A Physical Model for Analysing the Geometric Errors of Remote Sensing Imagery

GERSI

Executive Summary

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1. INTRODUCTION

1.1. Purpose and Scope

This document contains the GERSI Executive Summary.

This document is intended to provide an executive summary of the background, design and development of the GERSI toolkit.

This document has been produced in the frame of the WP 5200 (Synthesis and recommendations for algorithms and tests methodology) of the contract 20226/06/NL/HE between ESA-ESTEC and DEIMOS Space (DMS) for the study on “A Physical Model for Analysing the Geometric Errors of Remote Sensing Imagery” (GERSI).

1.2. Background

The process of acquiring remote sensing images introduces a series of distortions coming from the observer (sensor and platform) and the observed (atmosphere and Earth surface). Consequently, the acquired image needs to be processed in order to be exploitable by the final user as a geo-located image, i.e. an image where each pixel can be easily related to geographical coordinates on a reference map.

The accurate geometric correction of remote sensing images is a key issue in multi-source and multi-temporal data integration, management and analysis.

With the advent of the GMES (Global Monitoring for Environment and Security) missions, geo-location will be a central issue. The main purpose of the programme is to have continuous global monitoring and consequently a huge amount of data will be produced at high to medium resolution and will require accurate geo-location. This is considered a critical point in the framework of GMES, because the development of operational services would be eased by reducing, or suppressing, manual intervention in the generation of high quality geo-located images over areas with or without relief. Furthermore, any imaging sensor for Earth observation or planetary missions could potentially benefit from the outcome of this study.

For correcting an image three kinds of approaches exist: the "empirical methods", which are based on the use of GCPs (Ground Control Points) or searching spatial correlations of tie points with already geo-located images; and the "physical methods", which rely on a physical model accounting for all the distortion sources that affect the Line of Sight and which is used to determine the pixel geographic coordinates. A third method consists in combining the two previous approaches to better constrain the inverse problem.

Empirical methods are straightforward, but can be very time-consuming when dealing with big amounts of data, as they require significant human intervention, unless an automatic GCP matching algorithm can be devised and demonstrated to be operational. Additionally, these methods are not applicable over areas where the topography is unknown.

Physical methods have the big advantage of not requiring human intervention and, as a consequence, allow the automatic processing of large amounts of data. However, they still require knowledge of the targeted area topography. The surface relief can be derived, for instance, using stereoscopic techniques.

1.3. Context and Rationale

GERSI is a SW suite composed of three modules (LOSM, GECP and ESAT) that can be used as stand-alone tools or operated in a single environment. Each tool is conceived as a stand-alone executable, but can also be called by the user through a user-friendly GUI. The addition of a post-procesing module for graphical representation of the main outputs completes the high-level architecture design, as depicted in the following figure.

The core of the GERSI suite is the physical modelling of the line-of-sight and the automatic geometric correction process based on that physical model.

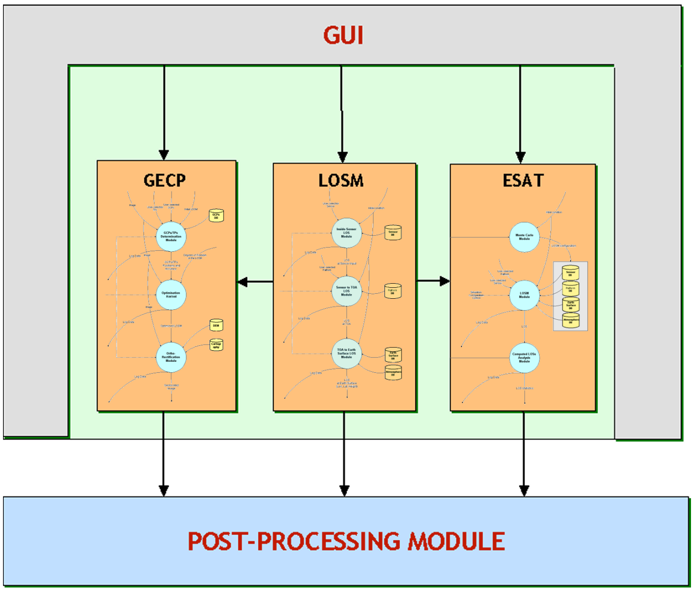


Figure 1: High-level Architecture of the GERSI SW Suite

Line-Of-Sight Model (LOSM)

The line of sight model (LOSM) simulates the line-of-sight function of an Earth observation sensor. It is applicable to all types of optical imaging sensors based on a linear or a 2D array of detectors, with a particular emphasis on sensors embarked on LEO missions. The model has been also designed to be easily adaptable to simulate other sensor types (e.g. passive microwave radiometers or SAR sensors).

GEometric Correction Processor (GECP)

The geometric correction processor (GECP) is a main part of the study. It can be seen as a demonstration module for application in GMES or in other existing/future ESA operational EOSS. Such an automatic geometry correction algorithm based on GCPs/TPs extraction, allows the user to improve the image geo-location accuracy, at least to a level equivalent to the one allowed by the lengthy manual extraction of control points.

Error Sources Analysis Tool (ESAT)

The analysis of the error sources limiting the geo-location accuracy is one of the major issues of the study. It is aimed at understanding the main contributors to the image performance, and at preparing the application of the automatic geometric correction processor (GECP). A dedicated tool, ESAT, has been developed, based on the LOSM. ESAT can also be used for parametric analyses in support to mission and payload design.

2. PROJECT HISTORY

This chapter presents the project objectives, the project team and the work structure description.

2.1. Project objectives

The GERSI proposal was prepared answering 20226/06/NL/HE.

The joint submission of this proposal from DEIMOS Space (Spain), DEIMOS Engenharia (Portugal) and Thales Alenia Space (France) came from the common desire to provide ESA with the most competitive solution to the stated problem and SW product demand, as well as from the perspective of creating an asset that shall enhance our involvement in the EOEP and GMES programmes.

This motivation is also reflected by the endorsement of the ESA policy of distributing the developed SW to a large community of user, so as to convert our efforts into a standard tool to be used, in first place, to support the design and data product specification of new mission as well as enabling a more affordable and reliable access to EOSS data via the automation of the geometrical error correction process.

With these motivations in mind, the three main objectives were defined:

- **Demonstrate that the geometric correction processing can be fully automated**
- **Develop a set of modular and expandable tools as support for system & payload design, future core elements of end-to-end simulators and proof-of-concept for ground processors**
- **Analyse the error sources limiting the geo-location accuracy**

These objectives led to develop three tools in the frame of the project:

- **The Line-Of-Sight Model (LOSM).**

  The LOSM is capable of simulating the line-of-sight of each pixel of a sensor located on an Earth Observation satellite, conceived as passive optical sensors (Pushbroom and 2D Snapshot sensors). The LOSM has been developed to be as general as possible, in order to be expandable to simulate the LOS of a wide range of EO instruments. This tool can be either used as stand-alone, or called from the GECP and ESAT tools.

- **The GEometric Correction Processor (GECP).**

  The GECP is based on a generic geometry correction core that has been kept independent from the specific sensor under study. A detailed GCPs/TPs detection module has been developed for a sensor that has been selected with ESA, and has been integrated into the GECP. The modularity of the proposed design allows the developer to complement the generic core with sensor-specific modules that increase the level of details of the modelling. The GECP integrates the LOSM in its operation.

- **The Error Sources Analysis Tool (ESAT).**

  The ESAT has been developed to study the effects on geolocation of the various error sources, and calls the LOSM adding analytical and random perturbations on its parameters in order to study their effects, using either a deterministic or a statistic approach.

Their use is three-fold:

- As a set of **support tools** for mission, system and payload design.
- As a core element for **end-to-end simulators** in the frame of the GMES and EOEP programmes.

- As a proof-of-concept for a future core element for **ground segment processors** for GMES/EOEP.

It is remarkable that the consortium was confident that the target of complete automation for the geometric correction processing is achievable through the proposed approach.

2.2. Project Team

The following figures show the project industrial consortium and the project team, with the correspondent responsibilities.

