Spacecraft tracking implications on operations and the design of small satellites

SmallSatTrack Study

Executive Summary

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1 INTRODUCTION

This Report describes the activities carried out by the Industrial Organisation formed by Telespazio S.p.A. as Prime Contractor, with three subcontractors: Tyvak, OHB Italia and e-GEOS. The Team was also supported by the S5Lab research team of CRAS (Centro Ricerca Aerospaziale Sapienza) acting as supplier and Italian Space Agency Expert acting as Scientific Advisor

1.1 Background and Objective(s)

1.1.1 Background

Recent trends in miniaturisation of space hardware combined with the provision of affordable and standardised spacecraft components and structures is opening up space to new players and is rapidly increasing the traffic into orbit. While launcher technology is essentially still using the same concepts as during the start of the space age, very different actors are now placing in orbit small and very small satellites (micro-, nano-, pico-, including standardised CubeSats), often piggybacking on medium/large class launch vehicles and aggregated in order to be released in large numbers from a single launch. Recent examples demostrated the release of hundred of satellites with a single launcher .

These small or very small satellites follow non-classical approaches both for their design and for their operations. They also bring with them new types of operators, some of which may have very limited resources for the development and the operation of their mission.

Depending on the operational altitude these small satellites, if effectively deployed as a large constellation, could become a source of severe concern for other established operators by potentially increasing the spatial object density above a critical level. This is currently under intensive study and no definite conclusions have been published yet.

Irrespective of the design approach and the maturity of the components, it is rather common for small satellites to follow a cost-efficient flight dynamics and operations scenario that is purely relying on publicly available two-line element (TLE) sets provided by the USSTRATCOM. No alternative data source of comparable completeness and availability exists today. This approach has, however, some major implications, as it fully relies on the ability of the US-SSN to rapidly track, discriminate, and identify the satellite. The sensitivity of the network is not published, but usually 10cm objects in LEO are assumed as a typical limit. However, the US-SSN TLEs do not guarantee a timely provision of needed input data to steer ground stations to establish contact with the mission. For most of the small satellites of the recent mass releases, the first TLE was available only after more than 1 week.

New technologies have to be found to improve the tracking of such as small object. This is the goal of this Study.

1.1.2 Objectives

The main objectives of the study have been:

- Describe the Commercial Off The Shelf (COTS) available technologies for augmenting tracking of small satellites from Earth.
- Analyse the return and timeliness in terms of surveillance networks identification, tracking, and orbit/attitude determination for augmented small satellites w.r.t. non- augmented versions.
- Assess the impact on system design and operations for pico and micro satellites when installing the identified technologies based on the identified COTS technologies.
- Analyse the potential of applying the same technologies from small satellites to larger satellites and rocket bodies.
- Derive a set of draft design and operation requirements, achievable with COTS or near term technologic developments on the satellite side.
- For the technologies, which are not COTS a possible development roadmap up to TRL 9 will be provided.
- Provide sufficient documentation to get unique identification of an object as a way of operationally supporting the Registration convention obligations independent of national surveillance networks

The team involved was able to provide all the necessary capabilities (management, system engineering, small and large satellite manufacturing and AIV, Laser and Radar tracking stations) to fully achieve the above list of objectives.

The long term objective of this team, at the end of this study is to submit to ESA, an unsolicited proposal for the direct verification of the most promising and more mature tracking technologies identified. In fact the proposing team has all necessary capabilities to eventually realize a flight demonstration unit (s) based on the outcome of this study. Therefore we are proposing the realization of a one or more cubesats (or small spacecraft), which will include also the sensors and s/s requested to implement the identified tracking methodologies. The idea is to do the manufacturing phase in short time and to identify a corresponding launch opportunity with the aim to verify the performances during a real flight using the ground station surveillance networks. In this way the authors are willing to verify the performances of the different most promising technologies selected, and will increase their corresponding TRL up to TRL#9.

1.2 Technical Implementation / Programme of Work

1.2.1 Proposed Work Logic

The overall work logic of the study is complaint with SoW requirements and will be organised as follows:

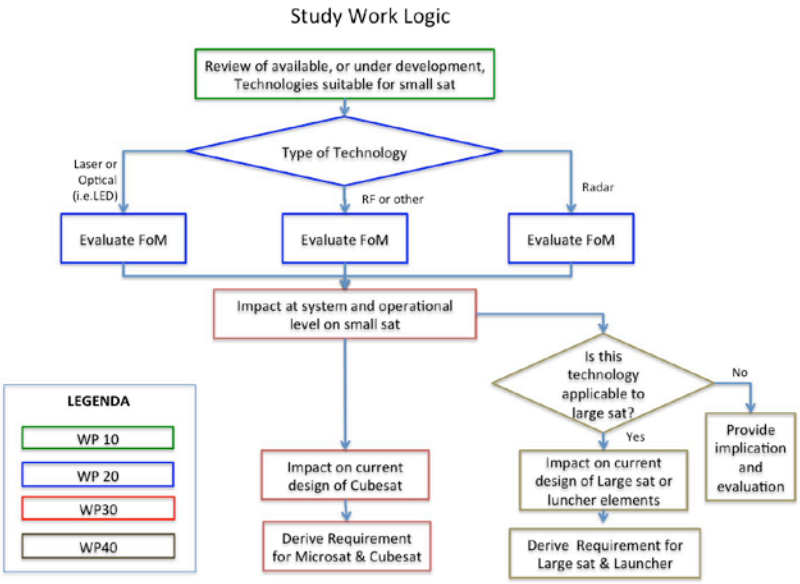

Figure 1-1: Work logic used in the study

1. The available, or under development, technologies to increase the observability of orbit and attitude motion of small satellite in space considering:
a. onboard passive elements suited to be tracked by active sensors on ground
b. onboard active elements suited to be tracked by active sensors on ground
c. onboard active s/s able to acquire and downlink to ground directly orbit and attitude data
have been identified and analysed.
2. The technologies explored were grouped in classes (i.e. Radar, Laser, RF and other)
3. The FoMs generic and specific on each technologies, belonging to the classes identified, were defined together with ESA and the related value for each technology identified was evaluated.
4. For the technologies identified more promising were evaluated the applicability to small satellites considering three classes of satellite where the system should be installed: smallsat- 3U Cubesat and picosat .
5. The impact of those technologies on the ground surveillance networks (mainly laser, observation and radar) in terms of tracking was assessed and quantified, together with the impact at system and operational levels on the small satellites.
6. The possibility of scaling the concept up towards large satellites, capsules and launcher elements shall be analysed with the same metric as applied for small satellites.
7. The conclusions of this study dealing with the feasibility of applying the tracking technology concepts to small satellites will be presented at the end of the study. A report containing draft requirements will be delivered. It will document the impact of the specific technologies on current design procedures and will provide indication where further support is required.

The above steps of the work logic sequence is depicted in the flow chart reported in the Fig.1

As per AD1 the WP30 looks into the concepts identified in both WP10 and WP20 to assess their impact applicability on small satellites design. In particular, the WP30 addresses the technology impact at system and operational levels on small satellites.

As shown in Figure 1-2, the study will be carried out by following a step-by-step approach based on the following phases:

A. Impact applicability assessment on various aspects of small satellites;
B. Technology implementation on multiple small satellite classes;
C. Results analysis and release of deliverable documents.

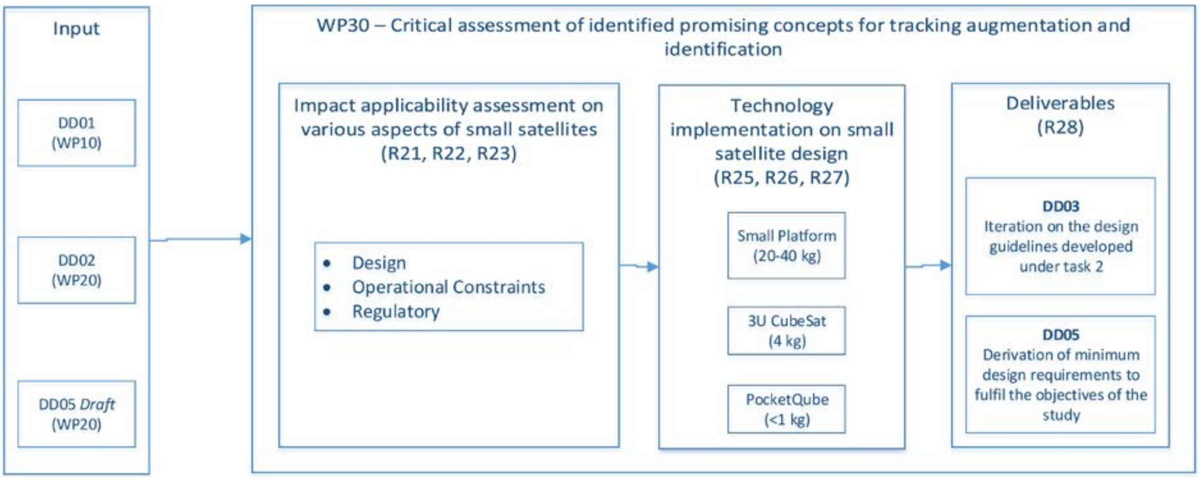

Figure 1-2: Work Logic flowchart from start up to the assessment of the identified concept

Acronyms and Abbreviations

The following table contains all acronyms and abbreviations used in the current document.

Acronym.	Definition
ASI	*Agenzia Spaziale Italiana* - Italian Space Agency
COTS	Commercial Off The Shelf
D4R	Design for Removal
ELROI	Extremely Low Resource Optical Identifier
EO	Earth Observation
FOM	Figure Of Merit
FWHM	Full Width at Half Maximum
FOV	Field Of View
FP	Final Presentation
FS	Flight Segment
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
GS	Ground Segment
IADC	Inter-Agency Space Debris Coordination Committee
ISAR	Inverse Synthetic Aperture Radar
ISON	International Scientific Optical Network
ISS	International Space Station
ILRS	International Laser Ranging Service
JSpOC	Joint Space Operations Center
KOM	Kick-off Meeting
LANS	Los Alamos National Security
LEO	Low Earth Orbit
LRR	Laser Retro Reflector
MEMS	Micro-Electro-Mechanical Systems
MLRR	Modulated Laser Retro Reflector
OBDH	OnBoard Data Handling
PM	Progress Meeting
RCS	Radar Cross Section
RF	Radio Frequency
RRR	Radar Retro Reflector
SAA	South Atlantic Anomaly
SLR	Satellite Laser Ranging
SoW	Statement of Work
TLE	Two-Line Element
TN	Technical Note
TRL	Technology Readiness Level
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
US SSN	United States Space Surveillance Network
VAFB	Vandenberg Air Force Base
WEB	World Wide Web or www or abbreviation WEB

Table 1-1:Acronyms and Abbreviations

2 THE PROPOSED TECHNOLOGIES

In the following a short description of the technologies the Team have identified is presented:

1. **Passive Electrical Radar Dipole**: A suitable technology is the installation of electromagnetic dipole interacting with the radar emission. Dipole are installed to increase the equivalent RADAR Cross Section

2. **Active Radar Repeater**: A Radio transceiver that, activated by a specific code detected by the receiver, is activating the transmitter (both receiver and transmitter are working on the same frequency of the radar with/or without Doppler compensation)

3. **Radar Reflector:** Usually a radar reflector is a passive structure used to reflect the impinging radar beam in the same direction from where the signal is arriving. The same idea could be used also with similar active device where the signal is regenerated and transmitted in the same direction

4. **ISAR**: The Inverse Synthetic Aperture Radar (ISAR) technology has been extensively applied to reconstruct the shape of objects, exploiting the relative movement between imaged object and the radar

5. **Passive Optical Tracking**: Usage of telescopes is still a valid method for LEO orbit determination. Their cost and technology can be in the accessible ranges for most users so large networks of amateur are existing across the world

6. **Passive Laser Retro-reflector (LRR)**: Laser micro-retro-reflectors are proposed as a potential system to discriminate several similar satellites of multiple launches or constellations and to determine their respective orbits

7. **Active Laser Retro-Reflector or Modulated Laser Retro-Reflector (MLRR or MRR)**: A shutter, mounted in front of the LRR, is activated by the impinging laser beam and is modulating the reflected laser signal. Continuous laser beam is requested

8. **Modulated LED's**: Light Emitting Diodes (LEDs) array installed on satellites for optical tracking with ground-based telescopes. The array could be also activated with a fixed sequence of short and long pulse as mark to identify the satellite

9. **Coloured LED's**: the authors proposed the use of a LED arrays with different wavelengths that can be tracked by more complex ground based telescopes having a CCD with a large wavelength capability to track sat and determine the identification

10. **Modulated Laser Beam**: the systems consists both of a micro-laser beacon attached to the spacecraft and a telescope system to track space objects.

11. **Space Transponder**: it should operate in a similar mode of a commercial "aircraft transponder", transmitting the satellite position and the orbit parameters by using a radio digital short transmission. It should minimize the transmission time to reduce interference and power consumption and could activated the Tx only when the satellite is in the visibility of one Ground Stations

12. **Radio Beacons**: on board radio-beacons might be used to track satellites through the ground signal analysis as acquired by fixed antenna. The system will allow univocal track of the flight object and its actual orbit using accurately timed Doppler shift data from a single or, even better, from multiple ground stations during the sat pass over the station.

3 TECHNOLOGIES ANALYSIS

An analysis of the identified technologies has been carried out and presented in form of tables to provide further indication for the subsequent step aimed at identify the most promising or effective one

3.1 Preliminary Qualitative Parameters Analysis

The first effort has been to select a number of features relevant for the satellite tracking and identification. The features have been defined so that it was possible to identify if the specific technology could provide or not that feature and for each technology we provide a simple yes/no correspondence

In addition the way the features were presented was that the affirmative correspondence was considered as a positive aspect, therefore the simple counting of the <Yes> for each technology was providing also a qualitative score for it. The features identified are reported on the header row.

