun Interpolation method		
	 Added description for hexagonal G-Matrix computation and its implications at L1c 		
	- Updated outputs of RFI Histogram in RFI Detection module		
2.16	Updated for L1PP v6.0.0 delivery:	2012-11-29	
	- Added Baseline Based FTT algorithms (Section 2.2.2.2)		
	 Moved content to TGRD document (System Response Function, Flat Target Generator, G and J+ Matrices Genrator and RFI Detection Module, including clarification on Antenna Patterns to use for the G-Matrix generation) 		
	L1OP document		
2.17	Updated for L1OP v6.0.0 delivery:	2013-05-02	
	Corrected Sky Brightness Temperature computation (Section 2.2.2.1.2), the EE-CFI already outputs the matrix in the correct reference		
2.18	Updated for L1OP v6.1.0 delivery:	2013-09-10	
	Updated to reflect the usage of the Full Cross-Polar G and J+ Matrices (Sections 2.2.2, 2.2.2.1, 2.2.2.1.1, 2.2.2.1.2, 2.2.2.1.5.1, 2.2.2.2.1, 2.2.3.1, 4.1.3, 4.2.3, 4.3.3 and 4.4.3)		
2.19	Updated for L1OP v6.2.0 delivery:	2014-03-25	
	Updated the describe correct computation of Earth Visibilities in Full Pol mode (Section 2.2.3.1)		
2.20	Updated for L1OP v7.0.0 delivery:	2015-06-05	
	Adapted to the usage of the LICEF Antenna Temperature if in ALL-LICEF mode		
2.21	Updated for L1OP v7.1.0 delivery:	2016-12-02	
	Updated to include Sun estimation and removal in the Back (Section 2.2.2.1.5)		
	Updated to include RFI contamination estimation (Section 2.2.2.1.8)		
	Updated to include Gibbs 2 implementation (Sections 2.2.2.1.4 and 2.2.2.2.2)		
2.22	Updated after v7.1.1 FAT	2017-01-31	



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Issue	Change description	Date	Approved
2.23	Updated for L1OP v7.2.0 delivery:	2017-11-28	
	- Updated for Fixed Model in Gibbs 2 (Section 2.2.2.2)		
	- Updated for new Sun Estimation method (over-sampling) (Section 2.2.2.1.5.4)		
	- Updated for new RFI contamination estimation performance update (Section 2.2.2.1.8)		
	- Corrected element of area expressions to take into account the hexagonal cell shape (Section 2.2.2.1.5 and 6.2)		
<u>2.24</u>	Updated for L1OP v7.2.1 delivery:	<u>2018-05-25</u>	
	 <u>- Updated Gibbs 2 description to explain in more detail the</u> generation of the Artificial Scene (Sections 2.2.2.1.3 and 2.2.2.2.2) 		
	- Added note on the new AUX_FRSNEL ADF usage (Section 2.2.2.1.4 and 2.2.2.2.2)		
	- Added Annex with detailed code for the irregular bilinear interpolation used to compute the Artificial Scene (Section 8)		
<u>2.25</u>	Clarified Tref addition (Section 2.2)	<u>2018-07-12</u>	
	Added clarification on the setting of LICEF or NIR temperatures in the zero-baseline (Section 2.2.1).		
	Removed "experimental" remark on Gibbs2 (Section 2.2.2)		
	Added comments on the addition of artificial scene temperatures from Gibbs2 and mitigation of Sea-Ice transitions (Section 2.2.2.1)		
	Added mention that rotation angles are also included in the L1b product (Section 2.2.2.1.4)		
	Corrected comment on removal of the Sun in the back - now the individual backlobes antenna patterns are used (Section 2.2.2.1.5.2)		
	Added mention of Sea-Ice transitions (Section 2.2.2.2.)		
	Removed obsolete paragraph on the L1c implications (Section $2.2.4$)		
	Added missing input Auxiliary Files (Section 4.1.1)		
	Corrected dimensions and format of Front/Backlobes AP data (Sections 4.1.3 and 4.2.3)		
	Added reference to all Sections describing the Sun removal (Section 4.2.4)		



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1. INTRODUCTION

1.1. Purpose

The main purpose of this document is to provide a detailed definition of the processes and algorithms contained in the Foreign Sources Correction and Image Reconstruction modules.

The document begins with a general overview of algorithms to be used, its main tasks and its role in the Level 1b Processor. Following the identification of a high-level architecture, a further top-down decomposition is presented to cover the whole set of algorithms involved in the calibration process which, in turn, will be described in detail.

1.2. Scope

The scope of this document is to describe the algorithms involved in the processing of the Foreign Sources Correction Module and Image Reconstruction Module, providing both architectural and functional definitions of the main features identified.

1.3. Acronyms and Abbreviations

For the list of acronyms, please refer to the "Directory of Acronyms and abbreviations" [RD.3].

1.4. Applicable and Reference Documents

1.4.1. Applicable Documents

Ref.	Code	Title	Issue & Date
AD.1	SO-SOW-CASA-PLM-0385	Level 1 Processor Prototype Development Phase 3 and Support Activities. Statement of Work	01
AD.2	SO-RS-ESA-PLM-0003	SMOS System Requirements Document	3.0
AD.3	SO-IS-DME-L1PP-0014	SMOS L1 Processor Input Output Data Definition (obsolete)	2.3
AD.4	SMOS-TN-IDR-GS-0005	SMOS L1 and ADF Product Specification	6.<u>6</u> _(Preliminary Version) <u>25/05/18</u>
AD.5	SO-IS-DME-L1PP-0003	SMOS L1 Auxiliary Data Format Specification (obsolete)	2.4



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AD.6	SO-TN-UPC-PLM-01	IN-ORBIT CALIBRATION PLAN	3.3
AD.7	SO-TN-UPC-PLM-0019	SMOS In Orbit Calibration Plan Phase C-D	1.5 17/01/07
AD.8	ECSS-E-40B	ECSS E-40 Software Engineering Standards	
AD.9	SO-DS-DME-L1PP-0011	SMOS L1 Algorithm Theoretical Baseline	2.10 29/10/10
AD.10	SO-DS-DME-L1PP-0006	SMOS L1 System Concept	<mark>2.9</mark> 29/10/10
AD.11	SO-DS-DME-L1PP-0012	SMOS L1 Processor Prototype Architecture	1.3
AD.12	SPS-TN-GMV-PL-0003	SMOS End-to-End Performance Simulator (SEPS) Architectural and Detailed Design Document	5.0
AD.13	SO-TN-ESA-SYS-6223	FTT Algorithm Theoretical Baseline Definition	1.0 28/02/08

Table 1: Applicable Documents

1.4.2. Reference Documents

Ref.	Code/Author	Title	Issue
RD.1	SPA-CAS-20200-TNO-001	System Performance Modelling	1.2
RD.2	R. Butora, M. Martín-Neira, A.L. Rivada,	<i>"Fringe Washing Function Calibration in Aperture Synthesis Microwave Radiometry",</i> Radio Science Vol. 38 No. 2, p. 1032	2003
RD.3	SO-LI-CASA-PLM-0094	Directory of Acronyms and abbreviations	4.0 10/11/2013
RD.4	SO-DS-DME-L1OP-0007	SMOS L0 to L1a Detailed Processing Model and ATBD	2.<u>24</u> <u>12/07/18</u>
RD.5	SO-TN-DME-L1OP-0024	SMOS L1 Full Polarisation Data Processing	1.6 16/07/07
RD.6	SO-TS-HUT-NIR-0005	NIR Calibration and Characterisation Plan	05E 29/11/06
RD.7	SO-TN-YLIN-NIR-0006	SMOS Phase C/D NIR Subsystem, NIR Technical Description	05A



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RD.8	SO-TN-UPC-PLM-0020	Technical Note on the Calibration by Moon Pointing	1.1
RD.9	E. Anterrieu	<i>"A resolving matrix approach to synthetic aperture imaging radiometer"</i> , IEEE Trans. Geosc. and Remote Sensing, Vol. 42, No.8, <i>"Stabilised Reconstruction algorithm</i>	200 4
		presentation", ESTEC	
RD.10	E. Anterrieu	<i>"Hexagonal xi-eta grid"</i> , response email to DME xi-eta grid question with attached matlab code	13th May 2005
RD.11	A. Camps et al	<i>"Impact and Compensation of Diffuse Sun Scattering in 2D Aperture Synthesis Radiometers Imagery", IGARSS</i>	2005
RD.12	A. Camps et al	<i>"Sun Effects in 2-D Aperture Synthesis Radiometry Imaging and their Cancellation",</i> IEEE transactions on geoscience and remote sensing Vol. 42, No. 6	June 2004
RD.13	A. Camps et al	"The processing of hexagonally sampled signals with standard rectangular techniques: application to 2-D large aperture synthesis interferometric radiometers", IEEE Trans. geosc. and remote sensing, Vol. 35, No.1, pp. 183-190.	Jan. 1997
RD.14	A. Camps	<i>"Application of Interferometric Radiometry to Earth Observation"</i> , PhD Dissertation, Universitat Politècnica de Catalunya	November 1996
RD.15	M. Goodberlet and J. Miller	<i>"NPOESS-Sea Surface Salinity",</i> Final Report, NOAA Contract #43AANE704017	December 1997
RD.16	SMOSP3-UPC-TN-0002 v 1.0	"Sun Self-estimation Algorithm" ¹	May 2007
RD.17	SMOSP3-UPC-TN-0002 v 1.0	"Sun Self-estimation Algorithm: Simulation Results"	July 2007
RD.18	SO-DS-DME-L1OP-0009	SMOS L1b to L1c Detailed Processing Model and ATBD	2.17 28/11/2017

¹ Document available at the L1PP project webpage: <u>http://www.smos.com.pt/project_results.html</u>

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RD.19	SO-TR-DME-L1PP-0202	SMOS L1PP Baselines Avoidance Algorithm	1.1 24/07/09
RD.20	SO-TR-DME-L1PP-0241	RFI Algorithms in L1PP	1.2 26/10/11
RD.21	SO-TN-IDR-GS-0005	SMOS Level 1 and Auxiliary Data Products Specifications	5.17
RD.22	SO-TGRD-DME-L1OP-0023	SMOS L1OP ADF Set Description / Table Generation Requirements Document	3.<u>13</u> 25/05/18
RD.23	SO-TN-UPC-PLM-0167	All LICEF mode implementation	1.1 15/04/15
RD.24	SO-IOP-ECE-TN-1368	Receiver and LFE Selection for ALL-LICEF Testing	1.0 05/05/15
RD.25	SO-TN-CBAP-GS-053.1	Implementation of the GIBBS 2 correction algorithm in the SMOS L1a to L1b data processor: Definition and assessment of its stability	1.e 2016/02/02
RD.26	SM-TN-AURO-L1OP-0001	TN on the L1OP RFI Flags	2.1 27/05/2017
RD.27	CESBIO TN	ATBD for Enhanced Direct Sun correction for SMOS	1.1 06/10/2017
<u>RD.28</u>	http://ahinson.com/algorithms_general/ Sections/InterpolationRegression/Inter polationIrregularBilinear.pdf	Anthony R. Hinson, Irregular Bilinear Interpolation	<u>1.0</u>

Table 2: Reference Documents



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2. DESCRIPTION OF ALGORITHMS

The image reconstruction is the most important part of the SMOS processor. It converts Calibrated Visibilities into Brightness Temperature Fourier components (see Figure 2). These Fourier components represent the reconstructed image in the Frequency domain, and can be used to obtain the Brightness Temperature values anywhere in the spatial domain.



Figure 2-1: Context Diagram for L1a to L1b processing.

For notation clarification, we shall be addressing throughout the rest of the document the polarisations on the *G*-matrix as H and V, although it is clear that as G is the System Response of the instrument those polarisations represent the polarisations in the natural axes of the instrument (i.e. TX and TY)

2.1. High Level Description

The main functionality of the L1a to L1b Processor is to do reconstruction of the L1a Calibrated Visibilities. The main module is therefore the *Image Reconstruction Module* (including Foreign Sources Correction and Error Mitigation), which transforms the calibrated visibilities into Brightness Temperature Fourier components. The output of this transformation are the L1b products that are consolidated in the same way as the L1a, containing Brightness Temperature Fourier components arranged in a time-ordered way according to the integration time. This time ordering has the effect that a given pixel may be contained in different snapshots, depending on the incidence angle with which the image was taken. The output to be passed to the L1c shall be the Fourier components of the reconstructed BT scene.

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In addition to the main Image Reconstruction Module, two other accessory modules are also implemented in the L1OP: the *Flat Target Generator Module* (see the DFD in Figure 3) and the *RFI Detection Module*, which are described in the L1OP TGRD document [RD.22].

The Flat Target Generator Module is responsible for generating an Auxiliary Data File for use in the Flat Target Transformation module. This data file is generated from External Target data, and contains information on a flat sky target, which is used by the Image Reconstruction Module to reduce the errors due to the Antenna Patterns (see Section 2.2.2.2.1).

The RFI Detection Module is responsible for generating an auxiliary file to populate the RFI list file. It should be noted that this module is ran on L1a Science and Telemetry data and that it produces no outputs other than a binary file with the most probable coordinates of RFIs (see Section 4.7).

2.2. Image Reconstruction Module

The Image Reconstruction (IR) Module is responsible for loading the L1a data, performing the appropriate transformations on the data in order to remove unwanted sources of signal and to reduce reconstruction errors, and finally for the reconstruction of the data and product writing. These processing steps of the IR Module are organized into eight processing units (nine when in External Target mode), of which two are major ones (semi-independent sub-modules) and six minor ones (see Figure 4). For the whole L1b Processor there is an orchestrator which deals with the computational sequence, calling each unit according to the diagram in Figure 4.

The distinction between minor and major units is twofold, since the major units are where the algorithms are much more complex, but also they deserve a distinct processing approach: the major units (Foreign Sources Computation and Error Mitigation) are processed scene by scene in a loop for the total number of scenes, whereas the in the minor units all scenes are processed simultaneously. This is done to improve code optimisation, as detailed in [RD.22].

The <u>minor processing units</u> should be included in the main L1b source file, since they are not too complex:

1+2) Data Loading and Preprocessing Units: these processing units consist in the loading of the required data and conversion from the Aux and/or L1a structure to L1b format, including the calculation of the land-sea pixels in the (ξ,η) -grid, as defined in [RD.22], and other preparatory tasks. These are simple tasks, although the conversion of the Calibrated Visibilities to L1b format has some increased complexity in the full-pol case.

After these two units the processing goes into the main loop in the number of scenes, where most of the image correction computations are performed. Since these are more complex task they will be detailed separately.

The last four minor processing modules are simultaneously applied to all scenes (and are therefore outside and after the loop in Figure 4):

5) <u>*G*-matrix Multiplication</u>: here the Loop Temperature Contrast Vectors (Sky plus Land, Sea and Sun Glint) computed in the Foreign Sources Computation and Error Mitigation Modules (see below) are multiplied by the *G*-matrix to determine the corresponding Loop Transformed Visibilities. This is a computationally heavy task since the complete *G*-matrix alone is quite large (see also Section 2.2.3).

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- 6) <u>Final Subtraction of Calculated Visibilities</u>: this is the simplest activity, in which the algorithm performs the subtraction of the output of the *G*-matrix Operations unit (i.e. the Loop Transformed Visibilities) from the Calibrated Visibilities.
- 7) <u>Image Reconstruction</u>: this is the main reconstruction unit, which converts the Calibrated Visibilities into Brightness Temperatures' Fourier Components, $\hat{T}_{_B}$, by multiplying the Visibilities by the J⁺-matrix. If Ideal Reconstruction mode is selected, however, the reconstruction is performed through an FFT instead of the J⁺-matrix multiplication.
- 8) <u>Adding the Reference Temperature back</u>: adding the Reference Temperature, T_{Ref} , is only performed in the L1b Module when processing External Target data, since it is otherwise a task performed in L1c² (see Section 2.2.4). Since the L1c Module cannot be executed with data acquired in External Target mode, this task is instead performed in the L1b Module;
- 9) Writing of L1b Products.

As for the major sub-processing units or sub-modules, these are the following:

- 3) <u>Foreign Sources Correction Module</u>: this sub-module calculates and removes the unwanted contributions from the Visibilities. It determines the Sky, Direct Sun, Direct Moon, RFI and Backlobes contributions and removes them from the Calibrated Visibilities this last contribution, the Backlobes, are removed only for the zero baseline (NIRs). Although strictly part of the Error Mitigation Module³, a Sea Temperature and a "One Kelvin Land Temperature Vector" are also calculated here (see sub-section 2.2.2.1 for details). These are later on passed on to the Error Mitigation Module for the estimation of the Land temperature. Finally, auxiliary data is also passed on to the L1c processor, in particular the Sun and Moon positions and magnitudes.
- 4) Error Mitigation Module: this sub-module performs the correction of the Corbella term for the System Response Function by setting a global reference temperature⁴, and also performs the calculations needed for the Gibbs removal, namely of the Land and Sea temperature vectors. The setting of a global Reference Temperature is done by removing the contribution of a flat (i.e. constant) scene at a given temperature, T_{Ref} ,³ from the Calibrated Visibilities. This constant scene should be obtained from measured data in External Target mode (the Flat Target Auxiliary Data File), thus performing simultaneously the Flat Target Transformation. If the Flat Target Transformation is not used, an artificial constant scene is used, where the visibilities are obtained by multiplying the *G*-matrix by a constant vector of temperature T_{Rec} . For the calculation of the Land and Sea temperatures required for the Gibbs removal, actually only the Land temperature is estimated here, since the sea temperatures vector is determined in the Foreign Sources Module (see Section 2.2.2.2 for details).

Notice that the Visibilities passed on to the L1c processor are in the Fourier space.

² Since L1OP v620, T_{Ref} has been set to 0 in the configuration baseline

³ The conceptual distinction between what should be considered as part of the Foreign Sources Removal or of the Error Mitigation is, in broad terms, that the FS contributions (Sun, Moon, etc.) are not added back, whereas the quantities calculated by Error Mitigation Module (Land, Sea and Reference Temperature) are removed only to decrease the reconstruction errors, and should be re-added later on, e.g. in the L1b to L1c processor.

⁴ A Reference Temperature, T_{Ref} , is a temperature with respect to which all other temperatures are given

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Figure 2-2: Image Processing Module, including Foreign Sources Correction and Error Mitigation.



2.2.1. Zero-Baselines Visibilities Processing

A delicate point in the Image Reconstruction is of the processing of the Visibilities corresponding to the zero-baselines, or Antenna Temperatures. Since L1OP v700 that the zero-baseline temperatures can be either computed from the NIR measurements (in NIR mode), or from the LICEF Antenna Temperatures (in ALL-LICEF mode). These LICEF Antenna temperatures have to be averaged for Full Polarization scenes in exactly the same way as the L1a System Temperatures (see RD [23]). Schematically, the standard sequence of L1a scenes

- 1. HHH
- 2. HVV
- 3. VHV
- 4. HVV
- 5. VVV
- 6. VHH
- 7. HVH
- 8. VHH

will generate 4 L1b scenes (H, VH, V, HV), all with the same H zero-baseline (from L1a Epoch 1) and V zero-baseline (from L1b Epoch 5).

In addition to this averaging among scenes (using always the LICEF Ta from the previous Pure Scene), the average of the measured Antenna Temperatures by the 66 LICEFs is weighted, using only the selection of LICEFs present in [RD.24].

The zero-baselines are special baselines, which are treated differently than the other baselines. The reasons for this distinction are first that Antenna Temperatures are absolute temperatures, given with respect to the absolute zero, so there is no Corbella term, whereas for all other baselines the Corbella term is present. The second reason is that some corrections (e.g. backlobes) are only performed for the NIRs. For this reason the processing of the NIR baselines is particularised below in Figure 5. The processing segment shown is very much simplified, since only the path corresponding to the Calibrated Visibilities is shown, and other variables are hidden, but should be obvious where it fits in the global diagram of Figure 4.

<u>Please note that in all following diagrams, the NIR super/subscript means "zero-baseline" and that its temperatures can now come from the average L1a LICEF temperatures or from the NIR temperatures, as explained in the previous paragraphs.</u>

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Figure 2-3: Simplified Data Flow Diagram of the processing of the zero-baselines.

To allow for a direct comparison of the differences in processing, the Foreign Sources and Error Mitigation Modules were expanded in the next diagrams for the zero-baselines, Figure 6, and for the remaining baselines in Figure 7.

Here it is shown explicitly the transformations that the Calibrated Visibilities go through, namely:



- The Calibrated Visibilities coming from the Preprocessor⁵ are fed into the Foreign Sources (FS) module;
- In the FS Module the relevant contributions are calculated and removed. *Notice that the backlobes Visibilities are only corrected for the Zero-Baseline*. The Visibilities are then passed on to the Error Mitigation (EM) Module;
- In the EM Module the Reference Temperature is set, either through the Flat Target Transformation (FTT) or the 1K Visibilities. *Notice that the scaling factors for the Zero-Baseline is different than for the remaining baselines.* This is because the Antenna Temperatures are given wrt the absolute zero in Temperatures, 0K, whereas all other baselines are given wrt the Receivers Temperature, T_{Rec} ;
- In the EM Module the Delta Temperatures needed for the Gibbs removal are also calculated, and sent to the *G*-matrix Multiplication processing unit to be converted into Visibilities;
- Finally, the Gibbs correction is applied in the Subtraction of Visibilities processing unit, by removing the Delta Visibilities from the Calibrated Visibilities, and the output is then sent to the Reconstruction processing unit.

⁵ These are basically the output of the L1a Module, except form format changes. In fact the only difference is that the NIR components in the wrong polarisation are removed, so the Visibilities now fill a vector of size 2346 instead of 2556.

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2.2.2. Main Loop

To keep the Figure 4 from getting too convoluted, the main Loop in the number of scenes was shown as a black box. Its global behaviour is now explained (see Figure 8), and its constituent modules are further detailed in Sections 2.2.2.1 and 2.2.2.2.



