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Enabling Technologies for a Multi-application Satellite: Alignment Campaign Definition

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Introduction

This work is entirely based on the study of the *Satellite alignment measurements*, with the purpose of producing and developing the specifications necessary for the implementation of the alignment campaign for **PLATiNO** program, starting from system and satellite requirements.
The project was launched and is financed by ASI (Agenzia Spaziale Italiana), whose goal is the definition and development of national enabling technologies for a standard "multi-purpose" platform, in order to support its potential future lines of activity.
Alignment measurements are led during the Satellite AIT (Assembly, Integration and Test) Campaign and they are crucial to verify the correct position of units within the constraints established by the requirements, and to confirm it after the environmental test campaign. In this context, the alignment campaign is applied at *platform* level and involves some critical units of the Communication System and Attitude and Orbit Control System (i.e. reaction wheels, star trackers, antenna).
The work opens up with a description of the general rules governing a Space product, with reference to ECSS normatives related to planning, verification and testing. Furthermore, to introduce the specific terminology, the platform is described in terms of components and subsystems as well as overall functions and missions. Then, the main activities carried out during the campaign are described and include:

1. Analysis of measurement methods and technologies: units have been studied in their structure and position for understanding the most suitable way to take measurements;

2. Selection of the instrumentation necessary for the realization of the measurements: different types of instruments have been analyzed in terms of accuracy, maximum admissible error and setup issues to address the instrument choice;

3. Preliminary set-up defintions, with considerations about set-up costs and overall timing of the alignment campaign.

With the continuation of the alignment activities, the campaign will see:

1. Definition of the measurement and acquisition setup;

2. Structure of the measurement campaign with the definition of the Alignment Plan and the implementation of the Alignment Activity Flow.

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A papà. Ti sento sempre.

Chapter 1

European Cooperation for Space Standardization (ECSS)

This chapter represents a prehamble to describe the general rules governing a Space Product and the normatives related to planning, verification and testing. In this context it is necessary to define a common frame of reference that can allow the various actors (or stakeholders) to align and to relate to each other. For a space project in Europe, this frame is represented by a coherent, single set of user-friendly standards known as **European Cooperation for Space Standardization**. A deep knowledge of these standards is crucial in all European Space activities. The main contents of the standards about the status of the project definition activities (starting from planning to verification and testing) that reveal to be relevant for the current context have been reported and described in the subsequent paragraphs.

1.1 ECSS-M-ST-10C Rev.1: Space Project Management

The ECSS-M-ST-10C Rev.1 standard (March 6, 2009) is dedicated to the management of a space project and, more specifically, to what is called *Project Planning and Implementation* [1]. This involves:

1. Establishing the **project requirements** and constraints derived from the mission statement;

2. Defining phases and formal milestones to control the project progress with respect to cost, schedule and technical objectives (i.e. project control function);

3. Defining *Project Breakdown Structures* (TBS), which represent the common and unique reference system for the project management to identify the tasks and responsibilities of each actor, facilitate the coherence

between all activities of the whole project and perform scheduling and costing activities;

4. Setting up a project organization to perform all necessary activities on the project.

A space project typically comprises a *space segment* and a *ground segment* which are implemented in parallel. They rely on and have interfaces with the *launch service segment*. These three segments establish a **space system**.
In general, a proposal to initiate a space project can be raised by any party. However, the most common initiators are individual or co-operative governments, national or international scientific communities or national or international space agencies.

1.1.1 Planning

During the early planning phase the customer-supplier chain needs to be defined in a coordinated, efficient and structured manner.
Customer requirements and constraints are prepared by the customer and put into a format suitable for direct application in an *Invitation To Tender* (ITT) or *Request for Proposal* (RFP). They address technical and programmatic requirements, as well as political, commercial, and industrial constraints to be applied to the project and they collectively represent the *Project Requirements Documents* (PRD).
In this context some crucial features need to be analysed to execute the space project from initiation to completion at all levels:

- The **purpose and objectives of the project**, which are defined by the project initiator in the mission statement, including key performance parameters and technical and programmatic constraints;

- The **evaluation of the resources**, the need to develop new technologies or reusing existing equipments. This is a major input to the assessment of required resources and facilities and to the subsequent technical and programmatic risk assessment, which also can have a significant influence on cost;

- The **need for human resources**, skills and technical facilities;

- The **project deliverables**, needed to meet the project initiator's mission statement;

- The **Project Management Plan**, that represents the top level project plan and defines the project management approach and methodology to be used throughout the life cycle of the project, together with an overview of all elements of project management disciplines.

In the ECSS standard, the **top level customer** is defined as the organization responsible for generating the top level space and ground segment business agreements, and for interface arrangements with other external space system elements.

1.1.2 Breakdown Structures

The establishment of a coherent organizational structure for implementing a project at all levels in the customer-supplier chain is a key factor for ensuring an efficient management approach. **Project breakdown structures** (PBS) reveal to be a great instrument for managing the project from a functional and technical point of view. They break the project down into manageable elements as described in the following points:

1. **Function tree** , that is a functional decomposition of the system performances. This approach is applied during the system definition phase. The purpose of a function tree is to illustrate all the functions that a product, a process or a project must execute and the links between them, in order to challenge these functions and develop a better response to the client's needs. The functions are linked together in a logical way and the model resulting from this diagram illustrates what will be done by the product;

2. **Specification tree**, that defines the hierarchical relationship of all technical requirements specifications for the different elements of a system or product;

3. **Product tree**, that identifies the elements that must perform the functions described in the function tree. The product tree may include the Ground Segment Equipment (GSE), the integration tools and test equipment, as shown in Figure 1.1. It forms the basis for the elaboration of the project work breakdown structure.

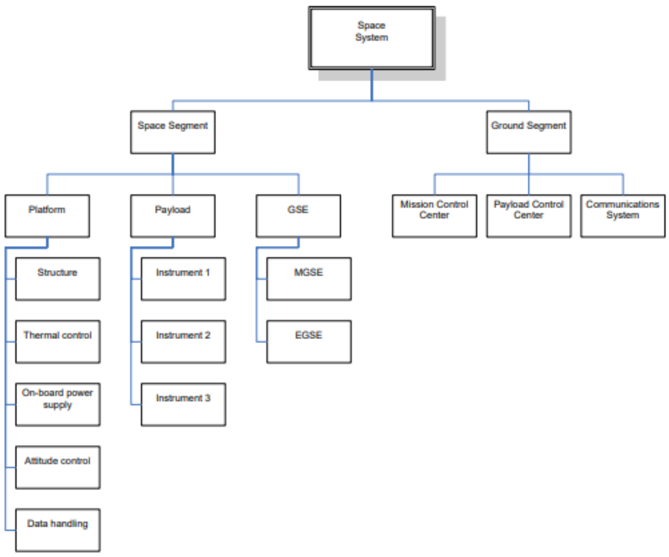


Figure 1.1: Product tree structure.

4. **Work Breakdown Structure** (WBS), that is the cornerstone of effective project planning, execution, controlling, monitoring, and reporting. It divides the project into manageable work packages, organized according to increasing levels of detail. A WBS also provides the necessary framework for detailed cost estimating and control along with providing guidance for schedule development and control, as shown in Figure 1.2.

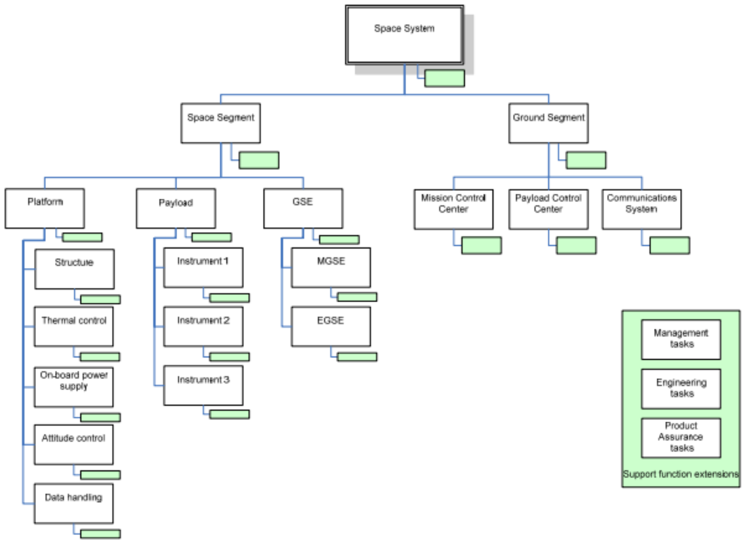


Figure 1.2: Work Breakdown tree structure.

5. **Work Package** (WP), that are the smallest unit of work that a project can be broken down to when creating a WBS. Control work packages are identified by the supplier at the level in the WBS where visibility and control are required, and for which reporting is to be performed. Control work packages are identified by the supplier at the level in the WBS where visibility and control is required, and for which reporting is to be performed.

6. **Organization Breakdown Structure** (OBS), that contains the precise definition of the project responsibilities. It depicts the proposed project organization in terms of contractual responsibilities. The project OBS shows the key personnel and the assigned responsible parties for each work package in the WBS.

1.1.3 Phasing

Project phases represent the necessary steps for the conception, design, implementation and execution of the project itself and cover the entire life span of its existence. Project phases are strongly representative of the current product level and the type of activities to be performed on the system. Each of the subsequent project phases is ended in the form of **project reviews**, the outcome of which determines readiness of the project to move forward to the next phase.

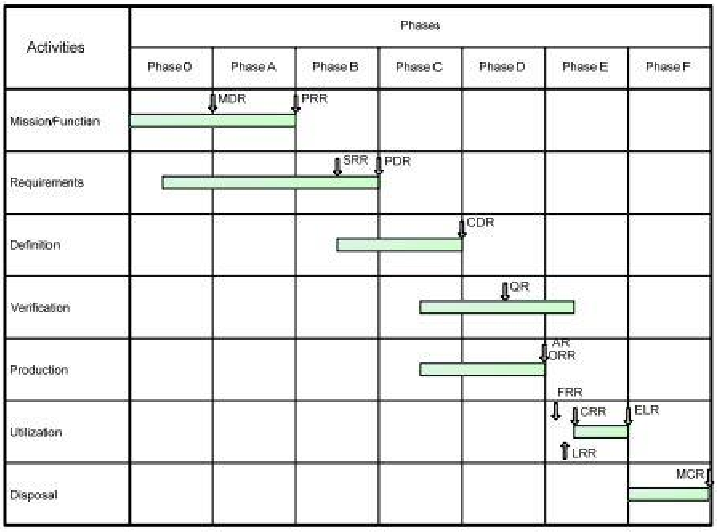


Figure 1.3: Typical project life cycle.

A typical project life cycle can be summarised by Figure 1.3.
Generally, phases 0, A, and B are focused mainly on the elaboration of functional and technical requirements and on the identification of the technical and programmatic constraints identified by the project initiator and top level customer. All activities and resources needed to develop the space and ground segments of the project are here identified as well as the initial assessments of technical and programmatic risk.
Phases C and D comprise all activities to be performed to develop and qualify the space and ground segments and their products.
Phase E comprises all activities to be performed to launch, commission, utilize, and maintain the orbital elements of the space segment and utilize and maintain the associated ground segment.
Phase F comprises all activities to be performed to safely dispose all products launched into space as well as ground segment.

Phase 0: Mission analysis/needs identification. During this phase mission needs, expected performances and safety goals are discussed and identified. This is mainly an activity conducted by the project initiator, the top level customer and representatives of the end users, who develop the preliminary technical requirements specifications, identify possible mission concepts and perform a preliminary risk assessment.
At the end of phase 0 the **Mission Definition Review** (MDR) is held. This review leads the customer release the mission statement and assess the preliminary technical and programmatic aspects. The outcome of this review is used to judge the readiness of the project to move into phase A.

Phase A: Feasibility. This is mainly an activity conducted by the top level customer and one or several first level suppliers. The project initiator establishes the preliminary *management plan*, the *system engineering plan* and *product assurance plan* for the project. Possible system architectures are here defined and compared with the identified needs, to determine levels of uncertainty and risks. In addition, during this phase the function tree is built down. Constraints relating to implementation, costs, schedules, organization, operations, maintenance and production are evaluated. Critical elements for technical and economic feasibility are identified and compared with possible technical solutions. Finally, model philosophy and verification approach are identified to be further elaborated during Phase B.
At the end of phase A the **Preliminary Requirements Review** (PRR) is held. This review leads the customer release the preliminary management, engineering and product assurance plans and the technical requirements specification. System concepts feasibility is confirmed, together with model philosophy and verification approach, to be carried forward into Phase B.

Phase B: Preliminary Definition. This phase sees the finalization of the management, engineering and product assurance plans and the preliminary Organizational Breakdown Structure (OBS) elaboration. Technical solutions for the system and their feasibility are here confirmed with respect to programmatic constraints. A preliminary design definition is elaborated for the selected system concepts and the verification program including model philosophy is determined. The Product Tree, the Work Breakdown Structure and the Specification Tree are finalized and the risk assessment is updated.
The associated reviews that need to be held at the end of phase B are the following:

1. **System Requirements Review** (SRR): it releases updated technical requirements specifications and assessment of the preliminary design definition and preliminary verification program;

2. **Preliminary Design Review** (PDR): it verifies the preliminary design. It contains the final management, engineering and product assurance plans, the final product tree, work breakdown structure and specification tree and finally the verification plan (including model philosophy).

Phase C: Detailed Definition. The type of tasks involved in this phase depends on the model philosophy selected for the project, as well as the verification approach adopted. The detailed design definition of the system at all levels in the customer-supplier chain is completed and the critical elements and components are selected and qualified. Assembly, integration and test planning for the system and its constituent parts is here completed and internal and external interfaces are defined, together with the preliminary user manual and the risk assessment.
The **Critical Design Review** (CDR) is held at the end of phase C. The outcome of this review is used to judge the readiness of the project to move into phase D. This review assesses the qualification and validation status of the critical processes and their readiness for deployment for phase D, confirms compatibility with external interfaces and contains the final design together with

assembly, integration and test planning. Flight hardware/software manufacturing, assembly and testing and user manual are released.

Phase D: Qualification and Production. During this phase qualification testing and associated verification activities are completed, as well as manufacturing, assembly and testing of flight hardware/software and associated ground support hardware/software. The interoperability testing between the space and ground segment is here checked and acceptance data package is prepared.
The associated reviews that need to be held at the end of phase D are the following:

1. **Qualification review** (QR): in this review, it is demonstrated that the design, including margins, meets the applicable requirements and the verification record is complete at this and all lower levels in the customer-supplier chain.

2. **Acceptance Review** (AR), confirming that the verification process has demonstrated that the product is free of workmanship errors and is ready for subsequent operational use. The "as-built" product and its constituent components is compared to the required "as designed" product and its constituent components. Delivery of the product is released as well as the certificate of acceptance.

3. **Operational Readiness Review** (ORR), that consists in verifying readiness of the operational procedures and their compatibility with the flight system. Ground segment for operations is accepted and released.

Phase E: Operations/Utilisation. The major tasks for this phase vary widely as a function of the type of project concerned. Generally all activities at space and ground segment level are performed in order to prepare the launch, together with early orbital operations. This phase includes on-orbit verification (and commissioning) activities, all on-orbit and ground segment activities to support the mission. Finally the disposal plan is completed.
The associated reviews that need to be held at the end of phase E are the following:

1. **Flight Readiness Review** (FRR), conducted prior to launch. The objective of this review is to verify that the flight and ground segments including all supporting systems such as tracking systems, communication systems and safety systems are ready for launch;

2. **Launch Readiness Review** (LRR), conducted just prior to launch. The objective of this review is to declare readiness for launch of the launch vehicle, the space and ground segments including all supporting systems such as tracking, communication and safety systems and to provide the authorization to proceed for launch;

3. **Commissioning Readness Review** (CRR), held at the end of the commissioning as part of the in-orbit stage verification. It allows declaring readiness for routine operations/utilization. This review is conducted after the completion of a series of on-orbit tests, to verify that all elements of the system are performing within the specified performance parameters;

4. **End-of-Life Review** (ELR), that verifies that the mission has completed its useful operation or service and ensures that all on-orbit elements are configured to allow safe disposal.

Phase F: Disposal. During this phase the disposal plan is implemented. The associated review that needs to be held at the end of phase F is the **Mission Close-out Review** (MCR), that ensures that all mission disposal activities are adequately completed.

1.1.4 V-Model

With the exception of the MDR, which normally involves only the project initiator and the top level customer, all other project reviews (up to and including the AR) are typically carried out by all project actors, down to the lowest level supplier in the customer-supplier chain. From the PRR to the PDR, the sequence of the reviews is "top down", starting with the *top level customer* and his top level supplier, and continuing the customer-supplier chain to the *lowest level supplier.* From the CDR to the AR, the sequence of reviews is "bottom up", starting with the lowest level supplier and its customer and continuing up to the first level supplier and the top level customer. This structure is called **V model** (Figure 1.4).

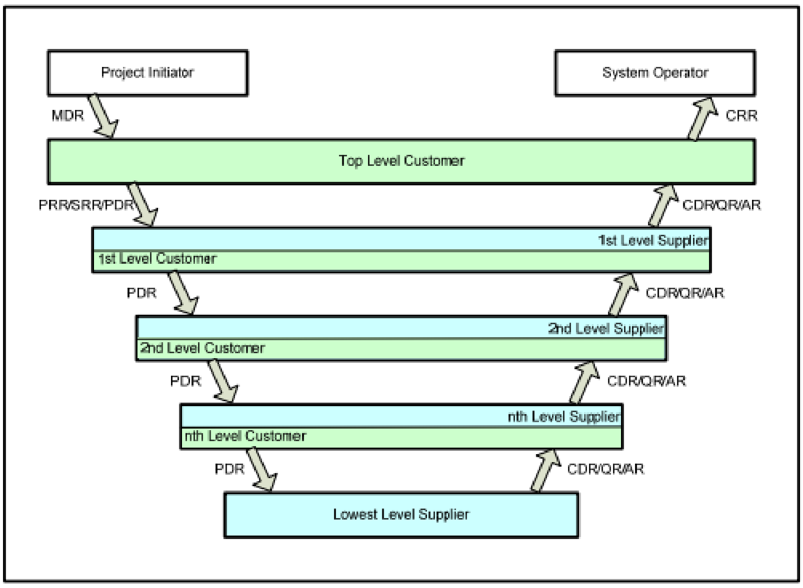


Figure 1.4: V-Diagram approach.

The V-model is the official project management method and provides guidance for planning and executing projects. It represents a development process that may be considered an extension of the waterfall model. Instead of moving down in a linear way, the process steps move to form the typical V shape. For this reason the diagram must be read "top-down" on the left side, and "bottom-up" on the right side. **Project definition** steps run the left side of the V with a level of detail that increases while reaching the bottom of the V (from system to unit); **test and integration** run the right side of the diagram with a level of detail that decreases reaching the top (from unit to system); at each step of integration, the relationships between each phase of the development life cycle and its associated phase of testing are demonstrated by **verification and validation**.

1.2 ECSS-E-HB-10-02: Models and Model Philosophy

The ECSS-EH-B-10-02 standard, dedicated to the verification guidelines [2], contains a detailed description of the models that may be adopted in the verification process and of the associated model philosophy.
During the development and verification process of a product various models are used. These models can either be *hardware* models, *virtual* models (software simulators and analytical models) or a combination of both (*hybrid* models). Differently, the model philosophy defines the optimum number and the characteristics of physical models required to achieve confidence in the product verification with the shortest planning and a suitable weighing of costs and risks.

1.2.1 Models Description

The main models adopted in the verification process are described hereafter:

- **Mock-Up Model** (MU). It is used in support of early design definition. According to their representativity Mock-Ups can be considered incremental tools, because they are progressively upgraded to reflect a final configuration.
- **Development Model** (DM). These Models are used in case of new design or where a redesign is performed. They are applicable to every type of product (e.g. electronic box, mechanisms, structural parts and thermal equipment) and can be subjected to functional and/or environmental testing. The DM is sometimes also called *Bread Board model* (BB).
- **Structural Model** (SM). It is fully representative of the end-product for structural aspects. Generally, it consists of a representative structure, with structural dummies of the flight equipment. It also includes representative mechanical parts of other subsystems (e.g. mechanisms and solar panels). The SM is also used for a final validation of test facilities, GSE and related procedures.
- **Structural-Thermal Model** (STM). It can be considered a Structural Model “re-defined” for thermal verification purposes after structural qualification.
- **Electrical and Functional Model** (EFM). Also called *integration model*, it is functionally representative of the end-products in both electrical and software terms. These models are used for functional and interface tests and for failure mode investigations.

- **Engineering Model** (EM). It is flight-representative in form, fit and function, usually without full redundancy. The Engineering Model is used for functional qualification, failure survival demonstration and it is also used for final validation of test facilities and GSE.
- **Engineering Qualification Model** (EQM). This model fully reflects the design of the end-product and it is used for functional performance qualification (including verification of procedures for failure detection, isolation and recovery and for redundancy management.
- **Qualification Model** (QM). It is the model that fully reflects the end product design in all aspects. The Qualification Model is used for complete functional and environmental qualification tests. It is used only for equipment and subsystems newly designed or when a delta qualification for adaptation to the project is performed. Qualification Model is not intended to be used for flight.
- **Life Test Model** (LTM). It is used to demonstrate by testing that the product can achieve the required lifetime and perform the required quantity of cycles. For qualification the tests are performed in the specified environment.
- **Protoflight Model** (PFM). This is the flight-end product on which, before flight, a partial or complete protoflight qualification test campaign is performed . The protoflight models only see acceptance or protoflight test levels. Limited life constraints, especially when mechanisms are present, are evaluated as for any flight model.
- **Flight Model** (FM). It is the flight end-product. It is subjected to formal functional and environmental acceptance testing.
- **Flight Spare** (FS). This model represents the spare-end product for flight. It is subjected to formal acceptance testing. Refurbished qualification product can be exceptionally used as Flight Spare.

1.2.2 Model philosophy

The selection of a model philosophy for a specific project is always a balance between the cost and the schedule of the program and the risk which can be taken (cost increases if specific models are necessary for early verification or check of critical aspects).
The model philosophy is defined by an iterative process which combines programmatic constraints, verification strategies and the integration and test programme, taking into account the development status of the current design solution (Figure 1.5). Typically, the development of a new product with new technology requires an extensive model philosophy which allows **full qualification**. On equipment level, BB and DM are used to identify problems at an early stage. On system level EMs are used, which avoid the cost and schedule impact of high reliability parts in QMs and FMs.
The model philosophy is also influenced by the *verification* and the *test strategy*. For specific verification tasks, specific test models can be required. A sequential use of a model on different levels and for different purposes can increase

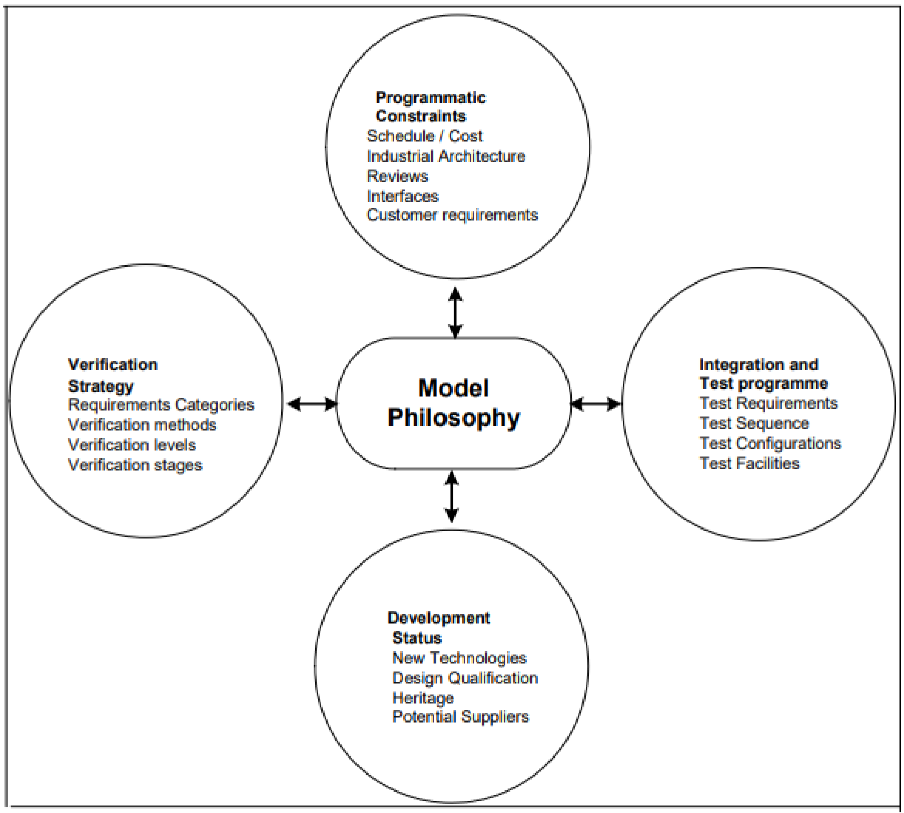


Figure 1.5: Factors influencing model philosophy.

the schedule duration, whereas parallel work on various models can shorten it. Several types of model philosophies can be employed according to verification requirements:

- **Prototype philosophy**. It is generally used in projects which are characterized by *new* or complex design and special mission requirements, and they can't be recovered or repaired after launch. The prototype approach makes extensive use of the aforementioned defined models to cover verification needs, so the disadvantage is typically **high cost**. On the other hand **risk level is low** and parallel activities on different models can be performed.

- **Protoflight model philosophy**. It is applied to projects with no critical design technology. The pure protoflight approach is based on a single model (PFM) to be flown after it has been subjected to a protoflight qualification and acceptance test campaign. The advantage of this approach is its **lower cost**, but on the other hand **risk level is increased**;

- **Hybrid model philosophy**. It is good compromise between prototype and protoflight approaches and advantages and disadvantages of this approach lie between those of the two in terms of risks, costs and schedule.

It is used in projects where advanced qualification activities are requested in areas of new design or in areas having criticalities. The hybrid approach always results in a protoflight model be flown after a protoflight test campaign. Specific qualification tests in the critical areas are carried out on dedicated models. In these areas only acceptance testing is performed on the PFM.

1.3 ECSS-E-ST-10-02C: Verification

The ECSS-E-ST-10-02C standard (March 6,2009) contains a detailed description of the verification process [3], aiming to demonstrate that the deliverable product meets the specified requirements: a satisfactory completion of the verification process is the basis for the **acceptance** of the product by the Customer. Verification process objectives can be summarised by the following points:

1. To demonstrate the qualification of design and performance at the specified levels;
2. To ensure that the product is in agreement with the qualified design and that it is free from workmanship defects and acceptable for use;
3. To confirm product integrity and performance at particular steps of the project life cycle (e.g. launch, commissioning, mission events and landing);
4. To confirm that the overall system (including tools, procedures and resources) is able to fulfil mission requirements.

The verification process activities mainly consist in **planning**, **execution**, **reporting**, **control** and **closeout** as shown in Figure 1.6. At the same time

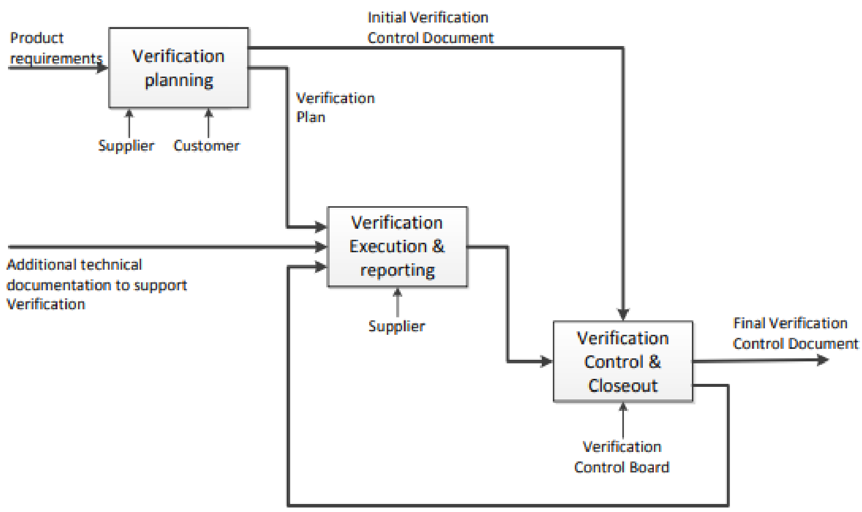


Figure 1.6: Activity flow in verification process.

the entire process and its implementation activities need to be documented by means of a specific set of verification documents, such as:

- *Verification Plan* (VP);
- *Assembly Integration and Test Plan* (AITP);
- *Verification Control Document*(VCD);
- Procedures and Reports.

1.3.1 Planning

The verification approach is established in early phases of a project by analysing the requirements to be verified, taking into account crucial aspects such as design peculiarities and constraints, availability and maturity of verification tools and methodologies, ground segment and in-orbit constraints, together with cost and schedule.
In generating the verification approach, the supplier conducts the following steps in an iterative process based on technical, cost and schedule considerations, ensuring that the approach is agreed by both the supplier and the customer.

1. Identify “what” are the products and requirements subject of the verification process;
2. Identify “how” to verify them by considering the methods stated in the technical specification;
3. Identify “when” to implement by applying the chosen verification strategy.

The logical flow starts with the identification of the **requirements** to be verified, follows with a proper selection of **methods**, **levels**, **stages** and **models** and is completed with the evidence of the verification **close-out**. The verification is performed incrementally at different product decomposition levels. The number and type of verification levels depends upon the complexity of the project and on its characteristics. The usual verification levels for a space product are **element**, **equipment**, **subsystem**, **segment** and overall **system**.

Verification Methods. The verification is executed by one or more of the following verification methods corresponding to the normal European practice:

- Verification by **test** shall consist of measuring product performance and functions under representative simulated environments;
- Verification by **analysis** shall consist of performing theoretical or empirical evaluation using techniques (such as systematic, statistical and qualitative design analysis, modelling and computational simulation) agreed with the Customer;
- Verification by **Review-of Design** (ROD) shall consist of using approved records or evidence that unambiguously show that the requirement is met (examples of such approved records are design documents and reports, technical descriptions, and engineering drawings);
- Verification by **inspection** shall consist of visual determination of physical characteristics (including constructional features, hardware conformance to document drawing or workmanship requirements, physical conditions, software source code conformance with coding standards).

Analysis, ROD and Inspections Programmes need to be reported in the Verification Plan.

Verification Stages. The verification process is implemented in subsequent verification stages along the project life cycle. The stages depend upon project characteristics and identify a type of verification.

- In the **Qualification** the supplier shall demonstrate that the design including margins meets the applicable requirements. This stage shall be carried-out on hardware and software which is representative of the end item configuration in terms of design, materials, tooling and methods;
- In the **Acceptance** the verification shall demonstrate that the product meets specified margins with the agreed deviations and it is free of defects when delivered by the supplier;
- In the **pre-launch** stage the verification shall demonstrate that the product is properly configured for launch activities and early operations. The verification shall confirm that the product is capable of functioning as planned during launch and early operations;
- In the **in-orbit** stage the verification shall address the minimum set of requirements that cannot be verified on ground. In this stage the verification shall characterize the system under operational conditions especially for the aspects that cannot be determined before the launch and it must be confirmed that the space and ground elements are compatible with each other;
- In the **post-landing** the verification shall address the product integrity and performance after the mission. In case the product is intended to be re-launched the verification shall address a health check at periodical intervals agreed with the customer, the product performance after modification, repair or replacement and the readiness for reuse.

1.3.2 Execution and Reporting

The verification process activities are incrementally performed at different product decomposition levels and in different stages, applying a coherent bottom-up strategy and utilizing a suitable combination of different verification methods. In particular the verification by test is carried-out on different physical models in agreement with the selected model philosophy.
The supplier shall identify those responsible for the implementation of the verification activities. The following reporting documentation needs to be processed:

- Test report;
- Analysis report;
- Review of Design report;
- Inspection report;
- Verification report.

When nonconformity is detected during the verification process, a *Nonconformance Report* (NCR) shall be processed too. The verification results shall be recorded by the supplier in these verification reports and provided to the *Verification Control Board* (VCB) for review.

1.3.3 Control and Close Out

The verification process is monitored in its execution by the Verification Control Board (VCB) and confirmed completed when, based on objective evidence, the VCD deems the product as verified against the identified requirements and the associated verification objectives. This has to be finally confirmed by the customer.
The VCB shall be established by the supplier and invite the participation of the customer, to assess the status of the verification process and it is set-up in relation to the complexity of the verification activities. The verification process shall be considered completed when the VCB confirms that:

1. Documented evidence is recorded in the VCD;
2. Identified requirements have been verified;
3. Associated product verification objectives are reached.

The conclusions of the VCB shall be submitted for approval to the customer.

1.4 ECSS-E-ST-10-03C: Testing

Standard environmental and performance test requirements for space products (mainly space vehicles, including transfer and re-entry vehicles, launch vehicles, ground systems and their constituents) are provided by ECSS-E-10-03 [4] and they are generally applicable to all projects.
This standard covers different stages of the product testing like qualification, *acceptance*, *pre-launch*, *in- orbit* and *post-landing* at different project levels, in accordance with the verification process [5]. Other detailed test requirements applicable to a particular project are defined in the related technical specifications and statements of work.

