Thermal Asteroid Impact Mission

Executive Summary

EUROPEAN SPACE AGENCY
CONTRACT REPORT

The work described in this report was done under ESA contract 4000117450/16/NL/PS.
Responsibility for the content resides in the author or organisation that has prepared it.

Document ID	CR-TAIM-D2
Issue	1.0
Date	July 7, 2017
Pages	21

	Name / Organization	Responsibility / Role	Signature	Date
Approved	Pierluigi Foglia Manzillo cosine measurement systems B.V.	Project Manager		20170707
Checked	Marco Esposito Nathan Vercruyssen cosine measurement systems B.V.	Quality Assurance		20170707
Prepared	Ljubiša Babić Pierluigi Foglia Manzillo Simon Silvio Conticello cosine measurement systems B.V. Marco Canetri GMV Portugal Cristian Corneliu Chitu Claudiu Prioroc Silvia Nechita Andrea Eftenaru GMV Romania	Scientist/Engineer		20170707

Change log

Date	Issue	Author	Section	Description
20170602	0.1	PFM	All	First release
20170707	1.0	PFM	First page	Copyright statement removed.

Table of Contents

1 Preamble

1.1 Purpose

The purpose of this document is to provide a succinct description of all the work done during the TAIM project. It covers the scope of the study and its context, provides a description of the programme of work and reports about the main achieved results.

1.2 Applicable documents

Table 1: Applicable documents

Doc ID	Reference	Issue	Date	Title
AD1	TEC-MMO/2015/319	1	30 October 2015	ESA Statement of Work
AD2	31610002	1	8 February 2016	cosine proposal in response to ESA ITT AO/1-8481/15/NL/PS
AD3	CR-TAIM-MM03	1.1	August 11th, 2016	MoM of the scientific user requirement discussion

1.3 Reference documents

Table 2: Reference documents

Doc ID	Reference	Issue	Date	Title
RD1	AIM: [AD50]	2.0	July 8th, 2016	Asteroid Impact Mission (AIM) Mission Objectives
RD2	CR-TAIM-TN1a	1.0	27 October 2016	Scientific User Requirements Document

Doc ID	Reference	Issue	Date	Title
RD3	Hulley, G. C., C. G. Hughes, and S. J. Hook (2012), J. Geophys. Res., 117, D23113, doi:10.1029/2012JD018506.	NA	NA	Quantifying uncertainties in land surface temperature and emissivity retrievals from ASTER and MODIS thermal infrared data.

1.4 Abbreviations and acronyms

AD	Applicable Document
AIDA	Asteroid Impact & Deflection Assessment
AIM	Asteroid Impact Mission
AU	Astronomical Unit
CDR	Conceptual Design Review
DART	Double Asteroid Redirection Test
DCP	Detailed Characterisation Phase
DKE	Dynamic Kinematic Environment
ECP	Early Characterisation Phase
ESA	European Space Agency
FES	Functional Engineering Simulator
FOV	Field Of View
GNC	Guidance Navigation and Control
HFM	High Fidelity Model
IR	InfraRed
MIL	Model In the Loop
MTF	Modulation Transfer Function
NETD	Noise Equivalent Temperature Difference
PX	Pixel
RD	Reference Document
SIL	Software In the Loop
SW	Software
TAIM	Thermal Asteroid Impact Mission
TIR	Thermal Infrared
TIRI	Thermal Infrared Instrument for AIM
TN	Technical Note
TRL	Technology Readiness Level

2 Introduction

ESA's Asteroid Impact Mission (AIM) is both a Technology Mission of Opportunity, and a mission to greatly improve our understanding of asteroid physical properties and their response to a hypervelocity impact event on their surface. The AIM mission is combined with the Double Asteroid Redirection Test (DART). Both missions complement one another in a joint asteroid impact test and observation campaign called Asteroid Impact & Deflection Assessment (AIDA).

The physical and dynamical characterisation of the mission’s target, the Didymos binary asteroid system, is of maximum importance in this joint mission and the main purpose of the AIM spacecraft. AIM will also provide the scientific community with a unique mission opportunity to a small body in the early 2020s. Moreover, AIM is a technology demonstration mission at the service of space science, as it will address techniques that will enhance the capabilities of future scientific missions.

The AIM mission target, Didymos, is a binary asteroid system composed of a primary body (“Didymain”) and a satellite secondary body (“Didymoon”) orbiting around the primary. The asteroid parameters considered in this proposal are listed in Table 3.

Table 3: Didymos main parameters

Parameter	Value
Diameter of primary	0.775 km ± 0.078 km
Diameter of secondary	0.163 ± 0.018 km
Distance of primary-secondary centers	1.180 ± 0.018 km
Sun distance at perihelion	1.013 au
Sun distance at aphelion	2.275 au
Heliocentric semi-major axis	1.644 au
Bolometric Bond albedo	0.07
Emissivity	0.9

The Thermal InfraRed Imager (TIRI) is Thermal IR imager of the AIM mission. It has been conceived to pursue both scientific and technology development goals. Indeed, on one side, it will be used to determine physical parameters of the Didymos surface, such as temperature, thermal inertia, chemical composition, as well as the shape of the surface rocks. On the other side, TIRI is supposed to aid the spacecraft navigation, by means of the analysis of TIR imagery. The successful demonstration of TIR based navigation would be of enormous value, as it would enable active navigation irrespective of the specific illumination conditions of the target object.

A European consortium, led by cosine measurement systems B.V. and including GMV-Romania and GMV-Portugal, has been in charge of the execution of the TAIM (Thermal Asteroid Impact Mission) project, whose output is the preliminary design of TIRI (Thermal InfraRed Imager).

In this report, we present an overview of the TAIM project activities, its study logic, the design of the instrument and navigation system and the achieved scientific and navigation performance.

3 Study logic

The European consortium that executed the TAIM project comprises cosine measurement systems B.V. as prime contractor and GMV-Romania and GMV-Portugal as sub-contractors.

cosine is since several years active in the development of low mass, compact hyperspectral instruments based on different technologies and has a long history of technology development for ESA. cosine's personnel have extensive experience both in the development of software for scientific applications, and the design, construction, and testing of scientific instruments for space applications. In particular, miniaturized payloads employing state-of-the-art technologies have been the focus of many recent activities, resulting in novel instruments ranging from high-energy applications down to infrared wavelengths.

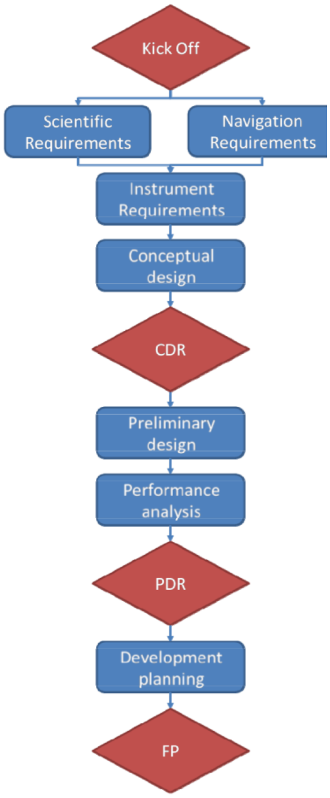

Figure 1: Study logic of the TAIM project.

GMV is a privately owned technological business group with an international presence. It has extensive experience in the development of Guidance Navigation and Control (GNC) technologies for space systems and has a long track record of R&D activities with ESA. In particular, its core competences and expertise with respect to the TAIM project lie in the development and validation of autonomous navigation techniques, with specific interest in relative navigation technologies for a wide range of scenarios.

