SMOS L1 System Concept

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1. INTRODUCTION

1.1. Purpose and Scope

This document describes the System Concept designed for the SMOS L1 Processor Prototype. It contains detailed context diagrams of the overall Processor, and subsequent divisions into particular items.

1.2. Acronyms and Abbreviations

AOCS	Attitude and Orientation Control System
API	Application Program Interface
BFP	Best Fit Plane
BT	Brightness Temperature
FTT	Flat Target Transformation
FWF	Fringe Washing Function
HKTM	Housekeeping Telemetry
I-HKTM	Instrument Housekeeping Telemetry
IGRF	International Geomagnetic Reference Field
IRI	International Reference Ionosphere
FOV	Field of View
L1PP	Level 1 Processor Prototype
NIR	Noise Injection Radiometer
PLM	Payload Module
PMS	Power Measurement Signal
PVT	Position, Velocity, Time vector
TEC	Total Electron Content
UTC	Universal Time

For the list of acronyms, please refer to the "Directory of Acronyms and abbreviations" [RD.8].

1.3. Applicable and Reference Documents

1.3.1. Applicable Documents

Ref.	Code	Title	Issue
AD.1A D.1	SO-SOW-CASA-PLM-0855SO-SOW-CASA-PLM-0380	Level 1 Processor Prototype Development Phase 3 and Support and Analysis Activities. Statement of WorkLevel 1 Processor Prototype Development Phase 2 and Support Activities. Statement of Work	1.001
AD.2	SPS-TN-GMV-PL-0003	SMOS End-to-End Performance Simulator (SEPS) Architectural and Detailed Design Document	4.1
AD.3	SO-RS-ESA-PLM-0003	SMOS System Requirements Document	3.0
AD.4	SMOS-TN-IDR-GS-0005	SMOS L1 and ADF Product Specification	5.17
AD.5	SO-TN-CASA-PLM-0017	SMOS Payload Technical Description	4
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
AD.8	ECSS-E-40B	ECSS E-40 Software Engineering Standards	
AD.9	SO-TN-DME-L1PP-0007	SMOS L0 to L1a Detailed Processing Model	2.13
AD.10	SO-TN-DME-L1PP-0012	SMOS L1 Processor Prototype Architecture Design document (obsolete, included in DPMs)	1.3
AD.11 AD.10	SO-SOW-ESA-GS-6647SO-TN-DME-L1PP-0012	SMOS Expert Support Laboratories for the period 2010-2014 - ESL Level 1 Calibration and ReconstructionSMOS L1 Processor Prototype Architecture Design document	1.21.3

Table 1: Applicable Documents

1.3.2. Reference Documents

Ref.	Code	Title	Issue
RD.1	EE-MA-DMS-GS-0001-1-5_090313	Earth Explorer Mission CFI Software MISSION CONVENTIONS DOCUMENT	1.4
RD.2	PE-TN-ESA-GS-0001	Earth Explorer Ground Segment File Format Standard	1.4
RD.3	EE-MA-DMS-GS-0002-3-7-2_080731	Earth Explorer Mission CFI Software GENERAL SOFTWARE USER MANUAL	2.2
RD.4	SMOS-DMS-TN-2300	SMOS L1 Input Data Description Report	1.3
RD.5	SMOS-DMS-TN-3210	Trade-off methodology and Summary Report	1.3

Ref.	Code	Title	Issue
RD.6	SPA-CAS-20200-TNO-001	System Performance Modelling	1.2
RD.7	SO-TN-CASA-PLM-0279	SMOS Command and Control	2.5
RD.8	SO-LI-CASA-PLM-0094	Directory of Acronyms and abbreviations	
RD.9	SMOS-DME-TN-4300	SMOS L1 Processor Computer Resources Requirements Document	1.1
RD.10	SO-IS-DME-L1PP-0002	SMOS L1 Product format Specification	2.3
RD.11	SO-DS-DME-L1PP-0011	SMOS L1 Algorithm Theoretical Baseline	2.107
RD.12	SO-TN-DME-L1PP-0024	SMOS L1 Full polarisation processing Technical note	1.5

Table 2: Reference Documents

2. SYSTEM CONCEPT CRITERIA

The following document describes the System Concept for the SMOS L1 Processor Prototype, detailing the processing flows and the required modules.

This document is the first design level of the SMOS Level 1 Processor Prototype, and as such shall be used, as shown in the figure below, to provide the basis for the architecture document and Detailed Processing Models.

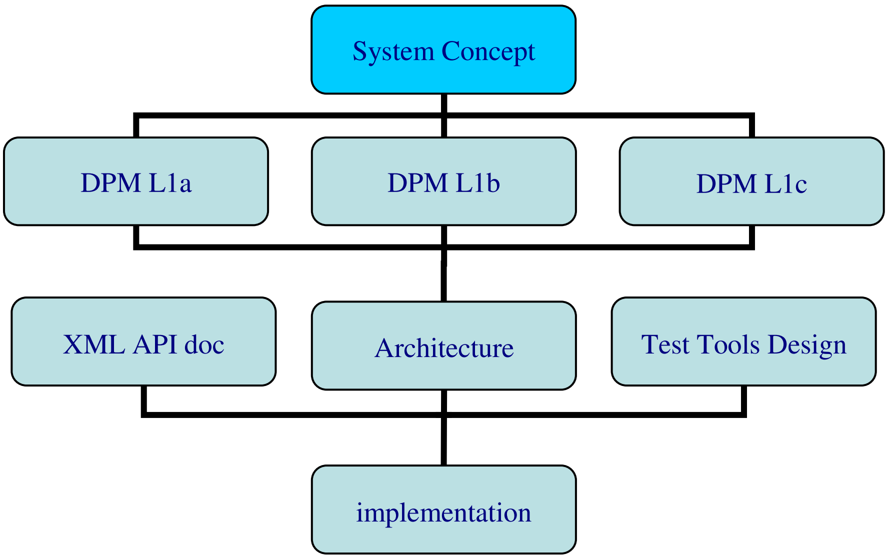

Figure 1: Design documents

The Processing Flow per instrument mode, has been produced using basically three types of diagrams:

- ***Data Flow Diagrams***: which identify the different processing steps, as well as the major inputs/outputs for each processing step. There are three different decomposition levels proposed, each including more detail than the previous one. The criteria adopted for representing items has been the following:
  - Processing functions: represented as blue circles. They are SW items tasked with ingesting and processing the input data into output data.
  - Auxiliary data: represented as green skewed boxes. They are external data required by the processing modules, meaning that this data is not produced within the L1 Processor nor produced by the PLM
  - L1 data: represented as yellow cylinders. They are data received from the L0 and transformed by the processing modules into more refined levels of L1, meaning that they are produced within the L1 or L0 Processors

- Interfaces: represented as arrows between items. In some cases the main flow is identified by a bolder arrow.

- ***Sequence Diagrams***: which indicate the sequence of the different tasks to be performed for the processing. A Sequence Diagram has been generated for the overall processing, in order to indicate the detailed sequence of processing and algorithms execution within each processing step.
- ***Context Diagrams***: which indicate the location of the L1 Processor within the rest of the elements of the DPGS.

3. SYSTEM CONCEPT FIRST DECOMPOSITION LEVEL

3.1. Context Diagram

The context diagram for this first decomposition is presented in the following figure, representing the main interfaces of the L1 Processor.

The purpose of the SMOS L1 Processor is to convert the MIRAS instrument outputs into Brightness Temperature measurements, geolocating them and providing observation angles and additional parameters.

The inputs to the processor shall be the SMOS raw data coming from the Front End Processor located at the SMOS PDPC, as well as data from the Auxiliary Data Server from which the auxiliary data is retrieved, such as calibration tables, TEC models… The L0 Processor shall be embedded into the L1, tasked with splitting the FEP raw data and consolidating it into appropriate L0 Products. L1A ancillary data needed for internal processing, like spacecraft position and attitude, is obtained from the Level 0 Ancillary data (I-HKTM) and refined to ease accessibility. The outputs of the L1 Processor shall be the intermediate and final products produced all along the processing steps, and shall be sent to both the PDPC Archive for storage and to the L2 Processor.

By convention, ancillary data is produced on board the satellite, and is formed by data not part of the scientific data. When the ancillary data is received on the ground, and packaged with the Ground Segment header (according to Earth Explorer File format) it becomes Auxiliary Data.

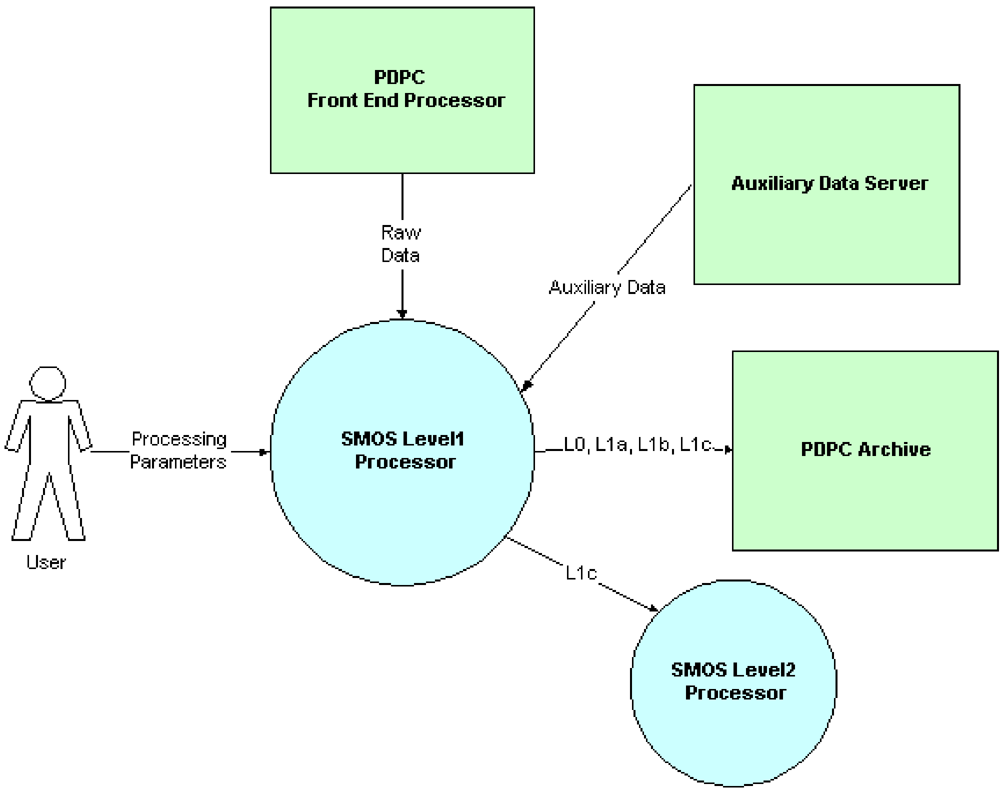

Figure 2: SMOS L1 Processor Context Diagram

3.1.1. L0 Processor

The data as it is generated by the Front-End Processor shall be consolidated into blocks of Source Data Packets aggregated by APID. This means that after every data dump to the operational Ground Station, there shall be one binary file per APID mode, containing all the Source Packets of that APID type downloaded in that pass. These Source Packets shall be ordered according to timestamp and Packet Sequence Control counters.

These Source Packets shall include all the packets generated since the last pass, and all the others stored on-board but not downloaded in the previous pass. Sensing times of the packets shall depend on the Downlink Scenario selected for operation.

It shall be the task of the L0 Processor to consolidate this data on a half-orbit basis, and to provide an XML ASCII header to each resulting product, so that at least basic time (start and end of sequence) and mode information can be extracted without the L1 Processor need to decode the Source Packets inside the file.

The data passed to the L1 Processor shall be these L0 Products, containing the data for each instrument mode and consolidated into an ascending or descending pass.

A processing strategy has been derived from this input condition, such that the L1 Processor gives precedence to the calibration measurements and processes them first. This shall enable having all the calibration coefficients in place for calibrating the nominal measurements.

3.2. Data Flow Diagrams

The data flow diagram for this first decomposition level is presented in Figure 3. MIRAS may operate in two different modes: dual and full polarisation. In dual polarisation mode, all receivers are set to the same polarisation (Horizontal or Vertical); in full polarisation mode, receivers are alternated between H and V polarisation according to a timeline scheme described in [AD.3]. No distinction is made at this level between both instrument modes. The differences in their processing approaches are located in the ordering and consolidation of calibrated visibilities before reconstruction as detailed in [RD.12].

The main module for producing L1a products is the Error Correction and Calibration module, where the L0 Science Data (CORR-TM) are calibrated and corrected before they are sent to the Image Reconstruction module. Calibration is based on coefficients built also from L0 Science Data when the instrument is operating in Calibration and Measurement mode as well as from Ground measurements. These measured in-flight calibration coefficients shall be set in L1a auxiliary products to make them more accessible to other modules, rather than accessing L0 data every time some parameter is needed. This module shall also be in charge of converting the L0 Ancillary data (I-HKTM) into a usable L1a format after converting data to engineering units.