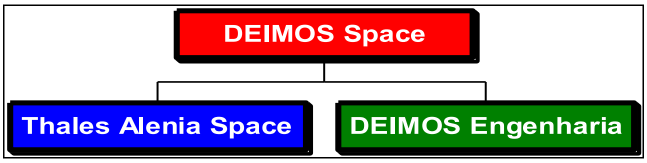


Figure 2: GERSI Industrial Consortium

2.3. Work Description

The following bullets provide a brief description of project tasks, implementing the study logic and proposed approach.

- **State-of-the-Art Review & Requirements Baseline**

  In this activity the Consortium has reviewed the existing approaches for LOS modelling, geo-locating remote sensing imagery and error sources analysis, selecting and specifying those deemed for implementation.

  - Review of Relevant EO missions
  - LOSM, GECP and ESAT software RB and TS

- **Design & Implementation**

  In this activity the Consortium has designed and implemented the different algorithms and tools based on existing requirements baseline and technical specifications performed previously.

  - LOSM, GECP and ESAT design and implementation
  - GUI Design and Development
  - Integration and testing

- **Verification & Validation**

  In this activity the Consortium has performed the definition and execution of verification and validation tests for the different algorithms and SW implemented.

  - Definition of test cases and results analysis
  - LOSM, GECP and ESAT verification and validation

- **Test case using data from an existing optical remote sensing instrument**

  In this activity the Consortium has first selected an existing optical imaging space-borne instrument. Then an analysis of the error sources limiting geo-location accuracy for the sensor has been carried out, before validation of the performance of the sensor selected.

- Selection of an existing optical imaging space-borne instrument
- Perform a sensitivity analysis of geo-location accuracy to all error sources
- Validation of sensor performance

Synthesis, recommendations and future work

In this activity the Consortium has provided synthesis of the entire finding obtained from the study, giving recommendations to the Agency and pointing future directions.

- Synthesis and recommendations for sensors
- Synthesis and recommendations for algorithms and tests methodology

Management

3. PRELIMINARY STUDY

The first task of the GERSI project, along with requirements definition for the three modules (LOSM, ESAT and GECP), foresaw the review and characterization of relevant Earth Observation missions.

The requirements definition activity also led to some studies whose results are reported in the next sections.

3.1. Review and Characterization of Relevant EO Missions

The objective of this activity was to present the results of a review and characterisation of relevant Earth Observation missions regarding remote sensing imagery features and capabilities. Special attention has been given to the current and future EO missions of particular relevance to this study, grouped with their relationship with ESA Earth Observation Programme.

The outcome of this study was the selection of a particular sensor, in agreement with the Agency, for the GECP/ESAT validation/verification, and for its test case.

Moreover the study has been performed to collect information necessary to design the LOSM module, since its design has to be applicable to all types of optical imaging sensors based on a linear or a 2D array of detectors, with a particular emphasis on sensors embarked on LEO missions. The model has been also designed to be easily adaptable to simulate other sensor types (e.g. passive microwave radiometers or SAR sensors).

The following optical instruments have been the main candidates for the combined application of the LOSM, GECP and ESAT:

- ❑ Linear scanner (Push-broom)
- ❑ Multi-pixel across-track scanner (Whisk-broom)
- ❑ Single-pixel scanner (scanning mirror)

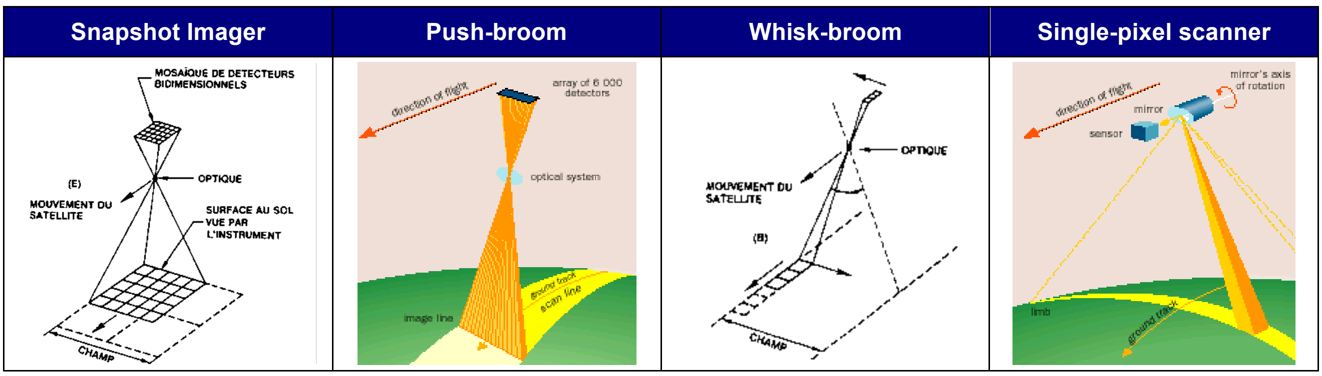


Figure 3: Schematics of the viewing modes for main optical instruments

Given the differences between the processing of the LOSM of GEO and LEO instruments, the GECP has been mainly oriented towards simulating LEO optical mission. In these missions the geolocation and image correction is performed off-line, and the critical aspect is to automatically process huge of data and sometimes without GCPs, while from GEO the sensor can be monitored in real time, with a corresponding correction of the LOSM.

Some sensors may require the addition of ad-hoc attitude guidance laws for on-board geometric error compensation or specific scanning schemes.

The LOSM in its baseline version is applicable to all type of optical viewing modes and the GERSI suite can be applied to a wide range of EO missions, either in its baseline version or with the addition of instrument-specific add-on modules.

A preliminary survey of the current and future EO missions of particular relevance to this study has been performed. The survey has been limited to missions with optical payloads, grouped into the four following categories:

- ESA - EUMETSAT
- Current or Foreseen Third Party Missions (European)
- Current or Foreseen Third Party Missions (Non-European)
- Other Possible Relevant Missions

For each mission the following data have been provided:

- Agency and Country
- Number of S/C in the operational system
- Operational Status (completed, operational, planned, etc.)
- Beginning of Life
- End of Life
- Sensor Name
- Sensor Bands
- Ground Resolution (for optical payloads only)

It is worth mentioning that 47 satellites with a total of 93 relevant optical payloads have been listed in this preliminary survey.

For the selection of suitable EO optical missions that satisfy a given observational requirement, it has been useful to group the missions in a few categories, depending on the sensor resolution:

- Optical – Very High resolution (< 2.5 m)
- Optical – High resolution (3-10 m)
- Optical – Mid-high resolution (10-30 m)
- Optical – Mid resolution (30-100 m)
- Optical – Mid-Low resolution (100-300 m)
- Optical – Low resolution (300-800 m)
- Optical – Very Low resolution (> 800 m)

In order to generate a shortlist of the most relevant EO missions as an input for the selection of the ORSI that will be modelled in details in the GECP, the following filtering criteria have been applied:

- Ground resolution lower than 400 m

- Possible availability of image data (BOL in or before 2006)
- Non-Third Party Missions are excluded, due to the likely unavailability of suitable data.

Then a characterization has been done of the most relevant European EO missions of interest providing the following information:

- Agency
- Country
- Number of S/C
- Status
- Beginning of Life
- End of Life
- Orbit type
- Mean semi-major axis
- Mean inclination
- Local time at ascending node
- Number of revolutions per day
- Orbit period
- Repeat cycle length
- Reference altitude
- S/C positioning accuracy
    - Radial
    - Along track
    - Across track
- Attitude pointing accuracy
    - Knowledge
    - Pointing
    - Rate

Note that if the orbit is a repeating Sun-Synchronous orbit (SSO) the revolutions per day are provided (as it is most common practice in EO mission analysis) instead of the mean semi-major axis.

Afterwards a characterisation of the relevant selected payloads has been performed. Whenever possible, the following information is provided for each sensor of the European EO missions of interest:

- Sensor type
- Field of View
- Instantaneous Field of View
- Field of Regard

- Swath width
- Ground resolution
- Number of focal planes
- Number of spectral bands
- Array size
- Detectors' type
- Co-registration information (band to band)

3.2. Review and Selection of Methods

The objective of this study was to present the results of a review and selection of methods and main algorithms to be implemented in LOSM, GECP and ESAT software tools.