Within the TAIM project, cosine has been responsible for the design and development of the TIRI instrument, while GMV-Romania has led the development of the TIRI navigation systems, with GMV-Portugal providing support about the simulation of the asteroid scenario.

The study logic of the TAIM project is reported in Figure 1. The activity was kicked-off in July 2016. During the first project phase, leading to the Conceptual Design Review, held in October 2016, the instrument scientific and technological objectives have been critically studied and, in synergy with the ESA competence teams, the instrument scientific and navigation requirements have been identified. Then, the instrument and the navigation system conceptual designs have been produced and presented to the Agency during the project CDR. In that context, several instrument configurations have been presented and traded-off. In consultation with the Agency, an instrument architecture, including two dedicated cameras, has been selected, in order to fully comply with both the scientific and navigation objectives.

During the following project phase, the preliminary design of the TIRI instrument and of its navigation system has been developed. A thorough analysis of the scientific and navigation performance has been carried out and the results compared to the performance requirements derived in the previous project phase. These activities have been presented to the Agency during the Preliminary Design Review, held in March 2017.

Finally, a development plan, reporting the necessary steps to bring TIRI and its navigation system to a Technology Readiness Level (TRL) equal to 8, has been prepared and presented to ESA at the TAIM Final Review, held in May 2017.

4 TIRI instrument goals and requirements

TIRI, the instrument imager of the AIM mission, has been conceived to pursue both scientific and technology development goals. The scientific goals concern the characterisation of the Didymos asteroid, while the technological objectives the use of a Thermal InfraRed imager to support the spacecraft navigation during different mission phases. In this section, we report the TIRI scientific and technological objectives (§4.1 and §4.2). Starting from these objective, the scientific and navigation requirements, have been derived and further divided into functional and performance. They are summarized in §4.3 and §4.4.

4.1 Scientific objectives

In Table 4, the TIRI primary and secondary scientific objectives are listed. The reported information is derived from RD1.

Table 4: Summary table of the TIRI scientific objectives

Code	Objective type	Description
S.TIR.3.p1	Scientific (primary)	to discriminate between bare rock and rough surfaces. This requires the measurement of the brightness temperature distribution over the surface from a single observation geometry for a rough estimate of thermal inertia.
S.TIR.3.s1	Scientific (secondary)	to characterize the surface temperature to an accuracy of 5K (goal 1K) at a spatial resolution of a few metres.
S.TIR.3.s2	Scientific (secondary)	to derive the thermal inertia at a spatial resolution of a few metres through observations at a range of local times and phase angles.
S.TIR.10.s3	Scientific (secondary)	to characterize the surface composition through spectral mapping of the surface with a resolution $\lambda/\Delta\lambda$ of 20-50 or through a smaller number of diagnostic spectral bands.
S.TIR.8.s4	Scientific (secondary)	to observe the evolution of the plume of dust ejected by Dart's impact on Didymoon
S.TIR.7.s5	Scientific (secondary)	to measure the thermal properties of Didymain.

4.2 Technological objectives

Table 5 reports the TIRI technology development objective, as reported in RD1.

Table 5: Summary table of the TIRI technological objectives.

Code	Objective type	Description
T.TIR.4.p1	Technological	To demonstrate the use of an IR instrument to support the asteroid rendezvous phase, by enabling the acquisition of complementary data for Flight Dynamics analyses.

4.3 Scientific requirements

From the review of the AIM mission objectives related to TIRI and the iterations with the ESA AIM team, the lists of the functional and performance requirements for the use of TIRI as scientific instrument have been derived. Table 6 and Table 7 report the TIRI navigation functional and performance requirements respectively.

Table 6: Summary table of the TIRI scientific user functional requirements.

Requirement ID	Reference
TIRI_SCI_FUNC_REQ001	TIRI shall enable to discriminate between bare rock and rough surfaces.
TIRI_SCI_FUNC_REQ002	TIRI shall enable the retrieval of the surface temperature of Didymos.
TIRI_SCI_FUNC_REQ003	TIRI shall enable the retrieval of the asteroid surface thermal inertia.
TIRI_SCI_FUNC_REQ004	TIRI should be able to retrieve the composition of the asteroid surface.

Table 7: Table of the TIRI scientific user performance requirements

Requirement ID	Reference
TIRI_SCI_PERF_REQ001	TIRI shall enable a rough estimate of the asteroid surface thermal inertia by measuring the time evolution of the asteroid brightness temperature.
TIRI_SCI_PERF_REQ002	TIRI shall retrieve the asteroid surface temperature with an accuracy of 5 K (goal 1 K) for temperatures higher than 200 K (100 K goal), at a spatial resolution of 20 m or higher from a distance of 40 km or lower.
TIRI_SCI_PERF_REQ003	TIRI shall enable the retrieval of the asteroid surface thermal inertia at a spatial resolution of few metres and for different local times and Sun phase angles.
TIRI_SCI_PERF_REQ004	TIRI should be able to retrieve the asteroid surface emissivity spectrum with a spectral sampling of 300 nm.

4.4 Navigation requirements

From the review of the AIM mission objectives related to TIRI and the iterations with the ESA AIM team, the lists of the functional and performance requirements for the use of TIRI as navigation camera have been derived. Table 8 and Table 9 report the TIRI navigation functional and performance requirements respectively.

Table 8: Summary table of the TIRI navigation user requirements.

Requirement ID	Reference
TIRI_NAV_FUNC_REQ001	TIRI shall determine the contour of the asteroid under all illuminations conditions.
TIRI_NAV_FUNC_REQ002	TIRI shall be able to track simultaneously unknown features (~100) under all illuminations conditions.
TIRI_NAV_FUNC_REQ003	TIRI should locate or track Mascot2 after landing in the night side of the asteroid.
TIRI_NAV_FUNC_REQ004	TIRI should be able to distinguish Didymoon and Didymain, if one partially occults the other.

Table 9: Table of the TIRI navigation performance requirements

Requirement ID	Reference
TIRI_NAV_PERF_REQ001	TIRI shall be able to simultaneously track 100 (TBC) unknown features

TIRI_NAV_PERF_REQ002	TIRI shall provide a sub-pixel accuracy in feature detection (0.5 pixels, 99.7% confidence interval).
TIRI_NAV_PERF_REQ003	The difference between the centre of brightness, calculated from the simulated image, and the real asteroid shape shall be within 1 pixel at 99.7% confidence interval.

5 TIRI instrument overview

During the TAIM project, several instrument configurations have been considered and traded – off, in order to define the best suited architecture for the instrument to achieve the scientific and technological objectives.