An additional module for correcting foreign sources influence in the Brightness Temperature (BT) retrieval is needed as well. Its purpose is to compute the visibilities resulting from the Sky, Sun and Moon contribution when they enter the FOV through aliases or reflected over the Earth's surface. This module shall reconstruct in a rough approximation the scene in order to compute a first estimate of the Sun truth (Sun Brightness Temperature)in the direct and reflected Sun position. This module shall also be used to remove contributions from antenna back-lobes, provided the full antenna patterns are measured and an estimate of the BT scene behind the instrument is computed. Flat Target

Transformation shall also be performed in this module, subtracting from the calibrated visibilities previously measured correlations from a deep sky scene.

The Image Reconstruction module presented here is a generic one. It shall be basically in charge of converting the calibrated visibilities of each snapshot (L1a) into Brightness Temperature Fourier Components (L1b). A baseline for two independent algorithms is available, both based on G Matrix approaches. Details shall be given in a later decomposition about the different approaches available, the data needed for each, and its advantages and limitations.

These reconstructed BT Frequency values shall be used later by the Geolocation module, in order to extract BT at Top of Atmosphere centred over an Earth Fixed Grid. This Geolocation module shall perform the interpolation and apodisation in one single step, using a Discrete Fourier Transform to particularise the BT values over each pixel. In this module it shall be possible to activate the strip-adaptive processing, which circularises the footprints on the ground, at the cost of an increase in the number of operations to be performed (i.e. processing time).

The Ionospheric Correction module shall compute the Total Electron Content (TEC) and geomagnetic angles for each snapshot, and pass it to the Geolocation module. This last module shall compute the Faraday rotation angle for each pixel, based on these values plus the S/C to pixel angles.

In the following figure, the main flow of nominal measurement L1 products has been highlighted in the arrows going from one module to another.

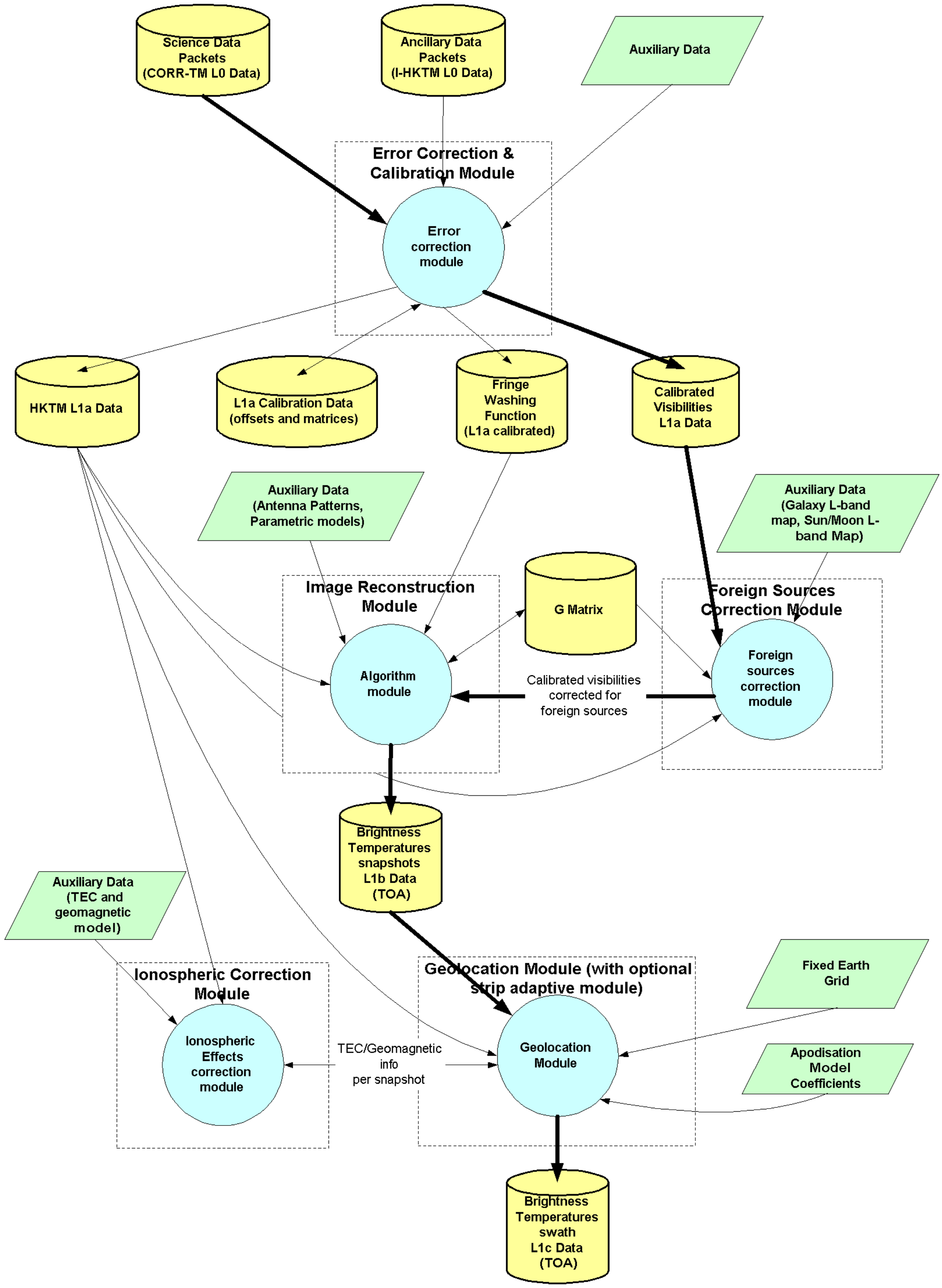

Figure 3: Processing Data Flow Diagram

The above figure represents an overall version of the different major processing steps, as well as the main inputs, outputs and intermediate results at each step. Further explanations about this processing flow are included in next section.

In the above diagram, inputs in yellow cylinders represent the dynamic data generated by the L1 Processor as well as the L0 Processor. Inputs in green skewed squares represent the static data used in the L1 Processing, available from manufacturer sources and on-ground measurements. Of this data, there is only one that may be available dynamically, which is the TEC measurements. This data is available with a periodicity of 24h, although there is a TEC model built into the L1 Processor as a fallback option.

The data representations shall be expanded in the corresponding chapters of section 4, to account for all the required inputs.

3.3. L1 Processor Concept Description

According to the data flow definition previously described, a concept of the L1 processor is shown in the following figure. In this figure, the main tasks of the processor are represented, as well as the main input and output data on each.

Input data is located in the green left column, output data is located in the pink right column, and the processing steps are located in the middle column. The main information passed between steps has been explicitly drawn as arrows between processes. It must be noted that some of the input data at later levels is produced as output data in earlier processes, like HKTM L1a, or L1a Calibration data within the Error Correction Module.

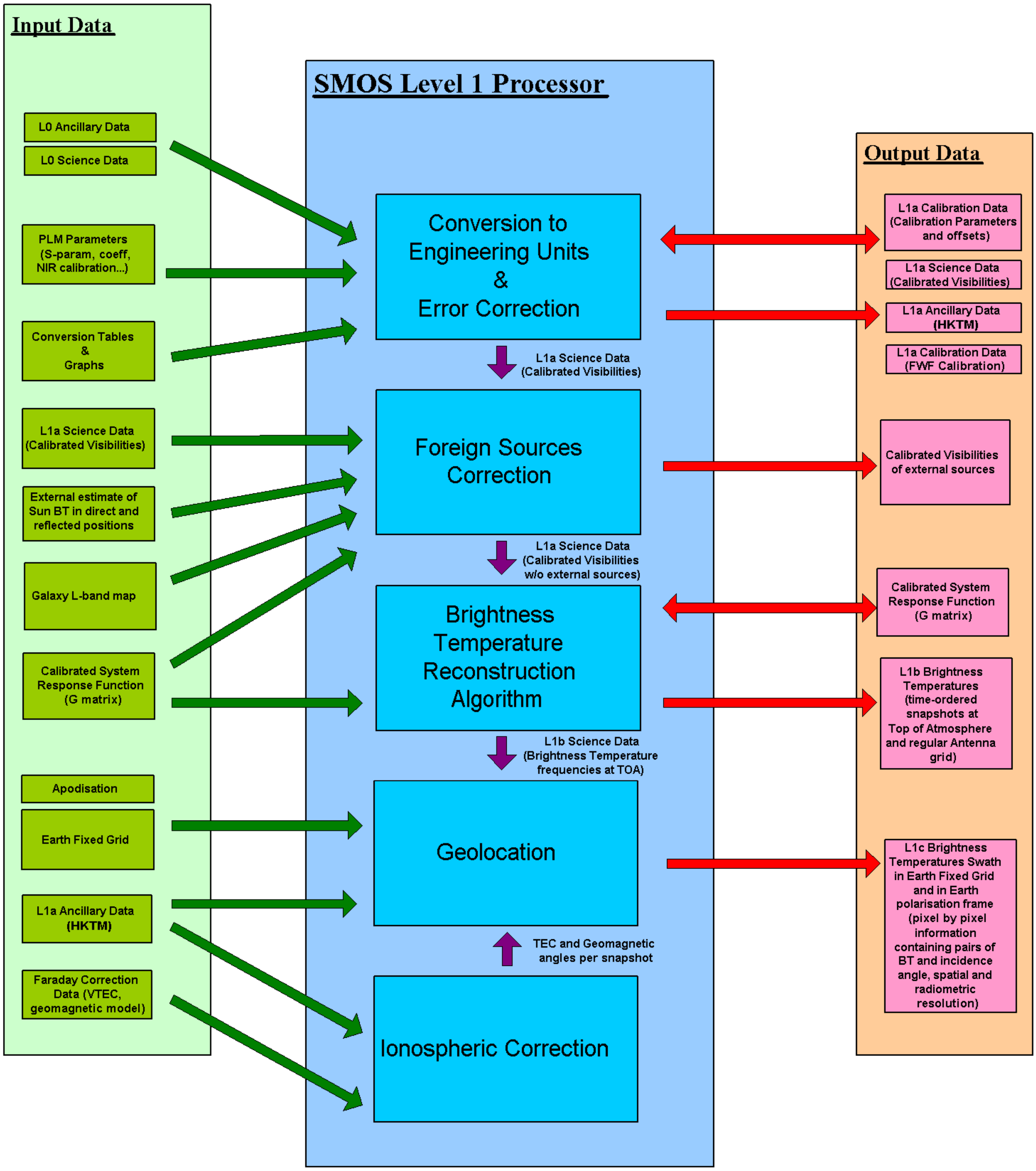

Figure 4: SMOS L1 Processor Concept

As a starting point in the development of the Level 1 Processor Prototype, the entry point shall be L0 Products, already formatted and consolidated by a L0 Processor, such that the Level 1 Processor would only need to use its outputs, namely L0 Ancillary Data (I-HKTM) and L0 Science Data (CORR-TM).

The L0 Processor that would be required for the nominal processing, shall only need to ingest the raw data as produced by the Front End Processor, consolidate it on a half-orbit basis (ascending or descending passes) and generate the corresponding ASCII XML header for each L0 product.

The L0 data to be processed contains the Ancillary and Science Data Packets. The former contain information on the Spacecraft and instrument, while the latter contains the raw correlations measured by the instrument. The APID within each packet shall indicate the operation mode of the instrument.

- **L1a Processing**

The first step of the L1 Processor shall be to convert all data coming from the spacecraft into engineering units appropriate for following computations (e.g. pulse length of NIR transformed into output power using manufacturer tables or graphs).

Calibration data shall be also produced; consisting on the correlators' output when the instrument is receiving uncorrelated or correlated noise, or the NIR measurements when imaging an external target (i.e. the Deep Sky).

Calibration measurements during noise injection shall produce correction factors (offsets and calibration parameters) to be used in the computation of the calibrated visibilities. The raw instrument's output in measurement mode (dual polarisation or full polarisation) shall be calibrated using those parameters and the physical temperature of the systems involved extracted from the I-HKTM. These calibrated visibilities shall be calculated for each integration time, time-tagged and time-ordered.

From the calibration measurements during Noise Injection, it shall be also possible to extract an estimated value of the Fringe Washing Function at three different time delays, to be later used during reconstruction.

External target observation shall produce new calibration products. The purpose of this external calibration is to calibrate the NIR that serve as a reference baseline for all other radiometers. External target calibration may also be used to validate the instrument (antenna patterns), to measure the Flat Target Response of the instrument, and to compute the G-Matrix for some IR algorithms. NIR calibration is simply performed by comparing the NIR output of a known scene (deep sky) against the expected output using the available characterisation of the NIR (gain and offset) and the BT distribution of the scene.

Ancillary data from the S/C and from the instrument shall be consolidated into separate HKTM L1a auxiliary products that provide fast information for each snapshot or integration time. PMS measurements shall be transformed from voltage measurements into antenna system temperatures that are later used to de-normalise the calibrated visibilities.