Micro-Sat / CubeSat

Method	Independent on Preliminary orbit knowledge (i.e.TLE)	Operative Day & Night	Immune to Clouds Coverage	Device dimensions compatible with Cubesat	Simple & Cheap Ground Station (<100Keuro each)	Passive element onboard small satellite	System autonomy with respect to hosting satellite	Simple Micro Satellite discrimination	Accurate Satellite Attitude determination	Accurate Micro-Satellite Unique Discrimination	Capability to retrieve other physical characteristics (area to mass ratio, shape,)	Draft Score
Radar Dipole	No	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	No	12
Radar Repeater	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes	No	12
Radar Reflector	No	Yes	Yes	Yes	No	Yes[7]	Yes[11]	Yes	No	Yes[7-10]	No	13
ISAR (Inverse Synthetic Aperture Radar)	No	Yes	Yes	No	No	Yes	Yes	No[12]	No[13]	No[12]	Yes	11
Laser Passive Retro-Reflector	No	Yes	No	Yes[4]	No	Yes	Yes	No	Yes	Yes	No	13
Passive Optical tracking[8]	No	No	No	Yes	Yes	Yes	Yes	No	No	No	Yes	14
Laser Modulated Retro-Reflector MRR	No	Yes	No	Yes	No	No	No	Yes	No	Yes	No	8
Pulsating LED[2]	No	No	No	Yes	Yes	No	No	Yes	No	Yes	No	11
Specific Frequency LED	No	No	No	Yes	Yes	No	No	Yes	No	Yes	No	10
Modulated Laser Beam	No	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	12
Space Transponder[3]	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes[14]	Yes[5]	No	14
Satellite Radio Beacon	Yes	Yes	Yes	Yes	Yes	No	Yes[9]	Yes	No	No	No	12

[1]Indicates the measurement is guaranteed in the reported time (2-3 hrs) without any mission-specific additional ground station
[2]The pulsating Led technology was demonstrated (2013) on a Japanese cubesat FITSAT-1 (NIWAKA) dedicated to this task. It required the use of large batteries and high-power LED Arrays on two sides of cubesat
[3]Based on the assumption the Space Transponder ground segment formed on a network of more than 60 micro-ground stations, globally distributed, is operative
[4]It is assumed here the utilization of small flat retro-reflector 1 cm diameter.
[5]For the object unique discrimination in case of satellites cloud or formation, since all satellites are entering in the visibility cone at the same time, a TDMA shall be implanted to assign transmission time slot to each sat
[6]The measure depends only on the precision of the navigation system unit, part of the Space Transponder onboard card
[7] The radar reflector is passive, but the deployment of the radar reflective surface could be active and controlled from ground
[8] The assumption here is to use the ground observation network formed by tens of observation stations
[9] It is possible to install a battery powered beacon activated by fixed signals emitted from ground station which is operative only the first 30 days of mission
[10] It is possible to have the unique identification in case of active radar reflector, switched by telecommand during radar observation (or measurement)
[11] It is <Yes> in case of Passive Radar Reflector, otherwise for Active Radar Reflector it is <No>
[12] Under the assumption all the satellite are very similar in aspect and geometry
[13] Under the assumption the micro-sat has symmetrical shape and therefore it is not so easy to discriminate the attitude on the basis of "blurry" images
[14] The attitude is measured by the internal sat sensor and communicate to the Space Transponder that include these data into the data burst transmitted to ground

Table 3-1 Micro-Sat/Cubesat: Qualitative parameters for technologies evaluation (1/2)

Micro-Sat / CubeSat

Method	Immune to Electro-magnetic disturb on RF	Immune to Space weather	Satellite position determination < 2-3 h from launch[1]	Direct Measurement (no ground data analysis)	Techno-logical simplicity	Accurate Satellite Location and Orbit determination	Already Tested on Small Satellite in Orbit	Simple Small Satellite Design Change	Cheap Small Satellite components to be added	Independent on Navigation System (GPS, GALILEO, GLONASS)	Draft Score
Radar Dipole	Yes	Yes	Yes	No	**No GS** Yes FS	Yes	No	No	Yes	Yes	12
Radar Repeater	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	12
Radar Reflector	Yes	No[15]	Yes	No	No	Yes	Yes	No	Yes	Yes	13
ISAR (Inverse Synthetic Aperture Radar)	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	11
Laser Passive Retro-Reflector	Yes	Yes	No	No	**No GS** Yes FS	Yes	Yes	Yes	Yes	Yes	13
Passive Optical tracking	Yes	Yes	Yes [8]	No	Yes	Yes	Yes	Yes	Yes	Yes	14
Laser Modulated Retro-Reflector MRR	Yes	No	No	Yes	**No GS** Yes FS	Yes	No	No	No	Yes	8
Pulsating LED[2]	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	11
Specific Frequency LED	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	10
Modulated Laser Beam	Yes	No	Yes[11]	Yes	No	Yes[12]	No	Yes[13]	Yes[14]	Yes	12
Space Transponder	No	No	Yes[3]	Yes	Yes	Yes[6]	No	Yes	Yes	No	14
Satellite Radio Beacon	No	No	No	No	Yes	No	Yes	Yes	Yes	Yes	12

[1]Indicates the measurement is guaranteed in the reported time (2-3 hrs) without any mission-specific additional ground station
[2]The pulsating Led technology was demonstrated (2013) on a Japanese cubesat FITSAT-1 (NIWAKA) dedicated to this task. It required the use of large batteries and high-power LED Arrays on two sides of cubesat
[3]Based on the assumption the Space Transponder ground segment formed on a network of more than 60 micro-ground stations, globally distributed, is operative
[4]It is assumed here the utilization of small flat retro-reflector 1 cm diameter.
[5]For the object unique discrimination in case of satellites cloud or formation, since all satellites are entering in the visibility cone at the same time, a TDMA shall be implanted to assign transmission time slot to each sat
[6]The measure depends only on the precision of the navigation system unit, part of the Space Transponder onboard card
[7] The radar reflector is passive, but the deployment of the radar reflective surface shall be active and controlled from ground
[8] The assumption here is to use the ground observation network formed by tent of observation stations
[9] It is possible to install a battery powered beacon activated by fixed signals emitted from ground station which is operative only the first 30 days of mission
[10] It is possible to have the unique identification in case of active radar reflector, switched by telecommand during radar observation (measurement)
[11]Based on the assumption the ELROI Modulated Laser beam ground segment formed on a network of more than 30 ground stations, globally distributed, is operative.
[12] Based on the ELROI presentation [RD-52 where it is stated that from the analysis of the modulated signal transmitted over about one hundred of seconds, the satellite tracking with metric precision is feasible.
[13] If stamp-size flight device is developed as planned
[14] If large mass production is implemented (cost of the flight unit order of a thousand of Euros)
[15] The mechanical part is immune, but the electronic requested to activate the reflector by tele-command from ground is influenced by space weather

Table 3-2 Micro-Sat/Cubesat: Qualitative parameters for technologies evaluation (2/2)

Pico-Sat

Method	Independent on Preliminary orbit knowledge (i.e.TLE)	Operative Day & night	Immune to Clouds Coverage	Device dimensions compatible with Cubesat	Simple & Cheap Ground Station (<100Keuro each)	Passive element onboard small satellite	System autonomy with respect to hosting satellite	Simple Pico Satellite discrimi-nation	Accurate Satellite Attitude deter-mination	Accurate Satellite Unique Discrimi-nation	Capability to retrieve other physical characteristics (area to mass ratio, shape.)	Draft Score
Radar Dipole	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No[2]	Yes	No	14
Radar Repeater	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes	No	
Radar Reflector	No	Yes	Yes	No	No	Yes[7]	No	Yes	No	No	No	
ISAR (Inverse Synthetic Aperture Radar)	No	Yes	Yes	No	No	Yes	Yes	No	Yes (?)	Yes(?)	Yes	
Laser Passive Retro-Reflector	No	Yes	No	Yes[1]	No	Yes	Yes	No	No[2]	No[3]	No	11
Passive Optical tracking	No	No	No	Yes	Yes	Yes	Yes	No	No	No	Yes	
Laser Modulated Retro-Reflector MRR	No	Yes	No	Yes	No	No	No	Yes	No	Yes	No	
Pulsating LED[2]	No	No	No	Yes	No	No	No	Yes	No	Yes	No	
Specific Frequency LED	No	No	No	Yes	No	No	No	Yes	No	Yes	No	
Modulated Laser Beam	No	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	12
Space Transponder[3]	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes[5]	No	
Ground Measurement based on Satellite Radio Beacon	Yes	Yes	Yes	Yes	Yes	No	Yes[4]	Yes	No	No	No	13

[1] It is assumed here the utilization of small flat retro-reflector 1 cm diameter, that the TLE are already known
[2] It is assumed here the dimension of Picosats are few centimeters square (i.e.2.5x2.5 cm) so that the micro-reflectors could be attached to the sat surface are so limited that the attitude identification is not possible
[3] It is assumed here the Picosats of few centimeters square (i.e.2.5x2.5 cm) so the number of micro-reflectors could be attached to the sat surface is so small that the unique identification based on different patterns is not possible
[4] It is possible to install a battery powered beacon activated by fixed signals emitted from ground station which is operative only the first 30 days of mission

Table 3-3 PicoSat: Qualitative parameters for technologies evaluation (1/2)

Pico-Sat

Method	Immune to Electro-magnetic disturb on RF	Immune to Space weather	Satellite position determination < 2-3 h from launch[1]	Direct Measurement (no ground data analysis)	Techno-logical simplicity	Accurate Satellite Location and Orbit determination	Already Tested on Pico Satellite in Orbit	Simple Pico Satellite Design Change	Cheap Pico Satellite components to be added	Independent on Navigation System (GPS, GALILEO, GLONASS)	Draft Score
Radar Dipole	Yes	Yes	Yes	No	No GS Yes FS	Yes	Yes	No	Yes	Yes	14
Radar Repeater	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	
Radar Reflector	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes	
ISAR (Inverse Synthetic Aperture Radar)	No	No	No	No	No	Yes	No	No	Yes	Yes	
Laser Passive Retro-Reflector	Yes	Yes	No	No	No GS Yes FS	Yes	Yes	Yes	Yes	Yes	11
Passive Optical tracking	Yes	Yes	Yes[8]	No	Yes	Yes	Yes	Yes	Yes	Yes	
Laser Modulated Retro-Reflector MRR	Yes	No	No	Yes	No GS Yes FS	Yes	No	No	No	Yes	
Pulsating LED[2]	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	
Specific Frequency LED	Yes	Yes	No	No	Yes	Yes	No	No	No	Yes	
Modulated Laser Beam	Yes	No	Yes[1]	Yes	No	Yes[2]	No	Yes[3]	Yes[4]	Yes	12
Space Transponder[3]	No	Yes	Yes	Yes	Yes	Yes[6]	No	Yes	Yes	No	
Ground Measurement based on Satellite Radio Beacon	No	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	13

[1] Based on the assumption the ELROI Modulated Laser beam ground segment formed on a network of more than 30 ground stations, globally distributed, and operative.
[2] Based on the ELROI presentation [RD-52 where it is stated that from the analysis of the modulated signal transmitted over about one hundred of seconds, the satellite tracking with metric precision is feasible.
[3] If stamp-size flight device is developed as planned
[3] If large mass production is implemented (cost of the flight unit order of a thousand of Euros)

Table 3-4 Pico-Sat:Qualitative parameters for technologies evaluation (2/2)

Small-Sat (50 kg class)

Method	Independent on Preliminary orbit knowledge (i.e.TLE)	Operative Day & Night	Immune to Clouds Coverage	Device dimensions compatible with smallsat	Simple/Cheap Ground Station (<100Keuro each)	Passive element onboard small satellite	System autonomy with respect to hosting satellite	Simple Small Satellite discrimi-nation	Accurate Small Satellite Attitude determination	Accurate Small Satellite Unique Discrimi-nation	Capability to retrieve other physical characteristics (area to mass ratio, shape,)	Draft Score
Radar Dipole	No	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	No	12
Radar Repeater	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes	No	12
Radar Reflector	No	Yes	Yes	Yes	No	Yes[7]	Yes[11]	Yes	No	Yes[7-10]	No	13
ISAR (Inverse Synthetic Aperture Radar)	No	Yes	Yes	Yes	No	Yes	Yes	No[12]	No[13]	No[12]	Yes	11
Laser Passive Retro-Reflector	No	Yes	No	Yes[4]	No	Yes	Yes	No	Yes	Yes	No	13
Passive Optical tracking[8]	No	No	No	Yes	Yes	Yes	Yes	No	No	No	Yes	14
Laser Modulated Retro-Reflector MRR	No	Yes	No	Yes	No	No	No	Yes	No	Yes	No	8
Pulsating LED[2]	No	No	No	Yes	Yes	No	No	Yes	No	Yes	No	11
Specific Frequency LED	No	No	No	Yes	Yes	No	No	Yes	No	Yes	No	10
Modulated Laser Beam	No	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	10
Space Transponder[3]	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes[5]	No	14
Satellite Radio Beacon	Yes	Yes	Yes	Yes	Yes	No	Yes[9]	Yes	No	No	No	12

[1]Indicates the measurement is guaranteed in the reported time (2-3 hrs) without any mission-specific additional ground station
[2]The pulsating Led technology was demonstrated (2013) on a Japanese cubesat FITSAT-1 (NIWAKA) dedicated to this task. It required the use of large batteries and high-power LED Arrays on two sides of cubesat
[3]Based on the assumption the Space Transponder ground segment formed on a network of more than 60 micro-ground stations, globally distributed, is operative
[4]It is assumed here the utilization of small flat retro-reflector 1 cm diameter.
[5]For the object unique discrimination in case of satellites cloud or formation, since all satellites are entering in the visibility cone at the same time, a TDMA shall be implanted to assign transmission time slot to each sat
[6]The measure depends only on the precision of the navigation system unit, part of the Space Transponder onboard card
[7] The radar reflector is passive, but the deployment of the radar reflective surface could be active and controlled from ground
[8] The assumption here is to use the ground observation network formed by tens of observation stations
[9] It is possible to install a battery powered beacon activated by fixed signals emitted from ground station which is operative only the first 30 days of mission
[10] It is possible to have the unique identification in case of active radar reflector, switched by telecommand during radar observation (or measurement)
[11] It is <Yes> in case of Passive Radar Reflector, otherwise for Active Radar Reflector it is <No>
[12] Under the assumption all the satellite are very similar in aspect and geometry
[13] Under the assumption the micro-sat has symmetrical shape and therefore it is not so easy to discriminate the attitude on the basis of "blurry" images
[14] The attitude is measured by the internal sat sensor and communicate to the Space Transponder that include these data into the data burst transmitted to ground

Table 3-5 Small-Sat: Qualitative parameters for technologies evaluation (1/2)