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The main objective of the Main Loop is to compute "delta" visibilities from the measured L1a Calibrated visibilities.

$$V_{\rm L1B}^{\rm p}({\bf u}) = V_{\rm L1A}^{\rm p}({\bf u}) - \Delta V^{\rm p}({\bf u}) \qquad \qquad Eq. 1$$

The Delta Visibilities themselves can be summarised as follows:

$$\Delta V_{j}^{p}(\mathbf{u}) = \Delta_{FS} V_{j}^{p}(\mathbf{u}) + \Delta_{EM} V_{j}^{p}(\mathbf{u}) + \Delta' V_{j}^{p}(\mathbf{u})$$
 Eq. 2

where:

$$\Delta_{\rm FS}V_{\rm j}^{\rm p}({\bf u}) = V_{\rm Sun, j}^{\rm p}({\bf u}) + V_{\rm Moon, j}^{\rm p}({\bf u}) + V_{\rm Backlobes, j}^{\rm p}({\bf u}) + V_{\rm RFI, j}^{\rm p}({\bf u})$$
Eq. 3

are the Delta Visibilities removed in the Foreign Sources Module, consisting of the Direct Sun and Moon, the Backlobes⁶ and RFI contributions;

are the Delta Visibilities removed in the Error Mitigation Module, which is simply the removal of the Visibilities corresponding to constant scene at a reference temperature, T_{Ref} , and includes the Flat Target Transformation;

$$\Delta' V_{j}^{p}(\mathbf{u}) = V_{\text{Sky},j}^{p}(\mathbf{u}) + V_{\text{Earth},j}^{p}(\mathbf{u}) + V_{\text{SunGlint},j}^{p}(\mathbf{u}) \qquad \qquad Eq. 5$$

are the Delta Visibilities which are calculated inside the main loop as Temperatures, $\Delta T_j^q(\boldsymbol{\xi})$. The Temperatures themselves are given by the contributions of a modelled Sky and Earth⁷ and the estimated Sun Glint:

$$\Delta T_{\mathbf{k}}^{\mathbf{q}}(\boldsymbol{\xi}) = T_{\mathrm{Sky},\mathbf{k}}^{\mathbf{q}}(\boldsymbol{\xi}) + T_{\mathrm{Earth},\mathbf{k}}^{\mathbf{q}}(\boldsymbol{\xi}) + T_{\mathrm{SunGlint},\mathbf{k}}^{\mathbf{q}}(\boldsymbol{\xi}) - \delta_{\mathbf{q}}T_{\mathrm{Ref}}\mathbf{1}_{\mathbf{k}} \qquad \mathbf{Eq. 6}$$

The Delta Visibilities, $\Delta' V_j^p(\mathbf{u})$, are obtained from these temperatures through the System Response Function, or *G*-matrix (see below). Notice that $\Delta T_j^q(\boldsymbol{\xi})$ is a Temperature Contrast, since it is given with respect to a Reference Temperature.

Notation:

In the formulae above and throughout this document, the notation is the following:

u is a shorthand notation for a (u, v) baselines pair;

 $\boldsymbol{\xi}$ is a shorthand notation for a ($\boldsymbol{\xi}, \boldsymbol{\eta}$) pair;

j is the (u,v)-baselines index, also used indiscriminately as the vector index, (j_1, j_2) , for a pair of

⁶ The Backlobes are corrected only for the zero baselines.

⁷ The Earth Temperature being understood as the modelled/estimated Temperature on the Sea and the Land, which should be responsible for the correction of the Gibbs effect near the Earth/Sky border and, in Gibbs Level 2 mode, for the (yet experimental) removal of this effect in the Land/Sea border. See Section 2.2.2.2 for more details.

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antennae;

k is the index for the (ξ, η) -grid, and can also be taken as a vector index (k_1, k_2) ;

p is a polarisation vector mode, (p_1, p_2) , for the pair of antennae, (j_1, j_2) , for which the visibilities have been measured;

q is the polarisation vector mode, (q_1, q_2) , of a Temperature scene, $\Delta t_i^{\mathbf{q}}(\boldsymbol{\xi})$;

 $\delta_{\mathbf{j}} = \delta_{j1j2}$ is the Kronecker delta, which is one in dual-pol mode, i.e. if $\mathbf{q} = (H, H)$ or $\mathbf{q} = (V, V)$, and zero otherwise;

 1_k is a vector of ones.

In order to compute the contribution of the different sources, the system response function should be considered:

with

 $\zeta(\boldsymbol{\xi}) \equiv \sqrt{1 - \xi^2 - \eta^2}$ the *Obliquity Factor* and

$$\Delta t \equiv \frac{u\xi + v\eta + w\zeta(\xi)}{f_0} \text{ is the Delay Time.}$$

This may be redefined in the discrete form as:

$$V_{j}^{p} = \sum_{k} \sum_{q} F_{n,j_{1},k}^{p_{1},q_{1}} F_{n,j_{1},k}^{p_{2},q_{2}} \frac{T_{B,k}^{q}}{Z,k} \hat{\tilde{r}}_{kj} e^{-i2pf_{0}\Delta t_{j,k}} dS_{k}$$
 Eq. 8

Where $\mathbf{u} \to \mathbf{u}_{j}$, $\boldsymbol{\xi} \to \boldsymbol{\xi}_{k}$, $d\boldsymbol{\xi}d\eta \to d\mathbf{S}_{k}$ represents the area of each $(\boldsymbol{\xi}, \eta)$ "pixel" of the integration domain, and all other quantities are self explanatory.

Finally using matrix notation, the following equation is obtained:

$$V_{j} = G_{j,k}T_{k}$$
 Eq. 9

It must be stressed that the *G*-matrix required in Equation 9 must be computed over the complete unit circle, unlike the one used in the Image Reconstruction process, which is only computed in the hexagonal domain (fundamental period).

The default grid used in Equation 9 to compute the Brightness Temperature vector distribution, T_k , is a $N \times N$ hexagonal grid, defined in the (ξ, η) domain $[-1, 1] \times [-1, 1]$. In this grid, all the pixels have the same area and the pixels outside the Unit Circle are simply not considered. However, due to the fact that

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Equation 5 presents a singularity in the unit circle ($\zeta_k = 0$), the implementation of the hexagonal (ξ, η)grid must "avoid" the unit circle pixels. In order to do so, the (ξ, η) domain should be restricted to the grid pixels that verify the following condition: $\xi^2 + \eta^2 \le 0.99$ (instead of considering the domain

$$\sqrt{\xi^2 + \eta^2} \le 1 \,).$$

From L1PP v6.0.0 onwards, the expanded hexagonal grid is used, as defined as in [RD.22] with $N_T = 196$, but circumscribing the Unit-Circle as described in [RD.22]. With this hexagonal grid the "pixel"

area is computed as
$$dS_{\mathbf{k}} = dS \equiv \frac{2}{\sqrt{3}} N^2 d^2$$
.

In order to apply the foreign sources correction algorithm, the Brightness Temperatures of each of the sources identified in Eq. 6 is determined and the corresponding visibilities computed. The following paragraphs describe the approach followed for determining the Brightness Temperatures of each of the sources.

The Galaxy Map used as baseline contains measurements for HV polarisation, and these shall be used when correcting full pol visibilities. However, there are no sources for Sun or Moon temperatures in HV pol, so they shall be assumed to be zero.

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Figure 2-6: Detailed Data Flow for the loop in the number of scenes.

2.2.2.1. Foreign Sources Computation Sub-module Details

The Foreign Sources Correction Sub-module is needed to remove the influence of external sources in the reconstruction process. This module calculates the Visibilities contributions that are generated by the presence of Sun, Moon or strong Sky, as well as RFI. These Visibilities, if properly calculated and subtracted from the calibrated visibilities, should eliminate the strong unwanted sources that appear in the FOV.

This method is used in the simulator to correct direct contributions from the Sun, Moon, Sky, Receivers temperature, Antenna Backlobes and Earth background visible in the aliased zone of the Field of View.

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This means that the reconstruction process does not work on the calibrated visibilities, but on a delta value where the previously identified sources have been removed.

For the **Sun removal**, a two-step approach is required, needing as well an initial reconstruction of the uncorrected calibrated visibilities to obtain the Sun truth as measured by MIRAS. The Sun truth is obtained at the nominal Sun directions (known through S/C position and attitude).

The *direct Sun* contribution may be computed immediately once the Sun temperature is measured in this approach.

For the *Sun Glint* contribution, Sun reflection over the Oceans is modelled through several auxiliary parameters, namely the Sun BT, wind speed and direction, and Sea Surface Salinity and Sea Surface Temperature. This is particularly important on sea reflections, and has some impact as well on land. The surface roughness produces a scattering of the reflected image, lowering the BT at the centre, but affecting a wider area. The current removal strategy consists on the identification of the affected sea pixels, where the Sun energy is distributed. The BT magnitude of the Sun can be obtained from the scene itself.

In any case, any particular correction of each effect is selectable within the module, being possible to activate any, or all of them, if the processing requires it. Information on which correction has been performed shall be part of the L1b product format.

The Foreign Sources Module has the following inputs:

- HKTM L1a Data
- □ Sky Brightness Temperatures Map
- Default Sun/Moon Brightness Temperatures Maps
- □ Antenna Patterns (including backlobes)
- System Response Function (*G*-matrix) previously computed
- List of RFI Pixels

The information on the correction applied and its validity is made available to the L2 users within the L1 format. It is also possible to generate the L1c data without any correction, such that the L2 users apply any correction they deem required.

The detailed DFD for the Foreign Sources Computation Sub-module is shown in <u>Figure 2-7Figure 2-7</u>. It consists of five units:

- 1) <u>Sky Temperatures Calculation</u>: this unit calculates a Sky Temperature Map using the information from the Galaxy L-band ADF and from the PVT and quaternion.
- 2) <u>Sun and Moon Calculation and Removal</u>: Calculates the Sun and Moon Visibilities and removes them from the Calibrated Visibilities, for which requires selected *G*-matrix columns. The Sun magnitude is estimated here and, together with the Sun position, this information is shared with the next two units.
- 3) <u>Sun Glint Calculation</u>: from the Sun position and magnitude and the bi-static scattering coefficients this unit determines the Sun Glint Temperatures.



- 4) <u>Backlobes Removal</u>: using the average Backlobes' Antenna Patterns, this unit estimates the contribution to the Antenna Temperatures, which is due to the backlobes pattern of the antennae. The contribution is removed ONLY for the zero baseline and it is performed for both nominal and external target data.
- 5) <u>Earth Calculation</u>: this is a helper unit to the Error Mitigation Module, which uses the Land-sea grid information. It has two possible behaviours, depending on the Gibbs correction level applied:
 - a) For Gibbs 1 correction (removal of constant, estimated Earth) the Sea Temperatures are not removed, and the only action taken is to set the One Kelvin Land Temperatures Vector to one in the Earth (i.e. Land and Sea). This is passed on to the Error Mitigation Module for the estimation of the Earth constant Temperature;
 - b) For Gibbs 2 correction (removal of (constant or not) fixed Fresnel Modelled Sea, and estimated fixed Land), it determines the constant Fresnel Sea Temperatures Vector, which are added to the previous Temperature corrections above, and a constant One Kelvin Land Temperatures Vector, to be multiplied by the fixed Earth Temperature and provided to the Error Mitigation Module for Temperature estimation of the Land to be removed. Sea-Ice transition, or other transitions, can be managed through the Water Fraction definition which is used in the application of the Fresnel Model over sea.
- 6) <u>RFI Calculation and Removal:</u> Calculates the Visibilities corresponding to each source identified in the RFI list and removes them from the Calibrated Visibilities, using the correspondent *G*-matrix columns. The temperature of the RFI is estimated using an algorithm based on the one for the Sun Removal.

Notice that the units 1, 3 and 5 above are calculated as Temperature Vectors, and must still be multiplied by the *G*-matrix in order to be transformed into Visibilities (see Figure 4). The unit 2 corrections (Sun and Moon) are immediately calculated in Visibilities and the correction is immediately applied, and the unit 4 corrections (backlobes) are only applied to the zero-baselines and so are also applied here.

Contrary to what happens for the Error Mitigation Sub-module, whose contributions are to be re-added back in the L1c processor, the contributions calculated here are later removed (still in the L1b processor) and are not re-added back. The only exception is the Land temperature in Gibbs 1 correction level or the artificial scene in Gibbs 2 correction level, since they must also be added back at a later stage in L1c. The only exception is the Sea Temperatures in Gibbs 2 correction level, since this must be added back at a later stage in L1c.



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Figure 2-7: Foreign Sources Calculation Sub-module.

2.2.2.1.1. Compute Sky, Land and Sea pixels

This function is needed to discriminate the NxN unit circle used within Foreign Sources and separate it into Sky and Earth, as well as Land and Sea.

First it is mandatory to initialise the EE-CFI elements used in geolocation, using the same method described in DPM L1c. The function $xp_target_altitude$ from the EE-CFI shall be used to determine the Earth-Sky contour. The contour is computed over 6 angular directions then fitted through an ellipse and interpolated to the (ξ, η) grid being used.

The pixels inside the contour are considered Earth, while the remaining ones are considered Sky. As we are using an NxN hexagonal grid, the pixels outside the Unit Circle are ignored.

It should be highlighted that when computing the contour of the earth, part of the (ξ, η) pixels corresponding to the contour can actually be on the back of the instrument. For instance, the figure below presents the contour for a tilt angle of 60°:

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	Tilt=60*			



Figure 2-8: Contour of the earth computed using the xp_target_altitude CFI function

What is shown in the previous figure is that part of the earth contour ellipse that appears projected in the unit circle belongs to the back of the instrument (segment of the ellipse between "tangent point 1" and "tangent point 2", with negative elevation). Therefore, for the ellipse pixels that have negative elevation, the contour will appear on the back. That means that, in the previous figure, we will have the following pixels corresponding to the Earth on the front and on the back:

- 1. Pixels with Earth on the front: grey area + interior of the ellipse;
- 2. Pixels with Earth on the back: grey area.

This function shall be used to compute which areas of the front and back unit circle belong to Sky or Earth, thus separating the NxN grid into two exclusive pixel lists within the Unit Circle.

For those pixels within the Earth area of the unit circle, a further decomposition is possible by using the LandSea Mask ADF (AUX_LSMASK). This decomposition is performed by transforming each (ξ, η) direction into lat-lon coordinates and using the closest ISEA grid point to retrieve the Landsea mask value.

2.2.2.1.2. Sky Brightness Temperature

For computing the Sky contribution to the Visibilities, the Brightness Temperatures of the pixels corresponding to the Sky need to be computed.

Using the list of pixels corresponding to the Sky, the right ascension and declination of each of the sky pixel is computed. Since the Galaxy Map ADF contains the temperatures for Right Ascension and Declination coordinates expressed in B1950 Reference Frame, two transformations are needed before retrieving the galaxy temperatures: Antenna Frame \rightarrow J2000 \rightarrow B1950. Pseudocode for this transformation can be seen as follows:



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Compute BF to J2000 rotation matrix (identical procedure as in L1c DPM section 5.2.4 using the information from the quaternions, Best Fit Plane ADF and Mispointing ADF) For each of the pixels in the sky xi eta list Compute BF_vector as [sqrt(1-xi*xi-eta*eta), eta, xi] J2000_vector = BF_vector * BF_to_J2000 matrix Convert(Right Ascension, Declination) in J2000 to (Right Ascension, Declination) in B1950 A[0][0] 0.9999256791774783; A[0][1] = 0.0111815116959975; A[0][2] = = 0.0048590037714450 =-0.0111815116768724; A[1][1] = 0.9999374845751042; A[1][0] A[1][2] =-0.0000271704492210 =-0.0048590038154553;A[2][0] A[2][1] =-0.0000271625775175;A[2][2] = 0.9999881946023742 B1950_vector = A * J2000_corrected_vector ra 1950 = atan2(B1950 vector[1], B1950 vector[0]) dec_1950 = asin(B1950_vector[2]) Get Galaxy Temperatures From ADF using (Right Ascension, Declination) in B1950 End

Finally, using Right Ascension and Declination, the Brightness Temperatures of those pixels are determined with the help of the L-Band Galaxy Map ADF which contains the maps of the galactic emission at 1420 MHz (SM_XXXX_AUX_GALAXY<ID>).

The resulting Temperatures, obtained directly from the L-Band Galaxy Map ADF, which contains the maps of the galactic emission at 1420 MHz (SM_XXXX_AUX_GALAXY<ID>), are expressed as Stokes Parameters, and they need to be converted to brightness temperatures.

If the polarisation axes of the Galaxy Map and the MIRAS instrument were aligned, the conversion would be the following one:

$$T_{H}^{Galaxy} = \frac{I+Q}{2}$$

$$T_{V}^{Galaxy} = \frac{I-Q}{2}$$

$$T_{HV}^{Galaxy} = \frac{U}{2} + \frac{V}{2}i$$
Eq. 10

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As the polarisation frame of the Galaxy Map and the polarisation frame of the instrument are not aligned, a further rotation is needed before computing the Brightness Temperatures in the MIRAS polarisation frame.

This rotation can be expressed as $T^{MRAS} = M \cdot T^{Galaxy}$ where and M is the Muller matrix as defined in [RD.20] and T is the vector of Brightness Temperatures:

$$M = \begin{bmatrix} A^{2} & AB & AB & B^{2} \\ -AB & A^{2} & -B^{2} & AB \\ -AB & -B^{2} & A^{2} & AB \\ B^{2} & -AB & -AB & A^{2} \end{bmatrix}, \text{ with } \begin{cases} A = \cos(\psi + \phi) \\ B = \sin(\psi + \phi) \end{cases}; T = \begin{bmatrix} T_{H} \\ T_{HV} \\ T_{VH} \\ T_{V} \end{bmatrix}$$
 Eq. 11

The angle ψ is the Faraday rotation angle⁸ and the angle ϕ is the geometric rotation angle.

The algorithm described in [RD.19] and used in the L1c module to perform the Geometrical Rotation (cf. [RD.18]) has been adapted to obtain the latter variable. The key differences are:

- 9. Instead of using the topocentric frame as origin of the emission vectors, the derived algorithm uses the galactic B1950 as the source frame. The direct consequence is that the rotation matrix should now transform coordinates from the BFP to the B1950 frame.
- 10. In order to calculate the emission and Ludwig vectors, the galaxy pointing angles must be calculated. The routine used is similar as the one described in Section 5.6 of [RD.18] but with the following changes:
 - (1) the target to satellite angles⁹ correspond to the right ascension and declination (in degrees) of the observed point of the galaxy;
 - (2) the satellite to target angles are obtained in a similar way as described in [RD.18], but using the right ascension and declination in the CFI functions¹⁰, expressed in Cartesian coordinates in the Earth Fixed frame, instead of the Earth pixel coordinates.

2.2.2.1.3. Earth Brightness Temperature

The new Gibbs removal method is based on the algorithm used previously to remove the Sky contribution. Its purpose is to remove spatial gradients from the image before reconstruction and to add them back in Brightness Temperatures instead of Frequencies to avoid contamination from the Gibbs ripples.

There shall be two methods for doing this. The first one <u>(Gibbs 1)</u> will remove only the Earth-Sky gradient, by computing a constant Earth value for all pixels in the unit circle that correspond to the

⁸ Currently in L1B, the Faraday rotation value is set to 0, as it is assumed that the Ionosphere is not crossed in the path from the Galactic Background to the MIRAS instrument.

⁹ Variable satellite_to_target_topo_frame in [RD.18]. The satellite_to_target_sc_frame variable is set to zero, since it is not used in the algorithm but is a member of the pointing_angles structure.

¹⁰ Note that in xp_target_extra_main the parameter choice should be set to XP_TARGET_EXTRA_MAIN_SAT2TARG_ATTITUDE.

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Earth. The second method (Gibbs 2) will go further and remove also the Land-Sea contour by using a constant Sea or a Sea model for Sea pixels and estimate a constant Land for Land pixels.

In the end, the visibilities are computed, as for the other sources, taking into account the system response function:

$$V_{Earth}^{pq}(u,v) = G(u,v;\xi,\eta)T_{Earth}^{pq}(\xi,\eta)$$
 Eq. 12

The equation used to estimate the constant Earth or Land Brightness Temperature is given by the following expression, as described in [RD.11], such that the mean brightness temperature value of the scene to be imaged is zero:

$$T_{Land}^{pq} = \frac{T_A^{pq} - V_{Sky+Sea+Sun/Moon+Sunglint+Back}^{pq}(0,0)}{\overline{V}_{Land}^{pq}(0,0)}$$
 Eq. 13

Where $\overline{V}_{Land}^q = G^{pq}(u;\xi)T_{Land1K}^p(\xi)$ are the visibilities that would be measured considering the Earth or Land areas in the unit circle as a uniform source with BT=1Kelvin and the term T_A^p is the antenna temperature at a given polarisation, which for horizontal and vertical polarisation can be computed from the instrument output (Antenna Temperature) and for cross-polarisation contribution it is computed from the self-correlations between LICEF_NIR in H and V ports.

As can be immediately observed, the only difference in the two methods lies in which area of the unit circle is going to be used for the constant Brightness Temperature estimation. For the first method, the whole Earth is considered to be estimate and no Sea Brightness Temperature will be computed. For the second method, only the Land part will be used in the estimation, assuming that the Brightness Temperature distribution of the Sea part is constant or known through the model.

2.2.2.1.4. Sea Brightness Temperature model

The Brightness Temperatures over Sea are computed according to:

$$T_{\nu}(\theta) = \left(1 - \Gamma_{\nu}(SST, SSS, \theta)\right)SST + 0.2\left(1 - \frac{\theta}{55^{\circ}}\right)WS$$

$$T_{h}(\theta) = \left(1 - \Gamma_{h}(SST, SSS, \theta)\right)SST + 0.2\left(1 + \frac{\theta}{55^{\circ}}\right)WS$$

$$Eq. 14$$

Where:

SST – is the Sea Surface Temperature, assumed to be 15°C;

SSS – is the Sea Surface Salinity, assumed to be 35psu;

WS – is the Wind Speed, set to 0 m/s since L1OP v7.1.0, to match CESBIO implementation

 θ – is the elevation angle from pixel to S/C

The Fresnel reflections coefficients model that has been used is the Klein&Swift '77 for sea water.