The two different measurement modes produce the same type of data up to this level, but different quantity. For the dual polarisation, correlation data among all antennas (measuring first horizontal and then vertical polarisation) are collected in an integration time of 1.2 seconds. For the full-polarimetric mode, four different sets of correlation data are collected in an integration time of 2.4 seconds (alternating antenna measurements between horizontal and vertical polarisations). Thus, the type of information that may be extracted from each of them is different.

This correlation data, plus the Antenna System Temperatures and the NIR output (zero baseline) shall form the output L1a measurement products, which shall be consolidated on an orbit basis, containing time-ordered calibrated visibilities vectors in a pole-to-pole configuration.

❑ L1b Processing

Conversion from L1a calibrated visibilities to Brightness Temperatures Fourier components shall be performed by the Image Reconstruction module.

The Image Reconstruction module shall compute the best approximation to the System Response Function and invert it for use with the L1a measurement products. Any external calibration or validation of the System Response Model shall be communicated to this module, so that it is able to update the modelling. This System Response Function, for example, shall be recomputed with any new calibration of the Fringe Washing Function (FWF), as it forms an inherent part of it.

The image reconstruction algorithm shall transform the calibrated visibilities into Brightness Temperature Fourier Components.

The output of this transformation shall be 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.

It shall also be needed to re-use a first estimate of the reconstructed scene as a starting point to reduce Sun aliases effects (direct and reflected Sun). This first estimate shall be computed in the Foreign Sources correction module, which, based on an updated Instrument System Response, shall compute the contribution in terms of calibrated visibilities, to be subtracted from the nominal L1a. This module shall also be able to correct the Corbella term from the System equation and remove the Sky and constant Earth temperature so that the Image Reconstruction solution is more accurate. In order to correct for Sun aliases, it shall be needed to perform a first uncorrected reconstruction in order to obtain the Sun “truth” as measured by the instrument.

❑ L1c Processing

In the L1c product, the snapshot information produced in L1b shall be geolocated and apodised over the Earth and aggregated over Earth fixed pixels in a swath. It shall not be rotated based on the change of polarisation reference and Faraday rotation angle, so the values reported in L1c for each pixel are expressed at Top of Atmosphere. L1c processing provides the Brightness Temperatures in the direction of the Earth fixed grids, along with their incidence angles.

For each pixel, the information of Brightness Temperatures is retrieved along chosen polarisations (e.g. TX and TY polarisation directions are parallel to Za and Ya directions on the Antenna Reference frame.

For the geolocation and apodisation part, a distinction can be made between “normal” processing and “strip-adaptive” processing. The difference between them is that the “normal” processing applies a unique apodisation to the complete snapshot (chosen based on the spatial resolution and radiometric sensitivity needed for Land or Sea), while the “strip-adaptive” processing uses a different apodisation function for each Earth fixed pixel contained within each snapshot. This last processing ensures that the retrieved ground pixels are circular and uniform in size throughout the FOV. The apodisation function coefficients for the strip-adaptive processing are computed based on the HKTM L1a and the Earth Fixed grid auxiliary data.

Strip-adaptive apodisation shall be a selectable option within this processing level. This procedure shall be applied to the Fourier components of the BT distribution, applying the particular apodisation window over each pixel at the same time as the Discrete Fourier Transform is performed. If no strip adaptive is selected, the DFT shall be performed anyway, but with a default apodisation window.

The disadvantages of the strip adaptive processing are that not all pixels in the alias-free FOV can be circularised (approximately above 50º incidence angle, this is not possible any more), and the operations required to compute the apodisation coefficients on a "per-pixel" basis introduce a processing overhead as compared to the nominal approach, where the same coefficients are used for all pixels in a snapshot.

During geolocation, for each integration time snapshot, the following information of each pixel in that particular snapshot shall be produced:

- Pixel centre coordinates in the Antenna Reference Frame
- Pixel centre coordinates in the Ground Reference Frame
- Pixel spatial resolution and elongation
- Pixel incidence and azimuth angles in all applicable reference frames (S/C frame and pixel frame), although the data annotated in the L1C products shall be the angles from pixel to S/C in the pixel local reference frame

The spatial resolution is only dependant on the apodisation applied, and may be computed beforehand in the case of non strip-adaptive. As an added value to L1c products, a figure of merit for the radiometric accuracy shall be provided, by defining for all pixels in a same snapshot the difference between the mean BT of the scene and the mean physical temperature of all receivers (Corbella). This term is the one that amplifies the errors present in the antenna pattern measurements, so it could help to discriminate valid scenes from "unsafe" ones for L2 users.

The radiometric accuracy for each pixel measurement shall also be computed here, as it is a function of the pixel observation angles, among other parameters.

For the computation of the rotation angles to Earth polarisation frame, an Ionospheric Contribution Module shall compute, based on auxiliary data and HKTM L1a data, a TEC and geomagnetic vector value for each snapshot and a reference frame rotation angle per pixel.

No ionospheric correction shall be applied on L1c products; instead, the Faraday rotation angle shall be computed for each pixel based on the TEC, geomagnetic angles and pixel observation angles. The geometric rotation angle (due to change of reference frame) shall also be computed here per pixel, but not applied. Additionally, the TEC and geomagnetic angles shall be reported per snapshot.

The last step in the processing is related to the grouping of the elements making part of the L1b product in a swath configuration instead of in a snapshot configuration. This swath configuration implies an ordering based on ground coordinates, where each pixel is represented only once inside the products, but which may contain several Brightness Temperature values for different incidence angles. Additional information on the pixel (area, orientation…) shall also be provided. It is, in fact, almost a re-ordering of the L1b product with specific apodisation applied, but not a straightforward approach, as the pixel size for a "same" geographical location changes in size in consecutive snapshots, and this effect should be taken into account when constructing the swath image. This last effect shall be disregarded if the optional strip-adaptive module has been used.

Additional information like flagging a pixel as belonging to Land or Sea, or obtaining the pixel elevation from a DEM could be done as an added value to the Earth Fixed grid in use, as the L1c shall be referring to pixels using a unique identifier.

3.4. Hierarchical Decomposition

The figure below illustrates the sequence diagram corresponding to the first hierarchical decomposition, and according to the processing steps described in the previous chapter.

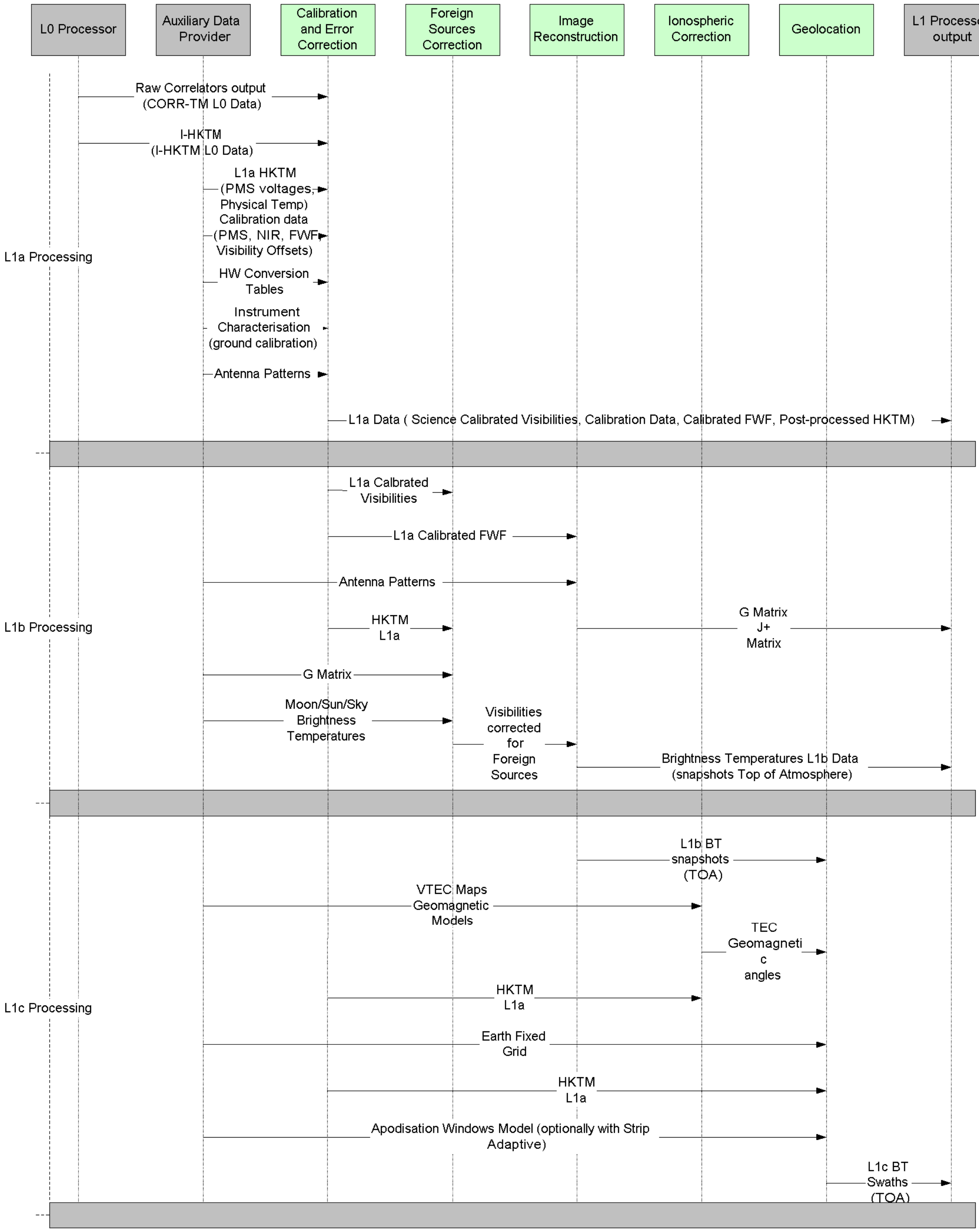

Figure 5: Processing Sequence Diagram

As indicated, the above diagram corresponds to the first hierarchical decomposition of the processing flow. Each major processing step identified in the context diagrams further above is shown here, indicating the order in which the steps should be performed. Following a systematic breakdown of the processing steps, the full processing flow is obtained.

3.5. HW&SW System Level Decomposition

The above diagrams do not support some aspects relevant for the system concept, such as the system level definition of HW and SW used for the Level 1 Processor.

3.5.1. Software platform

The diagram below illustrates the different software layers of the Level 1 Processor:

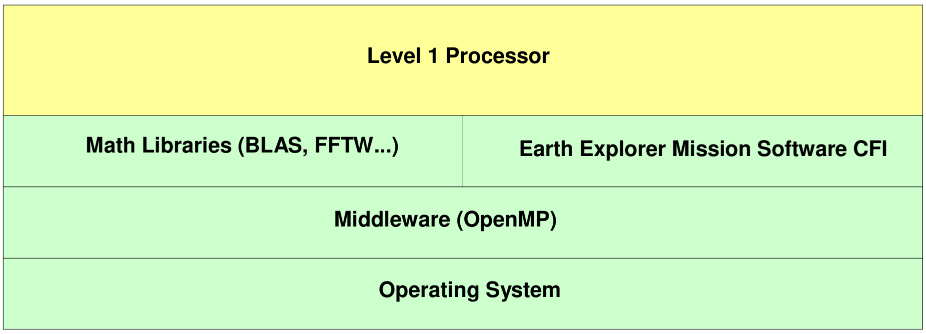

Figure 6: Level 1 Processor Software Layers Example

The Level 1 processor, composed by all the modules shown in Figure 4, is built on top of a set of libraries. These are used for a multitude of purposes, from Earth Explorer CFIs – used to read and write mission files -, to mathematical libraries (e.g. BLAS, FFTW, etc) – used to support the complex algorithms included in the L1 processor.

Then there is the need for middleware that supports multi-processing mechanisms. This is the case of OpenMP, which allows the proper usage of multi-processor machines.

Finally, the Operating System itself provides the core services to all the above-mentioned programs and libraries.

3.5.2. Hardware platform

In terms of hardware, the SMOS Level 1 Processor shall take advantage of a distributed system, being able to run on a single machine or distributed over multiple machines, each possibly having multiple CPUs.