Small-Sat (50 kg class)

Method	Immune to Electro-magnetic disturb on RF	Immune to Space weather	Satellite position determination < 2-3 h from launch[1]	Direct Measurement (no ground data analysis)	Techno-logical simplicity	Accurate Satellite Location and Orbit determination	Already Tested on Small Satellite in Orbit	Simple Small Satellite Design Change	Cheap Small Satellite components to be added	Independent on Navigation System (GPS, GALILEO, GLONASS)	Draft Score
Radar Dipole	Yes	Yes	Yes	No	**No GS** Yes FS	Yes	No	No	Yes	Yes	12
Radar Repeater	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	12
Radar Reflector	Yes	No[12]	Yes	No	No	Yes	Yes	No	Yes	Yes	13
ISAR (Inverse Synthetic Aperture Radar)	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	11
Laser Passive Retro-Reflector	Yes	Yes	No	No	**No GS** Yes FS	Yes	Yes	Yes	Yes	Yes	13
Passive Optical Tracking	Yes	Yes	Yes [8]	No	Yes	Yes	Yes	Yes	Yes	Yes	14
Laser Modulated Retro-Reflector MRR	Yes	No	No	Yes	**No GS** Yes FS	Yes	No	No	No	Yes	8
Pulsating LED[2]	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	11
Specific Frequency LED	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	10
Modulated Laser Beam	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes[11]	Yes	11
Space Transponder[3]	No	No	Yes	Yes	Yes	Yes[6]	No	Yes	Yes	No	14
Satellite Radio Beacon	No	No	No	No	Yes	No	Yes	Yes	Yes	Yes	12

[1]Indicates the measurement is guaranteed in the reported time (2-3 hrs) without any mission-specific additional ground station
[2]The pulsating Led technology was demonstrated (2013) on a Japanese cubesat FITSAT-1 (NIWAKA) dedicated to this task. It required the use of large batteries and high-power LED Arrays on two sides of cubesat
[3]Based on the assumption the Space Transponder ground segment formed on a network of more than 60 micro-ground stations, globally distributed, is operative
[4]It is assumed here the utilization of small flat retro-reflector 1 cm diameter.
[5]For the object unique discrimination in case of satellites cloud or formation, since all satellites are entering in the visibility cone at the same time, a TDMA shall be implanted to assign transmission time slot to each sat
[6]The measure depends only on the precision of the navigation system unit, part of the Space Transponder onboard card
[7] The radar reflector is passive, but the deployment of the radar reflective surface shall be active and controlled from ground
[8] The assumption here is to use the ground observation network formed by hundreds of observation stations
[9] It is possible to install a battery powered beacon activated by fixed signals emitted from ground station which is operative only the first 30 days of mission
[10] It is possible to have the unique identification in case of active radar reflector, switched by telecommand during radar observation (measurement)
[11] If large mass production is implemented
[15] The device here in intended to discriminate one specific satellite activating the reflector by tele-command from ground; the related electronic is influenced by space weather

Table 3-6 Small-Sat: Qualitative parameters for technologies evaluation (2/2)

4 TECHNOLOGIES ANALYSIS AND SELECTION

After the very preliminary qualitative analysis carried our during the study and reported in the previous chapter, a deeper evaluation of the identified technologies has been carried out and presented in form of tables in this document. This exercise is aimed at providing further indication for the subsequent step aimed at identify the most promising or effective technology for each of the three classes of satellites identified by ESA

4.1 Log-Log Plots

The first classification and representation made on the twelve technologies selected was a electromagnetic spectrum classification of the links used by them reported in Figure 3. In the upper part of the plot is represented also the electromagnetic opacity of the atmosphere and it is evident all the technologies are concentrated only in the part of the spectrum where the atmosphere is almost transparent to allow a long distance transmission with acceptable losses

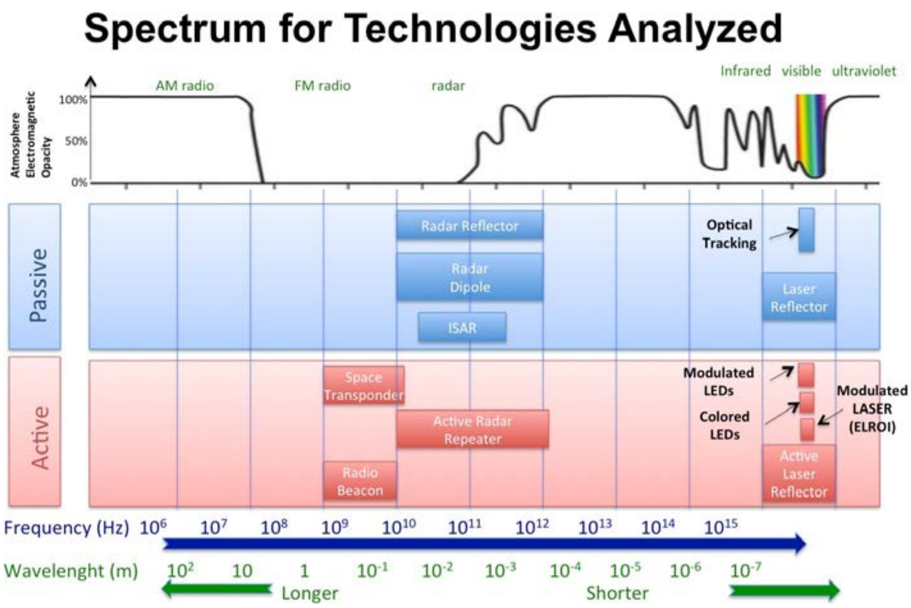

Figure 3 – Spectrum For Technologies Analyzed

4.1.1 Log-Log Mass-Volume comparison Plots

The first comparison of the technologies in the Log-Log scale was aimed at analyzing the degree of interference caused by the device selected in the satellite design. For this reason masses and volumes of the devices selected for each technology were reported providing a reasonable envelop. It is important to underline that the upper limit of the scale represent an entire 1U Cubesat, therefore closer the technology is to the upper limit more it is invasive into the design.

It is obvious that the technologies like ISAR or Optical Tracking, which do not require any specific device onboard, but are based only on the ground infrastructure, are located in the origin of the axes.

There are two specific technologies requiring further explanation.

The Passive Radar Reflector to be effective shall have dimensions that are larger than the Cubesat itself. Therefore it is expected a deployable technology will be used and in this case, when fully deployed it dimensions could exceed these on the Cubesat itself

The Modulated Laser technology (ELROI) made recently advances in the manufacturing of few prototypes will be launched in the next future. The prototypes have dimensions and masses of more than one order of magnitude respect to the industrial final product which should have dimensions stamp-like. For that reason the ELROI technology was represented with two different boxes to indicate what is available today as prototype and what is the goal of the developer when the capabilities will be demonstrated and a the version with large integration technology will be commercialized.

The onboard Mass-Volume comparison plot is reported in Figure 4

4.1.2 Log-Log Flight Unit-Ground Segment Cost comparison Plots

The second comparison made was based on the costs considering both Flight Segment and Ground Segment.

The Cost Log-Log Plot is reported on Figure 5

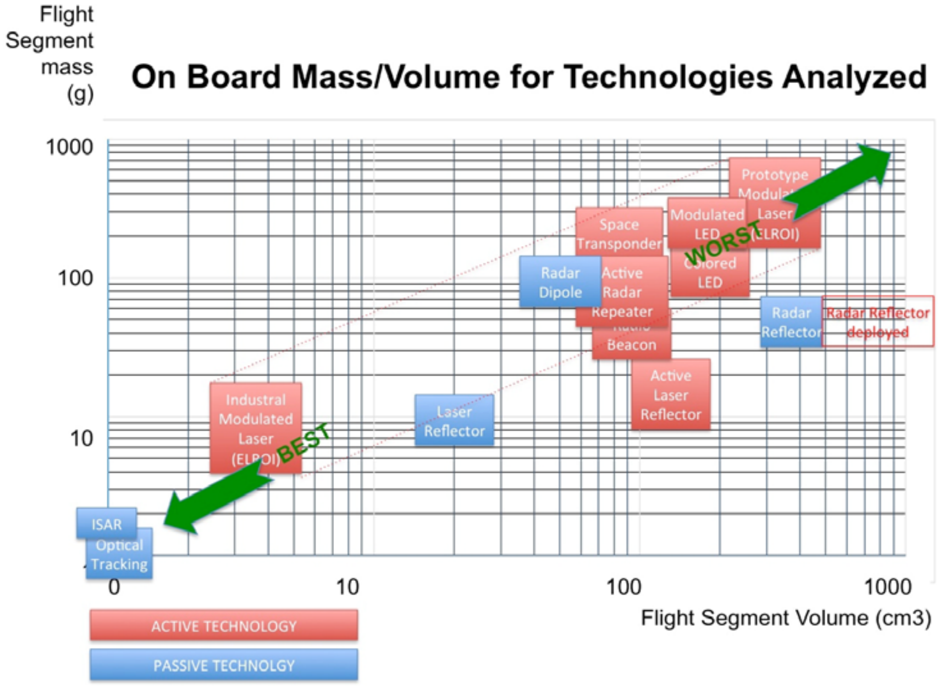

Figure 4 – On Board Mass/Volume for Technologies Analyzed

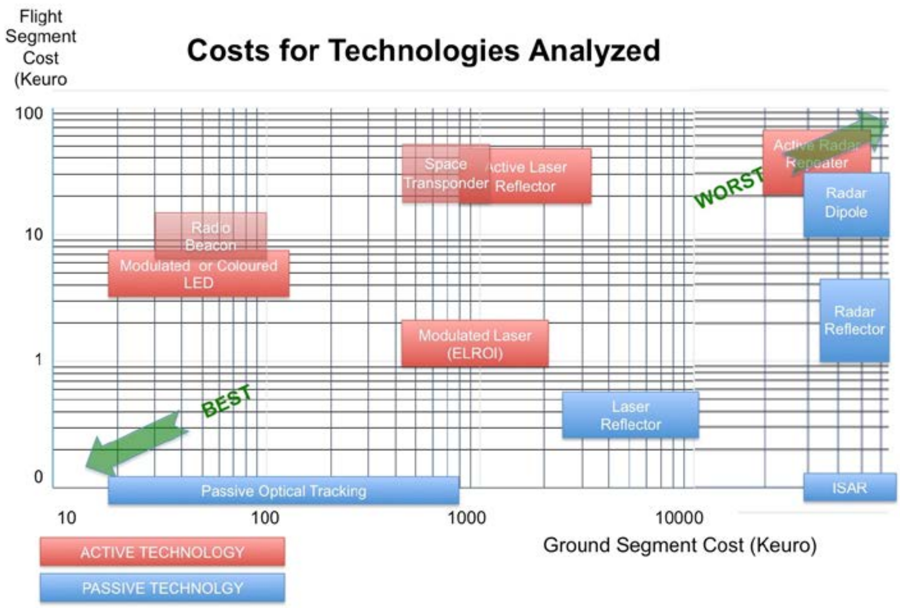

Figure 5 – Costs for Technologies Analyzed

4.2 Weighted Qualitative Parameters Analysis

4.2.1 Proposed scheme

According to deliverable DD01, a set of twenty-one features were identified as features relevant for the satellite tracking and identification, but the features were considered all with the same weight. An effort has been made to have a weighted consideration of all the parameters to re-evaluated the score. The weighted score for each considered parameter is reported below.

Proposed Weighted Score

Red Subset	Blue Subset	Green Subset
Device dimensions compatible with Cubesat	Operative Day & Night	Measurement independent on preliminary orbit knowledge (i.e.TLE)
Passive element onboard small satellite	Immune to Cloud Coverage	Simple & Cheap Ground Station (<100Keuro each)
System autonomy with respect to hosting satellite	Simple Satellite discrimination	Capability to retrieve other physical characteristics (area to mass ratio, solar panel deployment, etc.
Accurate Small Satellite Attitude Determin.	Immune to Electro-magnetic RF interference	Direct Measurement (no ground data analysis)
Accurate Small Satellite Unique Discrimination	Immune to Space Weather	Already Tested on Small Satellite in Orbit
Early Satellite position determination < 2-3 h from launcher release	Technological simplicity	Cheap Satellite components to be added
Accurate Satellite Location and Orbit Det.	Simple Satellite Design Change	Independent on Navigation System (GPS, GALILEO, GLONASS)
1.5 points per feature	0,9 points per feature	0.6 points per feature

Considered as most relevant features those indicating the accuracy in the measurements and the independence of the device respect to the hosting satellite (in a way to remaining operative even in case of satellite catastrophic failure :
Passive elements; system autonomy; Accurate position, orbit and attitude determination

On the basis of the weighted parameters a new, more accurate evaluation, has been made on all the technologies identified

Table 4-1 Proposed Weighted Features for Micro-/Cube-Sat

Table 4-2 Proposed Weighted Features for Pico-Sat

The rows reported in grey indicate the specific technology requires resources not available for this class of satellite (i.e. power, volume, mass, dimensions)

TECHNOLOGY	Immune to Electro-magnetic RF Interference	Immune to Space weather	Satellite position determination < 2-3 h from launch[1]	Direct Measurement (no ground data analysis)	Techno-logical simplicity	Accurate Satellite Location	Already Tested on Small Satellite in Orbit	Simple Small Satellite Design Change	Cheap Small Satellite components to be added	Independent on Navigation System (GPS, GALILEO, GLONASS)	Score Table 2	TOTAL SCORE	RANKING
Radar Dipole	0,9	0,9	1,5			1,5			0,6	0,6	6	13,2	4
Radar Repeater	0,9		1,5			1,5	0,6	0,9	0,6	0,6	6,6	12,3	7
Radar Reflector	0,9		1,5			1,5	0,6		0,6	0,6	5,7	12,9	5
ISAR (Inverse Synthetic Aperture Radar)	0,9	0,9				1,5		0,9	0,6	0,6	5,4	12,3	7
Laser Passive Retro-Reflector	0,9	0,9				1,5	0,6	0,9	0,6	0,6	6	14,4	1
Passive Optical Tracking	0,9	0,9	1,5		0,9	1,5	0,6	0,9	0,6	0,6	8,4	14,1	3
Laser Modulated Retro-Reflector MRR	0,9			0,6		1,5				0,6	3,6	8,4	12
Pulsating LED[2]	0,9	0,9			0,9	1,5	0,6		0,6	0,6	6	10,5	9
Specific Frequency LED	0,9	0,9			0,9	1,5			0,6	0,6	5,4	9,9	11
Modulated Laser Beam	0,9		1,5	0,6		1,5		0,9	0,6	0,6	6,6	12,9	5
Space Transponder[3]			1,5	0,6	0,9	1,5		0,9	0,6		6	14,4	1
Satellite Radio Beacon					0,9		0,6	0,9	0,6	0,6	3,6	10,5	9

Table 4-3 Proposed Weighted Features for Small-Sat

4.2.2 Ranking based on the qualitative features

In total there are three different qualitative evaluations on the identified features for each of the three classes of satellite.