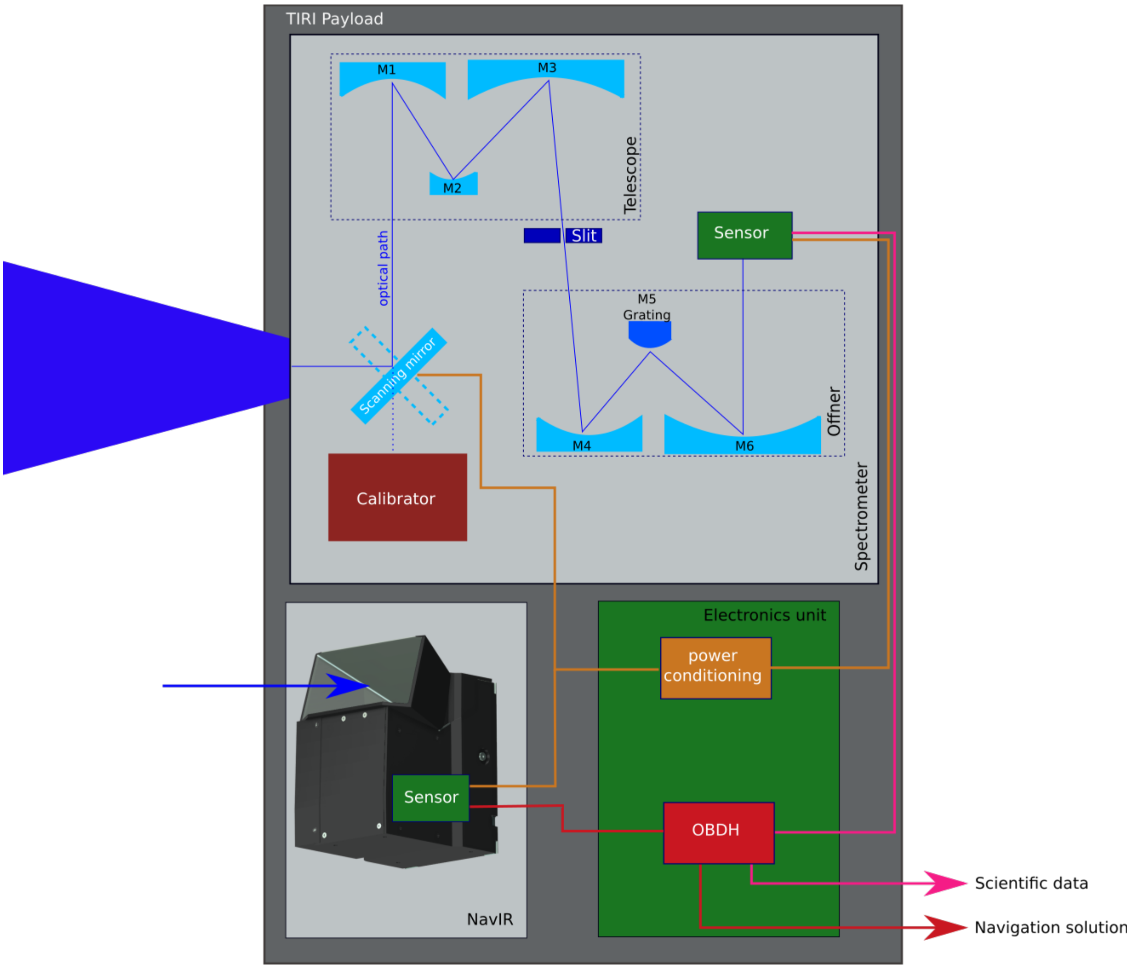

Figure 2: Block diagram of the TIRI instrument.

The result of this process has been the definition of an instrument architecture which includes two optical trains. The first one is a line-spectrometer which is in charge of the TIRI scientific objectives and which has been designed during the TAIM project. The second one is NavIR™, a thermal infrared navigation camera based on the HyperScout® design, developed by cosine for ESA under a GSTP contract.

As of now, TIRI includes the following subsystems:

1. Line spectrometer
2. NavIR™
3. Detectors

4. Opto-mechanics
5. Calibration Unit
6. Electronics Unit

Figure 2 exhibits the TIRI block diagram at the current design status. In this section, we briefly report about each of the aforementioned subsystems.

NavIR™ is the navigation camera of the TIRI instrument. It is based on the HyperScout® design, a hyperspectral imager working in the VNIR range, developed by a European consortium led by cosine under an ESA GSTP contract. It exhibits on a fully reflective telescope. A picture of the assembled telescope is reported in Figure 3, while the main optical parameters are reported in Table 10.
NavIR™ works over the entire TIR range, that is from 8 μm to 14 μm wavelengths, and exhibits excellent performance in terms of field of view. If coupled to a 640 x 480 pixel detector, exhibiting a 17 μm pixel size, its field of view is equal to 15 x 11.3 degrees. The instrument volume is also extremely limited (less than 1.5 cubic deciliter).

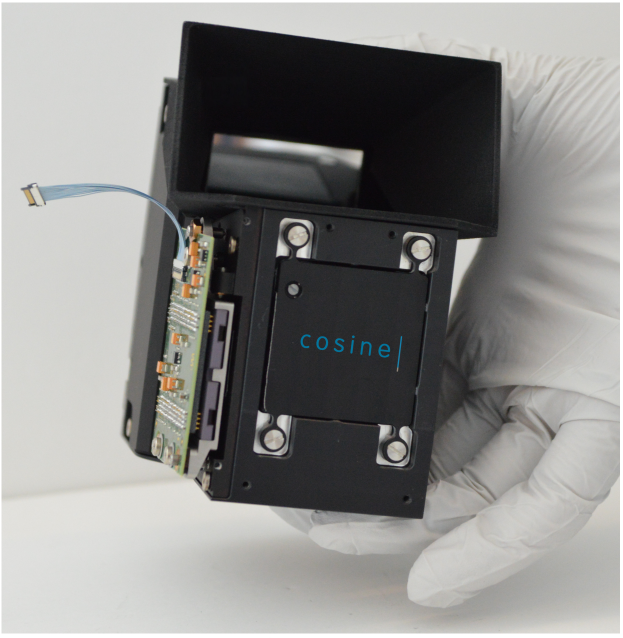

Figure 3: Picture of the HyperScout® instrument.

Table 10: Parameters of the Line spectrometer for NavIR™

Parameter	Value
Instantaneous field of view [mrad]	0.41
Field of view [deg]	15×11.3
Focal length [mm]	41.25
Aperture diameter [mm]	10.31
F-number	4
Sensor size [px^2]	640×480
Pixel size [μm]	17
Ground Sampling Distance [m]	16.4 at 40 km 4.1 at 10 km 0.82 at 2 km

Spectral range [μm]	8 - 14
Spectral resolution [μm]	6 μm

The TIRI line spectrometer has been designed within the TAIM project. Its optical layout includes two main blocks. The first one is a three mirror anastigmat (TMA) telescope, which focuses the radiation coming from the scene on ground on an intermediate focal plane. The second one, based on an Offner configuration, includes a reflective grating and generates a two dimensional image, where each horizontal line results being the image of the slit under a specific wavelength. The TIRI line spectrometer also includes a flat motorized mirror and it is used for scanning the target object in the direction orthogonal to the spectrometer foV and to direct into the optical path the output of the on-board calibrator.