The distribution over multiple machines is achieved by splitting the Level 1 Processor into multiple processes, each one being responsible for a dedicated set of computations, or for a given set of data.[1]

This is shown in the figure below, where the L1 Processor is deployed over a 3-layer distributed system:

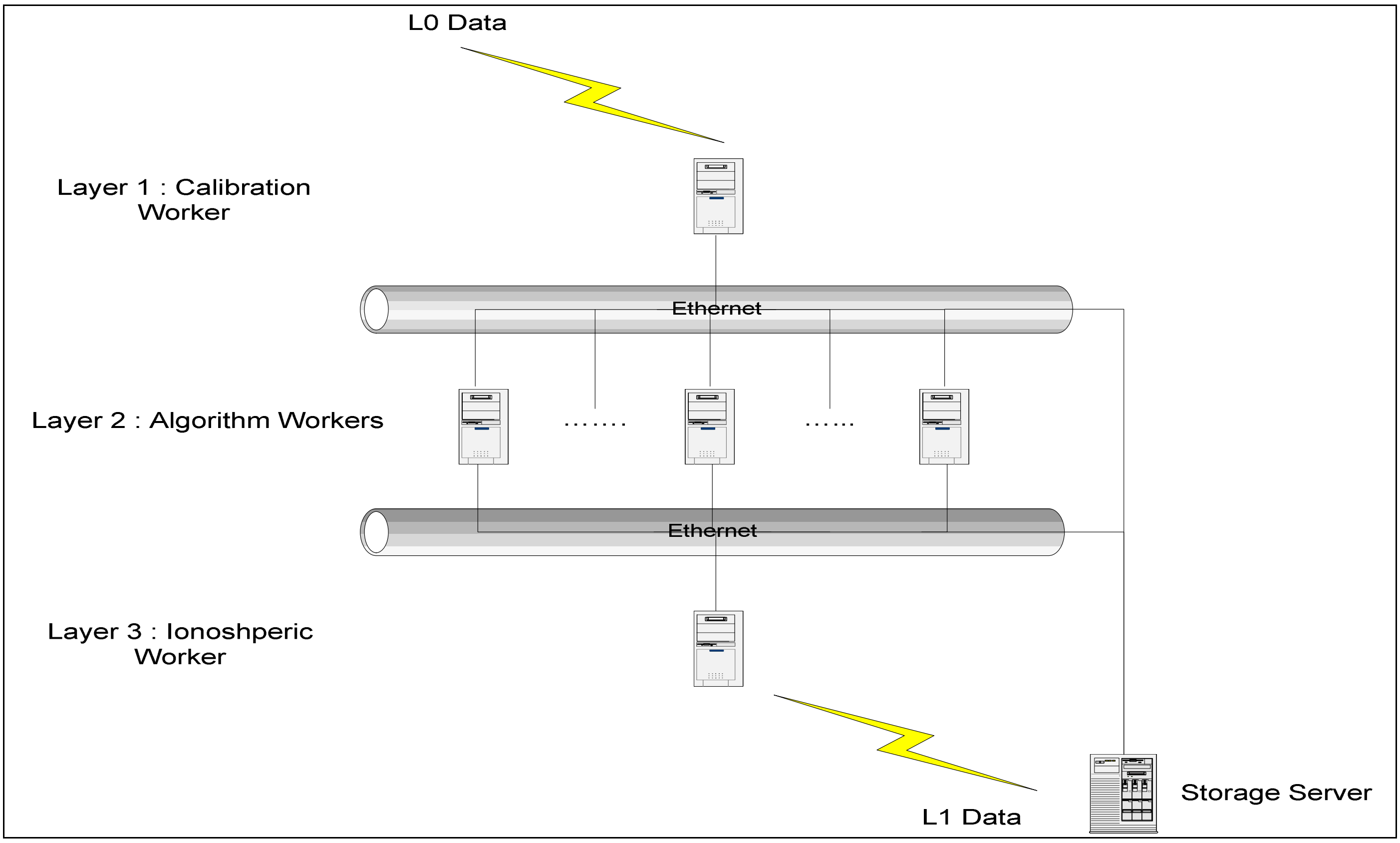

Figure 7: Proposed Architecture for the L1 processor

The first layer contains the Error Correction Module and it also works as a load balancer. After calibrating the visibilities it scatters the information (calibrated visibilities) and sends it to different machines on Layer 2.

Layer 2 has several machines, each one containing the Image Reconstruction Module. The number of machines depends on the chosen algorithm, as shown in [RD.9].

Layer 3 is the responsible for gathering the data produced by Layer 2, after which the Ionospheric and the Geolocation Module process the information.

[1] Processing the same set of data over multiple machines was considered previously, through the use of Message Passing Interfaces (MPI). However, as described in [RD.5], the performance gains were not satisfactory, so this option is not taken into account anymore.

Note that even in case of a distributed L1 processor, it has to be considered the case where it is not possible to process all the data in the available time. In this case, multiple L1 processors will be needed, each one being responsible for processing different scenes/orbits. This is to say that a second level of distribution is introduced, where multiple L1 processors will run simultaneously on multiple machines, without being aware of each other.

In any case, each machine may have more than 1 processor. To take advantage of the additional processing capability, the L1 processor shall make use of middleware (e.g. OpenMP), which allows distributing each process' load into the available processing units. The actual performance gains can only be calculated at development, but some indications for the image-processing module can already be found in [RD.5].

4. PROCESSING LEVELS DESCRIPTION

In the next part, a brief description of each processing level is provided, grouping them into modules and sub-processes within the complete L1 processing. Its input and output data are briefly outlined as well.

For each module, it shall be clearly defined the main functionality and interfaces with the remaining elements of the processor. This shall allow having a highly modular architecture, allowing the insertion of new CFI or algorithms very easily. In this way, changing the image processing algorithm, or updating the Earth Explorer CFI software shall not imply a re-engineering of the Level 1 processor (e.g. complete recompilation, interface re-definition…), but it shall be rather restricted to the dedicated modules. Any module shall be plugged into the backbone of the L1 Processor without affecting the rest of the modules.

4.1. Level 0 to Level1a

The Error Correction module processes all the Level 0 data coming from the L0 Processor. L0 Science data (CORR-TM) comprises the raw correlations data from DICOS. L0 Ancillary data (I-HKTM) shall provide the status of the spacecraft (state vector and attitude), the status of the MIRAS instrument health, plus voltage measurements from the PMS and NIR system, thermistors output and other additional data. L0 data is contained within data packets, each integration time providing one Ancillary Data Packet (I-HKTM) and 24 Science Data Packets for dual-pol operation.

All the I-HKTM data shall be converted into appropriate units by means of manufacturer tables and diagrams, or known formulae, and it shall be stored into an appropriate L1a product for easy reference in later modules, and to avoid extracting the data from L0 packets every time it is needed. This produces as output what has been called the HKTM L1a data (S/C and Instrument).

The Science Data Packets (CORR-TM) produced while in any of the calibration modes shall be processed by a dedicated subpart of the module, and will produce the calibration parameters and offsets required to calibrate the nominal observation measurements. As part of this processing, it shall also be needed to use the I-HKTM data produced while in calibration mode, which should already have been converted to HKTM L1a data. This calibration sub-process shall generate specialised L1a data required for the calibration of raw correlations. It shall also be possible to generate as part of the process a calibrated estimation of the FWF that is only used in the L1b module.

This process for generating the calibration coefficients requires Auxiliary Data Files (ADF), comprising S-parameters in all reference planes, ohmic efficiency, characterisation of the PMS detectors and antenna phases at reference planes. Further information on these ADF shall be provided in the ADF format definition.

NIR Calibration, or processing of Science Data Packets while in external target observation (Sky or Moon) shall be carried out as both nominal processing, with the objective of passing the calibrated visibilities to the IR algorithm and extract the reconstructed image of the external target, and as a particular processing to compare the theoretical response of the NIR to the measured one. This last process shall force the calibration of the NIR model that is used in this module and, although it is clear that it should be part of the L1 processing, it might be performed at a calibration facility external to the Error Calibration Module and passed as Auxiliary Data.

The following image shows the data flows in this module for processing of calibration data:

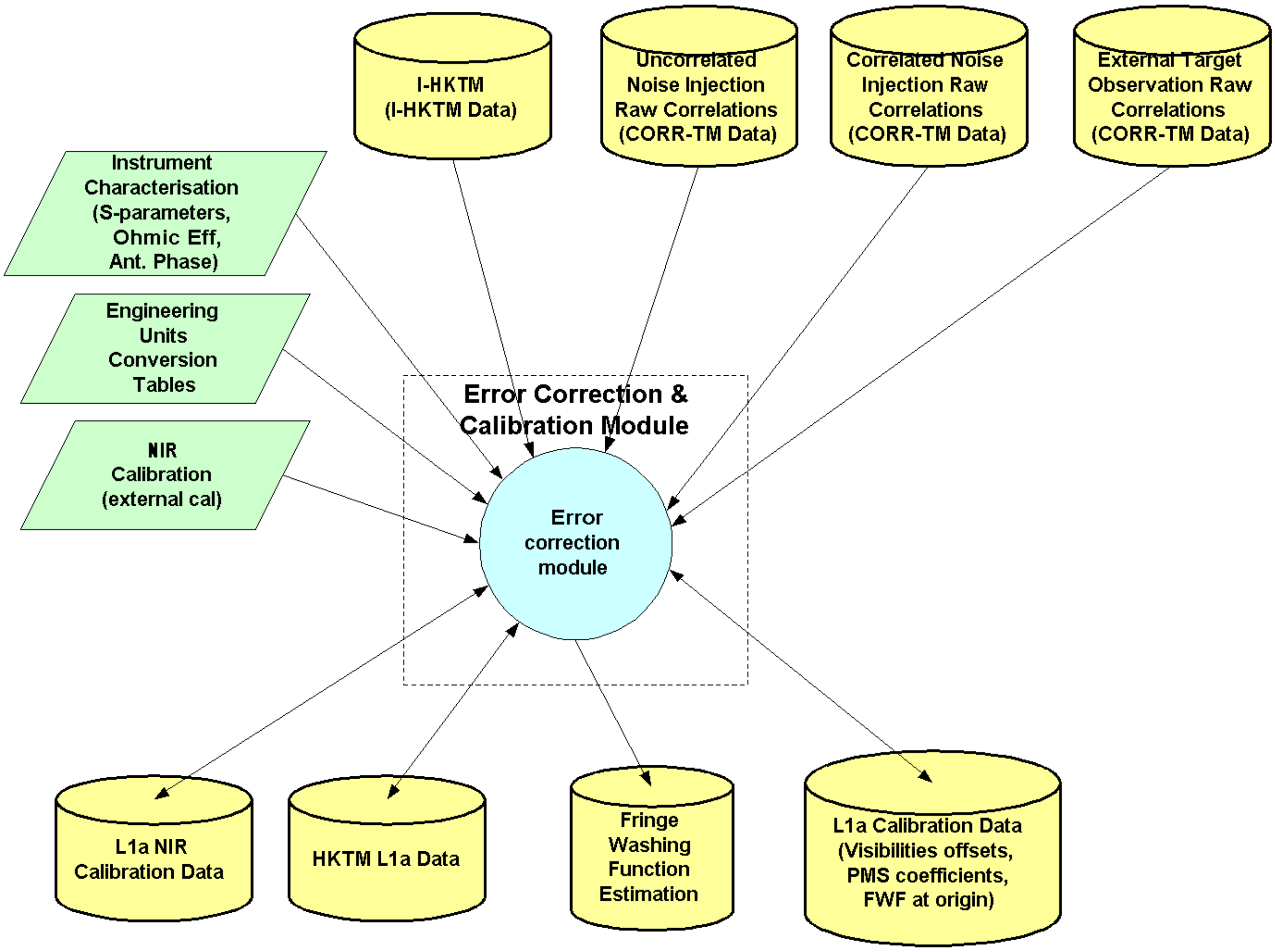

Figure 8: Calibration and Error Correction Module (Calibration Data Processing)

Science Data Packets generated while in nominal mode (dual or full polarisation) shall be calibrated with the previously created calibration L1a products, and be consolidated in time ordered scenes. The contents shall be an array of ordered Calibrated Visibilities per each scene. The information on which baseline (u, v pair) corresponds to each visibility shall be defined within the product format. Additional information on correlator failures, antenna failure shall be contained within the HKTM L1a product referencing the scene or integration time where it happened.

As is shown in the following figure, the data flow for Measurement mode data processing is based on data previously created with calibration data and HKTM L1a.