3.2.1. LOSM

This Line Of Sight Model simulates the image/pixel generation going from the focal plane of the instrument and the associated spatiotemporal coordinates of each pixel (i,j,t) to the Earth surface location in terms of geodetic coordinates (latitude, longitude and altitude), Cartesian ECF coordinates and map projected coordinates.

The quality of the study depends on the quality and features of the developed LOSM: the LOSM is the core of the study and has to be a complete physical and generic model.

"Complete physical" model means the LOSM includes realistic transfer functions simulating each physical elements which impacts the line of sight - Satellite (Orbit position, Attitude, Sensor and platform), Atmosphere (Refraction), Earth's surface (Curvature, Rotation, Topography), Map projection.

A physical LOSM is an essential component to perform the study and achieve the two main objectives:

- Analysis of the error sources limiting the geo-location accuracy. Each error source is taken into account and combined in order to highlight the main contributors.
- Validation of the gain brought by automatic geometric correction methods. These methods are based on LOS physical modelling.

A "Generic" model is required for simulating a large range of remote sensing instruments. The model is mainly dedicated to optical payload, but it is open to accept other sensor types (e.g. passive microwave radiometers or SAR sensors). The types of optical imaging sensors are based on a linear or a 2D array of detectors in push-broom or whisk-broom mode.

The LOSM simulates the following types of LOS (please refer to Table 1):

- The Nominal LOS corresponds to the LOS without error sources (no realisation error, no launch error, no in-orbit error), by assuming a perfect satellite concept in orbit.
- The True or Actual LOS corresponds to the previous LOS with error sources (realisation, misalignment before the launch, then all the other errors occurring during the launch and in orbit). The image data acquired by the payload is submitted to the true LOS behaviour.

- The ground estimated or measured LOS (just before the in orbit commissioning) corresponds to the true LOS "corrected" by the alignment and realization errors. Some error contributors (mainly static error sources of the payload, like focal plane cartography, optical distortion, focal length realization, …) are measured and known, but these LOS error contributors remain affected by a knowledge error relative to the measurement Ground Support Equipment.
- The commissioning estimated or measured LOS (just after the in orbit commissioning) corresponds to the ground estimated LOS updated after the orbital calibration phases. Geometric corrections coefficients assessed during the commissioning phases are used to improve the knowledge of LOS. In particular, this includes: an update of static error sources of the payload, as focal plane cartography, optical distortion, focal length realization, … the data issued of bias calibration. Therefore, the error sources of LOS remain affected by a knowledge error relative to the in orbit measurement method.
- The improved estimated or measured LOS (after filtering of on board telemetry) corresponds to the commissioning estimated LOS improved by using the auxiliary data (essentially telemetry) of the current image. It can gather such data as: attitude (Star Tracker, Gyro,…), Orbit position, velocity and time (GNSS, …). These data can be used as such or after a ground filtering. Without the use of GCPs, this type of estimated LOS is usually used to perform the geo-location and co-registration accuracy.
- The optimized estimated or measured LOS (after using GCPs/TPs and dedicated geometric correction processor) corresponds to the previous estimated LOS of which the knowledge is improved after optimization process by taking advantages of reference points extracted from endogenous or exogenous data.

The nominal LOS is used to build up true LOS (the true LOS is unknown).

The ground estimated LOS, the commissioning estimated LOS and the improved estimated LOS are possible inputs of GECP.

The optimized estimated LOS is computed by GECP.

All these functions types have been modelled by LOSM.

Table 1 : Types of LOS Models to be simulated by LOSM

Name and definition of the location models		Elementary models to build up the location model with LOSM	
		Nominal model	**Measurements / Perturbation models**
fLOS nominal	theoretical model of image	- Theoretical kinematics law (attitude) - Focal plane - Sampling time - Theoretical optical law - Scan mirror(s) - Theoretical kinematics law of scan mirror(s)	none
fLOS true	true or actual location model of image	same as nominal fLOS	- AIT realisation (static) - launch (static) impact - in-orbit (dynamic) impact
fLOS measured before launch	location model of images (product L1A/L1B) after launch before commissioning	same as true fLOS	- AIT measurements

Name and definition of the location models		Elementary models to build up the location model with LOSM	
		Nominal model	Measurements / Perturbation models
fLOS measured after IOT	location model of images (product L1A/L1B) after commissioning	idem	- AIT measurements - In orbit test measurements
fLOS measured of classical L1B product	location model of images (product L1A/L1B) during operational phase	idem	- AIT measurements - In orbit test measurements - on-board measurements (ancillary data in telemetry) with possible ground filtering
fLOS measured of classical L1C product	location model of orthorectified images (product L1C) during operational phase	idem	idem
fLOS measured of L1B product after GECP	location model of images (product L1A/L1B) during operational phase using GECP	idem	- AIT measurements - in orbit test measurements - on-board measurements (ancillary data in telemetry) with possible ground filtering - optimised perturbation model
fLOS measured of L1C product after GECP	location model of orthorectified images (product L1C) during operational phase using GECP	idem	idem

3.2.2. ESAT

ESAT is based on generic and physical Line Of Sight Model and aims at analyzing error sources limiting the accuracy of the pixel geo-location. This tool is one of the major issues of the study to understand the main contributors of the performance, and prepare the application of the automatic geometric correction processor.

The geo-location accuracy is computed as the distance between the actual or true location and the estimated or measured location.

The Error Source Analysis Tool helps the operator to identify the main error source for the performance of the LOSM by varying input parameters of the LOSM. The line of sight modelled after the ESAT analysis is then used in the GECP to compute the Tie Points with better accuracy.

The main objectives of ESAT are to:

- **establish the geo-location performance budget.** This is a powerful budget tool to assess performances during the Earth Observation Space System program definition and development phases. The EOSS program aims at specify and design EOSS architecture (on-board and ground processing), make technical trade-off, assess performances, sensitivity analysis, point out and assess hardware discrepancies / anomalies impact onto performance,…). ESAT could become the reference one to perform the geo-location budget for ESA programs.
- **analyze the impact of main source errors onto the performance before GECP using**.
    - ESAT provides the relative impact between error sources, what permits to identify the main contributors (i.e. degrees of freedom) on which the optimization of the geometric correction processor will be applied. Without this analysis, it's very difficult to optimize the line of sight: the process can be too long and can have some difficulties solving the line of sight model due to the number of free variables. So, ESAT permits to adjust (and simplify) the physical model to be optimized with GECP.

- Eventually, the analysis of the error sources limiting the geo-location accuracy is very important in order to know the search window on which the matching processing is applied to extract the GCPs/TPs.

- **simulate the geometric calibration method during commissioning phase** for remote sensing space system on which automatic GCP extraction methods can not be applied (as SPOT for instance). The tool could be used to identify the part of the remaining biases after calibration.
- **understand the in-orbit behaviour of the sensor during the commissioning and operational phases** by using first the output of budgets, analysis and test measurements before the launch, then the telemetry and control points such as GCPs in images. This type of tool could be used to have better feed-back of satellite in-orbit behaviour.

The different types of analysis which fall within the competence of ESAT are summarized in the following table.

Table 2: Different ESAT Analysis Types

Definition of different performance types computed by ESAT		Objectives	Error contributors used to compute the geo-location accuracy by the classical budget tool (classical approach)
Pointing accuracy	fLOS true – fLOS nominal	Estimation of the individual impact of each error source	❑ AIT realisation (static) ❑ Launch impact (static) ❑ In-orbit impact (dynamic)
Geo-location accuracy of images (product L1A/L1B) after launch before commissioning	fLOS true – fLOS measured before launch	Can be used to estimate IOT measurements	❑ AIT measurements accuracy (static) ❑ Launch errors (static) ❑ In-orbit errors (dynamic)
Geo-location accuracy of images (product L1A/L1B) after commissioning	fLOS true – fLOS measured after IOT	Used to estimate the geo-location accuracy without filtering	❑ AIT measurements accuracy (static) ❑ IOT measurements accuracy (static) ❑ In-orbit errors (dynamic)
Geo-location accuracy of images (product L1A/L1B) during operational phase	fLOS true – fLOS measured of classical L1B product	Used to estimate the geo-location accuracy without GECP	❑ AIT measurements accuracy (static) ❑ IOT measurements accuracy (static) ❑ On-board measurement accuracy (dynamic) ❑ Ground filtering accuracy (dynamic) ❑ Non measured residual error like micro-vibrations (dynamic)
Geo-location accuracy of images (product L1A/L1B) during	fLOS true – fLOS measured of L1B product after GECP	Used to estimate the performance with GECP	Optimisation ground processing residual error including or not:

operational phase using GECP			❑ AIT measurements accuracy (static) ❑ IOT measurements accuracy (static) ❑ On-board measurement accuracy (dynamic) ❑ Ground filtering accuracy (dynamic) ❑ Non measured residual error like micro-vibrations (dynamic)

3.2.3. GECP

The GEometric Correction Processor is intended to improve the image geo-location accuracy by optimizing the parameters of the Line Of Sight Model using Ground Control Points and Tie Points measured in the images.