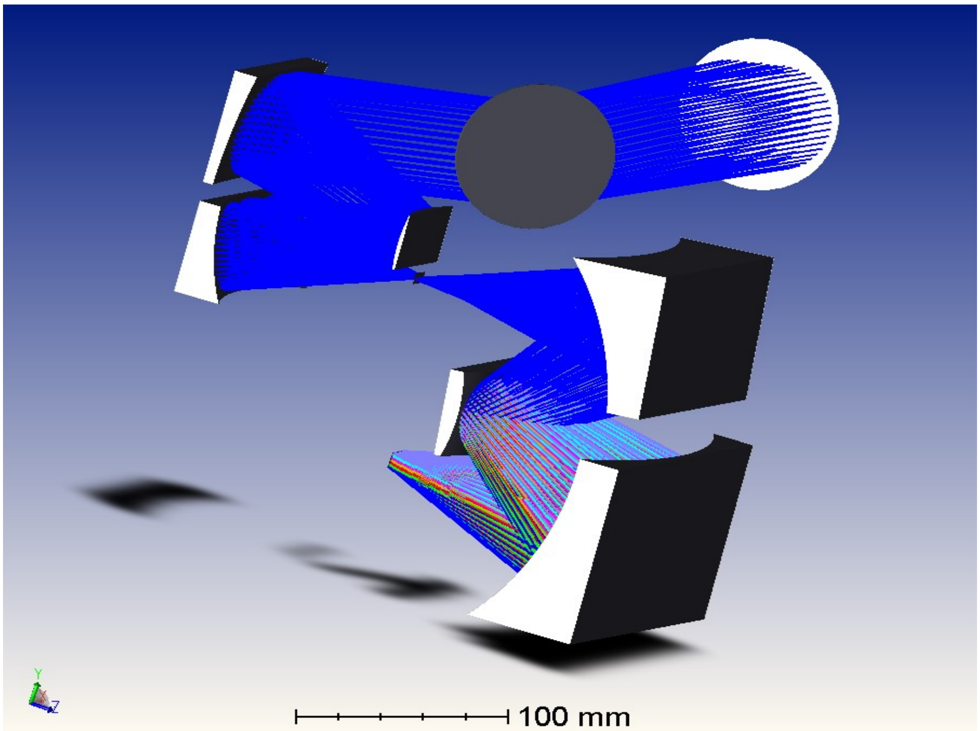

Figure 4: 3D layout of the line spectrometer proposed for TIRI.

Table 11: Parameters of the Line spectrometer for TIRI

Parameter	Value
Instantaneous field of view [mrad]	0.15
Field of view [deg]	5.5
Focal length [mm]	113.5
Aperture diameter [mm]	56.75
F-number	2
Sensor size [px^2]	640×480
Pixel size [μm]	17
Ground Sampling Distance [m]	6 at 40 km 1.5 at 10 km 0.30 at 2 km

Spectral range [μm]	8 - 14
Spectral resolution [nm]	12 at 8 μm 21 at 14 μm

The instrument main figures are summarized in Table 11, while Figure 4 reports the 3D layout of the optical system. In the proposed configuration, the spectrometer optics would require a volume of 290×280×160 mm^3.

The TIRI instrument exhibits diffraction limited optical performance. Figure 5 reports the geometrical spot size (left) and the MTF (right), evaluated for the axial and the extreme field angles and for a wavelength equal to 11 μm. Such wavelength corresponds to the central line of the detector array. Irrespective of the field angle, the geometrical spots are well confined within the Airy disk and the MTF curves clustered in close proximity of the diffraction limit.

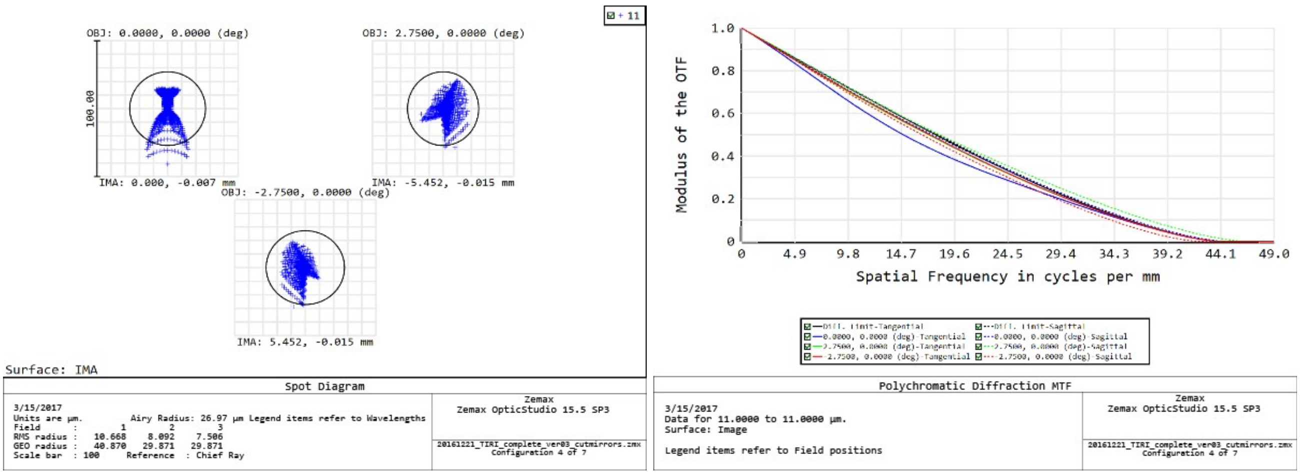

Figure 5: Geometrical spot size for different field angles and for a wavelength equal to 11 microns (left) - Modulation transfer function for different field angles and for a wavelength equal to 11 microns (right).

In order to allow TIRI to comply with its scientific objectives, the spectrometer needs to be able to perform in-flight geometric and radiometric calibration. Radiometric calibration is a process that converts raw detector data expressed in digital numbers into at-aperture spectral radiance units. For TIRI, high radiometric calibration accuracy is required in order to determine the asteroid surface temperature with sufficient accuracy. Therefore, the instrument gain offset and slope must be calibrated in-flight.

For the offset determination, it is sufficient to look at cold space. Given the relatively large size of the TIRI field of view, if compared to the Didymos system, it is likely that in almost every image cold-space looking pixels will be present. Therefore, a gain offset compensation might be performed at frame level. Gain slope correction requires the presence on board of a known source at a temperature different from 4 K: the calibration source. In the optical and mechanical designs of the system, an on-board calibrator has been integrated, as well as a pointing mirror, able to direct the calibrator output radiation in the nominal optical path of the spectrometer.

TIRI electronics system is based on existing cosine heritage and designs, including one that is currently being prepared for flight in Q3 2017. This subsystem is capable to read-out the frames captured by the two TIRI sensors (one for each of the two optical trains) and process them. For the scientific instrument, it is envisaged that in memory time averaging of subsequent frames will be carried out to enhance the noise performance. On the other hand, the on board processor can run the navigation algorithms and provide the spacecraft with a navigation solution based on TIR imagery.

The TIRI mechanical assembly integrates all the subsystems in the same enclosure. Both optical systems are mounted such to share the boresight direction. The position and orientation of some of the mirrors, the detector and the slit is adjustable. The estimated mass budget of the payload is around 11 kg (margins included). Figure 6 reports two views of the TIRI mechanical model.

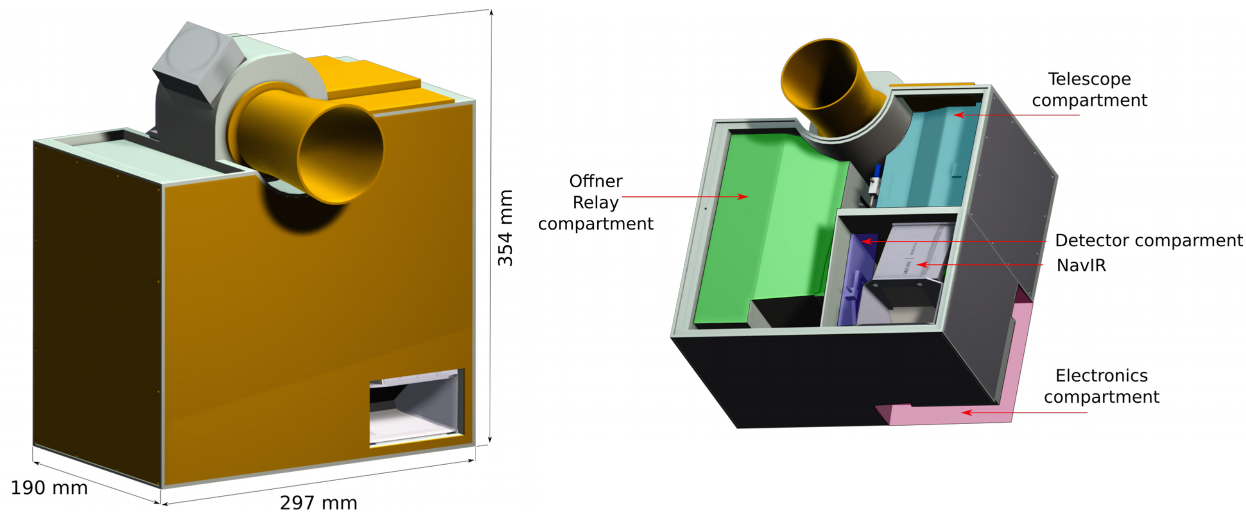

Figure 6: Overall TIRI envelope (left); TIRI Optical elements (right).