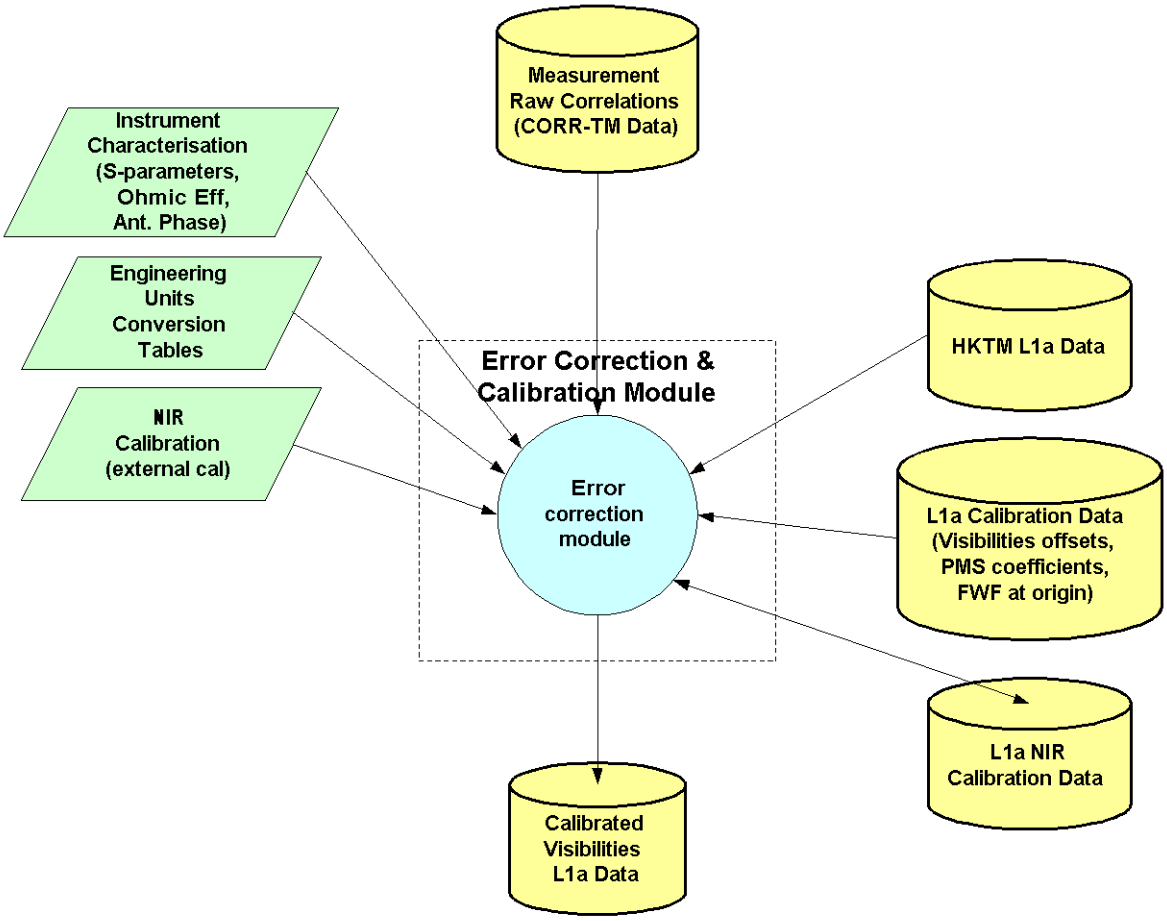

Figure 9: Calibration and Error Correction Module (Measurement Data Processing)

This processing module shall contain specialised sub-modules that shall be described in the Detailed Processing Model. They include the Auto-calibration process, and also the Redundant Space Calibration processing. Further decomposition of these sub-modules and their functionalities is described in the Detailed Processing Model and Architecture Design documents [AD.9] and [AD.10].

4.2. Level 1a to Level 1b

The next diagram contains the most important part of the processor, which is the image reconstruction algorithm. This step is not reversible, once the Brightness Temperatures are calculated, meaning that if the algorithms evolve in some way, it shall be necessary to re-process the L1a data to obtain the new L1b data.

This processing step (L1a to L1b) has been separated into two different modules. The first module shall attempt a correction of the influence of external sources into the reconstruction process, while the second module is the reconstruction process itself.

As part of the L1a processing, an initial Foreign Sources Correction module shall be needed, based on the UPC algorithm approach of subtracting the Sky and a constant Earth Brightness Temperature that was implemented in SEPS, but consisting of calculating the visibilities contribution that are generated by the presence of the Sun, Moon or strong Sky sources in the FOV. These visibilities, if properly calculated and subtracted from the calibrated visibilities, would eliminate the strong sources that appear in the FOV and produce better results with the Image Reconstruction algorithms.

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 shall be obtained at the nominal and reflected 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 reflected Sun contribution, it shall be necessary not only to determine the Sun temperature at the reflection point, but also to compute an estimated area of the reflection surface. This area shall be estimated using several default geophysical parameters apart from the self-estimated Sun BT. The effect of the Sun BT is dominant in the modelling of the reflected source, and using averaged values for the other variables does not introduce relevant errors. These averaged values are Sea Surface Salinity=35psu, Sea Surface Temperature=15ºC, Wind Speed=5m/s, Wind Direction=0º (North). This is particularly important on sea reflections, and has some impact as well on land. This method has already been implemented by UPC in SEPS v4, and is currently accepted as the baseline for removing reflected sources.

This module shall also remove a constant Earth background temperature (improves reconstruction efficiency and enables reconstruction over an extended alias free FOV) and the Corbella term from the visibilities system equation based on the physical temperature of the LICEF receivers.

In the latest baseline, this last step is considered equivalent to the Flat Target Transformation (FTT). This process will take advantage of the so-called Corbella equation and, using previously measured correlations from a deep sky observation, subtract the measured term corresponding to the physical temperature of the LICEF receivers.

The process consist simply of measuring the FTT auxiliary correlations while in deep sky observation, subtracting them at the beginning of the Foreign Sources correction, and adding them after image reconstruction to the Brightness Temperature Fourier components.

In any way, any particular correction of each effect shall be considered as 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.

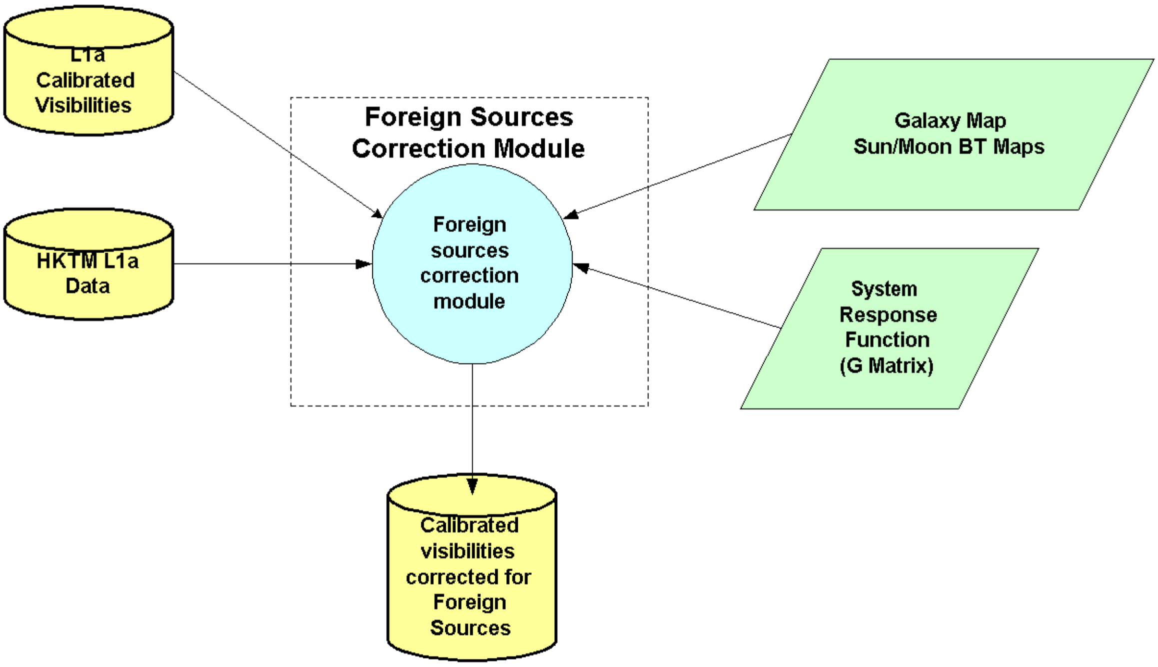

Figure 10: Foreign Sources Correction Module

The effectiveness of this correction shall be verified during the testing and operations of the L1 Processor prototype. The information on the correction applied and its validity shall be made available to the L2 users within the L1 format. It shall also be possible to generate the L1c data without any correction, such that the L2 users apply any correction they deem required.

The second module (Image Reconstruction module) performs the image reconstruction process on the calibrated visibilities, producing snapshots Brightness Temperature Fourier components. This frequency spectrum is composed by the basic hexagonal period of the instrument (i.e. star domain frequencies), and not only of the spectrum of the alias-free FOV.

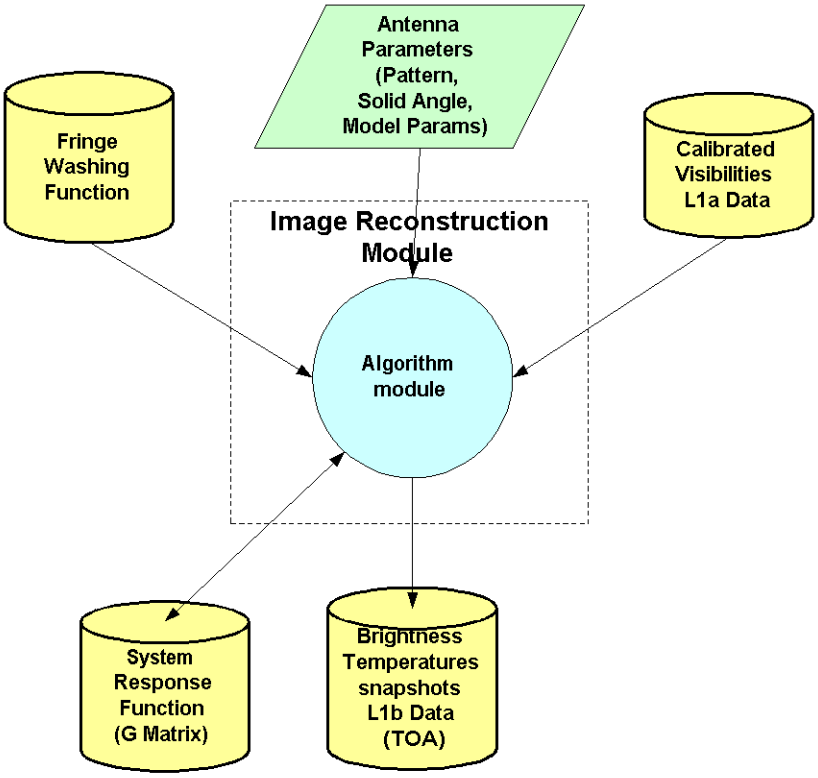

Figure 11: Image Reconstruction Module

The information passed to the L1c shall consist of the Fourier components of the reconstructed scene.

Detailed information into the possible Image Reconstruction techniques shall be analysed in the Processing Modules Description chapter. Mainly each algorithm model is related to computing the best approximation to the real System Response function, so they shall need the ground measured antenna patterns and the calibrated coefficients of the FWF. Other parameters influencing the System Response may include estimations of the antenna positions (deviations from nominal baselines).

The current adopted algorithm baseline consists on two algorithms based on G Matrix approaches, so the purpose of this module shall not only to reconstruct the calibrated visibilities, but also to compute and calibrate such G Matrix.

Generally, the outcome of the Image Reconstruction module shall be the Brightness Temperatures Fourier Component distribution. An auxiliary product shall be used to generate and represent all the coefficients used for the SR function (also known as G matrix), which may be calibrated externally by other methods and updated to this module.

As mentioned before, the current baseline for L1b output is a list of BT Fourier Component snapshots. These Fourier Components have obviously no apodisation applied, so they shall be the input required for the L1c processing.

4.3. Level 1b to Level 1c

The last step of the processing chain shall perform a combination of the Brightness Temperature snapshot values retrieved previously into swath format. Instead of being ordered by integration time and containing the info for each pixel on the FOV, they shall be ordered by pixels identified in a Fixed Earth Grid, each of them containing the Brightness Temperature values related to different incidence angles and different integration times. This step shall also perform the required apodisation of the BT values.

The Geolocation module shall compute the BT values and their incidence angles in the direction of the required Earth fixed points, while at the same time computing the characteristics of the footprint (area and orientation). This is achieved without errors by applying a Discrete Fourier Transform on the L1b BT frequency components and particularising over the Fixed Earth grid points. Using "normal" processing, the pixel size for a same geographical location changes in size in consecutive snapshots, as the apodisation applied in the DFT is the same regardless of the point position. This effect shall make it necessary to provide footprint information to the L2 users so that it can be taken into account.

Input data for the Level 2 processing shall always be a geo-sorted L1c product.

If the optional strip-adaptive module is used, the pixel size remains uniform all along its pass trough the FOV, as the apodisation coefficients applied within the DFT change with the point position within the FOV. The DFT allows the apodisation and interpolation to the Earth Fixed grid in the same processing step. Further discussion on the strip adaptive impact on the whole model presented above, not only the L1c, shall be presented in chapter 6.

This module shall compute sets of temperature values, H and V for dual-pol operation (real valued), and H, V and HV for full-pol operation (HV is complex valued). ~~The BT values are produced in consecutive integration times, and shall be passed to the Ionospheric Correction module in order to apply the rotation correction from instrument to ground.~~

The footprint info shall be attached to each BT value, along with the incidence angle and special flags. These flags shall report the position of the pixel within the FOV (in/out of alias-free FOV, in/out of extended alias-free FOV and close to the diagonal) as well as represent any external source that may affect the pixel, like a direct Sun alias, reflected Sun alias, RFI sources, etc. Further information on these flags may be found in the L1 product format document [RD.10].