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$$\Gamma_{v}(SST, SSS, \theta) = \left[\frac{\cos\theta - \sqrt{\varepsilon_{s} - \sin^{2}\theta}}{\cos\theta + \sqrt{\varepsilon_{s} - \sin^{2}\theta}}\right]^{2}$$

$$Eq. 15$$

$$\Gamma_{h}(SST, SSS, \theta) = \left[\frac{\varepsilon_{s}\cos\theta - \sqrt{\varepsilon_{s} - \sin^{2}\theta}}{\varepsilon_{s}\cos\theta + \sqrt{\varepsilon_{s} - \sin^{2}\theta}}\right]^{2}$$

With the following complex dielectric values, for the instrument operating frequency (f) 1413.5MHz:

$$\operatorname{Re}(\varepsilon_{s}) = \varepsilon_{\infty} + \frac{\varepsilon_{t} - \varepsilon_{\infty}}{1 + (\tau_{sw}f)}$$

$$\varepsilon_{t} = \varepsilon_{0} \times a_{0}; \tau_{sw} = \tau_{sw}^{0} \times b_{0}$$

$$\varepsilon_{0} = 87.174 - 1.949 \times 10^{-1} \times SST - 1.279 \times 10^{-2} \times SST^{2} + 2.491 \times 10^{-4} \times SST^{3}$$

$$a_{0} = 1 + 1.613 \times 10^{-5} \times SST \times SSS - 3.656 \times 10^{-3} \times SSS + 3.21 \times 10^{-5} \times SSS^{2} - 4.232 \times 10^{-7} \times SSS^{3}$$

$$\tau_{sw}^{0} = 1.1109 \times 10^{-10} - 3.824 \times 10^{-12} \times SST + 6.238 \times 10^{-14} \times SST^{2} - 5.096 \times 10^{-16} \times SST^{3}$$

$$b_{0} = 1 + 2.282 \times 10^{-5} \times SST \times SSS - 7.638 \times 10^{-4} \times SSS - 7.76 \times 10^{-6} \times SSS^{2} + 1.105 \times 10^{-8} \times SSS^{3}$$

And

$$Im(\varepsilon_{s}) = \frac{(\varepsilon_{t} - \varepsilon_{\infty})\tau_{sw}f}{1 + (\tau_{sw}f)^{2}} + \frac{\sigma_{t}}{2\pi f \times 8.854 \times 10^{-12}}$$

$$\sigma_{t} = \sigma_{0} \times e^{-\phi}; SST_{25} = 25^{\circ}C - SST$$

$$\sigma_{0} = 1.8252 \times 10^{-1} \times SSS - 1.4619 \times 10^{-3} \times SSS^{2} + 2.093 \times 10^{-5} \times SSS^{3} - 1.282 \times 10^{-7} \times SSS^{4} \qquad Eq. 17$$

$$\phi = 2.033 \times 10^{-2} \times SST_{25} + 1.266 \times 10^{-4} \times SST_{25}^{2} + 2.464 \times 10^{-6} \times SST_{25}^{3} - -SSS \times (1.849 \times 10^{-5} \times SST_{25} - 2.551 \times 10^{-7} \times SST_{25}^{2} + 2.551 \times 10^{-8} \times SST_{25}^{3})$$

It should be noted that these dielectric constants were computed empirically by the model authors and they define the model itself – they are not configurable values, as the SST or the wind speed.

Once the Brightness Temperatures on the ground have been computed, it is needed to rotate them to the polarisation frame of the instrument in Top of Atmosphere. This rotation is performed using only the Geometric Rotation angle, and no Faraday rotation, by means of the following relationship:

$$T_{X_{rec}} = T_{H_{ground}} \cos^{2} \theta_{Fg} + T_{V_{ground}} \sin^{2} \theta_{Fg} + T_{HV_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} + T_{VH_{ground}} \cos \theta_{Fg} \sin \theta_{Fg}$$

$$T_{Y_{rec}} = T_{H_{ground}} \sin^{2} \theta_{Fg} + T_{V_{ground}} \cos^{2} \theta_{Fg} - T_{HV_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} - T_{VH_{ground}} \cos \theta_{Fg} \sin \theta_{Fg}$$

$$T_{XY_{rec}} = -T_{H_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} + T_{V_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} + T_{HV_{ground}} \cos^{2} \theta_{Fg} - T_{VH_{ground}} \sin^{2} \theta_{Fg}$$

$$T_{YX_{rec}} = -T_{H_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} + T_{V_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} - T_{HV_{ground}} \sin^{2} \theta_{Fg}$$

$$T_{YX_{rec}} = -T_{H_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} + T_{V_{ground}} \cos \theta_{Fg} \sin \theta_{Fg} - T_{HV_{ground}} \sin^{2} \theta_{Fg} + T_{VH_{ground}} \cos^{2} \theta_{Fg}$$



Where θ_{Fg} is the Geometric Rotation angle computed as in section 3.1.4 of [RD.18]. Since L1OP v720, a static computation of the above model for a maximum Earth ellipse is provided as an Auxiliary Data File (AUX_FRSNEL) and the rotation angles are annotated in the L1b product. This avoids the implementation of the above algorithm – all Sea pixels can be set to the temperature at the location (ξ, η) as in the ADF, for every snapshot.

2.2.2.1.5. Direct Sun and Moon Visibilities

This algorithm will both compute and correct the effect of the Sun/Moon point sources in the L1a Calibrated Visibilities.

First of all, the Sun/Moon positions in the antenna frame need to be computed using the Earth Explorer CFI libraries (*xl_sun* and *xl_moon*) and the instrument attitude. Since both Sun and Moon are seen from MIRAS as point sources, their contribution will be limited to a single pixel in the (ξ,η) domain¹¹.

After determining the body (ξ,η) position in the antenna frame, the Sun/Moon Brightness Temperatures is computed. One of the three following approaches can be used for determining the Sun/Moon Temperatures:

- 1. Estimate from the L1A visibilities (only applicable to the Sun);
- 2. Read from an Auxiliary Data File if measurements are available (SM_XXXX_AUX_SUNT_<ID> / SM_XXXX_AUX_MOONT_<ID>);
- 3. Use default values 110.000K for the SUN H and V Temperature; 250K for the Moon H and V Temperatures. For HV polarisation the default values of the temperatures are currently set to 0.
- 4. Estimate the Sun from the L1a visibilities using an over-sampled grid ([RD.27])

Once the Brightness Temperatures of the Sun/Moon are computed, the corresponding visibilities may be obtained from the following equation [RD.12, Equation 17]:

$$V_{Sun/Moon,dir}^{pq}\left(u,v\right) = T_{Sun/Moon,dir}^{pq} \cdot \overline{V}_{Sun/Moon,dir}^{pq}\left(u,v\right)$$
 Eq. 19

where:

 $T_{Sun/Moon,dir}^{pq}$ - is the Sun/Moon temperature (estimated from visibilities, read from an ADF or using default values);

 $\overline{V}_{Sun/Moon,dir}^{pq}(u,v)$ - corresponds to the visibility samples (without units) that would be measured by the instrument corresponding to unitary point sources located at the positions of the direct sun/moon.

The following paragraphs explain how to compute the terms $T_{Sun/Moon,dir}^{pq}$ and $\overline{V}_{Sun/Moon,dir}^{pq}(u,v)$.

2.2.2.1.5.1. Estimation of the Sun Brightness Temperature from the Visibilities - T_{Sundir}^{pq}

¹¹ Since the sun and moon are seen as point sources, the corresponding visibilities will be computed using the exact (ξ, η) positions of the bodies instead of using the pre-defined (ξ, η) square/polar grids, which may introduce important approximation errors on the positions of the sources.

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The estimation of the Sun/Moon brightness temperatures from the visibilities may be performed following the approach described in [RD.12], i.e., if we consider negligible fringe-washing effects, $\tilde{r}_{j,k} = 1$, and similar antenna patterns, i.e. $F_{n:j}(\xi_k) = F_n(\xi_k)$, Eq. 8 reduces to something similar to a Discrete Fourier Transform¹²:

$$V_{j}^{q} = \sum_{k} \left| F_{n}\left(\xi_{k}\right) \right|^{2} \frac{T_{B}^{p}\left(\xi_{k}\right) - T_{Rec}\delta_{p}}{\zeta\left(\xi_{k}\right)} e^{-i2\pi\Delta t/f_{0}} dS_{k}$$

$$\Leftrightarrow V_{j}^{q} = DFT^{-1}\left(T_{Mod}^{p}\left(\xi_{k}\right)\right)$$

$$Eq. 20$$

where

$$T_{Mod}^{p}\left(\xi_{k}\right) \equiv \sum_{k} \left|F_{n}\left(\xi_{k}\right)\right|^{2} \frac{T_{B}^{p}\left(\xi_{k}\right) - T_{Rec}\delta_{p}}{\zeta\left(\xi_{k}\right)} dS_{k}$$
 Eq. 21

is a modified Brightness Temperature used in the computation, $F_n(\xi_k)$ corresponds to the average of the 72 existing antenna patterns measurements and $dS_k = \frac{\sqrt{3}d^2}{2}$ corresponds to the pixel area in the (u,v) domain (as described in [RD.13]).

The terms $T_{Sun,dir}^{pq}$ can then be estimated from the visibilities as described in [RD.16, Eqs. 1 to 4]:

$$T_{Sun,dir}^{pq} = \frac{T_{Raw}^{pq}}{\overline{T}_{Sun,dir}^{pq}} = \frac{F^{-1} \left(V^{pq} \left(u, v \right) - V_{Rec}^{pq} \left(u, v \right) \right)}{F^{-1} \left(\overline{V}_{Sun,dir}^{pq} \left(u, v \right) \right)}$$
 Eq. 22

Where:

 $V^{pq}(u,v)$ - corresponds to the calibrated L1a visibilities;

 T_{Raw}^{pq} - is a "raw" brightness temperature image;

 $\overline{T}_{Sun,dir}^{pq}$ - is the instrument's response for a 1 K amplitude point-source computed in the direction of the pixel corresponding to the Sun direction;

$$V_{\text{Rec}}^{pq}(u,v)$$
 - Receivers visibilities, $V_{\text{Rec}}^{pq}(u,v) = T_{\text{Rec}}V_{1K}^{pq}$

 $\overline{V}_{Sun/Moon,dir}(u,v)$ - corresponds to the visibility samples (without units) that would be measured by the instrument corresponding to unitary point sources located at the positions of the direct sun;

 $^{^{12}}$ Eq. 8 is not the exact definition of a DFT but could be re-defined as such by using a mathematical manipulation of the exponential term (see for instance Eq. 23 of [RD.13] showing a similar Inverse DFT case).

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Although not documented in [RD.16], UPC proposed an additional improvement on the sun estimation algorithm, which allowed obtaining the results presented in [RD.17]. This modification consists on the usage of some knowledge of the scene brightness temperature for improving the estimation in Eq. 22 by modifying its numerator:

$$T_{Sun,dir}^{pq} = \frac{T_{Raw}^{pq}(\xi_{Sun}, \eta_{Sun}) - T_{Scene Average}^{pq}}{\overline{T}_{Sun,dir}^{pq}(\xi_{Sun}, \eta_{Sun})} = \frac{F^{-1}(V^{pq}(u, v) - V_{Rec}^{pq}(u, v)) - T_{Scene Average}^{pq}}{F^{-1}(\overline{V}_{Sun,dir}^{pq}(u, v))}$$
 Eq. 23

Where $T_{Scene Average}^{pq}$ is computed as the average of the raw image - T_{Raw}^{pq} - in the vicinity of the Sun position (ξ_{Sun}, η_{Sun}) . After several simulations, UPC concluded that the best results are obtained when $T_{Scene Average}^{pq}$ is computed as the average over a [11×11] pixels square, centred at the Sun position - (ξ_{Sun}, η_{Sun}) .

Since L1OP v7.1.0, $T_{Sun,dir}^{HV}$ is estimated from the measurements and saved in the L1b product but not subtracted from the images.

Implementation details:

The Inverse Fourier Transforms presented in Eq. 23 are implemented using standard rectangular FFT libraries. However, as explained previously, the FFT routines cannot be applied directly to the hexagonal visibilities samples.

In order to apply rectangular FFTs, the visibilities need to be re-arranged in a $[N \times N]$ rectangular matrix. This visibilities re-arrangement processis detailed below:

first we compute the rectangular [N×N] sampling grid as explained in [RD.22] document and Eq. 22a of [RD.13]:

$$(u_{FFT}, v_{FFT}) = \left(\frac{d}{2}(k_1 + 2k_2), \frac{\sqrt{3}d}{2}k_1\right), \text{ where } k_1, k_2 \in [0; N-1];$$

2. then, for each visibility sample V(u,v), we will check which is the position (k_1,k_2) on the sampling grid that verifies the condition:

$$\left|\left(u_{FFT}\left(k_{1},k_{2}\right),v_{FFT}\left(k_{1},k_{2}\right)\right)-\left(u,v\right)\right|<\frac{d}{4};$$

3. Finally, we add to the (k_1,k_2) position of a $[N \times N]$ Visibilities matrix (initially padded with zeros), the visibility samples V(u,v) divided by the (u,v) pair redundancy:

$$V_{FFT}(k_{1},k_{2}) = V_{FFT}(k_{1},k_{2}) + \frac{V(u,v)}{N(u,v)}$$

where N(u,v) is the total number of visibility samples corresponding to the frequency (u,v).

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After the application of the previous steps for re-arranging the visibilities, the FFT routines can be used. It should be highlighted that the $T(\xi, \eta)$ matrixes obtained as output of the FFT will be sorted

according to the
$$(\xi_{FFT}, \eta_{FFT})$$
 grid defined by [RD.22]: $(xi_{FFT}, eta_{FFT}) = \left(\frac{1}{N_T d}k_1, \frac{1}{\sqrt{3}N_T d}(k_1 + 2k_2)\right)$.

It should be highlighted that the algorithm described in this section for the Sun BT estimation from the visibilities, although could theoretically be applied both to the Sun and to the Moon, only performs well for the Sun estimation. The conclusions reached by UPC are that the technique does not work directly for the Moon, due to the fact that $T_{Moon,dir}^{pq} \ll T_{Sun,dir}^{pq}$ and $T_{Moon,dir}^{pq}$ is of the order of magnitude of T_{Earth}^{pq} , being the moon confused with the Earth background. Therefore the estimate of the moon brightness temperature is set to a fixed value of 250 K. In the case of the Sun estimation in the back, the estimation is performed exactly in the same way.

2.2.2.1.5.2. Computation of the Sun/Moon visibilities corresponding to a 1K source - $\overline{V}_{Sun/Moon,dir}^{pq}$

The term $\overline{V}_{Sun/Moon,dir}^{pq}(u,v)$ from Eq. 19 can be computed using the System response function. i.e.:

$$\overline{V}_{Sun/Moon,dir;j}^{p}(u) = \iint_{\xi^{2}+\eta^{2} \leq 1} \sum_{q} \frac{F_{n,j_{1}}^{p_{1},q_{1}}(\xi)F_{n,j_{1}}^{p_{2},q_{2}}(\xi)}{\sqrt{\Omega_{1}\Omega_{2}}} \frac{1}{\zeta(\xi)}\hat{r}_{kj}(-\Delta t)e^{-j2\pi f_{0}\Delta t}d\xi d\eta \qquad Eq. 24$$

However, as described in [RD.16], a singularity problem arises when one tries to compute $V_{Sun,dir}^{pq}(u,v)$ when the Sun position is close to the unite circle $(\xi^2 + \eta^2 = 1)$, that is, when the Sun is 90° away from the boresight direction. If the Sun is considered as a point source, this problem is overcome by changing the coordinate system from the (ξ,η) director cosines to the spherical one:

$$\xi = \sin\theta \cos\phi$$

$$\eta = \sin\theta \sin\phi$$

Eq. 25

Eq. 24 will then become:

$$V_{Sun,dir}^{pq} = \frac{1}{\sqrt{\Omega_1 \Omega_2}} \int_0^{2\pi} \int_0^{\pi} T_{B,Sun}(\theta,\phi) F_{n,1}^p(\theta,\phi) F_{n,2}^{q^*}(\theta,\phi) \tilde{r}_{12} \left(-\frac{u_{12}\sin\theta\cos\phi + v_{12}\sin\theta\sin\phi + w_{12}\cos\phi}{f_0} \right) \quad \textbf{Eq.}$$

$$\exp(-j2\pi \left(u_{12}\sin\theta\cos\phi + v_{12}\sin\theta\sin\phi + w_{12}\cos\theta \right) \sin\theta \,d\theta \,d\phi \quad \textbf{26}$$

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where, for a point source Sun, we have:

$$T_{B,Sun}(\theta,\phi) = \frac{T_{B,Sun0} \Omega_{Sun}}{\sin \theta_{Sun}} \delta(\theta - \theta_{Sun}) \delta(\phi - \phi_{Sun})$$
 Eq. 27

According to [RD.16], when trying to account for the Sun's finite beamwidth, the integration of Eq. 26 becomes more difficult and an additional coordinate transformation is needed. Accounting as well for the Cross-polar Antenna Patterns, the visibilities corresponding to the Sun $(V_{Sun,dir}^{pq})$ can be expressed as follows:

$$V_{Sun,dir}^{xx} = \frac{1}{\sqrt{\Omega_{1}\Omega_{2}}} \iint_{\xi^{2}+\eta^{2}\leq 1} \frac{(R_{x,1}R_{x,2}^{*} + C_{x,1}C_{x,2}^{*}) T_{B,Sun}(\xi,\eta)}{\sqrt{1-\xi^{2}-\eta^{2}}} \tilde{r}_{12} \left(-\frac{u_{12}\xi + v_{12}\eta + w_{12}\sqrt{1-\xi^{2}-\eta^{2}}}{f_{0}} \right) e^{-j2\pi \left(u_{12}\xi + v_{12}\eta + w_{12}\sqrt{1-\xi^{2}-\eta^{2}}\right)} d\xi d\eta = \\ = \frac{\Omega_{Sun}}{\sqrt{\Omega_{1}\Omega_{2}}} T_{B,Sun}(\theta_{Sun},\phi_{Sun}) [R_{x,1}R_{x,2}^{*} + C_{x,1}C_{x,2}^{*}] \tilde{r}_{12} \left(-\frac{u_{12}\sin\theta_{Sun}\cos\phi_{Sun} + v_{12}\sin\theta_{Sun}\sin\phi_{Sun} + w_{12}\cos\phi_{Sun}}{f_{0}} \right)$$

$$exp(-j2\pi \left(u_{12}\sin\theta_{Sun}\cos\phi_{Sun} + v_{12}\sin\theta_{Sun}\sin\phi_{Sun} + w_{12}\cos\phi_{Sun}\right) \left\{ 1 + \left[j\frac{w_{12}}{2} - \frac{1}{12\pi} - \frac{\pi}{2}(u_{12}^{*} + v_{12}^{*}) \right] \Omega_{Sun} \right\}$$

$$V_{Sum,div}^{yy} = \frac{1}{\sqrt{\Omega_{1}\Omega_{2}}} \iint_{\xi^{1}+\eta^{2}\leq 1} \frac{\left(R_{y,1}R_{y,2}^{*} + C_{y,1}C_{y,2}^{*}\right) T_{B,Sum_{1}}(\xi,\eta)}{\sqrt{1-\xi^{2}-\eta^{2}}} \tilde{r}_{12} \left(-\frac{u_{12}\xi + v_{12}\eta + w_{12}\sqrt{1-\xi^{2}-\eta^{2}}}{f_{0}} \right) e^{-j2\pi \left(u_{12}\xi + v_{12}\eta + w_{12}\sqrt{1-\xi^{2}-\eta^{2}}\right)} d\xi d\eta = \\ = \frac{\Omega_{Sum}}{\sqrt{\Omega_{1}\Omega_{2}}} T_{B,Sum_{1}}(\theta_{Sum},\phi_{Sum}) [R_{y,1}R_{y,2}^{*} + C_{y,1}C_{y,2}^{*}] \tilde{r}_{12} \left(-\frac{u_{12}\sin\theta_{Sum}\cos\phi_{Sum} + v_{12}\sin\theta_{Sum}\sin\phi_{Sum} + w_{12}\cos\phi_{Sum}}{f_{0}} \right)$$

$$exp(-j2\pi \left(u_{12}\sin\theta_{Sum}\cos\phi_{Sum} + v_{12}\sin\theta_{Sum}\sin\phi_{Sum} + w_{12}\cos\phi_{Sum}\right) \left\{ 1 + \left[j\frac{w_{12}^{*}}{2} - \frac{1}{12\pi} - \frac{\pi}{2}(u_{12}^{*} + v_{12}^{*}) \right] \Omega_{Sum} \right\}$$

and



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$$V_{Son,dir}^{yx} = \frac{1}{\sqrt{\Omega_{\Omega_{2}}^{\Omega_{2}^{-}}}} \iint_{\xi^{+}\eta^{+} \leq 1} \frac{(C_{y,l}^{*}R_{x,2}^{*} + R_{y,l}C_{x,2}^{*}) T_{B,Son,}(\xi,\eta)}{\sqrt{1 - \xi^{2} - \eta^{2}}} \tilde{r}_{12} \left(-\frac{u_{12}\xi + v_{13}\eta + w_{13}\sqrt{1 - \xi^{2} - \eta^{2}}}{f_{0}} \right) e^{-j2\pi \left(u_{15}\xi + v_{17}\eta + w_{13}\sqrt{1 - \xi^{+} - \eta^{2}}\right)} d\xi d\eta = \frac{\Omega_{Son}}{\sqrt{\Omega_{1}\Omega_{2}}} T_{B,Son,}(\theta_{Son}, \phi_{Son}) [C_{y,l}R_{x,2}^{*} + R_{y,l}C_{x,2}^{*}] \tilde{r}_{12} \left(-\frac{u_{12}\sin\theta_{Son}\cos\phi_{Son} + v_{12}\sin\theta_{Son}\sin\phi_{Son} + w_{12}\cos\phi_{Son}}{f_{0}} \right) Eq. (25)$$

where

- R_{pn} and C_{pn} are respectively the co- and cross-polar antenna patterns at p-polarization corresponding to the nth antenna;

- Ω_{Sun} is the sun solid angle which is: $\Omega_{\text{Sun}} = \frac{\pi}{4} \beta_{\text{sun}}^2 = \frac{\pi}{4} (0.586)^2$;

$$-\begin{bmatrix} x^{"} \\ y^{"} \\ z^{"} \end{bmatrix} = \begin{bmatrix} \cos\theta_{Sun} & 0 & -\sin\theta_{Sun} \\ 0 & 1 & 0 \\ \sin\theta_{Sun} & 0 & \cos\theta_{Sun} \end{bmatrix} \cdot \begin{bmatrix} \cos\phi_{Sun} & \sin\phi_{Sun} & 0 \\ -\sin\phi_{Sun} & \cos\phi_{Sun} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$
 and the baselines, defined

in (x, y, z) coordinate system $(u_{12}, v_{12}, w_{12}) = (x_2 - x_1, y_2 - y_1, z_2 - z_1)/\lambda$ become:

$$u_{12}^{"} = \cos\theta_{Sun} \cos\phi_{Sun} u_{12} + \cos\theta_{Sun} \sin\phi_{Sun} v_{12} - \sin\theta_{Sun} w_{12}$$

$$v_{12}^{"} = -\sin\phi_{Sun} u_{12} + \cos\phi_{Sun} v_{12}$$

$$Eq. 31$$

$$w_{12}^{"} = \sin\theta_{Sun} \cos\phi_{Sun} u_{12} + \sin\theta_{Sun} \sin\phi_{Sun} v_{12} + \cos\theta_{Sun} w_{12}$$

Implementation details for the 4-point method, used for the Sun in the front of the instrument: The selection of a particular ($\xi - \eta$ indexes) in the *G*-matrix system response function corresponds to selecting a particular column of the matrix. However, from an implementation point of view, the term $\overline{V}_{Sun/Moon,dir}^{pq}$ cannot be computed from the System response function due to the following factors: 1. the *G*-matrix function is computed for a fixed (ξ,η) grid while the Sun/Moon appear at precise $(\xi_{S/M},\eta_{S/M})$ positions that need to be used with accuracy (grid approximation errors need to be

avoided for these point sources);

(



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- 2. The "pixel area" used in the *G*-matrix computation $\frac{2}{\sqrt{3}} (N_T d)^2$ is different from the Sun/Moon point sources area;
- 3. The Obliquity Factor, which caused the singularity close to the unit circle, disappears from the Eqs. 28 to 30 due to the usage of a different coordinate system.