6 TIRI navigation system design

The TIRI Navigation algorithms have been tested and validated in a functional engineering simulator (FES) based on the GMV in-house developed AIM GNC prototype. The FES allows integration of the navigation algorithms and validation with single run and Monte Carlo simulations (MIL – model in the loop and SIL – SW in the loop) through a series of simulations based on the AIM mission phases, namely Early Characterization Phase (ECP), Detailed Characterization Phase (DCP) and final descent, using as navigation sensor the TIRI camera. The relative navigation system takes navigational data in the form of thermal images of the target asteroid, and determines the spacecraft's position and velocity relative to the asteroid.
In this sense the FES allows for high fidelity simulation. This capability has been developed by implementing image generation and image processing algorithms as Simulink library blocks.
The FES simulator is actually a GNC prototype because it is not only a navigation filter, it is a detailed, high fidelity model of the SC and the environment on which the GNC is working. It receives in input a clock signal and a bus with the initial state values. The output produced (GNC and DKE – dynamic kinematic environment data) are received as input by the Results & Validation block to evaluate GNC performance and to save data for post-processing purposes.

6.1 TIR Navigation Algorithms

TIR navigation system is used for relative navigation. The Relative Navigation System is based on Visual and thermal navigation (VBN – Vision-Based Navigation). The selected TIR IP algorithm system is in charge of identifying and tracking unknown features on the surface of the asteroid. By unknown features, it is meant features that are not inside any database and of which no *a priori* information is available. These algorithms can be divided into two main classes:

- Centroiding algorithms (baseline when the entire primary body can be seen in the images – this occurs in the ECP phase)
- Feature tracking algorithms (used in DCP and descent phases)

The image centroid tracking algorithm relies on the possibility to detect the target by identifying the asteroid brightness and isolating it from the background (the centre of the asteroid will be identified with the centre of the bright image). When both Didymain and Didymoon appear in the field of view, the presence of the secondary asteroid in the images can create difficulties in the processing. In order to account for these situations, the determination of the centre of brightness was proposed for the centroid image processing algorithms for the early characterization phase.
For the close observation, the transition from far to close observation and the final descent phases, the

relative navigation is performed using unknown feature tracking. In the image processing context, 'unknown landmarks' are transient image features corresponding to fixed points on the asteroid surface of unknown position in the asteroid body frame. In case of the TAIM activity the landmark detection and tracking based navigation is done at high fidelity level. The approach consists in analysing the images taken from the camera or cameras used and extracting the landmarks, detecting features in the first image and then searching for the same features in the following images.

7 TIRI scientific performance analysis

A performance analysis of the TIRI spectrometer has been carried out to verify the instrument compliance with the required accuracy of 5 K for the land surface temperature retrieval. Here, the different instrument contributions to the uncertainty in the retrieved surface temperature and the strategies to reduce these contributions, are briefly recalled. Then, the performance compliance matrix together with the main conclusions of the performance analysis is reported.

Uncertainty in the land surface temperature retrieved from the TIRI spectrometer data can be broken down into four contributions [RD2,RD3]:

- the temperature retrieval model uncertainty
- the calibration uncertainty
- the measurement noise
- the thermal background fluctuation noise.

The first contribution, as its name suggests, is related to the land surface temperature retrieval model. The remaining three contributions are related to the instrument and its calibration.

Strategies to reduce the measurement noise and thermal fluctuation noise have been investigated.

For what concerns the measurement noise, at the expenses of the spatial and/or spectral resolution, pixel binning leads to an increase of the SNR proportional to the square root of the number of binned pixels. Time averaging of subsequent frames also allows a SNR increase (proportional to the square root of the number of averaged frames), effectively increasing the frame integration time. However, this effective integration time cannot exceed a maximum value, as low frequency noise components become dominant and degrade the SNR as the number of averaged frames is further increased.

However, averaging over multiple frames would also not lead to a reduction in the thermal background fluctuation noise. Indeed, the time scale of the thermal fluctuations is fixed by the mass and thermal inertia of the instrument and is expected to be orders of magnitude longer than the maximum allowed "effective integration time" which is the maximum time duration over which asteroid and satellite can be considered in relative stillness. Hence, the background temperature would not fluctuate around the set temperature within the period of frame averaging, which would not result in a NETD reduction.

The following ways can be used to reduce the thermal background fluctuations:

- Reduce the emissivity of the TIRI mirrors by coating them with a low emissivity material, such as Gold.
- Reduce the thermal emission of the optical components and the structure by reducing their operating temperature.
- Reduce the thermal background fluctuations by improving the stabilization of the background temperature.
- Perform frequent calibration of the thermal background, regularly looking a cold space and exploiting the cold space looking pixels which are expected to be within every frame.

7.1 Scientific performance compliance matrix

In the present section, we report on the compliance of the achieved performance with the TIRI scientific performance requirements. The scientific requirements have been derived from the AIM mission scientific objectives, and are reported in Table 7.

At the end of the TIRI preliminary design and performance analysis phases, we proceeded with a verification of the compliance of the obtained instrument scientific performance with the original requirements. It is verified that the proposed TIRI design and its performance are fully compliant with the scientific performance requirements reported in Table 7. A detailed compliance matrix is reported in Table 12.

It is worth pointing out that the entire TIRI design has aimed to be fully compliant with all the scientific performance requirements. This lead to the integration of an additional optical system to be used as navigation camera and the adoption of a complex optical configuration, including a telescope and a relay optics, for the spectrometer. Moreover, to comply with the thermal accuracy requirement, while keeping a high spectral resolution, the spectrometer needs to exhibit extreme thermal control and perform frequent calibration. For instance, if the asteroid surface emissivity spectrum retrieval is not performed, that is TIRI_SCI_PERF_REQ004 is not met, the remaining three requirements could be met using a less complex optical system with less engineering budgets. If only a course estimate of the asteroid surface thermal inertia would be needed, that is meeting only TIRI_SCI_PERF_REQ001, it could be possible to perform it by only using NavIR™, the TIRI navigation camera, without integrating the spectrometer in the instrument.