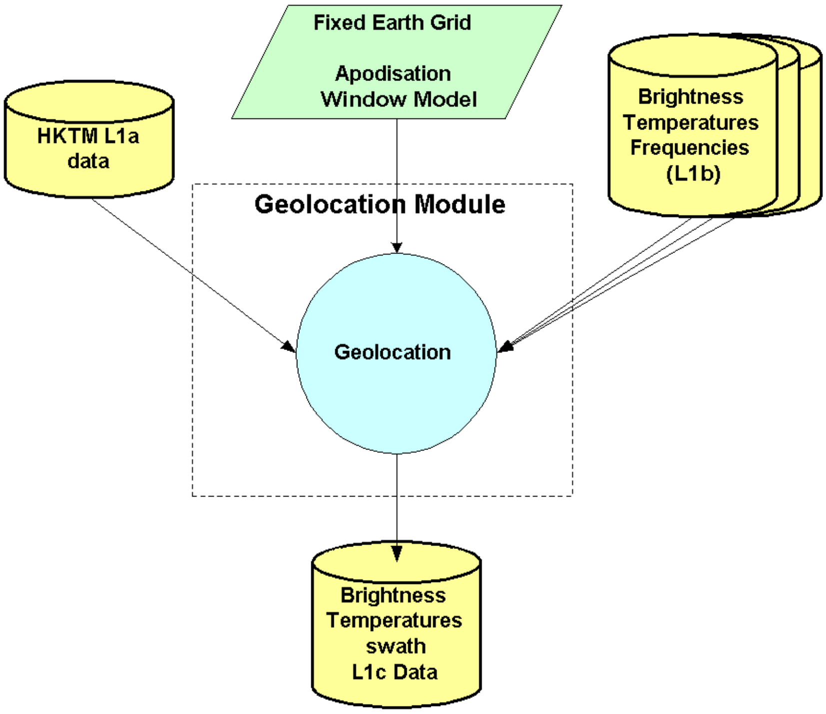

Figure 12: Geolocation Module

The Ionospheric Correction module shall compute (using a model or Aux files) the TEC and geomagnetic angles applicable to each snapshot, and pass them to the Geolocation module. The computation of the Faraday rotation angle is straightforward, once all the input required (TEC, geomagnetic vector and pixel incidence angle) have been computed by this module based on HKTM L1a data. Both Faraday rotation and the rotation due to geometrical projection of the polarisation values from Instrument reference frame to Ground reference frame shall be reported in the L1c per pixel and measurement.

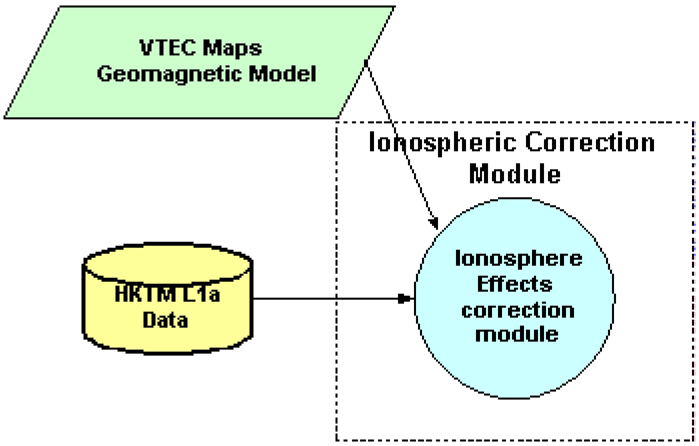

Figure 13: Ionospheric Correction Module

This module shall compute one TEC value and one geomagnetic vector value per each snapshot, so that the Faraday correction for each footprint inside can be computed using these values and the incidence angle of each value within the footprint. It is considered that TEC and geomagnetic variations are sufficiently small within the scene FOV such that one mean value of each can be considered as the baseline. The rotation angle due to the change of reference from instrument to ground shall also be computed here on a per-pixel basis.

The information required for the rotation angles computation shall be extracted from specific auxiliary data combined with HKTM L1a data. It shall be attached internally to the L1c data, in the initial time-ordered list of snapshots parameters, so that L2 users may re-compute this rotation, if they so desire.

As mentioned before, some directions in the snapshot (±45º in the antenna frame) cannot be properly corrected for rotation in L2 in dual polarisation mode, as the rotation matrix is singular and cannot be inverted. Pixels affected by this singularity, which does not affect full polarisation products, shall be identified within the L1c products and flagged.

4.4. Apodisation Window Computation

As a particular annex to this Processing Levels Description, it must be mentioned the different approaches to retrieve the apodisation function values, and where to apply them in the Image Reconstruction algorithm.

For the normal approach, a series of known apodisation functions have been already studied, having been the Blackman one selected as optimum in terms of trade-off between spatial resolution and radiometric sensitivity. This function is applied as a symmetrical function in all the FOV, and used to retrieve all the pixels in one step.

For the strip-adaptive approach, there shall be a non-symmetrical apodisation function that has to be applied to every pixel in the Antenna Reference Frame, so that a circular footprint is obtained after the transformation to the Ground Reference Frame. This function shall be a 2D function; whose values depend on the (ξ,η) values, meaning that a different function would be applied to every different pixel.

The selected apodisation function shall be applied to the reconstructed L1b BT frequency components, within the Geolocation module, right after the Image Reconstruction process. However, within the Image Reconstruction module, a default apodisation shall be applied to the presented BT values, although these BT values shall not be used in the L1c computation. Only the BT frequency domain values are used in the L1c computation.

Strip-adaptive processing, if selected, shall modify the apodisation function to be applied before the L1c. It shall be remarked that for interpolation from L1b grid to L1c grid, if the former is Antenna Fixed and the latter is Earth Fixed, the same approach of computing the Equivalent Array Factor may be taken, with the exception that in the nominal processing the apodisation function remains always the same, while in the strip-adaptive processing, it shall be necessary to alter its parameters according to the footprint being interpolated.

5. PROCESSING MODULES DESCRIPTION

A more detailed description of the processing steps to be performed in each module is shown in the following chapters.

5.1. Error Correction

The method used to calibrate the visibilities is described in [AD.6] and [AD.9], but mainly it is based in producing a set of calibration parameters and offsets based on the instrument's output while the instrument is receiving correlated and uncorrelated noise. This output, needs to be combined with the PMS output of all receivers and the physical temperature at each integration time, in order to de-normalise the calibrated visibilities. The calibration parameters and offsets produced during noise injection are stored and used in between calibrations.

In normal measurement mode, the instrument's output, NIR measured temperatures and receivers measured physical temperature is combined with these computed calibration parameters and offsets, in order to produce the calibrated visibilities that are considered the measurement L1a output.

As part of this calibration mode, the fringe washing function term that shall be used later in the image reconstruction process shall be also computed. The antenna phase patterns and the ohmic efficiency of the receivers as well as the S-parameters of the Noise Distribution Network and receiver's switches must be measured with the biggest accuracy possible, since they are crucial input for the calibration procedures. These last measurements must be made on ground before the instrument is flying, and shall include a characterisation against temperature drifts, to be used in flight combined with the thermistors readings in the I-HKTM.

The calibration procedure will rely on two temperatures of noise injection for amplitude and phase calibration of the hub receivers. The procedure is easily extrapolated for use in the arms calibration with distributed noise injection. The NIR calibration is performed while imaging external targets, being the deep sky the baseline external scene for this procedure. External targets may also be used for computation of the Flat Target Response function, and to calibrate the G-Matrix using known scenes (i.e. Earth-Sky border).

The calibration timeline will consist of short and long calibration periods. The correlated and uncorrelated noise injection for antenna calibration will be performed several times per orbit, while noise injection for FWF estimation will be performed less frequently (TBD). Every two weeks, the instrument will enter the NIR calibration mode. Full orbits in calibration mode are also planned on a monthly basis. In addition, interpolation and/or extrapolation of L1a auxiliary calibration parameters might be needed to correctly apply them to data gathered in between calibration periods. Interpolation/extrapolation shall be based on physical temperatures at the time of applying the coefficients, against the ones measured together with the calibration coefficients. The calibration timeline is still undefined, but the system shall be able to handle continuous calibration operations, as during commissioning, the instrument may be operated in calibration for extended periods of time.

The error correction module will have a data driven behaviour. Instead of relying on a fixed timeline, it will retrieve from the Level 0 data format the instrument mode and route the data to the appropriate sub-modules.

5.2. Foreign Sources Correction

This preliminary correction of the visibilities is used so far by the UPC implementation provided in SEPSv3, as can be seen in [AD.2]. This method is used in the simulator to correct reflected and "direct" (through aliases) contributions from the Sun, Moon and Sky background.

A description of its basic functionality may be extracted from the description in [RD.11].

The direct and reflected position of the Sun and Moon are located in the antenna frame and their coordinates computed. The visibilities that would be measured by a 1K source located at those coordinates (0K elsewhere) is computed, using the best estimations of the antenna patterns and fringe washing function. These visibilities are then converted back into brightness temperatures by means of an IFFT, which give a rough estimation of the brightness temperature of the Sun or Moon in the direction of the same coordinates computed previously.

For this purpose, the Sun and Moon positions in the antenna frame shall be computed using the Earth Explorer CFI processing of the HKTM L1a data. The same antenna parameters that are calibrated for the Image reconstruction process shall be used here to simulate the system response and generate a set of visibilities that can be subtracted from the original set of calibrated visibilities before passing them to the Image Reconstruction module.

The reflected Sun shall be accounted as well in this way, by computing the Sun reflected Brightness Temperature, and using default geophysical parameters to model the reflection. MIRAS shall be measuring its own Sun truth in the direct and reflected directions at all times.

This module shall also be in charge of performing all the processing related to the Flat Target Response. Upon reception of External Target observation while in deep sky pointing, this module shall generate the FTT auxiliary correlations to be used later in the processing. The FTT auxiliary correlations are obtained by performing an average of the correlations for each pair of receivers during deep sky observation (6 minutes).

In nominal processing, these FTT auxiliary correlations shall be subtracted from the measured correlations before Image Reconstruction, including a scaling factor that accounts for the physical temperature difference between the time at which the FTT auxiliary data was measured and the time of nominal measurements. After Image Reconstruction, similar FTT auxiliary correlations (containing the visibilities expected from a uniform scene and of the Sky observed during deep sky) shall be added again to the Brightness Temperature Fourier components, taking into account that the addition must be performed now over the baselines, so averaging will be needed for those correlations covering the same baseline.

5.3. Image Reconstruction

In the following points, several approaches for using in the Image Reconstruction Module are shown and described, specifying their needed input and output data.

The two main approaches to retrieving the BT distribution from the visibilities are Iterative approaches and Matrix Calibration approaches. A third method has been studied as well, the Beam Forming algorithm, which has been extracted from a technique used in processing of Synthetic Aperture Radar and sonar images.

The selected baseline consists on two G Matrix based algorithms: UPC G Matrix and Stabilised G Matrix. They shall be described first, and the other approaches shall be described afterwards. The G Matrix approach was first proposed by D. Le Vine, C. Ruff et al, and the two selected baselines simply propose alternate modelling for its computation.

Although only two algorithms from the first chapter have been selected as the processing baseline, the rest of algorithms are also described to keep trace of the study performed.

5.3.1. Response Matrix Calibration Algorithms

UPC G matrix, Stabilised G Matrix and DLR Point Source algorithms are considered under this chapter. These methods are based on retrieving the System Impulse Response matrix, which converts Brightness Temperatures into visibilities. Once the System Impulse Response matrix is known over a regular antenna grid, it is inverted and multiplied by the measured visibilities to retrieve the BT of each scene on this regular antenna grid.

DLR Point Source depends on measuring well known sources on each point of the Antenna Frame where the Brightness Temperatures are to be extracted, in order to retrieve the System Response on each of these points. These well known sources may be for the moment the Sun or the Moon, the Galaxy or the Earth-Sky horizon, positioned throughout the whole FOV. Using the known sources and the instrument output, it shall be possible to recreate the matrix transforming one into the other.

Stabilised G Matrix approach relies on obtaining as well the System Response matrix by means of calibration and measurement of known scenes. The input data in this case are parametric models of the different constituents of the G Matrix (antenna patterns, receiver filters and antenna positions), which are calibrated using known scenes.

UPC G matrix computes the System Response G matrix based on the on-ground measured antenna patterns and the Fringe Washing Function (known initially and calibrated later on). The system represented by the G matrix does not use in this case a model, but already defined L1 and auxiliary products.