On the other hand, computing "manually" Eqs. 28 to 30, implies, from an implementation/architecture point of view, loading the 72 antenna patterns Auxiliary Files and the Fringe Washing Function product before computing the $\overline{V}_{Sun/Moon.dir}^{Pq}$ term.

Therefore, in order to minimise the impact on the architecture as well as the computational overhead, the approach proposed for computing $\overline{V}_{Sun/Moon,dir}^{Pq}$ is based on the usage of the *G*-matrix (which is already loaded when processing the Foreign Sources Correction) and applying different correction factors.

Recalling the System Response Function, defined previously we have:

$$G(\mathbf{u};\boldsymbol{\xi}) = \frac{1}{\zeta(\boldsymbol{\xi})} \frac{F_{j_1}(\boldsymbol{\xi})F_{j_2}(\boldsymbol{\xi})}{\sqrt{\Omega_k\Omega_j}} \hat{r}_{kj}(-\Delta t)e^{-j2\pi f_0\Delta t}d\boldsymbol{\xi}$$

By particularising the $(\xi - \eta \text{ indexes})$ for the points in the *G*-matrix spatial grid closer to the Sun/Moon positions - $(\xi_{S/Mgrid}, \eta_{S/Mgrid})$ - we get the *G*-matrix columns corresponding respectively to the co-polar and cross-polar contributions to the visibilities of a point source located at $(\xi_{S/Mgrid}, \eta_{S/Mgrid})$: $G_R(u,v;\xi_{S/Mgrid}, \eta_{S/Mgrid})$ and $G_C(u,v;\xi_{S/Mgrid}, \eta_{S/Mgrid})$. Due to the finite gridding of the unit circle, the closest spatial grid to be selected should also fulfill the condition $\xi^2 + \eta^2 \leq 0.99$.

If we consider that the fringe washing function and the antenna patterns do not present high variations, we may assume that:

$$\frac{\hat{F}_{k}(\boldsymbol{\xi}_{S/M\,grid},\boldsymbol{\eta}_{S/M\,grid})\hat{F}_{j}^{*}(\boldsymbol{\xi}_{S/M\,grid},\boldsymbol{\eta}_{S/M\,grid})}{\sqrt{\Omega_{k}\Omega_{j}}}\hat{r}_{kj}\left(-\frac{u\boldsymbol{\xi}_{S/M\,grid}+v\boldsymbol{\eta}_{S/M\,grid}+wOF_{S/M\,grid}}{f_{0}}\right)\approx \frac{\hat{F}_{k}(\boldsymbol{\xi}_{S/M},\boldsymbol{\eta}_{S/M})\hat{F}_{j}^{*}(\boldsymbol{\xi}_{S/M},\boldsymbol{\eta}_{S/M})}{\sqrt{\Omega_{k}\Omega_{j}}}\hat{r}_{kj}\left(-\frac{u\boldsymbol{\xi}_{S/M}+v\boldsymbol{\eta}_{S/M}+wOF_{S/M}}{f_{0}}\right)$$

Where $(\xi_{S/M}, \eta_{S/M})$ and $(\xi_{S/M grid}, \eta_{S/M grid})$ correspond respectively to the exact Sun/Moon position and to the spatial sample on the *G*-matrix grid closer to the real Sun/Moon position.

Rewriting Eqs. 29 and 30, taking into account the previous considerations, we have:



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Where F_{OF} , F_{exp} and $F_{pixel area}$ are the correction factors applied to the G-matrix in order to obtain $\overline{V}_{Sun/Moon,dir}^{pq}$:

 $F_{OF} = \sqrt{1 - \xi_{S/Mgrid}^2 - \eta_{S/Mgrid}^2}$ - factor for correcting the division by the Obliquity Factor performed in

the G-matrix computation;

 $F_{\rm exp} = \frac{e^{-j2\pi \left(u_{12}\xi_{S/M} + v_{12}\eta_{S/M} + w_{12}\sqrt{1 - \xi_{S/M}^2 - \eta_{S/M}^2}\right)}}{e^{-j2\pi \left(u_{12}\xi_{S/Mgrid} + v_{12}\eta_{S/Mgrid} + w_{12}\sqrt{1 - \xi_{S/Mgrid}^2 - \eta_{S/Mgrid}^2}\right)} - \text{factor used for correcting the Sun/Moon position}$

error introduced by the exponential term in the G-matrix, when approaching the Sun/Moon position using the grid;

$$F_{pixelarea} = \frac{\Omega_{s/M} \cdot \left\{ 1 + \left[j \frac{w_{12}^{"}}{2} - \frac{1}{12\pi} - \frac{\pi}{2} \left(\left(u_{12}^{"} \right)^{2} + \left(v_{12}^{"} \right)^{2} \right) \right] \Omega_{s/M} \right\}}{\frac{2}{\sqrt{3}} (N_{T} d)^{2}} - \text{ factor for correcting the pixel area}$$

introduced in the G-matrix and for adding the area factor corresponding to the new coordinate system and to the fact that the Sun/Moon are seen as finite disks.

Following this approach, one can compute the $\overline{V}_{Sun/Moon,dir}^{pq}$ simply using the G-matrix and a priori knowledge of the Sun/Moon position when the Sun is in the front.

For the removal of the Sun in the back, the main difference is that there is no G-Matrix available for the backlobe antenna patterns and the G-column corresponding to the exact Sun position must be computed explicitly, according to Eqs. 28 to 30, using the average the backlobes antenna patterns.

2.2.2.1.5.3. Computation of visibilities corresponding to a 1K source - $\overline{V}_{Sun/Moon,dir}^{pq}$ - using 4-**Point Interpolation**

The introduction of an optional hexagonal grid in the definition of the G-matrix (as represented by Figure 2-9Figure 2-9) implied a revisit on the method to perform the Sun Self Estimation.

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		 Regula Hexag 	ar Cartesia onal Grid	an Grid ((NGMAT	NGMAT 196)	128)			
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Figure 2-9: Zoom on hexagonal and Cartesian grids for forward modelling

Due to the differences between the spacing between any two adjacent points of the rectangular grid and the hexagonal one and given the fact that the Antenna Patterns' measurements near the edges of the Unit-Circle suffer abrupt variations, the estimated BT for the Sun, as described in the Implementation Details of Section 2.2.2.1.5.2, for two adjacent points is not smooth and may be affected by the uncertainty in the APs.

To minimize these errors DEIMOS has introduced a 4-point interpolation to compute the visibilities corresponding to the 1K source. The procedure is the same as the one described in Section 2.2.2.1.5.2, but instead of using only the closest (η, ξ) index that corresponds to a given row of the G-matrix, the algorithm selects the four closest indexes to the (η_{SUN}, ξ_{SUN}) (i.e., the four closest G-matrix rows), assigning weights to apply to each of the four G-matrix rows. The weights are computed as a function of the distance between the Sun position and the position of the indexes in the grid. The selection of the four points to interpolate is done strictly for (η, ξ) pairs that fall inside the valid radius for the Sun estimation.

2.2.2.1.5.4. Estimation of the Sun Temperatures using an over-sampled grid

A further enhancement of the Sun Temperature estimation was proposed by CESBIO ([RD.27]). The underlying technique is to oversample the xi-eta domain and estimate the theoretical response of a point source in 37 points around the expected Sun position, **after** Gibbs 2 has been applied to the measured visibilities.

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Figure 2-10: Oversampling grid (blue) around the sun center location (yellow), drawn over the standard grid (black). Numbers below show the number of positions for each support size. In this example oversampling ratio is 4. The chosen number of points for the L1OP implementation is 37 (all points within a single G-matrix cell).

As is done in the standard sun correction algorithm (Section 2.2.2.1.5.2), one column of the G matrix is computed and is used to compute visibilities originating from a 1K point source at this location. These visibilities are then replicated all over the fine grid, shifting it around by multiplying them by a phase ramp

$$V_{1Kp} = V_{1K0} e^{2jp \left[\Delta x i_p u + \Delta e t a_p v\right]}$$
 Eq. 32

Since the Sun correction is now applied after Gibbs 2, the Sun temperature estimation must minimize the residual along tails. But to account for local average of the residual, it is in fact the distance between that average and tails area that is minimized. An independent temperature will be computed for each position, minimizing Gibbs 2 residual along tails, defining the tails zone as the blue zone in the following figure and the zone outside and around sun position as the green zone:



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Figure 2-11: Based on the a priori sun center position, areas are defined to constraint the estimation of sun brightness temperatures over the fine grid

An additional term is added to limit estimated sun brightness temperature exploration around the first estimate of the Sun temperature (T_0 , using the method in Section 2.2.2.1.5.2) and the total brightness temperature. This additional term is weighted down in order to leave some flexibility to the estimates.

The following system of equations has to be solved in order to the vector of temperatures for each point T_i . '*' indices refers to sun tails in the blue are and 'o' indices to the green area in the previous figure (excluding sun tails and sun spot).



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$$\begin{bmatrix} F^{-1}(V - V_{G2})_{1} - \langle F^{-1}(V - V_{G2})_{0} \rangle \\ F^{-1}(V - V_{G2})_{j} - \langle F^{-1}(V - V_{G2})_{0} \rangle \\ F^{-1}(V - V_{G2})_{n^{*}} - \langle F^{-1}(V - V_{G2})_{0} \rangle \\ \vdots \\ \frac{1}{W^{nnPOS}} \\ \vdots \\ \frac{1}{W^{nnPOS}} \\ \vdots \\ \frac{1}{W} \\ \frac{1}{W}$$

where

 $F^{-1}(V - V_{G2})$ – is the Fast Fourier Transform of the difference between the measured visibilities and the Gibbs2 synthetic visibilities (Section 2.2.2.2.2);

 $\langle F^{-1}(V - V_{G2})_{O} \rangle$ - is the Fast Fourier Transform of the difference between the measured visibilities and the Gibbs2 synthetic visibilities only for the background region (green section of Figure 2-11)

 T_0 – is the first estimate of the Sun Temperature (from Section 2.2.2.1.5.2)

W – is a weight w to be finely tuned to get the best compromise in condition number versus sensitivity. For now, it is fixed at 10^6 .

nPos – is the number of over-sampled points. In L1OP implementation this number is fixed to 37.

j – is the number of points in the tails section (blue section of Figure 2-11);

 $F^{-1}(V_{1K1})_{n^*}$ - is the Fast Fourier Transform of the synthetic visibilities only for the tail points. There will be 37 columns of $F^{-1}(V_{1Ki})_{n^*}$, corresponding to the number of oversampled points

 T_i – is the set of estimated temperatures for the 37 points

The above equation is already written in the form $b = AT_i$ and can be inverted as an over-determined linear system. And the final Sun estimated visibilities are

$$V_{Sun} = \sum_{i} V_{1ki} T_i$$
 Eq. 34

A final post-processing is applied to discard estimates affected by close RFI sources. After estimating the 37 T_i , a check is done on the outer region of the super-sampled points as shown in the next figure:

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Figure 2-12: Areas of the fine grid used in the post processing

The maximum observed in the outer row (blue area) of the fine grid must not exceed the one observed in the inner rows (green area). In such cases, the algorithm will default back to the standard procedure (Section 2.2.2.1.5.2) and output T_0 .

2.2.2.1.6. Sun Glint Brightness Temperature

For the Sun glint, Sun reflection over Oceans is modelled through several auxiliary parameters, namely the Sun BT, the incidence and scattered angles of each pixel with respect to the sun and some precomputed scattering coefficients.

The Sun Glint Effect removal is based on an algorithm proposed by N. Reul from IFREMER. According to this algorithm (see Annex), the solar energy scattered by a given surface impinging the antenna at the position (ξ, η) in the director cosine frame is represented by the radiometric temperature:



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Where:

 $\sigma_{HH}^{0}, \sigma_{VV}^{0}, \sigma_{HV}^{0}, \sigma_{VH}^{0}$ – are the bistatic scattering coefficients of the sea surface for HH, VV, HV and VH polarisations respectively;

 $\vec{n}_i = \vec{n}_i(\theta, \phi)$ – is the direction (incidence and azimuth angles) of Sun radiations at the earth surface position (ϕ, ψ) corresponding to the MIRAS coordinates (ξ, η) at time t;

 $\vec{n}_s = \vec{n}_s(\theta_s, \phi_s)$ – is the direction (incidence and azimuth angles) of the scattered Sun glint signals;

 θ – is the scattering elevation angle¹³;

 $\beta_{sun/2} \approx 0.0293^{\circ}$ – is the angular radius of the Sun as viewed from the Earth;

 $T_{Sun}(\vec{n}_i, t)$ – is the brightness temperature of the Sun at 1.4GHz in the direction \vec{n}_i and time t.

Equations 27 and 28 can be further simplified by considering that within the solid angle subtended by the Sun as seen from any of the observed terrestrial targets, the local Sun direction \vec{n}_i is almost constant:

$$T_{Bsunglint}^{pq}\left(\xi,\eta,t\right) = \frac{T_{Sun}\left(\vec{n}_{i},t\right)\Omega_{sun}}{4\pi\cos\theta} \left[\sigma_{pp}^{0}\left(\vec{n}_{s},\vec{n}_{i}\right) + \sigma_{pq}^{0}\left(\vec{n}_{s},\vec{n}_{i}\right)\right]$$
 Eq. 37

where Ω_{sum} (steradian) is the solid angle intercepting the Sun as seen from the earth:

$$\Omega_{sun} = 2\pi \left[1 - \cos \left(\frac{\beta_{sun}}{2} \right) \right] \cong 8.2 \times 10^{-5} \, [sr]$$
 Eq. 38

In order to determine the bistatic scattering coefficients the following sea surface parameters at the target $T = (\varphi, \psi, t)$ need to be known:

- □ The sea surface salinity (SSS);
- \Box The sea surface temperature (SST);

¹³ Since the incidence and scattering elevation angles may be different (depending on the pixel), θ is computed as the average between incident and scattered angle: $\theta = \frac{\theta_i + \theta_s}{2}$.

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D The 10 meter height wind speed and direction (U_{10}, φ_u) .

As demonstrated in [RD.11], the effect of the Sun BT is dominant in the modelling of the Sun glint, and using averaged values for the other variables does not introduce relevant errors. These averaged values are SSS = 35 [psu], SST = 15 [°C] and $U_{10} = 7[m/s]$, Usage of this model is considered as the baseline for computing the Reflected Sun contribution to be subtracted to the visibilities.

Previous studies show that due to the small sensitivity of the computed Sun glint temperature $T_{Bsunglint}^{pq}(\xi,\eta,t)$ to the variations of SSS, SST and wind speed and direction, one can assume the

following globally averaged mean values: SSS = 35 [psu], SST = 15 [°C], $U_{10} = 7 [m/s]$, $\varphi_u = \text{TBD}$.

The approach proposed by N. Reul is to determine the bistatic scattering coefficients from Look-Up-Tables (LUT) based on the following parameters:

- □ Sun incidence angle θ_i [deg];
- □ Relative azimuth angle between Sun and MIRAS observation angle $-\phi_i \phi_s$ [deg];
- □ MIRAS observation incidence angle $-\theta_s$ [deg];
- **D** The 10 meter height wind speed and direction (U_{10}, φ_u) .
- □ The LUT currently being used contains information only for $U_{10} = 7 [m/s]$.
- □ This algorithm receives as input the Sun Brightness Temperature computed in Section 2.2.2.1.5.1 and the pixels corresponding to the Earth and determines, for the (ξ, η) pixels corresponding to the ocean the following parameters:
- □ Sun (to pixel) incidence direction (θ_i, ϕ_i) ;
- □ Pixel to MIRAS observation angles (θ_s, ϕ_s) ;
- □ These parameters, computed using EE CFI Pointing library allow to compute the three parameters needed for retrieving the scattering coefficients: θ_i , $\phi_i \phi_s$, θ_s . These three parameters are used to interpolate the LUT and obtain the scattering coefficients for each of the pixels.
- □ Applying Eq. 34 $T_{Bsunglint}^{pq}(\xi,\eta)$ is computed for each (ξ,η) corresponding to the ocean. The (ξ,η) positions of the vector that do not correspond to the ocean are set to zero.
- □ Finally, the obtained Brightness Temperatures are set in Ground polarisation frame and must be rotated to the Instrument frame, using the same rotation as explained before for the Sea model Brightness temperatures (section 2.2.2.1.4)

For the operational baseline regarding Sunglint removal, the following considerations have to be taken into account:

□ The value of the Sun Brightness Temperature estimated as in section 2.2.2.1.5.1 may not be the best one to remove reflected Sun effects, so the value of the Sun BT used in the sunglint removal algorithm shall be configurable (i.e. self-estimated, read from ADF or default)

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- □ Due to a minor problem in the EE-CFI when computing the pixel to Sun illumination conditions, it is recommended to use a geodetic altitude for all pixels slightly above the reference ellipsoid (i.e. 0.001m), otherwise the CFI may return that a given pixel is not illuminated if the altitude is below the ellipsoid.
- □ When computing the list of pixels affected by sunglint, the LUT does not provide reliable scattering coefficients below 15° Sun illumination angle. Thus, all pixels having a Sun illumination angle of less than 15° shall be assumed to have no sunglint contamination (i.e. no correction is required)
- □ Due to negative scattering coefficients appearing after spline interpolation of the LUT, the recommended method to derive the scattering coefficients shall be a simple tri-linear interpolation between the closest applicable angles.
- □ Finally, during the Commissioning Phase, the correction derived from the Sunglint correction introduced more error than the L2 required and has been deactivated until further notice.

2.2.2.1.7. Backlobes Visibilities

The Brightness Temperature distribution entering through the backlobes has an effect that is highly dependent on the level of the backlobes radiating patterns (which are very low). As it has been shown during the IVT campaigns that the level of these backlobes pattern is very close to the noise level with which they were measured, the measurements themselves are not very reliable.

It is then assumed that the Backlobe correction performed in L1b will only be a first order correction over the Zero-baselines.

In order to compute the Backlobes visibilities an Auxiliary Data File, which represents the average of the 72 antennas patterns for the backlobes shall be used. As we only compute the Zero-baselines, there are no fringe-washing effects ($\tilde{r}_{kj}(i, j, k, l) = 1$) and the backlobes visibilities can be computed using an equation similar to Eq. 20:

$$V_{Back}^{pq}(0,0) = \sum_{i} \sum_{j} \left| \overline{F}_{Back}\left(\xi_{i,j},\eta_{i,j}\right) \right|^{2} \frac{T_{Back}^{pq}\left(\xi_{i,j},\eta_{i,j}\right)}{OF(\xi_{i,j},\eta_{i,j})} dS_{i,j}$$
 Eq. 39

Where:

$$T_{Back}^{pq}\left(\xi,\eta\right) = T_{Sun/Moon\ dir}\left(\xi_{S/M},\eta_{S/M}\right) + T_{Sky}^{pq}\left(\xi_{Sky},\eta_{Sky}\right) + T_{Earth}^{pq}\left(\xi_{Earth},\eta_{Earth}\right) \qquad Eq.\ 40$$

represents the addition of the different sources that appear on the back of the instrument.

In order to compute the backlobes temperature, the pixels corresponding to the Earth and Sky in the back of the instrument are determined. For these pixels, T_{Sky}^{pq} and T_{Earth}^{pq} are set to default values: 2.7K and 290K respectively¹⁴. The term $T_{Sun/Moon dir}^{pq}$ is only used if the Sun/Moon appear on the back of the

¹⁴ Taking into account the fact that the backlobes contribution is very small, it was preferred to use default values for the Earth and Sky contribution instead of computing the exact Sky BT for each pixel. This allows having a better algorithm performance without penalising in a significant way the precision of the Backlobes BT computation.

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instrument (otherwise it is set to zero). However, as described in Section 2.2.2.1.5 the Moon brightness temperatures are not estimated when the Moon appears on the back. Therefore, for the pixels corresponding to the Moon, $T_{Moon \, dir}^{pq}$ shall be set to the latest estimation of the Moon temperatures. If no estimation was performed previously, default values read from Auxiliary Data Files shall be used.