It is interesting to note that selecting only 6 technologies we have all those that occupy the first 5 places for all the three different weighted and unweighted selections

So at the end, even though the approach could be considered questionable, in additional of the three ranking for each of the three classes of satellites, it was considered also an average value to get an unique overall ranking based on the qualitative features

TECHNOLOGY	OVERALL QUALITATIVE RANKING
Radar Dipole	4
Radar Repeater	7
Radar Reflector	5
ISAR (Inverse Synthetic Aperture Radar)	8
Laser Passive Retro-Reflector	1
Passive Optical Tracking	3
Laser Modulated Retro-Reflector MRR	12
Pulsating LED[2]	9
Specific Frequency LED	11
Modulated Laser Beam	5
Space Transponder[3]	1
Satellite Radio Beacon	9

TECHNOLOGY	OVERALL QUALITATIVE RANKING
Radar Dipole	1
Radar Repeater	0
Radar Reflector	0
ISAR (Inverse Synthetic Aperture Radar)	0
Laser Passive Retro-Reflector	3
Passive Optical Tracking	0
Laser Modulated Retro-Reflector MRR	0
Pulsating LED[2]	0
Specific Frequency LED	0
Modulated Laser Beam	2
Space Transponder	0
Satellite Radio Beacon	3

Table 4-4 Overall Qualitative Feature ranking for Micro-Sat and Cubesats(left) and Pico-Sat (right)

TECHNOLOGY	OVERALL QUALITATIVE RANKING
Radar Dipole	4
Radar Repeater	7
Radar Reflector	5
ISAR (Inverse Synthetic Aperture Radar)	7
Laser Passive Retro-Reflector	1
Passive Optical Tracking	3
Laser Modulated Retro-Reflector MRR	12
Pulsating LED[2]	9
Specific Frequency LED	11
Modulated Laser Beam	5
Space Transponder[3]	1
Satellite Radio Beacon	9

Table 4-5 - Overall Qualitative Feature ranking for Small-Sat

4.3 Quantitative Parameters Analysis

As further step an evaluation of the qualitative measurement capabilities offered by the different technologies has been carried out and included into a dedicated table.
The technologies being so different each other, it is difficult to find parameters involved in the orbital identification process, which are common to all the technologies. The comparison of radar systems with laser equipment and radio transmissions is hard. The only possibility found to find common parameters has been to use those for which the systems have been conceived and that represent the final output expected by the process.
It means that being dedicated to the orbit determination, to the spacecraft attitude measurement and to the unique identification the parameters used have been those used in these measurement.
Therefore the Table was prepared to elaborate the precision of each technology in the measurement of these parameter and illustrated below

Method	Satellite Position Accuracy obtained [m]	Satellite Velocity Accuracy [m/s]	Satellite Heading Angle Accuracy [deg]	Satellite Attitude Accuracy [deg]	Mass of the corresponding subsystem to be added [kg]	Average Power consumption due to addition of the selected method [W]	Size of the corresponding subsystem to be added [cm³]	Minimum distance for satellite discrimination in a cluster [m]
Reference Technology: Radar/Optical from	<100.0	0.5	0.2	No	0.0	0.0	0	>1000.0
Radar Electrical Dipole	<50.0	10.0	< 2.0	No	0.05-0.1	0.0	5.0-10.0[c]	>1000.0
Radar Repeater	10.0	0.1	1.0	No	0.1	1.0	20.0-150.0	10.0
Radar Reflector	10.0	0.1	1.0	No	0.2-0.3	0.0	200.0	>100.0
ISAR (Inverse Synthetic Aperture Radar)	5.0	0.1	1.0	1.0-3.0	0.0	0.0	0.0	>100.0
Laser Passive Retro-Reflector	<1.0	<0.001	0.1	1.0-3.0[g]	0.04[b]	0.0	20.0[d]	10.0
Passive Optical Tracking	100.0	0.5-1.0	0.5	5.0-10.0	0.0	0.0	0.0	>1000.0
Laser Modulated Retro-Reflector MRR	5.0	<0.001	0.5	1.0[e]	<0.1 [f]	0.1	150.0[e]	20.0
Pulsating LED Array	10.0	0.1	0.1	3.0-10.0	.05	0.1	100.0	100.0
Specific Frequency LED array	10.0	0.1	0.1	3.0-10.0	.05	0.1	100.0	100.0
Modulated Laser Beam	>1000.0	0.1	0.5-1.0	No	0.02	<0.05	1.0-5.0	100.0
Space Transponder	10.0[a]	0.15 [b]	0.1[b]	0.1[c]	0.1	0.3-0.5	150.0	10.0
Satellite Radio Beacon	>1000.0	5.0-10.0	>5.0	No	0.0	0.5-1.0	100.0	>1000.0
LEGENDA	Worst Result			Best Result		Not Available		

[A] the position data are transmitted to ground, but the position measurement is made by on-board Navigation system and transmitted to ground (so the achievable precision is that of the navigation board)
[B] the velocity data are transmitted to ground, but the velocity measurement is made by on-board Navigation system and transmitted to ground (so the achievable precision is that of the navigation board)
[C] the attitude data are transmitted to ground, but the attitude measurement is made by on-board AOCS and transmitted to ground
[D] It is intended the use of a certain number of micro-LRR of 1 cm³ each with a weight of 2 g each, distributed on the satellite sides also for attitude determination
[E] MLRR installed on each side of the satellite so the communication system could be used in any attitude and the "answer" is different and indicates which satellite side is responding
[F] Evaluation of the size and mass for one MLRR component plus the electronic board
[G] Strongly dependent from the minimum distance between the reflector and therefore in affected by the satellite dimensions (the figures reported represent already the limit for the cubesat)
[H] Technology suitable for unique satellite identification. The telescope used to acquire the signal doesn't provide precise position/orbital determination and probably it could be coupled with SLR to achieve it.
[I] It include the folded reflector of 0.5 m² and the deploying mechanism

Table 4-6: Quantitative parameters for technologies evaluation

Method	Satellite Position Accuracy obtained [Score]	Satellite Velocity Accuracy [Score]	Satellite Heading Angle Accuracy [Score]	Satellite Attitude Accuracy [Score]	Mass of the corresponding subsystem to be added [Score]	Average Power consumption due to addition of the selected method [Score]	Size of the corresponding subsystem to be added [Score]	Minimum distance for satellite discrimination in a cluster [Score]	TOTAL	Overall Quantitative Ranking
Reference Technology: Radar/Optical from JSPOC	>10000	TBD	TBD	No	0	0	0	>1000		
Radar Electrical Dipole	1,0	1,0	1,0	0,0	1,0	2,0	1,0	0,5	7,5	9
Radar Repeater	1,0	1,0	1,0	0,0	1,0	1,0	1,0	2,0	8	8
Radar Reflector	1,0	1,0	1,0	0,0	0,5	2,0	0,5	1,0	7	10
ISAR (Inverse Synthetic Aperture Radar)	1,0	1,0	1,0	1,0	1,0	2,0	2,0	1,0	10	2
Laser Passive Retro-Reflector	2,0	2,0	2,0	1,0	1,0	2,0	1,0	1,0	12	1
Passive Optical Tracking	1,0	1,0	1,0	0,5	2,0	2,0	2,0	0,5	10	2
Laser Modulated Retro-Reflector MRR	1,0	2,0	1,0	1,0	1,0	1,0	1,0	1,0	9	5
Pulsating LED Array	1,0	1,0	2,0	1,0	1,0	1,0	1,0	1,0	9	5
Specific Frequency LED array	1,0	1,0	2,0	1,0	1,0	1,0	1,0	1,0	9	5
Modulated Laser Beam	0,5	1,0	1,0	0,0	1,0	1,0	1,0	1,0	6,5	11
Space Transponder	1,0	1,0	1,0	2,0	1,0	1,0	1,0	2,0	10	2
Satellite Radio Beacon	0,5	0,5	0,5	0,0	2,0	0,5	1,0	0,5	5,5	12
Average Result 1.0	Worst Result		0.5	Best Result		2.0	Measure not availabe		0	

Table 4-7: Quantitative parameters Ranking

4.4 Preliminary Operative Parameters Analysis

Another table for direct comparison of preliminary operative parameters for the different technologies.

The Table indicates only if the considered parameter is provided/used by that technology so the table provides just the answer is <Yes> or <No> (there is still some To be Verified to be solved by further analysis)
In this case the answer Yes or Not does not provide any evidence one technology is better than another, but just that the specific technology provides such as characteristic
To transform the preliminary operative parameters table into a ranking table the following approach has been preliminary selected:
Since the affirmative answer it is considered as a positive aspect in terms of complexity of operation this very simple score has been adopted
For positive (affirmative) result it was assigned the value = 1,0
For negative result it was assigned the value =0,0
The table reports the ranking result for the quantitative evaluation

METHOD	ORBIT DETERMINATION	ATTITUDE DETERMI-NATION	ACTIVE TECHNO-LOGY	PASSIVE TECHNOLOGY	DIRECT ONBOARD MEASUREMENT	INDEPENDENT FROM SATELLITE RESOURCES	FULLY AUTOMATIC	SELF-TRIGGERED OR BY ENVIRONMENTAL CONDITIONS	ACCURATE SATELLITE UNIQUE DISCRIMINATION
Radar Dipole	YES	NO	NO	YES	NO	NO	NO	NO	YES
Radar Repeater	YES	NO	YES	NO	NO	NO	NO	NO	YES[1]
Radar Reflector[2]	YES	NO	YES[2]	YES[2]	NO	YES	NO	NO	YES[1]
ISAR (Inverse Synthetic Aperture Radar)	YES	YES	NO	YES	NO	YES	NO	NO	NO
Laser Passive Retro-Reflector	YES	YES	NO	YES	NO	YES	NO	NO	YES
Passive Optical Tracking	YES	NO	NO	YES	NO	YES	NO	YES	NO
Laser Modulated Retro-Reflector MRR	YES	YES[a]	YES	NO	NO	NO	NO	YES	YES
Pulsating LED Array	YES	YES	YES	NO	NO	NO	NO	YES	YES
Specific Frequency LED array	YES	YES	YES	NO	NO	NO	NO	YES	YES
Modulated Laser Beam	YES	NO	YES	NO	YES	NO	YES	NO	YES
Space Transponder	YES	YES[a]	YES	NO	YES	NO	YES	YES	YES
Satellite Radio Beacon	YES	NO	YES	NO	NO	NO	NO	NO	NO
LEGENDA	NO			YES					

[1] If the repeater activation is triggered by a specific code could be allow the identification [2] Could be Active or Passive Technology (we indicated YES in both columns) [3] The Active reflector could be triggered by ground command.

Table 15-5.8: Operative parameters for technologies evaluation

METHOD	ORBIT DETERMINATION	ATTITUDE DETERMI-NATION	ACTIVE TECHNOLOGY	PASSIVE TECHNOLOGY	DIRECT ONBOARD MEASUREMENT	INDEPENDENT FROM SATELLITE RESOURCES	FULLY AUTOMATIC	SELF-TRIGGERED OR BY ENVIRONMENTAL CONDITIONS	ACCURATE SATELLITE UNIQUE DISCRIMINATION	OPERATIVE SCORE	OPERATIVE RANKING
Radar Dipole	1,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	1,0	3,0	10
Radar Repeater	1,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	1,0	3,0	10
Radar Reflector[2]	1,0	0,0	1,0	1,0	0,0	1,0	0,0	0,0	1,0	5,0	2
ISAR (Inverse Synthetic Aperture Radar)	1,0	1,0	0,0	1,0	0,0	1,0	0,0	0,0	0,0	4,0	8
Laser Passive Retro-Reflector	1,0	1,0	0,0	1,0	0,0	1,0	0,0	0,0	1,0	5,0	2
Passive Optical Tracking	1,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	4,0	8
Laser Modulated Retro-Reflector MRR	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0	5,0	2
Pulsating LED Array	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0	5,0	2
Specific Frequency LED array	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0	5,0	2
Modulated Laser Beam	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	5,0	2
Space Transponder	1,0	1,0	1,0	0,0	1,0	0,0	1,0	1,0	1,0	7,0	1
Satellite Radio Beacon	1,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0	2,0	12

Table 4-8: Preliminary operative parameters Ranking

4.5 Cost Comparison

Also the cost is an important parameter to take into account for the evaluation of the most promising technology. Considering this aspect it was decided to take into consideration the costs of both Flight and Ground Elements.
Concerning the Flight devices, It is important to underline that dealing also with Picosat and Cubesat, the cost of the onboard unit shall be considered be of the order of magnitude of the typical Cubesat board ranging from a few hundred of Euros up to a maximum of 50-100 Keuro for the most complicated ones like the complete AOCS device with include also reaction wheels and magnetometes.
The Ground stations for tracking and the related networks, usually, are being built and operated for the need of Commercial multi-million satellite or even for the National security interest. In this case the cost issue has not been taken into account. For this reason the ground stations cost for the different technologies are in a very wide range starting from hundreds of Euros for a small amateur radio station able to capture satellite radio beacon up to hundreds million Euro for a Radar station belonging to a SSN.
Also the cost of a service dedicated to the tracking of the hundreds of future microsats has been roughly evaluated, considering to be operative almost continuously 24 hours even though largely automatized into the operation, when possible. However at the moment the cost of the service has not been taken into consideration for the ranking.
For the ranking a very simple approach has been used as first attempt. The log-log plots has been divided into different levels crossing the plane Ground and Flight Segment from 0 up to the maximum

cost, as illustrated in Figure 7. Each technology envelop has taken the rank corresponding to the level in which roughly it lays.
The overall Cost ranking for the selected technology has then been derived.