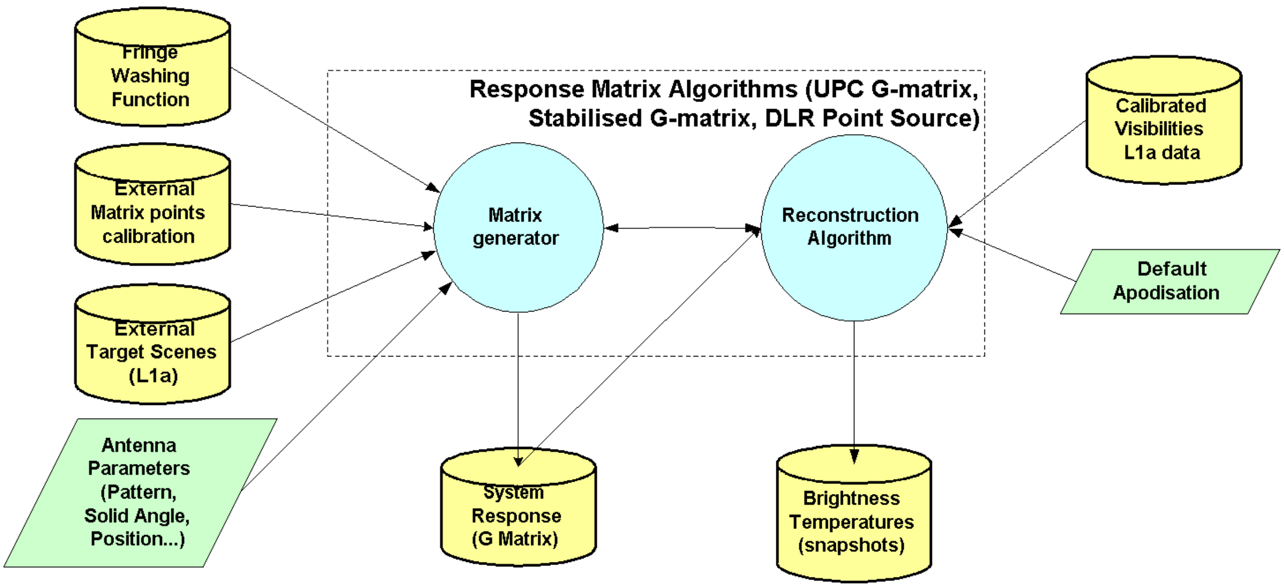

Figure 14: Response Matrix Algorithm Module

These algorithms may be divided into a Matrix generator module, which is tasked with computing the results of the calibration process and “inverting” the matrix, and a Reconstruction module, which uses the matrix to compute the BT from the visibilities.

This matrix shall be stored in the file system and accessed by the Reconstruction module, as well as stored in memory and its particular elements accessed as needed. It is proposed to create the matrix as an additional product, either L1a or AUX, as it is expected to change according to independent calibrations performed. This matrix shall be recomputed frequently, depending on the calibration schema and the thermal variations experienced by the instrument.

This matrix inversion is the same regardless of the algorithm used to construct it. It is transformed first into the Fourier domain, multiplied by its complex conjugate, inverted, and multiplied again by the complex conjugate. Instead of extracting the Brightness Temperatures, when this resulting matrix is multiplied by the visibilities, it retrieves Fourier Domain values of the would-be Brightness Temperatures. These Fourier values may be easily converted into spatial domain BT values by means of an inverse FFT.

These algorithms are based on heavy matrix calculation and inversion, but just once every calibration. For each scene, only a matrix multiplication and sometimes FFT shall be performed, so the modelling for these contributions shall be made using specific mathematical libraries (GSL, BLAS, LAPACK…) and FFTW available open source libraries.

5.3.2. Iterative Algorithms

UPC Extended-CLEAN and DLR Corrective algorithms enter within this description, as they retrieve the Brightness Temperature values through several iterations.

Specific input data must be provided to this type of algorithms, in order to define a starting point for convergence (loop gain factor). An initial image to compare the iterations has also to be produced, either as an ideal transformation of the visibilities like in the case of UPC, or through the re-use of a previously obtained image like in the case of DLR.

Extended-CLEAN also removes the Sky and Earth contributions from the visibilities before performing the Inverse Fourier Transform, so that the FOV is extended and convergence is improved. This removal shall be incorporated into the Foreign Sources Correction Module described in chapter 5.2.

DLR Corrective algorithm computes the visibilities back from the Brightness Temperature distribution, and uses them to correct the original visibilities.

Both methods iterate until the difference between the BT resulting from one iteration and the previous one decrease below a given threshold. This threshold is computed specifically for each scene.

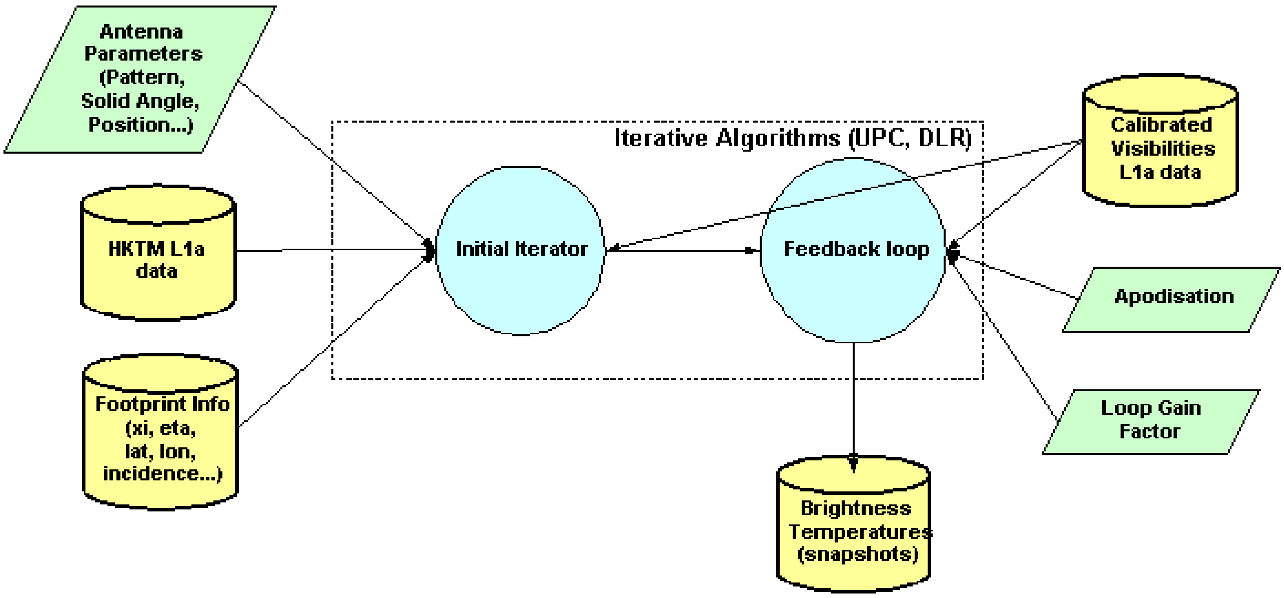

Figure 15: Iterative Algorithm Module

These algorithms are based on heavy repetition of Inverse Fourier Transforms for each scene, and so the modelling for these contributions shall be made using FFTW available open source libraries.

5.3.3. Beam Forming Algorithm

This method is based on obtaining the system transfer function of the radiometer, using the most accurate values of antenna patterns, fringe washing term and antenna physical temperatures, but particularised over the reconstruction grid points instead of over a regular grid. This system transfer function is later used to compute the inversion matrix, based on a space variant pulse compression filter.

It is necessary to compute the System Response matrix for every (ξ,η) pair of values, and apply it to the whole set of visibilities values. This method relies on a heavy assumption that the square matrix G^*G is mostly diagonal, and the system solution may be approximated by a set of independent point sources.

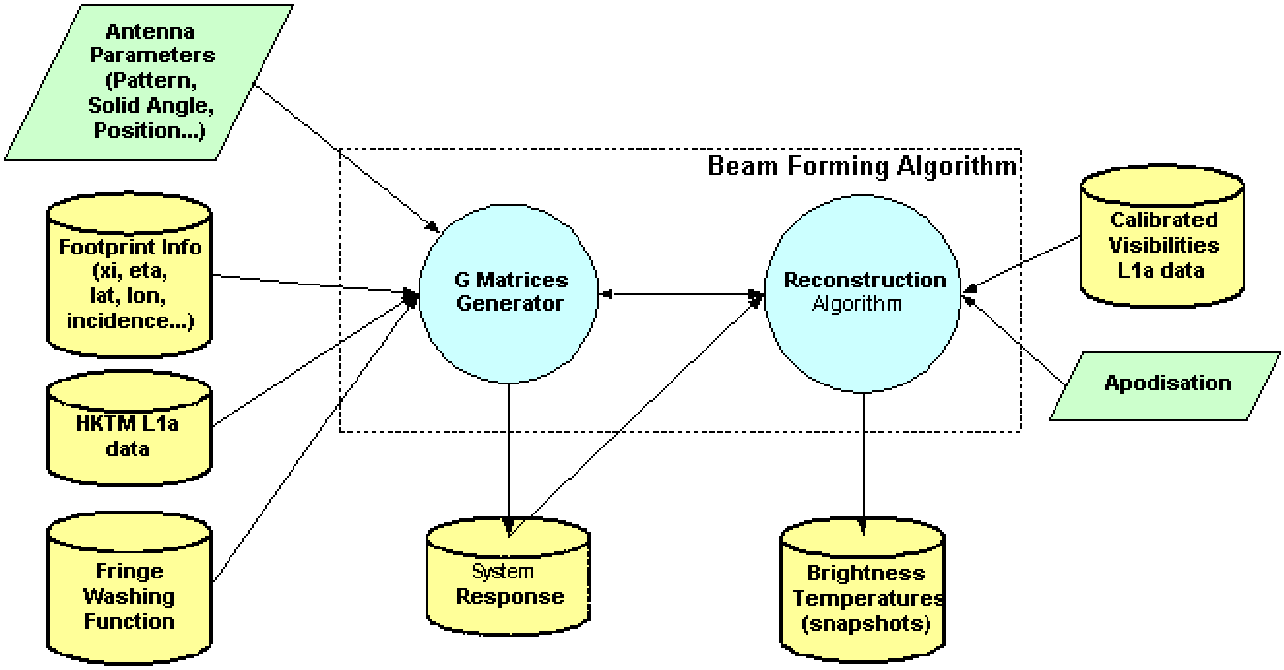

Figure 16: Beam Forming Algorithm Module

This algorithm main characteristic is then to compute as many inversion matrices as pixels in the image, and multiply them to the visibilities. Its applicability remains still to be decided by ESA[2].

5.4. Ionospheric Correction

This module shall simply compute the ionospheric parameters required to compute the Faraday rotation angle for each pixel

It shall compute the TEC and geomagnetic vector values corresponding to a certain snapshot from the auxiliary data, and store them as internal information, easing the later computation of rotation for pixels of the same snapshot.

As a preliminary approach, a simple function based on the HKTM L1a data (UTC time, position and attitude) shall be able to extract the TEC and geomagnetic angle from the variety of auxiliary files and models available. Computation of Faraday rotation shall be simply applied later in the Geolocation module by combining the H and V BT measurements from consecutive snapshots and their observation angles together with the TEC and geomagnetic angle corresponding to those snapshots.

The rotation due to the change of polarisation reference frame (instrument to ground) shall be also performed here, and applied to all products. This rotation is only dependant on the instrument attitude, so it can be easily computed from the L1a HKTM data.

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[2] Beam Forming has been tested as part of a Phase 1 CCN for reconstructing images over a regular grid in a similar way to UPC G matrix method. Several differences were found in the solution comparison, the principal one is an amplification factor of 1.5 in every scene, the second are differences in the BT distribution ranging from +30K to –20K after this factor has been corrected.

The initial part of the L1c product subset shall define the snapshots contained within and their characteristics, among them these ionospheric values. In this way, any L2 user may re-compute the Faraday rotation angle if he chooses to.

5.5. Geolocation Module

This module shall only need the output of the Image Reconstruction module and it will geolocate and apodise all data by means of a DFT, and group all products into a single swath product. It shall invoke the Faraday correction module based on data from consecutive snapshots, and it shall also apply the previously mentioned strip-adaptive processing if it has been selected.

The module shall know what is the desired output grid product, containing the Fixed Earth grid to which the BT values shall be interpolated. Previous to writing the values from the current snapshot it is processing, it shall perform the interpolation of its values to match the desired grid. Interpolation technique shall be based on an Discrete Fourier Transform, either using a set of 2D apodisation windows that allow for the strip adaptive processing or a default apodisation for Land or Sea purposes.

These 2D apodisation windows in which it is based shall be obtained at later stages of the current L1P prototype design.

5.5.1. FOV calculator

This component performs all the computations on pixel information, being a component within the Geolocation Module.

This module shall compute the footprint size and orientation corresponding to the projection and apodisation of the BT snapshot over each Fixed Earth grid points. For this purpose, it shall need the spacecraft's position and attitude data at the time of the snapshot, and the apodisation window that shall be used to taper the visibilities samples. Either the attitude data provided by PROTEUS in the HKTM L1a data, or more refined data like restituted data shall be required. Further flagging due to the footprint position within the FOV shall also be computed using this data.