Table 12: TIRI scientific performance requirements compliance matrix

Requirement ID	Description	Compliance	Remarks
TIRI_SCI_PERF_REQ001	TIRI shall enable a rough estimate of the asteroid surface thermal inertia by measuring the time evolution of the asteroid brightness temperature.	Compliant	TIRI allows for a correct retrieval of the brightness temperature and of its time evolution. As demonstrated in RD2, this allows for a course estimate of the surface thermal inertia. Using the spectrometer (F/# = 2), this requirement is met with excellent radiometric performance. If limited radiometric performance could be accepted, this performance requirement could be met by only using the navigation camera (F/# = 4), without the need of implementing an optical system as complex as the proposed spectrometer.
TIRI_SCI_PERF_REQ002	TIRI shall retrieve the asteroid surface temperature with an accuracy of 5 K (goal 1 K) for temperatures higher than 200 K (100 K goal), at a spatial resolution of 20 m or higher from a distance of 40 km or lower.	Compliant	TIRI allows for the retrieval of the asteroid surface temperature with an accuracy of 5 K for temperatures higher than 185 K. It implements a number of spectral bands that is much larger than five, that is the number required to perform a correct temperature retrieval, as suggested by the ESA AIM science team. The temperature accuracy has been broken down into two contributions: one related to the retrieval model, the other to the measurement, calibration, and thermal background fluctuation noise. According to the specific target temperature, spectral pixel binning and

			averaging over time of subsequent frames can be implemented to reduce the measurement and calibration noise. Thermal background fluctuation noise severely limits the instrument performance. It cannot be reduced by time averaging, but by either improving the stabilization of the background temperature or performing frequent calibration of the thermal background. The TIRI spectrometer is compliant with the requirement in terms of spatial resolution. At 40 km from the target and for the two extreme wavelengths, the spatial resolution is equal to 6.88 m at 8 µm and 12.04 m at 14 µm, respectively.
TIRI_SCI_PERF_REQ003	TIRI shall enable the retrieval of the asteroid surface thermal inertia at a spatial resolution of few metres and for different local times and Sun phase angles.	Compliant	As discussed with the ESA AIM science team, the compliance with the TIRI_SCI_PERF_REQ002 requirement, implies the compliance with the TIRI_SCI_PERF_REQ003 requirement. A temperature retrieval accuracy of 5K is assumed to be sufficient to provide an accurate quantitative estimate of the asteroid surface thermal inertia.
TIRI_SCI_PERF_REQ004	TIRI should be able to retrieve the asteroid surface emissivity spectrum with a spectral sampling of 300 nm.	Compliant	TIRI allows for determining the emissivity spectrum of the asteroid surface with 300 nm resolution and 5 K thermal accuracy, for surface temperatures higher than 185 K. The aforementioned values of thermal accuracy and spectral resolution are deemed sufficient to achieve a quantitatively accurate estimate of the surface emissivity. The fulfilment of this requirement, especially for lower asteroid temperatures, critically relies on the the instrument thermal control system, as the performance limiting factor is the thermal background fluctuation noise. It is required that TIRI is kept at low temperature (240 K or lower) with a thermal stability lower than 100 mK. An alternative to extreme cooling and thermal stabilization would be a frequent calibration strategy. This is possible, as during most of the scientific observation phase of the AIM mission, TIRI will exhibit in every frame a large number of cold-space looking pixels, which allow for a background correction at frame level.

			Finally, it has to be remarked that the emissivity spectrum does not depend on the asteroid temperature. Hence, in order to retrieve it, it is possible to use only observations at high surface temperatures, which result being more favourable in terms of measurement noise.

8 Asteroid imagery simulation

Figure 7 gives an overview of the strategy put in place to generate reliable synthetic thermal infrared images. During the development of the full chain, several challenges had to be faced to achieve a TIRI simulator generating images with a trustworthy level of realism.

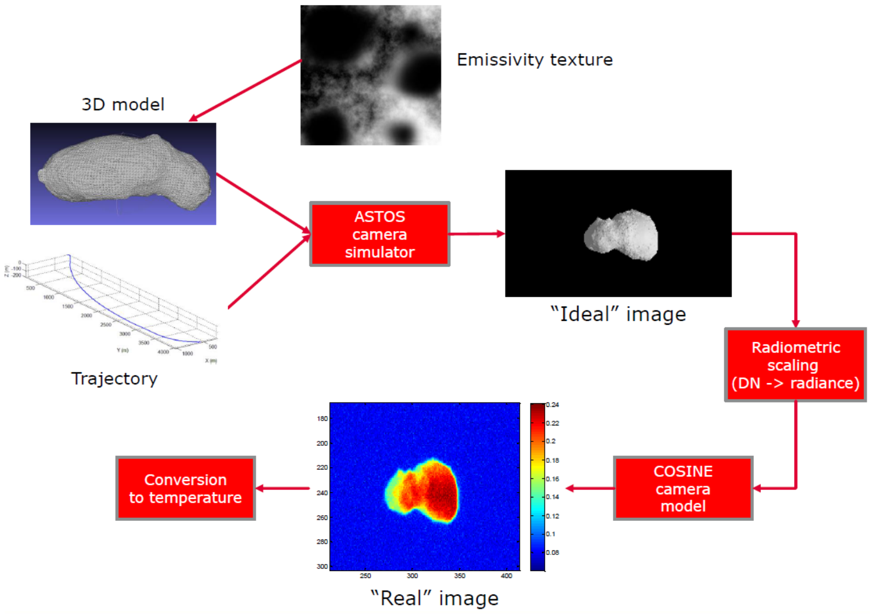

Figure 7: Work flow

In the chain, the first step is the characterization of the scenario to be implemented in the ASTOS camera simulator, that is the tool that will provide the ideal images. Basically, the ASTOS camera simulator is used just as a tool for rendering the scene since the real TIRI camera model is developed on purpose by cosine. The characterization of the scenario includes the preparation of the 3D models and the implementation of the trajectory in the simulator. Once the ideal images are available, before processing them with the TIRI camera model provided by cosine, a radiometric scaling is needed. We consider the output of the cosine camera model as the "real" images, which will go through the navigation chain. In Figure 7 is also shown a final step to convert the real image in a temperature distribution. This step has been performed in order to validate the final temperature distribution on the asteroid surface with the one expected from literature.
During preliminary simulations, the need of a more accurate characterization of the mathematical model of the asteroid appeared. In particular, more realistic thermal images are considered essential for the assessment of the navigation performance. In order to satisfy this important need, an additional step was added to the workflow. This step consists in generating a target-tailored texture which describes the distribution of the asteroid properties over the surface. This texture is then wrapped around the 3D model of the asteroid that is provided to the ASTOS tool. In this way, we are introducing

real effects on the images (although the fidelity of the distribution cannot be assessed for the lack of ground truth data) that could make more robust the design of the navigation algorithms.
Figure 8 shows the effect of the application of the texture image on the 3D models. The results show that in this way we have an additional "degree of freedom" in the characterization of the final look of the asteroid. We can reproduce regions of the asteroid with higher and other with lower emissivity.

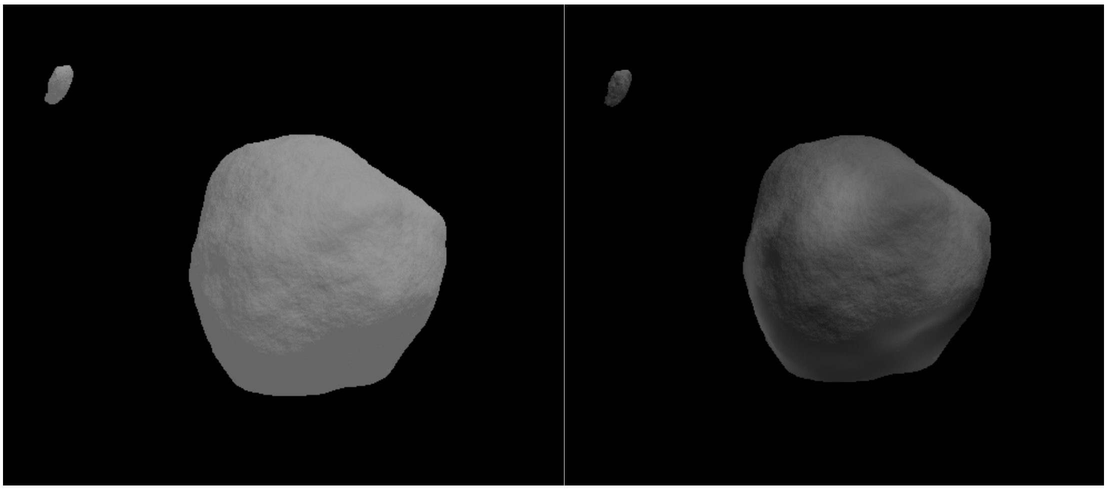

Figure 8: Effect of the emissivity map texture.