2.2.2.1.8. RFI Contamination Levels flagging

Since L1OP v710, a new algorithm was implemented to flag the estimated contaminated pixels by the known RFI sources, according to their estimated temperature in each snapshot (as proposed in [RD.26]. This algorithm has been further optimised in L1OP v7.2.0 and most of the computations were moved to the L1c processing module.

In L1b, only the synthetic RFI system response is computed in temperature frequencies as follows:

$$V_{RFI_o} = G * T_{RFI_0}$$

$$\widehat{T_{RFI}} = \frac{J * BW * V_{RFI_0}}{\max \left(real(IFFT(J * BW * V_{RFI_0})) \right)}$$
Eq. 41

Where

- G is the co-polar G matrix
- T_{RFIo} is a vector of the ξ/η unit circle grid, with all zeros and a one in the position $\xi=\eta=0$
- J is the co-polar J matrix,
- BW is a diagonal matrix that has the Baseline Weights in its diagonal.

and passed on to the L1c processing module for the rest of the computation.

2.2.2.2. Error Mitigation Sub-module

In <u>Figure 2-13Figure 2-13</u> the DFD for the detailed Error Mitigation sub-module is shown. It consists of two smaller independent units:

- 1) <u>Removal of Flat Target Visibilities</u>: here the Flat Target Visibilities, $V_{\text{Sky},j}(u)$, (obtained by the instrument while in External Target Mode) are loaded from the FTT ADF and subtracted from incoming Calibrated Visibilities ($V'_{j}(u) = V_{j}(u) V_{\text{Sky},j}(u)$). The Flat Target Scaling Factor, *sFactor*, is also calculated and passed on to the L1c.
- 2) <u>Gibbs Calculation</u>: this unit is responsible for estimating the Land Temperature, T_{Land} , corresponding to the list of pixels that belong to the Earth or Land area in the unit circle (depending on the Gibbs level applied). The output is then a Temperatures Vector, $T_{Land}+T_{Sea}$, with values T_{Land} for the pixels that fall on land and T_{Sea} on the sea pixels. In the case of Gibbs 1, the estimated Land Temperature, T_{Land} , is passed on to the L1c processor such that the constant land can be re-added there. In case of Gibbs 2, the full image frequencies are passed to L1c, for addition to the reconstructed BTs. Notice

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that, contrary to what happens in the Flat Target unit above, the Land and Sea contribution is not removed from the Calibrated Visibilities at this point, but only at a later stage (see Figure 2-2Figure 2-2).



Figure 2-13: Error Mitigation sub-module.

2.2.2.1. Removal of the Reference Temperature Contribution and the Flat Target Transformation

The first step in the Error Mitigation module is to set a global Reference Temperature for the Visibilities. This is especially important since the Zero-baselines are given as absolute temperatures, i.e. with respect to the absolute zero, but all other baselines are given with respect to the receivers temperature, T_{Rec} . The general form of this correction term is



$$\Delta V_{EM,(nir)}^{q}(0) = \delta_{q} T_{A}^{nir} V_{1K,(nir)}^{q}(0), \text{ for the NIR}$$

$$\Delta V_{EM,j}^{q}(u) = \delta_{q} \left(T_{A}^{kj} - T_{Rec}^{kj} \right) V_{1K,j}^{q}(u), \text{ for the all other baselines}$$
Eq.42

If no Flat Target is used, the L1OP determines the 1K Visibilities by multiplying a 1K vector by the *G*-matrix, however, the default algorithm is to perform simultaneously a Flat Target Transformation to reduce the errors in the antenna patterns. In this case the term that sets the Reference Temperature to T_{Ref} is:

$$\Delta V_{EM,(nir)}^{q}(0) = \delta_{q} T_{A}^{\text{NR}}, \text{ for the NIR}$$

$$\Delta V_{EM,j}^{q}(u) = \delta_{q} \frac{T_{A}^{kj} - T_{Rec}^{kj}}{T_{Ref}' - T_{Rec}'^{kj}} V_{FTT,j}^{q}(u), \text{ for the all other baselines}$$
Eq. 43

where:

 $V_{FTT,j}(\mathbf{u})$ is the measurement of a set of FTT calibrated visibilities, obtained while the instrument is pointing to the deep sky;

 $T_{\rm A}^{\ \ kj}$ is the average Antenna Temperature for the two receivers that build the baseline. It is computed according to the Reference Temperature¹⁵ configuration flag;

 T_{Rec}^{kj} is the average of the physical temperature of the two receivers that build up the baseline;

 T'_{Ref} is the average Brightness Temperature of the Unit Circle being observed by the instrument during the acquisition of the Flat Target visibilities;

 T'_{Rec}^{kj} is the average of the physical temperature of the two receivers that build up the baseline during the acquisition of $V^q_{FTT,j}(u;T'_{Ref}-T'_{Rec})$;

The equation above is valid for all baselines except for the Zero-baselines, which are not affected by the Corbella term. It should be noted that this correction has the effect of changing the offset of the Brightness Temperature scene that shall be reconstructed to T_{Rec} . This means, that a correction to the final BT Fourier components is required, by simply adding this averaged term to the L1b output. As opposed to the previous implementation of the FTT, no further corrections are required to the Brightness Temperature output (e.g. no adding back of FTT Sky or 1K visibilities).

For HV baselines the physical temperatures used to compute the scaling factor will be taken from the average between H and V physical temperatures.

2.2.2.2.2. Gibbs 2 Algorithm

 $T_{\text{Ref}}^{\mathbf{p}} = \delta_{\mathbf{p}} \delta_{\mathbf{pq}} \langle V_{\text{NIR}}^{\mathbf{q}} \rangle$; 2, for the average of the Antenna Temperatures in both polarisations $T_{\text{Ref}} = \frac{\langle V_{\text{NIR}}^{H} + V_{\text{NIR}}^{V} \rangle}{2}$. Since L1OP v6.0.0, the reference temperature is set to 0, as recommended by UPC.

¹⁵ The choice of the Reference Temperature used in the L1PP is configurable by a "Reference Temperature flag". The allowed possibilities are 0, for zero Kelvin, $T_{\text{Ref}} = 0$; 1, for the average of the Antenna temperatures in each pol,

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Since L1OP v7.1.0, the Gibbs 2 algorithm is supported. This algorithm subtracts an estimated base image to the measurements, with the Sea modelled by a fixed Fresnel model and a fixed Land temperature and the Land temperature estimated from the average measurement temperature and It was implemented based on the description in [RD.25], and using the methods described in Sections 2.2.2.1.3 and 2.2.2.1.4.

For the temperature over the ocean F_{O} , we use a Fresnel model close to the one used in the operational Level 2 Ocean Salinity Retrieval algorithm described in Section 2.2.2.1.4. As mentioned at the end of that section, L1OP now uses a pre-computed static scene for the whole orbit, covering all possible pixels inside the Earth ellipses along the orbit. After several tests, it has been decided that the constant temperature over Land can be fixed to 250K.

In this approach, <u>f</u>For each snapshot, <u>we suppose that</u> the corresponding <u>Artificial Scene</u> in the unit circle has one constant t_L over the Land pixels and a constant Fresnel model distribution F_O over the Ocean pixels, <u>with a smoothing over the coastlines</u>. The <u>coastline-smoothed</u> artificial scene <u>temperatures</u>, T_L in the unit circle can be written as:

$$T = t_L \times (200 - \text{WaterFraction})/200 + F_O \times (\text{WaterFraction}/200)$$
 Eq. 44

-where WaterFraction is loaded from the Land-Sea Mask ADF and can have any value between 0 (pure Land) and 200 (pure Sea).—<u>Sea-Ice transitions can also be included in the definition of the Water Fraction and handled transparently by this algorithm.</u>

To find the appropriate Water Fraction values (which are defined in the DGG grid) to be used for the temperature computation for each pixel of the Artificial Scene, several steps have to be taken:

- 1. The position of the Earth limb is determined and the Sky pixels (outside the Earth disc) are set with T=0
- <u>2. The (ξ, η) pixels inside the Earth disc are geolocated in the DGG</u>
- 3. For each of the geolocated pixels, their 4 closest neighbours in the Land-Sea Mask are found (using an Euclidian distance)
 - a. If 4 neighbours are found, the Water Fraction is bilinearly interpolated to the pixel position, according to the method described in Annex 4 (Section 8).
 - b. If 4 neighbours are not found (which will happen for pixels at high/low latitudes, near the earth limb or near the edges of the unit circle), the nearest neighbour Water Fraction value is assigned

A further smoothing is applied after Eq. 44 for pixels near the limb or near to edges of the unit circle, to mitigate strong artefacts produced by eventual mis-assignements:

$$\frac{T = T \times (90 - elevation_angle)/(90-88)}{T = T \times (1 - radius)/(1-0.99)}$$
Eq. 45

where *radius* is the radius defined by the pixel (ξ, η) position and *elevation_angle* is obtained during the geolocation of each particular point.

The artificial visibilities are obtained by multiplying the <u>estimated Land and SeaArtificial Scene</u> temperatures by the G-Matrix and are then subtracted from the measured visibilities. The artificial scene frequencies are passed to L1c, to be added back to the geolocalised BTs.



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2.2.3. Processing Strategy

In the computation of the visibilities of the different sources, it should be remarked that considerable amounts of data are loaded into memory and handled (*G*-matrix, Calibrated Visibilities Data sets, Auxiliary Data Files, Data accessed from the cache, etc.). Therefore, it is important to optimise the processing and establish some trade-offs between processing time and precision of the results.

2.2.3.1. <u>G-matrix</u>

Starting from L1OP v6.1.0, the full G-Matrix is loaded into memory, to take into account all cross-polar contributions to all polarizations:

$$G = \begin{bmatrix} G_{T_{HH}}^{HH} & G_{T_{VV}}^{HH} & G_{T_{HV}}^{HH} \\ G_{T_{HH}}^{VV} & G_{T_{VV}}^{VV} & G_{T_{HV}}^{VV} \\ G_{T_{HH}}^{HV} & G_{T_{VV}}^{HV} & G_{T_{HV}}^{HV} \end{bmatrix}$$

This means that all delta visibilities vectors are defined as (HH+VV+HV). In particular, the Earth estimated visibilities for the Gibbs algorithm, have now a T3 and T4 component and it must be computed by multiplying the Full Pol block by both T_{Earth}^{HH} and T_{Earth}^{VV} :

$$V_{Earth}^{HV}(u,v) = G_{T_{HH}}^{HV}T_{Earth}^{HH}(\xi,\eta) + G_{T_{VV}}^{HV}T_{Earth}^{VV}(\xi,\eta) \qquad Eq. \ \underline{46}$$

2.2.4. L1c Implications

In <u>Figure 2-14Figure 2-14</u> the DFD for the restructured L1c, including the changes induced by the L1b restructuring, is shown. If the Gibbs correction is applied, in the case of Gibbs level 2, i.e., the Land and Sea separately, then this implies that it has to be re-added back in L1c using the same LandSea mask, so that the borderlines coincide in the two steps (removal and re-addition).



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Figure 2-14: L1c DFD

The usage of the new hexagonally expanded G-matrix as the instrument forward model introduces a small drawback in the computation performance of the Land and Sea temperatures that will be added back in L1c. The different sizes in the resolution of the (ξ, η) grids (128 to 196) makes it impossible to use the FFT algorithm to go back and forward between the spatial and frequency domains, forcing LAPACK to use the DFT algorithm, thus increasing the processing time per scene.

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An initial estimate indicates that there is an increase from ~2000 to ~6000 seconds in the generation of a half orbit of L1e Science Products in Full pol mode.



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3. L1B PROCESSING HIGH LEVEL DESCRIPTION

3.1. Image Reconstruction Data Flow

The following figure shows the image reconstruction module data flow. It shows the input data, the internal modules dependency and the output data.



Figure 3-1: L1b Data Flow

In the previous figure it is represented the processing flow of the Image Reconstruction Module.



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4. DETAILED PROCESSING MODEL

4.1. Input Data Reader and Preprocessor

The first units to be performed for the Image Reconstruction in the L1b Module are the Input Data Reader, which loads all relevant files into memory, and the Preprocessor, which converts the file data into appropriate L1b format.

The following steps are performed by the L1b data reader and the preprocessor:

- □ Read all input data;
- □ Convert all data into L1b format.

4.1.1. Inputs

□ L1a Calibrated Visibilities

- Science Data, Dual Polarisation (SM_xxxx_MIR_SC_D1A_<ID>)
- Science Data, Full Polarisation (SM_xxxx_MIR_SC_F1A_<ID>)
- External Target Data, Dual Polarisation (SM_xxxx_MIR_TARD1A_<ID>)
- External Target Data, Full Polarisation (SM_xxxx_MIR_TARF1A_<ID>)
- □ L1aHKTM File containing the S/C position, attitude, receivers physical temperature, NIR temperatures and Antenna Temperatures (SM xxxx TLM MIRA1A <ID>)
- □ Auxiliary data files:
 - FTT Target Transformation Measurements (SM_xxxx_AUX_FTTx_<ID>)
 - Average Antenna Patterns (SM_xxxx_AUX_PATT<ID>)
 - *G*-matrix auxiliary file (SM_xxxx_AUX_GMAT__<ID>)
 - Inverted J Matrix auxiliary file (SM_xxxx_AUX_JMAT_<ID>)
 - Galaxy Map (SM_xxxx_AUX_GALAXY<ID>)
 - Sun Brightness Temperatures (SM_xxxx_AUX_SUNT_<ID>)
 - Moon Brightness Temperatures (SM_xxxx_AUX_MOONT_<ID>)
 - FTT Target Transformation Measurements (SM_xxxx_AUX_FLATT_<ID>)
 - Discrete Global Grid (SM xxxx AUX DGG <ID>)
 - Land/Sea Mask (SM_xxxx_AUX_LSMASK_<ID>)
 - Baseline Weights (SM_xxxx_AUX_BWGHT_<ID>)
 - •___Bistatic Scattering Coefficients (SM_xxxx_AUX_BSCAT_<ID>)
 - Fresnel Model over the Earth ellipse (SM xxxx AUX FRSNEL <ID>)



- Payload Carachterization Parameters (SM_xxxx_AUX_PLM_<ID>)
- Fringe Wash Function coefficients (SM xxxx AFWD1A <ID>)
- Best Fit Plane (SM_xxxx_AUX_BFP_<ID>)
- Bulletin B for the appropriate orbit (SM_xxxx_AUX_BULL_B_<ID>)
- RFI Source List (SM_xxxx_AUX_RFILST_<ID>)
- Element failure list (SM_xxxx_AUX_FAIL_<ID>)

4.1.2. Outputs

□ All data above in L1b format.

4.1.3. List of Variables

The following table describes the variables used in the subsequent implementation section. Variables are listed as input, local and output (I, L, O). The *Size* column indicates the number of elements constituting that variable, and NOT the size of the variable in bytes (this information can be taken from the *Type* column). Whenever the size of a variable differs between Dual- and Full-pol processing modes, both values are shown with (D) or (F) in brackets after the corresponding value.

Variable name	Description	Definition	Туре	Class	Unit	Size
lla_filename	L1a Filename	N/A	Char	Ι	N/A	Pointer
output_path	L1b Output Path	N/A	Char	Ι	N/A	Pointer
load_g_matrix_nir_row s	Flag to load <i>G</i> -matrix NIR rows	N/A	Boolean	Ι	N/A	1
load_g_matrix	Flag to load <i>G</i> -matrix	N/A	Boolean	Ι	N/A	1
processing_flags	Structure containing processing flags	N/A	t_processi ng_flags	Ι	N/A	1
cal_visib_dual_data_co rrected or cal_visib_full_data_cor rected	Vectors containing the complex L1a Calibrated Visibilities for Dual or Full-pols	Sec. 2.2	Complex	Ι	К	2556 (D) 3x2556 (F)
l1a_hktm_data	L1a HKTM data	N/A	t_l1a_hkt m_data	Ι	N/A	Pointer



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Variable name	Description	Definition	Туре	Class	Unit	Size
time_data	Time data	N/A	t_adf_tim e_data_sc ene	Ι	N/A	Pointer
p_licef_coordinates_dat a	LICEF coordinates	N/A	Double	0	N/A	Pointer
weight_visibs	Weights to be applied to each baseline (for example to filter out hinge baselines)	N/A	Double	0	N/A	9390 (D) 15996 (F)
aux_ftt	Flat Target input data	Sec. 2.2.2.2	t_aux_ftt	0	N/A	Pointer
galaxy_map_data	Sky map	Sec. 2.2.2.1.2	t_aux_gal axy_map	0	N/A	Pointer
landSea_grid_data	Land/Sea Grid data	Sec. 2.2.2.1.3	t_dp_aux_ grid	0	N/A	Pointer
scatt_coeffs_data	Bi-static scattering coefficients	N/A	t_l1b_bsc at_cache_ data_struc ture	0	N/A	Pointer
average_antenna_patter ns	Average Antenna Patterns Front (<u>Hexagon</u>) and Backlobes (<u>Unit in</u> <u>the 196x196 Hexagonal</u> <u>GridCirele</u>). All co- and cross-polar for X and Y- pols.	N/A	t_11b_ave rage_ant_ patts	0	N/A	2x4x196 ²
g_matrix_nir_rows	NIR rows of <i>G</i> -matrix	N/A	Double	0	N/A	2x3x196 ²
g_matrix	Complete <i>G</i> -matrix in Full-pol and H and V blocks in Dual-pol	L1OP TGRD document [RD.22]	Double	0	N/A	9390x4x 196 ² (D) 15995x4 x196 ² (F)
visibs_one_kelvin	One Kelvin Visibilities Vector	N/A	Double	0	K	9390(D) 15996(F)
jplus_matrix	J ⁺ -matrix (Inverted J Matrix)	L1OP TGRD document [RD.22]	Double	0	N/A	15996x1 1164



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Variable name	Description	Definition	Туре	Class	Unit	Size
l1a_header	L1a header	N/A	Void	-	N/A	Pointer
cal_visib_dual_data_co rrected or cal_visib_full_data_cor rected	Vectors containing the complex L1a Calibrated Visibilities for Dual or Full-pols	Sec. 2.2	Complex	Ι	К	2556 (D) 3x2556 (F)
l1a_hktm_data	L1a HKTM data	N/A	t_l1a_hkt m_data	Ι		Pointer
aux_ftt	Flat Target data in input format	Sec. 2.2.2.2.1	Double	Ι	K	Pointer
flat_target_transformati on_flag	Flat Target Transformation Flag	N/A	Boolean		N/A	1
xi_kk, eta_kk	Xi and eta coordinates in the hexagon	L1OP TGRD document [RD.22]	Double	Ο	N/A	196 ²
baselines_star	(<i>u</i> , <i>v</i>) baseline coordinates (for the star)	L1OP TGRD document [RD.22]	Double	Ο	mm	Pointer
apodisation_window	Apodisation Window	N/A	Double	0	N/A	9390(D) 15996(F)
11b_ftt_data	Flat Target data in L1b format	Sec. 2.2.2.2	Double	0	K	9390(D) 15996(F)
11b_visibs_data	Calibrated visibilities in L1b format	Sec. 2.2	Double	0	K	9390(D) 15996(F)

Table 3: L1b reader (blue) and Preprocessor (orange) Variable List



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Variable name	Description	Definition	Туре	Class	Unit	Size
Direct_Sun_Correction _Type	Flag for switching On/Off direct Sun removal	N/A	int	Ι	N/A	1
	Variable for choosing the strategies used for the determination of the direct Sun Temperature (Self-Estimation, Read from file, use default values)					
Use_Sun_Interpolation	Flag to use 4-Point interpolation in the Sun Self Estimation BT Computation.	N/A	boolean	Ι	N/A	1
Reflected_Sun_Correcti on_Type	Flag for switching On/Off Sun Glint removal.	N/A	int	Ι	N/A	1
Direct_Moon_Correctio n_Type	Flag for switching On/Off direct Moon removal	N/A	int	Ι	N/A	1
	Variable for choosing the strategies used for the determination of the direct Moon Temperature (Self- Estimation, Read from file, use default values)					
Sky_Contribution_Corr ection_Type	Flag for switching On/Off Sky removal	N/A	int	Ι	N/A	1
Backlobes_Correction_ Type	Flag for switching On/Off Backlobes contribution removal	N/A	boolean	Ι	N/A	1
Earth_Contribution_Co rrection_Type	Flag to correct for the Gibbs effect	N/A	int	Ι	N/A	1
	Variable to select type of Earth to remove (Constant Earth, Modeled Land/Sea)					
Flat_Target_Correction _Type	Flag for switching On/Off the activation of the FTT algorithm	N/A	boolean	Ι	N/A	1



Variable name	Description	Definition	Туре	Class	Unit	Size
Copolar_Processing	Flag for choosing between the utilization of Copolar <i>G</i> -matrix or complete (Copolar+Cross Polar) <i>G</i> -matrix	N/A	boolean	Ι	N/A	1

Table 4: Elements of the processing flags input structure relevant for the L1b processor

4.1.4. Implementation

Before using the corrected visibilities with the *G* or J^+ -matrix, the elements in the 2556 complex element vector for each scene must be ordered to match the row ordering of *G*. It has been mentioned before, that the number of calibrated visibilities in each scene is 2556, whereas the number or rows in G is 2346 complex plus 3 real elements for H or V polarisation and 3303 complex elements for HV polarisation.

The reduction in dual polarisation is achieved by simply discarding the NIR-LICEF calibrated visibilities which are not measured in the proper polarisation. For example, in an H polarisation scene of calibrated visibilities, the correlations performed with the NIR-LICEF in V polarisation are to be discarded (lines and columns number 3, 27 and 51 on Figure 5).

In full polarisation, it shall be necessary to combine the 3 scenes available for one integration time. This requires discarding of certain NIR-LICEF correlations, but also averaging of other correlations which are measured redundantly, as shown in [RD.5]. In short, the ordering of the calibrated visibilities into a vector suitable to be multiplied by J^+ is the same as it has been explained for the rows of G in [RD.22].

At this point it is also a good practice to match the visibilities in one epoch to the ancillary information available in the L1a HKTM data, and to also load any auxiliary data that is going to be needed (Galaxy Map, Average Patterns...)