The geometric correction processor could be applied to these main cases (we assume images taken by the same sensor on the same spacecraft):

- Optimising the LOS from a single image using GCPs (geo-location purpose),
- Optimising the LOS of multiple images using both GCPs and TPs, methods called “bundle block adjustment” (geo-location purpose),
- Optimising the LOS between some images (such as multispectral images) using TPs (co-registration purpose).

The study has been focused on the two first cases concerning the geo-location purpose. But, the tools are open to be usable for the co-registration purpose.

The geometric correction processor involves three steps:

- Automatic determination of GCPs/TPs locations in the raw image.
- Optimisation of the physical LOS model parameters to minimise the error between the location of GCPs/TPs projected in the image using the LOS model and the location of GCPs/TPs measured in the image.
- Creation of the geo-located image using the optimised LOS model.

4. GERSI FUNCTIONALITIES

4.1. Software Tools Functionalities

After some preliminaries activities (as described in Section 3), the GERSI suite user and system requirements have been derived from the Statement of Work and the functionalities for each implementation modules have been derived.

In the next sections the GERSI suite functionalities, detailed for each one of its components, are described.

4.1.1. HMI

The HMI module used in the GERSI project is simplified, tailored version of a bigger HMI used in another DEIMOS project, the ECSIM.

The GERSI suite is delivered as a set of stand-alone modules for ease of re-use, but also as an integrated framework driven by a user friendly human-machine interface (HMI) that guides the user to efficiently carry out the simulation activities.

Concretely, the HMI eases the use each one of the three GERSI tools, providing:

- Model management to control and to handle all models that can take part of simulation sessions;
- Simulation management, this is the definition, modification and deletion of simulations in the repository;
- Simulation execution;
- Post-processing and visualization of the simulation results.

The Figure 4 describes the HMI use case diagram, with the interaction between the user and the system.

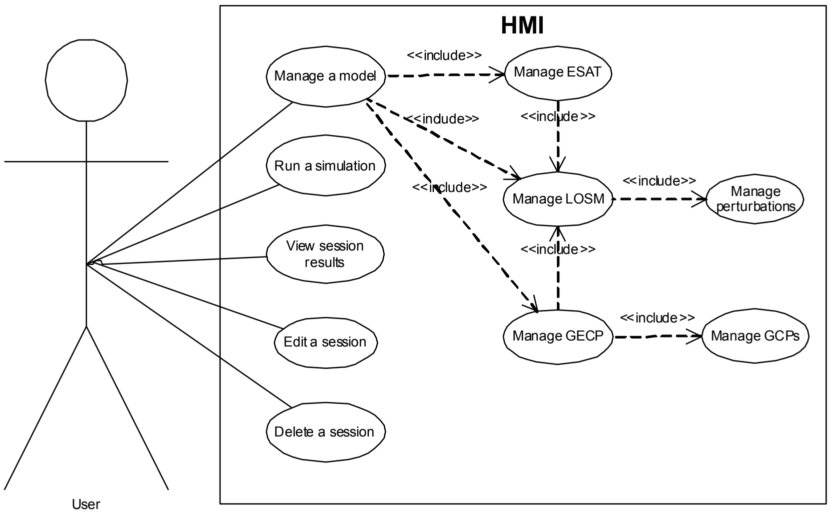


Figure 4: HMI Use Cases Diagram

This HMI module acts as the user interface for the GERSI project, that is, the aggregate of means by which people (the users) interact with this particular system. The user interface provides means of:

- Input, allowing the users to manipulate a system
- Output, allowing the system to produce the effects of the users' manipulation.

The HMI term refers to the 'layer' that separates a human that is operating a machine from the machine itself.

The actor named "User" is a person that interacts directly with the HMI module via its Graphical User Interface (GUI). This user is the responsible to start all the HMI operations.

4.1.2. LOSM

Within the GERSI tools, the objective of the LOSM module is to define LOS models. These models will be used by the GECP and ESAT tools, by means of a LOSM library. Additionally, a stand-alone module will allow the user to interact with the LOSM by performing direct and inverse localization (i.e. LOSM executable). The stand alone module can be used both from HMI and command line.

In the next two figures it is possible to see the use case diagram both for the LOSM executable and the LOSM library.

The user, throughout the HMI or the command line, can perform a direct (i.e. pixel to ground) or inverse (i.e. ground to pixel) localization using the LOSM as an executable. Running a LOSM executable includes the definition of all the parameters of the LOSM model configuration, the definition of the perturbations (i.e. input files) and to define the file where the output will be saved (i.e. output files).

The GECP and ESAT can also perform a direct or inverse localization, but using the LOSM as a library. Calling the LOSM library includes the definition of all the parameters of the LOSM model configuration and the definition of the perturbations (i.e. input files). In this case no definition of output files is foreseen.

4.1.3. ESAT

The ESAT tool may be used as a standalone command line program or through a separate HMI.

Within the GERSI tools, the objective of the ESAT module is to analyze the geolocation error sources by means of Monte Carlo simulations.

ESAT makes use of the LOSM library in order to model the Line Of Sight of the instruments and compute the localisation functions.

In the next figure it is possible to see the use case diagram for the ESAT tool.

The user, throughout the HMI or the command line, can perform an analysis of the geolocalization error sources. Running an ESAT executable includes:

- the definition of all the parameters of the ESAT model (i.e. scenario and statistics parameters),
- the definition of input files (i.e. LOSM configuration, LOSM perturbations, ESAT random perturbations),
- the execution of the Monte Carlo simulation,
- the analysis of the simulations results,

- the definition of the file where the output will be saved (i.e. output files).