Method	Cost of Onboard Device [K€]	Cost of the Ground Infrastructure (approx) [Meuro]	Cost of the Service or Operations [Meuro] 1 man/year=100 Keuro
Reference Technology: Radar/Optical from JSPOC	0	100	3 -- 5
Radar Electrical Dipole	10	100	3 -- 5
Radar Repeater	50	100	3 -- 5
Radar Reflector	10	100	3 -- 5
ISAR (Inverse Synthetic Aperture Radar)	0	100	3 -- 5
Laser Passive Retro-Reflector	3--5	3-10	1
Passive Optical Tracking	0	1-3 (x 10-30 stations)	1
Laser Modulated Retro-Reflector MRR	10	100	3 -- 5
Pulsating LED Array	30--50	1-3 (x 10-30 stations)	1
Specific Frequency LED array	10--30	1-3 (x 10-30 stations)	1
Modulated Laser Beam	5-10[a]	1-3 (x 10-30 stations)	1
Space Transponder	50[b]	0,25-1.5[c] (x10-60stations)	1
Satellite Radio Beacon	10--30	1-3 (x 10-30 stations)	1--2
LEGENDA	Worst Result		
	Best Result		

a) The cost of the onboard device is derived on the basis of the brochure indicating the development will be made using micro-electronics technology to achieve low consumption and low cost of the singe device (it is a patent of Los Alamos Labs)
b) the cost here represents the costs of the single commercial devices used to assemble the system (OBC+Nav+Tx-Rx). If developed ad hoc device the cost could be decrease of the half.
c) The ground infrastructure cost is based on the assumption of a cost of 25 K€ for the NCC (Network Control center and 5K€ for a single station) 25 Keuro is based on one single ground station while 150 K€ already includes a network of 20 stations)

Table 4-9 Technologies first Cost Comparison

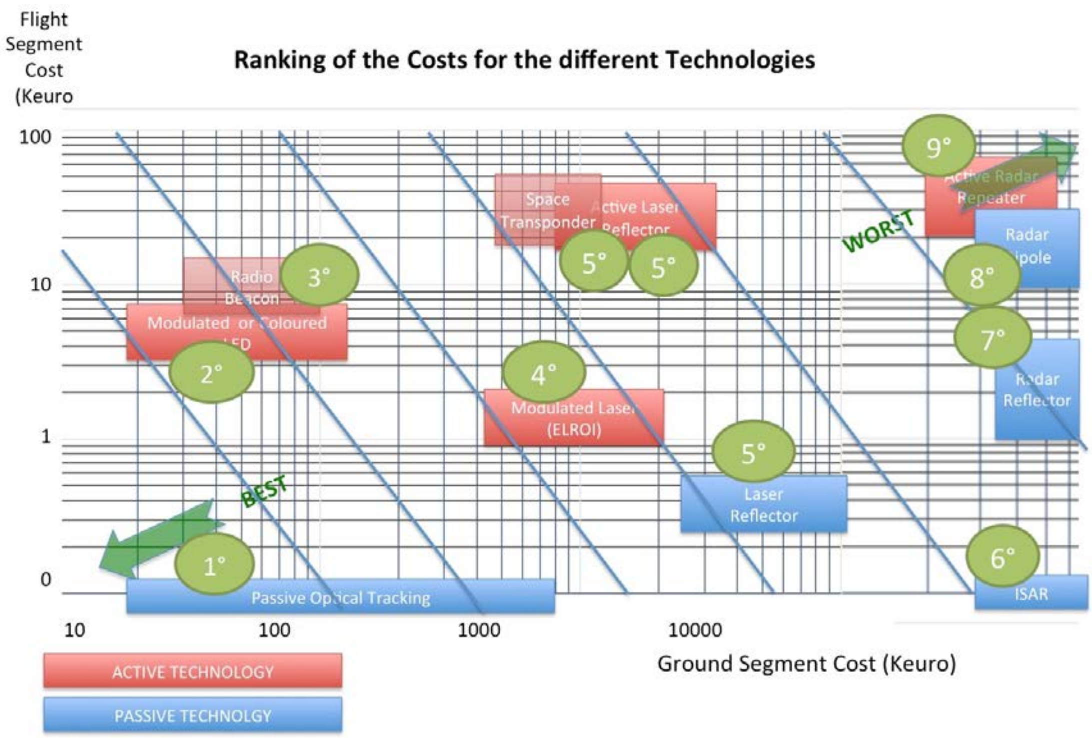

Figure 6- Ranking for the Costs of the different Technologies

4.6 Technology Readiness Level (TRL) and Operative Status analysis

Another table for direct comparison of Technology Readiness Level (TRL) and Operative Status for the different technologies has been provided.
TRL evaluation is reported with some additional clarification reported in the note for some technology.

Concerning the Operative Status probably some clarification is provided:
The DEMO column, with affirmative value, indicates a prototype of that has been realized and launched already in orbit (so usually YES correspond to TRL of 9). It does not mean the test is successful, but the demo elements have been developed.
The CUSTOM MADE indicates several prototypes or tests have been made by different entities, but there is not any commercial product available
The COTS or ROUTINE indicates that the elements are commercial and can be procured and the technology including the process is well documented and known. The term ROUTINE has been used because there are technologies that do not require any specific device, but they refer to operative processes usually performed on data acquired by ground centers or networks

4.7 Preliminary Impact on Existing Ground Segment and on Processes

The last three tables presented here provide a preliminary indication if the implementation of the selected technologies has an impact on the existing ground segment already used for medium and Large-sat in LEO, MEO and GEO.
Since the evaluation has been made for the three classes of satellites selected by ESA, that are Pico-sat, Micro-sat & Cubesat and Mini-sat (50 Kg class), three different tables have been prepared.
In the same table also another column providing preliminary indication on the implications of the selected technology on the processes currently used for each technology for the determination of satellite orbit and of its attitude.
Even in this case the preliminary evaluation has been made with a separate column for each specific class of satellite The preliminary results are provided in Table 4-12, Table 4-13, Table 4-14 and Table 4-15.

METHOD	TRL	DEMO[1]	CUSTOM MADE[2]	COTS or ROUTINE
Radar Dipole	9	YES	?	NO
Active Radar Repeater	9	YES	?	NO
Radar Reflector	6[5]-9	YES	YES	YES[6]
ISAR (Inverse Synthetic Aperture Radar)	8-9	YES [3]	YES [3]	NO
Laser Passive Retro-Reflector	9	YES	YES	YES
Passive Optical Tracking	9	YES	YES	YES
Laser Modulated Retro-Reflector MRR	6-7	?	?	NO
Pulsating LED Array	9	YES [3]	YES [3]	NO
Specific Frequency LED array	8-9	YES [3]	YES [3]	NO
Modulated Laser Beam	6-7	NO	NO	NO
Space Transponder	6-7[4]	NO	NO	NO
Ground Measurement based on Satellite Radio Beacon	9	YES	YES	YES

[1] DEMO indicates a prototype has been realized and tested in Space
[2] CUSTOM MADE indicates several prototypes or tests have been made by different entities, but there is not any commercial product available
[3] The reference is to the technology for the Ground Infrastructure needed to detect, track and identify the object
[4] Even though a Prototype has not been developed yet, the relatively high TRL is justified because the technology used 3 separate elements (UHF-VHF transmitter, Navigation Board and On-board Computer) that exist as standalone COTS product
[5] The TRL 6 represent the value for the Active Radar reflector while TRL 9 is for Passive Radar Reflector
[6] YES is reported for Passive Radar device

Table 4-10: Preliminary Evaluation of TRL level and of the Development Status

Pico-Sat

TECHNOLOGY/METHOD	Impact on Existing Ground Segment for PicoSat	Impact on Processes
Radar Dipole	No	No
Active Radar Repeater	No, but not possible to install onboard device due size and power	N/A
Radar Reflector	No, but not possible to install onboard device due size and power, however the picosat should be visible by radar since they are able to track up to 1-2 cm size debris	No
ISAR (Inverse Synthetic Aperture Radar)	Yes, but at the moment the current technologies, even increasing radar performances, are not able to achieve acceptable results	Yes
Laser Passive Retro-Reflector	Yes, increasing telescope magnification/resolution and Laser power/frequency it could be possible to track stabilized picosat equipped with 1 retro	Yes
Passive Optical Tracking	Yes, but at the moment the current technologies, even increasing telescope magnification/resolution, they are not able to achieve acceptable results	Yes
Laser Modulated Retro-Reflector MRR	No, but not possible to install onboard device due size and power	N/A
Pulsating LED Array	No, but not possible to install onboard device due size and power	N/A
Specific Frequency LED array	No, but not possible to install onboard device due size and power	N/A
Modulated Laser Beam*	No, but it is still at level of Lab prototype protected by ITAR	No
Space Transponder	No, but not possible to install onboard device due size and power	N/A
Ground Measurement based on Satellite Radio Beacon	Yes, using antennas with high gain and simultaneous measurement by several stations it could be possible to track picosat equipped with beacon	Yes

Table 4-11: Impact on Existing Ground Segment & on Processes for PicoSat

Micro-Sat & Cubesat

TECHNOLOGY/METHOD	Impact on Existing Ground Segment for Micro-Sat & CubeSat	Impact on Processes
Radar Dipole	No	No
Active Radar Repeater	No, but the technology has not been tested yet due to cubesat failure	No
Radar Reflector	No	No
ISAR (Inverse Synthetic Aperture Radar)	Yes, but at the moment the current technologies, even increasing radar performances, are not able to achieve acceptable results due to low resolution of images	Yes
Laser Passive Retro-Reflector	Yes	Yes for attitude determination
Passive Optical Tracking	No, at the moment with the current technologies, they could be able to achieve acceptable results (however no attitude determination is possible)	No (no attitude determination)
Laser Modulated Retro-Reflector MRR	No	No
Pulsating LED Array	No	No
Specific Frequency LED array	No	No
Modulated Laser Beam*	No, but it is still at level of prototype with a completely new dedicated ground segment	No
Space Transponder	No, but it is still at level of concept with a completely new dedicated ground segment	No
Ground Measurement based on Satellite Radio Beacon	No	No

Table 4-12: Impact on Existing Ground Segment & on Processes for MicroSat

Small-Sat (50 Kg Class)

TECHNOLOGY/METHOD	Impact on Existing Ground Segment for Small-Sat	Impact on Processes
Radar Dipole	No (but not requested due to sat size)	No
Active Radar Repeater	No	No
Radar Reflector	No	No
ISAR (Inverse Synthetic Aperture Radar)	Yes, at the moment the current technologies, increasing radar performances they could be able to achieve reasonable results (it depends by satellite geometry)	Yes
Laser Passive Retro-Reflector	Yes	Yes for attitude determination
Passive Optical Tracking	No,at the moment with the current technologies, they could be able to achieve acceptable results also for attitude determination is the satellite is not symmetric	No
Laser Modulated Retro-Reflector MRR	No	No
Pulsating LED Array	No	No
Specific Frequency LED array	No	No
Modulated Laser Beam*	No, but it is still at level of prototype (expected first launch 2018)	No
Space Transponder	No, but it is still at level of study even though the single elements are available COTS	No
Ground Measurement based on Satellite Radio Beacon	No	No

Table 4-13: Impact on Existing Ground Segment & on Processes for SmallSat

5 OVERALL SELECTED TECHNOLOGY RANKING

At the end an effort to derive an overall ranking taking into consideration:

1) The Qualitative Feature assessment
2) The Quantitative Parameters and Capabilities
3) The Operative Parameters
4) The Cost associated to the implementation

The TRL and the development status has not been taken into account at the moment for the overall ranking evaluation, and it has been computed simply calculating the average of the sum of the ranking achieved in each category.

The overall Ranking has been computed for each of the three class of satellite selected: Picosat, Micro/Cubesat and Small Sat.

At the moment the ranking of the Cubesat and small sat resulted very similar in the average and the same in the overall ranking.

The results are reported in the Table 5-1, Table 5-2 and Table 5-3

Table 5-1– Overall Ranking for MicroSat & Cubesat Class

Table 5-2– Overall Ranking for PicoSat Class

Table 5-3– Overall Ranking for SmallSat Class

6 CRITICAL ASSESSMENT OF IDENTIFIED PROMISING CONCEPS

6.1 Selected Technologies

From the previous iterations four technologies were selected to be the most promising for small satellites tracking enhancement, each one for primary application to different platforms, as summarized in the matrix below:

	Picosats	CubeSats	Smallsats
Modulated Laser Beam	Selected		
Laser Retro-Reflector		Selected	
Space Transponder		Selected	
Modulated LEDs			Selected

Table 6-1: Selected technologies for the various S/C classes

The system-level impacts of these concepts and a robustness analysis to assess their operational performance were evaluated with application to reference missions identified for each spacecraft class. An applicability matrix indicating the possibility to adapt each concept to each satellite class was then developed. The results of these analyses are summarized in the following paragraphs.

The reference mission scenarios and spacecraft characteristics considered for the analysis are summarized in the table below:

Spacecraft class	**Picosat**	**CubeSat** 3U	**CubeSat** 3U	**Smallsat** 30kg	**Smallsat** 30kg
Mission Scenario	Space Weather	Earth Observation	Telecom	Earth Observation	Telecom
Orbit	550x550 km	550x550 km	550x550 km	550x550 km	550x550 km
Pointing	None	Nadir (active)	Nadir (active)	Nadir (active)	Nadir (active)
Lifetime	1 y	3 y	3 y	7 y	7 y
Payload Volume	70 cm^3	1.75 U	1.25 U	60 L	45 L
Payload Mass	100 g	2.5 kg	1.5 kg	15 kg	10 kg
Payload Power	0.5 W	4 W	8 W	20 W	45 W
Platform Cost	100 k€	650 k€	650 k€	2500 k€	2500 k€

Table 6-2: Reference Platforms and Missions

6.2 System Level Impacts and Robustness Analyses

6.2.1 System level impacts summary

The following table quantifies the system level impacts described in the previous paragraphs, in terms of percentual impact on the quantities reported in Table 6-2: Reference Platforms and MissionsTable 6-2.