1.4.1 Testing Philosophy

The logic process flow starts from the **verification requirements**, defining the model philosophy and the verification matrix, and arrives at the identification of the detailed **test requirements**. In this frame, while defining a test baseline for a general project, the specific item characteristics (i.e. design maturity and margins, qualification status, model philosophy, etc.) and the programmatic characteristics (i.e. cost, acceptable risks, etc.) shall be considered. Testing is the preferred verification method with the lowest risk but, althought it represents a large expense. Tables are provided with the applicability and the optional requirements at the various levels and for the different stages. A **baseline test matrix** and a **levels and duration test matrix** are presented in this section for both space segment *equipment* and space segment *element*, and for each testing stage, as well as the test programme in the tables below. Some extracts relative to *qualification* stage are reported in the Figures 1.7 and 1.8.

Test	Reference clause	Ref. to Level & Duration	Applicability versus types of space segment equipment												Application notes
			a	b	c	d	e	f	g	h	i	j	k	l	
General															
Functional and performance (FFT/RFT)	5.5.1.1		R	R	R	R	R	R	R	R	R	R	R	R	For k (solar array), the deployment test is mandatory before and after the environmental tests (manual deployment before the environmental tests).
Humidity	5.5.1.2		X	X	X	X	X	X	X	X	X	X	-	X	For k (solar array) and l (solar panel), see ECSS-E-ST-20-08.
Life	5.5.1.3	See Table 5-2 No 1	X	X	R	R	X	X	R	X	X	R	-	-	To be performed on dedicated model. For l (solar panels), the life tests are covered by the ECSS-E-ST-20-08.
Burn-in	5.5.1.4		X	-	-	X	-	-	X	-	-	-	-	-	The test is performed in parallel with other funct. & environm. tests.
Mechanical															
Physical properties	5.5.2.1		R	R	R	R	R	R	R	R	R	R	R	R	Upon agreement with customer the CoG and MoI is not measured by test but calculated.
Static load	5.5.2.2	See Table 5-2 No 2	X	X	X	X	X	X	X	X	X	X	X	-	One of the three types of test is performed if not covered by the sinusoidal vibration test.
Spin	5.5.2.2	See Table 5-2 No 3	X	X	X	X	X	X	X	X	X	X	X	-	
Transient	5.5.2.2	See Table 5-2 No 4	X	X	X	X	X	X	X	X	X	X	X	-	
Random vibration	5.5.2.3	See Table 5-2 No 5	R	X	R	R	R	R	R	R	X	X	X	-	For k (solar array), the random vibration test should be added to acoustic test for fixed solar array mounted directly to the spacecraft side wall (without offset bracket).
Acoustic	5.5.2.4	See Table 5-2 No 6	-	X	-	-	-	-	-	-	X	X	R	-	For b (antennas), i (optical), j (mechanism), random vibration or, acoustic or both tests are selected depending on the type, size and location of the space

No	Test	Levels	Duration	Number of applications	NOTES
1	**Life**	Expected environment and maximum operational load	For duration and cycles: For mechanisms, apply ECSS-E-ST-33-01 Table 4-3 For batteries, apply ECSS-E-ST-20	1 test	
2	**Static load**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data (10 seconds minimum)	Worst combined load cases	Worst combined load cases are determined by analysis
3	**Spin**	$\sqrt{KQ}$ x spin rate The qualification factor KQ is given in ECSS-E-ST-32-10	As specified by the project	1 test	
4	**Transient**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data	As specified	
5	**Random vibration**	Maximum expected spectrum +3 dB on PSD values If margins higher than 3 dB are specified by the Launcher Authority, they apply.	2 minutes	On each of 3 orthogonal axes	
6	**Acoustic**	Maximum expected acoustic spectrum +3 dB If margins higher than 3 dB are specified by the Launcher Authority, they apply	2 minutes	1 test	

Figure 1.7: Qualification test baseline matrix and test level and durations frames for space segment equipment.

Qualification Testing. The objectives of the qualification tests are the formal demonstration that the design implementation and manufacturing methods have resulted in hardware and software conforming to the specification requirements. This includes the demonstration that the items perform satisfactorily in the intended environments with a sufficient margin.
As the environments used during qualification tests are more severe than those predicted to occur during flight (in order to account for variability in subsequent production articles and other uncertainties), the qualification margins used for qualification tests are also presented. Each identified standard test is then detailed in terms of objectives, relationship with the hardware models, requirements, set-up and, if necessary, guidelines for tailoring sequence and margins, where applicable.

Test	Reference clause	Ref. to Level & Duration & Number of applications	Applicability	Conditions
General				
Optical alignment	6.5.1.1		R	
Functional (FFT / RFT)	6.5.1.2		R	
Performances (PT)	6.5.1.3		R	
Mission (MT)	6.5.1.4		R	
Polarity	6.5.1.5		R	
Launcher Interface	6.5.1.6		X	Mandatory for space segment element interfacing with launcher if not performed on FM (see Table 6-3).
Mechanical				
Physical properties	6.5.2.1		R	
Modal survey	6.5.2.2		X	
Static	6.5.2.3	Table 6-2 No 1	X	Mandatory if not performed at structure subsystem level

No	Test	Levels	Duration	Number of applications	NOTES
1	**static load**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data	worst combined load cases	Worst combined load cases are determined by analysis
2	**Spin**	$\sqrt{KQ}$ x spin rate The qualification factor KQ is given in ECSS-E-ST-32-10	As specified by the project.	1 test	
3	**Transient**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data	1 test on 3 axis or 1 longitudinal axis	
4	**Acoustic**	Maximum expected acoustic spectrum +3 dB If margins higher than 3 db are specified by the Launcher Authority, they apply	2 minutes	1 test	
5	**Random vibration**	Maximum expected spectrum +3 dB on PSD values If margins higher than 3 db are specified by the Launcher Authority, they apply.	2 minutes	on each of 3 orthogonal axes	

Figure 1.8: Qualification test baseline matrix and test level and durations frames for space segment element.

Qualification testing shall be conducted on dedicated qualification models except when using protoflight approach. They shall be completed and design improvements or modification incorporated and qualified prior to the authorization for the flight product manufacturing.
In case destructive tests are needed (e.g. Burst test), a representative model different from the QM shall be used or the test shall be performed at the end of the qualification programme.

Acceptance Testing. The purpose of these tests is to demonstrate conformance to specification requirements and to act as quality control screens to detect manufacturing defects, workmanship errors, incipient failures and other performance anomalies, not readily detectable by normal inspection techniques.

The acceptance tests are formal tests conducted to demonstrate the adequacy and the readiness of an item for delivery and subsequent usage. They are conducted on flight models under environmental conditions not more severe than those expected during the mission.
This section too presents the standard tests in terms of objectives, relationship with the hardware models, requirements and, if necessary, guidelines for tailoring sequence and margins, where applicable. As well as qualification, the acceptance section contains a test matrix and a test sequence, at equipment and space element levels which provides a baseline for testing activities.
Acceptance testing shall be performed on each flight product, except the one used as Protoflight, to assure freedom from workmanship defects and flawed materials in conformance with ECSS-E-ST-10-02. The acceptance programme shall be performed, after a qualification programme has been completed (the FM is built from the same design file than the QM or the PFM used for qualification).

Protoflight Testing. Protoflight testing is the combination of the qualification and acceptance testing objectives on the first flight model. The protoflight approach can be applied at each level of decomposition of space system. To minimize risk, a space segment elements protoflight approach can include tests on dedicated models, which can later be refurbished in PFM.
ln a minimum risk programme like in the prototype approach, the products subjected to qualification tests are themselves not eligible for flight. For this reason in most projects the protoflight approach is used in order to optimize cost and schedule of the projects while maintaining an acceptable degree of technical risk. Generally, this approach is adopted for projects with the following characteristics:

- no technology critical design;
- heavy schedule constraints (e.g. mandatory launch date);
- extensive use of already qualified hardware;
- trade-offs between the risk and the cost, accepting a higher risk as part of a low cost implementation.

The advantages of this approach are low costs and reduced time schedule but with increased risks, serial activity flow on the same model and simultaneous qualification and acceptance activities.
The protoflight approach is based on qualification levels and acceptance durations. For this reason wide reference to objectives, methods and requirements is made with respect to the qualification and acceptance sections.
Protoflight testing shall be performed on the first flight model to provide evidence that the space segment element or equipment performs in accordance with the specifications in the intended environments with the specified qualification margins and to confirm its readiness for delivery and subsequent usage, being free from workmanship defects. In case destructive tests are needed (e.g. Burst test), a representative model different from the PFM shall be used.

Pre-Launch Testing. The purpose of pre-launch testing is to verify by end-to-end tests that each critical path in the system before launch is satisfactory and that there are no out-of-tolerance conditions or anomalous behaviour, for demonstrating successful integration of the flight element with the launch element. In particular, it is highlighted i that pre- launch tests have to ensure that:

- no damage to, or performance degradation of the flight item has occurred during shipment or handling;
- all launch site assembly activities have been completed properly, all associated interfaces are verified, and their parameters are within the specified limits;
- rotating with the launch vehicle has been completed successfully, so all functional interfaces between the flight and the launch element and between the launch element and the ground support and facilities have been verified.

It has to be noted that the extent of pre-launch testing, the appropriate test sequences and the test procedures are unique for each launcher and for each project. One of the goals is to minimise testing at the launch site to reduce cost and schedule. Therefore it may be possible to specify pre-launch tests only in general terms (functional, propulsion, compatibility, integrated launch system test, etc).

1.4.2 Test Reviews

The test programmes conducted at space segment equipment and space segment element are reported in Table 1.1 and 1.2 and they are typically decomposed in blocks. The definition of the blocks of requirements shall be agreed between the customer and supplier and depends mainly on the item under test, the facility and the contractual agreement. A test block can include one or more tests. For equipment, usually one test block covers the full test programme.

General	Functional & Performance, humidity, life test, Burn-in Test
Mechanical	Physical Properties Measurement, Acceleration Test (Static, Spin, Transient), Random Vibration, Acoustic, Sinusoidal Vibration, Shock Test, Microvibration
Structural Integrity	Leak Test, Proof Pressure, Pressure Cycling, Design Burst Pressure, Burst Test
Thermal	Thermal Vacuum, Thermal Ambient
Electrical/RF	EMC, Magnetic, ESD, Passive Intermodulation, Multipaction, Corona and Arc Discharge
Mission Specific Test	Audible Noise Test [...]

Table 1.1: Test Programme at Space Segment Equipment Level.

Each test block shall include the following formal reviews:

General	Optical Alignment Measurement, Functional & Performance, Mission, Polarity, Launcher Interface
Mechanical	Physical Properties Measurement, Modal Survey Test, Static Load test, Spin Test, Transient, Acoustic, Random Vibration, Sinusoidal Vibration, Shock Test, Microvibration, Susceptibility
Structural Integrity	Proof Pressure, Pressure Cycling, Design Burst Pressure, Burst Test, Leak Test
Thermal	Thermal Vacuum, Thermal Ambient, Thermal Balance
Electromagnetic	EM Compatibility, EM Autocompatibility, Passive Intermodulation, Magnetic Fields Measurement
Mission Specific Test	Aero-thermodynamic Test
Crewed Mission Specific Test	Micro-vibration Emission, Toxic off Gassing, Audible Noise Test

Table 1.2: Test Programme at Space Segment Element Level.

- **Test Readiness Review** (TRR), to authorize the test execution. It will give a decision on the quality, adequacy and consistency of the corresponding documentation (test specification and procedures), the test article (HW and SW), the configuration and on the identified open anomalies. For major tests, several TRR will be held prior to each planned sub-phase (TB/TV, sine vibration and acoustic noise for example). The TRR are formal reviews verifying the readiness status of all elements participating to the test (procedures, facilities, personnel, hardware configuration).

- **Post Test Review** (PTR), to formally declare the test completed and to allow the release of the item under test and test facility for further activity. The release of the test facility includes the breaking of the test configuration. The PTR confirms that all test data were acquired, recorded, and archived in conformance with the test specification and establishes that tests were performed according to the AITP, the test specification and the test procedures, with the exceptions of what is covered by agreed procedure variations or NCRs (*Non-Conformance Report*);

- **Test Review Board** (TRB), to review all results and to conclude on the test completeness and achievement of objectives.The TRB addresses topics such as test documentation availability (including test report, facility report when relevant, inspection report, list of NCRs, etc), compliance with the test specification and variations to the AITP or status of compliance of the item under test to the relevant requirement.

1.4.3 Test Documentation

The Test programme documentation involves Assembly, integration and test plan (AITP), Test specification, Test procedure, and Test report generated at all product levels. These documents are derived from the System Engineering Plan (SEP) and from the Verification Plan (VP).

- **Assembly, Integration and Test plan** (AITP) that is the master plan for the product AIT process. It describes the complete AIT process and demonstrates together with the verification plan how the requirements are verified by inspection and test. It contains the overall AIT activities and the related verification tools (GSE and facilities), the involved documentation, the AIT management and organization. It also contains the AIT schedule. It is one of the major inputs to the project schedule and is used to provide the customer a basis for review and evaluation of the effectiveness of the AIT programme and its proposed elements. The AITP is complementary to the verification plan and takes into account the test standards defined in the Customer requirements. The availability of the verification plan is a prerequisite to the preparation of the AITP.

- **Test specification** (TSPE), that describes in detail the test requirements applicable to any major test activity. In particular, it defines the purpose of the test, the test approach, the item under test and the set-up, the required GSE, test instrumentation, test schedule etc. The TSPE is used at each level of the space system decomposition (i.e. equipment, space segment element), it provides the requirements for the activities identified in the AITP and is used as a basis for writing the relevant test procedures and test. In writing the test specification potential overlaps with the test procedure is minimized (i.e. the test specification gives emphasis on requirements, the test procedure on operative step by step instructions);

- **Test procedure** (TPRO), that gives directions for conducting a test activity in terms of description, resources and constraints, and provides detailed step-by-step instructions for conducting test activities with the selected test facility and set-up in agreement with the relevant AITP and the test requirements. It contains the activity objective, the applicable documents, the references to the relevant test specification and the test facility configuration, the participants required, the list of configured items under test and tools and the step-by-step activities. The TPRO is prepared for each test to be conducted at each verification level. The same procedure can be used in case of recurring tests. It incorporates the requirements of the test specification and uses detailed information contained in other project documentation. In certain circumstances involving a test facility (for example during environmental tests) several test procedures can be combined in an overall integrated test procedure. The “as-run” procedure becomes part of the relevant test report.

- **Test Report** (TRPT), that describes test execution, test and engineering assessment of results and conclusions in the light of the test requirements (including pass-fail criteria). The test report contains the scope of the test, the test description, the test article and set-up configuration, and the test results including the as-run test procedures, the considerations and conclusions with particular emphasis on the close-out of the relevant verification requirements including deviations.

Chapter 2

PLATiNO Overview

2.1 A multi-mission platform

In the last years, Italian Space Agency (ASI) has turned great attention to the development of technologies and the strengthening of innovative systemic capabilities. As for technologies, it supports initiatives dedicated to low Technology Readiness Level (TRL), high TRL and In-Orbit Validation (IOV). As for to system capabilities, there are development lines dedicated to prototype and innovative programs such as remote sensing of the earth, hyperspectral optical systems (SHALOM) and radar (GEOSAR).
In this context, the Small Satellites line saw the birth of the **PLATiNO Program** (mini Piattaforma spaziaLe ad Alta TecNOlogia), an all-electric multi-purpose 200 kg satellite platform, deployable in constellation and suitable for a wide range of multi-mission applications (Optical, SAR, Telecom, etc.). Hopefully, in the coming years, the program will continue in other *micro* (under 100Kg) and *nano/pico* (under 10 kg) classes and expanding the intervention area beyond the low orbit.
PLATiNO has the aim of consolidating a leading role by the Italian industry in the development of high-tech **multi-mission modular platforms** [6], which foresee as main feature the *multi-applicability*, intended as the reuse for different missions (payloads), without deep re-design and delta-qualification activities (*product-oriented* approach). The primary objective is the definition of national technologies enabling future ASI missions through an innovative platform able to embark a whole range of scientific and application P/L, that allows to qualify and test Italian technologies on on-board devices.
The opportunities for the country are remarkable considering the spectrum of new applications deriving from the different architectures made possible by the initiative (e.g. formation flying, constellations of new P/L for Earth Observation or Telecommunications).
After a first agreement signed in December 2019, a long term agreement was signed in June 2020 regulating the relations, in the industrialization and marketing phase of the PLATiNO Program, between **SITAEL, Leonardo, Airbus Italia** and **Thales Alenia Space Italia**.
The agreement responds strongly to the interest of the world market in the innovative "high-tech mini space platform" that is the basis of the PLATiNO

program. Financed by ASI and the Italian Government with an investment of over 100 million Euros, the program provides, to crown the in-flight qualification, the realization of *two missions* scheduled for launch in 2022 and 2023 respectively. In addition, ASI intends to carry out a third mission with timing compatible with that of the second, taking advantage of the low-cost recurring platform.
In order to make available, for the numerous national initiatives and in international cooperation, a high efficiency and low cost platform also for missions beyond the LEO orbit, all the upgrades necessary for adaptation to the space environment beyond the LEO orbit will be made, with the ability to support payloads with heterogeneous characteristics and oriented to a wide range of operational missions, as well as Exploration areas and Deep Space.

2.1.1 Missions

Mission scenarios (and relevant Payloads) candidate for PLT-1 and PLT-2 have been described in a *Mission Description Document*, containing two sizing missions that coould be assumed as reference and payload candidates for PLT-1 and PLT-2 missions [7]. Currently, the following sizing missions have been identified:

- **PLT-1: SAR mission**. PLATiNO-1 mission validates the PLATiNO platform embarking a Micro-SAR payload from Thales Alenia Space Italia. The mission envisages a first phase at 619 km operating in *passive* mode and a second phase at 410 km operating in *active* mode: the orbit transfer is performed making use of Sitael HT100 Electric Thruster and validates the platform orbit maneuvering capabilities. Thanks to the extremely high power PLATiNO platform is able to provide, PLATiNO-1 can guarantee a scan time per orbit nowadays unmatched in the Micro-SAR sector.

Figure 2.1: Platform and SAR antenna representation.

- **PLT-2: TIR Mission**. PLATiNO-2 mission envisages the development of the second satellite based on PLATiNO platform and embarks a Thermal Infrared (TIR) payload, validating PLATiNO multi-applicability feature. Developed by Leonardo and Sitael, PLATiNO-2 TIR will acquire images that will be used to provide valuable services for territories control and protection such as monitoring waters, glaciers, pollutants, state of crops and vegetation, energy consumption in urban areas. PLATiNO-2 is also equipped with the magnetically shielded HT 100, an improved version of Sitael electric thruster, making PLATiNO-2 one of the first missions in the world to observe the Earth in the Thermal Infrared from a very low orbit – less than 400 km – and thus significantly improving the resolution of the acquired images.

Figure 2.2: Thermal and Infrared Payload representation.

2.1.2 Platform Design

The platform is composed by a number of subsystems to provide all required support functions to any embarked Payload and guarantee the required operative profile during the satellite lifetime. In terms of design solutions, the platform is built on *modular* approach, as shown in Figure 2.5 [8]:

- **Bus Module (BM)**: standard service module structure with all main platform subsystems placed in it (with a highly standardized internal layout), providing also the standard Launch Vehicle interface (LV I/F, on bottom panel) and all the interface with Solar arrays and Payloads;

- **Solar Array Assembly (SAA)**: the assembly of the solar array panels, configured as fixed/deployable/drivable/mixed , that interfaces with BM and Payload Support Structure if needed. The SAA includes the mechanisms such as root hinge, Hold Down Release Mechanisms (HDRMs) or Solar Array Deployment Assembly (SADA) if present. Typically SAA layout depends from mission features (orbit, S/C flight attitude, power need);

- **Payload Support Structure (PSS)**: the assembly represent the generic supporting structure to interface and sustain (thermo-)mechanically the specific P/L. It is mission-dependent, but it is already defined a set of PSS allowing the accommodation of candidate P/Ls. It can be composed of simple frame structure with additional lateral/top panels mated on the frame or by additional trays;

- **P/F External Appendages**: all the P/F external appendages (AOCS sensors, COMM antennas) that are accommodated on BM possibly (or PM if strictly needed), depending on required layout/orientation of specific mission (i.e. flight attitude).

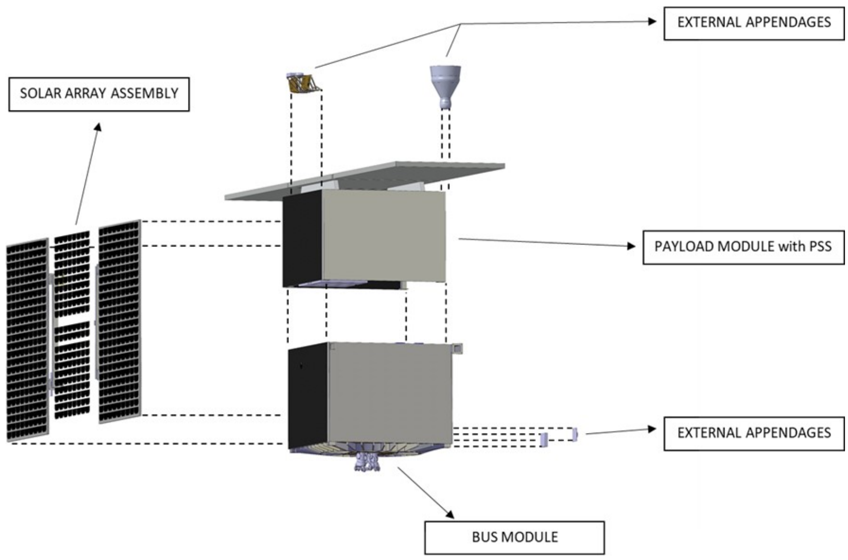


Figure 2.3: PLATiNO Platform Modular Approach.

The *functional* architecture is built around the Command & Control Central Unit (i.e. **IPAC**) and the Power Control & Distribution Unit (**PCDU**), providing the set of functional I/Fs such as power supply and communication buses (CANBus or SpaceWire optionally) and dedicated input/output lines.
The design at S/S level is summarized hereafter:

- **Thermo-structure**: a compact, lightweight and efficient frame-based bus module, allowing the accommodation of all internal units (onto panels and webs), guaranteeing the mechanical and thermal loads compatibility. The standard Bus Module structure foresees a standard mechanical (and thermal) I/F with the Payload Structure, which is designed to fit the selected P/Ls (multi-mission design).

- **Electrical Power S/S**: it provides different power generation and energy storage solutions (solar arrays different layouts and battery modularity),

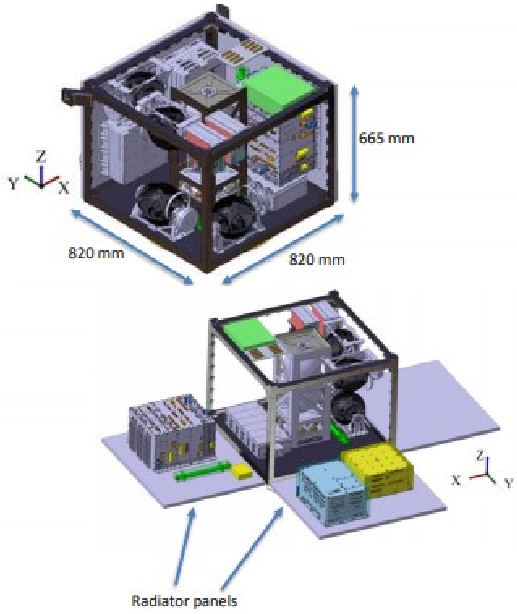


Figure 2.4: PLATiNO Thermo-structure representation.

to fit the missions needs. The S/S is built around a compact PCDU, capable of managing up to 1.2 kW of on-board power. An optional SADA is foreseen for high/constant power profile missions;

- **Avionics S/S**: based on a highly integrated multi-core on-board computer (IPAC) and providing P/L data handling (mass memories) functions, it manages all the P/F (and S/C) operations, in terms of command and control. The AOCS is based on high pointing accuracy sensors (*Star Trackers*) and high torque capability actuators (Mini-Control Moment Gyro), with the feature of a gyro-less architecture.

- **Electric Propulsion S/S**: a Hall effect thruster (**HT-100**) based subsystem, providing high delta-V capability (up to 800 m/s). The S/S is managed by a PPU (Processing Power Unit), providing both high voltage to HET and command & control functions. A propellant (Xenon) fine regulation (flow control) system is present on-board, as well as the xenon tank, which is modular depending on mission needs.

- **Communication S/S**: built around a highly integrated transceiving unit (ICU, Integrated Communication Unit). The X-band P/L data transmission is performed by a brand new active (electronic steering) antenna, with high data rate (up to 500 Mbps). An optional Ka-band Inter-satellite link (to enable the use of the platform in constellation) is also present.

The platform adaptability to a wide set of mission scenarios (multi-applicability) implies that the platform concept design shall be standardized and configurable at the same time.
To answer this specific constraint, the platform design shall be conceived as the union of:

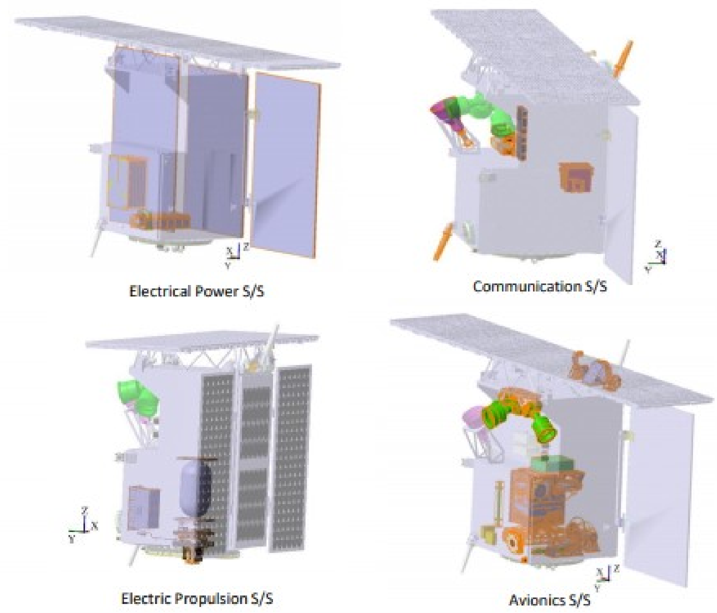


Figure 2.5: PLATiNO Sub-systems.

1. **Baseline Design**: standard features (at architecture & S/S-unit level), not mission-dependent, which represent the platform constitutive elements and provide the high level of global product standardization;

2. **Design Options**: the set of design options that characterize the platform for the specific mission scenario requirements, by providing the required performances.

These options can be classified into two types:

- Sizing of the platform S/S or item based on mission scenario (i.e. solar array sizing, tank volume, payload structure);

- Use of an optional equipment (i.e. not in baseline), without impacting the standard S/S architecture.

The set of Design Options will be pre-defined together with the baseline and will be part of platform design definition phase and also qualified together with the baseline part, through the definition of envelope configurations and multiple qualifications, mainly on platform intermediate models (i.e. S/S benches, V-Flatsat, STM).

Chapter 3

Alignment Campaign

Alignments represents one of the significant activities of the Assemby, Integration and Test process. The aim of an alignment measurement is to ensure the correct position of some critical units, typically part of the AOCS and Communication System, according to which is specified by the Platform requirements. The general approach is to perform these class of measurement before and after crucial phases of the AIT campaign. The first measurement is typically conducted after the **integration** of the unit; then, a further measurement is performed before the starting of the **environmental test campaign** (for ensuring AIT activities have not affected the unit position or orientation); the last alignment check is performed at the end of the environmental test campaign.

3.1 Alignment Approach

In the frame of PLT-1 AIT, alignments will be performed on both SM and PFM. On the SM the alignment campaign has the aim to proof critical test configurations (in terms of unit stability) and to forecast the best sequence to implement for the PFM. Differently, during the PFM test campaign the entire alignment requirements verification is performed.
All the alignment measurements are reunited in **alignment blocks**, depending on the involved units and the correspondent AIT phase. Table 3.1 gives an overview of the alignment blocks that need to be performed during the campaign [10], in particular:

1. *Mini Control Momentum Gyro (Mini-CMG) Alignment On Bench*;
2. *Platform Alignment*;
3. *Pre Thermal Vacuum (Pre-TVAC) Alignment*;
4. *SAR Integration and Alignment*;
5. *Pre/Post Vibration Campaign Alignment*;

involving the following units:

a. *Mini-CMG*;

b. *Multi-Head Star Traker (MH-STT)*;

c. *Thruster Units (TU)*;

d. *SAR Antenna*;

e. *X Band Passive Antenna (XBPA)*.

Furthemore, to verify the structure deformations, the following panels are submitted to alignment:

A. *Intermediate Plate*;

B. *Top Plate*.

Aligment	**Units**	**Campaign**	**Block**
Mini CMG Alignment on Bench	MGMG AU	PFM	Al_01
P/F alignment	STT, MCMG AU, TU	SM (STT, TU)	SM-AL01
		PFM	Al_02
Pre-TVAC Alignment	STT, TU, IP, TP	PFM	AL_03
Antenna Integration and Alignment	SAR	PFM	Al_04
Pre Vibrations Alignment	STT, XBA, TU, IP, TP	SM	SM-AL02
		PFM	Al_05
Post Vibrations Alignment	STT, XBA, SAR (TAS-I),TU, TP, IP	SM	SM-AL03
		PFM	Al_06

Table 3.1: Platform Alignments Overview.

Alignments concerning the Platform will be carried out by Sitael (i.e. SAR integration and alignment will be performed by TAS-I) and will be detailed in the next paragraphs, including a description of involved units, their provisions and their configurations.
Additionally, to give an overall idea of the alignment block sequence, the **alignment flow** for SM and PFM has been built down. It is necessary to approve the TRR (Test Readiness Review) right before the start, and a PTR (Post-Test Review) at the end of the activity, for each model (SM and PFM). The need of interim TRR and PTR is usually evaluated during the AIT campaign.
Moreover, activities to be performed during the alignment measurement can be summarized by the following points:

1. **Alignment set-up preparation**. That is the placement of the measurement instrument(s) and set-up organisation, such as PC connection, item under test and MGSE (Mechanical Ground Support Equipment) placement in the desired position;

2. **Instrument calibration**. Depending on the measurement technology, this activity includes all step needed to have the measurement system ready to be used;

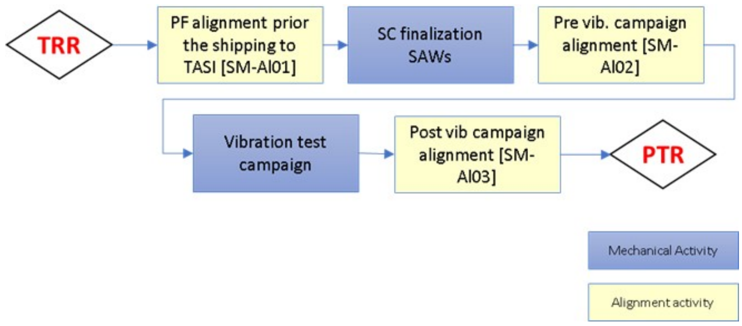


Figure 3.1: SM Alignment Flow.

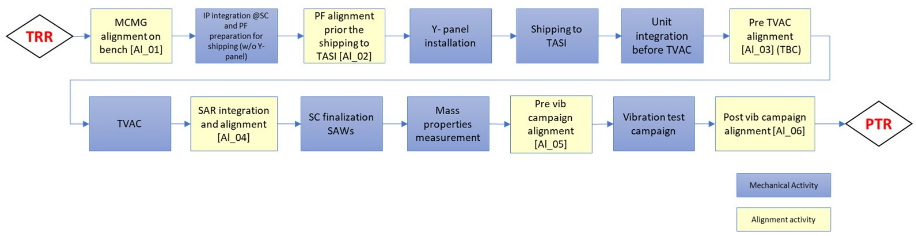


Figure 3.2: PFM Aligment Flow.

3. **MGSE levelling**. This activity is required whenever the position of the MGSE shall be known for a correct measurement post processing;

4. **Coordinate system construction**. All the measurement will be evaluated with reference to this reference system.

5. **Alignment**. Measurement activity;

6. **Set-up reconfiguration**. This activity is required if a step-up modification is needed to reach the measurement target and the OGSE recalibration is required after this change;

7. **Post-processing**. Evaluation of the results recorded in the measurement software with reference to the required position.

3.1.1 Units

In the current paragraph, the units which the alignment measurements will be performed on are presented and described [11].

Mini Control Momentum Gyro. The mini-CMG Actuation Units assembly is composed by four mini-CMG AU installed on the intermediate plate (Figure 3.3). They belong to the AOCS S/S, so they ensure the S/C attitude control, transforming the input received by the mini-CMG Control Unit in output forces. Typically mini-CMG AU are operating at least three on four. A precise alignment of these unit is important to have force vectors in the right direction.