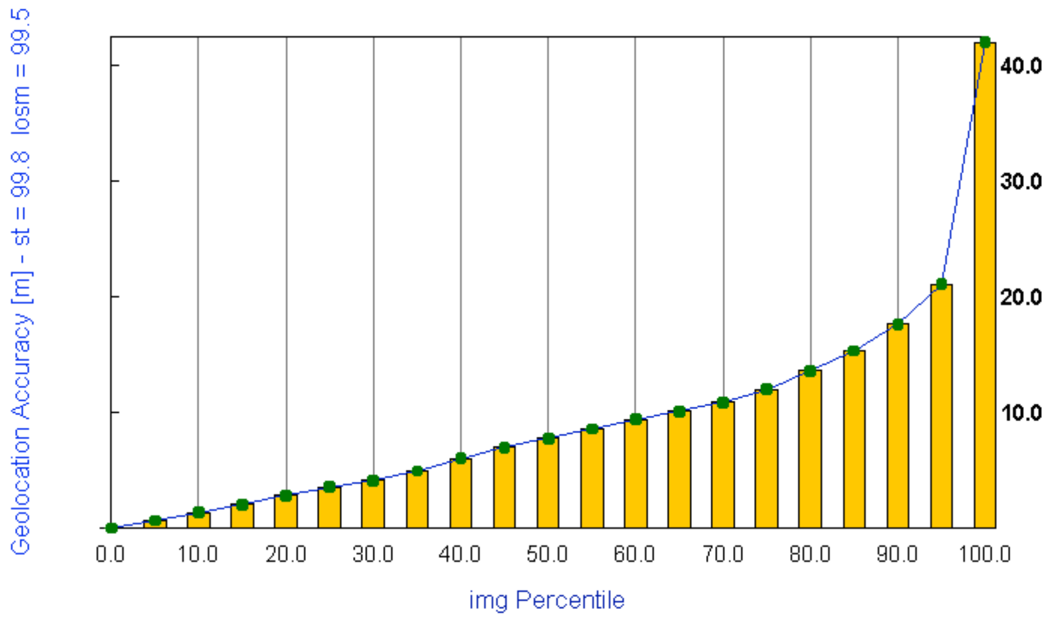


Figure 5: ESAT Post Processed Data with two Percentile Threshold Values

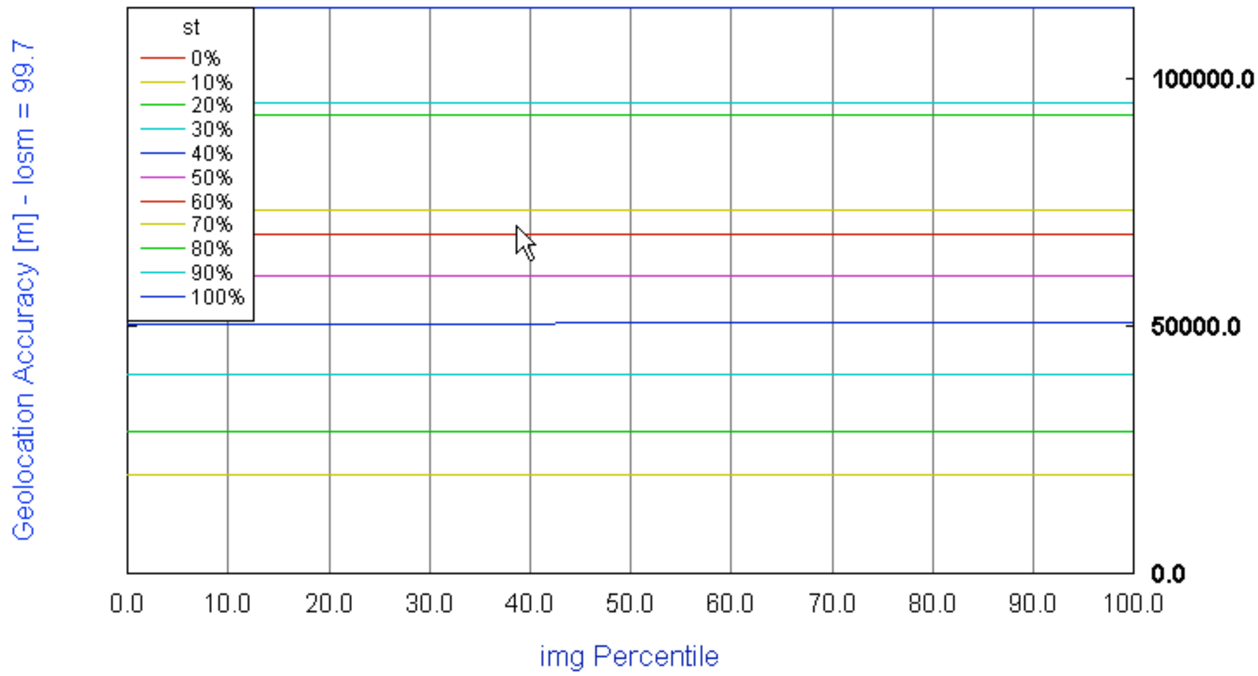


Figure 6: ESAT Post Processed Data with one Percentile Threshold Value

4.1.4. GECP

GECP tool may be used as standalone command line program or through a separate GUI.

Within the GERSI tools, the objective of the GECP module is to improve the geo-location accuracy and create orthoimages by optimising LOS models based on Ground Control Points and Tie Points.

GECP makes use of the LOSM library of functions in order to model the Line Of Sight of the instruments and compute the localisation functions.

In the next figure it is possible to see the use cases diagram for the GECP tool. The overall GECP use case diagram has been detailed in three partial diagrams in order to focus the attention on every of the three main processes that compose the tool.

The user, throughout the HMI or the command line, can perform a geolocation improvement analysis. Running a GECP executable includes:

- the definition of all the parameters of the GECP model (i.e. determination, optimisation and correction),
- the definition of input files (i.e. LOSM configuration, LOSM perturbations, raw image, GCPs, optimization steps),
- the determination process of GCPs and TPs,
- the optimisation process of the LOS,
- the correction process of the input image,
- the definition of the file where the output will be saved (i.e. output files).

The improving of geolocation of an input image was foreseen as the unique use case for the GECP. Nevertheless in the final GECP implementation some extensions of this use case have been implemented as independent use cases.

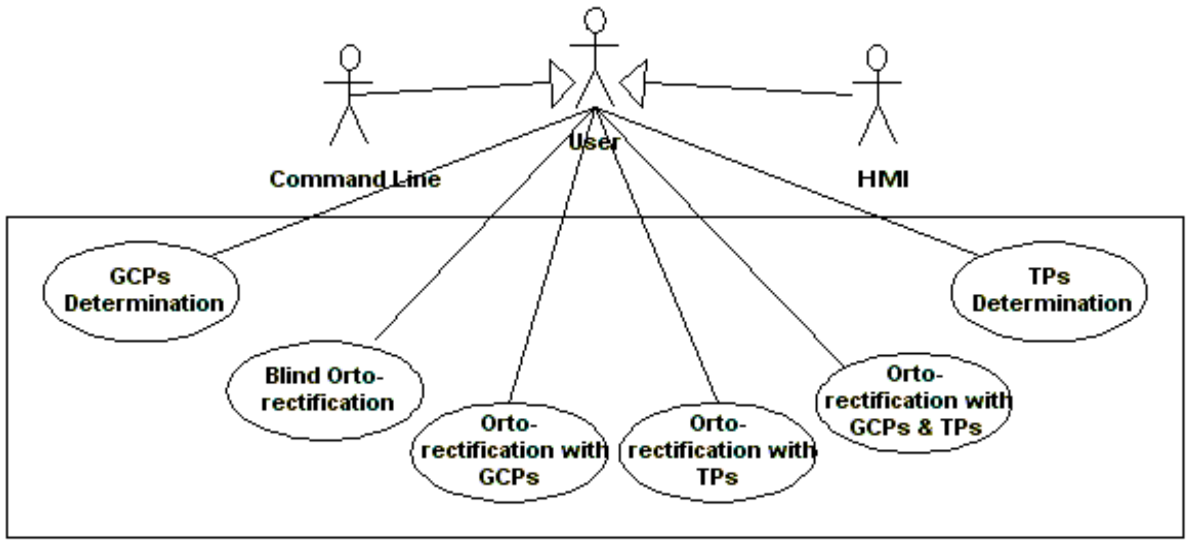


Figure 7: GECP Use Case Diagram

In this way the user can independently perform six different operations by means of the GECP (please refer to Figure 7):

- determination of GCPs,
- determination of TPs,
- blind-Orthorectification,
- improvement of geolocation using GCPs,
- improvement of geolocation using TPs,
- improvement of geolocation using GCPs and TPs.

GCPs and TPs determination are extension of the improve geolocation use case. They are performed as preliminary steps of an ortho-rectification but they can also be performed as a stand-alone use case. They are used to compute a set of tie points between two images or to determine the positions of a set of ground control points in an image. They are configured through a GECP configuration file. It relies on Image processing in order to prepare images for correlation: filtering, resampling, normalisation and projection. Correlation enables tie points selection and scoring as well as image matching through correlation and correlation window size determination.

Tie points and ground control points are then saved in an output file as tie points lists or GCP lists.

Optimisation is an extension of the improve geolocation use case, but it cannot be performed as a stand-alone use case. It is configured through a GECP configuration file and an optimisation parameters file. The optimisation parameter file defines the LOS parameters to be optimised and their optimisation bounds.

The optimal LOS values are then saved in a output file.

Image corrector Optimisation is an extension of the improve geolocation use case. It is performed as the last step of an ortho-rectification process, but it can also be performed as a stand-alone use case (**blind ortho-rectification**). It is configured through a GECP configuration file. It reads a raw image and uses the LOSM module to project the image onto a Map projection.

The resulting orthoimage is saved on file.