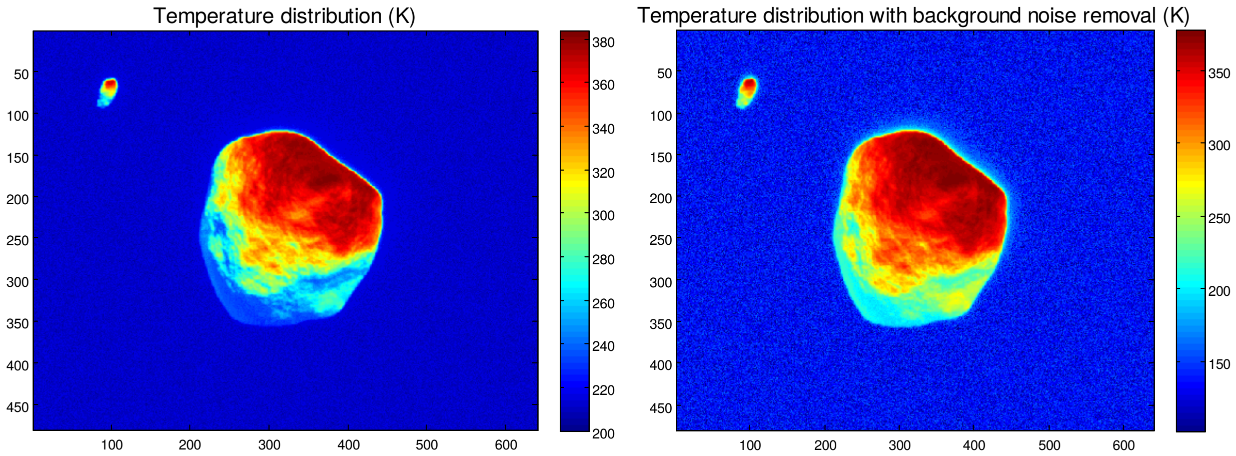

Figure 9: Asteroid surface temperature distribution before (left) and after (right) the background removal step.

After a radiometric scaling step, the TIRI camera model is applied to the images. It realistically reproduces the performance of a fully reflective thermal infrared camera. A second radiometric scaling process is required to obtain radiance values. At this point, we can convert radiance value associated to each pixel into temperature values.
The temperature distribution can be tuned finding the right trade off between values of the emissivity map texture, reflectance coefficient of the 3D model material, intensity of the sun and radiometric scaling factor. Moreover, a step to subtract the detector offset, due to thermal emission of the optical system itself, is applied. The described process allows the reproduction of the desired temperature distribution (Figure 9).
The way to realistically simulate thermal inertia effects for the asteroid surfaces has been tackled. ASTOS simulator does not allow simulating thermal inertia effects. Properties of the 3D model are constant during the entire simulation and the IR emission instantaneously follows the Sun illumination, reproducing a case in which thermal inertia is zero and temperature changes are instantaneous.
As a qualitative assessment of the thermal inertia effect has been considered essential, a workaround solution has been implemented. In principle, a qualitative analysis in case of finite thermal inertia can be done considering additional sources of light. Basically, considering 3 suns with phase angles

between them and different intensity is possible to reproduce the delay in the thermal transients due to the thermal inertia. As showed in Figure 10, if the additional suns are placed along the direction of the asteroid rotation and if they have decreasing intensity, in a certain way the result is that the imaged landmarks will change their temperature slowly. Adjusting the intensity values of the 3 suns and the phase angles is possible to reproduce high or low thermal inertia condition.

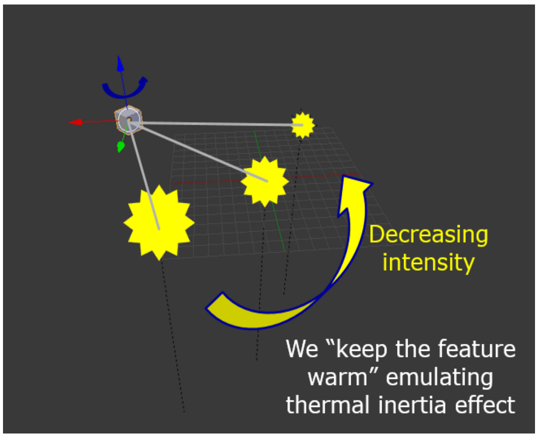

Figure 10: Strategy put in place to simulate different thermal inertia effects

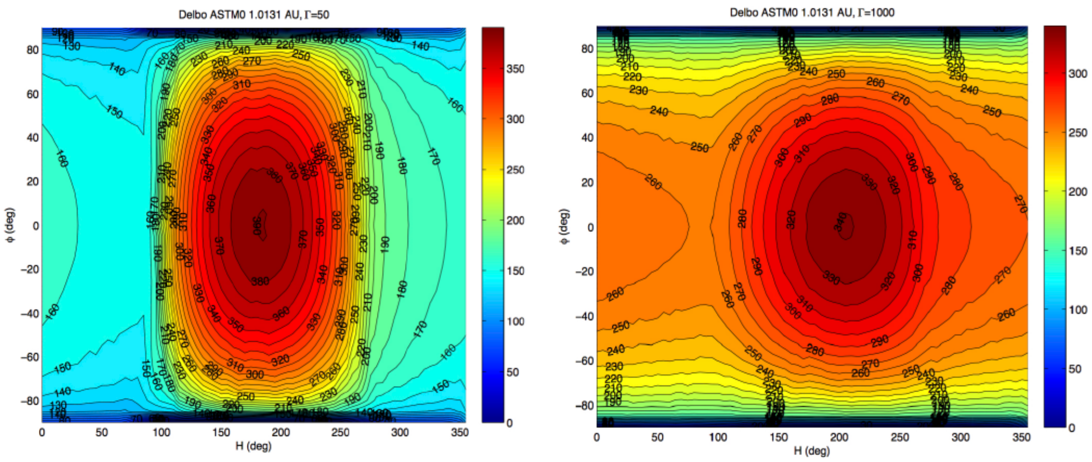

Figure 11: Temperature maps of Didymoon for low and high thermal inertia assuming a spherical shape of the body and 1 AU distance to the sun. Courtesy of M.Delbo.