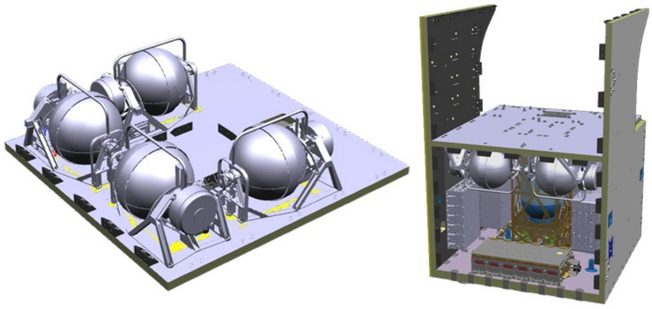


Figure 3.3: Mini-CMG representation on IP (left) and S/C(right).

Multi-head Star Trackers. The MH-STT is composed by three STT units (operating at least two on three) and it is installed on the Top Plate (Figure 3.4). The MH-STT is used during the nominal mission phase, in order to achieve fine attitude measurements to support the P/L activity. At least two STT shall operate and the MHST software (SW) manages the attitude quaternion computation.
The MH-STT SW includes also as calibration parameters three transformation matrices describing the Optical Heads orientations with respect to an external reference frame.
The alignment measurements performed on the MH-STTT aim to calculate the calibration parameters.

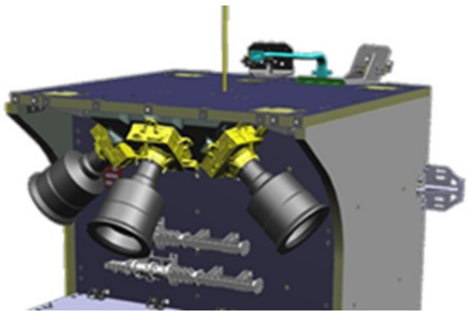


Figure 3.4: MH-STT representation on TP.

X-Band Passive Antenna. The XBPA is installed on the Intermediate plate on a support ensuring a 30 degrees inclination of the RF axis with reference to the vertical Satellite direction. The XBA belongs to the COMM S/S and the direction of the RF axis shall be known to ensure the right pointing accuracy (Figure 3.7).

Thruster Units. The Thruster plate is located on the P/F Bottom Panel and accomodates two Hall Effect Thruster Unit (HT100) on PLT-1 operating one per time (fully redundance configuration). The thrust vector shall be aligned

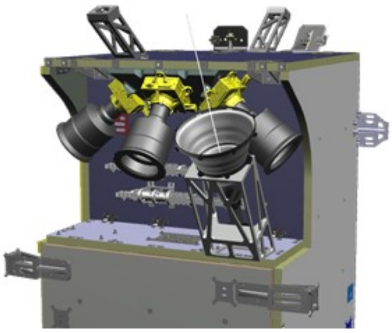


Figure 3.5: XBPA representation on IP.

with the satellite center of gravity (CoG) to allow all the operations planned during the PLT mission. If the thrust vector has a lever arm with reference to the S/C CoG a couple is developed and the measurement of the angle between the TU axis and the S/C optical reference system gives the input parameter to allow the compensation of any angular moment with the AOCS S/S.

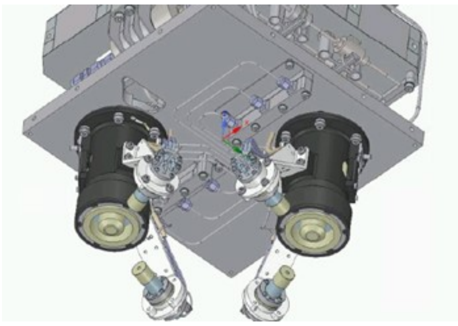


Figure 3.6: Thruster Units.

Other units. There are alignment requirements also for other units of the AOCS S/S and COMM S/S, for which the verification method is not by test, so they shall be verified by *analysis* or by review of design (see section 1.3.1):

- **Fine Sun Sensors** (FSS);
- **Sun Sensors** (SS);
- **Magnetometers** (MAG);
- **Magneto-torquer** (MTQ);
- **GPS Antenna**(GPSA);
- **S-Band Antenna**(SBA).

For these units, required alignment accuracy is not that high, for this reason they will be not considered in the current analysis.

3.2 Requirements and Constraints

3.2.1 Master Reference System

The Master Reference System [12] is referred in this paper as the Spacecraft **Mechanical Reference Frame** (MRF). The origin of the MRF is located at the geometric centre of the interface between the Lightband (that is the Launch separation device) and the Bottom Panel of the S/C. The three axes are defined as follows:

1. the Z_m axis is perpendicular to the separation plane towards Satellite upper plane;
2. the Y_m axis is perpendicular to the Solar Arrays plane and pointing from the origin towards the direction opposite to the Solar Arrays plane;
3. the X_m axis completes the right-handed orthogonal.

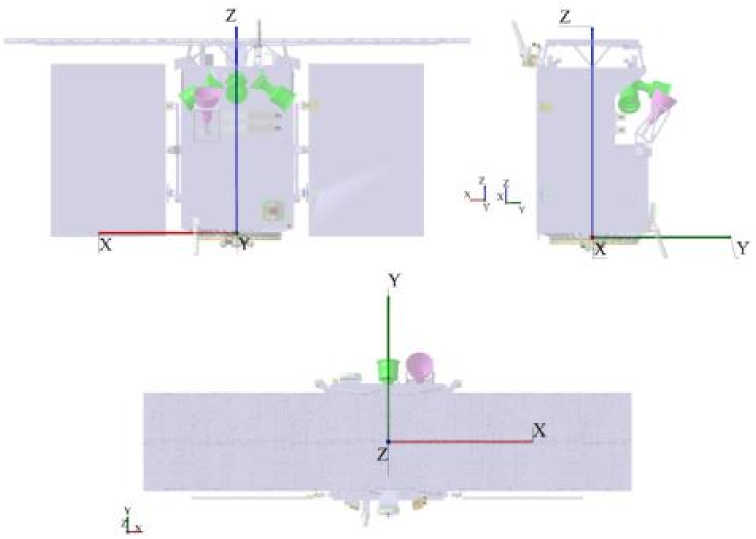


Figure 3.7: S/C Mechanical Reference Frame.

Moreover, in the context of the alignment campaign, it is necessary to define the **Optical Reference Frame** (ORF), that will represent the global reference which most of the measurements will be referred to and, from the position of the ORF, it shall be possible to "transfer" each measurement in the S/C Reference Frame (MRF), typically by means of a *rotational matrix*.
The requirements that govern the Optical Frame definition are reunited in Table 3.2.

Title	Requirement
Optical Reference Frame	*The Spacecraft Optical Reference Frame shall be defined by a reference mirror cube located at a stable position on the Spacecraft. It will remain visible throughout the AIT phase and pre-launch check out. A secondary reference mirror cube is recommended to be installed as a back-up. The unit vectors along* (X_{S0},Y_{S0} *and* Z_{S0}) *shall be nominally parallel, and in the same sense to the unit vectors along* (X_{SC},Y_{SC} *and* Z_{SC}). *The Spacecraft Optical Reference Frame shall be used for Payload and Spacecraft level alignments.*
Master Reference Cube	*The Platform shall embark Master Reference Cubes to be used for Platform Alignment purposes, in a configuration accessible during all AIT configuration (Platform AIT, Spacecraft AIT).*

Table 3.2: Optical Reference Frame Requirements.

Mirror cubes are widely used in optical alignments for monitoring and qualifying critical systems, that need highly precise accuracy when measured. They can be made of out of different types of glass or stainless steel, typically polished with reflective thin film coatings.

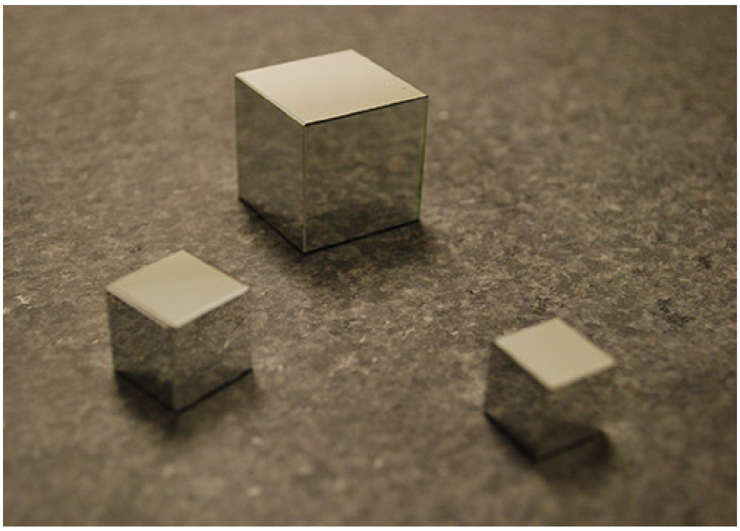


Figure 3.8: Mirror cubes of different dimensions. Cube side can typically vary between 1.5 cm and 2.5 cm.

In this context, mirror cubes embarked on the P/F shall be mounted on the aligning unit so that the *normal direction* of one of its faces could be representative of one ore more axes of the unit (typically *pointing* direction or *actuation* direction). For this reason, it is necessary to mount the alignment cubes with very high accuracy (they can be either bonded or mounted on plate, as in Figure (3.9)).

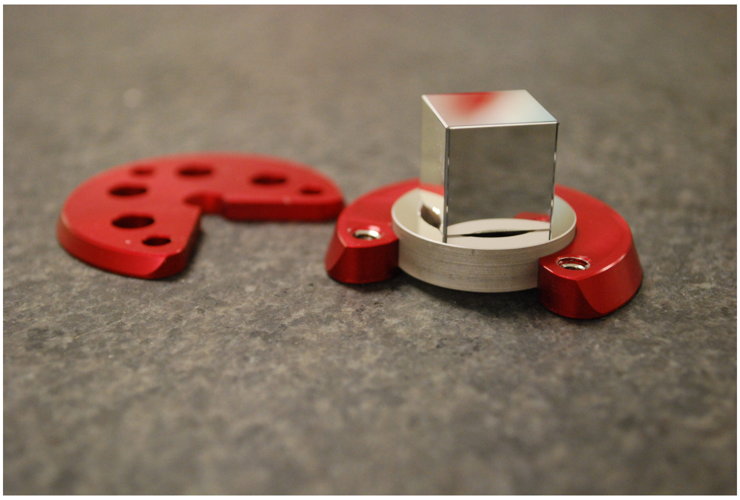


Figure 3.9: Mirror Cubes mouted on plate.

As for the **Master Reference Cubes**, they will be accomodated on the Bottom panel as shown in Figure 3.10 . The placement of the cubes will be responsibility of the AIT. The panels supplier will perform the measurement of the Mechanical Reference Frame (located as described before), that represents the crucial measurement of the entire Alignment Campaign. The Master Reference Cubes will be properly located on the Bottom Plate, and their position will be subsequently measured with reference to a specified hole on the panel, whose coordinates will be known. At the end of this process, it will be possible to determine the global rotational matrix of the MRC in the S/C Mechanical Reference System.

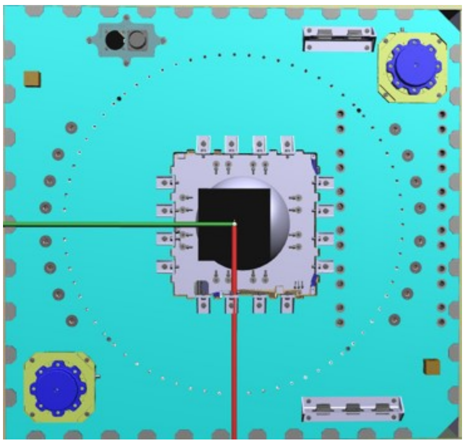


Figure 3.10: Bottom Panel representation. The circular hole pattern defines the interface with the Lightband.

3.2.2 PFM: Provisions and Configurations

As described in 2.2.1, most of aligning units are provided by design with mirror cubes, that shall be in some way representative of the unit orientation on the Platform. This section is detailed with the unit expected configurations on the P/F and the auxiliary **Mechanical Ground Support Equipment** (MGSE), intended as the instrumentation that will be needed for the S/C handling during the AIT Campaign; furthermore, the correspondent requirements assigned at P/F level have been reported.

Mini Control Momentum Gyro. The mini CMG Actuation Units shall be accomodated on the IP in configuration 2+2, that means:

- 2 AU with gimbal axis aligned with X_{SC} axis and one opposite to each other;
- 2 AU with gimbal axis aligned with Y_{SC} axis one opposite to each other.

Therefore, all of the gimbal axes shall be on the same plane.
A mirror cube has been located on each actuation unit and the following alignment requirements have been assigned (Table 3.3):

Title	**Requirement**
mCMG Alignment Constraints	*The mini-CMG alignment shall respect the following constraints :* • *the alignment between two parallel gimbal axes shall be better than 0.02 degrees;* • *the angle between two perpendicular gimbal axes shall be better than 0.01 degrees.*
mCMG Alignment Accuracy	*The mini-CMG Actuation Units shall be aligned with an accuracy of 0,02 deg 3 axis with respect to actuation axis.*

Table 3.3: Mini-CMG Alignment Requirements.

From the table above, the accuracy required for these measurements is $0.02\,deg$ on three axes with respect to actuation axis, intended as the S/C Y_{SC} axis.

The alignment of the mini-CMG Assembly is performed **twice** during the PFM AIT campaign, after the integration on panel and after the integration of the panel at satellite. The MGSE of these configurations are represented in Figure 3.14.

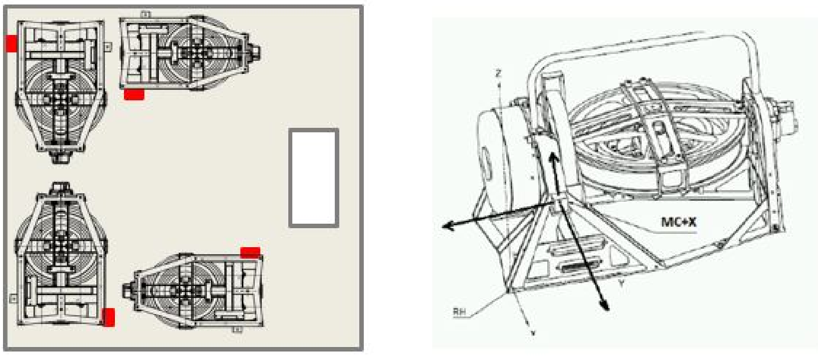


Figure 3.11: Mirror Cube on mini-CMG.

1. **Alignment On Panel**. The units are installed on the intermediate panel. The IP is provided with a mirror cube too, and measurements of this first configuration will be referred to this one. IP is placed in turn on the **Integration Stand** (IS), an MGSE that allows to overturn the panel with different orientations. The position of the IS is a crucial detail in the set-up building, and it shall be chosen to facilitate the alignment measurements.

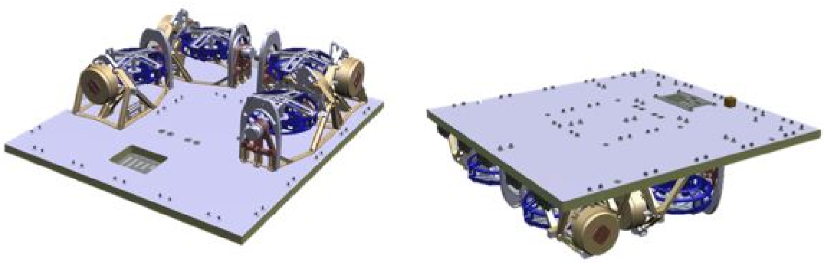


Figure 3.12: Mini-CMG on IP and IP mirror cube.

2. **Alignment On Satellite**. The IP with the mini-CMG AU installed is integrated at S/C and this alignment is performed before the shipping to the other integration facility in the configuration shown in Figure 3.13. The MGSE used for this configuration will be the Vertical Stand (VS).

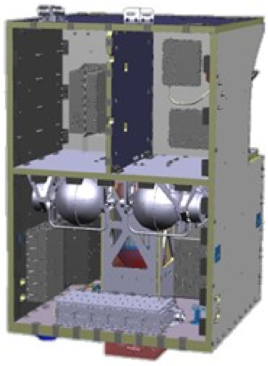


Figure 3.13: Intermediate Panel integrated on S/C.

Figure 3.14: Integration Stand (left) and Vertical Stand (right).

Multi-head Star Trackers. MH-STT are accomodated on the P/F top plate and each unit is provided with a mirror cube, properly located at the base of each sensor. Aligment requirements are contained in Table 3.4.

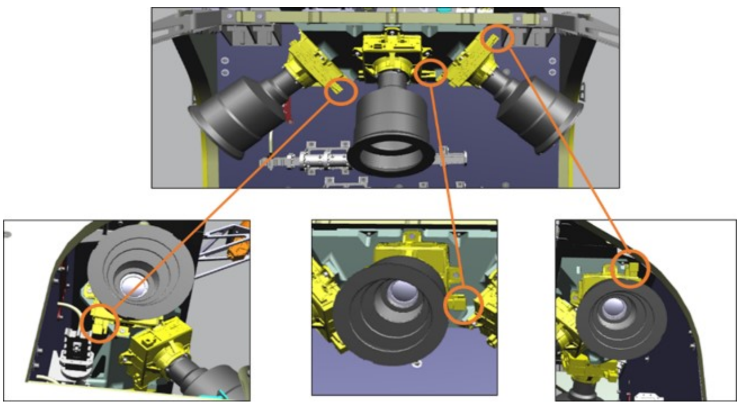


Figure 3.15: Mirror cubes on STTs.

Title	Requirement
Alignment accuracy	*The Star Tracker sensors shall be mounted with an alignment accuracy of* $0,1$ *deg (3 axis) with respect to nominal axis.*
Configuration	*3 Star Tracker Heads shall be accommodated on Satellite in accordance with following transformation matrices (TBC)* $\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{STT1} = \begin{bmatrix} -0.627912 & -0.044475 & -0.777013 \\ -0.070654 & 0.997501 & 9.454 \cdot 10^{-7} \\ 0.775071 & 0.0549 & -0.629485 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{MRF}$ $\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{STT2} = \begin{bmatrix} -1 & 0.000053 & 0.000049 \\ 0.000072 & 0.733538 & 0.679648 \\ 0 & 0.679648 & -0.733538 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{MRF}$ $\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{STT3} = \begin{bmatrix} -0.627846 & 0.044471 & 0.777066 \\ 0.070655 & 0.997501 & 0.000001 \\ -0.775124 & 0.054904 & -0.629419 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{MRF}$

Table 3.4: MH-STT Alignment Requirements.

Units must be accommodated on the S/C according three transformation matrices, that refer to the orientation of the Star Tracker nominal axis with respect to the MRF. The MH-STT will be measured **four times** during the PFM alignment campaign.

1. **Pre-shipment.** This first measurement is performed after the units integration at P/F and before the shipment to the TAS-I facility. The P/F is configured as shown in Figure 3.16 and the MGSE of this configuration is the Vertical stand.

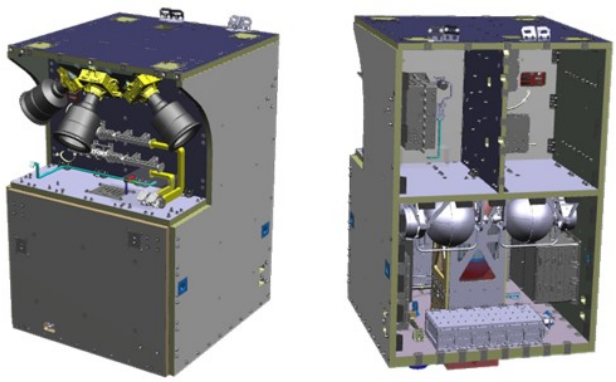


Figure 3.16: P/F configuration in Pre-shipment.

2. **Pre-TVAC.** The second measurement is made after the shipping to TAS-I and before the Thermal Vacuum test. The P/F is configured as shown in Figure 3.17.[1] The Satellite is placed on the **Tilting Trolley** (TT), an MGSE that allow to place the satellite in horizontal and vertical position and to rotate on the Z axis.

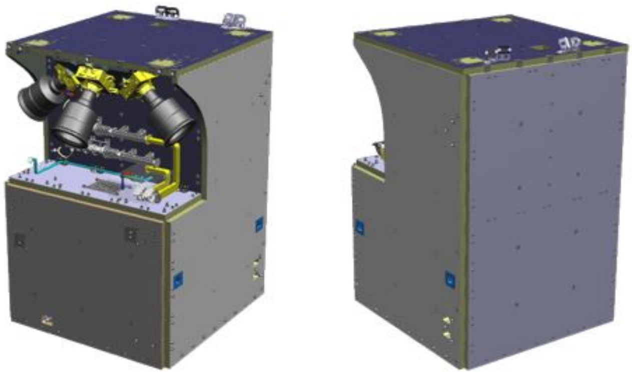


Figure 3.17: P/F configuration in Pre-TVAC.

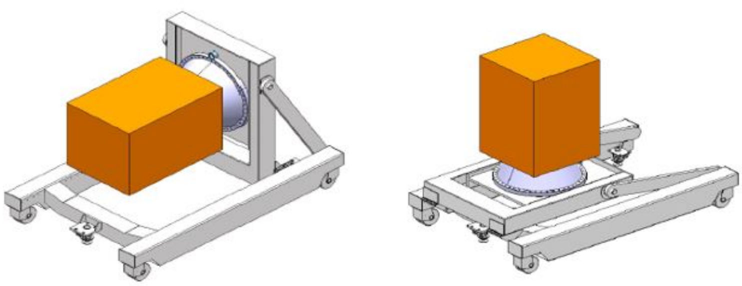


Figure 3.18: Tilting Trolley representation.

3. **Pre/Post Vibrations.** The third measurement is made after the installation of SAR antenna and SAW, and before the vibration test campaign. The last measurement is made after the vibration test campaign to verify the alignment stability. The P/F configuration is represented in Figure 3.19.

[1] In Pre-Shipment configuration, STT aligment is performed right before the access panel installation (Y- panel). In Pre-TVAC configuration (in TAS-I facility), the access panel is opened for the PLE (Payload Equipment) installation, and subsequently closed before the TVAC.

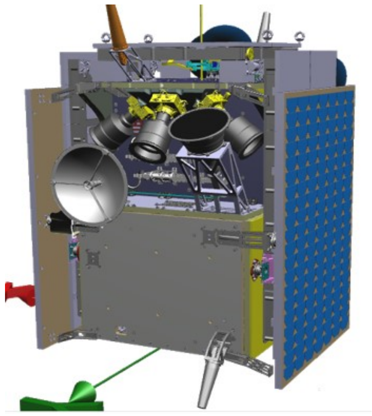


Figure 3.19: P/F in final configuration.

X-Band Passive Antenna. Since this unit is installed right after the TVAC, it will be measured **twice** during the PFM campaign: the first alignment measurement is made directly before the vibration test, the second measurement is made after the vibration to verify the alignment stability. For this reason, a single configuration is detected for the P/F, that is **Pre/Post Vibrations**, as in Figure 3.19, with the auxiliary TT.
The aligment requirements assigned on XBA are described in the Table 3.5. At the current time, **no mirror cube is predicted for XBA**.

Title	**Requirement**
XBPA Horn configuration	*X band passive horn antenna shall be accommodated with RF axis tilted by 30° from SC Z mech axis (rotation around SC X mech axis).*
XBPA Alignment accuracy	*The X band Passive Antenna shall be aligned with an accuracy of* $0,02\,deg$.

Table 3.5: XBPA Alignment Requirements.

Alignment concerning the X Band Antenna foresees that it must be accommodated on the S/C with axis tilted of 30° with respect to the Z_{SC} of the satellite. This alignment requires an accuracy of 0.02°.

Thruster Units. The alignment requirement concerning the TUs is applied to the thrust vector, that is required to pass through the Satellite CoG (Table 3.6). The alignment measurements on TU are the same of that will be performed on STT. In fact, thrusters will be measured **four** times during the PFM campaign:

1. **Pre Shipment.** The first measurement is made after the integration of EP-Box at P/F and prior the shipping to TAS-I. P/F is in configuration shown in Figure 3.16.

2. **Pre-TVAC**. The second measurement is made before the TVAC in TAS-I. P/F is in configuration shown in Figure 3.17.

Title	Requirement
Thrusters alignment accuracy	*The Thrusters shall be aligned with a tolerance of 0,1 deg half cone with respect to nominal axis.*
Thrusters configuration	The thrusters shall be accommodated on the bottom face (-Z) with the thrust vector passing through PLT-1 CoG defined as Follows: CoG average (BOL;EOL) : $[4.36 - 25.04672.86]$ mm, considering thruster reference frame with origin located at the following coordinates: $(TUN)\,Origin : [58; 38; -10]$ $(TUR)\,Origin : [-58; -78; -10]$

Table 3.6: XBPA Alignment Requirements.

3. **Pre/Post Vibrations**. The third measurement is made after the mass properties measurement and before the vibration test campaign. The last measurement is made after the vibration test campaign to verify the alignment stability. P/F is in configuration shown in Figure 3.19.

At the current time, **no mirror cube is predicted for the thruster unit**. Thrusters alignment is not faced in this work.

Structure Verification. During the alignment campaign, the structure deformations near to sensible units (MCMG AU, STT, SAR) shall be verified **after the environmental** test campaign. For this reason, further reference cubes are predicted on intermediate plate , top plate and MH-STT support. This last one would be useful in case the MH-STT measurement turns out to be particularly complicated and a further reference frame would be needed.

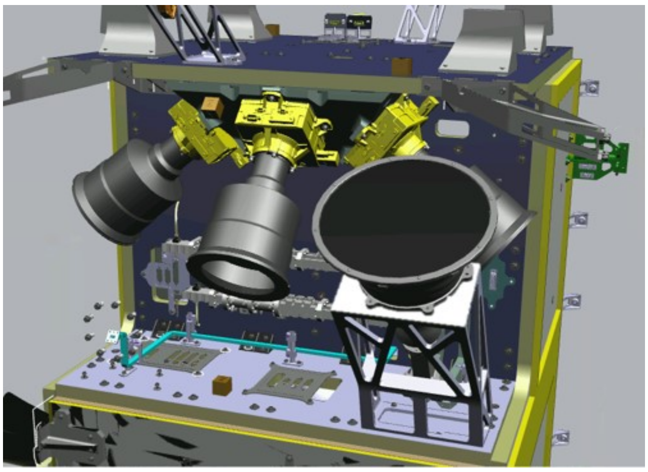


Figure 3.20: Aligning cubes on structure.

3.2.3 SM: Provisions and Configurations

Although only a few alignments were planned to be executed on the Structural Model (see Table 3.1), the current trend is to **perform on SM the same alignments measurements foreseen for PFM**.
Basically, the Structural Model has the aim to validate the structure and the design, to verify the compatibility with the MGSE and, above all, to test the interfaces for checking their stability. In fact, the SM will be embarked with the **dummy masses**, that will be representative of each unit in terms of mass, CoG and interface. Integration and testing on the SM shall highlight critical components configurations, and they will be needed to forecast the best sequence to implement on PFM.
Alignment measurements follow the same baseline. Performing on the SM the entire campaign foreseen for PFM will be needed to:

- check the visibility and accessibility of each unit;
- get some expertise in the utilisation of the chosen instrument(s);
- validate the measurement method and set-up.

It must be noticed that **mirror cubes are not expected to be mounted on dummies**. Cubes utilisation will be evaluated by the AIT team in case the chosen measurement method requires their installation.

Chapter 4

Available Technology

Since the alignments to be carried out are based on the measurement of angular quantities, **theodolites** and **laser trackers** are currently the two most appropriate tools for this campaign. Theodolites have always been used in metrology, they are reliable and characterized by remarkable accuracy. Laser trackers perform better in distance measurement (for this reason they are mostly used for large-scale applications), but after the development of some models with encoders integration it is also possible to use them for the measurement of angles. Furthermore, the team was asked to evaluate another laser-based instrument, **Leica 3D Disto**, a tool that was already present on site, for understading if it could be suitable to the required applications.
The relevant characteristics of these instruments are described in the current chapter, together with some of the crucial features that need to be taken in consideration in view of a measurement set-up.

4.1 Theodolite

Theodolite is an optical telescope tool for measuring **azimuth** angles (i.e. contained in a horizontal plane) and **elevations** (i.e. contained in a vertical plane) and they are particularly suitable for high precision angular measurements.

Figure 4.1: Theodolite representation.

It consists essentially of a base, a telescope and a horizontal and a vertical graduated circle [13]. The base is equipped with a level and screws to adjust the verticality of the main axis of the instrument. The conditions under which theodolite is said to be rectified are:

1. two-to-two orthogonal axes;
2. intersecting at a single point, called an instrumental center.

In addition, before carrying out the measurements, it is necessary to center the bubble of the level, that is, to ensure that the central tangent of the level is parallel to the support line. This allows to obtain the necessary precision in measurements (Figure 4.2).

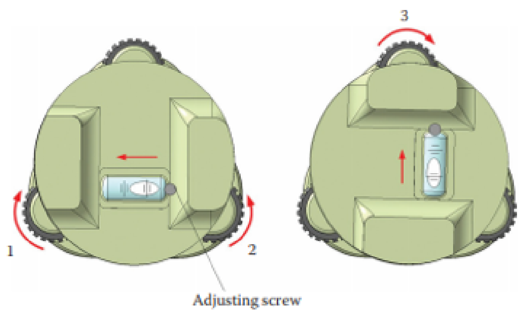


Figure 4.2: Theodolite level bubble.

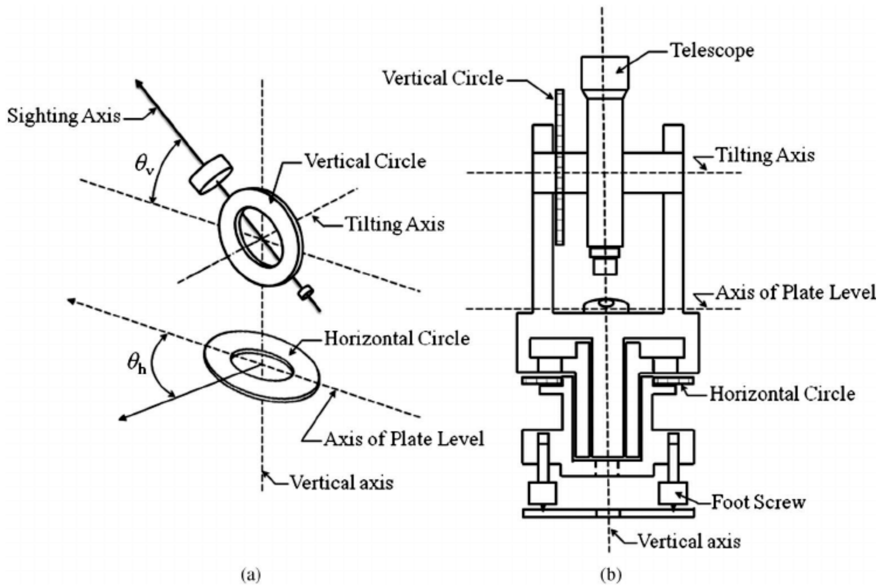


Figure 4.3: Theodolite main axes.

To measure the azimuth angles with the theodolite, the first reading must be carried out with the vertical circle on the left (*first position of use*) and the second with vertical circle on the right (*second position of use*). This results in the two conjugate readings. To obtain the correct reading (that is, free from errors of eccentricity and horizontality and orthogonality) the average of conjugate readings is calculated (**Bessel rule**).

4.1.1 Systematic errors occurring in theodolite

Systematic errors concern imperfections in the instrument or set-up construction [14]. These errors are usually persistent and afflict the entire measurement.
In the case of theodolites, a first group of errors is due to **imperfections in axes positions**, typically occurring when the set-up is built and the instrument is placed and regulated. The main axes in a theodolite are the following and they are showed in figure 4.3:

1. **Plate Level Axis**;
2. **Vertical Axis**;
3. **Tilting Axis**;
4. **Sighting Axis**.

If these axes are ideally perpendicular to each other, it means the instrument is ideally free from systematic errors.

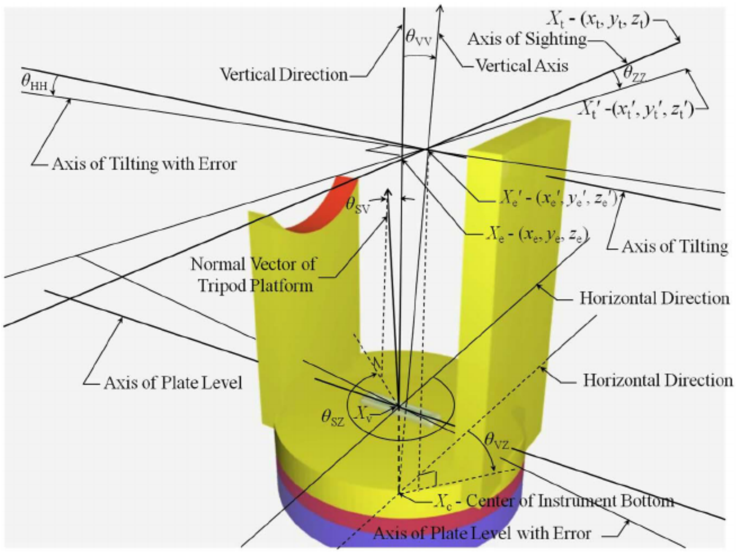


Figure 4.4: Theodolite axes displacements.