The complete ortho-rectification process consists of GCPs/TPs determination (i.e. only GCPs, only TPs, and both GCPs and TPs), LOS optimisation and image correction. In this case the configuration of the use case consists in a GECP configuration file and an optimisation parameters file.

As output will be generated tie points lists and/or GCPs lists, optimal LOS values and the resulting orthoimage.

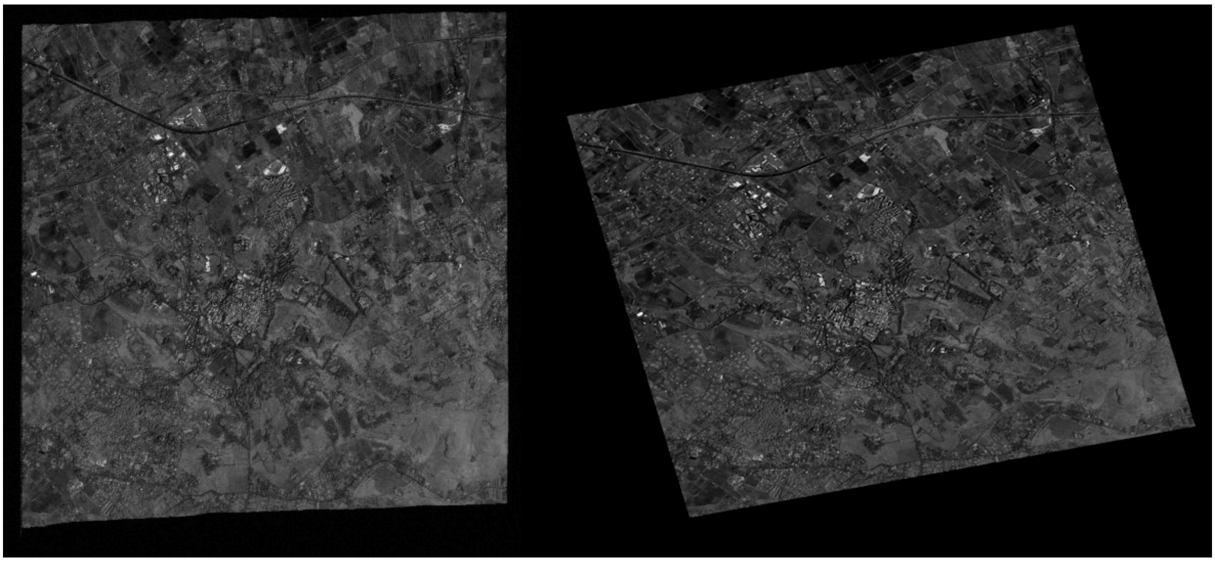


Figure 8: Raw data (left) and GERSI ortho-rectified and map projected image (right)

5. GERSI ARCHITECTURE

Once defined the GERSI suite user and system requirements, an architectural design has been produced.

In the next sections the GERSI suite architecture, detailed for each one of its components, is described along with general considerations about design assumptions and system decomposition.

5.1. Design Assumptions

The methodology used for architectural modelling was aimed at isolate conceptual modules with clear defined boundaries and characteristics at a high-level system context level. This approach also eased the system and interfaces requirement definition.

Once obtained clear high-level system decomposition and drawn the system and interfaces requirements, the following activity has been to design the architecture of the tool allocating the above stated requirements.

Both for the high-level system and for the architectural design the Unified Modelling Language (UML) has been used.

The design environment were composed by a platform independent Eclipse plug-in based application (which can be easily extended for mission specific needs) and a specialised design tool for UML modelling:

- the UML design tool (i.e. Poseidon for UML) has been used for software design, code generation and documentation generation;
- the C/C++ development environment (i.e. Eclipse CDT – C/C++ Development Tooling) for compiling and debugging the code.

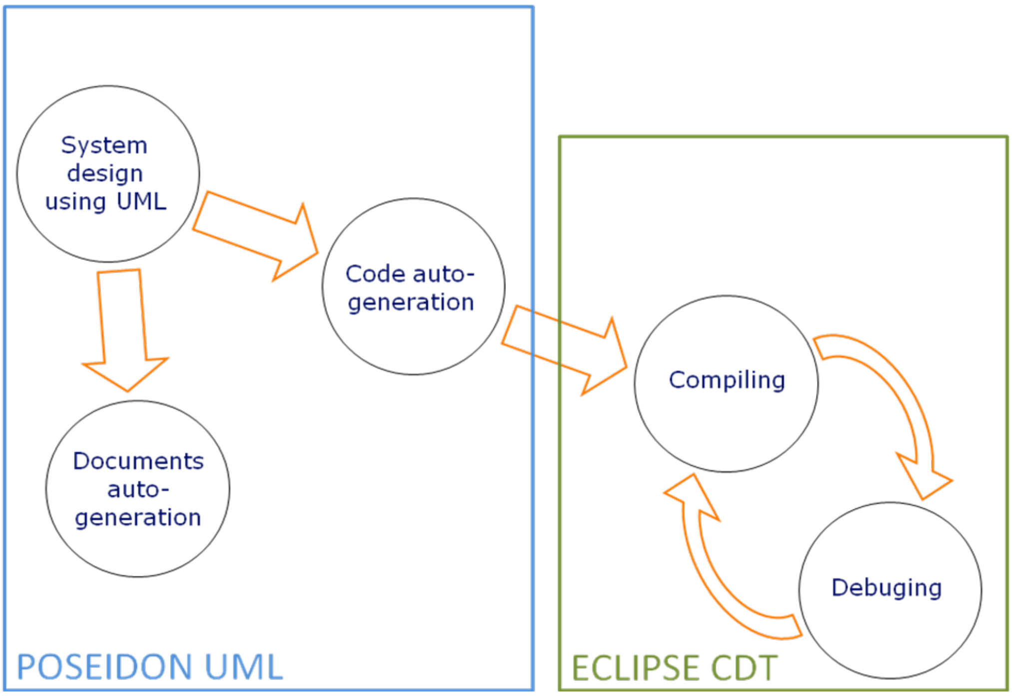


Figure 9: GERSI Coding Approach

5.2. System Decomposition

5.2.1. High-Level System Context

The following figure shows the high-level system context of the GERSI suite. The tools are broken down in 4 packages:

- The LOSM library, which is self content and provides all LOS model related functions
- The GECP tool, which depends on the LOSM library and is composed of three separate tools: GCPs/TPs determination tool, Optimisation tool, Image correction tool
- The ESAT tool, which depends on the LOSM library
- The LOSM stand-alone tool, which depends on the LOSM library
- The HMI, which serves as user-friendly graphical interface and framework to interact with the rest of the GERSI modules, in order to change their parameters, to manage the simulations, to intercept the result of these executions and to call the post-processing operations.

Notice that the entire GERSI suite tools (LOSM, GECP and ESAT) can also be executed via command line.