4.1.5. Error Handling

Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
1	Unable to read ADF file or L1a Product File.	ERROR_DATA_CORR UPTED	Output error log Processing unit returns with no data processed.	No



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Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
2	Unable to find HKTM data in cache.	ERROR_NO_FILE_AV AILABLE	Log Warning message. Set quality flag for the scene and source being removed. Continue Looping all scenes.	Yes
3	Unable to find the correct time from HKTM in cache.	ERROR_NO_HKTM_I NFORMATION	Log Warning message. Set quality flag for the scene and source being removed. Continue Looping all scenes.	Yes
4	Unable to allocate memory for local variables.	ERROR_ALLOCATIN G_MEMORY	Output error log Processing unit returns with no data processed.	No

4.2. Foreign Sources Correction Module

At this level we are going to correct the L1a calibrated visibilities from Foreign Sources effects. A detailed description of this module is presented in Section 2.2.2.1.

4.2.1. Inputs

□ See previous Figure.

4.2.2. Outputs

- □ Corrected Visibilities;
- □ SunGlint, Sky, Land 1K and Sea Temperatures Vectors.
- □ RFI System Response frequencies

4.2.3. List of Variables

The following table describes the variables used in the subsequent implementation section. Variables are listed as input, local and output (I, L, O). The *Size* column indicates the number of elements constituting that variable, and NOT the size of the variable in bytes (this information can be taken from the *Type* column).



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Variable name	Description	Definition	Туре	Class	Unit	Size
processing_flags	Structure containing processing flags	Sec. 4.1.3	t_processi ng_flags	Ι	N/A	1
g_matrix	Complete <i>G</i> -matrix in Full-pol and H and V blocks in Dual-pol	L1OP TGRD document	Double	Ι	N/A	9390x4x 128 ² (D)
	oroons in Dawr por	[RD.22]				15995x4 x196 ² (F)
visibs_one_kelvin	One Kelvin Visibilities Vector	N/A	Double	Ι	К	9390(D) 15996(F)
average_antenna_patter ns	Average Antenna Patterns Front (Hexagon) and Backlobes (<u>in the</u> <u>196x196 Hexagonal</u> <u>GridUnit Circle</u>). All co- and cross-polar for X and Y-pols.	N/A	t_l1b_ave rage_ant_ patts	I	N/A	2x4x196 ²
galaxy_map_data	Sky map	Sec. 2.2.2.1.2	t_aux_gal axy_map	0	N/A	Pointer
scatt_coeffs_data	Bi-static scattering coefficients	N/A	t_l1b_bsc at_cache_ data_struc ture	0	N/A	Pointer
time_data	Time data	N/A	t_adf_tim e_data_sc ene	Ι	N/A	Pointer
landSea_grid_data	Land/Sea Grid data	Sec. 2.2.2.1.3	t_dp_aux_ grid	0	N/A	Pointer
p_licef_coordinates_dat a	LICEF coordinates	N/A	Double	0	N/A	Pointer
11b_visibs_data	Vectors containing the complex L1a Calibrated Visibilities for Dual or Full-pols	Sec. 2.2	Complex	Ι	K	2556 (D) 3x2556 (F)
sun_body_data	Sun data	N/A	t_11b_bod y_data	0	N/A	Pointer
moon_body_data	Moon data		t_11b_bod y_data	0	N/A	Pointer



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Variable name	Description	Definition	Туре	Class	Unit	Size
11b_temps_sunGlint_sc ene	Vectors containing the brightness temperatures of the Sun Glint. $T^{\mathbf{p}}_{\text{SunGlint}}(\xi, n)$.	Sec. 2.2.2.1.6	double	0	K	[Nbr of Scenes] x 2x196 ²
11b_temps_sky_scene	Vector containing the brightness temperatures of the Sky. $T^{\mathbf{p}}_{\text{Sky}}(\xi,\eta).$	Eq. 6	double	L	K	[Nbr of Scenes]X [4X196X 196]
11b_temps_land_scene	Vector for each scene with a 1K earth brightness temperature on Land. $T^{\mathbf{p}}_{\text{Land} \text{IK}}(\xi, \eta).$	Eq. 6	double	L	K	[Nbr of Scenes]X [2X196X 196]
11b_temps_sea_scene	Vector containing the brightness temperatures of the Sea. $T^{\mathbf{p}}_{\text{Sea}}(\xi,\eta).$	Eq. 6	double	0	К	[Nbr of Scenes]X [2X196X 196]
11b_rfi_freqs_data	RFI System Response in frequency domain	Sec. 2.2	double	0	N/A	2791

Table 5: Foreign Sources Variable List

4.2.4. Implementation

Two different functions are used for removing the foreign sources contribution to the visibilities:

- foreignSourcesComputationDual;
- foreignSourcesComputationFull.

The first function is used for Dual-polarisation mode, while the later is used for Full-polarisation mode. Although two different functions are used, the approach is similar in both functions. Details on the algorithms are in Section 2.2.2.1.

The diagram below shows the detailed processing steps for the Foreign Sources Correction module.



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Figure 4-1: Sequence Diagram for the Foreign Sources Correction Module

The algorithm starts by identifying the pixels corresponding to the Earth and to the Sky according to the current position and attitude of the satellite. After determining the pixels that correspond to the Earth and Sky, the Earth pixels are flagged as belonging to the Land or the Sea according to LandSea mask. The Brightness Temperatures and visibilities of the following sources are then computed sequentially:

□ Sky BT – For each of the pixels that correspond to the sky, the BT is determined using the Galaxy map ADF (SM_xxxx_AUX_GALAXY<ID>). Before retrieving the BTs from the ADF, the pixels

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coordinates must be transformed into Right Ascension and Declination using the attitude information available in L1A HKTM Product and the EE CFI function xl_quaternions_to_vectors;

- □ Land 1K and Sea BT Using the LandSea mask, two vectors are generated: a 1K Temperatures vector for Land and an estimated Sea temperatures vector. The details of the Sea Temperature estimation can be checked in Section 2.2.2.1.4;
- □ Direct Sun BT uses EE CFI functions for determining the Sun position. Then EE CFI is also used for checking if the Sun is eclipsed by the Earth, i.e., if the Instrument-Sun vector intersects the Earth. The BT of the Sun can then be estimated from the visibilities as described in Sections 2.2.2.1.5.1 to 2.2.2.1.5.4, read from an ADF (SM_xxxx_AUX_SUNT__<ID>), or, in alternative, set to a default value. The following EE CFI Functions are used: xl_sun, xp_target_inter, xl_change_cart_cs, xl_time_init, xl_time_close, xp_attitude_init, xp_attitude_close;
- □ Sun Glint BT The Sun Glint algorithm receives as input the list of pixels corresponding to the Earth. Then it determines which pixels correspond to the sea (the Sun glint removal will be performed only for those pixels). For each of the pixels, the vectors Sun to Earth Pixel (incident) and Earth Pixel to Instrument (scattered) are computed. From these vectors, the incidence and scattered angles are determined and used for retrieving the scattering coefficients from the LUTs, using a cubic interpolation. The Scattering Coefficients are finally used for computing the Sun Glint Brightness Temperatures of the sea pixels;
- □ *Direct Moon BT* the same function is used for determining the Direct Sun and Direct Moon BTs. The algorithm is the same with the exception that EE CFI Function xl_moon is used instead of xl_sun, and the ADF used for retrieving the Moon BT is SM_xxxx_AUX_MOONT_<ID>;
- \square *RFI BT* the same function is used for determining the Direct Sun and RFI BTs. The algorithm is the same with the exception that the RFI lat-lon positions are read from the RFILST ADF, and the BT self-estimation is performed over the expected xi-eta coordinates in the antenna plane;
- Backlobes BT the antenna backlobes algorithm assumes that the energy entering through the backlobes is computed taking into account the backolbes antenna patterns. Therefore, the current model determines the sources of brightness temperature entering through the back of the instrument and then computes the corresponding zero baseline components of the visibilities considering negligible fringe washing function effects (fwf=1) and all the backlobe antenna patterns equal, i.e. using a fourier transform approximation. The sources of brightness temperature entering through the backlobes are: Sun/Moon if they appear in the back of the instrument (the corresponding pixel positions are set to a previously estimated temperature or to a fixed temperature read from the corresponding ADFs¹⁶), the pixels corresponding to the Sky on the back (set to a fixed value of 2.7K) and the pixels corresponding to the Earth on the back (set to a 290K). After computing the brightness temperature distribution on the back, an Fourier transform shall be applied, as described in Equations 39 and 40.

The visibilities corresponding to each of the previous "foreign sources" are computed differently depending on the source:

¹⁶ The Sun Brightness temperature shall not be estimated when the sun appears on the back, as explained in section 3.3.1.1.. Therefore, if a previous scene, with the sun in the front, was used to estimate the sun BT, this BT should be used. Otherwise, a default value or read from an ADF shall be used.

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- □ The Sky, Sea and Sun Glint BT are determined in the Temperatures domain and later (outside the Foreign Sources module) added to the Land Temperatures and then multiplied by the *G*-matrix in order to obtain the corresponding visibilities;
- □ The Land 1K vector in a vector which takes the values of one in the land and zero everywhere else. This is sent to the Error Mitigation Module, where the land temperature vector is estimated;
- □ For the Sun, Moon and RFI visibilities, since these contributions correspond to point sources with sizes and positions different from the pixels area and positions used in the *G*-matrix grid, the *G*-matrix can not be used directly for obtaining the visibilities from the BT. Instead, the approach described in 3.3.1.1 is applied;
- □ Finally, the backlobes contribution cannot use the *G*-matrix either, since it was computed with the front lobe antenna patterns. Instead, the backlobes visibilites are computed through a Fourier transform, using the backlobe antenna patterns.

The second part of the algorithm consists in computing the Earth and the receivers' contribution to the visibilities:

- □ Receivers BT the Receivers BT influence is considered over the complete Unit Circle, i.e., in all the pixels. Each of the elements of the Receivers BT vector is set to the average physical temperature of the receivers, computed with the data available in the L1A HKTM product;
- □ Earth BT finally the Earth BT is computed as described in Section 2.2.2.1.3. All the pixels (BT vector elements) corresponding to the earth will be set to the computed Earth Brightness Temperature.

Finally, the Receivers and the Earth BT vector are multiplied by the *G*-matrix in order to determine their contributions to the visibilities. The multiplication is done in accordance to the equations shown in section 2.2.3.

During the processing, whenever a correction is applied on any snapshot, the corresponding flag in L1b is raised for that snapshot. In addition, the corrupted RFI snapshot flag is raised if the amount of RFI estimated BT inside all RFI sources exceeds the RFI snapshot threshold from the L1 configuration.

It is important to highlight that the algorithm receives as input the following flags, which will determine the sequence of processing:

- Direct_Sun_Correction_Type- activate/deactivate the direct Sun contribution removal, and flag used for choosing the algorithm used in the Sun BT computation: Estimate from visibilities, Read from and ADF (SM_xxxx_AUX_SUNT_<ID>), or use a default value (as described in[AD.04]);
- Direct_Moon_Correction_Type- activate/deactivate the direct Moon contribution removal, and flag used for choosing the algorithm used for computing the Moon BT: Estimate from visibilities, Read from and ADF (SM_xxxx_AUX_MOONT_<ID>), or use a default value (as described in AD.04
- Reflected_Sun_Correction_Type- activate/deactivate the Sun glint removal;
- Sky_Contribution_Correction_Type- activate/deactivate the Sky contribution removal;



- Backlobes_Correction_Type- activate/deactivate the Backlobes zero baseline contribution removal;
- Copolar_Processing- flag to choose between using only the copolar *G*-matrix or the complete (copolar+cross polar) *G*-matrix, as explained in [RD.22]

The flag for applying RFI mitigation is particular to each RFI source and is contained within the RFILST ADF.

4.2.5.	Error	Hand	ling
7.2.3.		nunu	mz

Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
1	Error From CFI Libraries.	ERROR_FROM_CFI_L IB	Log Warning message. Set quality flag for the scene and source being removed. Continue Looping all scenes.	Yes
2	Unable to allocate memory for local variables.	ERROR_ALLOCATIN G_MEMORY	Output error log Processing unit returns with no data processed.	No

 Table 6: Foreign Sources Correction Error Handling

4.3. Error Mitigation Module

This module sets the Reference Temperature and calculates the Earth (=Land+Sea) components for correction of the Gibbs effect near the sharp boundaries at the Earth/Sky and Land/Sea borders.

As detailed before, the Reference Temperature is set through the removal of the Visibilities corresponding to a constant scene at Temperature T_{Ref}^{kj} . If the Flat Target Transformation is selected (through the appropriate selection for the configuration flag) then the removed Visibilities used to set the Reference Temperature are obtained from the Flat Target product visibilities (measured by the instrument while in External Target mode), otherwise an artificial set of 1K Visibilities is used.

For the Gibbs effect removal, the level is set through a Gibbs level flag; if set to zero, no correction is performed. If set to 1, the Earth Temperature is estimated to be later removed; if set to 2, then a constant Land temperature set to 250K and the Sea Temperature is estimated by the Fresnel model described in Section 2.2.2.1.4.

4.3.1. Inputs

- □ Flat Target data or One Kelvin Visibilities;
- □ Calibrated Visibilities.

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4.3.2. Outputs

- □ Estimated Earth/Land Temperatures;
- □ Visibilities with Reference Temperature corrected;
- □ Frequencies of the artificial scene (Gibbs 2 mode only)

4.3.3. List of Variables

Variable name	Description	Definition	Туре	Class	Unit	Size
processing_flags	Structure containing processing flags	N/A	t_processi ng_flags	Ι	N/A	1
g_matrix	Complete <i>G</i> -matrix in Full-pol and H and V blocks in Dual-pol	L1OP TGRD document [RD.22]	Double	Ι	N/A	9390x4x 128 ² (D) 15995x4
visibs_one_kelvin	One Kelvin Visibilities Vector	N/A	Double	I	К	9390(D) 15996(F)
11b_ftt_data	Flat Target data in L1b format	Sec. 2.2.2.2	Double	Ι	К	9390(D) 15996(F)
weight_visibs	Weights to be applied to each baseline (for example to filter out hinge baselines)	N/A	Double	Ι	N/A	9390 (D) 15996 (F)
11b_temps_loop_scene	Vector with FS Temperature corrections (SunGlint, Sky and Sea Temperatures)	N/A	Double	Ι		
11b_temps_land_scene	Vectors containing the estimated brightness temperatures of the Land.	Sec. 2.2.2.2	double	0	K	[Nbr of Scenes] x 2x196 ²
	$T^{\mathbf{p}}_{\text{Land}}(\xi,\eta).$					
11b_visibs_dual_scene	Calibrated visibilities in L1b format	Sec. 2.2	Double	I+O	К	9390(D) 15996(F)
11b_temps_freqs_data	Artificial Gibbs 2 scene in frequency domain	Sec. 2.2	double	0	N/A	11164

Table 7: Error Mitigation Module Variable List

4.3.4. Implementation

Two different functions are used for the error mitigation (including Flat Target Transformation):

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• errorMitigationDual;

• errorMitigationFull.

The first function is used for Dual-polarisation mode, while the later is used for Full-polarisation mode. Although two different functions are used, the approach is similar in both functions. For more details see Section 2.2.2.2.



Figure 4-2: Sequence Diagram for the Error Mitigation Module

The diagram above shows the Error Mitigation processing steps. Then, the two main functionalities of the Error Mitigation Module are the following:



- Removal of the Reference Temperatures : It starts by setting the Reference Temperature according to level selected by the appropriate flag (see [RD.22]). Then the Reference Temperature is remove from the Calibrated Visibilities, but this depends on weather the Flat Target Transformation is applied or not.
 - If the FTT is applied, then the measured Flat Target Visibilities are multiplied by the appropriate scaling factor (see Section 2.2.2.2.1) and then subtracted to the Calibrated Visibilities;
 - If the FTT is NOT applied, then the artificial One Kelvin Visibilities, i.e. the *G*-matrix multiplied by a 1K vector, are multiplied by the appropriate scaling factor (see Section 2.2.2.2.1) and then subtracted to the Calibrated Visibilities;
- □ *Estimation of the Land Temperatures*: For the land temperature estimation the Visibilities for the SunGlint, the Sky and the Sea must be known, as well as the visibilities for a 1K constant temperature on Land. Since the corresponding Temperature Vectors are determined in the Foreign Sources module, they must be multiplied here by the *G*-matrix in order to be transformed into Visibilities, which are then used to estimate the Land Temperatures (see Section 2.2.2.2 for details). In Gibbs 2 mode, the Land Tempearature is set to a fixed 250K.

4.3.5. Error Handling

Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
1	Unable to allocate memory for local variables.	ERROR_ALLOCATIN G_MEMORY	Output error log Processing unit returns with no data processed.	No

Table 8: Error Mitigation Error Handling

4.4. Image Reconstruction Module

The image reconstruction module uses the modules described in the previous section. It performs the image reconstruction process on the L1a calibrated visibilities, producing snapshots of the reconstructed images and their corresponding frequency components.

First the processor must do a loop depending on the number of scenes included in the L1a product, and then invoke the foreign sources correction module. This module will correct from foreign sources the L1a calibrated visibilities and it is described in detailed in Sections 2.2 and 4.1.

The next step is to calculate the brightness temperatures frequencies $\hat{T}(u,v)$ using the visibilities and the inverted J Matrix. The final product must contain a matrix of brightness temperatures in a fixed antenna grid on the antenna polarization reference frame (T), and a vector of Fourier Domain components obtained after reconstruction $\hat{T}(u,v)$. To obtain (T) it is only needed to apply the IFFT to

the $\hat{T}(u,v)$ vector.

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Figure 4-3: Image Reconstruction Processing Steps

4.4.1. Inputs

- □ FS and EM Corrected Calibrated Visibilities
- \Box J⁺-matrix.

4.4.2. Outputs

- □ Brightness Temperatures snapshots
 - Land Product Dual Polarization (SM_xxxx_MIR_SCLD1B_<ID>)
 - Land Product Full Polarization (SM_xxxx_MIR_SCLF1B_<ID>)
 - Sea Product Dual Polarization (SM_xxxx_MIR_SCSD1B_<ID>)
 - Sea Product Full Polarization (SM_xxxx_MIR_SCSF1B_<ID>)



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4.4.3. List of Variables

The following table describes the variables used in the subsequent implementation section. Variables are listed as input, local and output (I, L, O). The *Size* column indicates the number of elements constituting that variable, and NOT the size of the variable in bytes (this information can be taken from the *Type* column).

Variable name	Description	Definition	Туре	Class	Unit	Size
jplus_matrix	<i>J</i> ⁺ -matrix (Inverted J Matrix)	L1OP TGRD document [RD.22]	Double	Ι	N/A	15996x1 1164
11b_visibs_data	Vectors containing the complex L1a Calibrated Visibilities for Dual or Full-pols	Sec. 2.2	Complex	Ι	K	2556 (D) 3x2556 (F)
weight_visibs	Weights to be applied to each baseline (for example to filter out hinge baselines)	N/A	Double	Ι	N/A	9390 (D) 15996 (F)
p_licef_coordinates_da ta	LICEF coordinates	N/A	Double	Ι	N/A	Pointer
average_antenna_patter ns	Average Antenna Patterns Front (Hexagon) and Backlobes (Unit Circle). All co- and cross- polar for X and Y-pols.	N/A	t_l1b_ave rage_ant_ patts	Ι	N/A	2x4x196 ²
ivt_flag	Flag for usage with IVT data	N/A	boolean	Ι	N/A	Boolean
ideal_breakpoint_string	String for Ideal reconstruction breakpoints names	N/A	Char	Ι	N/A	Pointer
11b_temps_freqs_data	Brightness Temperatures snapshot in frequency domain	Sec. 2.2	double	0	N/A	2791

Table 11: Image Reconstruction Variable List



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4.4.4. Implementation

<pre>error = load_j_matrix(j_mat_filename, inv_j_matrix);</pre>
<pre>for(i=0; i!=n_scenes;++i){</pre>
<pre>error = compute_foreign_sources_correction(lla_visibilities, gmatrix ,</pre>
<pre>visibilities_corrected);</pre>
<pre>error = compute_bt_snapshot_freq(inv_j_matrix, visibilities_corrected,</pre>
<pre>bt_freq_snapshot) ;</pre>
error = write_freq_snapshot(bt_freq_snapshot, bt_freq_snapshot_filename);
}

The following text describes last step to produce a complete L1b product. First it is needed to correct the L1a calibrated visibilities from the foreign sources contribution. The function responsible for this task is *compute_foreign_sources_correction*, and a detailed description is done in section 4.1.

After some of the foreign sources have been corrected, the delta visibilities that remain to be computed are obtained from multiplication of G and the Brightness Temperature vectors from Eq.6. The delta visibilities are subtracted from the L1b visibilities so that all foreign sources are removed.

Then it is time to use the inverted *J*-matrix, in order to multiply it by the calibrated visibilities corrected. This step is done in *compute_bt_snapshpot_freq* function and using LAPACK methods to do the matrix-vector product operation.

Before the matrix vector multiplication, the corrected visibilities have to be weighted with the Baseline Weights ADF values, which provide a weighted filtering of the instrument output. For example, these weights have been used in the IVT2 campaign to filter out the baselines across hinges as they were too noisy to be used.

```
for(i=0; i<size_of_visibilities_vector;++i){
    weighted_visibilities[i] = visibilities_corrected[i] * baseline_weights[i];
}
trans='N';nrows = inv_j_matrix_rows; ncols = inv_j_matrix_columns;
alpha=1.;beta=0.;incx=1;
dgemv_(&trans, &nrows, &ncols, &alpha, inv_j_matrix, &nrows, weighted_visibilities,
&incx, &beta, bt_freq_snapshot, &incx);</pre>
```

It is very important to highlight that the baseline weights ADF is to be configured by the end user, so it is his responsibility to ensure that all the baselines weights are correct and coherent. For example in the case of the hinges, it is not enough to set to zero the affected receiver pair correlations, but it is also required to compensate the effect of this missing correlations in the remaining ones that cover the same baseline. The baseline weights ADF has the average weights for usage in both H and V polarizations,

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except for the NIR-LICEF baselines, where independent H and V weights can be applied to each channel of the NIRs.

In the LAPACK function above, the J^+ -matrix is passed as a vector, ordered column-wise, that is, the first elements in the vector correspond to the first column of J^+ , until all elements in the first column are present, then the second column comes, and so on.