Another category of errors includes those occurring in the **reading system**. These are typically:

1. **Vertical Circle Index Error**;
2. **Eccentricity of the circles**.

In electronic theodolites, these errors can be adjusted automatically.

Tripod Centring and Levelling Errors. The first phase of setup preparation consists in placing the tripod (Figure 4.5):

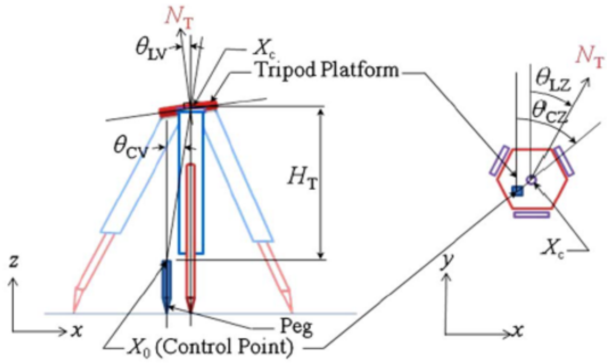


Figure 4.5: Tripod placement errors.

The tripod is ideally thought to be in the position represented by the point X_0, and furthermore its plate (represented by the normal vector N_t) shall be perpendicular to the vertical direction. In this situation the tripod shall be perfectly centered and levelled. Differently, two angular displacements can be checked:

$$\theta_C = (\theta_{CV}, \theta_{CZ})$$

$$\theta_L = (\theta_{LV}, \theta_{LZ})$$

where θ_V and θ_Z represents the angular components in the xz and xy plane respectively. These can be found taking into account that the normal vector N_T has two different-from-zero components if it is not perfectly vertical.

Vertical Axis Error. After placed the tripod, the instrument must be placed on it and here levelled. By regulating foot screws, it is possible to adjust vertical axis (Figure 4.6). If it is not made correctly, the displacement θ_V can occur with its two components in yz and xy plane. Again, the vector N_V (defined from the instrument bottom) is not perfectly vertical:

$$\theta_V = (\theta_{VV}, \theta_{VZ})$$

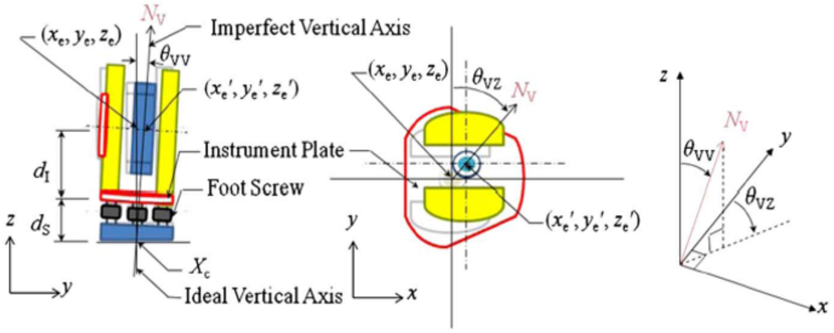


Figure 4.6: Vertical Axis error.

Plate Level Error. Theodolite plate level whose normal is N_S is regulated with foot screws to guarantee it is parallel to the ground (Figure 4.7):

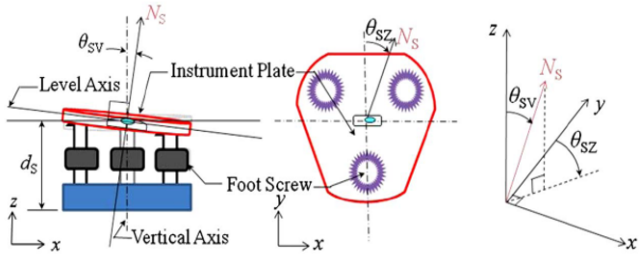


Figure 4.7: Plate level error.

The displacement that can be found in case of misalignment is θ_S:

$$\theta_S = (\theta_{SV}, \theta_{SZ})$$

After placed the instrument, operator can make two others type of error while pointing the target, due to imperfections in instrument construction:

Imperfect Tilting Axis. Tiltig axis is intended the direction orthogonal to the vertical circle. In case of bad construction (Figure 4.8), it may have a deviation from the horizontal in the yz plane and also in the xy plane:

$$\theta_H = (\theta_{HV}, \theta_{HZ})$$

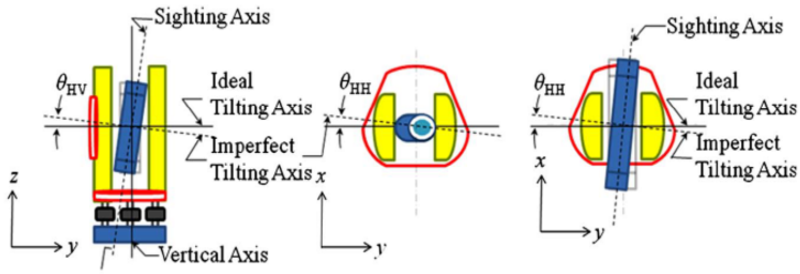


Figure 4.8: Tilting axis error.

Imperfect Sighting Axis. Sighting axis is intended the instrument pointing axis. In case of bad construction (Figure 4.9), it may show a deviation from the vertical in the yz plane. In this case it is a residual displacement in pointing:

$$\theta_{point} = (\theta_{ZZ}, \theta_{ZZ})$$

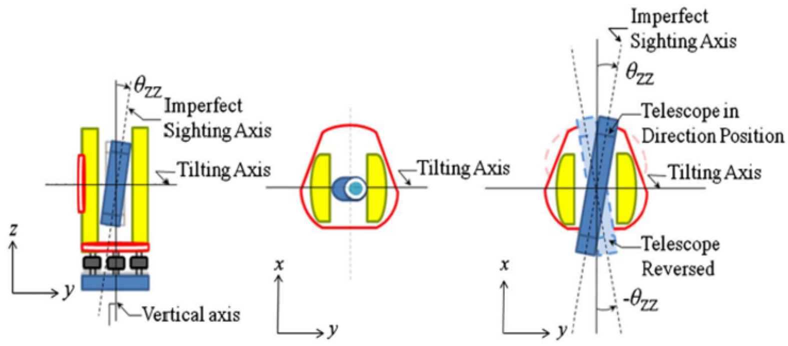


Figure 4.9: Sighting axis error.

All these angular displacements (i.e. angular components) afflict the value of the horizontal and vertical angle read by the theodolite (azimuth and elevation respectively).

4.1.2 Application in an Optical Measurement Set-up

An optical measurement set-up with theodolites typically involves two or more instruments, and the overall accuracy of the system increases with the number of theodolites used. This is the most frequent and reliable method adopted to determine the relative alignment between various components on a test object (i.e. S/C) with respect to a common coordinate system.
Generally, the optical axis of each component is previously related to an external optical reference surface, such as a mirror or an **optical reference cube**, mounted rigidly to the component. The position in the 3D space of the mirror

cube is defined when it is possible pointing **at least two of its faces** and two theodolites are needed to do that.

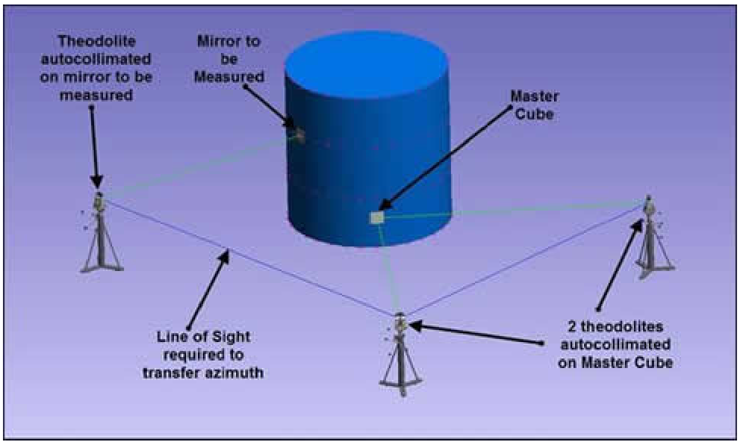


Figure 4.10: Example of Measurement Set-up with three theodolites.

The working principle of the theodolite in this set-up is the **autocollimation**, that occurs when collimated light emanating from the theodolite is returned along the same path after its reflection from the reflective surface (mirror or cube face). **By pointing one of the cube faces, theodolite can measure azimuth and elevation angles of that face**. A level of skill is required by theodolite operators to gain line-of-sight and to autocollimate on various reflective surfaces at various heights and angles that may be required to measure all required cube faces of components on a given test object.
Theodolites are so located around the spacecraft in a manor to achieve good visibility for each aligning sensor [15]. Each theodolite in the system must be critically leveled before a measurement can be made and every measurement must be referenced to the **primary** theodolite, which acts as the facility or laboratory azimuth reference for all measurements in the system.[1] **Primary theodolite should not be moved from its position**, since it represents the main reference system during the measurement (pointing the Master Cube on the item). The theodolite from which light is actually autocollimated on a cube face is called the **subject** theodolite for that measurement. Often, a subject theodolite cannot be referenced directly to the primary theodolite. The go-between is another theodolite called a **secondary** theodolite (bridge configuration).

[1]While the natural reference for the theodolite vertical reading (elevation) is the gravity direction, no natural reference for the theodolite horizontal circle (azimuth) exists. That is why it is necessary to introduce another theodolite.

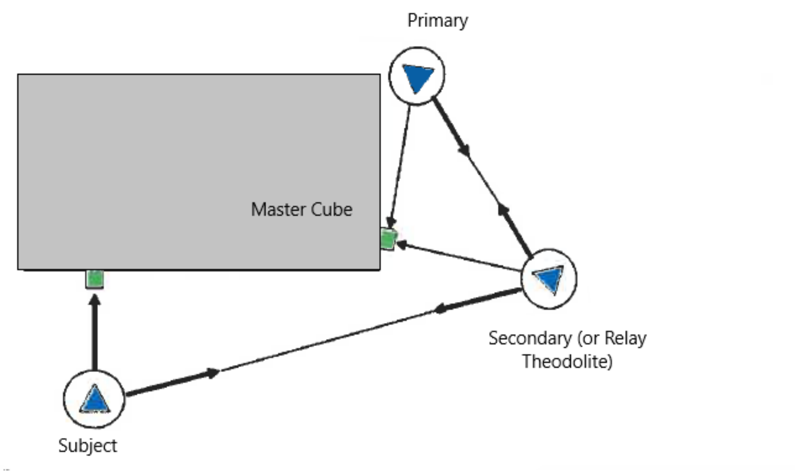


Figure 4.11: Primary, Subject and Auxiliary Theodolite.

In summary, fundamental steps of measurement of a single unit mirror cube with 3 theodolites can be summarised as follows:

1. **Primary Theodolite Placement**(i.e. centring on the tripod, levelling and calibration);
2. **Subject Theodolite Placement**;
3. **Secondary Theodolite Placement**;
4. **Subject Collimation with Mirror Cube**;
5. **Subject Reference to Secondary**;
6. **Secondary Reference to Primary**;
7. **Measurement and Computation**.

Computation represents, along with the set-up construction, the most involved phase of the entire measurement. A software can be used to triangulate the readings among the theodolites, typically coupled with Excel calculation sheets. The output of the calculation shall be the **rotational matrix** or simply the **roll**, **pitch** and **yaw** of the subject cube in the reference system of the Master. The analytic procedure implies transformations among the reference systems and director cosines calculation [16], but this is strictly related to the required application.
In case of measurement of several units, theodolites are relocated in order to ensure a good identification of the mirror cube. As said before, primary is typically not moved from its first position. In case it is, the entire setup needs to be restored and overall timing of the measurement increases significantly.

4.2 Laser Tracker

Laser trackers have become the most accurate metrology tool for use in large volume dimensional metrology and their use is widespread within several industries such as aerospace, surveying, automotive manufacture, civil engineering and large-scale engineering.

Laser trackers require a cooperative target to return the beam back to the instrument. Targets used are typically corner-cube reflectors and cat's eye reflectors. Corner-cube reflectors mounted in a hollow sphere (usually called **Spherical Mounted Retro-reflectors**, SMRs) are perhaps the most commonly used reflectors in practice.

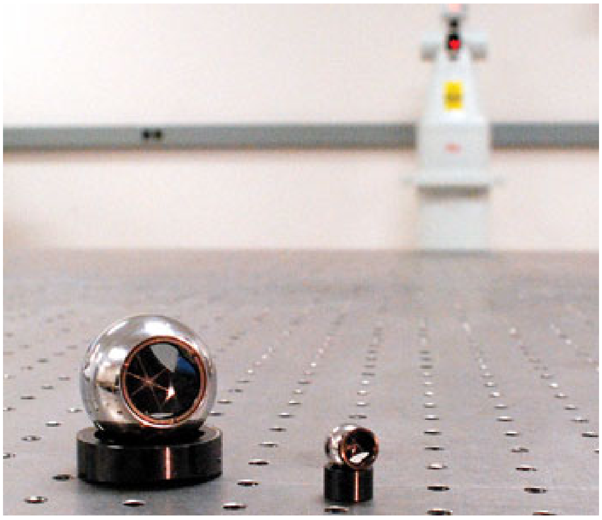


Figure 4.12: Spherical Mounted Reflectors.

Dynamic measurements are generally performed with the operator holding the SMR in his hand, *static* measurements are performed with the SMR mounted stably on a magnetic **nest** (Figure 4.12). There are also several SMR **adaptors** commercially available that allow the measurement of hole location, axis of a hole, edges, etc. A hole offset adaptor consists of a magnetic nest to hold the SMR and a shank that is inserted into a hole. The offset distance between the center of the SMR and the top surface of the hole is specified by the manufacturer. Whereas an SMR by itself might not be suitable for measurement of a hole location, adaptors allow such measurements to be performed thus extending the scope and applicability of laser tracker measurements.

A schematic of one design of a tracker is shown in Figure 4.13 [17]. The instrument has two rotation axes – a **standing axis** (vertical axis) and a **trasit axis** (horizontal axis), orthogonal to each other and that intersect at a point that is the origin for the spherical coordinate system defined by the tracker. The path of the laser beam from the instrument to the target ideally intersects this origin and it is perpendicular to the transit axis. Two angle **encoders** are mounted coaxially with the standing axis to read the horizontal angle and with the transit axis to read the vertical angle respectevely. The encoders are not shown in Fig 4.13.

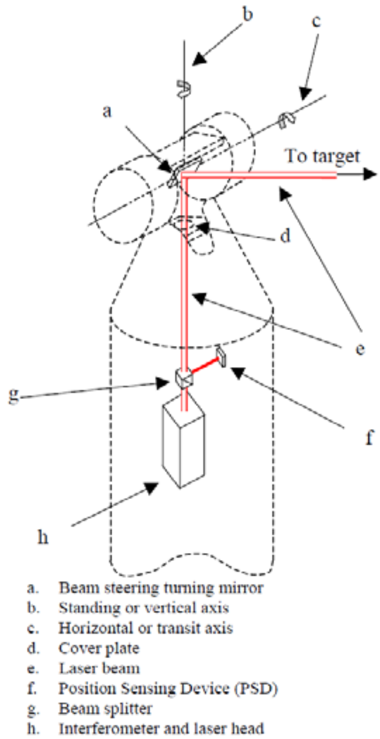


Figure 4.13: Laser tracker main axes.

Generally, laser trackers show some useful features such as:

- targets portability, that let the user move freely during the measurement, provided that laser beam is captured by the SMR and stays in its operative range;
- dynamic measurement, with data output rate of thousands of points in one second;
- very fast data processing, thanks to the support of a dedicated **software**, that allows a real time visualization of the measurement in terms of distance and angles.

Measurements are referred to the laser own reference system, and it can easily be re-located in case of low visibility of the units. Setup organization is fast and generally easy to install.
In a *direct measurement*, after identifying one or more suitable surfaces on the aligning unit, the operator shall simply move the SMR on that surface in two different ways:

1. taking a number of **discrete** points;
2. taking a points **flow**.

Operators can impose geometric constraints in the software from the measured points; in this way, the tool is able to build up planes or axes, depending on what is required by the measurement.

4.2.1 Interferometer (IFM)

Many LT models are equipped with a He-Ne laser interferometer (IFM) for measuring radial displacement. The laser beam is split into two parts, with one portion remaining within the instrument to act as the reference while the other part, known as the measurement beam, is steered to the target and is reflected back to the instrument. The measurement beam is superimposed on the reference beam, resulting in **optical interference**: it consists of bright and dark fringes corresponding to *constructive* and *destructive* interference, respectively, between the two superimposed beams. As the path traversed by the measurement beam changes by a distance corresponding to half of its wavelength ($\lambda/2$), the optical interference alternates between bright and dark fringes. Thus, by counting the number of times the fringes are alternated (and by knowing λ), the displacement of the target can be calculated.
IFM scan only measure relative displacement. In order to determine the absolute distance of the target from the center of rotation of the instrument, manufacturers provide a reference point on the body of the instrument (i.e, a *home position*) that is located at a known distance from the origin.
Accuracy of IFM largely depends on the measurement environment. It is well known that temperature, pressure, relative humidity, and composition of the air, affect refractive index and, therefore, the wavelength of light in air (temperature is the most critical).
An advantage of He-Ne IFMs is the robustness of the system, but it has the great disadvantage of **re-establishing the home position** of the target in the event of a break in the beam. For these reasons tracker manufacturers began introducing absolute distance meters (ADMs) in addition to IFMs in their systems.

4.2.2 Absolute Distance Meter (ADM)

ADM systems typically determine distance to target by modulating the amplitude, frequency, or polarization of a laser beam. Conceptually, an ADM can be constructed by sinusoidally modulating the amplitude of a laser diode beam at a precise frequency. By comparing the phase of the return beam with a portion of the beam emerging from the laser diode, the location of the retroreflector within one modulated wavelength can be determined very accurately. If the beam is interrupted, the operator doesn't need to return to a known position and "reset" the unit. He simply had to reposition the beam and continue the measurement.
Typically ADMs were noticeably less accurate than interferometers, but today ADMs have reached the same accuracy range. Moreover, some models have even integrated both ADM and IFM technology into a single unit of measurement called *Absolute Interferometer* or AIFM.

4.2.3 Systematic errors occurring in Laser Trackers

As well as for theodolites, the performance of a laser tracker is degraded by misalignments, offsets, non-linearities and eccentricities of the beam steering mechanism and of the angular encoders within the laser tracker, leading to errors in the measured coordinates [18].
As described in Section 4.2, standing axis and transit axis of the tool shall be ideally orthogonal to each other. The laser beam origin is also located at the intersection of the two axes and the initial beam direction is normal to the transit axis; moreover, the two angular encoders are mounted such that each one is coaxial with the respective rotation axis (Figure 4.14):

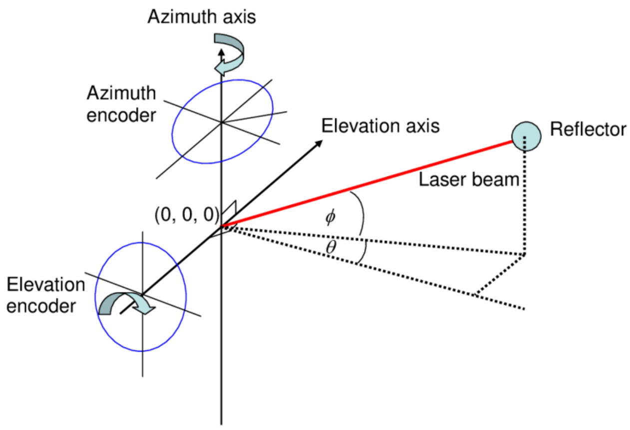


Figure 4.14: Laser tracker ideal reference system.

In a real laser tracker, a series of imperfections are present, due to manufacturing tolerances and design constraints, and these can be conceptualised as a series of error parameters which are shown in Figure 4.15:

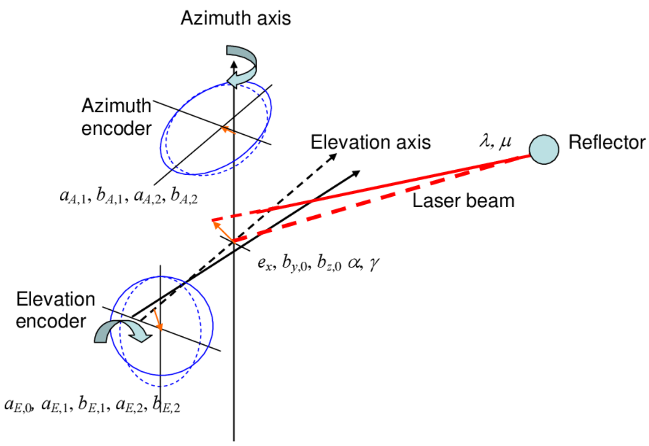


Figure 4.15: Laser tracker reference system with errors.

All the errors that appear in the picture may be classified as follows:

Gimbal axis offsets and alignment errors:

1. e_x, the elevation axis offset from azimuth axis;
2. α, the azimuth axis angle in yz plane;
3. γ, the beam axis angle in xy plane;
4. a_{E0}, the elevation angle offset.

Origin errors:

1. λ, the range offset;
2. μ, the scale factor for range;
3. b_{y0}, beam offset (y-direction) from origin;
4. b_{z0}, beam offset (z-direction) from origin.

Angular scale errors. Scale errors in the encoder are spacing errors in the gratings. In literarture, this type of error is typically decomposed into Fourier components. Hereafter a and b refers to the Laser Tracker reading error in front-face and back-face respectevely:

1. a_{A1}, b_{A1}, the azimuth scale error, first order Fourier term;
2. a_{A2}, b_{A2}, the azimuth scale error, second order Fourier term;
3. a_{E1}, b_{E1}, the elevation scale error, first order Fourier term;
4. a_{E2}, b_{E2}, the elevation scale error, second order Fourier term.

Furthermore, errors in the **target** construction shall be considered. SMRs suffer from three types of error sources:

1. **Vertex centering error**, the distance between the optical center and the mechanical center of the SMR. The centering error can be both radial and lateral with respect to the incident laser beam. Centering accuracies are as small as ±2.5 min some commercial SMRs currently available
2. **Dihedral angle error**, due to the fact that the angle between any two of the three mirror faces of the SMR is not exactly 90. These angles may differ by a few arc-seconds, resulting in the reflected beam returning in a direction that is not parallel to the incident beam.
3. **Polarization error**, in large reflectors with panels matched for polarization. If there is polarization mismatch, the interferometric pattern may not be created properly.

In order to compensate for these errors, laser tracker manufacturers provide online **correction of systematic effects using software algorithms** running on the tracker controller system. The correction software relies on a model that describes the beam steering mechanism and its errors. The parameters of the model are usually derived from a series of measurements performed either by the manufacturer (when the tracker is manufactured) or by the user (prior to each use of the instrument).

4.2.4 Application in an Optical Measurement Set-up

Althought mirror measurements employed in alignments have traditionally been performed using theodolites, several techniques involving Laser Trackers have recently been developed.
These techiques [19] take advantage from the fact that LT can measure *images* of retroreflectors from plane mirrors. It can be configured in the software to measure both the image of an SMR and the actual SMR in its true position. With the positions of these two measurements, the mirror is uniquely determined as the plane halfway between the two with its normal defined by the line connecting the two.

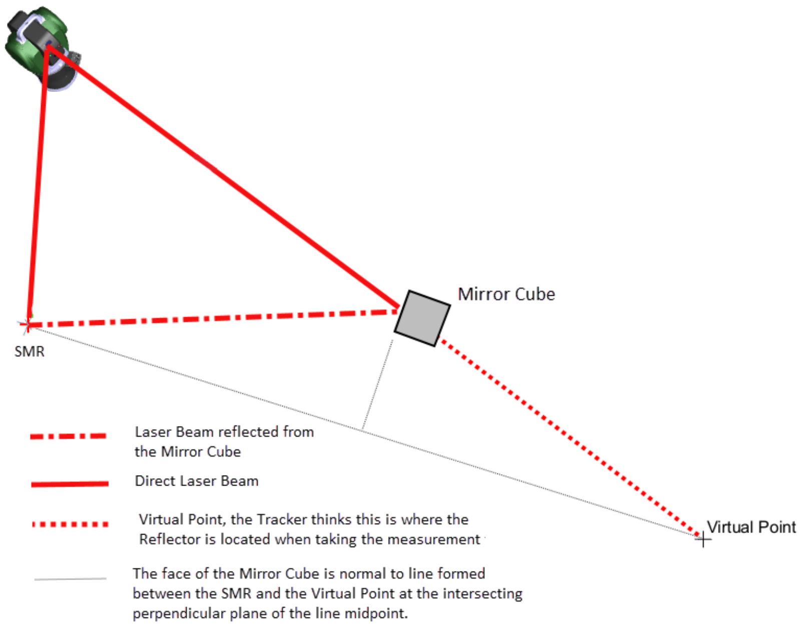


Figure 4.16: Virtual Point generation.

To measure the position of a mirror, the Laser Tracker must be set up in such a way that the laser beam can reflect off the mirror to an SMR, mounted on a stable nest or mount, that can also be measured directly by the Laser Tracker (Figure 4.16).

1. The first measurement is that of the Mirror Cube: the projected beam on the fixed SMR provides a distance measurement of a point that appears beyond the mirror, the **Virtual Point**;

2. The second measurement is a direct measurement of the SMR from the tracker (Figure 4.16);

3. In the software settings, it is possible to select a *Mirror Point Construction*, that allows to obtain the mirror position (Figure 4.17).

The set-up described can be further refined if more than one mirror are mounted on the object. Moreover, this provides a powerful application of the laser tracker for optical alignment without degrading accuracy.

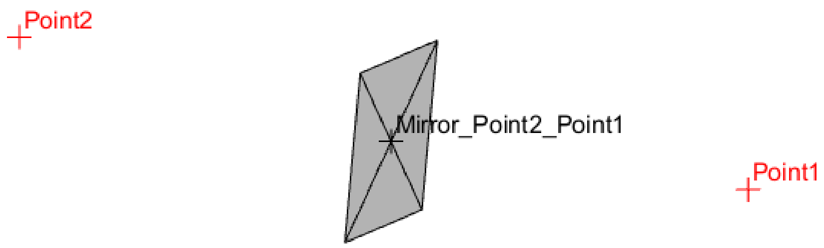


Figure 4.17: Measured points and mirror in the software.

4.3 Leica 3D Disto

The Leica 3D Disto is a three-dimensional measurement and projection system based on a laser beam, that can measure distances and angles (thanks to the integrated goniometer), mostly used on large-scale building applications. It is more similar to a total station and it results very performing as a *laser scanner* on large surfaces.

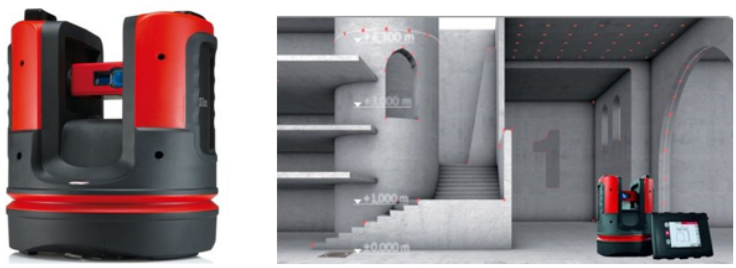


Figure 4.18: 3D Disto representation.

Differently from theodolite or laser tracker, this tool has **no heritage in optical measurements** or, more in general, in space applications, although it has interesting functions related to the using of its distance meter and goniometer for measuring angles.
A measurement with 3D Disto can be performed using different functions [20], that allow to establish a reference system as needed or to scan a surface, for example:

1. Autoleveling. When the sensor is on, measurements are automatically referred to the gravity direction and horizon plane, if the tool inclination is between 0 and 3 degrees;

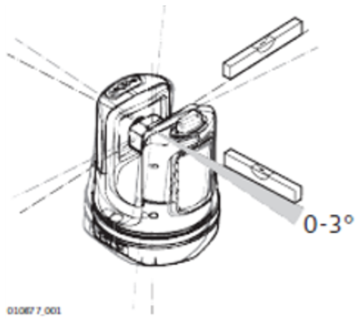


Figure 4.19: Autoleveling.

2. Scan Function. 3D Disto can build a grid of points with a certain step, and subsequently it can find a plane;

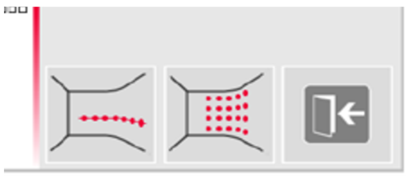


Figure 4.20: Scan Functions.

3. Safe Points. Safe points connect measurements to a coordinate system, allowing to move the tool from the initial location or continue measurements in a second moment.

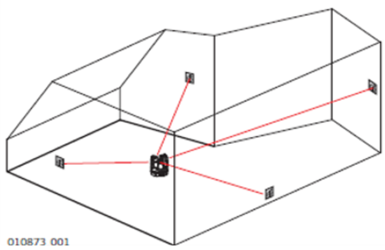


Figure 4.21: Safe Points measurements.

When a measurement is taken, the control unit allows to save data easily in a .txt and .csv format; after, they can be exported to be analysed.

To establish if the instrument is appropriate for the requested measurements and for the set-up constraints, the calculation procedure of the accuracy analysis has been conducted on 3D Disto, as well as for the two chosen models of theodolite and laser tracker respectevely, and it has been described in chapter 5. Moreover, an experimental analysis has been conducted on the tool and the related test reports will be presented in Chapter 7.

Chapter 5

Accuracy Analysis

The current chapter contains the explanation of the analytic procedure which the entire accuracy analysis is based on. Among the analysed models of theodolites and laser tackers, some have been chosen to be the object of this analysis. Since most of these models result certified according to ISO or ASME normative[1] , this procedure is mainly based on the **error propagation** influence.

5.1 Measurement Constraints

As described in Chapter 3, the alignment requirements verification is performed entirely during the SM and the PFM campaign, and they are specified for each unit in terms of placement, configuration and provisions, as well as required measurement accuracy.
In this context, two general requirements govern the entire alignment campaign, as shown in Table 5.1.

Title	**Requirement**
Alignment Measurement Accuracy	*The on-ground alignment measurement shall be performed with a measurement accuracy better than 0.005 deg half cone.*
Alignment Stability	*Alignment Stability is intended as the alignment error pre-post mechanical environment test campaign measured during SC AIT Phase. The error between the on-ground pre-vibration and the on-ground post-vibration alignment orientation shall be lower than 0.01 deg calculated on three axis or half cone for all sensors and antennas which requires alignment measurement.*

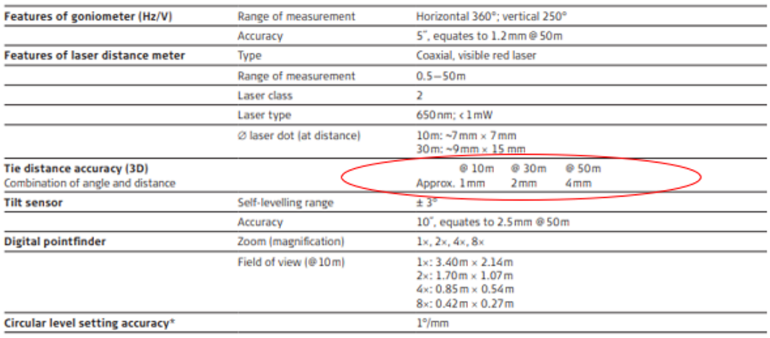
Table 5.1: General Alignment Requirements.

[1]This means that the tools have been properly tested and any criticalities occurring in the se-tup that may afflict accuracy have been already considered.

From the assigned requirements, it results that the only constraint able to orientate the choice of the instrument concerns the **accuracy** required to the instrument. Consequently, the guiding value for the subsequent accuracy analysis will be 0.005°= 18 ”.

5.2 Models

Some theodolites and laser trackers models have been taken in consideration, to have an overall idea of the available accuracies and to understand if they are suitable the requirements needs. The same analysis has been conducted on 3D Disto too, whose description has been reported in 4.3
Most of the datasheets related to theodolites directly report an **angular** accuracy value, while those of laser trackers report a **linear** accuracy value, a function of the measuring distance. Differently, 3D Disto accuracy is given with respect to different distances of the tool from the measuring object.



Features of goniometer (Hz/V)	Range of measurement	Horizontal 360°; vertical 250°
	Accuracy	5", equates to 1.2mm @ 50m
Features of laser distance meter	Type	Coaxial, visible red laser
	Range of measurement	0.5–50m
	Laser class	2
	Laser type	650nm; < 1mW
	∅ laser dot (at distance)	10m: ~7mm × 7mm 30m: ~9mm × 15mm
Tie distance accuracy (3D) Combination of angle and distance		@ 10m @ 30m @ 50m Approx. 1mm 2mm 4mm
Tilt sensor	Self-levelling range	± 3°
	Accuracy	10", equates to 2.5mm @ 50m
Digital pointfinder	Zoom (magnification)	1×, 2×, 4×, 8×
	Field of view (@ 10m)	1×: 3.40m × 2.14m 2×: 1.70m × 1.07m 4×: 0.85m × 0.54m 8×: 0.42m × 0.27m
Circular level setting accuracy*		1°/mm

Figure 5.1: 3D Disto datasheet frame.