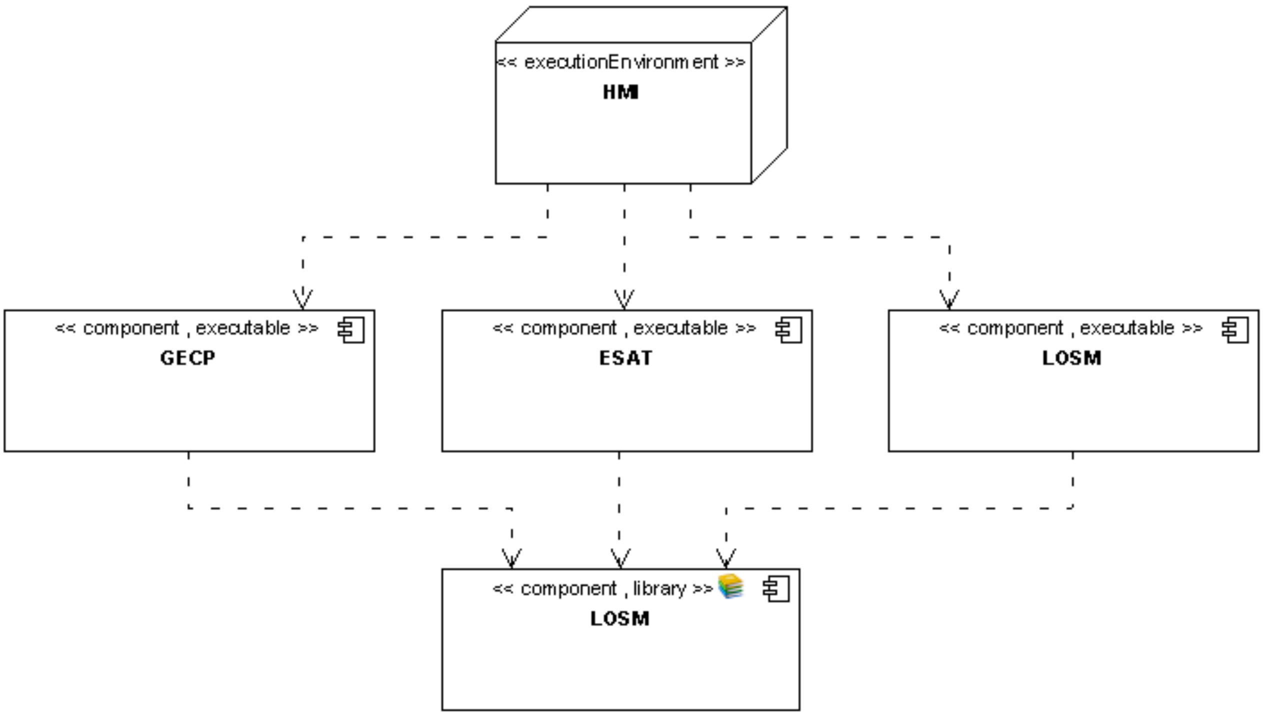


Figure 10: GERSI High-level System Context

In the Final Report details are given both on the high-level data flow and on the architectural modules of the three tools.

6. GERSI IMPLEMENTATION

6.1. Software Development

The key drivers for the software coding and tool structure development in the frame of the GERSI Project have been derived from the software requirements contained in the SoW. These high-level requirements are related to the following main issues.

- **Programming language**. The modules of the GERSI suite (LOSM, ESAT and GECP) have been developed using C++, in order to ensure software modularity throughout an Object Oriented design. The HMI has been developed using Java.
- **Programming guidelines**. The software has been well commented in the code. In addition it has been documented by a Software User's Manual that defines the input and output data of the various tools, and contains the procedural instructions for the use of the program(s). The software has also been coded in order to guarantee cross-platform portability.
- **Software architecture**. The GERSI software architecture is modular and comprises a set of independent modules, which can be used as stand-alone tools to perform different analysis.
- **Target platform**. The GERSI software has been developed for three platforms: Windows XP, Linux 32 bits and Linux 64 bits. For the Linux platform the GERSI compatibility has been proved for Ubuntu and OpenSUSE distributions.
- **Software development approach**. The GERSI software modules have been developed using an object oriented approach. It has been used a modelling tool that auto-generated the source code. Afterwards that code was compiled and debugged in a C++ development environment.
- **Software installation and running**. The SW installation is based on a folder structure that allows file handling and program execution control. The software can be installed by means of an automatic installer process that initialises also all the environmental variables necessary for the GERSI execution.

In the Final reports details on of the validation and Verification of GERSI are given, along with a section describing the GERSI delivery, deployment and use.

6.2. Application to Optical remote Sensing Instrument

Along with the design and implementation of the three modules composing GERSI (LOSM, ESAT and GECP), one of the project objectives was the selection of an existing space-borne instrument (and its products), and the analysis of the error sources limiting the geo-location accuracy.

As outcome of the study described in the Section 3.1, the best candidate to be selected as existing space-borne instrument for analysing the error sources limiting the geo-location accuracy was the CHRIS sensor on the PROBA platform.

The choice was justified considering the following characteristics as preferred:

- Push-broom scheme
- Ground resolution > 20 m and < 100 m

- Availabilty of imaging data
- Availabilty of suitable telemetry
- Adequate platform ponting performances

After many iterations between DMS and the Agency (that took place during the entire GERSI design, implementation and V&V phase), it resulted impossible retrieving sufficient information about CHRIS-PROBA for modelling a feasible LOSM for testing the error sources limiting the geo-location accuracy.

Jointly DMS and ESA accorded to de-scope CHRIS-PROBA and to select another existing space-borne instrument, with more available information.

The choice felt on the HRVIR sensor of the SPOT 4 satellite, but using the multispectral band instead of the originally foreseen PAN due to its 20m resolution. In the next table it is shown the refined selection of ORSI that was the output of the "Review and characterization of relevant EO missions".

Again the search for information regarding the geometry of the sensor was quite tough, due to the high level of complexity of the GERSI LOS model and the correspondent lack of details provided by the satellite operator.

On this basis the following was agreed, i.e. to try modelling the LOSM for a SPOT 4-HRVIR image at the best of Consortium capabilities

6.2.1. SPOT Data

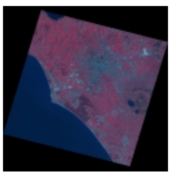
A key task of the GERSI study is to automatically process a Level 1A product by means of the GECP, in order to obtain a geo-localized and ortho-rectified image.

Once the ESA and the Consortium selected SPOT 4-HRVIR as existing space-borne instrument for the WP4000 activities, some images provided by SPOT Image as suitable for this task and the area around ESRIN (Frascati, Italy) have been chosen.

Each image shall be provided with additional information, in order to set up the LOSM.

The selected images for this task are two images of the Frascati area, downloaded from the EOLISA server, along with their metadata. In the following table the available downloaded images are reported.

Table 3: SPOT 4-HRVIR Available Images

Scene ID	Product Level	Band	Resolution [m]	Preview	Metadata	Size
4 066-265 07-03-13 10:16:34 1 I	L1A	XS	20		YES	3000x3000
4 066-265 07-03-13 10:16:34 1 I	L2A	XS	20		YES	3000x3000

6.2.2. LOSM Modelling

In order to perform the automatic geo-localization and ortho-rectification of the SPOT 4 Level 1A product over Frascati, it is necessary to define all the inputs for the GECP.

Since the GECP has been kept independent from the specific sensor under study, the set up of its inputs relies on the user expertise in the image processing area.

The compilation of the inputs for the LOSM (that will be used by the GECP) is not trivial since the model itself is based on a physical modelling of the line-of-sight.

An analysis of the LOSM input parameters was conducted. Then a cross check against the information provided by the DIMAP data was performed, identifying which parameters are contained in the SPOT metadata, which ones can be derived from such metadata.

In case some parameters cannot be defined by means of DIMAP data, their value has been retrieved from other sources (e.g. CNES SPOT Missions Websites).

In case nor the DIMAP data nor other sources can provide values for the LOSM definition, ad hoc analyses has been performed in order to estimate feasible values for the missing parameters and hence model the LOSM.

Summarising, a dual approach to define the LOSM model has been followed:

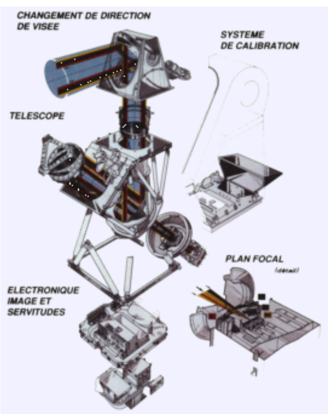
- direct, throughout the SPOT Image web site and the DIMAP metadata, after a pre-processing when necessary;
- indirect, throughout external tools analysis, in order to estimate a feasible value for parameters whose definition is not provided.

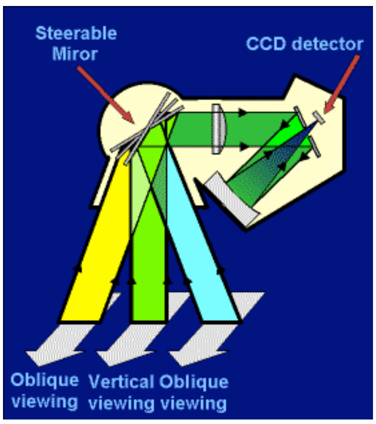
6.2.2.1. Considerations about LOSM Sensor Model

The LOSM Sensor model is based on the assumption of a linearised optical path from the detector to the Earth surface, not taking into account the real geometry of the optics. This simplification drives the user to define a LOSM sensor model using his knowledge about the real sensor.