Tracking Technology	**Laser beacon**	**LRRs**	**LRRs**	**Space XPDR**	**Space XPDR**	**LED beacon**	**LED beacon**
Spacecraft Class	Picosat	CubeSat	CubeSat	CubeSat	CubeSat	Smallsat	Smallsat
Mission Scenario	Space Weather	Telecom	EO	Telecom	EO	Telecom	EO
Payload Volume	20÷40 %	1 %	1 %	16 %	12 %	< 1 %	< 1 %
Payload Mass	20÷40 %	2 %	1 %	13 %	8 %	< 1 %	< 1 %
Payload Power	50 %	6 %	12 %	19 %	38 %	5 %	2 %
Cost	5÷10 %	< 1 %	< 1 %	8 %	8 %	2 %	< 1 %
Anomaly Resolution	No	No	No	Yes	Yes	Yes	Yes

Table 6-3: System level impacts of the selected technology in the reference scenarios

6.3 Technologies cross-compatibility

A last point to consider is the cross-compatibility of the four selected solutions to other platforms other than the ones they were initially selected for.

1. **Modulated Laser Beam**: this technology is self-contained and could easily be implemented on any spacecraft, provided that shadowing due to protruding surfaces is accounted for.

2. **Passive Laser Retro-reflector (LRR)**: this technology is passive, cheap and easy to integrate, and could easily be implemented on any spacecraft, provided that shadowing due to protruding surfaces is accounted for, and that no sensors can be blinded by the incoming Laser beam. On Picosats, however, it couldn't be used to obtain attitude information (no space for different patterns on the different faces).

3. **Space Transponder**: this technology can easily be implemented in satellites larger than CubeSats (with reduced system impacts), but is too demanding in terms of mass, volume and power to be fitted on a Picosat.

4. **Modulated LED's**: this technology can easily be implemented in CubeSats (albeit with increased system impacts with respect to Smallsats), and indeed it has already been flown as a demonstrator in various CubeSat missions.

The following applicability matrix of the selected technologies to the three analyzed satellite classes summarizes these considerations:

	Picosats	CubeSats	Smallsats
Modulated Laser Beam	Applicable	Applicable	Applicable
Laser Retro-Reflector	Applicable (low performance)	Applicable	Applicable
Space Transponder	Not applicable	Applicable	Applicable
Modulated LEDs	Not applicable	Applicable	Applicable

7 SCALING OF THE DESIGN TO LARGER SPACECRAFT

This chapter summarizes the results of the activities carried out by OHB Italia Team supported by Telespazio S.p.A. concerning the "Usage of observability augmentation concepts for spacecraft", as scheduled in the WP40. In the related document (DD04), the possibility and the related implications of using the tracking concepts identified for the smaller satellites in the previous analyses on larger satellites and rocket bodies were investigated and discussed. Also, the design guidelines for smaller satellites were examined with regards to their applicability to larger objects (i.e. larger satellites or rocket bodies). Furthermore, a contingency situation has been defined and the capability of correctly determine the attitude of such spacecraft has been analyzed. Finally, a way of using the considered technologies for supporting the international regulations on space objects identification (Registration Convention) was discussed and presented.

Concerning the usage of observability augmentation concepts for spacecraft, the main results of the possibility and the related implications of using the tracking concepts (already identified for the smaller satellites) on larger satellites and rocket bodies were presented. The same was done concerning design guidelines for smaller satellites with regards to their applicability to larger objects (i.e. larger satellites or rocket bodies). Last, issues and results of a contingency situation were presented and the considered technologies were taken into account as a way of supporting the international regulations on space objects identification (Registration Convention).

In order to evaluate the scalability of the tracking augmentation concept, which are applicable to small satellites on larger space objects, a quantitative and qualitative analysis has been carried out for two classes of space objects, namely *larger satellites* (mass greater than 50 kg in this project) and *rocket bodies*. The first class includes those satellites that can retrieve their attitude and position only by means of an on-board system; the latter includes those bodies that orbit uncontrolled around the Earth and without any on-board system able to identify their attitude and position.

Table 5 summarizes the overall qualitative ranking for the two classes considered. They consider a weighted score among a set of twenty-one features (

Table 29) identified as features relevant for the satellite tracking and identification considering spectrum scalability, on-board mass/volume scalability, and cost evaluation.

Measurement independent on preliminary orbit knowledge (i,e,TLE)
Operative Day & Night
Immune to Clouds Coverage
Device dimensions compatible with CubeSat
Simple & Cheap Ground Station (<100Keuro each)
Passive element onboard small satellite
System autonomy with respect to hosting satellite
Simple Satellite discrimination
Accurate Small Satellite Attitude Determination
Accurate Small Satellite Unique Discrimination
Capability to retrieve other physical characteristics (area to mass ratio, shape)
Immune to Electro-magnetic RF interference
Immune to Space Weather
Early Satellite position determination < 2-3 h from launcher release
Direct Measurement (no ground data analysis)
Technological simplicity
Accurate Satellite Location and Orbit Determination
Already Tested on Small Satellite in Orbit
Simple Satellite Design Change
Cheap Satellite components to be added
Independent on Navigation System (GPS, GALILEO, GLONASS)

Table 4 - List of relevant features This table applies both for larger spacecraft and rocket bodies; when the word "satellite" is mentioned both these two classes are included.

TECHNOLOGY	OVERALL QUALITATIVE RANKING
Radar Dipole	5
Radar Repeater	5
Radar Reflector	5
ISAR (Inverse Synthetic Aperture Radar)	8
Laser Passive Retro-Reflector	1
Passive Optical Tracking	2
Laser Modulated Retro-Reflector MRR	12
Pulsating LED	10
Specific Frequency LED	11
Modulated Laser Beam	4
Space Transponder	2
Satellite Radio Beacon	9

TECHNOLOGY	OVERALL QUALITATIVE RANKING
Radar Dipole	4
Radar Repeater	4
Radar Reflector	4
ISAR (Inverse Synthetic Aperture Radar)	7
Laser Passive Retro-Reflector	1
Passive Optical Tracking	2
~~Laser Modulated Retro-Reflector MRR~~	
Pulsating LED	9
Specific Frequency LED	10
Modulated Laser Beam	3
~~Space Transponder~~	
Satellite Radio Beacon	8

Table 5 - Overall Qualitative Feature ranking for Larger Satellites (to the left) and for Rocket Bodies (to the right).

The preliminary operative analysis performed in DD02 "Development of Concepts for identification of Small and Large Satellites" is based on the capability of a specific technology to provide such characteristics. The preliminary operative parameters selected were Orbit Determination, Attitude Determination, Passive Technology, Direct Onboard Measurement, Independent from Satellite Resources, Fully automatic (or at least capability to provide automatic service), Self-Triggered or Triggered by Environmental conditions, and Accurate Satellite Unique Discrimination.

It is clear how this analysis can be considered not size-dependent and same outcomes of DD02 "Development of Concepts for identification of Small and Large Satellites" apply here.

A cost comparison with respect to the one made in DD02 "Development of Concepts for identification of Small and Large Satellites" has been performed. It is assumed that, for the on-board part, the same device mounted on small satellites can be integrated directly on larger satellites and rocket bodies. This assumption implies that no differences arise regarding the on-board part. The only exception regards the passive radar electrical dipole, for which the deployable structure must be adapted to the satellite dimensions in order to be effective. For this technology the cost of the on-board part increases according to dimensions of the object considered.

Concerning the Ground Stations, larger objects are more easily tracked in space, relaxing constraints of the Ground Segment and making the outcomes of this part of DD02 "Development of Concepts for identification of Small and Large Satellites" conservative for larger spacecraft and rocket bodies.

The overall Cost ranking for the selected technology is therefore assumed to be similar, considering the orders of magnitude, to the ones in DD02 “Development of Concepts for identification of Small and Large Satellites”.
As already done in DD02 “Development of Concepts for identification of Small and Large Satellites”, an overall ranking taking into consideration the following items has been carried out:

5) the Qualitative Feature assessment
6) the Quantitative Parameters and Capabilities
7) the Operative Parameters
8) The Cost associated to the implementation.

The TRL and the development status have not been taken into account at this stage for the overall ranking evaluation.
The “Overall Ranking” has been computed for each of the two class of satellite selected: large spacecraft and rocket bodies sorting the average from the lowest value to the greatest one.
Columns “Overall Quantitative Ranking”, “Operative Ranking”, and “Cost Ranking” are the ones applied in DD02 “Development of Concepts for identification of Small and Large Satellites”, as already explained in previous sections.
Values in the “Average” column have been computed simply calculating the average of the sum of the ranking achieved in each category.

The results are reported in Table 31 and Table 32.

LARGER SATELLITES						
TECHNOLOGY	OVERALL QUALITATIVE RANKING	OVERALL QUANTIITATIVE RANKING	OPERATIVE RANKING	COST RANKING	AVERAGE	OVERALL RANKING
Radar Dipole	5	9	10	12	9	10
Radar Repeater	5	8	10	11	8,5	11
Radar Reflector	5	10	2	10	6,75	9
ISAR (Inverse Synthetic Aperture Radar)	8	2	8	9	6,75	8
Laser Passive Retro-Reflector	1	1	2	6	2,5	1
Passive Optical Tracking	2	2	8	1	3,25	3
Laser Modulated Retro-Reflector MRR	12	5	2	6	6,25	7
Pulsating LED	10	5	2	2	4,75	4
Specific Frequency LED	11	5	2	2	5	5
Modulated Laser Beam	4	11	2	5	5,5	6
Space Transponder	2	2	1	6	2,75	2
Satellite Radio Beacon	9	12	12	4	9,25	12

Table 6 - Overall Ranking for Larger Satellites

ROCKET BODIES						
TECHNOLOGY	OVERALL QUALITATIVE RANKING	OVERALL QUANTIITATIVE RANKING	OPERATIVE RANKING	COST RANKING	AVERAGE	OVERALL RANKING
Radar Dipole	4	9	10	12	8,75	9
Radar Repeater	4	8	10	11	8,25	8
Radar Reflector	4	10	2	10	6,5	6
ISAR (Inverse Synthetic Aperture Radar)	7	2	8	9	6,5	6
Laser Passive Retro-Reflector	1	1	2	6	2,5	1
Passive Optical Tracking	2	2	8	1	3,25	2
~~Laser Modulated Retro-Reflector MRR~~	n.a.	~~5~~	~~2~~	~~6~~	n.a	n.a.
Pulsating LED	9	5	2	2	4,5	3
Specific Frequency LED	10	5	2	2	4,75	4
Modulated Laser Beam	3	11	2	5	5,25	5
~~Space Transponder~~	n.a.	~~2~~	~~1~~	~~6~~	n.a.	n.a.
Satellite Radio Beacon	8	12	12	4	9	10

Table 7 - Overall Ranking for Rocket Bodies

The Laser Passive Retro-Reflector results as the preferred envisaged technology for Larger Satellites; this is true also for Rocket Bodies.

Regarding the attitude determination in case of a contingency, while analyzing the different tracking concepts, two different sub-cases were taken into account. The first one regards ACTIVE OBJECTS, the ones that do not provide attitude determination as well as the ones that require on-board knowledge of the attitude can be excluded, and the second one regards PASSIVE OBJECTS, which are defined as space objects with no active usable resources whatsoever (e.g. rocket body parts, old satellites or debris).

For active objects, some of the technologies were directly excluded from the analysis because they do not provide attitude determination as well as the ones that require on-board knowledge of the attitude. Among the set of technologies considered, the remaining applicable ones are then: ISAR, Laser Passive Retro-Reflector, Laser Modulated Retro-Reflector MRR, Pulsating LED Array and Specific Frequency LED Array.Considering the definition of contingency, the list of parameters identified in DD02 “Development of Concepts for identification of Small and Large Satellites” can be rearranged with new weights and a new score for each of the remaining technology can be calculated. Result that in case of a contingency situation happening to an ACTIVE OBJECT, the best solution for attitude determination would be using a Laser Passive Retro-Reflector technology.

The same initial assumptions made for the ACTIVE OBJECT case are still valid for the PASSIVE OBJECT case, which is now considered. In addition to these, the technologies that require satellite resources are in this case excluded from the analysis. The remaining technologies become then just the following: ISAR, and Laser Passive Retro-Reflector.In this case, though, the Inverted SAR could represent a better solution when applied to PASSIVE OBJECTS, since it does not require an active system to be mounted on-board the space object, thus limiting any chance of system failure.

Shortly it is discussed the possibility of using one (or more) of the technologies presented in this study in order to allow unique identification of an object in space, as a way of operationally supporting the Registration Convention obligations independently from national surveillance networks.it is clear that some of the technologies must be taken out of the discussion, due to their intrinsic impossibility of uniquely distinguish among the space objects, as correctly reported in the last column of the table.

METHOD	ORBIT DETERMINATION	ATTITUDE DETERMI-NATION	ACTIVE TECHNOLOGY	PASSIVE TECHNOLOGY	DIRECT ONBOARD MEASUREMENT	INDEPENDENT FROM SATELLITE RESOURCES	FULLY AUTOMATIC	SELF-TRIGGERED OR BY ENVIRONMENTAL CONDITIONS	ACCURATE SATELLITE UNIQUE DISCRIMINATION
Radar Dipole	1,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	1,0
Radar Repeater	1,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	1,0
Radar Reflector[2]	1,0	0,0	1,0	1,0	0,0	1,0	0,0	0,0	1,0
ISAR (Inverse Synthetic Aperture Radar)	1,0	1,0	0,0	1,0	0,0	1,0	0,0	0,0	0,0
Laser Passive Retro-Reflector	1,0	1,0	0,0	1,0	0,0	1,0	0,0	0,0	1,0
Passive Optical Tracking	1,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0
Laser Modulated Retro-Reflector MRR	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0
Pulsating LED Array	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0
Specific Frequency LED array	1,0	1,0	1,0	0,0	0,0	0,0	0,0	1,0	1,0
Modulated Laser Beam	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0
Space Transponder	1,0	1,0	1,0	0,0	1,0	0,0	1,0	1,0	1,0
Satellite Radio Beacon	1,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0

Table 8 - Preliminary operative parameters for technologies evaluation

The optimal way of achieving accurate discrimination among the objects without relying on any of such surveillance network shall be using on-board systems that can operate in synergy with ground to allow the correct identification of the orbiting object. Passive technologies are preferred over active ones because they always allow identification and such operation acquires most of its importance during the last phases of a satellite’s life cycle, where satellite capability of actively collaborate with ground is limited or absent (contingency situation).Excluding from the analysis the technologies that does not allow unique discrimination (grey font in the table) and considering only the parameters related to size and cost, the intermediate score shows that the use of a Space Transponder could be the most effective, followed equally by the use of LEDs (pulsating or operating at a specific frequency).