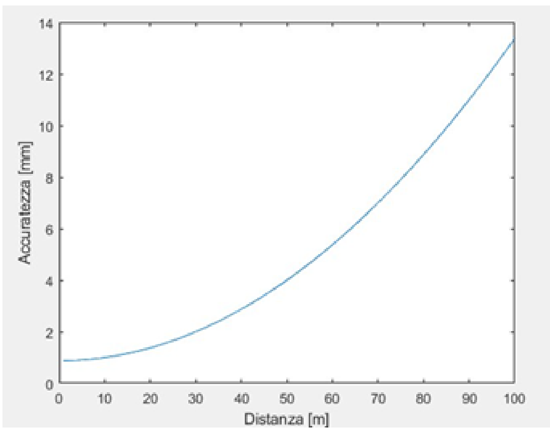


Figure 5.2: 3D Disto accuracy function.

These values have been interpolated in MatLab (with polynomial line, Figure 5.2) for obtaining accuracy evolution with respect to distance. Assuming a mean working distance[2] of $2.5\,m$, it is possible to find the value that will be assumed in the current discussion.
A summary of the encoutered values has been reported in Table 5.2 and 5.3. From this point on, Laser trackers and 3D Disto will be classified as *laser-based systems.*

Model	**Angular Accuracy** ["]
Leica TM6100A [21]	0.5
Sokkia DT 40-Series [22]	2 - 9
South NT023 [23]	2
Nikon NE102, NE103 [24]	5

Table 5.2: Theodolites Models.

Model	**Linear Accuracy** [μm]
Hexagon (AT403, AT960) [25]	$15 + 6/m$ (MPE)
FARO (S,E,S6,E6) [26]	$20 + 5/m$ (MPE)
3D Disto	882.8

Table 5.3: Laser-based systems models.

Since theodolites accuracy is already an angular value, the discussion about error propagation results particulary intuitive, and it can be easily applied to **all the models** of Table 5.2. Differently, for laser-based systems real angular value needs to be obtained by calculation. The procedure is more complex and will be explained in Section 5.3.2.
The analysed model for laser trackers will be **Hexagon AT430**. It has seen applications in very different measurement environments and it has a heritage in space applications. Its measurement volume is about 320 metres and it is compatible with a wide range of tools and accessories, such as SMRs or the Leica B - Probe (Figure 5.3).

5.3 Error Propagation

In this section, the error propagation into an established and hypothetical set-up measurement will be explained. Precisely, according to what is often required by an alignment measurement, the object of the subsequent calculation will be the **angle between two surfaces.**[3]

[2]The working distance is equal to the length of the laser.
[3]That is intended as the angle between the two respective normal vectors.

Figure 5.3: Hexagon AT403.

5.3.1 Measurement with Theodolites

A set-up with two theodolites is studied, considering two cubes with different orientations in the 3D space as shown in Figure 5.4. In fact, this situation can be enough representative of one of the alignment measurements that need to be conducted during the campaign, such us on XBA.

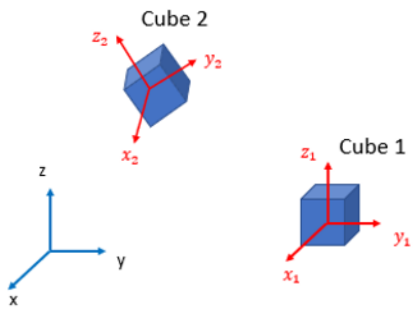


Figure 5.4: Cubes in the 3D space.

Typically, the relative position between the two cubes will be defined by a **rotational matrix** that results from the combination of three elementary rotations of the first reference system (rotation around x, around y and around z in sequence). The aim of this calculation is to understand which angular informations can be obtained while each theodolite is poiting one face of the respective cube to build up a rotational matrix.
As described in 4.1, theodolites measure two angles: an *elevation* in the **vertical** plane xz (or yz) and an *azimuth* in the **horizontal** plane xy.
The subsequent assumptions have been made:

1. Theodolite T_1 is pointing the yz face of cube 1. It represents the **primary theodolite**, and so the azimuth reference. Elevation e_1 will be directly read;

2. Theodolite T_2 is pointing the yz face of cube 2. It represents the **subject theodolite**. Elevation e_2 will be directly read, while azimuth will be

referred to the primary in autocollimation.

The following highlighted angles can be obtained:

- Rotation around y axis (R_y), studying elevation plane (Figure 5.5);
- Rotation around z axis (R_z), studying horizontal plane (Figure 5.6).

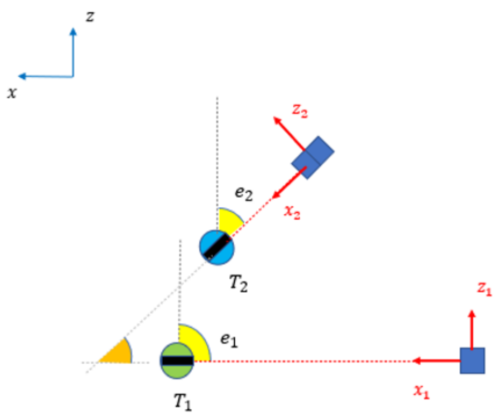


Figure 5.5: Elevation plane.

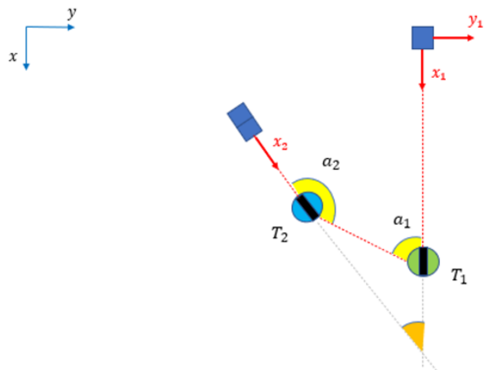


Figure 5.6: Azimuth Plane.

Considering that theodolites point being perpendicular to cube faces, the following geometric relations can be written:

$$R_y = e_1 - e_2;$$

$$R_z = a_1 + a_2 - 180.$$

Both theodolites T_1 and T_2 measure with angular uncertainties, u_1 and u_2 ; that means that by applying error propagation, the two previous relations can be written as:

$$R_y = (e_1 \pm u_1) - (e_2 \pm u_2) = (e_1 - e_2) \pm (u_1 + u_2);$$

$$R_z = (a_1 \pm u_1) + (a_2 \pm u_2) - 180 = (a_1 + a_2 - 180) \pm (u_1 + u_2).$$

In this way the total propagated error u_{tot} that afflicts the measurements is highlighted. Assuming to work with two theodolites of the same type, $u_1 = u_2 = u$:

$$u_{tot} = 2u.$$

After these considerations, it is possible to apply this accuracy analysis to the models described in Table 5.2. The results are described in section 5.4.(TBC)

5.3.2 Measurement with Laser-based systems

The same set-up shown in Figure 5.4 is considered. The measurement approach this time consists in the following steps:

1. The instrument is properly located and prepared for the measurement;
2. Operator touches two orthogonal faces of cube 1, taking a certain number of points upon each one with the SMR;
3. Operator touches two orthogonal faces of cube 2, taking a certain number of points upon each one with the SMR;
4. The software builds the measured surfaces and the respective three-axes reference system on each cube, giving as output a *rotational matrix*.

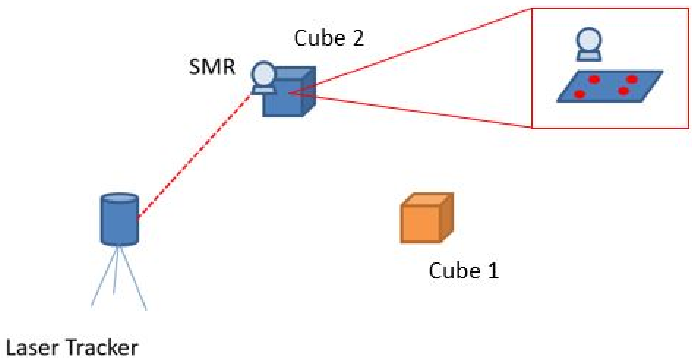


Figure 5.7: Measurement with Laser Tracker. Detail of SMR on surface.

Hexagon Laser Trackers are supported by the **Spatial Analyzer** software, that allows a real-time visualization of the measurement in terms of distance and angles (*dynamic measurement* in polar coordinates). At the end of the test, data can be saved in a .txt or .csv format when the measurement is completed.

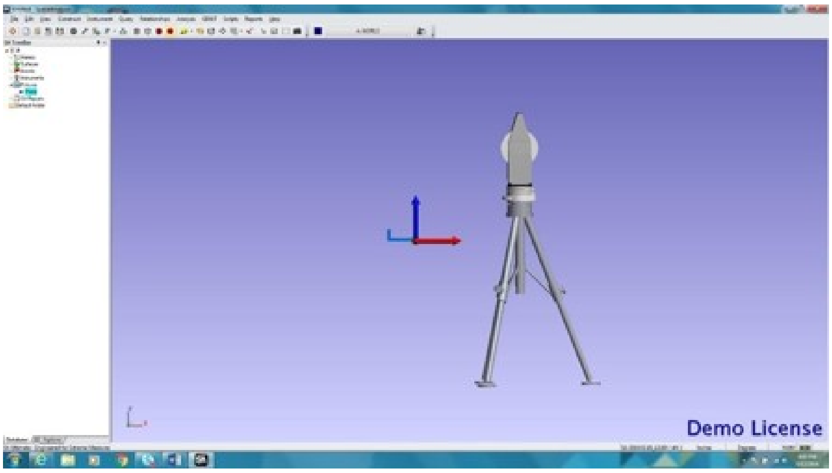


Figure 5.8: Spatial Analyzer environment.

Analyzed models of which in Section 5.2 show a *linear* value of accuracy (i.e. an accuracy referred to a distance measurement) and the calculation procedure that allows to obtain an angular accuracy value is exposed, starting from a geometric interpretation of the distance error. The essential steps followed in this procedure are the followings:

1. Starting from a theoretical point in a given reference system, **the error on its distance becomes an uncertainty on the linear coordinates of the point** x, y and z;
2. The error on coordinates is propagated on n theoretical points that define a plane;
3. Calculation of the interpolating plane of points with error (**error plane**);
4. **Calculation of the angle** between theoretical plane and plane with error.

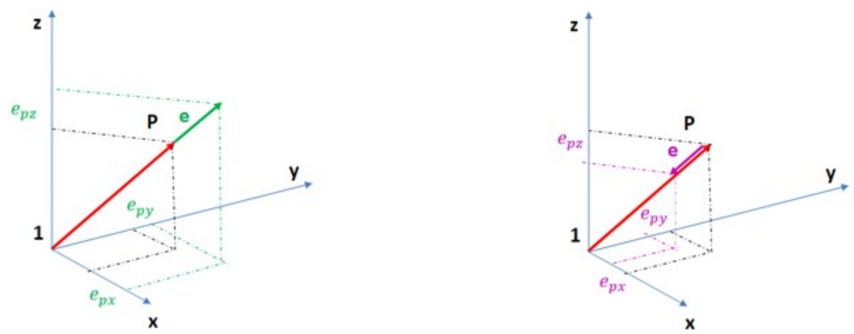


Figure 5.9: Geometric interpretation of error.

The distance error is interpreted as a segment e in the 3D space, and its value is known from datasheet. By using trigonometric formulas, the projected error along the axes, i.e. the error on the linear coordinates x, y and z can be calculated (Figure 5.10):

$$e_{Pxy} = e\cos\alpha$$
$$e_{Pz} = e\sin\alpha$$
$$e_{Px} = e_{Pxy}\sin\beta$$
$$e_{Py} = e_{Pxy}\cos\beta$$

where angles α and β are calculated by knowing the point coordinates. In this way error on coordinates is expressed as a $1x3$ vector:

$$e_p = \begin{pmatrix} e_{Px} & e_{Py} & e_{Pz} \end{pmatrix}$$

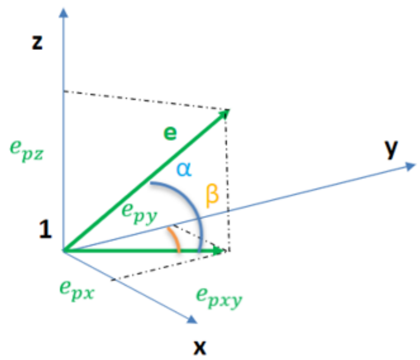


Figure 5.10: Calculation of uncertainty along axes.

These considerations are iterated for n theoretical points, defining an **Error Matrix**:

$$E = \begin{bmatrix} e_{1x} & e_{1y} & e_{1z} \\ e_{2x} & e_{2y} & e_{2z} \\ & \vdots & \\ e_{nx} & e_{ny} & e_{nz} \end{bmatrix} \tag{5.1}$$

In turn, these n theoretical points belong to a chosen **theoretical plane**[4] , whose equation is known:

$$ax + by + cx + d = 0$$

and its normal vector is calculated as follows:

$$n_0 = \begin{pmatrix} n_{0x} & n_{0y} & n_{0z} \end{pmatrix} = \begin{cases} n_{0x} = -a/d \\ n_{0y} = -b/d \\ n_{0z} = -c/d \end{cases}$$

[4]In this context the theoretical plane has always been considered as an *horizontal* plane, with normal vector $n = (0; 0; 1)$.

Subsequently, the n points will be calculated *with error*[5] and this procedure will be detailed in the next paragraph. In this way it is possible to determine the interpolating plane (**error plane**) by solving an oversized array equation in a $[A]\{x\} = \{y\}$ form, where:

- $[A]$ is a $n \times 3$ matrix containing the points coordinates;
- $\{x\}$ is a 3×1 matrix returning the plane normal vector, so $\{x\} = \{n_e\}$;
- $\{y\} = \{1, 1, .., 1\}$ n-dimensional.

Among different resolution methods, the following equation allows to obtain the solution that **minimizes the interpolating error**:

$$\{x\} = (A_T A)^{-1}(A_T\, y).$$

In conclusion, the angle between the two planes is the angle between the two normal vectors, i.e.:

$$\alpha = \frac{\{x\} \cdot \{n_0\}}{||\{x\}|| \cdot ||\{n_0\}||}. \tag{5.2}$$

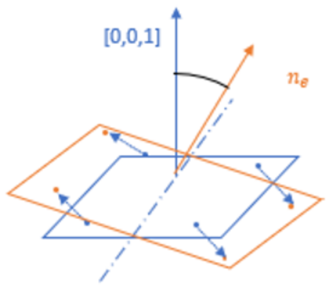


Figure 5.11: Angle between theoretical and with-error plane, $n = 4$.

Error Distributions. Considering that error con manifest as "more" or "less" on a measure, **different error planes exist for a single theoretical plane**. The number of the possible ways in which error matrix expressed by Equation 5.1 can distribute clearly depends on the number of points n defining the theoretical plane. In combinatorics, this number is that of **dispositions with repetitions**, equal to 2^n.

[5]There is not a single way in which error matrix can afflict the theoretical plane. Error can occur as maximum or minimum so it can distribute differently on points. Possible error distributions have been discussed in the subsequent paragraph.

Figure 5.12: Possible way of error distribution on plane defined by 9 points. Error sign on a single point e_i means that all the coordinates e_{ix}, e_{iy} and e_{iz} have the same sign.

2^n error planes mean 2^n angles calculated. For having an overall idea of the entity of the error, the **error media**, the **standard deviation**, the **maximum** and the **minimum** error have been determined among the 2^n angles. Furthermore, the **surface area** and the **number of points** influence have been investigated, so the calculation has been conducted by varying these parameters. The results will be illustrated in Section 5.4.

Numerical Procedure. The numerical procedure has been developed in MatLab and Octave, with the support of Excel calculation sheets.
The main steps of this procedure are explained considering n theoretical points:

- **Importing Data**:
  1. a matrix D with the dispositions built up in Excel. This matrix is $2^n \times n$ and it will be needed in the matrix error calculation E. D is copied in a .txt file for being imported;
  2. a matrix Q loaded by a .txt file, that is the matrix with the theoretical points and it is $n \times 3$ dimensional;
- **Input of the calculation**:
  1. Measuring distance;
  2. Instrument accuracy;
  3. *Origin error*: it is a vector with the origin coordinate error. This must been considered because in the Disto reference system the origin is the first measured point, typically called point 1. Any other points will be measured in the reference system thus defined. That means that each measured point will be affected by the Reference System uncertainty, i.e. by point 1 position[6] . For Laser Trackers, origin error is considered equal to zero.

[6]This value has been obtained after experimental measurements with Disto. Further details are contained in the Annex.

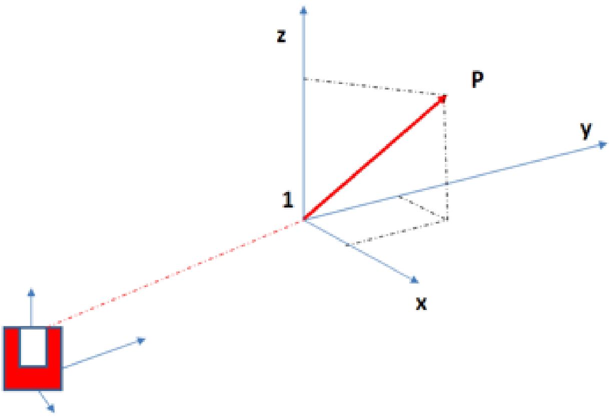


Figure 5.13: Disto Reference System Definition.

- **Calculation of Error Matrix**, with coordinates error (that is $n \times 3$);
- **Iteration**. The cycle calculates:
  1. the new error matrix E with each line of the dispositions matrix D;
  2. the matrix of points with error Q_{err};
  3. the normal vector of the error plane x;
  4. the angle between x and the normal vector of the theoretical plane. This value is the **angular accuracy**, object of this calculation.
- **Calculation of media, standard deviation, maximum and minimum error.**

5.4 Results

5.4.1 Theodolites

As described in Section 5.3.1, error propagation in a measurement set-up with theodolites has resulted in very simple calculations. The overall uncertanties of each model have been reunited in Table 5.4, for being compared with the established target, i.e. 0.005°= 18".

Model	**Angular Accuracy** ["]	**Total Propagated Error** ["]
Leica TM6100A	0.5	**1**
Sokkia DT 40-Series	2 - 9	**4- 18**
South NT023	2	**4**
Nikon NE102, NE103	5	**10**

Table 5.4: Theodolites accuracy results.

From the table above, **each analysed model respects the on-ground accuracy requirement**.

5.4.2 Laser Tracker AT403

The analysis has been conducted considering the influence of *surface area* and *number of points*.

Effect of surface area. The following functions have been obtained for *mean error* and *standard deviation*, considering a squared surface defined by 4 points at its vertices. The side of the surface has varied from 1 cm to 80 cm. Calculations have been conducted considering **Standard Error** (half of Maximum Permissible Error, MPE).

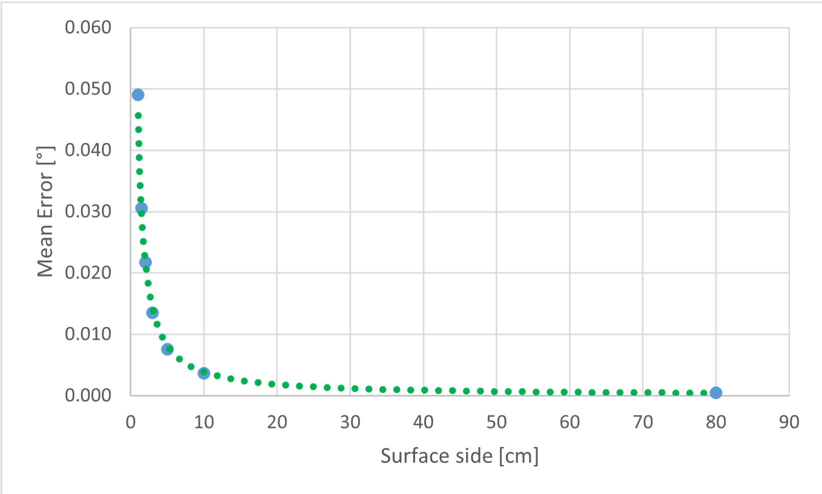


Figure 5.14: Mean Error function with side of surface, $n = 4$.

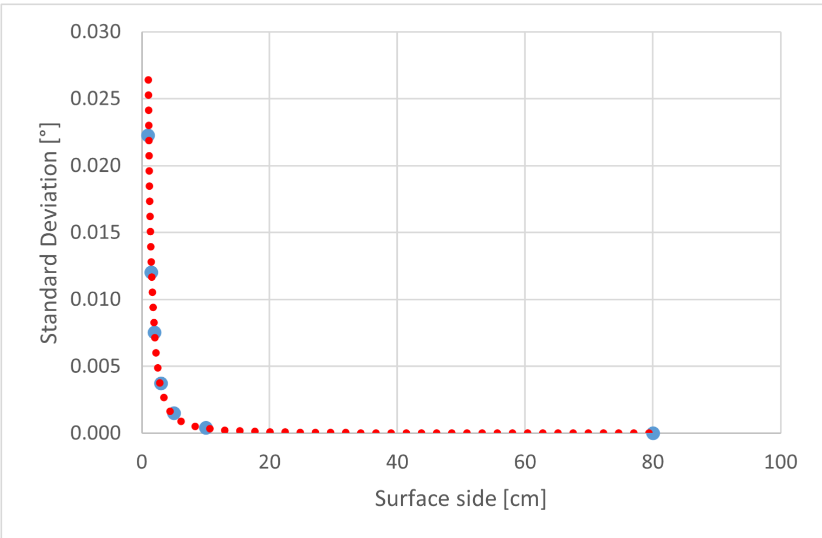


Figure 5.15: Standard Deviation function with side of surface, $n = 4$.

Effect of number of points. The following functions have been obtained for *mean error* and *standard deviation*, considering a squared surface defined by an increasing number of points (from 4 to 15). The side of the surface is 10 cm, given the impossibility of taking a large number of points on smaller surfaces. Calculations have been conducted considering **Standard Error** (half of Maximum Permissible Error, MPE).

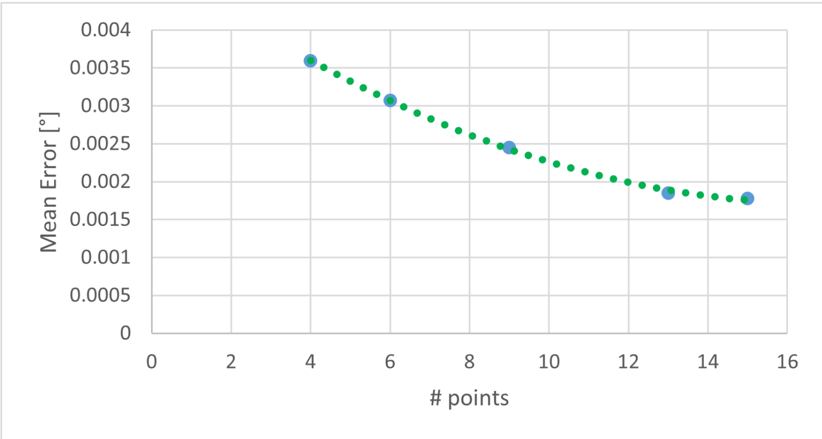


Figure 5.16: Mean Error function with number of points, $l = 10cm$.

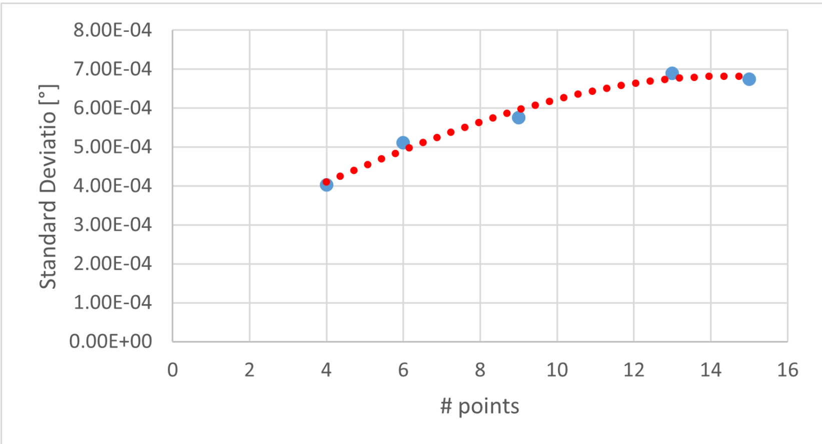


Figure 5.17: Standard Deviation function with number of points, $l = 10cm$.

It is possible to notice that the above graphics show a decreasing trend (that is, an increasing accuracy), althought the effect of increasing surface area is more consistent than increasing number of points. In particular, LT accuracy reaches acceptable values (with respect to the target) with surfaces of side about 10 cm. Differently, it results high performing on wider surfaces.

In the current context, since measurements need to be referred by requirements to the unit optical mean with respect to the MRC, surfaces that can be representative of the **dimensions of a typical mirror cube** (side $1.8 - 2.5\,cm$) have been studied and the results have been reunited in the Table 5.5 and 5.7, where two different laser distances have been considered.

Laser distance = $2.5\,m$					
$L[cm]$	n	**Media [°]**	**Standard Deviation [°]**	**Maximum Error [°]**	**Minimum Error [°]**
2	4	0.022	0.008	0.031	0.011
	9	0.017	0.007	0.032	0.003
3	4	0.013	0.004	0.018	0.008
	9	0.01	0.004	0.019	0.002

Table 5.5: Accuracy results for AT403, $d = 2.5\,m$.

Laser distance = $1.5\,m$					
$L[cm]$	n	**Media [°]**	**Standard Deviation [°]**	**Maximum Error [°]**	**Minimum Error [°]**
2	4	0.017	0.006	0.025	0.008
	9	0.013	0.006	0.026	0.002
3	4	0.011	0.003	0.014	0.007
	9	0.008	0.003	0.015	0.002

Table 5.6: Accuracy results for AT403, $d = 1.5\,m$.

A shorter laser distance allows to slightly improve the results. Nevertheless, since the aforementioned dimensions are imposed by the required measurements, **obtained accuracy values** in terms of maximum error (even with a lower laser distance) **can't satisfy the target**.

5.4.3 Leica 3D Disto

The analysis has been conducted as well as for AT403, considering the influence of surface area and number of points. The obtained functions have been represented hereafter.

Effect of surface area. The following functions have been obtained for *mean error* and *standard deviation*, considering a squared surface defined by 4 points at its vertices. The side of the surface has varied from $1\,cm$ to $80\,cm$.

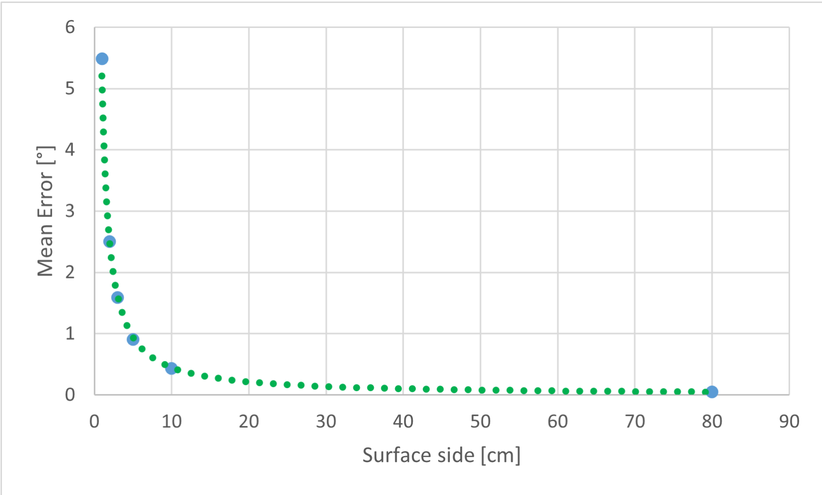


Figure 5.18: Mean Error function with side of surface, $n = 4$.

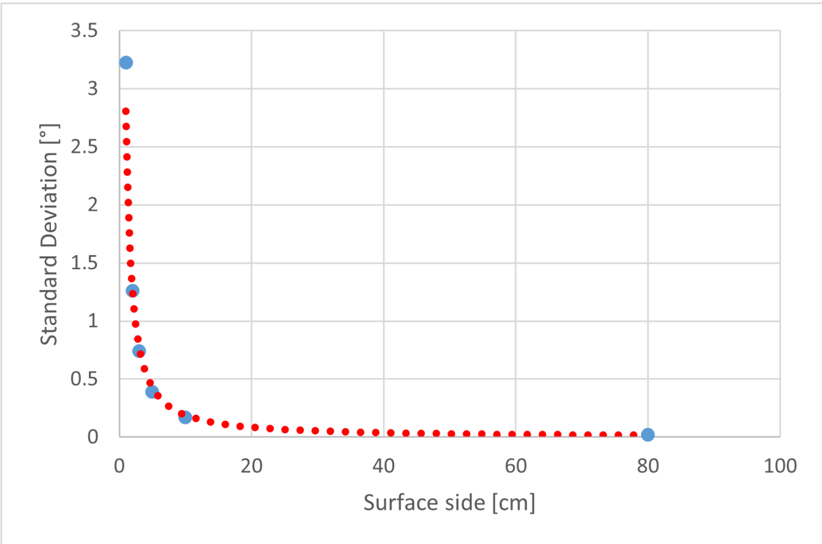


Figure 5.19: Standard Deviation function with side of surface, $n = 4$.

Effect of number of points. The following functions have been obtained for *mean error* and *standard deviation*, considering a squared surface defined by an increasing number of points (from 4 to 15). The side of the surface is $10\,cm$.

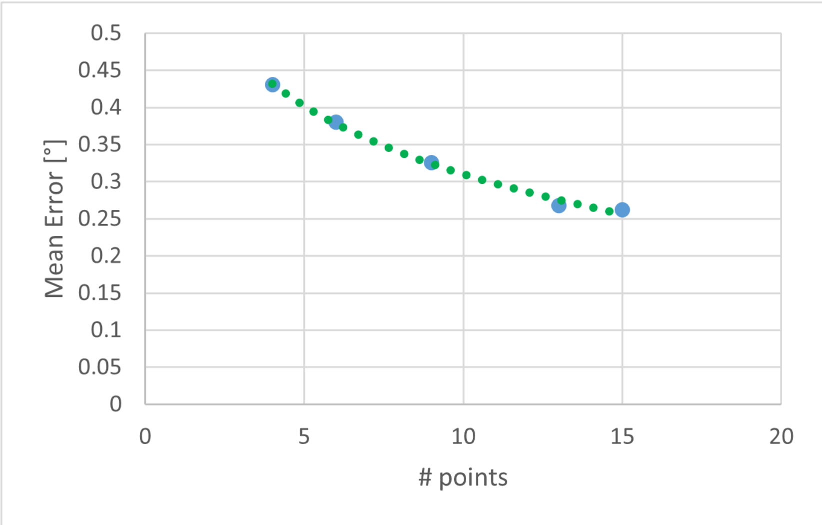


Figure 5.20: Mean Error function with number of points, $l = 10cm$.

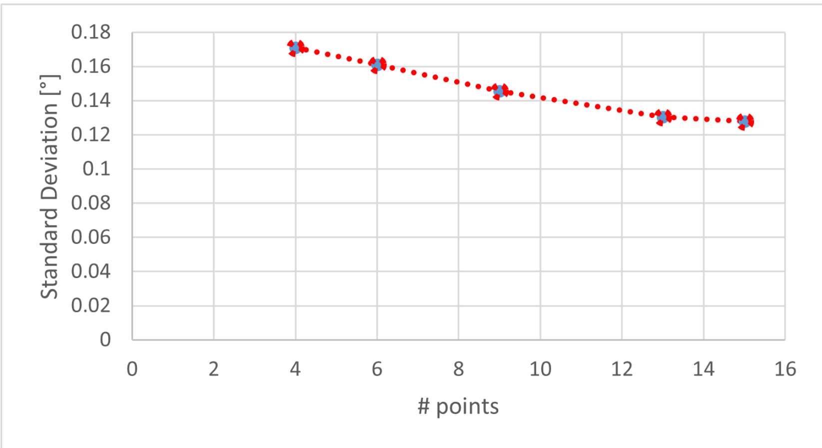


Figure 5.21: Standard Deviation function with number of points, $l = 10cm$.

It is possible to notice that, althought the same decreasing trends of LT have been obtained, error values are very different (greater of a couple of orders of magnitude).
Again, surfaces that can be representative of the dimensions of a typical mirror cube (side 1.8 - 2.5 cm) have been considered. Calculations have been conducted with the linear accuracy as obtained in Section 5.2.