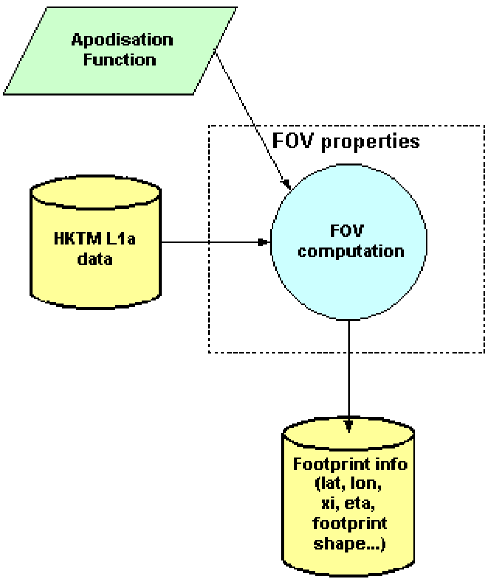

Figure 17: FOV properties Module

For this approach, the latitude and longitude coordinates of every Fixed Earth grid point must be converted into the (ξ,η) coordinates in the Antenna Frame through this module, which uses the HKTM L1a data to compute them. It shall be possible to compute within the same module the incidence angle present at each ground pixel. The best estimate of the Best Fit Plane based on antenna position coordinates shall be used for all purposes of geolocation. The Antenna Frame coordinates shall be later used as input to the DFT process for obtaining the Brightness Temperature at Top of Atmosphere.

All the functions accessing data from the HKTM L1a data shall use EE CFI software provided by ESA, as a common point for calculation of orbital and attitude data.

This sub-module shall also need a Land/Sea Mask file to distinguish between land, sea and mixed pixels.

5.5.2. Strip Adaptive (selectable)

The strip-adaptive processing shall be a selectable option within the Geolocation module. This selection shall allow this module to perform the interpolation of each scene from the Fixed Antenna grid to the Earth Fixed grid, while at the same time circularising and regularising the footprint spatial resolution.

The advantage of this processing is that the resulting Earth pixels shall be coincident with every other snapshot pixels, and the contribution on each of them shall be uniform. The same Earth Fixed Grid as in the nominal processing shall be used, in order to compute the (ξ,η) values of the Antenna frame where the BT needs to be extracted.

The process requires a previous modelling of the apodisation coefficients for each grid point depending on its position within the FOV. Once the position is known, the apodisation coefficients are retrieved and passed to the Geolocation module for use in the Discrete Fourier Transform.

The disadvantages of this method are that not all pixels in the alias-free FOV can be circularised without incurring in heavy losses of efficiency (above 50º incidence angle approx.), which reduces the amount of information that can be obtained from one snapshot. Additionally, the retrieval of the apodisation coefficients needs to be performed for each pixel of each snapshot, as opposed to the nominal processing, where the same coefficients are applied to all pixels in one snapshot. This computation of the strip-adaptive apodisation coefficients introduces a processing overhead that is not negligible.

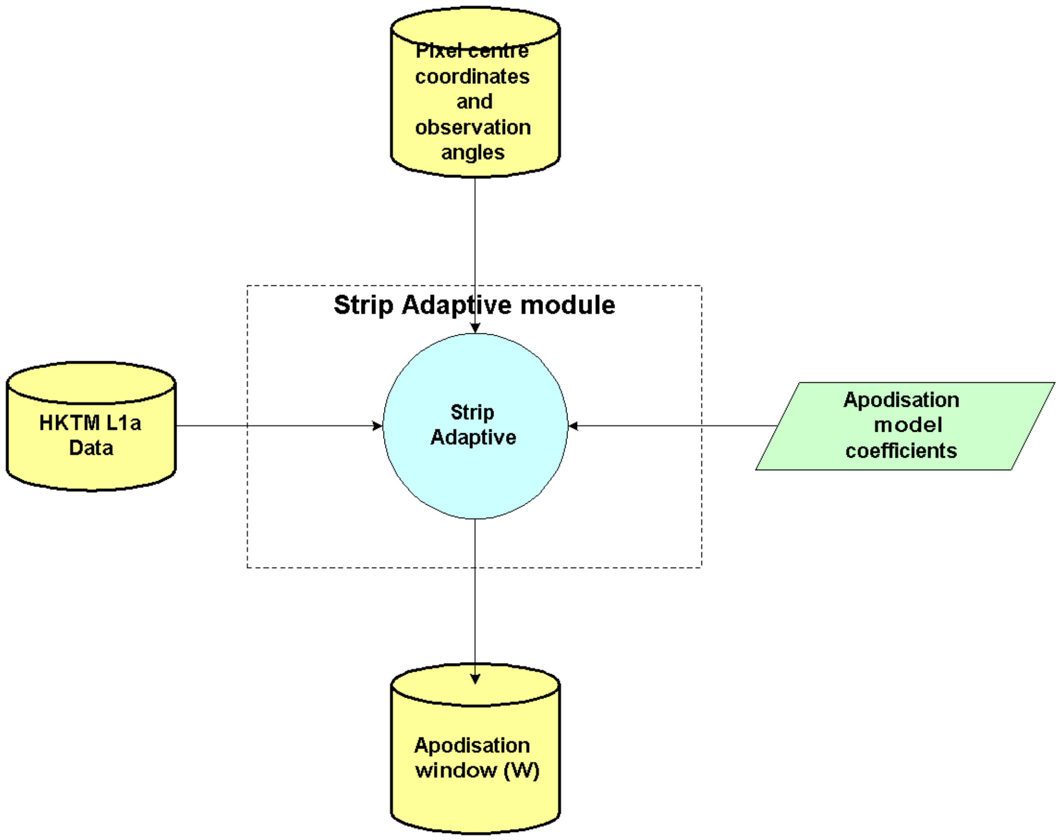

Figure 18: Strip Adaptive Module (selectable)

6. STRIP ADAPTIVE IMPACT ON PROCESSING APPROACH

As part of the processing strategy it is not yet clear if the final results of Brightness Temperatures shall be meaningful, unless a strip adaptive approach is used during the whole processing. This is due to the fact that the same pixel has to be observed under different incidence angles with no variation in its constituents.

Using normal processing, a regular fixed grid on the antenna is used for image reconstruction, and later it is projected into the corresponding Earth grid, resulting in non equi-spaced, non-equi-sized footprints.

Strip adaptive aims to retrieve the Earth grid footprints such that they are equi-spaced and equi-sized, providing as well the same beam efficiency in all of them. This can be achieved by two approaches[3].

In this chapter, these approaches shall be described along with the changes that shall be applied to the System Concept derived previously to accommodate them. Some mention has been already made before, but it will be included into much more detail. Impact on the System Concept is restricted solely to the strip-adaptive module.

Both approaches require a non-regular grid on the antenna frame, such that when it is projected back onto the ground, it results into a regular grid with equi-spaced footprints. So, the starting point is the need to have a defined Earth fixed grid common to all products that shall be the baseline for the points in which the Brightness Temperature values shall be retrieved. This Earth fixed grid shall be transformed into the appropriate antenna grid at the time of each snapshot (based on HKTM L1a data).

- **DFT Approach**

This approach is based on using a Discrete Fourier Transform on the Brightness Temperature solution expressed in the frequency domain. This must be so, as the final grid is non-regular, and FFT cannot be used anymore.

This DFT interpolation to the Earth Fixed grid is combined with a space variant 2D apodisation function that has to be applied to the BT Fourier Components during this DFT. This 2D apodisation ensures that the resulting footprints are also equi-sized, and their constituents do not change from one snapshot to another.

The only module affected by this approach is the strip-adaptive module. During the Geolocation, interpolation to the Ground is performed by means of a DFT, so the objective now is to provide the appropriate apodisation coefficients such that the shape of the instrument beam over each point results in a circular footprint when projected on the ground.

The module must start, as it has been mentioned before, with an Earth fixed grid and the HKTM L1a data, in order to compute the appropriate antenna grid position ((ξ,η) values).

It shall be necessary to provide as L1b the values of Brightness Temperatures in the frequency domain, and a modelling of the apodisation coefficients variation with the antenna grid position.

[3] Both of them were investigated during the CCN following the main pre-development study on Phase 1

❑ Interpolation Approach

The interpolation shall be performed by means of a 2D interpolation filter that shall be derived from the 2D apodisation function. The objective is that through the application of this filter, the fraction of constituents inside each footprint in consecutive snapshots will remain the same. The resulting footprints shall be equi-sized as well.

It is equivalent to the previous method, except that the interpolation is always performed in the spatial domain, so the method is applied over the reconstructed Brightness Temperatures in a fixed Antenna grid.

The apodisation coefficients and the antenna grid coordinates of each Earth grid point are used for computing the Equivalent Array Factor, similar to a weight mask that is placed over the BT distribution to perform a discrete integral (sum of all the element by element multiplication). This operation retrieves a BT value for the corresponding Earth Fixed point and must be repeated as many times as needed.

As it has been mentioned before, strip adaptive has some disadvantages as well, namely the fact that not all pixels in the alias-free FOV can be circularised without incurring in heavy losses of efficiency (above 50º incidence angle approx.), and also because the retrieval of the apodisation coefficients needs to be performed for each pixel of each snapshot, as opposed to the nominal processing, where the same coefficients are applied to all pixels in one snapshot. This computation of the strip-adaptive apodisation coefficients introduces a processing overhead that is not negligible.

7. OUTPUT PRODUCT FORMAT

The format specification of the SMOS L0, L1a, L1b and L1c shall be in accordance to the Earth Explorer standards defined in [RD3]. Further information on the product format contents may be found in [RD.10].

Each product shall contain a Header and a Data Block, which may be contained in the same physical file, or in two separated physical files: a Header File and a Data Block File.

The Header shall be divided in two parts:

- A Fixed Header (FH) with identical structure to all SMOS files
- A Variable Header (VH) that allows defining and structuring different information for each file type. In the specific case of the products we are describing, the Variable Header shall contain the Main Product Header and the Specific Product Header for each type of product.

The Data Block shall contain one or more Data Sets, each of them containing a list of Data Records, preferably with identical structure. The most desirable structure is a Data Block containing a single Data Set with a list of identical Data Records. If this approach is not possible, the Data Block may contain a list of different Data Sets with different Data Records, but inside each Data Set, the Data Records should be identical. Data Sets with variable Data Records structure shall also be acceptable.

The Main Product Header shall be identical to all SMOS product files, while the Specific Product Header shall contain the definition of the contents of the Data Block for each product type, i.e. number and name of Data Sets, etc.

The Data Block structure in this specific case may be already defined in a brief description for each product type:

- **Level 0**

It shall be formed by a unique Data Set containing a list of Data Records. Each of this Data Records shall be formed by a complete set of Annotated Instrument Source Packets generated in an integration time period (snapshot). Source Packets may be of ancillary type or science type. For each snapshot or integration time in dual-pol mode, there shall be one ancillary packet and 24 science packets. Their format and contents is contained in [RD.7].

- **Level 1a**

For measurement products, it shall be formed by a unique Data Set containing a list of Data Records. Each of this Data Records shall be formed by a group of vectors containing the calibrated visibilities at a given polarisation (72x71/2 values) and the integration time.

In case the operation mode is dual-polarisation, there shall be one vector per Data Record and integration time, containing the calibrated visibilities on the selected polarisation (i.e. H and V). In case the operation mode is the full-polarimetric mode, every alternate integration time there shall be three vectors, containing the calibrated visibilities during the three time sub-intervals where one antenna is operating in one polarisation and the other two in the opposite polarisation.

There shall be also additional L1a products containing the calibration parameters and offsets computed after Correlated and Uncorrelated Noise Injection measurements. These products shall be used for calculation of the measurement L1a products based on the L0 raw correlation. Additionally, one L1a product containing calibrated terms of the Fringe Washing function may be created if the 3 time delayed measurements are produced in L0.

A product transforming all the needed HKTM data from L0 to a more usable format shall also be created here. This HKTM L1a product shall be used throughout the L1 Processor for spacecraft position and attitude determination among other things.

- **Level 1b**

It shall be formed by a unique Data Set containing a list of Data Records. These Data Records shall be formed by a group of vectors containing the Brightness Temperatures Fourier Components for different polarisation (e.g. H and V) and the integration time. These Fourier Components contain the full information on the Brightness Temperature spectrum of each scene, while at the same time being the minimum representation.

Each vector represents a scene, so apart from the integration time, there shall be a list of parameters inherent to that scene as the UTC time, PVT and AOCS values.

In case the measurement has been in full-polarimetric mode not only T_x and T_y spectrum shall be available, but also the spectrum for the third and fourth Stokes parameters U and V.

- **Level 1c**

It shall be formed by several Data Sets containing a list of Data Records. The first Data Set shall contain the list of scenes and their parameters (UTC time, TEC value and geomagnetic vector value among others).

The second Data Set shall contain a list of ground pixel coordinates and a vector of Brightness Temperatures at a given polarisation together with their incidence and azimuth angles and scene reference id. In case the measurement has been in full-polarimetric mode not only T_h and T_v shall be set for each incidence angle, but also the third and fourth Stokes parameters U and V. These records shall be of variable size, as the number of measured BT values depends on the position of the grid point within the swath.

The values per pixel shall also include the radiometric accuracy, Faraday rotation angle, geometrical rotation angle, and footprint resolution (axes of elliptical footprint).

A unique numbering shall identify each pixel, which shall refer it to the Fixed Earth Grid used as auxiliary data. As part of a separate ESA contract dealing with the Fixed Grid, some strategy is being taken in the identification of pixels, such that the unique identifier is also useful for a fast indexing of the data.