TECHNOLOGY	Independent on Preliminary orbit knowledge (i.e. TLE)	Device dimensions compatible with CubeSats	Simple/Cheap GS (<100 K€ each)	Technology Simplicity	Simple Small Satellite Design Change	Cheap Small Satellite components to be added	Score
Radar Dipole		1.5				0.6	**2.1**
Radar Repeater		1.5			0.9	0.6	**3**
Radar Reflector		1.5				0.6	**2.1**
~~*ISAR*~~					~~*0.9*~~	~~*0.6*~~	~~*1.5*~~
Laser Passive Retro-Reflector		1.5			0.9	0.6	**3**
~~*Passive Optical Tracking*~~		~~*1.5*~~	~~*0.6*~~	~~*0.9*~~	~~*0.9*~~	~~*0.6*~~	~~*4.5*~~
Laser Modulated Retro-Reflector MRR		1.5					**1.5**
Pulsating LED Array		1.5	0.6	0.9		0.6	**3.6**
Specific Frequency LED Array		1.5	0.6	0.9		0.6	**3.6**
Modulated Laser Beam		1.5			0.9	0.6	**3**
Space Transponder	0.6	1.5	0.6	0.9	0.9	0.6	**5.1**
~~*Satellite Radio Beacon*~~	~~*0.6*~~	~~*1.5*~~	~~*0.6*~~	~~*0.9*~~	~~*0.9*~~	~~*0.6*~~	~~*5.1*~~

Table 9 - Proposed Weighted Features for Micro-/CubeSats

In addition to this, most of the objects that will be launched in the near future will be smaller and cheaper with respect to the actual trend, limiting on-board resources available for the tracking sub-system. These considerations, plus considering cost of the on-board device considered as well as the implementation one and the operational costs, brings to Table 35.

TECHNOLOGY	Cost of Onboard Device [K€]	Cost of the Ground Infrastructure (approx) [Meuro]	Cost of the Service or Operations [Meuro] 1 man/year=100 Keuro
Reference Technology: Radar/Optical from JSPOC	0	100	3 -- 5
Radar Electrical Dipole	10	100	3 -- 5
Radar Repeater	50	100	3 -- 5
Radar Reflector	10	100	3 -- 5
~~*ISAR*~~	~~*0*~~	~~*100*~~	~~*3 -- 5*~~
Laser Passive Retro-Reflector	3--5	3-10	1
~~*Passive Optical Tracking*~~	~~*0*~~	~~*1-3 (x 10-30 stations)*~~	~~*1*~~
Laser Modulated Retro-Reflector MRR	10	100	3 -- 5
Pulsating LED Array	30--50	1-3 (x 10-30 stations)	1
Specific Frequency LED Array	10--30	1-3 (x 10-30 stations)	1
Modulated Laser Beam	5-10[a]	1-3 (x 10-30 stations)	1
Space Transponder	50[b]	0,25-1.5[c] (x10-60stations)	1
~~*Satellite Radio Beacon*~~	~~*10--30*~~	~~*1-3 (x 10-30 stations)*~~	~~*1--2*~~

Table 10 - Technologies first cost comparison

As a result, the three technologies can be considered equal. On the other hand, though, the costs for the required on-board device are higher for the Space Transponder and lower for the LED array systems, although the costs for the needed infrastructures are slightly lower for the Transponder. Therefore, it becomes clear from this analysis that implementing one of these technologies could result in a way of operationally support the Registration Convention, allowing the unique identification of any object (provided with the aforementioned technology) on request, keeping into account limitations related to size, weight and cost of the launched objects.

8 DESIGN GUIDELINES

The contents of this chapter have been derived starting from a draft guideline developed in the WP 20 “Development of concepts for identification of small and large satellites” which generated the DD02. The present document DD05 was further reviewed with accepted design guidelines & requirements in this final version as part of the task of the WP 30 “Critical assessment of identified promising concepts for tracking augmentation and identification” where the DD03 has been produced.

8.1 Selected Technologies For Each Class Of Satellite

In the following the technologies that the authors have selected are reported for each class of satellite identified by ESA for this study. The three classes of satellite identified are:

1) Picosat (side of 5 cm or less)
2) CubeSat (side of 10 cm)

3) Smallsat (in general less than 100 kg)

8.1.1 Selected Technologies for Picosat

Modulated Laser Beam: the space element consists of a micro-diode-laser beacon, producing light in all the direction, attached to the spacecraft, which generated a unique code containing a specific serial number. The ground system is based on a telescope equipped with a photon-counting sensor to track space objects and to decode the signal to identify univocally the space object.

8.1.2 Selected Technologies for CubeSats

"Passive" Laser Retro-Reflector (LRR): Laser passive micro-retro-reflectors are proposed as a potential system to discriminate several similar satellites of multiple launches or constellations and to determine their respective orbits.

and

"Active" Space Transponder: Operating in a similar mode of a commercial "aircraft transponder", it is transmitting the satellite position and the orbit parameter on a radio by using digital short transmission. Space Transponder should minimize the transmission to reduce interference and power consumption, so it is activated only when the satellite is in the visibility of one of the dedicated Ground Stations.

8.1.3 Selected Technologies for Smallsat

Passive Optical Tracking: Usage of telescopes is still a valid method for LEO orbit determination. Their cost and technology can be in the accessible range for most users so large networks of amateur are existing across the world.

and

Pulsating LEDs: Light Emitting Diodes (LEDs) array installed on satellites for optical tracking with ground-based telescopes. The array could be also activated with a fixed sequence of short and long pulse as mark to identify the satellite.

8.2 Guidelines For Picosat

8.2.1 Picosat Characteristics

Picosat is a generic term to indicate very small satellites with dimensions of a few centimeters per side. There are no common standards among the developers for the design of Picosats, therefore, in this study, the characteristics of an example picosat had to be defined.

Figure 8 depicts the envelope of the Picosat used as baseline with its main dimensions.

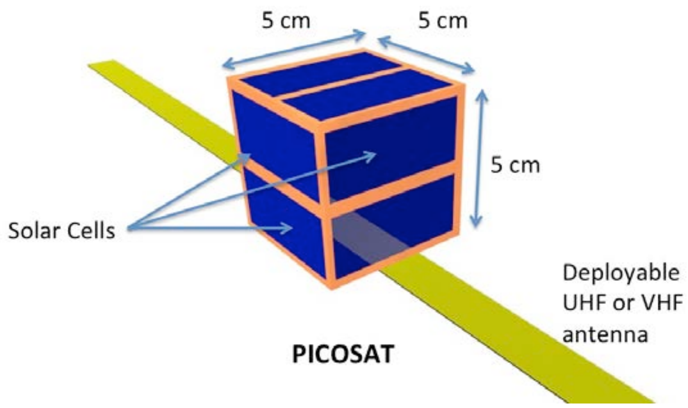

Figure 7 – Drawing of PICOSAT used as baseline in this study

8.2.2 Tracking device for Picosat

The device selected as suitable for Picosats shall fit in an envelope of few centimeters. Los Alamos National Laboratories (LANL) has recently (2015) developed and patented the Extremely Low Resource Optical Identifier (ELROI), a cost effective, robust mean of tracking satellites and other objects in space.

The LANL ELROI is a unique system for identification, tracking and diagnosis of space objects and consists both of an on-board laser beacon and a ground telescope system to track space objects. The laser beacon produces an extremely low power optical signal that transmits an identification code from orbit to ground. The transmission is omnidirectional, so the beacon requires no pointing system. The autonomy of the beacon allows it to be used on both passive debris and active spacecraft, and to keep operating after the spacecraft is decommissioned.

The space vehicle is identified through a unique code, or "license plate", emitted by the beacon.
A unique LANL ground receiver enables this concept. It is composed of a small telescope with LANL's NCam technology, a high-speed photon counting camera that significantly reduces cost over more complex optical telescopes.

This modest optical system can identify a specific optical signal with very little power by using a narrow wavelength filter and processing gain. A 0.25 mW signal from low earth orbit can be identified in 100 seconds of observation, even on a background of a 1 square meter satellite in full sunlight.

8.2.3 Design Guidelines

The main characteristics of the tracking device, to be included in the spacecraft design, are reported in the following table.

Characteristic	Specification
Dimensions	20 x 20 x 5 [mm]
Mass	Approx. 5 g
Number of devices	1, if attitude controlled 2, on opposite sides, if in low spinning, for omnidirectional coverage
Power	Approx. 1 mW (autonomous, equipped with solar cell and internal battery)
Fixation	Glue on sat external surface sun exposed
Pointing	Not required. 180° coverage omnidirectional laser emission. For total coverage two devices mounted on opposite sides are required.
Lifetime	Comparable to the one of the hosting satellite
Other	

The Interfaces with the instruments are reported in the following tables also contain the quantitative data to be used as generic requirement for the installation of the device on the specific spacecraft, that in this chapter is represented by a Picosat of 5 cm side.

Interface	Required (Y/N)	Note or Characteristics
Mechanical	Y	Clean external surface 2 cm x 2 cm where the device is to be glued with appropriate space-grade adhesive
Thermal	N	Very low power
Electrical	N	Device is autonomous, equipped with solar cells and battery
Data	N	Only sat-specific identification code is transmitted
BUS	N	As above
Other		

The ELROI device shall be glued on the external surface of the satellite as illustrated in Figure 9.

The glue to be used could be a high-performance two-component epoxy resin, the specific type to be used depending on the surface materials. These adhesives are generally workable for a few minutes and cure at ambient temperature for a few days. The surface finish shall attain an adequate level of roughness (e.g. face knurling).

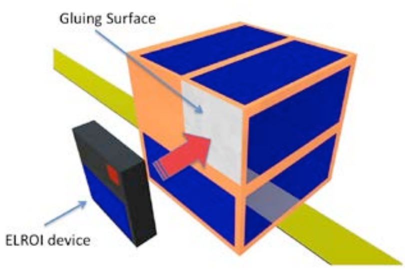

Figure 8 – ELROI device installed on a PICOSAT

If the envelope of the picosat shall be maintained in the 5x5x5 cm envelope, to fulfill for instance the requirement of the sat dispenser, a small slot shall be designed to accommodate the device inside the requested volume.

Drawings of ELROI Installation on Picosat are depicted in Figure 10.

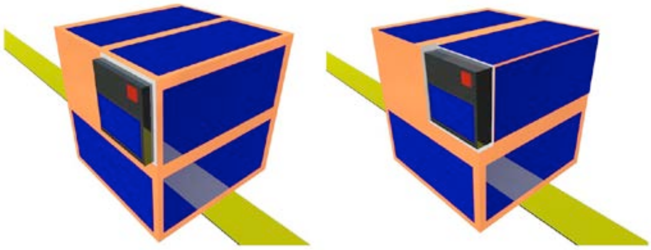

Figure 9 – Drawings of Picosat with ELROI device installed

left: flash mounted and protruding right: installed in a dedicated slot

8.3 Guidelines For Cubesat

8.3.1 CubeSat Characteristics

CubeSats are nanosatellites of standardised dimensions, composed of one or more units. Each CubeSat unit is 10x10x10 cm in size and has a launch mass of up to 1.33 kg. CubeSats were originally born to provide cost-effective platforms for university or radio ham projects. Smaller in size and faster to develop than bigger classes of satellites, CubeSats offer students a true hands-on experience in designing, developing, testing, and operating a real spacecraft system and its ground segment. Today, however, CubeSats have also started to show an increasing potential for commercial use, with many active missions to date, and are recognised as one of the current top trends in space activities.

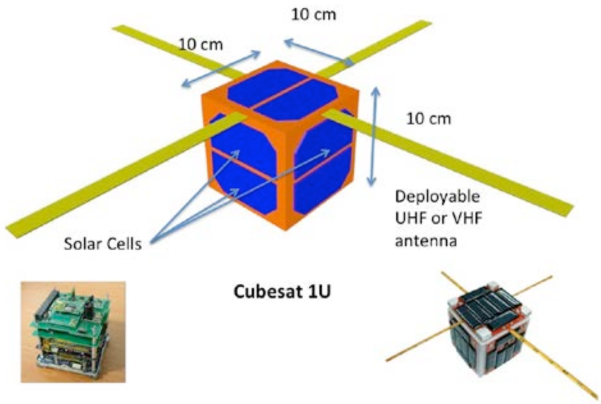

Figure 10 – Drawings of CubeSat used as baseline in this study

(pictures of real systems are also displayed)

8.3.2 Tracking device for CubeSat

For the CubeSat the current study identified two suitable devices:

1) Passive micro-Laser Retro Reflector
2) Active Space Transponder

The first should be used with Laser Ranging ground station equipped with additional software for the identification of the number of retro-reflector installed on the visible satellite side and, as consequence, for the identification of the spacecraft attitude.

The second is instead an active device, powered by the satellite, and connected with the satellite bus. The device is able to acquire the spacecraft position using the internal navigation system and able to transmit satellite identification, position, and orbital parameter to dedicated ground stations, once the satellite is in visibility.

8.3.3 Design Guidelines for LRR

The main characteristics of the first tracking device, the Passive Laser Micro Retro Reflectors (LRR), to be included in the spacecraft design, are reported in the following table.

Characteristic	Specification
Dimensions	0.5" (diameter) or 1.0 cm (diameter) x 5 mm (thickness)
Mass	Approx. 2 g
Number of devices	1+, if attitude controlled 6+, at least one on each side, if in low spinning, for omnidirectional coverage More (e.g. 15) if attitude determination is required.
Power	No
Fixation	Glue on sat external surface
Pointing	Attitude stabilization required if not mounted on every side. LRR has 90° (+/-45°) coverage laser reflection. For total coverage in any attitude devices shall be mounted on all the sides, with different number and disposition if attitude determination is required.
Lifetime	Unknown
Other	

The Interfaces with the device LRR are reported in the following tables also contain the quantitative data to be used as generic requirement for the installation of the device on the specific spacecraft, which in this chapter is represented by a 1U CubeSat of 10 cm side.