Laser distance = $2.5\,m$					
$L[cm]$	n	**Media [°]**	**Standard Deviation [°]**	**Maximum Error [°]**	**Minimum Error [°]**
2	4	2.50049	1.2582459	4.3881998	0.499552963
	9	2.024465	0.9922709	4.840866919	0.094537611
3	4	1.58805524	0.74061	2.629807318	0.374637261
	9	1.266113	0.634	2.859388	0.04122475

Table 5.7: Accuracy results for 3D Disto, $d = 2.5\,m$.

From the above data, 3D Disto is able to reach the established target with very larger surfaces (side $80\,cm$). This allows to conclude that **it is not suitable to the examined applications**.

5.5 AT403 results improvement

To have an improvement of the obtained accuracy results for Laser Tracker AT403, a further analysis have been conducted. The goal of this analysis is trying to predict the behavior of a **random error in a series of repeated measurements** and to investigate the **minimum number of repetitions** that need to be taken on each point of the surface that guarantee the required accuracy.

5.5.1 Measurement repeatability

The procedure has been carried out once again with the support of MatLab. The random error is assigned on each point of the surface as follows:

$$e = \sigma \cdot randn(1, 1) \tag{5.3}$$

The sequence of numbers produced by *randn* is determined by the settings of the uniform random number generator. According to 5.3, this function generates values from the **normal** distribution with *mean value* equal to zero, and *standard deviation* equal to σ.
Considering the meaning of a *standard* accuracy, error is assigned with a 95% probability, corresponding to a confidence level of 2, i.e. the standard deviation σ can be calculated as follows:

$$\sigma = \frac{e_{datasheet}}{2}$$

Repeated measurements are intended the repetition N_{rep} of *each point of the examined surface* considering a random error assigned as in 5.3. The matrix error is built as described in Section 5.3.2, but this time error on each point is the **mean value** of the N_{rep} repetitions.
The theoretical plane is defined by 4 points, chosen at the vertices of a squared surfaces of side $20\,mm$, that can represent a mirror cube face of side $25\,mm$. The

effect of the number of repetitions on each point has been studied, by varying the repetition range.

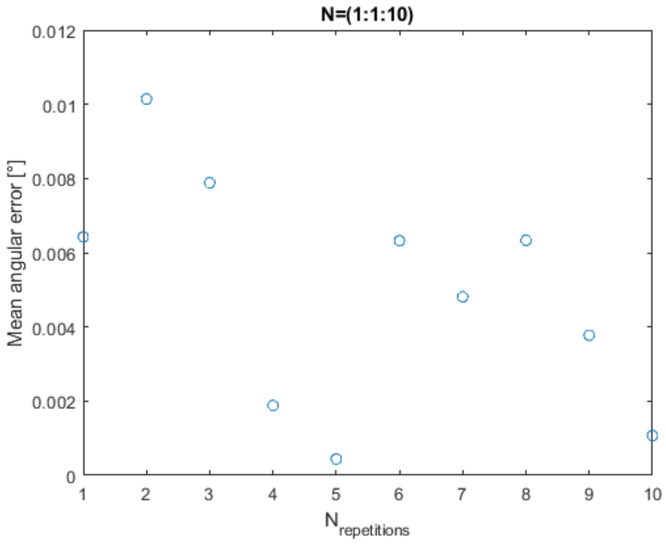


Figure 5.22: Effect of the number of repetitions on angular error, $N_{rep} = (1 : 1 : 10)$.

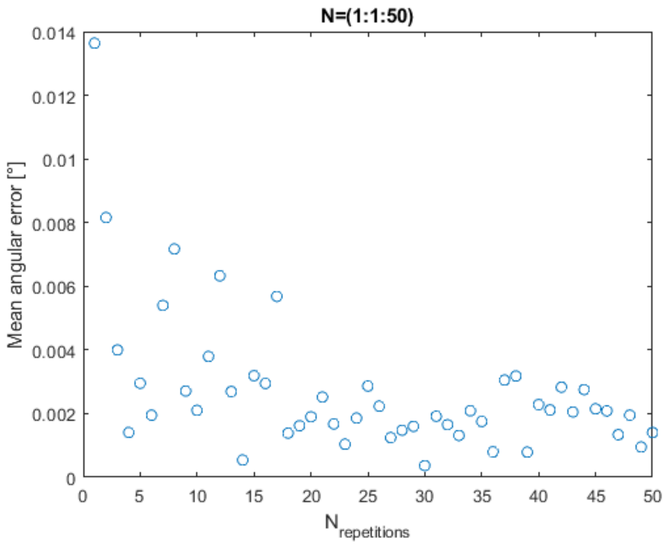


Figure 5.23: Effect of the number of repetitions on angular error, $N_{rep} = (1 : 1 : 50)$.

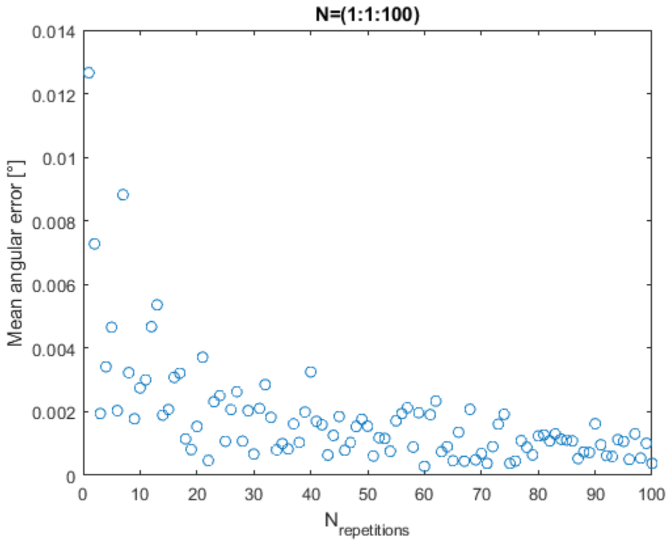


Figure 5.24: Effect of the number of repetitions on angular error, $N_{rep} = (1 : 1 : 100)$.

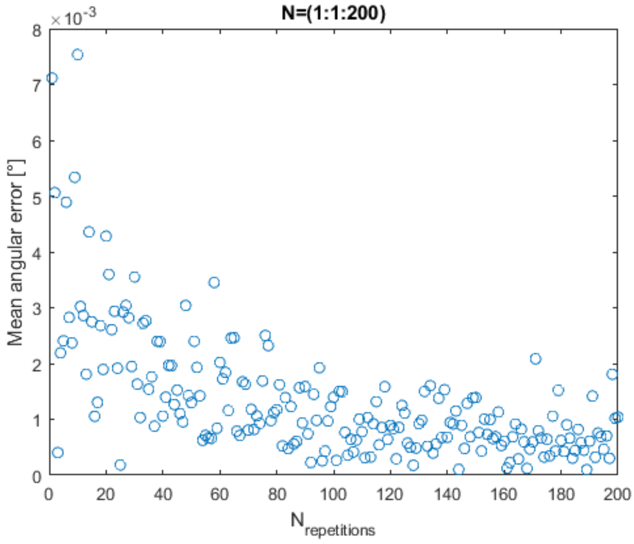


Figure 5.25: Effect of the number of repetitions on angular error, $N_{rep} = (1 : 1 : 200)$.

According to the previous figures, this approach doesn't allow to visualize the minimum number of repetitions that guarantees an improvement of the previous results. It is possible to conclude that by increasing the number of repetitions, values will settle down around a asymptotic value close to zero. Moreover, it has been found that by launching the simulation several times at the same N_{rep}, **obtained results are considerably dispersed**.

To get away from this, the N_{rep} measurements series has been numerically repeated a sufficiently large number of times. This procedure will be explained in the subsequent section.

5.5.2 Numerical Procedure

. The numerical procedure has been developed in MatLab and it has the samee structure of that described in 5.3.3.
The main steps of this procedure are explained considering 4 points on a theoretical squared surface of side $20\,mm$.

- **Importing Data**:
    1. a matrix Q loaded by a .txt file, that is the matrix with the theoretical points and it is 4×3 dimensional;
- **Input of the calculation**:
    1. Measuring distance: $2.5\,m$ has been considered;
    2. Instrument accuracy: from Standard Error accuracy of Laser Tracker, $(15 + 6/m)\mu m$ and considering the measuring distance, 0.015° is obtained;
    3. N_{rep}, vector with the number of repetitions performed on a single point:

    $$N_{rep} = \begin{bmatrix} 1 & 2 & 5 & 10 & 20 & 50 & 100 & 200 & 500 \end{bmatrix}$$

    4. $M = 500$, that is number of times the i-th element of N_{rep} series is repeated. This is a constant value for the simulation, and it shall be sufficiently high.
- **Iteration and Calculation**. There are four main cycles. Hereafter they are described from the inner to the outer one:
    1. the first cycle runs on the i-th element of N_{rep} on the single point of the surface; this cycle calculates the error on coordinates and it allows to obtain the **mean value and the standard deviation on the series of the i-th element of** N_{rep}, right out of the cycle;
    2. the second cycle runs on the number of points defining the surface, i.e. $n_{points} = 4$; out of this cycle, the plane error and the **angular error** are obtained;
    3. the third runs M-times for repeating the series of the i-th element of N_{rep}; out of this cycle, the **mean angular error and the standard deviation on the M-series** is calculated. This is the cycle that allows to normalize data dispersion.
    4. the last cycle runs on the dimension of vector N_{rep}, for studying different number of repetitions; the results of this cycle is a **vector of mean angular error values and a vector of standard deviation values**, each one corresponding to the i-th element of N_{rep}.

5.5.3 Results

In this procedure, the **maximum error** (intended as the sum between the mean error and the standard deviation) has been calculated. The obtained functions are represented in Figure 5.26 and 5.27.

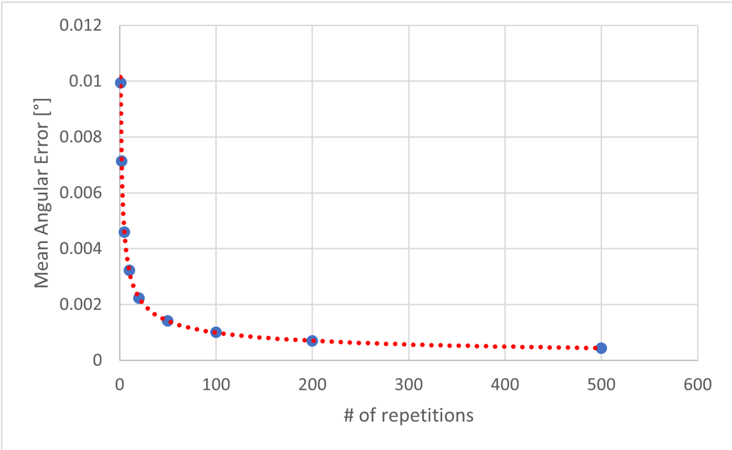


Figure 5.26: Mean error function with number of repetitions, $M = 500$.

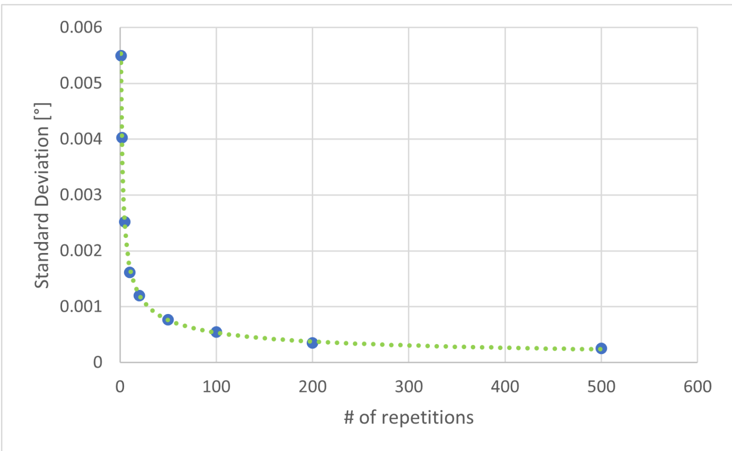


Figure 5.27: Standard Deviation function with number of repetitions, $M = 500$.

In conclusion, the obtained values can be further associated with a range of variability ($Err \pm 0.001^{\circ}$) that is encountered by launching the script multiple times. For improving the degree of conservation of this analysis, a 'deterioration' in the results can be identified. The final results have been reported in Table 5.8, including the influence of different laser distances.

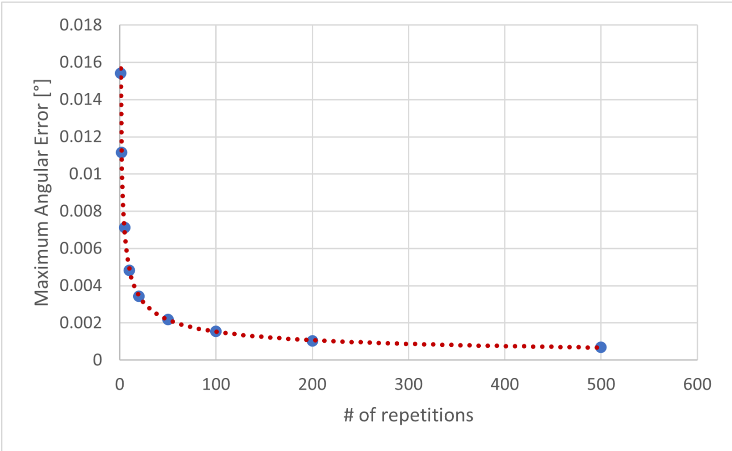


Figure 5.28: Maximum Error function with number of repetitions, $M = 500$.

Repeatibility analysis results			
# of repetitions	**Distance** $2.5\,m$	**Distance** $2\,m$	**Distance** $1.5\,m$
1	0.016427	0.01511706	0.013957486
2	0.012167	0.01097468	0.00953872
5	0.008115	0.00711664	0.006453212
10	0.005836	0.00525463	0.004943126
20	0.004429	0.00413557	0.003686072
50	0.003176	0.00289495	0.002717824
100	0.002556	0.00242756	0.002215713
200	0.002048	0.0019984	0.001883798
500	0.001686	0.00162378	0.001559717

Table 5.8: Repeatibility analysis results.

This last analysis allows to conclude that for distances of $2.5\,m$ and $2\,m$, the target of 0.005 ° is reached by repeating each point of the surface at least 20 times. By reducing the laser distance, this result gets better at the minimum number of repetitions of 10.

5.6 Conclusions

The accuracy analysis is crucial to establish if theodolite and laser tracker, the most suitable instruments for performing an alignment measurement, can respect the master constraint of the requirements concerning the **on-ground measurement accuracy**. The target fixed by this constraint is 0.005°.
The analysis showed that theodolites can fully respect this value, since they are characterized by very high accuracy. Differently, laser trackers proved to

be very performing on large surfaces, but not so well on surfaces that can be representative of a mirror cube face, as required by the measurements. For this reason, a further analysis has been necessary, at the end of which the target of 0.005° on the aformentioned surfaces can be reached with repeated measurements.
These results do not allow to exclude one instrument or another yet. Further considerations need to be conducted, concerning the possible building set-up and related complications, as well as costs, timing of measurement and data post processing. These features will be faced up in Chapter 6 and 7.

Chapter 6

Set-up with Theodolites

The main objective of the current chapter is showing how measurements can be performed on each unit with a specified set-up with theodolites. The following features will be detailed:

1. an hypothetical **step-by-step procedure** in the form of a flowchart;
2. any **issues and criticalities** concerning P/F alignment configurations and units accessibility;
3. a more empiric evaluation of the instruments in terms of **costs and set-up complexity**;
4. considerations about **data post processing and overall measurement timing**.

The following set-up have been thought to be applicable to the PFM. The specified requirements for each units have been described in Chapter 3.2.2.

NOTE: Those described in this chapter shall be considered as an *input* for the future alignment set-up building, since these measurements will be performed by skilled staff from companies operating in the field. The subsequent set-up are the result of the study of many academic papers.

6.1 Mini-CMG

6.1.1 PFM Al-01: Alignment on bench

The mini-CMG are installed on the intermediate panel, that is located on the Integration Stand (IS): therefore, it will be in a horizontal position, to ensure a measurement as stable as possible. The actuators have been enumerated as shown in Figure 6.1.
The aim of this measurement is to verify the position of the gimbal axis of each mini-CMG, confirming that they result:

1. on the same plane;
2. aligned two by two;
3. orthogonal between them.

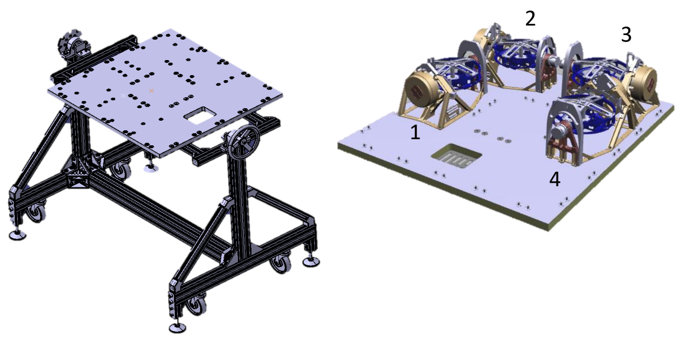


Figure 6.1: Integration Stand and intermediate panel with mini-CMG.

Each actuator is provided with a mirror cube; moreover a further mirror cube is located on the panel, to be the main reference of this measurement (**Panel Mirror Cube, PMC**). The three-axes reference system is shown in Figure 6.2.

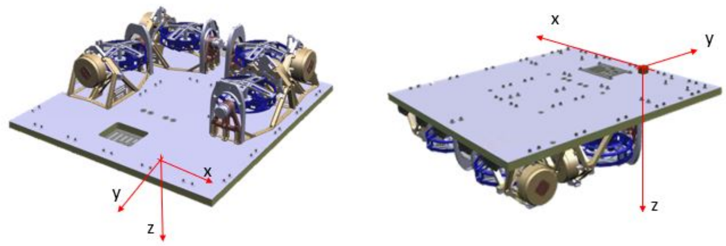


Figure 6.2: Panel reference system.

In a horizotal position of the panel, it must be considered that mirror cube faces that can be pointed are those in y and x direction. The chosen set-up for the required measurement has been structured as follows:

- 3 theodolites will be needed, the *primary* P and two *subjects* T_1 and T_2 respectevely;
- **Primary and T_1 will define the panel reference system**. Primary is pointing PMC face in y direction and it is not moved, T_1 is pointing PMC face in x direction;
- Theodolite T_2 will be located so that it can point unit mirror cube face in both y and x direction . That is the **moving** theodolite.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 6.3 . It can be applicable to the measurement of each one of the four mini-CMG.[1] Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 6.1.

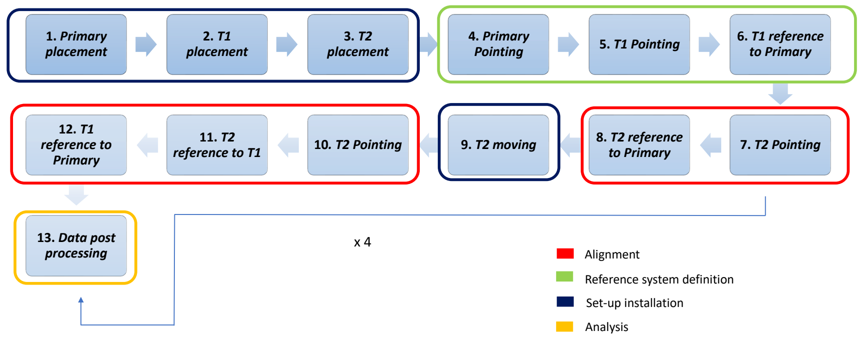


Figure 6.3: Alignment flowchart for mini-CMG.

The suggested solution is represented in Figures 6.4-6.7. These measurements have been studied considering the up-view of IP installed on IS, i.e. the **azimuth plane** xy. This allows to visualize clearly involved directions and angles.
Units and MGSE have been sketched to highlight any criticalities of this configuration and to investigate, when possible, a better solution.

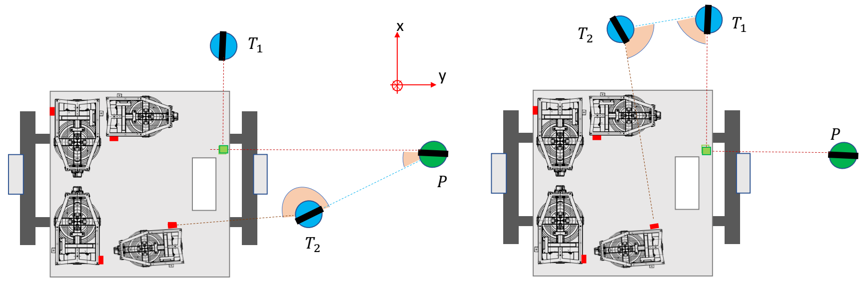


Figure 6.4: Alignment of mini-CMG 1.

[1]The alignment sequence of the flowchart may slightly vary between actuators. Depending on theodolite T_2 position, it can either refer directly to primary or to T_1 through *bridge configuration.*

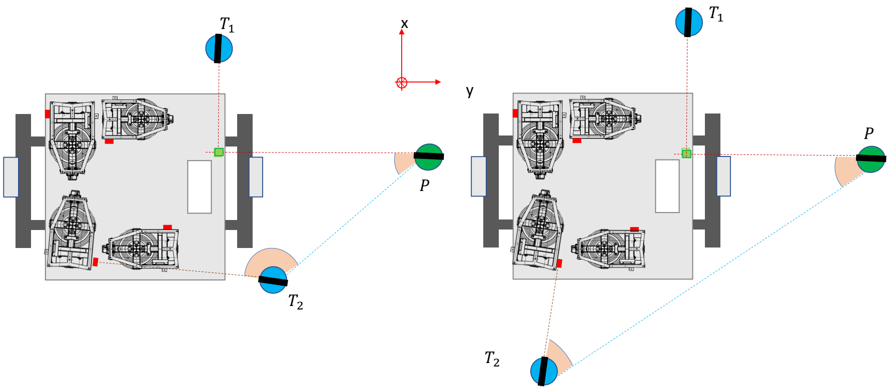


Figure 6.5: Alignment of mini-CMG 2.

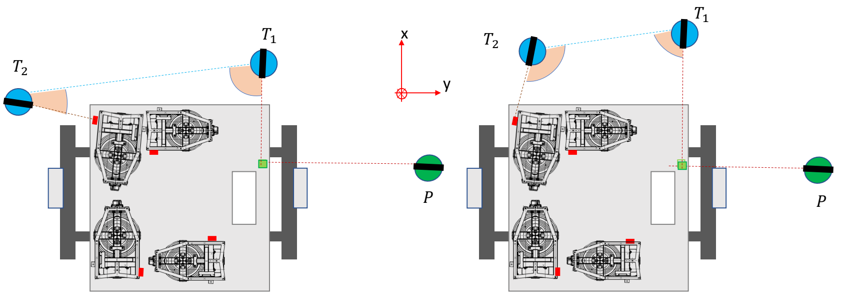


Figure 6.6: Alignment of mini-CMG 3.

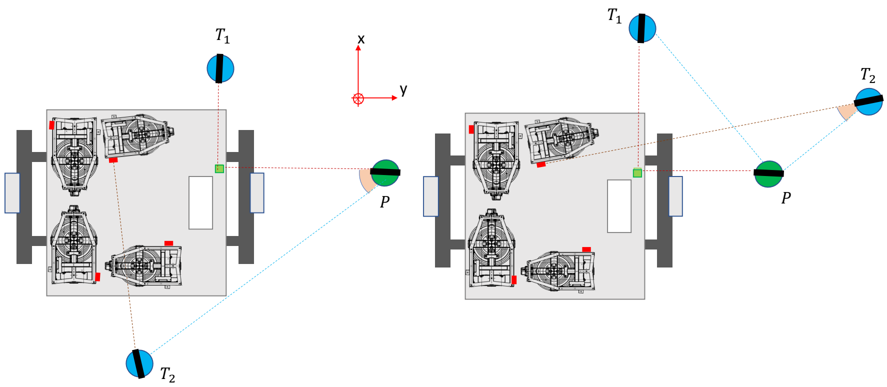


Figure 6.7: Alignment of mini-CMG 4.

Fuction	Operation	Description	Time [min]
Set-up Installation	1. P Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	2. T_1 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	3. T_2 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	9. T_2 Movement	Switching and dismounting from its position, new installation on tripod, tripod regulation, theodolite calibration and warm-up	15
Reference system definition	4. P Pointing	Collimation with y face of PMC	2
	5. T_1 Pointing	Collimation with x face of PMC	2
	6. T_1 reference to P	Collimation between the two theodolites	5
Alignment	7. T_2 Pointing	Collimation with y face of uMC	2
	8. T_2 reference to P	Collimation between the two theodolites	5
	10. T_2 Pointing	Collimation with x face of uMC	2
	11. T_2 reference to T_1	Collimation between the two theodolites	5
	12. T_1 reference to P	Collimation between the two theodolites	5
Analysis	13. Post Processing	PC power on, software starting, calculations	1440 (1 day)

Table 6.1: Alignment flow blocks explanation for mini-CMG 1.

Issues. This procedure has shown some criticalities that would prevent to entirely perform the measurements, concerning accessibility to MC and visibility of its faces. These features are listed in Table 6.4.

Mirror Cube	Set-up Issue
Panel	-
Mini-CMG 1	Covered by mini-CMG 4 while pointing MC x face
Mini-CMG 2	Covered by mini-CMG 1 while pointing MC y face
Mini-CMG 3	-
Mini-CMG 4	Covered by mini-CMG 1 while pointing MC x face

Table 6.2: Mini-CMG set-up issues.

The result of this would be that only **mini-CMG 3 can be entirely measured** with all the actuators mounted on the intermediate panel.
Since **MC on actuators can't be moved from their current position**, some solutions have been proposed to solve this criticalities:

1. Integrating and after measuring one actuator at a time;
2. Mounting a further MC on mini-CMG 1 or mini-CMG 4.

At the current time, the first solution seems not applicable, because mini-CMG 1 and 4 would continue to influence each other accessibility; therefore, unit integration does not guarantee that the others remain stable as required.
For this reason, the baseline is to locate a second MC on the other side of mini-CMG 1 or 4. It shall be characterized as well as the MRC on Bottom Panel, i.e. with a CMM, so that its position could be known with respect to the existing cube. In this way it could be use as reference for the measurement.

6.1.2 PFM Al-02: P/F Alignment

In this configuration, intermediate panel is installed on P/F as shown in Figure 7.4. The MGSE of this configuration is the Vertical Stand.

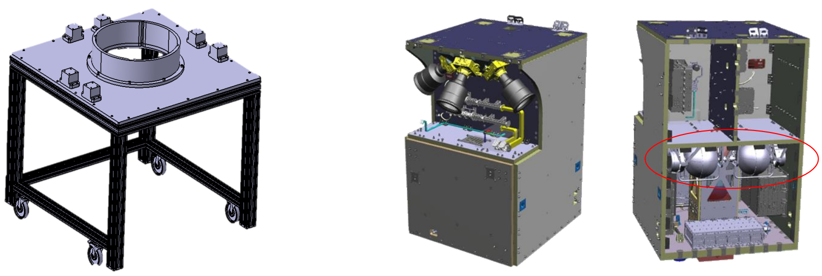


Figure 6.8: Vertical Stand and IP installed on P/F.

The aim of this measurement is the same of that described in Section 6.1.1. In this way it could be seen if integration has changed something in the units position.
According to IP position on P/F, **only two actuators result exposed**, i.e. mini-CMG 2 and mini-CMG 3, and only **if the access panel Y- is not mounted**. Moreover, only one mirror cube is visible between them that is mini-CMG 3 (Figure 6.9).

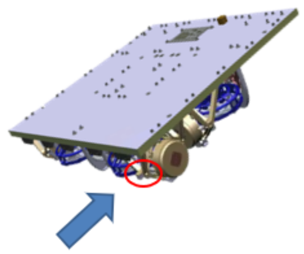


Figure 6.9: Mini-CMG 3 position on IP.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 6.14, applied to the measurement of mini-CMG 3. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table ??.

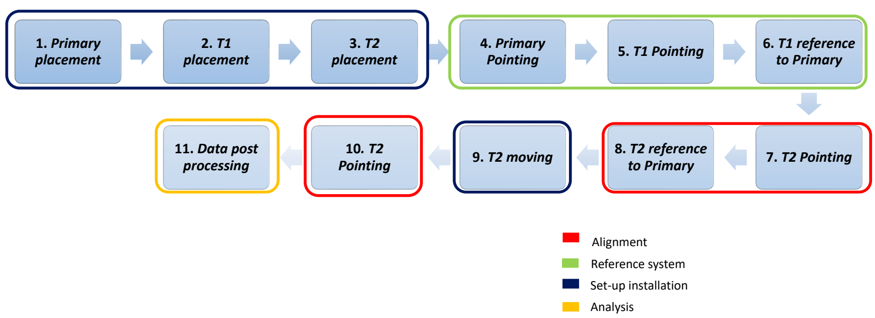


Figure 6.10: Alignment flow for mini CMG 3.

The suggested solution is represented in Figures 6.11. This measurement has been studied considering the up-view of P/F installed on VS (i.e. the **azimuth plane** xy) and the side-view too (i.e. the **elevation plane** zy)[2] . This allows to visualize clearly involved directions and angles.

[2]Elevation plane allows a "direct" measurement of the angle with reference to the gravity direction. That is why reference to primary is not needed after T_2 moving.

Fuction	**Operation**	**Description**	**Time [min]**
Set-up Installation	1. P Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	2. T_1 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	3. T_2 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	9. T_2 Movement	Switching and dismounting from its position, new installation on tripod, tripod regulation, theodolite calibration and warm-up	15
Reference system definition	4. P Pointing	Collimation with y face of PMC	2
	5. T_1 Pointing	Collimation with x face of PMC	2
	6. T_1 reference to P	Collimation between the two theodolites	5
Alignment	7. T_2 Pointing	Collimation with y face of uMC	2
	8. T_2 reference to P	Collimation between the two theodolites	5
	10. T_2 Pointing	Collimation with x face of uMC	2
Analysis	11. Post Processing	PC power on, software starting, calculations	1440 (1 day)

Table 6.3: Alignment flow blocks explanation.

Units and MGSE have been sketched to highlight any criticalities of this configuration and to investigate, when possible, a better solution. The chosen set-up for the required measurement has been structured as follows:

- 3 theodolites will be needed, the *primary* P and two *subjects* T_1 and T_2 respectevely;
- **Primary and T_1 will define the panel reference system**. Primary is pointing PMC face in y direction and it is not moved, T_1 is pointing PMC face in x direction;
- Theodolite T_2 will be located so that it can point unit mirror cube face in both y and x direction . That is the **moving** theodolite.

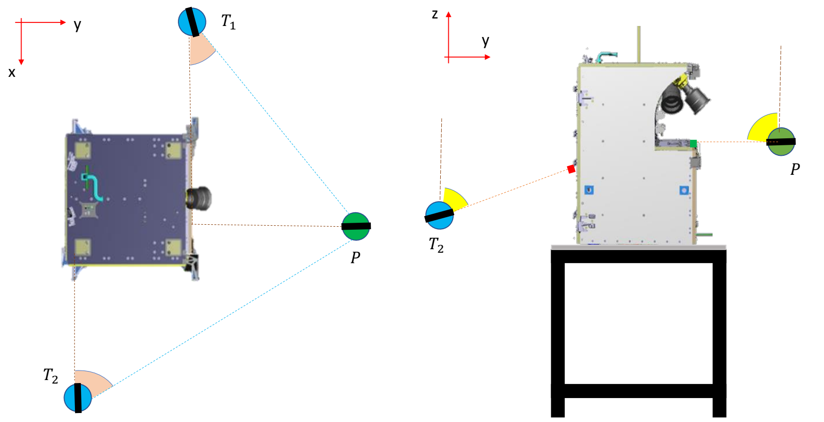


Figure 6.11: Alignment of mini-CMG 3.

Issues. Criticalities of the exposed procedure are mostly related to unit mirror cube visibility. The rediscovered features are listed in Table 6.4.

Mirror Cube	**Set-up Issue**
Panel	-
Mini-CMG 1	NOT MEASURABLE
Mini-CMG 2	NOT MEASURABLE
Mini-CMG 3	x direction pointing covered by $X+$ panel
Mini-CMG 4	NOT MEASURABLE

Table 6.4: Mini-CMG set-up issues.

As for mini-CMG 1,2 and 4 visibility one of the proposed solution was to **create some openings** on $X+$ and $X-$ panels, if uMC position could be modified. Since this can not be possible on PFM, the only information that can be obtained from this measurement is related to the parallelism in y direction between uMC and PMC.
For the aforementioned reasons, the current baseline for this measurement is **measuring only the PMC with respect to the S/C Master Reference Cube** accomodated on bottom panel. In this way PMC would be established as representative of the mini-CMG AU.

6.2 Multi-Head STT

The Multi-Head Star Trackers are installed on P/F top plate as shown in Figure 6.12 and each sensor is provided with a MC on the support basis.
The main objective of this measurement is the **calculation of a rotational matrix** for each sensor, with respect to the reference system of the MRC.