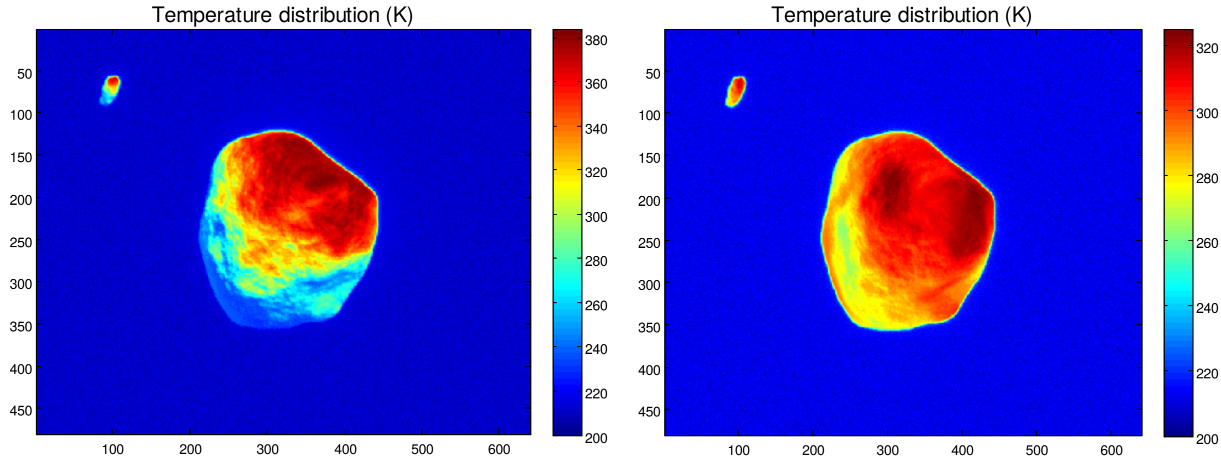

Figure 12: Temperature distribution over the asteroid surface in case of low and high thermal inertia

Figure 11 shows the temperature maps found in literature and Figure 12 shows the results obtained with our simulations. The final temperature distribution in the synthetic thermal images generated with

the TIRI simulator results to be quite in line with the expected ones.
The full chain described so far has been tuned and set up during the simulator preparation phase and in parallel image sequences for the different phases of the mission, have been generated and provided to GMV – Romania, for the three considered mission phases:

- Early Characterization Phase (ECP);
- Detailed Characterization phase (DCP);
- Descent Phase.

9 TIRI navigation performance analysis

An analysis to assess the performance of the on board navigation operations with respect to on-ground and an analysis of data compression schemes (e.g. lossy vs lossless) applicable to navigation have been performed. The analysis was performed with the AIM FES (Functional Engineering Simulator) that integrates the On Board Software (OBSW) algorithms in a series of simulations based on the AIM mission phases, namely Early Characterization Phase (ECP), Detailed Characterization Phase (DCP) and final descent, using as main navigation sensor the TIRI navigation camera. Various simulations were performed under different conditions in order to analyse the TIRI ability to provide adequate navigational data. The conditions under which the tests were run concern the thermal inertia levels, the compression level of the images, and the contrast of the thermal signature with respect to the background.
The effect of a finite asteroid thermal inertia has been qualitatively studied in two cases, considering a high thermal inertia case and low thermal inertia case. Changes in the thermal inertia does not seem to noticeably degrade or improve the navigation performance.
In all cases, a similar tuning of the filter was used. The differences revolve around the order of centimetres for the position error, and mm/s for the velocity error. The removal of the background noise in the synthetic images improve the navigation performance.
For the ECP, the navigation is simulated using synthetic images generated with the TIRI camera model and a centroid determination algorithm.
The results of the test are illustrated through the following plots: the relative position error (Figure 13) and the relative velocity error (Figure 14). The actual error is depicted in a solid blue line, while the standard deviation is depicted in solid red lines. It appears that for both position and velocity the navigation error is lower than the error boundary over most of the simulation time.
For both the DCP and the descent phase, a landmark tracking algorithm is used. Table 13 reports the main results of the simulations performed for the descent phase of the mission, for different levels of the asteroid thermal inertia..

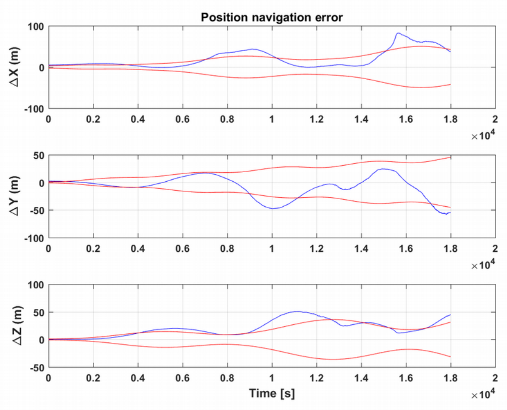

Figure 13: HFM-ZI-T03 – Position navigation error

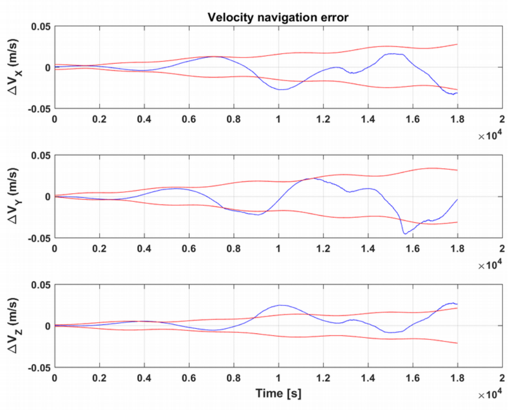

Figure 14: HFM-ZI-T03 – Velocity navigation error

Table 13: Navigation performance assessment on thermal inertia magnitude for final descent

TEST	Position error [m]	Position error standard deviation [m]	Velocity error [m/s]	Velocity error standard deviation [m/s]
Zero thermal inertia	16.3341	5.5760	0.0083	0.0022
Low thermal inertia	17.4474	5.5760	0.0087	0.0023
High thermal inertia	19.5430	5.6410	0.0087	0.0025
Low thermal inertia and noise removal	19.2622	5.5760	0.0094	0.0023

In this scenario, the following conclusions can be drawn:

- Changing the thermal inertia level leads to an improvement of the results, especially concerning the velocity navigation error and the position on the Y and Z axes;
- Considering that in all cases a similar tuning of the filter was used, the differences revolve around the order of centimetres for the position error, and mm/s for the velocity error;
- The images with the background noise removal improve the navigation performance;
- During final descent there is little degradation in performance due to high thermal inertia. The high thermal inertia is expected to degrade the contrast of the landmark, making them harder to be tracked by the navigation filter. In final descent this behaviour is not that obvious, but the navigation degradation of the higher thermal inertia images with respect to low thermal images is more evident.

Table 14 reports the results of the navigation performance analysis for the DCP phase of the mission. In this context, no significant improvement can be observed when using images relative to different thermal inertia levels; the navigation performance is similar in all the three presented cases. This can be observed as well when comparing the mean values of the standard deviation for each case; the differences revolve around the order of maximum 35 m in case of the position navigation error, for the chosen period of simulation.

Table 14: Navigation performance assessment on thermal inertia magnitude

TEST	Position error [m]	Position error standard deviation [m]	Velocity error [m/s]	Velocity error standard deviation [m/s]
Zero thermal inertia	32.0922	31.9004	0.0137	0.0215
Low thermal inertia	35.3420	45.9793	0.0042	0.0292
High thermal inertia	33.0666	41.6469	0.0059	0.0286

10 Conclusions

During the TAIM project, the preliminary design of TIRI, the AIM Thermal InfraRed Imager, has been developed. The performance of the instrument have been evaluated and resulted fully compliant with both the scientific and the navigation performance requirements.

The proposed TIRI design takes advantage of all the technology developments performed in recent years in TIR sensors, optical manufacturing and materials, electronics and navigation algorithms.

The results is a medium sized payload enabling the unprecedented possibility of performing both scientific and navigation tasks. The proposed design shows that the attainable radiometric performance and spectral resolution are suitable to perform remote sensing of the a near-Earth asteroid, such as Didymos, to retrieve its relevant physical parameters, such as temperature, thermal inertia, composition and to characterise the shape of the asteroid surface rocks. The navigation performance analysis showed that it can be successfully employed for determining an accurate navigation solution in all the observation scenarios of interest.