The pseudo-inverse J^+ , and the *G*-matrix used to create it, as described in previous sections, require calibrated visibilities in two consecutive scenes. This is because they consider the cross-polarisation contamination of one scene into the other by means of the cross-polar terms used in the computation. This establishes a requirement in the processing which must be taken into account.

The result of the matrix-vector multiplication is finally stored in the vector *bt_freq_snapshot, which* contains the brightness temperatures Fourier components in the frequency domain $\hat{T}(u, v)$.

Transformation of $\hat{T}(u,v)$ to *T* domain is not needed in L1b, but for future reference it is still defined here. It is simply needed to apply an IFFT to the brightness temperature frequencies calculated before. The function will use FFTW functions on a square matrix containing the BT frequencies ordered in a suitable way for performing 2D FFT:

The L1b products will be generated by the functions *write_bt_xxxx* according to product format definitions [AD.4].

Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
1	Error From CFI Libraries.	ERROR_FROM_CFI_L IB	Log Warning message. Set quality flag for the scene and source being removed. Continue Looping all scenes.	Yes
2	Unable to allocate memory for local variables.	ERROR_ALLOCATIN G_MEMORY	Output error log Processing unit returns with no data processed.	No

4.4.5. Error Handling



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Error Nr	Error Description	Error Code Returned	Program behaviour	Quality flag raised
3	Unable to write output date	DATA_CORRUPTED	Output error log Processing unit returns with no data processed.	No

Table 10: Image Reconstruction Error Handling

4.5. Product Generation

L1b products shall be generated in accordance to the format described in [AD.4]. In this section it is described how to fill each substructure within each product type.

4.5.1. MPH

See section 4.1.1 of [AD.4] for the generic description. All fields in the MPH are applicable to all L1b products and are filled according to the following rules:

- □ Ref_Doc: Hardcoded in the L1OP software to reflect which reference document is applicable (SO-TN-IDR-GS-0005)
- □ Acquisition_Station: Taken from the input L1a MPH
- Derived to "DMEP"
- □ Logical_Proc_Centre: Hardcoded to "DME"
- □ Phase, Cycle, Rel_Orbit: Values taken from EE CFI function xo_orbit_rel_from_abs
- □ Abs_Orbit: Absolute orbit at Sensing_Start, extracted from EE CFI function xo_time_to_orbit
- □ OSV_TAI, OSV_UTC, POSV_UT1: Taken from the input L1a MPH
- □ Leap_Second: Value retrieved from the EE CFI function xl_time_get_leap_second_info
- X_Position, Y_Position, Z_Position, X_Velocity, Y_Velocity, Z_Velocity: Values taken from EE CFI function xo_propag
- □ Vector_Source: Depending on the data used for initialising the propagators it may be IG (propagation initialised with GPS data in ancillary packet), SP (propagation initialised with SOGS Predicted data) or SR (propagation initialised with SOGS Restituted data)
- Product_Confidence: Set to NOMINAL if no errors occur during processing or ERROR if errors 2-5 occur.

4.5.2. SPH

The generic format of L1b products SPH is defined in section 4.1.2 and 4.4.1.2 of [AD.4].

The SPH is the same for all types of L1b products (dual-full, nominal-external observation). All fields in the SPH are applicable to all L1b products and are filled according to the following rules:



- □ SPH_Descriptor: Set to MIR_SC_D1B_SPH, MIR_TARD1B_SPH, MIR_SC_F1B_SPH or MIR_TARF1B_SPH depending on the type of input L1a
- □ Precise_Validity_Start: UTC time of the first snapshot inside the Measurement Data Set
- □ Precise_Validity_Stop: UTC time of the last snaphsot inside the Measurement Data Set
- □ Abs_Orbit_Start, Start_Time_ANX_T: Values extracted from EE CFI function xo_time_to_orbit using Precise_Validity_Start as input
- □ Abs_Orbit_Stop, Stop_Time_ANX_T: Values extracted from EE CFI function xo_time_to_orbit using Precise_Validity_Stop as input
- □ UTC_at_ANX: Value extracted from EE CFI function xo_orbit_to_time using Abs_Orbit_Start and zero seconds as input
- □ Long_at_ANX: Value extracted from EE CFI function xo_propag_extra using Abs_Orbit_Start and zero seconds as input
- Ascending_Flag: Set to A (Ascending) if Abs_Orbit_Stop > Abs_Orbit_Start, or D (Descending) if Abs_Orbit_Stop = Abs_Orbit_Start
- Semiorbit_Start/Semiorbit_Stop: Taken from the input L1a SPH
- □ Correlator_Layer: Taken from the input L1a SPH
- Checksum: Computed for each product using *cksum* command
- □ Header Schema: Taken from the value available from the official L1 schemas
- Datablock_Schema: Taken from the value available from the official L1 schemas
- □ Header Size: Computed for each product header
- Datablock_Size: Computed for each product using *cksum* command
- □ HW_Identifier: Hardcoded to L1OP
- □ Quality_Information: Filled according to [AD.4]
- □ Reconstruction_Image_Algorithm and Foreign_Sources_Correction: Taken from available CNFL1P

4.5.3. Data Set

The product format variables are filled according to the list of variables presented in the previous chapters. The following sections detail which elements shall be set as output (see also section 4.4.1.3.1 of [AD.4]).

4.5.3.1. Temp_Snapshot_Dual

- □ Snapshot_Time, Snapshot_ID, Snapshot_OBET: Values taken from visibilities_corrected structure
- □ X_Position, Y_Position, Z_Position, X_Velocity, Y_Velocity, Z_Velocity, Vector_Source: Values taken from l1a_pvt_data structure.
- □ Q0, Q1, Q2, Q3: Values taken from l1a_aocs_data structure
- □ Flags: Values taken from snapshot_flags structure

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- □ Scene_BT_Fourier: Taken from bt_freq_snapshot structure
- □ Accuracy is computed by performing the subtraction (average Antenna Temperature average physical temperature). The average Antenna Temperature is computed from the three NIR in the same polarisation as the scene (in NIR mode), or from the average LICEF Antenna Temperatures (in ALL-LICEF mode); the average physical temperature is computed from the 72 LICEF
- □ Physical_Temperatures_STD, System_Temperatures_Avg: Values computed from rec_bt structure, retrieved from the applicable L1a HKTM data
- □ Foreign Sources Flags: Values taken from temp snapshot
- Direct_Sun_Pos, Reflected_Sun_Pos, Direct_Moon_Pos: Values computed directly
- Direct Sun BT: Value taken from sun and moon bt data structure
- □ Constant_Earth_BT: Values computed directly

4.5.3.2. Temp_Snapshot_Full

Same as the previous case.

Note:

With the implementation of the RFI mitigation algorithms, two bits from the L1b flags have been reused – the FTT Flag and the RFI Flag.

Being the Flat Target Transformation a mandatory algorithm, the flag that described the usage of the FTTX ADF has been reassigned. It identifies if any RFI mitigation has been applied in the L1b Foreign Sources' module. Nevertheless, the (correct) usage of the FTT ADF can also be traced with the **Calibration_Error_Flag**, from the **Quality_Information** DSR in the MIR_SC_X1B product.

The initial RFI Flag that was defined, was based on the $\max(M_{kj})$ criteria. However, during the Commissioning Phase this value has proved to be un-effective. Therefore, the L1b RFI Flag is now providing information if there is a strong RFI as detected during the L1b processing (max RFI self-estimated BT above a defined threshold).

It should be noted that these two flags have <u>information on a snapshot level</u>. For more information on the flagging, please refer to [RD.21] and [RD.20].



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5. ANNEX 1: ALGORITHM FOR SUNGLINT EFFECT REMOVAL AT LEVEL 1

This annex presents the note provided by N.Reul and J. Tenerelli from IFREMER regarding the algorithm for removing the Sun Glint.

5.1. Introduction

In the present report, we detail the theoretical basis and some methodologies to remove sunglint impact on SMOS L1 measurements.

The L1 sunglint correction algorithm presented here is based on the approach developed in [1],[2], see at the end of this Annex. It consists in subtracting to the measured and calibrated visibility samples, in addition to other and already identified contributions (receivers' physical temperature, sky, direct sun, ...), the contributions from a priori estimated sunglint visibilities.

These are given by:

$$V_{sg}^{p,q} = \frac{1}{\Omega_{1}\Omega_{2}} \cdot \iint_{\xi^{2}+\eta^{2}\subset SG} \frac{T_{Bsg}^{p,q}(\xi,\eta)}{\sqrt{1-\xi^{2}-\eta^{2}}} \cdot \hat{F}_{n1}^{p}(\xi,\eta) \cdot \hat{F}_{n2}^{q^{*}}(\xi,\eta) \cdot \hat{F}_{12}\left(-\frac{u_{12}\xi+v_{12}\eta}{f_{o}}\right)$$
(1)

$$\cdot \exp\left(-j2\pi(u_{12}\xi+v_{12}\eta)\right)d\xi d\eta$$

where $\Omega_{1,2}$ is the solid angle of the antenna, $(\xi,\eta) = (\sin\theta\cos\varphi,\sin\theta\sin\varphi)$ are the director cosines defined with respect to the X and Y axes in the antenna reference frame (X is perpendicular to the orbital plane; Y upward titled from the velocity vector), SG is the domain in the director cosine within which the sunglint phenomenon is occurring with significant intensity, $T_{Bsg}^{p,q}(\xi,\eta)$ is the polarized brightness temperature due to solar radiations scattered by earth surface in the direction of observation (θ,φ) , $\hat{F}_{n1,2}^{p,q}(\xi,\eta)$ are the normalized antenna copolar voltage patterns at p and q polarizations, $\hat{r}_{12}(-u_{12}\xi+v_{12}\eta/f_o)$ is the fringe-wash function, f_o is the center frequency ($f_o = c/\lambda_o$), and $(u_{12},v_{12})=(x_2-x_1,y_2-y_1)/\lambda_o$ is the spatial frequency sampled (baseline) that depends on the antenna position difference.

In the following section we describe how to evaluate the key unknowns of the sunglint visibilities as defined in Eq 1, namely the $T_{Bse}^{p,q}(\xi,\eta)$ terms.



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5.2. Sunglint brightness temperature model



5.2.1. General Theory

Let's assume that an incremental terrestrial area dA located within, or closed to, the MIRAS antenna field of view is illuminated by the sun radiations along the direction of the unit vector \vec{n}_i . Part of the intercepted energy is scattered in the direction \vec{n}_s , i.e., toward the radiometer antenna. Therefore, the direction of sunglint signals $\vec{n}_s = (\theta_s, \varphi_s)$ is directly related to the MIRAS angles of observations (θ, φ) , in the cosine director frame by: $\theta_s = \theta$ and $\varphi_s = \varphi + \pi$. Then, the solar energy scattered by dA and impinging the antenna at the position (ξ, η) in the director cosine frame and at time t is represented by the radiometric temperature $T_{Bsg}^{p,q}(\xi, \eta) = T_{Bsg}^{p,q}(\theta_s, \varphi_s, t) = T_{Bsg}^{p,q}(\theta, \varphi - \pi, t)$, and is given for h and v-polarization respectively by:

$$T_{Bsg}^{h}(\xi,\eta,t) = \frac{1}{4\pi\cos\theta} \int_{0}^{2\pi} \int_{0}^{\beta_{sun}/2} \left[\sigma_{hh}^{o}(\vec{n}_{s},\vec{n}_{o}) + \sigma_{hv}^{o}(\vec{n}_{s},\vec{n}_{o}) \right] T_{sun}(\vec{n}_{o},t) d\Omega_{o}$$

$$T_{Bsg}^{V}(\xi,\eta,t) = \frac{1}{4\pi\cos\theta} \int_{0}^{2\pi} \int_{0}^{\beta_{sun}/2} \left[\sigma_{vv}^{o}(\vec{n}_{s},\vec{n}_{o}) + \sigma_{vh}^{o}(\vec{n}_{s},\vec{n}_{o}) \right] T_{sun}(\vec{n}_{o},t) d\Omega_{o}$$
⁽²⁾

where $\sigma_{hh}^{o}, \sigma_{vv}^{o}, \sigma_{vh}^{o}$ and σ_{hv}^{o} are the bistatic scattering coefficients of the sea surface for HH, VV, VH and HV polarizations, respectively, at scattered direction $\vec{n}_s = (\theta, \varphi + \pi)$ and incident direction \vec{n}_o . The scattering elevation angle is denoted θ . The integration limits is over the solid angle subtented by the

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sun where $\frac{\beta_{sun}}{2}$ is the angular radius of the sun as viewed from the earth. At 1.4 GHz, $\frac{\beta_{sun}}{2} \approx 0.293^\circ$, which is 10% greater than the optical angular radius [3]. $T_{sun}(\vec{n}_o, t)$ is the brightness temperature of the sun at 1.4 GHz in the direction \vec{n}_o and at time t.

Equations (2) show that in order to estimate the brightness temperature $T_{Bsg}^{p,q}(\xi,\eta)$ corresponding to a sunglint event at a position *T* on the earth surface, determined by the latitude φ and longitude ψ of the observation and at a given time *t*, the following parameters are needed:

- 1) \vec{n}_o : the direction (incidence and azimut angles) of sun radiations at the earth surface position (φ, ψ) corresponding to MIRAS coordinates (ξ, η) at time *t*.
- 2) $T_{sun}(\vec{n}_o, t)$: the brightness temperature of the sun at 1.4 GHz in the direction \vec{n}_o and at time t, and,
- 3) $\sigma_{hh}^{o}, \sigma_{vv}^{o}, \sigma_{vh}^{o}$ and σ_{hv}^{o} : the bistatic scattering coefficients of the sea surface for HH, VV, VH and HV polarizations, respectively, at scattered direction \vec{n}_{s} , incident direction \vec{n}_{i} , and corresponding to the sea state conditions at target T=(ϕ, ψ, t).

Parameters 1) can be obtained from accurate ephemerides. The main difficulties in estimating $T_{Bsg}(\vec{n}_s,t)$ therefore consist in providing accurate estimates for the brightness temperature of the sun at 1.4 GHz and for the sea surface bistatic coefficients at L-band.

It is assumed in the present algorithm, that the brightness temperature of the sun at 1.4 GHz is unpolarized, and independent of the direction of incidence \vec{n}_o , that is $T_{sun}(\vec{n}_o,t) = T_{sun}(t)$. The time t being defined here as the UTC time of L1 snapshot acquisition. Moreover, we assume it is provided as input to the present module by the Level 1 processor.

Furthermore, the following model simplification is used here to estimate the amount of solar energy scattered by the sea surface and impinging the MIRAS antenna. We assume that within the solid angle subtented by the sun as seen from any of the observed terrestrial targets, the local sun direction \vec{n}_i is almost constant, so that, at any target *T*, the radiometric sunglint temperatures $T_{Bgg}^{p,q}(\xi,\eta,t)$ can be approximated locally by:

$$T_{Bsg}^{p,q}(\xi,\eta,t) \approx \frac{T_{sun}(t)\Omega_{sun}}{4\pi\cos\theta} \Big[\sigma_{pp}^{o}(\vec{n}_{s},\vec{n}_{o}) + \sigma_{pq}^{o}(\vec{n}_{s},\vec{n}_{o})\Big] \quad (3)$$

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where Ω_{sum} (steradian) is the solid angle intercepting the sun as seen from the earth:

$$\Omega_{sun} = 2\pi \left[1 - \cos(\beta_{sun} / 2) \right] \cong 8.2 \times 10^{-5} \, sr$$

Therefore, in the following, we only detail the methodologies to estimate the bistatic scattering coefficients of the sea surface.

5.2.2. Bistatic scattering coefficients for the rough sea surface at Lband

In the present work, the bistatic scattering coefficients of the rough sea surface needed in Equations (3) are estimated using the Small Slope Approximation theory ([4], [5]), which is known to work well from moderate to high incidence angles ($40^{\circ} \le \theta_i \le 80^{\circ}$). The lower order-approximation (referred to as the SSA-1) is used here and is appropriate for both large- (the Kirchhoff regime) and small scale (the bragg regime) roughness within a single theoretical scheme.

The calculation yields the following expression for a dimensionless scattering cross section $\sigma^{o}_{\alpha\alpha_{o}}$ for scattering of the wave of polarization α into the wave of polarization α_{o} :

$$\sigma_{\alpha\alpha_{o}}^{o}(\vec{n}_{s},\vec{n}_{o}) = \frac{1}{\pi} \left| \frac{2q_{k}q_{o}}{q_{k}+q_{o}} B_{\alpha\alpha_{o}}(\vec{n}_{s},\vec{n}_{o}) \right|^{2} e^{-(q_{k}+q_{o})^{2}\rho(0)} \int \left(e^{(q_{k}+q_{o})^{2}\rho(\vec{r})} - 1 \right) e^{-i(\vec{n}_{s}-\vec{n}_{o})\cdot\vec{r}} d\vec{r}$$

where (q_k, q_o) represent the vertical projections of the wavevectors and the kernel functions $B_{\alpha\alpha}(\vec{n}_s, \vec{n}_o)$ are given in Appendix of [6]. These kernels are geometric functions of the dielectric

constant: we used the Klein and Swift's model [7] to estimate the dielectric constant of sea water at Lband.

Here, the function $\rho(\vec{r})$ is defined by the relation:

$$\left\langle \exp\left[iQ(h(\vec{r}_1) - h(\vec{r}_2)\right]\right\rangle = \exp\left[-Q^2\left(\rho(0) - \rho(\vec{r}_1 - \vec{r}_2)\right)\right]$$

where <...> means averaging over the space homogeneous statistical ensemble of sea surface roughness, described by the surface elevation signal $h(\vec{r}_1)$, and $Q = q_k + q_i$. For Gaussian statistics ρ represents the correlation function of roughness and can be expressed strictly in terms of a roughness spectrum:

$$\rho(\vec{r}) = \int_{0}^{2\pi} \int_{0}^{\infty} W(\vec{k}) \exp\left[i\,\vec{k}\cdot\vec{r}\,\right] d\vec{k}$$

where $W(\vec{k})$ is the directional wavenumber spectrum of the rough sea surface at surface wavenumber vector \vec{k} .

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In the present work, sea surface statistics is assumed Gaussian and ρ is obtained from the sea surface spectrum model of Kudryavtsev al. [8]. In our approach, the calculation of $\sigma_{\alpha\alpha_o}^{\circ}$ is simplified using an azimuthal harmonic decomposition for the autocorrelation function. Moreover, to calculate accuratly the autocorrelation function, we introduced a sufficiently dense net on the surface wavenumber vector plane within the range $10^{-3} \le k \le 10^3$ rad/m, applying a uniform step with respect to log(k) rather than to k.

5.2.3. Practical Implementation into the L1 Processor

Ideally, one would need the values of the following ocean surface parameter to correctly evaluate the terms in Equation (3):

- \checkmark the sea surface salinity (SSS),
- \checkmark the sea surface temperature (SST),
- ✓ the 10 meter height wind speed and direction (U_{10}, ϕ_u)

at target T=(ϕ, ψ, t) observed at cosine director coordinates (ξ, η) and at time t.

As shown in [2], the impact of sea surface salinity and temperature on the radiometric sunglint temperatures $T_{BSg}^{p,q}(\xi,\eta,t)$ estimated using Eq. 3 was found to be negligible. For $T_{SUN}=218.000$ K, a variation of ±5 psu results in a variation of the peak's amplitude of ±0.14 K, and a variation of ±5°C results in a variation of the peak's amplitude of approximately ±0.2 K. Therefore, in a Sunglint cancellation algorithm, these two variables can be assumed to be constant and equal to globally averaged mean values: SSS= 35 psu and SST~15°C. As well, a very preliminary analysis in [2] seems to indicate that when the spill over of the sunglint area in the Extended-Alias Free -FOV region is qualitatively small, the impact of wind strength & direction is negligible.

For the implementation in the L1 algorithm we propose a solution that make use of a look up-table for the bistatic coefficients assuming the wind speed is constant and equal to 7 m/s and the sea surface is isotropic (wind direction dependence is removed). A c++ code for interpolating the LUT is provided as well. These are detailed in the following.

5.2.3.1. Lookup table for bistatic coefficients

The lookup table (LUT) is provided in a matlab .mat file named "lut.bistatic.mat". It contains bistatic scattering coefficients as a function of incoming radiation incidence angle ($\theta_o \equiv$ theta_o), relative azimuth between incoming radiation and radiometer look direction ($\varphi_s \equiv$ phi_s), radiometer incidence angle (θ_s

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≡theta_s), and wind speed (only 7 m/s for this LUT). The LUT is only function of the input parameters as given in Tables 1

Input parameter	Range	increment
Sun incidence angle θ_{ρ} [deg]	0°->90°	5°
Relative azimuth angle between sun and MIRAS observation angle φ_s [deg]	0°->360°	5°
MIRAS observation incidence angle θ_s [deg]	0°->90°	0.5°

Table I: Input parameters, range and increments needed to generate a look up table for computing the bistatic coefficients that are required for sunglint brightness temperature evaluation.

The following lists the variables in the LUT MATLAB file.

Scattering coefficients are dimensioned as:

sigma_VV_0_ssa1(theta_o, phi_s, theta_s, ws),

where:

LUT Parameter name	Description	Unit
theta_o	incoming solar radiation incidence angle	[deg, 0=nadir]
phi_s	relative azimuth between incoming and outgoing waves. This is defined as: phi radiometer - phi incoming sunradiation + 180	[deg, math convention].
theta_s	radiometer incidence angle	[deg, 0=nadir]
ws: 7	wind speed	[m/s]

For all angles we use the math convention that is positive counterclockwise from east direction.

EXAMPLE:

If radiometer is looking towards the northeast, $phi_radiometer = 45 \text{ deg}$, and if sun radiation is incident from the north, $phi_o = 90 \text{ deg}$, and so $phi_s = phi_radiometer - phi_incoming_radiation + 180 = phi_radiometer - phi_o + 180 = 45-90 + 180 \text{ deg} = 135 \text{ deg}$.