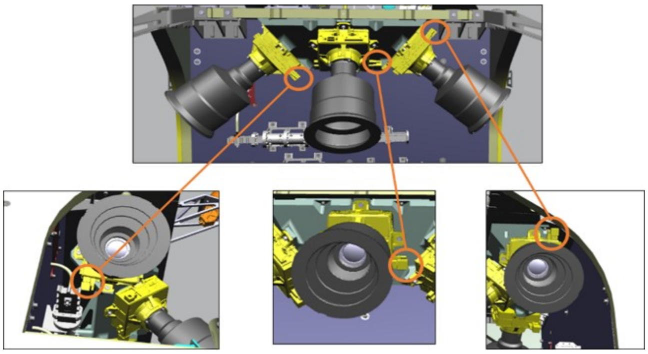


Figure 6.12: Mirror cubes on STT.

This section will be explained as follows:

1. Description of the adopted set-up based on uMC faces accessibility;
2. Application of the set-up to the specified configuration;
3. Issues and criticalities of each configuration.

The main objective of this measurement will be finding the three elementary rotations (around X_{SC},Y_{SC} and Z_{SC}) for building up the rotational matrix. The aforementioned angles can be measured in the following way:

- Two rotations can be calculated using the measurement of the Primary P and of a first theodolite T_1:
  - Rotation around X_{SC} by studying the *elevation* plane ZY_{SC};
  - Rotation around Z_{SC} by studying the *azimuth* plane XY_{SC};
- The calculation of the third rotation requires a relocation of T_1 and the introduction of a second theodolite T_2:
  - Rotation around Y_{SC} by studying the *elevation* plane XZ_{SC};

As usual, primary is not moved from its position and it always points Y_{SC} direction of MRC for each sensor. The three-axes reference system based on each STT mirror cube is named $(XYZ)_B$ and it is positioned as shown in Figure 7.6. Z_B represents the sensor *pointing axis*.

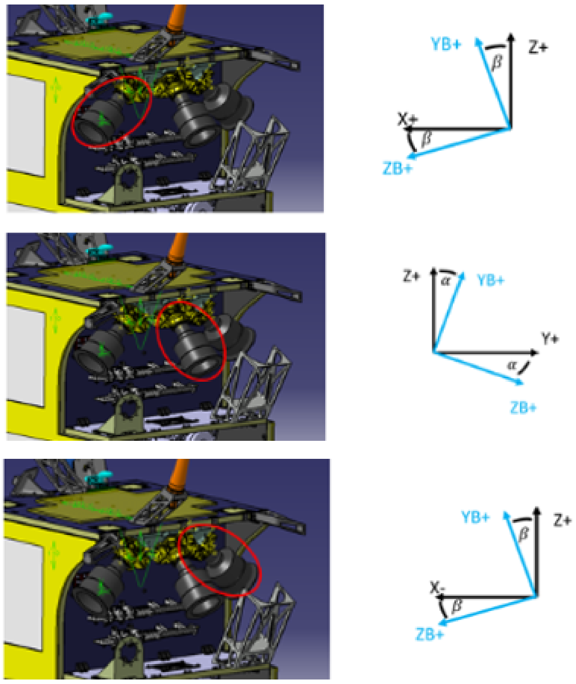


Figure 6.13: Reference system on STT1(up), STT2 (center) and STT3 (down).

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 6.14 and it can be applied to each one of the three STT. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 6.5.

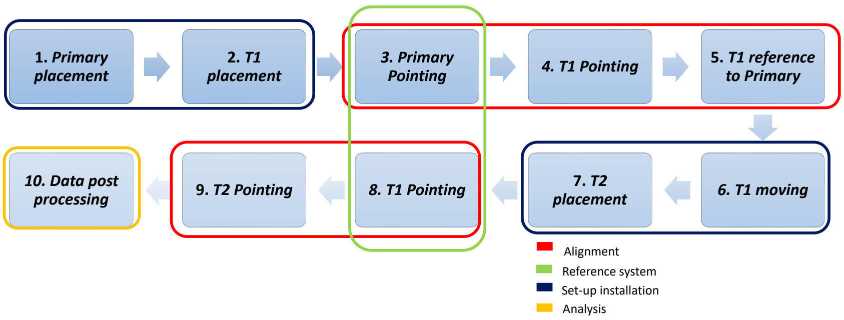


Figure 6.14: Alignment flow for STTs.

Units on P/F have been sketched to highlight any criticalities of this configuration and to investigate, when possible, a better solution. The three STT measurement has been detailed in terms of mirror cubes pointing directions.

Fuction	Operation	Description	Time [min]
Set-up Installation	1. P Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	2. T_1 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	6. T_1 Movement	Switching and dismounting from its position, new installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	7. T_2 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
Alignment	3. P Pointing	Collimation with Y_{SC} face of MRC	2
	4. T_1 Pointing	Collimation with X_B face of uMC	2
	5. T_1 reference to P	Collimation between the two theodolites	5
	8. T_1 Pointing	Collimation with X_{SC} face of MRC	2
	9. T_2 Pointing	Collimation with Z_B face of uMC	2
Analysis	10. Post Processing	PC power on, software starting, calculations	1440 (1 day)

Table 6.5: Alignment flow blocks explanation for STT 1.

STT 1 pointed directions	
Theodolite	**Mirror Cube**
P	Y_{SC}
T_1	X_B
T_{1R}[3]	X_{SC}
T_2	Z_B

Table 6.6: STT 1 pointed directions.

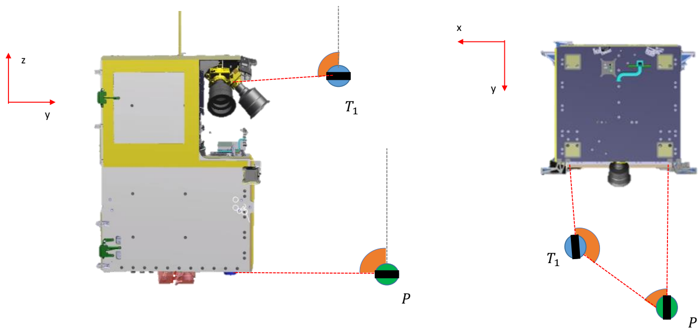


Figure 6.15: STT 1 Alignment (rotation around X_{SC} and Z_{SC}).

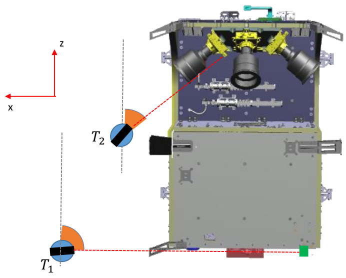


Figure 6.16: STT 1 Alignment (rotation around Y_{SC}).

STT 2 pointed directions	
Theodolite	**Mirror Cube**
P	Y_{SC}
T_1	Z_B
T_{1R}	X_{SC}
T_2	X_B

Table 6.7: STT 2 Pointed directions.

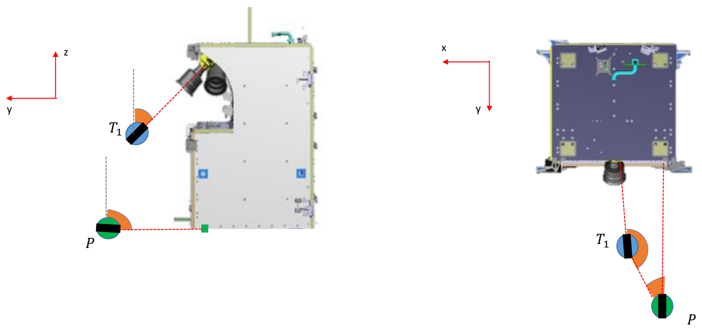


Figure 6.17: STT 2 Alignment (rotation around X_{SC} and Z_{SC}).

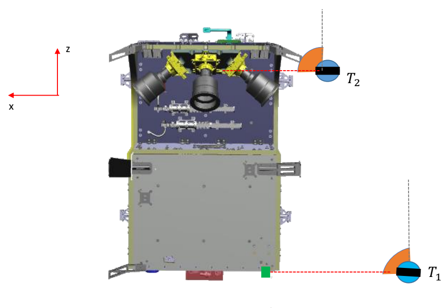


Figure 6.18: STT 2 Alignment (rotation around Y_{SC}).

STT 3 pointed directions	
Theodolite	**Mirror Cube**
P	Y_{SC}
T_1	Z_B
T_{1R}	X_{SC}
T_2	X_B

Table 6.8: STT 3 Pointed directions.

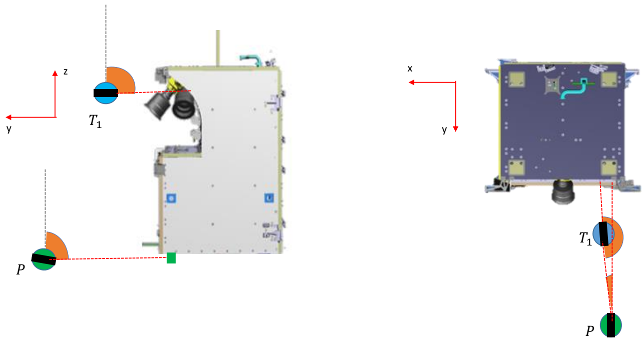


Figure 6.19: STT 3 Alignment (rotation around X_{SC} and Z_{SC}).

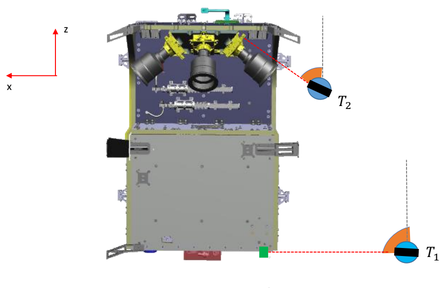


Figure 6.20: STT 3 Alignment (rotation around Y_{SC}).

6.2.1 PFM Al-02: Pre-shipment

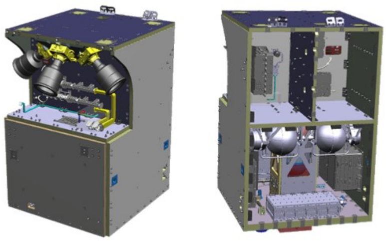


Figure 6.21: P/F in pre-shipment configuration.

The MGSE of this configuration shall be the VS. It must be considered that the tripod which the theodolite is placed on should reach a height of about 3 meters (Figure 6.22).

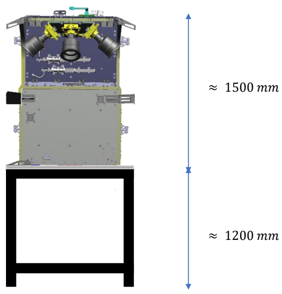


Figure 6.22: P/F on VS.

Since commercial tripods can typically reach heights between 80 and 140 cm the **measurements of all rotations for each star tracker would be problematic** without a higher tripod. Otherwise, this problem is not encountered if S/C would be placed on **Tilting Trolley**(if available).

6.2.2 PFM Al-03: Pre-TVAC

The MGSE of this configuration shall be the TT. This P/F configuration is similar to that of pre-shipment, but in this case the problem of the tripod height is not encountered, since the TT can support the P/F close enough to the ground (Figure 6.24). For this reason, **it would be possible measuring all the rotations for each STT**.

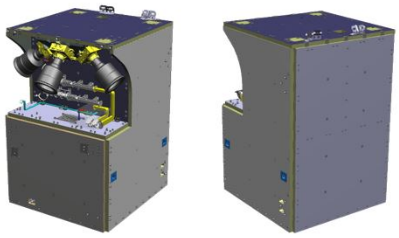


Figure 6.23: P/F in pre-TVAC configuration.

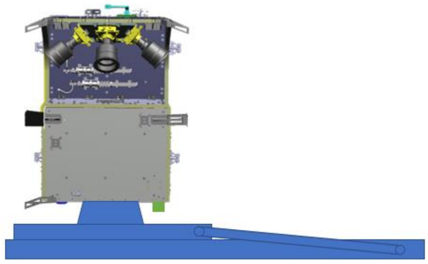


Figure 6.24: P/F on TT.

6.2.3 PFM Al-05/Al-06: Pre/Post Vibrations

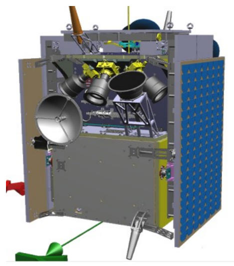


Figure 6.25: P/F in final configuration.

The MGSE of this configuration shall be the TT. Further units results integrated, such as ISL and XBA, together with SAA. This would complicate the visibility of both the unit mirror cubes and the MRC, if the satellite were in a *stowed* configuration. In particular the following direction would not be visible:

1. Z_B face of STT 1;
2. Z_B face of STT 3;
3. Y_{SC} and X_{SC} of MRC.

In conclusion, the described procedure has shown some criticalities that would prevent to entirely perform these measurements, concerning set-up installation and accessibility to MC and visibility of its faces. All these features have been summerized in Table 6.9.

Configuration	**Set-up issues**
Pre-shipment	Tripod height
Pre-TVAC	-
Pre/Post Vibrations	uMC and MRC not visible

Table 6.9: STT set-up issues.

Two possible solutions could be evaluated:

1. **Deployment of SAA**;
2. **TT in horizontal position**.

Indeed, the problem of unit mirror cubes visibility would not arise if the satellite were in a *deployed* configuration. Differently, with the TT in a horizontal position, two faces of the MRC may still not be accessed and SAAs may be tough to handle.
In conclusion, the proposed measurement for the multi-head STT with the above solutions turned out to be **a feasible solution**.

6.3 X-Band Passive Antenna

6.3.1 PFM Al-05/Al-06: Pre/Post Vibrations

XBA is accomodated on IP and the alignment requirement foresees the measurement of the antenna pointing axis, being tilted of 30° with respect to the Z_{SC} axis.

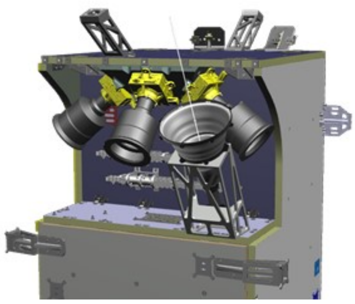


Figure 6.26: XBA on IP.

At the current time, as specified before, no mirror cube is predicted for XBA and this would exclude the possibility of carrying out a measurement with theodolites. For this reason, the following proposed set-up has been built considering the possibility to have a *hypotetical* mirror cube on the XBA support (Figure 7.8). The MGSE of this configuration is the TT.

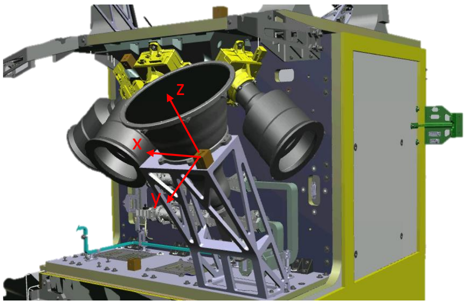


Figure 6.27: Hypothetical mirror cube on XBA.

The following set-up has been structured as follows:

- Two theodolites are sufficient for the required measurement, the Primary P and the theodolite T_1;
- The inclination of the antenna is obtained by studying elevation plane ZY_{SC};
- The primary points the Y_{SC} face of the MRC;
- T_1 points the y face of the antenna mirror cube.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 6.28. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 6.10.

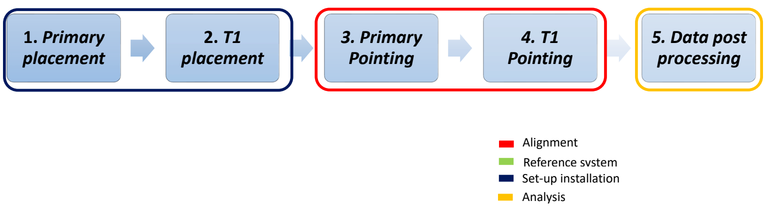


Figure 6.28: Alignment flowchart for XBA.

The suggested solution is represented in Figures 6.29-6.30.

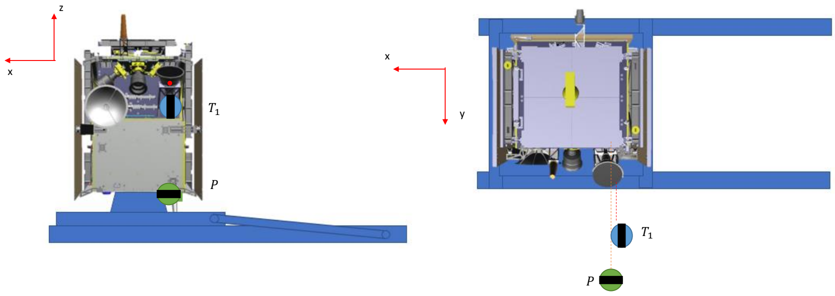


Figure 6.29: Aligment of XBA (elevation and azimuth plane).

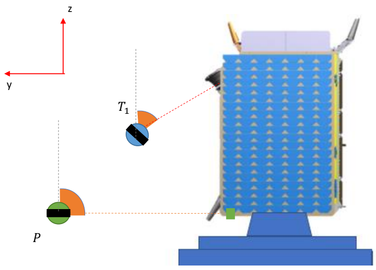


Figure 6.30: Alignment of XBA (elevation plane).

Fuction	**Operation**	**Description**	**Time [min]**
Set-up Installation	1. P Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
	2. T_1 Placement	Installation on tripod, tripod regulation, theodolite calibration and warm-up	15
Alignment	3. P Pointing	Collimation with Y_{SC} face of MRC	2
	4. T_1 Pointing	Collimation with y face of uMC	2
Analysis	5. Post Processing	PC power on, software starting, calculations	1440 (1 day)

Table 6.10: Alignment flow blocks explanation for XBA.

Issues. Typically, TT in vertical position does not get in the way of the measurement of the XBA mirror cube, but two faces of MRC may still not be visible (Table 6.11).

Mirror Cube	Set-up Issue
Master	X_{SC} direction covered by SAA; Y_{SC} direction covered by S-Band Antenna.
XBA	-

Table 6.11: XBA set-up issues.

Again, a possible solution could be having the **SAA in a deployed configuration**. Other solutions for Y_{SC} direction are being evaluated in case S-Band antenna would influence MRC accessibility.a

6.4 Theodolite empirical evaluation

6.4.1 Overall Measurement Time

In this section the entire alignment campaign duration is estimated, based on tables built up in this chapter.
All the analyzed configurations are detailed, considering the effect of the subsequent factors:

1. k, number of times the measurement is repeated on a single unit. Typically in a set-up with theodoltes $k = 1$;
2. n, number of units.

The overall measurement time for a single alignment block has been calculated as follows:

- For mini-CMG:

$$\Delta t = \Delta t_{inst} + k \cdot n \cdot (\Delta t_{ref} + \Delta t_{alig} + \Delta t_{pp}$$

- For STT

$$\Delta t = n \cdot (\Delta t_{inst} + k \cdot (\Delta t_{ref} + \Delta t_{alig})) + \Delta t_{pp}$$

- For XBA:

$$\Delta t = \Delta t_{inst} + k \cdot n \cdot (\Delta t_{ref} + \Delta t_{alig}) + \Delta t_{pp}$$

where:

- Δt_{inst} is the **set-up installation time**;
- Δt_{ref} is the **reference system measurement time**;
- Δt_{alig} is the **uMC measuring time**;
- Δt_{pp} is the **post-processing time**.

Unit	Block	ΔT_{inst}	ΔT_{ref}	ΔT_{alig}	**k**	**n**	ΔT_{pp}	ΔT
Mini-CMG	PFM Al-01	60	9	19	1	4	1440	1672
	PFM Al-02	60	9	9	1	1	1440	1543
STT	PFM Al-02	60	0	13	1	3	1440	1659
	PFM Al-03	60	0	13	1	3	1440	1659
	PFM Al-05	60	0	13	1	3	1440	1659
	PFM Al-06	60	0	13	1	3	1440	1659
XBA	PFM Al-05	30	0	4	1	1	1440	1474
	PFM Al-06	30	0	4	1	1	1440	1474

Table 6.12: Alignment blocks estimation time

Total Duration	**min**	**hours**
	12799	**213.32**

Table 6.13: Alignment campaign duration.

It shall be noticed that for the STT measurement, the primary reference system needs to be restored for each sensor, while for XBA no theodolite movement is needed. That is why their formula are different.
The results have been summerized in Table 6.12, as well as the overall time of the entire alignment campaign. The subsequent ΔT_i values are expressed in *minutes*.
From the above results it can be concludeded that the duration of the entire alignment campaign with theodolites will last almost **27 days**.

6.4.2 Full set-up cost

The set-up cost analysis has been conducted considering as reference unit the **one-hour wage of a metalworker employee**, according to which is predicted by the Metalworking Industry contract.
Among the levels, 5^{th} metalworking level has been considered:

Cathegory	**Employees**	**Minimum wage**
5	Intermediate and Skilled Workers	1806.99

Table 6.14: Minimum wage for a 5^{th} metalworking level.

Therefore, a full set-up with theodolites shall includes the elements described in Table 6.15.

Theodolite (including box, battery and cabling)	≈ € 20k
Tripod	≈ € 1k
Software Licence	≈ € 5k per year
Number of required tools	3
Cost of full set-up	≈ **€ 68k**

Table 6.15: Mean costs for a set-up with theodolites.

Considering the calculated hours from Table 6.13, it is reasonable to conclude that:

1. In case of *purchasing*, the entire estimated set-up cost shall be increased with the cost that the company would pay for the entire alignment campaign duration, based on the minimum one-hour wage[4] obtainable from Table 6.14;

2. in case of set-up *rental*, the entire estimated set-up cost shall be calculated considering that the external service has a mean cost of € 60 per hours.

The obtained results have been reunited in Table 6.16.

Hours	**Purchase**	**Rental**
213.32	≈ € 73k	≈ € 13k

Table 6.16: Final cost estimation of the alignment campaign.

[4]This must be calculated cosidering that company typically pays *twice* the minimum one-hour wage.

Chapter 7

Set-up with Laser Tracker

The main objective of the current chapter is showing how measurements can be performed on each unit with a specified set-up with Laser Trackers. The following features will be detailed:

1. an hypothetical **step-by-step procedure** in the form of a flowchart;
2. any **issues and criticalities** concerning P/F alignment configurations and units accessibility;
3. a more empiric evaluation of the instruments in terms of **costs and set-up complexity**;
4. considerations about **data post processing and overall measurement timing**.

The following set-up have been thought to be applicable to the PFM and they are based on the common approach according to which **SMR would touch with 4 points two not-parallel surfaces on the unit mirror cube and on the reference mirror cube** (panel or master).

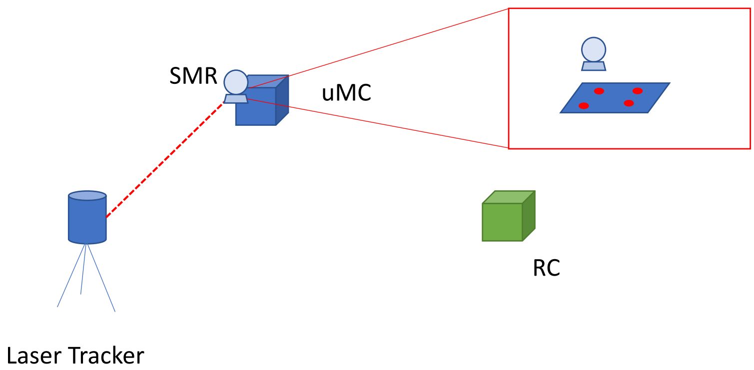


Figure 7.1: Adopted set-up for aligning units.

The software would associate the measured points on one face with a plane and it will be possible to find its normal vector, so that constraints between cubes faces can be controlled.
Alignment configurations for each unit are detailed in the subsequent sections. Requirements, provisions and MGSE are clearly the same of those described in Chapter 6.

NOTE: The set-up described in this chapter recalls the procedure detailed in Section 5.3.3, i.e. the construction of surfaces (called *datum*) by taking a certain number of points using the SMR. It will be demonstrated how, althought it can not immediately respect the accuracy requirement, this set-up is easier to install and cubes accessibility issues are not encountered since, whereas possible, a surface on the unit itself can be used.
However, the current baseline foresees the possibility to build up an actual *optical* set-up, based on laser reflection and triangulation, as described in Section 4.2.5. This option is being evaluated.

7.1 Mini-CMG

7.1.1 PFM Al-01: Alignment on bench

With the panel in a horizontal position on IS, **all the exposed faces of uMC and PMC are accessible for the SMR**, for example:

- Faces in x and y direction for uMC;
- Faces in z and x direction for PMC.

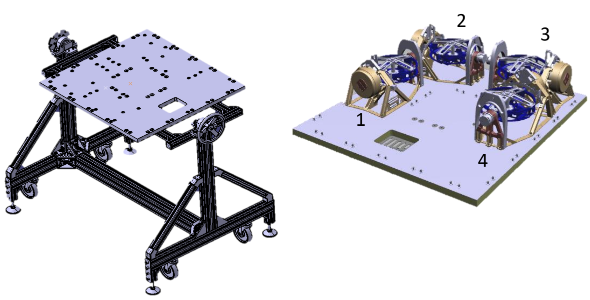


Figure 7.2: Integration Stand and intermediate panel with mini-CMG.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 7.3 . It can be applicable to the measurement of each one of the four mini-CMG. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 7.1.

Function	Operation	Description	Time [min]
Set-up Installation	1. Laser Traker Placement	Installation on tripod, tripod regulation, LT warm-up	40
	2. Software Running	PC power on, Software starting, selection of the type of SMR and the measurement geometry	5
Datum	3. SMR movement	SMR taking 4 points on the uMC face in y direction	0.6667
	4. Points association	Points naming and identification of surface	0.1333
	5. SMR movement	SMR taking 4 points on the uMC face in x direction	0.6667
	6. Points association	Points naming and identification of surface in the software	0.1333
	7. SMR movement	SMR taking 4 points on the PMC face in z direction	0.6667
	8. Points association	Points naming and identification of surface	0.1333
	9. SMR movement	SMR taking 4 points on the PMC face in x direction	0.6667
	10. Points association	Points naming and identification of surface in the software	0.1333
Alignment	11. Data obtaining	Closing measurement session and saving data	5
Analysis	12. Post Processing	Study of the obtained results	720 (12 hours)

Table 7.1: Alignment flow blocks explanation for mini-CMG 1.

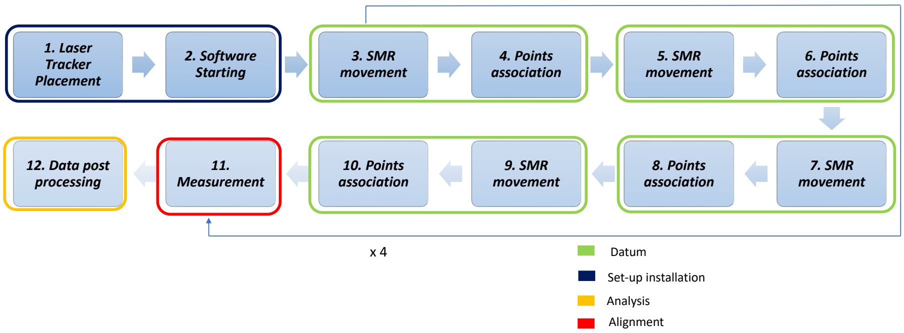


Figure 7.3: Alignment flowchart for mini-CMG.

7.1.2 PFM Al-02: P/F Alignment

On the panel integrated on P/F (on VS) **all the exposed faces of uMC of mini-CMG 3 and PMC are accessible for the SMR**, in particular:

- Faces in z and y direction for uMC of mini-CMG 3;
- Faces in z and y direction for PMC.

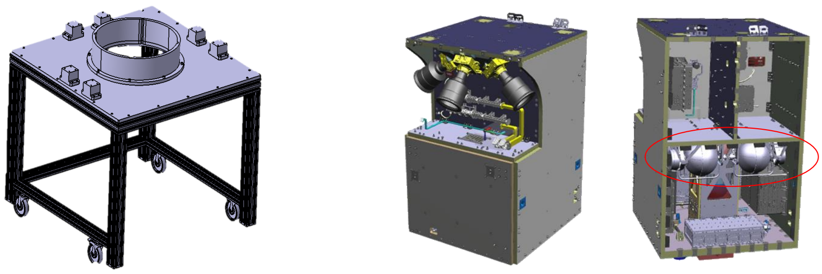


Figure 7.4: Vertical Stand and IP installed on P/F.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 7.5. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 7.2.

Function	Operation	Description	Time [min]
Set-up Installation	1. Laser Traker Placement	Installation on tripod, tripod regulation, LT warm-up	40
	2. Software Running	PC power on, Software starting, selection of the type of SMR and the measurement geometry	5
Datum	3. SMR movement	SMR taking 4 points on the uMC face in y direction	0.66677
	4. Points association	Points naming and identification of surface	0.1333
	5. SMR movement	SMR taking 4 points on the uMC face in z direction	0.6667
	6. Points association	Points naming and identification of surface in the software	0.1333
	7. SMR movement	SMR taking 4 points on the PMC face in y direction	0.6667
	8. Points association	Points naming and identification of surface	0.1333
	9. SMR movement	SMR taking 4 points on the PMC face in z direction	0.6667
	10. Points association	Points naming and identification of surface in the software	0.1333
Alignment	11. Data obtaining	Closing measurement session and saving data	5
Analysis	12. Post Processing	Study of the obtained results	720 (12 hours)

Table 7.2: Alignment flow blocks explanation for mini-CMG 3.

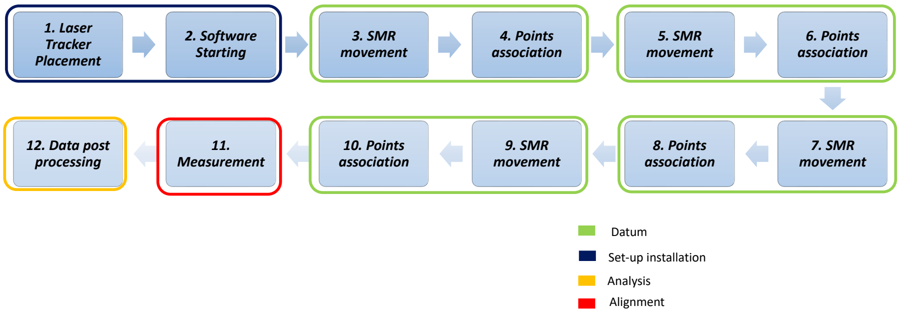


Figure 7.5: Alignment flowchart for mini-CMG 3.

7.2 Multi-Head STT

The measurement sequence is applicable to all the foreseen configurations[1] , i.e.:

1. PFM Al-02: P/F Alignment;
2. PFM Al-03: Pre-TVAC;
3. PFM Al-05/06: Pre/Post Vibrations.

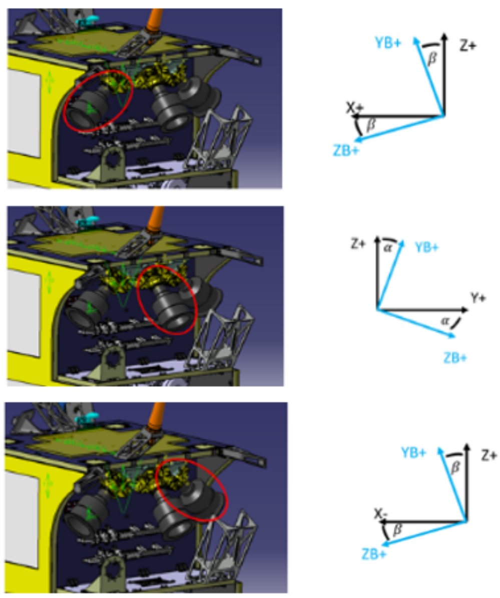


Figure 7.6: Reference system on STT1(up), STT2 (center) and STT3 (down).

[1]The visible STT mirror cube faces are the same.

There will be accessible the following uMC faces:

- X_B and Z_B faces of STT1 MC;
- Y_B and Z_B faces of STT2 MC;
- X_B and Z_B faces of STT3 MC;

Differently, all the exposed faces of MRC are accessible, for example X_{SC} and Y_{SC} will be measured.
The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 7.7. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 7.3.

Function	**Operation**	**Description**	**Time [min]**
Set-up Installation	1. Laser Traker Placement	Installation on tripod, tripod regulation, LT warm-up	40
	2. Software Running	PC power on, Software starting, selection of the type of SMR and the measurement geometry	5
Datum	3. SMR movement	SMR taking 4 points on the uMC face in X_B direction	0.6667
	4. Points association	Points naming and identification of surface	0.1333
	5. SMR movement	SMR taking 4 points on the uMC face in Z_B direction	0.6667
	6. Points association	Points naming and identification of surface in the software	0.1333
	7. SMR movement	SMR taking 4 points on the MRC face in X_{SC} direction	0.6667
	8. Points association	Points naming and identification of surface	0.1333
	9. SMR movement	SMR taking 4 points on the MRC face in Y_{SC} direction	0.6667
	10. Points association	Points naming and identification of surface in the software	0.1333
Alignment	11. Data obtaining	Closing measurement session and saving data	5
Analysis	12. Post Processing	Study of the obtained results	720(12 hours)

Table 7.3: Alignment flow blocks explanation for STT.