Assuming the user gets information about the sensor assembly geometry, he shall be able to define a linearised optical path (Figure 11, right) starting from a complex sensor model (left and centre).

HRVIR Sensor Assembly	HRVIR Sensor Model	LOSM Sensor Model





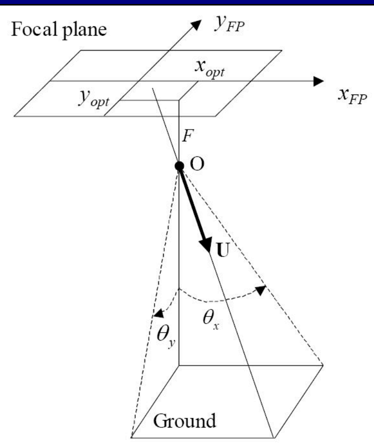


Figure 11: Sensor Assembly and Models Comparison

6.2.3. Use Cases

For the analysis of the error sources limiting the geo-location accuracy, two SPOT 4 products were available, namely:

- L1A XS (20m, B1, B2, B3, SWIR)
- L2A XS (20m, B1, B2, B3, SWIR)

With a product we refer to an image with its correspondent metadata.

The geolocation accuracy of SPOT 4 has been estimated to be about 300-500m.

Moreover an analysis of the necessary information to model the LOSM was previously performed, along with a review of the DIMAP metadata contained in the SPOT products and the other possible information present in the SPOT Image website.

On this basis DMS and TASF performed several iterations to agree on a suitable use case for performing the analysis of geometric correction of a L1A product.

Hereafter the selected use case is specified.

6.2.3.1. Use Case Specifications

The multi-spectral L1A product (namely L1A XS 20m B2) is selected as raw image to ortho-rectify and geo-localise by means of the GECP.

An associated LOSM (namely LOSM1) corresponding to L1A XS 20m B2 product is modelled.

Two sets of GCPs are selected using Google Earth:

- GCPs used to optimise the LOSM
- GCPs used to check the result accuracy

The GCPs used to optimise the LOSM are referenced on the L2A XS 20m B2 that, for this use case, is considered the reference image.

Since the SPOT L2A products are projected on the WGS84 ellipsoid, all the GECP process can be performed without the need of a DEM.

With these inputs it is possible to run a GECP for optimising the LOSM1 and correcting the L1A product.

For the optimisation process the following parameters will be optimised:

- satellite average Roll
- satellite average Pitch
- satellite average Yaw
- sensor focal length

The expected outputs are:

- The (column, raw) values for each GCP in the two images (L1A, L2A)

- Optimised LOSM
- Orthorectifed image from L1A XS 20m B2

6.2.3.2. Use Case Analysis

The results of the use case can be analysed both qualitatively and quantitatively.

Qualitative analysis

A comparison between the ortho-rectified image and the L2A XS 20m B2 image will be performed.

The geolocation enhancement obtained with the optimised LOSM will be verified by comparing the result with the second set of GCPs (the GCPs not used in GECP).

The assessment of the residual discrepancies on the GCPs used to optimise the LOSM will be also analysed.

Quantitative analysis

The geolocation enhancement obtained with the optimised LOSM will be verified by comparing the result with the second set of GCPs (the GCPs not used in GECP).

The assessment of the residual discrepancies on the GCPs used to optimise the LOSM will be also analysed.

6.2.4. GECP Tests

Once defined the use case for the analysis of the error sources limiting the geo-location accuracy and configured all the inputs necessary for executing the GECP, the testing activities started.

Tests Outcome

The GECP test was conducted with a dual approach:

- ortho-rectification with GCPs, as nominal use case
- blind ortho-rectification with refined LOSM, for testing the robustness of GECP

The ortho-rectification with GCPs was run as specified in Section 6.2.3.1. This test led to detect memory management limitations due to the large size of the input image and to the operative system architecture (Windows XP).

The blind ortho-rectification executions highlighted some GECP limitations when applied to the current SPOT use case. Even though the GECP V&V process was conducted successfully, it relied on the particular assumptions made in the acceptance tests specifications.

The application of the GECP to the SPOT real case drives to some recommendations oriented to generalise the GECP implementation towards a wider range of space-borne remote sensing instruments.

The tests executed with the SPOT use case provided precious information that can be used to define a very precise task list for refining the GECP implementation for generalising its application to every optical sensor embedded on a LEO satellite.

7. CONCLUSIONS AND FUTURE PERSPECTIVES

7.1. Achievements of GERSI Project

The GERSI project has achieved its three main objectives:

- Demonstrate that the geometric correction processing can be fully automated
- Develop three modular and expandable tools (LOSM, GECP and ESAT) as support for system & payload design, future core elements of end-to-end simulators and proof-of-concept for ground processors
- Analyse the error sources limiting the geo-location accuracy

In the frame of the project, three modular and expandable tools have been developed:

- The Line-Of-Sight Model (LOSM)
  - It models the line-of-sight of each pixel of a sensor located on an Earth Observation satellite, conceived as passive optical sensors (Pushbroom, 2D Snapshot and Wiskbroom sensors).
  - It has direct (from pixel to Earth) and inverse (from Earth to pixel) localization functions.
  - It is generic and expandable in order to simulate a wide range of EO instruments.
  - It can be used stand-alone, or called from the GECP and ESAT tools.
- The GEometric Correction Processor (GECP)
  - It is a generic automatic geometry correction processor, based on the LOS physical model.
  - It is independent from the specific sensors.
  - It implements automatic GCPs/TPs detection module, which can be used as stand-alone.
  - It implements an optimization module searching for the optimal LOS model.
  - It implements a correction module based on the optimal LOS model, which can be used as stand-alone ("blind ortho-rectification").
- The Error Sources Analysis Tool (ESAT)
  - It analyses the error sources limiting the geo-location accuracy, based on the LOS physical model.
  - It is based on both a deterministic and a statistic approach.

Their use is three-fold:

- As a set of **support tools** for mission, system and payload design.
- As a core element for **end-to-end simulators** in the frame of the GMES and EOEP programmes.
- As a proof-of-concept for a future core element for **ground segment processors** for GMES/EOEP.

It is remarkable that the target of complete automation for the geometric correction processing has been achieved through the proposed approach.

7.2. Future Work

The GERSI project, reaching its objective, has demonstrated the possibility of performing fully automated geometric correction of optical Earth observation sensors.

The application of the GECP and hence of the LOSM to synthetic (validation and verification process) and real images (application to an optical remote sensing instrument) has highlighted possible aspects that could be improved with future works.

The algorithms both of LOSM and GECP can be optimised in terms of computation time and memory occupation. These improvements can have a real profitable impact when processing a large amount of data, as it happens in a real scenario of an operative mission.

Another approach for drastically reduce the computation time of the GECP would be the use of parallel programming. The logic itself of the use the GECP does of the LOSM orients towards parallel computation, e.g. using GPUs.

As demonstrated during the application of GERSI to an optical remote sensing instrument, the GECP could benefit by means of few changes of its own generalisation to be applied to all the possible missions of LEO Earth observation.

ESAT itself could benefit from reduced computation times and wider Monte Carlo campaigns could be set up.

The experience gathered by the Consortium using ESAT has shown wide margins of upgrading the tool capabilities for better analysing geolocation error sources.

The enhancement of ESAT could be achieved extending the already implemented capabilities, both in terms of perturbations modelling and post-processing.

Beside an extension of the random perturbations (statistical methods), the implementation of analytical methods to perform estimations could be foreseen.

The ESAT could also be upgraded in order to analyse not only the geolocation accuracy, but also Absolute Pointing Error (APE), Absolute Measurement Error (AME), Relative Pointing Error (RPE) and Generalized Relative Measurement Error (GRME).

The User Interface could also be enhanced in order to give to the user more powerful and extended instruments for analysing the tools results, as the visualisation of the detected GCPs and TPs, or the superimposition of images.

Two dedicated studies performed in the frame of the GERSI project have demonstrated the benefits and detected the implementation issues to add an orbit estimation module to the LOSM and to correct the effect of the light speed effect.

END OF DOCUMENT