Ancillary data used to generate the LUT:

freq: 1.4130e+09: assumed radiometer frequency [Hz]



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sss: 35: s	ea sfc salinity [PSU]
sst: 15: s	ea sfc temp [degC]
freq_units: 'Hz':	frequency units
sss_units: 'PSU':	SSS units
sst_units: 'degC'	SST units
ws_units: 'm/s':	wind speed units
theta_o_units: 'd	eg': units for incoming radiation incidence angle [deg, 0=nadir].
phi_s_units: 'de [deg, math conv	g': units for relative azimuth between incoming and outgoing waves ention].
theta_s_units: 'd	eg': units for radiometer incidence angle [deg, 0=nadir].
dielectricModel:	'KleinSwift': name of dielectric constant model used
waveModel: 'Ku	dryavtsev 1999': name of wave model used for roughness

Coordinate dimensions for the 4D LUT:

theta_o: [1.0000e-03 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90] phi_s: [1x73 double] (0-360 deg by 5 deg and overlapping endpoints). theta_s: [1.0000e-03 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90] ws: 7

Scattering coefficients:

sigma_VV_0_ssa1: [19x73x19 double]: VV-pol bistatic scattering coefficient sigma_VH_0_ssa1: [19x73x19 double]: VH-pol bistatic scattering coefficient sigma_HV_0_ssa1: [19x73x19 double]: HV-pol bistatic scattering coefficient sigma_HH_0_ssa1: [19x73x19 double]: HH-pol bistatic scattering coefficient

Note: Due to limitations in the LUT generation, scattering coefficients for theta_s below 15° are not considered reliable (can even be negative), so all scattering coefficients requested for an angle below 15° shall be set to zero.

5.2.3.2. Cubic Hermite Interpolation code

Particular care shall be taken when interpolating rough sea surface bistatic coefficients from a LUT. The LUT input parameters are sampled at 5° steps for the incident/scattering directions, and very small changes in these angles around the specular direction make very significant and nonlinear changes in calculation of the bistatic scattering coefficients. Performing a multi-linear interpolation from the LUT to estimate the scattered signals is therefore not recommended as it might generate severe

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underestimation in the specular direction. As illustrated in Figure (21), spline interpolation is much more accurate.



b)



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c)

Figure 5-1: Error due to interpolation method. (a): Example of true and interpolated Bistatic Coefficient in VV. (b) zoom around the specular direction. (c) interpolation error in Decibels.

Although spline interpolation method is working correctly it is cpu time consuming. To avoid the interpolation errors and to keep the calculation time small, we recommend using a Cubic Hermite interpolation routine to evaluate the bistatic coefficients at given values from the LUT file. We provide C^{++} code to interpolate the LUT using cubic Hermite interpolation:

bistaticHarmonics_SSA1_KA.cc: C++ code to interpolate the LUT using cubic Hermite interpolation. *bistaticHarmonics_SSA1_KA.mexglx*:* C++ code compiled on a Fedora Core 3 platform.

STEPS FOR INTERPOLATION:

1) Establish a grid of points at which to interpolate.

Points are determined by a set of coordinate arrays:

theta_o: incidence angle of incoming sun radiation [deg].

phi_s: difference between radiometer look direction and incoming radiation azimuth angles [deg] (radiometer - incoming) + 180 deg.

theta_s: radiometer (or scattered radiation) incidence angle [deg].

ws: wind speed [m/s].



Angles use the math convention (positive counter clockwise). Note that the azimuth angle convention is such that if the outgoing wavevector is oriented in the same direction as the incoming wavevector, its angle relative to the incoming wavevector is 180 deg. This corresponds to radiation leaving the surface in the direction opposite that of the incoming radiation.

The points may be arranged however you like (vector, matrix), but each coordinate array must be one of the following:

- an array of length greater than one with the same dimensions

as all other arrays greater than length one, or

- one constant value

2) Call the MATLAB mex function bistaticHarmonics_SSA1_KA(). Input parameters are as follows:

ws: [361x1441 double]: wind speed [m/s].

The result will be a structure containing these variables (depending on options, only some of these may exist):

svv0_ssa1: [361x1441 double]:	VV-pol scattering coefficient
svh0_ssa1: [361x1441 double]:	VH-pol scattering coefficient
shv0_ssa1: [361x1441 double]:	HV-pol scattering coefficient
shh0_ssa1: [361x1441 double]:	HH-pol scattering coefficient
theta_o: [361x1441 double]: if	ncoming sun radiation incidence angle [deg].
phi_s: [361x1441 double]: c azimuth angle + 180 [deg] (rad look	difference between radiometer look direction and incoming radiation k dir - incoming + 180 deg).
theta_s: [361x1441 double]: s	cattered radiation incidence angle [deg].
ws: [361x1441 double]: wi	nd speed [m/s].



5.2.3.3. Launch baseline

Despite what has been mentioned in the previous chapter, the preferred option for interpolation within the LUT shall be a simple linear interpolation between the two closest points. As we are dealing with a 3D LUT, this shall be a tri-linear interpolation between the 8 points delimiting a cube.

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6. ANNEX 2: DETAILED DESCRITION OF FOREIGN SOURCES CORRECTION ALGORITHM IMPLEMENTATION

This annex presents a detailed description of some of the functions of the FSC Module. It describes in particular the functions used for removing the different sources.

6.1. getEarthAndSkyPixelsList

This function gets the position, velocity and attitude information from L1a HKTM data and determines the Earth contour using CFI functions. The contour is then interpolated to the (ξ, η) grid being used. The pixels inside the contour are considered Earth, while the remaining ones are considered Sky. For the Square grid, the pixels outside the Unit Circle are ignored.

```
getAOCSData( &aocs_data, obet)
getPVTDataLlb( &pvt_data, obet)
initialiseAttitude(pvt_data, aocs_data, &attitude_id)
for(azimuth = 0; azimuth < 360; azimuth ++) {
   get Earth Contour using xp_target_altitude and xp_target_extra_main functions
}
determine pixels in the front and on the back that correspond to the Earth
determine pixels in the front and on the back that correspond to the Sky</pre>
```

It should be highlighted that when computing the contour of the earth, part of the (ξ, η) pixels corresponding to the contour can actually be on the back of the instrument. For instance, the figure below presents the contour for a tilt angle of 60°:



Figure 6-1: Contour of the earth computed using the xp_target_altitude CFI function

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What is shown in the previous figure is that part of the earth contour ellipse that appears projected in the unit circle belongs to the back of the instrument (segment of the ellipse between "tangent point 1" and "tangent point 2", with negative elevation). Therefore, for the ellipse pixels that have negative elevation, the contour will appear on the back. That means that, in the previous figure, we will have the following pixels corresponding to the Earth on the front and on the back:

- 1. Pixels with Earth on the front: grey area + interior of the ellipse;
- 2. Pixels with Earth on theback: grey area.

6.2. getSunDirectContribution / getMoonDirectContribution

Both functions getSunDirectContribution and getSunDirectContribution call a more generic function getBodyDirectContribution which receives as input argument the type of Body (Sun/Moon) and computes the visibilities corresponding to the Sun/Moon for subtracting to the calibrated visibilities the Sun/Moon temperature to the vector containing the Brightness Temperatures of the different sources. The following algorithm is executed:

```
T_sun = computeBodyDirectBt ( &aocs_data, obet );
V_sun_1k = getBodyOneKelvinVisibilities (pvt_data, aocs_data, g_matrix_filename)
V_sun = T_sun * V_sun_1k // Eq. 22
```



The function computeBodyDirectBt is described below:

```
getAOCSData( &aocs_data, obet);
getPVTDataL1b( &pvt data, obet)
getBodyPositionInAntennaFrame( snapshot_time, pvt_data, aocs_data,
                                body_type, body pos in AF);
If (Elevation < 0) Set Flag BODY_IN_THE_BACK and return
If (checkIfBodyIsEclipsedByEarth() == TRUE) Set Flag BODY ECLIPSED BY EARTH and return
// Compute The Body Brightness Temperature
switch ( sun_bt_algorithm/sun_bt_algorithm ) {
 case DEFAULT :
      setDefaultBodyTemperature;
     break;
 case READ FILE :
      readBodyTemperatureFromFile;
     break;
 case ESTIMATE :
      estimateBodyTemperatureFromVisibilities
}
Add determined Sun/Moon Brightness Temperature to the Brightness Temperatures vector
```

The function estimateBodyTemperatureFromVisibilities performs the Sun self estimation described in Section 2.2.2.1.5, paragraph "Estimation of the Sun Brightness Temperature from the Visibilities":



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For performing all the computations, the functions getBodyOneKelvinVisibilities and computeIFFT2 are also needed. These functions are described below:

The getBodyOneKelvinVisibilities function is described in detail in Section 2.2.2.1.5, paragraph "*Computation of the Sun/Moon visibilities corresponding to a 1K source*". Below is a summary, for the 4-point case:



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```
V 1k = getBodyOneKelvinVisibilities(body position, g matrix)
£
GMAT column = get g-mat column corresponding to the body position in xi, eta
V 1k = GMAT column corrected copolar + GMAT column corrected cross polar
GMAT column corrected = GMAT column * [ OF * (1/dS GMAT) ] * OMEGA BODY *
           * { 1 + [ j*(w''/2) - (1/(12*pi)) - (pi/2)*(u''^2 + v''^2)]*OMEGA BODY } *
           * exp_term_sun / exp_term_grid
      OMEGA BODY = Beta^2 * (180/pi) * (pi/4) - is the sun/moon solid angle, and Beta is
Where
0.586^{\circ} for the Sun and 0.5^{\circ} for the Moon;
 dS GMAT
               - is the pixel area in the GMAT grid: 2/(sqrt(3) NT^2 d^2)
 u'', v'' and w'' - correspond to the baselines coordinate transformation of needed
                   for passing from (Xi, Eta) to (theta, phi) domain.
 exp_term_sun = exp( -i*2*pi*( u * xi_sun + v * eta_sun + w * OF_sun) )
 exp_term_grid = exp( -i*2*pi*( u * xi_sun_grid + v * eta_sun_grid + w * OF_sun_grid)
The transformation (u, v, w) \rightarrow (u'', v'', w'') is computed as follows
   u''
          = cos(theta)*cos(phi)*u + cos(theta)*sin(phi)*v - sin(theta)*w;
          = -\sin(phi) * u
   v''
                                     + cos(phi)*v;
   w''
          = sin(theta)*cos(phi)*u + sin(theta)*sin(phi)*v + cos(theta)*w;
```

6.3. getSunGlintContribution

The Sun Glint Contribution is removed applying the algorithm described in Section 2.2.2.1.6 and presented in more detail in Annex 1. The getSunGlintContribution receives as main inputs the time, the flag for switching On/Off the removal of sun glint, the list of pixels representing the Earth and the previously determined temperature of the sun.

The following steps are then performed:



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// Read HKTM Data
1. getPVTDataL1b(&pvt, time);
2. getAOCSData(&aocs, time);
// Use xl_sun CFI function
<pre>3. getSunPositionInEF(time, sun_position_EF);</pre>
// Use xp_target_inter, xp_target_extra_main and xp_target_extra_vector CFI functions
<pre>4.getPixelsPositionInEF(pvt, aocs, earth_xi_eta_list, &earth_pixels_position);</pre>
// Use Get Grid Function fom Data Provider
<pre>5. getLandSeaFlag(snapshot_time, &earth_pixels_position);</pre>
//Use getPixelAngles, xp_target_generic and xp_target_extra_target_to_sun functions
<pre>6. getScatteringAngles(&pvt_data, &aocs_data, &earth_pixels_position,</pre>
<pre>&scattering_angles_list) ;</pre>
// Get Coefficients from cache and Interpolate them
<pre>7. retrieveScatteringCoefficients(time, &scattering_angles_list, &scattering_coeffs_list);</pre>
For each pixel with landsead_flag = PIXEL_SEA
Apply Equations 37 and 38
Add the Sun Glint Brightnes Temperature to the vector containing the diffent sources
End

6.4. getReceiversContribution

This function simply computes the receivers' average physical temperature for each scene and stores this information in the vectors receivers_average_temp and receivers_BT_vector. The temperature of the receivers is stored in the L1a HKTM products.

The vector receivers_average_temp is used by the Backlobes function for removing the Receivers temperature contribution to the backlobes visibilities and the receivers_BT_vector is used later for determining the Receivers visibilities as described in section 3.3.5.

6.5. getBacklobesContribution

The backlobes brightness Temperature is determined as described in section 3.3.4. The function getBacklobesContribution receives as main inputs the flag backlobes (for activating/deactivating the removal of the backlobes contribution), the average receivers physical temperature and the structure foreign_sources_data->scene[i] containing all the flags and



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information about the previously computed Sun and Moon Brightness Temperature. If the flag backlobes is set to "true", the functions first computes the brightness temperatures distribution on the back of the array and then computes the corresponding visibilities using the average antenna pattern from the back Fn back:

```
Tb_back = computeBacklobesBtVector
V_back(i,j) = SUM in(xi, eta) {(1/OF(xi,eta)) * (Fn_back(Xi,Eta)*Fn_back_conj(Xi,Eta))
 * exp{-j*2*pi* (u*Xi + v*Eta + w*OF(Xi,Eta)) } * dXi*dEta * (Tb_back) }
```

The function computeBacklobesBtVector performs the following algorithm:

```
if (foreign_sources_data->scene[i].sun_flag == BODY_IN_THE_BACK) {
    Add foreign_sources_data->scene[i].sun_bt to Tb_back
}
if (foreign_sources_data->scene[i].moon_flag == BODY_IN_THE_BACK) {
    Add foreign_sources_data->scene[i].moon_bt to Tb_back
}
getEarthAndSkyPixelsListInTheBack(&back_earth_xi_eta, &back_sky_xi_eta);
for pixels in &back_earth_xi_eta Add 290K to Tb_back // 290 can be configured
for pixels in &back_sky_xi_eta Add 3,5K to Tb_back // 3,5 can be configured
for all pixels Add -receivers_average_temperature to Tb_back // Term -Trec
```



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7. ANNEX 3: REFERENCE FRAMES

This annex presents a small overview of the reference frames in SMOS and particularly in L1OP.



Figure 7-1: Reference frames in SMOS

The H-polarisation direction corresponds to the Arm A. In the clockwise direction of V-polarization lie Arms B and C, resp.

The MIRAS coordinate frame is defined as

The PLM coordinate frame is defined as a reference frame centred on the HUB and with:

- x-axis positive in the direction LICEF NIR BC 03 to LICEF BC 01;
- y-axis and positive in the direction of the axis contained between arms A and B;
- the direction formed by the natural normal vector to the XY plane;

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The PLM frame is used to compute the (ξ, η) coordinates witch L1OP uses to associate all inverse Fourier Transformed Temperatures at this level.



Figure 7-2: More reference frames in SMOS (adapted from DTU)



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8. ANNEX 4: ARTIFICIAL SCENE INTERPOLATION

When computing the Gibbs 2 artificial scene, the Water Fraction values in the DGG have to be bilinearly interpolated to the projected Artificial Scene pixel position in the DGG. However, since the DGG is an irregular grid, a specific function had to be implemented, according to the method described by Anthony R. Hinson in [RD.28].

Since this code is not available in any standard library its full implementation is presented below:

<u>//</u>
<pre>// FUNCTION : irregularBilinearInterp()</pre>
// DESCRIPTION : Interpolate P over an irregular grid
<u>// :</u>
// DATA IN : Input surrounding points must be set from upper to bottom
<pre>// : and left to right:</pre>
// : surrounding_x[0] -> UPPER LEFT
// : surrounding_x[1] -> UPPER RIGHT
// : surrounding_x[2] -> BOTTOM LEFT
// : surrounding_x[3] -> BOTTOM RIGHT
_ <u>// :</u>
// : Considering distance s -> percentage along the vertical sides to point P
// : and distance t -> percentage along the horizontal sides to point P
· <u>// :</u>
// : With a significant bit of algebra we can calculate distance t
// : as the solution of the equation of second order polynomial
· <u>// :</u>
// : At ² + Bt + C = 0
// DATA INOUT :
· <u>// :</u>
// DATA OUT :
· <u>// :</u>
// RETURN : Value interpolated
· <u>// :</u>
<u>//</u>
double irregularBilinearInterp(const double Px,
const double Py,
<pre>const double* const surrounding_x,</pre>
<pre>const double* const surrounding_y,</pre>
<pre>const double* const surrounding_value)</pre>
<u>1</u>



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/*	*/				
/* 1. Variables declaration + Initialization*/					
/* */					
double s = 0.;					
double t = 0.;					
double t1 = $0.;$					
double t2 = 0.;					
double s1 = 0.;					
double s2 = $0.;$					
double A = 0.;					
double B = 0.;					
double C = 1.;					
double $x1 = 0.;$					
double $x2 = 0.;$					
double x3 = $0.;$					
double y1 = 0.;					
double $y2 = 0.;$					
double y3 = 0.;					
double $x21 = 0.;$					
double $x31 = 0.;$					
double $x42 = 0.;$					
double $x43 = 0.;$					
double $y21 = 0.;$					
double $y31 = 0.;$					
double $y42 = 0.;$					
double $y43 = 0.;$					
bool is vertical parallel	= false;				
bool is_horizontal_parallel	= false;				
bool is_method1	= false;				
bool is method2	= false;				
bool is_method3	= false;				



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Code

:

/ $/$ $/$ $/$ $/$ $/$ $/$ $/$ $/$ $/$
/* */
x1 = surrounding x[0];
$x^{2} = surrounding x[1];$
$x^3 = surrounding x[2];$
<pre>x21 = surrounding_x[1] - surrounding_x[0];</pre>
x31 = surrounding_x[2] - surrounding_x[0];
<pre>x42 = surrounding_x[3] - surrounding_x[1];</pre>
<pre>x43 = surrounding_x[3] - surrounding_x[2];</pre>
<u>y1 = surrounding y[0];</u>
<u>y2 = surrounding_y[1];</u>
y3 = surrounding_y[2];
y21 = surrounding_y[1] - surrounding_y[0];
y31 = surrounding_y[2] - surrounding_y[0];
y42 = surrounding_y[3] - surrounding_y[1];
y43 = surrounding_y[3] - surrounding_y[2];
/* */
/* 3. Check which method to apply */
$\frac{7}{15} \text{ vertical parallel} = (((x31 * y42) - (x42 * y31)) == 0.);$
$\frac{7}{15} = \frac{1001200141}{1001200141} = \frac{1}{1001} \left(\frac{1001}{1001} + \frac{1001}$
$\frac{15 \text{ vertical parallel}}{16 \text{ parallel}} = (1205((x21 + y42) - (x42 + y31)) <= 1.0e^{-3});$
is method1 = ((!is vertical parallel & !is horizontal parallel)
(!is vertical parallel & is horizontal parallel));
<pre>is_method2 = (is_vertical_parallel & !is_horizontal_parallel);</pre>
<pre>is_method3 = (is_vertical_parallel & is_horizontal_parallel);</pre>



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/* */
/* 3a. Perform calculations according to */
/* methods */
/* */
if (is_method1) {
/* */
/* 4. Calculate the second order equation*/
/* coefficients */
/* */
A = (x31 * y42) - (y31 * x42);
B = (Py * (x42 - x31)) - (Px * (y42 - y31)) + (x31 * y2) - (y31 * x2) + (x1 * y42) - (y1)
* x42);
C = (Py * x21) - (Px * y21) + (x1 * y2) - (x2 * y1);
/* */
/* 5. Calculate the equation solutions */
/* */
t1 = (((-1) * B) + sqrt((B * B) - (4 * A * C))) / (2 * A);
t2 = (((-1) * B) - sqrt((B * B) - (4 * A * C))) / (2 * A);
/* */
/* 6. Check which solution is between 0 */
/* and 1. If not set output NaN */
/* */
$if ((t1 \ge 0, \delta\delta t1 \le 1.)) $
t = t1:
$\frac{1}{1}$
$\frac{1}{1} = \frac{1}{1} \left(\frac{1}{1} \left(\frac{1}{1} \right)^2 - \frac{1}{1} \left(\frac{1}{1} \right)^2 \right)^2$
$\frac{t = t_2}{2}$
else {
// is_nan = true;
return ((double) (0.0 / 0.0));
<u>}</u>
/* */
/* 7. Calculate distance "s" (percentage) */
/* */
s = (Py - y1 - (y31 * t)) / (y2 + (y42 * t) - y1 - (y31 * t));


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else if (is method2) {			
/* */			
/* 4. Calculate the second order equation*/			
/* coefficients */			
/* */			
A = (x21 * y43) - (y21 * x43);			
B = (Py * (x43 - x21)) - (Px * (y43 - y21)) + (x1 * y43) - (y1 * x43) + (x21 * y3) - (y21)			
<u>* x3);</u>			
C = (Py * x31) - (Px * y31) + (x1 * y3) - (x3 * y1);			
/* */			
/* 5. Calculate the equation solutions */			
/* */			
s1 = (((-1) * B) + sqrt((B * B) - (4 * A * C))) / (2 * A);			
s2 = (((-1) * B) - sqrt((B * B) - (4 * A * C))) / (2 * A);			
/* */			
/* 6. Check which solution is between 0 */			
/* and 1 */			
/* */			
if ((s1 >= 0. && s1 <= 1.)) {			
s = s1;			
<u>}</u>			
else if ((s2 >= 0. && s2 <= 1.)) {			
s = s2;			
}			
else {			
<pre>// is_nan = true;</pre>			
return ((double) (0.0 / 0.0));			
<u>}</u>			
/* */			
/* 7. Calculate distance "t" (percentage)*/			
/* */			
$t = (P_y - y1 - (y21 * s)) / (y3 + (y43 * s) - y1 - (y21 * s));$			



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else if (is_method3) {				
/* */				
<pre>/* 7. Calculate distance "t" and "s" (percentage)*/</pre>				
/* */				
s = (((Px * y31) - (x1 * y31) - (x31 * Py) + (x31 * y1)) / ((y31 * x21) - (x31 * y21))				
<u>);</u>				
t = ((-Px * y21) + (x1 * y21) + (Py * x21) - (x21 * y1)) / ((y31 * x21) - (x31 * y21));				
<u>}</u>				
/* */				
/* 8b. Return interpolated value using the*/				
/* standard bilinear interpolation */				
/* formula */				
/* */				
return ((surrounding_value[0] * (1 - s) * (1 - t)) +				
(surrounding_value[1] * s * (1 - t)) +				
(surrounding_value[2] * (1 - s) * t) +				
<pre>(surrounding_value[3] * s * t));</pre>				
- }				