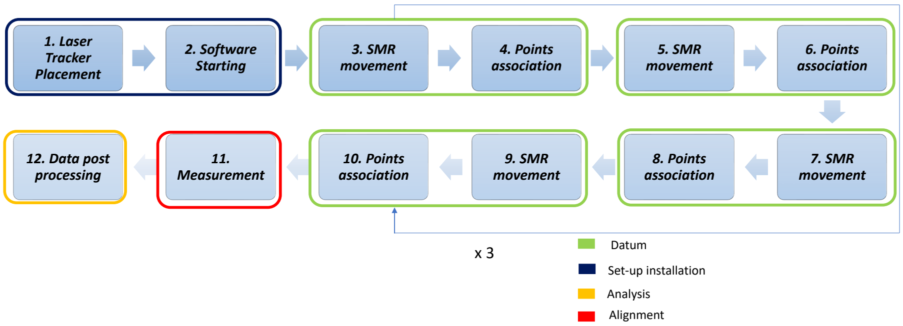


Figure 7.7: Alignment flowchart for STT.

7.3 X-Band Passive Antenna

In case a mirror cube is actually placed on the antenna support, all its exposed faces could be accessible as well as MRC, i.e.:

- z and y face of uMC;
- X_{SC} and Y_{SC} of MRC.

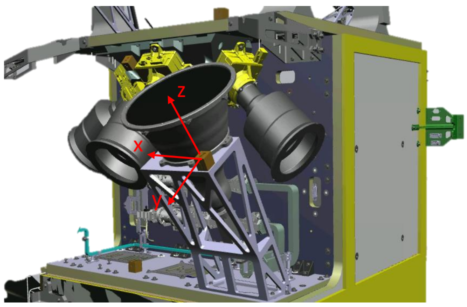


Figure 7.8: Hypothetical mirror cube on XBA.

The fundamental steps that need to be conducted have been summerized by the flowchart in Figure 7.9. Moreover, the operations described in the flowchart can be further detailed with an employed time estimation for the specified block, as shown in Table 7.4.

Function	Operation	Description	Time [min]
Set-up Installation	1. Laser Traker Placement	Installation on tripod, tripod regulation, LT warm-up	40
	2. Software Running	PC power on, Software starting, selection of the type of SMR and the measurement geometry	5
Datum	3. SMR movement	SMR taking 4 points on the uMC face in y direction	0.6667
	4. Points association	Points naming and identification of surface	0.1333
	5. SMR movement	SMR taking 4 points on the uMC face in x direction	0.6667
	6. Points association	Points naming and identification of surface in the software	0.1333
	7. SMR movement	SMR taking 4 points on the PMC face in z direction	0.6667
	8. Points association	Points naming and identification of surface	0.1333
	9. SMR movement	SMR taking 4 points on the PMC face in x direction	0.6667
	10. Points association	Points naming and identification of surface in the software	0.1333
Alignment	11. Data obtaining	Closing measurement session and saving data	5
Analysis	12. Post Processing	Study of the obtained results	720(12 hours)

Table 7.4: Alignment flow blocks explanation for XBA.

7.4 Issues

The measurement of all the aligning units are charachterized by the same issue, i.e. **mirror cube faces are small** with respect to typical Laser Tracker applications: it can result difficult taking discrete points on these surfaces, beside the fact that measurement accuracy is lower.
The following solutions may be considered:

1. A smaller reflector could be used, such as the 0.8 inches SMR. If necessary, if MGSE would obstruct SMR visibility from the tracker, a magnetic support bar could be used.

2. Whereas possible, surfaces different from mirror cubes can be considered, to have the possibility of measuring a wider surface directly on the unit.

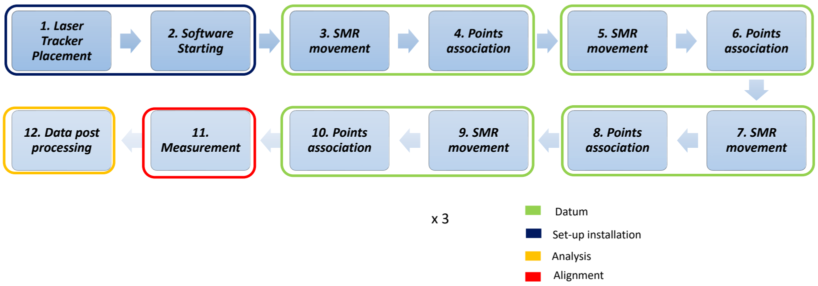


Figure 7.9: Alignment flowchart for STT.

But finding these surfaces is not always possible, and it could be a feasible solution only if the chain of tolerances is known, since alignment requirements are referred to a specified optical mean.

Figure 7.10: SMR of different dimensions.

7.5 Laser Tracker Empirical Evaluation

7.5.1 Overall measurement timing

In this section the entire alignment campaign duration is estimated, based on tables built up in this chapter.
All the analyzed configurations are detailed, considering the effect of the subsequent factors:

1. k, number of times the measurement is repeated on a single unit. Since repeated measurements will be considered in the *datum measurement time*, $k = 1$;

2. n, number of units.

The overall measurement time for a single alignment block has been calculated as follows:

$$\Delta t = \Delta t_{inst} + k \cdot n \cdot (\Delta t_{dm} + \Delta t_{obt}) + \Delta t_{pp}$$

where:

- Δt_{inst} is the **set-up installation time**;
- Δt_{dm} is the **datum measurement time**. Since it has been demonstrated in Chapter 5 that laser trackers can respect the accuracy requirement only in the context of the repeateted measurements, this measurement time has been evaluated as follows:

Time to process 4 points	0.8 min
Minimum number of repetitions per point	20
Time to process all the points	16 min
Number of surfaces	4
Time to process all the surfaces	**64 min**

Table 7.5: Datum measurement time.

- Δt_{obt} is the **data obtaining time**;
- Δt_{pp} is the **post-processing time**.

The results have been summerized in Table 7.6, as well as the overall time of the entire alignment campaign. The subsequent ΔT_i values are expressed in *minutes*.

Unit	**Block**	ΔT_{inst}	ΔT_{dm}	ΔT_{obt}	**k**	**n**	ΔT_{pp}	ΔT
Mini-CMG	PFM Al-01	45	64	5	1	4	720	1041
	PFM Al-02	45	64	5	1	1	720	834
STT	PFM Al-02	45	64	5	1	3	720	972
	PFM Al-03	45	64	5	1	3	720	972
	PFM Al-05	45	64	5	1	3	720	972
	PFM Al-06	45	64	5	1	3	720	972
XBA	PFM Al-05	45	64	5	1	1	720	834
	PFM Al-06	45	64	5	1	1	720	834

Table 7.6: Alignment blocks estimation time

From the above results it can be concludeded that the duration of the entire alignment campaign with laser tracker will last almost **16 days**.

Total Duration	**min**	**h**
	7431	**123.85**

Table 7.7: Alignment campaign duration.

7.5.2 Full set-up cost

The set-up cost analysis has been conducted considering as reference unit the **one-hour wage of a metalworker employee**, according to which is predicted by the Metalworking Industry contract.
Among the levels, 5^{th} metalworking level has been considered:
Therefore, a full set-up with Laser Tracker shall includes the elements described

Cathegory	**Employees**	**Minimum wage**
5	Intermediate and Skilled Workers	1806.99

Table 7.8: Minimum wage for a 5^{th} metalworking level.

in Table 7.9.

Tracker (including box, battery and cabling)	≈ € 120k
Tripod	≈ € 1k
Software Licence	≈ € 5k per year
Number of required tools	1
Cost of full set-up	**≈ € 126k**

Table 7.9: Mean costs for a set-up with Laser Tracker.

Considering the calculated hours from Table 7.7, it is reasonable to conclude that:

1. In case of *purchasing*, the entire estimated set-up cost shall be increased with the cost that the company would pay for the entire alignment campaign duration, based on the minimum one-hour wage[2] obtainable from Table 7.8;

2. in case of set-up *rental*, the entire estimated set-up cost shall be calculated considering that the external service has a mean cost of € 60 per hours.

[2]This must be calculated cosidering that company typically pays *twice* the minimum one-hour wage.

The obtained results have been reunited in Table 7.10.

Hours	**Purchase**	**Rental**
123.85	$\approx$ € 129k	$\approx$ € 8k

Table 7.10: Final cost estimation of the alignment campaign.

Conclusions

This work was created with the aim of comparing two valid technologies that are typically used in a Satellite alignment campaign and to understand which of the two is best suited to the needs dictated by the satellite design, although the presence of mirror cubes on some units suggests a predisposition to a measurement with theodolites.
The noteworthy features that emerged from this analysis are summerized in Table 7.11:

Feature	**Theodolite**	**Laser Tracker**
Compliance with accuracy requirements	✓	With repeateted measurements
Set-up complexity	High	Low
Campaign duration	27 days	16 days
Purchase cost	73k	129k
Rental cost	13k	8k

Table 7.11: Comparison between theodolites and laser tracker.

The applicability of the chosen set-up has been studied and possible solutions to emerged issues have been proposed. The first thing to be considered clearly concerns the accuracy required to the instrument, and this would allow to conclude that **the alignment campaign shall be entirely performed with theodolites, but under the following conditions**:

1. A further mirror cube is installed on mini-CMG 1 or 4 (PFM Al-01);
2. The panel mirror cube of IP is measured with respect to the MRC and P/F is placed on TT (PFM Al-02);
3. A mirror cube is intalled on XBA support and the P/F is in a deployed configuration (PFM Al-05/06).

This solution results to be also the most convenient in case the company chose to purchase the measurement set-up.
However, since a set-up with theodolites turned out to be particulary complex in terms of number of tools, number of set-up restoring and overall timing of campaign, **the measurement set-up with laser tracker can be considered by requiring an external service, but accepting the subsequent conditions**:

1. the achievement of the required accuracy has been demonstrated numerically;

2. since the proposed set-up is not strictly an optical one, some variables must be considered depending on the operator sensibility, SMR movement,and other factors related to the dynamic measurement.

For these reasons, it is reasonable concluding that the most reliable solution seems to be that with theodolites.

Open Point. Currently, the team is evaluating the possibility of using mirror cubes according to their primary function, (i.e. as *reflectors*) by building an optical set-up with Laser Tracker, as that described in Section 4.2.4, based on the measurement of the *mirrored point* of the SMR, located in a stable position, using laser triangulation and according a specified function that can be set in the software. In fact this set-up results to be the one able to optimize the tracker accuracy.

Aknowledgements

I would like to start this page by saying that I am extremely satisfied of the outcome of this thesis and that the work which it originates from has exceeded my expectations. Knowing that one day a satellite will be launched and knowing that I had the opportunity to work on it (even in a very little part) is something that fills with pride and satisfaction like few.
At Sitael I found a dynamic environment where collaboration is everything, every day is different from the previous one and where I met some beautiful peaple.
My first thanks are for Luca, for welcoming me to your team and for giving me the opportunity to work on this project. I soon realized how many your responsibilities were and above all how precious your time was, so thank you for cutting out some for this thesis and for all your precious teachings.
A big thank you is for Maria Bruna. I can only imagine how difficult it is working with someone starting from zero, so thank you for following me in pretty much everything, without ever bringing with superiority towards me. I am very glad I worked with you!
To Maria Bruna, Giuseppe G. and Michele I say thank you for all the help of these months and for letting me into your small group even before we met. With you the journey to Mola has never been boring!
Finally, my thanks are for all the guys of the AIT: Elisabetta, Claudio, Nicola, Alfredo, Felice, Francesco, Daniele and Gianluca, for having immediately made me feel comfortable in an environment unknown to me like the Company, as well as Giuseppe A., Venanzio, Ada and Luciana. I know I am not a person who speaks so much, but on the other hand I listen a lot and I have had the opportunity to learn something from each of you.
My last thanks are for my friends, my big family and for the peaple of my life.
Antonio, because after five years you still know how to leave me speechless. There are no right words to explain what you mean to me.
Agnese, because even if you're the youngest I always learn something from you and I wonder why you don't believe in yourself as well as I believe in you. You're my half and the most amazing girl I know.
Mom, because you were standing when everything collapsed. You're the rock of our family and my safe place in the world.

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ANNEX 1: MatLab Script

```
%%% Trasferimento incertezza da distanza a coordinate x,y e z+ incertezza
%%% su origine

close all
clear all
clc
%%%% Importa dati
%% 1.Crea matrice disposizioni su excel 'Disposizioni con ripetizione'
% 2. Copia in txt 'disposizioni'
% 3. Crea matrice punti e copiala su matrice_punti.txt
format long

Q=load('matrice_punti.txt'); %matrice dei punti acquisiti (teorici)
L=(Q(3,1)-Q(1,1))/10;
D=load('disposizioni.txt');
N=length(Q) ; %numero di punti su cui si effettua la misura
num_disposizioni=2^N; %numero di disposizioni
n=[0;0;1]; %vettore normale al piano

%%%%%% Calcolo della matrice degli errori assoluti %%%%%%

dist=2.5; %m, distanza ipotetica del tracker dall'oggetto

err_d_abs= %0.8828125 per disto, 15+6/m per LT MPE
err_origin=[0 0 0];%mm 0.416728874 0.692653206 0.35486 per disto
for i=1:length(Q)
        d(i)=sqrt(Q(i,1).^2+Q(i,2).^2+Q(i,3).^2);

        err_d_rel(i)=err_d_abs./d(i);

        alfa_rad=asin(Q(i,3)./d(i));
        beta_rad=atan(Q(i,2)./Q(i,1));

        err_xy_abs(i)=err_d_abs.*cos(alfa_rad);
        %%%Propagazione Errore Origine
        err_x_abs(i)=err_origin(1)+err_xy_abs(i).*cos(beta_rad);
        err_y_abs(i)=err_origin(2)+err_xy_abs(i).*sin(beta_rad);
        err_z_abs(i)=err_origin(3)+err_d_abs.*sin(alfa_rad);

        err_x_rel(i)=err_x_abs(i)./Q(i,1);
        err_y_rel(i)=err_y_abs(i)./Q(i,2);
        err_z_rel(i)=err_z_abs(i)./Q(i,3);
        i=i+1;

end
ERR_ABS_XYZ=[err_x_abs' err_y_abs' err_z_abs'];
ERR_REL_XYZ=[err_x_rel' err_y_rel' err_z_rel'];

%%%% Nuovi punti calcolati con errori ASSOLUTI
i=1;
d=ones(N,1);  %termine noto dell'equazione matriciale Q x= d dove in x ci saranno i
coefficenti del piano
err_angolo_rad=zeros(num_disposizioni,1); %vettore in cui saranno salvati tutti gli
angoli calcolati
```

```
err_angolo_deg=zeros(num_disposizioni,1); %vettore in cui saranno salvati tutti gli
angoli calcolati
for i=1:length(D)
  E=diag(D(i,:))*ERR_ABS_XYZ;
  Q_err=Q+E;
  %calcolo del piano con formula x=inv(QT Q)*QT *d
  x=inv(transpose(Q_err)*Q_err)*transpose(Q_err)*d;
  %Calcolo angolo tra piano e verticale
  %Salvo nelle variabili a,b,e c le tre componenti del vettore x. Sono le
componenti del vettore normale al piano
  a=x(1);
  b=x(2);
  c=x(3);
  err_angolo_rad(i)= atan(sqrt(a^2+b^2)/c);
  err_angolo_deg(i)=rad2deg(err_angolo_rad(i));
  i=i+1;
end
err_d_abs
num_disposizioni
L
Q
err_angolo_medio=mean(err_angolo_deg)
dev_st_angolo=std(err_angolo_deg)
err_angolo_max=max(err_angolo_deg)
err_angolo_min=min(err_angolo_deg)
```

```
clear all
clc


format long

e_datasheet=0.051; %%%STD a 1.5 metri
confidenza=2; % 2 se errore dato con livello di confidenza 95%, 1 se livello di
conf 68%, 3 se livello di confidenza 99%
dev_std_e=e_datasheet/confidenza;

Q=load('matrice_punti.txt');
N_rep=[1 2 5 10 20 50 100 200 500];  %gira su j
N_points=length(Q);

M=500;

for j=1:length(N_rep)
    for h=1:M
ERR_X_ABS=zeros(N_points,1);  %%%vettori con i valori medi
ERR_Y_ABS=zeros(N_points,1);
ERR_Z_ABS=zeros(N_points,1);


for i=1:N_points

    dist(i)=sqrt(Q(i,1).^2+Q(i,2).^2+Q(i,3).^2);
    alfa_rad=asin(Q(i,3)./dist(i));
    beta_rad=atan(Q(i,2)./Q(i,1));
```

```
    err_x_abs=zeros(N_rep(j),1);
    err_y_abs=zeros(N_rep(j),1);
    err_z_abs=zeros(N_rep(j),1);

for k=1: N_rep(j)

       %errore casuale commesso sull'k esimo punto, estratto randomicamente da
distribuzione gaussiana con
       %media 0 e dev_std_e come deviazione standard.

        err_d_abs(k)=dev_std_e*randn(1,1);
        err_xy_abs(k)=err_d_abs(k).*cos(alfa_rad);

        err_x_abs(k)=err_xy_abs(k).*cos(beta_rad);
        err_y_abs(k)=err_xy_abs(k).*sin(beta_rad);
        err_z_abs(k)=err_d_abs(k).*sin(alfa_rad);
end
   ERR_X_ABS(i)=mean(err_x_abs);
   ERR_Y_ABS(i)=mean(err_y_abs);
   ERR_Z_ABS(i)=mean(err_z_abs);

   DEV_ST_X(i)=std(err_x_abs);
   DEV_ST_Y(i)=std(err_y_abs);
   DEV_ST_Z(i)=std(err_z_abs);

end  %%%da qui ho il piano e posso misurare l'errore angolare
random_error_matrix=[ERR_X_ABS ERR_Y_ABS ERR_Z_ABS];
stand_dev_matrix=[DEV_ST_X' DEV_ST_Y' DEV_ST_Z'];

Q_err=Q+random_error_matrix;

  %Calcolo del piano con formula x=inv(QT Q)*QT *d
  d=ones(length(Q),1);  %termine noto dell'equazione matriciale Q x= d dove in x ci
saranno i coefficenti del piano


  x=inv(transpose(Q_err)*Q_err)*transpose(Q_err)*d;
  %Calcolo angolo tra piano e verticale
  %Salvo nelle variabili a,b,e c le tre componenti del vettore x. Sono le
componenti del vettore normale al piano
  a=x(1);
  b=x(2);
  c=x(3);
  err_angolo_rad(h)= atan(sqrt(a^2+b^2)/c);
  err_angolo_deg(h)=rad2deg(err_angolo_rad(h));
end   %%%qui ho l'errore in corrispondenza di N(J)
MEDIA(j)=mean(err_angolo_deg);
DST(j)=std(err_angolo_deg);
end
MEDIA'
DST'
MAX=MEDIA'+DST'
```

Alignment Measurement with 3D Disto 12/01/2021

	Name & Function	Date	Signature	
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TABLE OF CONTENTS

1. INTRODUCTION

1.1. Scope

The current report contains the full description of the test made on January 12, 2021 with the 3D Disto on STT dummies installed in a satellite representative configuration, with the purpose of simulating at an alignment measurement upon PLT-1 Satellite. The main objectives that needed to be reached during these measurements are the following:

- To know more closely 3D Disto potential and get some expertise on its use;
- To evaluate the better position for the Measurement Reference Frame (this shall be similar as more as possible to the Satellite Master Reference Frame);
- To check planes that can be used as references;
- To measure units inclination with respect to the Reference Frame (post-processing).

1.2. Context

The AIT plan requires to perform a certain number of alignments on PLT-1 units (see Alignment plan for further details). Right now, there is no equipment to perform these measurements, since the investigation of the reliable technologies is still going on and the instrument choice and the consequent setup building is in phase of definition.

In this context, the possibility of using 3D DISTO, already present in MERMEC, has been evaluated. To have greater understanding of its application feasibility and to establish if the instrument is appropriate for the requested measurements, the team has decided to perform the measurement upon the STT dummies, the most suitable available units because of their overall geometry, very similar to that of STT on Satellite.

1.3. Reference Documents

ID	Ref.	Title
[RD 1].		

ID	Ref.	Title	Tailoring	
[AD 1].				

2. TEST PREPARATION

The test activity is performed in the Shaker Room of Sitael and the entire AIT Thermo-Mechanical team together with two MERMEC engineers is present. All personnel involved have reviewed the measurement procedure before beginning AIT activities and understand what hazards may be encountered. The test procedure shall be notified to the customer as applicable.

2.1. Instrument Supply

Those present make sure that the instrument supply has been properly transported to the Shaker Room and that it is properly closed and ready to be opened.

The instrument supply involves:

- A red box, containing the 3D Disto, battery, palmtop , PC cables and stickers for targets;
- A black box, containing user manual and additional documentation;
- The box containing the tripod.

CAUTION is required in the handling of the ITEM in order to avoid damaging of the structures.

2.2. Test Environment

As already specified, the current measurements have been performed in the Shaker Room of Sitael in the following environmental conditions:

- Temperature: ambient
- Relative humidity: ambient
- Pressure: ambient

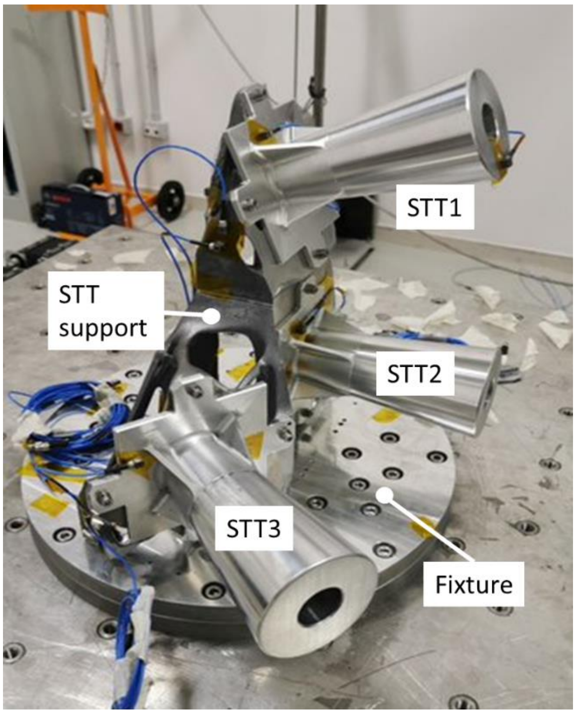
NOTE: during the satellite AIT campaign the environmental constraint will be the following:

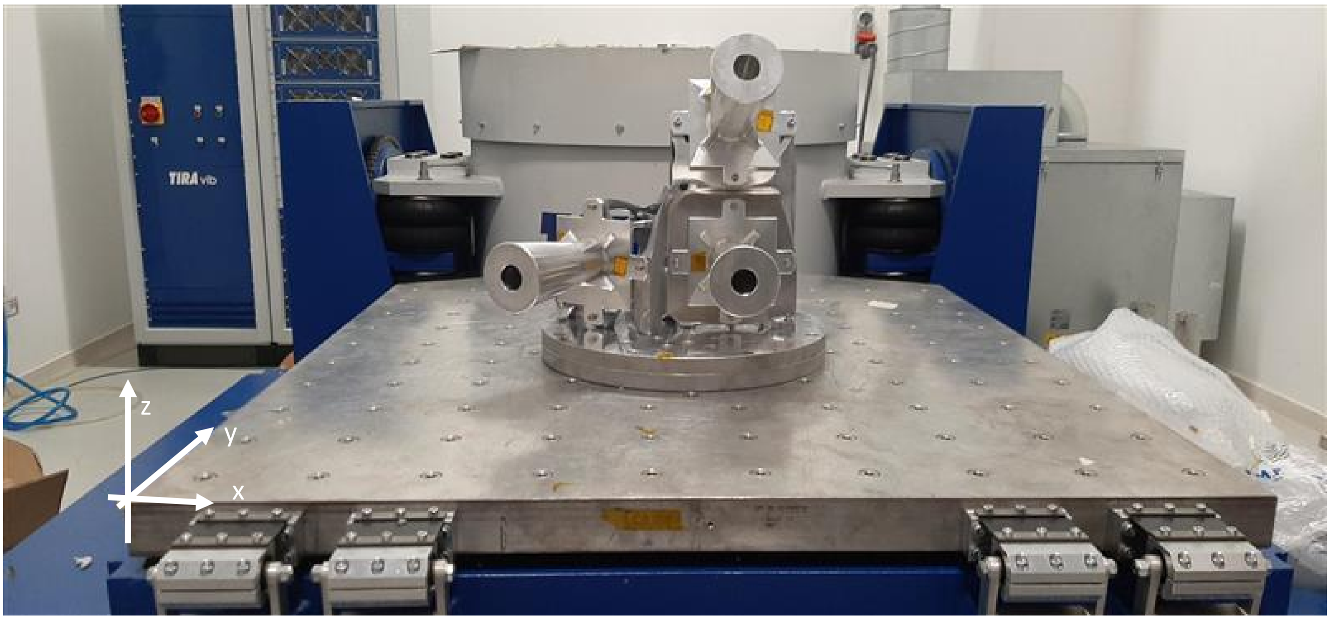
- Temperature: 22°C ± 3°C
- Relative humidity: 55% ± 15% RH
- Pressure: ambient
- Cleanliness: clean room ISO 8

2.3. Setup Organization

2.3.1. Item description

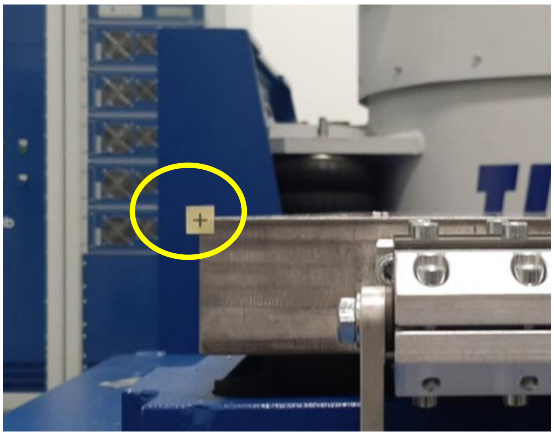
To be relevant this demonstration shall be made in a configuration as close as possible to the that reached during satellite AIT. For this reason the STT dummies have been chosen and properly mounted as shown in figure :



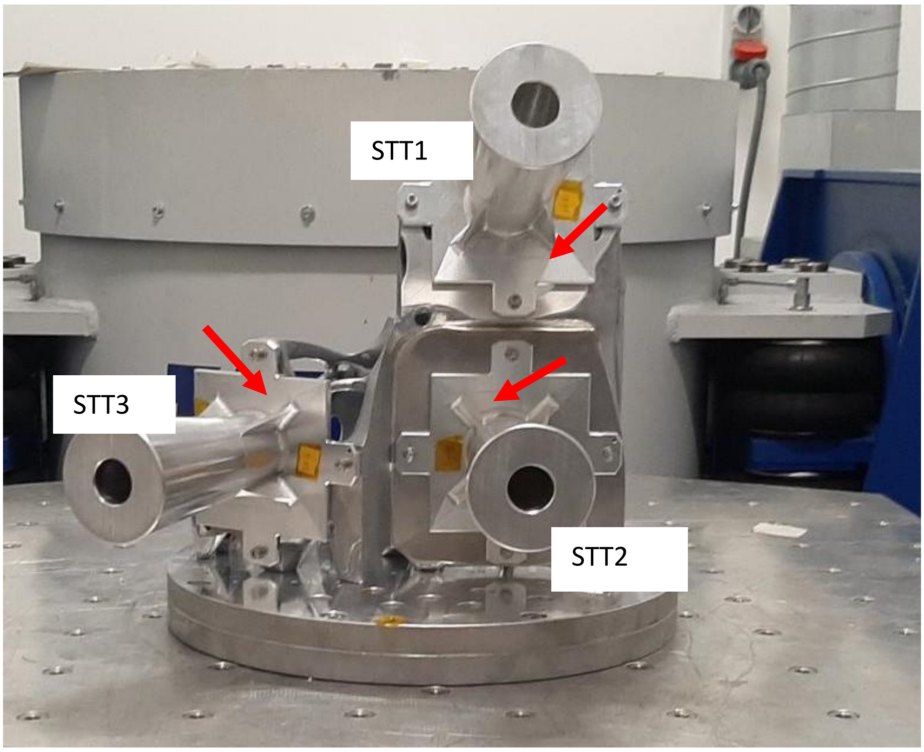


As shown in the above figure it has been established that the main measurement reference system should be located on the upper left apex of the platform. In fact, this point can be well representative of an external reference for the Satellite. The three-orthogonal axes x, y and z will be recognized by 3D Disto as E, N and H respectively.

Since an apex can be difficult for the laser to point, it has been necessary to apply a sticker.



As for the reference chosen for the three units, it has been established to take the plane on each support surface. Points that are taken on these surfaces don't need stickers applications and can be checked in an easier way.

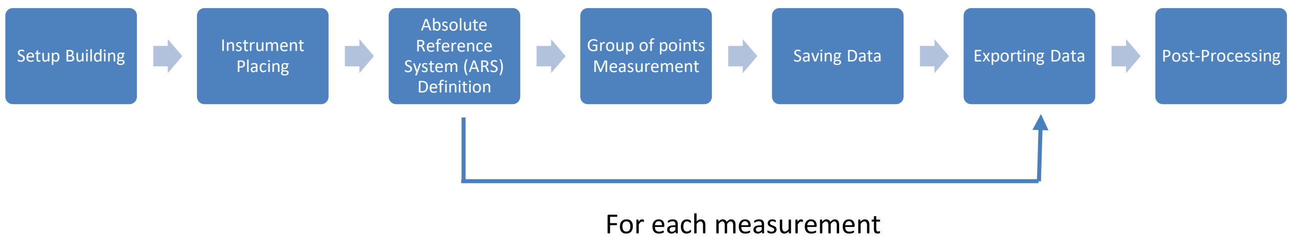


2.3.2. Instrument placing

Since the position of the reference frame has been established, the instrument will be placed so that it can involve in its visual cone the entire setup. Given the overall height reached by the dummies on the platform, it has been established to locate the 3D Disto on the ancillary tripod. Tripod is regulated in height and so fixed, while the 3D Disto is fixed on its plate level. The tool is turned on and started to warm-up.

2.4. Test Execution

The main phases of the test can be summarized by the following activity flow:



3D Disto recognizes the ASR points as Point 1 and Point 2. All the other points enumeration follows from Point 3 and stops when measurement is over and ready to be saved.

During the test, *two* measurements have been taken and data saved:

- **Measurement 1: STT 3 with respect to ARS;**
- **Measurement 2: STT 1, STT 2, STT 3 with respect to ARS and Slip Table.**

NOTE: Since STT 3 surface has been measured twice, taken points will be elaborated in the post processing for a further error analysis.

2.4.1. Absolute Reference System (ARS) Definition

3D Disto is able to build up the ARS in two different way:

- **Auto-leveling**: A built-in tilt sensor ensures that measurements refer to the true horizon or true lead line, defined by gravity. The inclination is controlled by a special sensor and the instrument levels itself if the inclination is less than 3°. In this situation, the tool needs to measure just two points for building up the absolute reference system, where the first represents the ARS origin;
- **No auto-leveling**: if the auto-leveling function is deactivated, two measured points (the first is the origin) defines the horizontal direction, and the vertical is perpendicular to it in the origin. A further constraint needs to be imposed for blocking the reference system degrees of freedom.

For the current test, ARS is defined with auto-leveling on. As said in 2.3.1, the upper left apex (with target sticker on it) of the platform is chosen as Point 1 and origin. Point 2 is chosen arbitrarily on xz surface.

After taking the points, 3D Disto shows on the palmtop all the useful data such as distance, height, inclination.

2.4.2. Group Definition

In the current test, points have been measured on the chosen surface in two different ways:

- **Single-point measurement**;
- **Grid measurement**: this function allows to scan a surface first by selecting some points to create an outline, then selecting the desired distance between one point and another inside the delimitated area.

The following table contains the details of the two measurements in terms of group, points enumeration and measurement mode. TBC

Measurement	Group	Points	Surface	Measurement Mode	Notes
1	1	1-2	XZ of the Slip Table	Single-Point	ARS
	2	3-12	STT3 Support	Single-Point	Measuring Unit
2	1	1-2	XZ of the Slip Table	Single-Point	ARS
	2	3-12	STT 1 Support	Single-Point	Measuring Unit
	3	13-22	STT 2 Support	Single-Point	Measuring Unit
	4	23-32	STT 3 Support	Single-Point	Measuring Unit
	5	33-52	XY of the Slip Table	Single-Point	Geometrical Reference
	6	53-72	XZ of the Slip Table	Single-Point	Geometrical Reference
	7	73-92	YZ of the Slip Table	Single-Point	Geometrical Reference
	8	93-112	XY of the Slip Table	Grid step 10 mm	Geometrical Reference
	9	113-132	XZ of the Slip Table	Grid step 10 mm	Geometrical Reference
	10	133-152	YZ of the Slip Table	Grid step 10 mm	Geometrical Reference

2.5. Post Processing

Measurement 1 and 2 have been saved in two folders, named 210112_001 and 210112_002 respectively. Each folder contains all the taken points in a .txt., .csv and .dxf format. Points will be imported in Catia to build up surfaces and to impose constraints.