Interface	Required (Y/N)	Note or Characteristics
Mechanical	Y	Clean external surface 1.5 cm x 1.5 cm where the device is glued. If no protrusion is required small indent shall be designed on each side for the devices insertion (flush mounted)
Thermal	N	Passive
Electrical	N	Passive
Data	N	Passive
BUS	N	As above
Other		

The micro-LRR devices could be glued on the external surface of the satellite as illustrated in Figure 12. The glue to be used could be a high-performance two-component epoxy resin, the specific type to be used depending on the surface materials. These adhesives are generally workable for a few minutes and cure at ambient temperature for a few days. The surface finish shall attain an adequate level of roughness (e.g. face knurling).

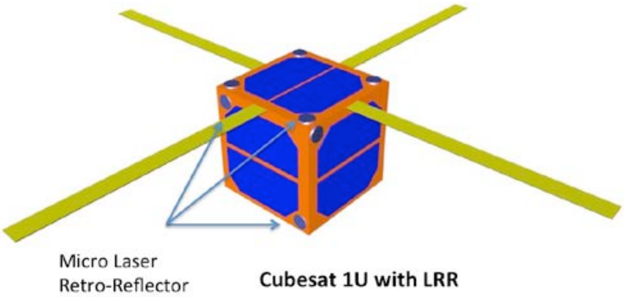

Figure 11 – Drawings of CubeSat equipped with LRR

8.3.4 Design Guidelines for Space Transponder

The main characteristics of the second suitable tracking device the Space Transponder, to be included in the spacecraft design, are reported in the following table.

Characteristic	Specification
Dimensions	1 CubeSat standard PCB (approx. 96x91 mm)
Mass	100 g
Number of devices	1
Power	Yes, approx. 5 W peak, 1 W average, when transponder is in view of a ground station and transmitting (estimate)
Fixation	Installed on the Internal structure
Pointing	Attitude stabilization required (even coarse) for the navigation and Rx-Tx antennas
Lifetime	Expected the typical life of space qualified PCBs (5 years)
Other	The device requires the implementation of navigation and Rx-Tx antennas including wirings.

The Interfaces with the device LRR are reported in the following tables also contain the quantitative data to be used as generic requirement for the installation of the device on the specific spacecraft, which in this chapter is represented by a 1U CubeSat of 10 cm side.

Interface	Required (Y/N)	Note or Characteristics
Mechanical	Y	Internal electronic slot (91x96 mm) and cabling to antennas
Thermal	Y (TBC)	Conductive cooling clamping or not required
Electrical	Y	Standard power bus connection (e.g. 5V and/or 3V3)
Data	Y	Data link for secondary telemetry transmission and acquisition of secondary command line (Space Transponder has also RX capabilities) Attitude data for the transmission to ground
BUS	Y	See above
Other		

The Space Transponder devices shall be installed in the internal electronic slot of the satellite as illustrated in Figure 13.

It should occupy only one internal slot and could share the Rx-Tx and navigational antennas of the CubeSat system, since the device uses standard VHF-UHF CubeSat links and GNSS receivers (commercial GPS patch antennas for CubeSat are available as illustrated in Figure 14

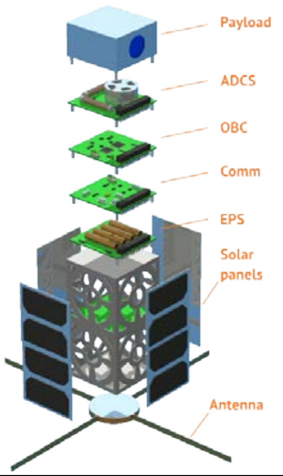

Figure 12 – Generic CubeSat Internal structure
(ref. SpaceBillboard.com)

Figure 13 – GPS patch antenna
(ref. NanoAvionics)

8.4 Guidelines for Smallsats

8.4.1 Smallsat Characteristics

Smallsat is an umbrella term to categorize satellites with a total mass of less than a few hundred kg. The use of Smallsats, often in constellations, is becoming more and more widespread in the space industry, for a wide spectrum of missions such as communications and Earth observation. These platforms allow reduced launch costs (being able to be launched in bulk or sometimes “piggyback” on launches of bigger satellites), faster and cheaper designs, and ease of production scaling, which in turn allows for large constellations.

In this context, the term “Smallsat” will be used to refer to a small platform with a mass of a few tens of kg (i.e. specifically a microsatellite).

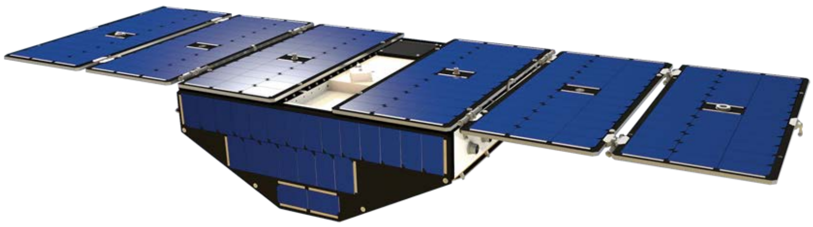

Figure 14 – CYGNSS, a 30 kg smallsat used for climate studies

8.4.2 Tracking device for Smallsats

For these systems the current study identified two suitable devices:

1) Passive Optical Tracking
2) Pulsating LEDs

The first should be used with a network of ground stations equipped with automated optical telescopes to autonomously find and track satellites and orbital debris, as well as obtaining additional information from the photometric signature of the observed objects.

The second is instead an active device, which would flash high-powered LEDs on the satellite surface in a known identification pattern, to be observed by dedicated ground stations.

8.4.3 Design Guidelines for Passive Orbital Tracking

The main characteristics for the first tracking device, i.e. passive orbital tracking, are listed in the following table, even though many characteristics are not applicable, since the system requires no physical implementation on the spacecraft.

Characteristic	Specification
Dimensions	NA
Mass	NA
Number of devices	NA
Power	No
Fixation	NA
Pointing	No pointing is required. Attitude could be inferred from photometric signature (TBD).
Lifetime	Unlimited (limited by ground segment availability)
Other	

No Interfaces onboard the spacecraft are required, naturally, since no physical device needs to be installed.

Interface	Required (Y/N)	Note or Characteristics
Mechanical	N	NA
Thermal	N	NA
Electrical	N	NA
Data	N	NA
BUS	N	NA
Other		

8.4.4 Design Guidelines for Modulated LEDs

The main characteristics of the second suitable tracking device to be included in the spacecraft design, i.e. the Modulated LEDs, are reported in the following table.

Characteristic	Specification
Dimensions	100 cm^3
Mass	50 g
Number of devices	1+, if attitude controlled 4+, at least if in low spinning, for omnidirectional coverage, according to the achievable light cones and device placement.
Power	Approx. 1W peak per 4-LED array, average depends on duty cycle and number of arrays.
Fixation	Installed on the external faces
Pointing	Attitude stabilization required if visibility is not omnidirectional. For total coverage in any attitude devices shall be mounted on at least 2 sides and according to their light emission cones, possibly with different number and disposition if attitude determination is required.
Lifetime	Unknown, probably limited by LED lifespan (approx. 5 years TBC)
Other	

The Interfaces with the Modulated LEDs are reported in the following tables also contain the quantitative data to be used as generic requirement for the installation of the device on the specific spacecraft, that in this chapter is represented by a Smallsat of 20/40 kg.

Interface	Required Y/N)	Note or Characteristics
Mechanical	Y	Surface mounting or embedding on external faces, fastening method TBD
Thermal	Y (TBC)	Conductive cooling clamping or not required
Electrical	Y	Power bus connection (e.g. 28V, 5V, 3V3)
Data	Y (TBC)	Data link for secondary telemetry transmission (if required).
BUS	Y	See above
Other		

An example of high power LEDs for spacecraft tracking mounted on a small platform is provided in Figure 16 below, in which the Ursa Maior CubeSat is displayed.

Figure 15 - LED mounting on Ursa Maior CubeSat [RD-05]

8.5 Applicability of Design Guidelines for Larger Satellites & Rocket Bodies

The Applicability and Shortcomings of Design Guidelines derived for Smallsats when applied to Larger Satellites and Rocket Bodies is illustrated here. This chapter discusses the results obtained in the previous chapter regarding Smallsats (in the form of design guidelines, specifications, requirements, etc.) with the purpose of verifying the possibility of using such results when applying a scaling up approach to these platforms and systems. Consequently, the only considered results will be the ones for the closest size category to larger satellites and rocket bodies, which are the Smallsats. Larger satellites, in fact, are defined as platforms with a mass superior to the ones that fall within the Smallsats definition.

8.5.1 Characteristics

As already stated, the definition of Larger Satellites starts from the definition of Smallsats itself. Since in the previous chapter Smallsats were defined as “small platform with a mass of a few tens of kg (i.e. specifically a microsatellite)”, Larger Satellites are therefore defined in this context as *platforms with a mass of minimum few tens of kg up to hundreds of kg*. Rocket bodies are instead defined as *space objects with no active usable resources whatsoever and dimensions comparable with the ones from Larger Satellites*. Although this definition may not include all the Rocket Bodies available (smaller Rocket Bodies could be excluded from this), rocket parts that are worth analyzing usually have dimensions at least one size category superior to the spacecraft they are supposed to carry. Therefore, considering Rocket Bodies to fall within the size category of Larger Satellites is an acceptable assumption, considering satellites the size of Smallsats and over. Smaller parts can be hence analyzed as inferior category platforms with a non-collaborative behavior (such as dead CubeSats or Picosats).

8.5.2 Tracking Devices

The highest ranked technologies for Larger Satellites and Rocket Bodies are Laser Passive Retro-Reflectors (LRRs) as illustrated in Chapter 7.

Furthermore, the second highest ranked technology for Larger Satellites would be the Space Transponder but again, as stated in the relative chapter of DD04, such technology is not available for that size category, leading to the next highest ranked technologies, which are for both Larger Satellites and Rocket Bodies the Passive Optical Tracking and the Pulsating LEDs. This is perfectly in line with the results obtained for Smallsats. These three technologies will be therefore analyzed.

8.5.3 Applicability of Design Guidelines from smaller sizes

LRRs have been considered in chapter 8.3.3 for CubeSats. Design Guidelines derived for such platforms are entirely applicable for Larger Satellites, given the greater dimensions of the latter that allow more availability of masses, volumes and surfaces.

Attention must be paid to the localization of the reflectors; in fact, unlike CubeSats, Larger Satellites easily comprises platforms with different shapes and with extendable solar arrays. Such particular configurations may lead to the obscuration of one or more reflectors mounted aboard the satellites, degrading the capability of such technology to correctly identify the system or its attitude. This can be although solved thanks to the larger dimensions of the spacecraft mounting multiple redundant reflectors in different positions, so that in any given attitude of the spacecraft, a minimum combination of reflectors are available for laser pointing. This is especially valid when the technology is to be applied to Rocket Bodies, whose shapes can usually vary greatly.

Another important issue to consider when applying this technology to Larger Satellites is the lifetime of the overall spacecraft. The higher the size category, the longer the satellites usually operates in orbit. This could lead to a degradation of the reflector's optical properties (or its adhesion, if glued), that needs to be kept into account when considering the use of such technology up to the end of life of the system. Retroreflectors, when used in this size category, could also be mounted via mechanical fastening, instead of gluing.

Similar assumptions apply to the second considered technology, which is the Pulsating LEDs or Modulated LEDs. As per the retroreflectors, LEDs must be put in positions such as they are visible from ground with a minimum configuration (i.e. a minimum number of LEDs must be visible during each observation). This reflects into a particular care that must be put when designing the position of each LED onto the platform.

Finally, regarding Passive Optical tracking, the same considerations made for Smallsats in chapter 8.4.3 are still valid; plus, larger dimensions are undoubtedly an advantage when considering this technology.

9 TRACKING AUGMENTATION AS A WAY TO SUPPORT REGISTRATION CONVENTION OBLIGATIONS

As stated in DD04, chapter 6, the capability of mapping, detecting and identifying objects (whether they are collaborative or not) that orbits the Earth has been acquiring more importance recently, driving institutions to face the issue of finding a reliable way of knowing what is orbiting the Earth and where.

In December 2017, the Federal Communications Commission (FCC), the U.S. government agency that oversees satellite launches, explicitly forbade a California-based company called Swarm Technologies to proceed with the launch of four pico-satellites named "SpaceBEEs", because of the lack of tracking capability for such small items. Although, in January 2018, the launch took place anyway with an Indian Polar Satellite Launch Vehicle (PSLV), marking the first-known unauthorized launch of a commercial satellite in American history. The target altitude for such satellites was 580 kilometres – roughly 1.5 times which of the International Space Station, which orbits at an average height of 390 km – but the SpaceBEEs' orbit will eventually decay closer to Earth because of the planet's atmospheric drag. After the satellites' operational phase, they will likely remain in orbit for 4 to 9 years, depending on the final orbit of the satellites and the influence of the Sun.

These tiny satellites measure 10x10x2.8 cm, meaning they are even smaller than a standard 1U CubeSat, making them too small to be easily tracked by the U.S. military's Space Surveillance Network (SSN), the FCC wrote in a letter dated December 12th, 2017. And the satellites would only be able to generate telemetry data (therefore including attitude and position information) during their operational phases.

This set a dangerous precedent, with the possibility of having satellites extremely difficult to be tracked by any present system. Such event may be considered to pose limited threat by now, as long as it is still contained, but its potential danger increases dramatically when considering the number of satellites of such dimensions that will be launched in the near future. Plus, according to the most recent estimations (that led to the definition of the Kessler Syndrome), any collision may lead to other multiple collisions, as in a "domino" effect that could jeopardize space assets and missions.

To reduce and mitigate this risk, institutions and governments may want to impose regulations on the future launches, forcing manufacturers and operators to provide their satellites with tracking capabilities.

Two levels of intervention are therefore foreseeable.

The first, most stringent level includes all the regulations and laws that would force manufacturers to mount aboard their spacecraft a specific tracking technology (possibly depending on the size of the platform) in order to obtain the authorization for launch. This would affect the design of any future mission, because of the need of a specific tracking system to be mounted.

A second level of intervention, less restrictive, may be set by imposing manufacturers to provide their systems with a tracking augmentation technology, but leaving the choice of which technology to the manufacturer, as long as they are able to somehow show evidences that such technology can meet minimum requirements for tracking capabilities.

These evidences may be represented, for example, by a certification that the tracking system producer could be required to provide to the customers that mount its technology, and such certification could be for example granted by a "super partes" institution, government or entity (e.g. ESA).

This case would also drive a positive evolution of the tracking technology development, since better performances could lead to "higher ranks" certifications that could lead to higher incomes for the system producer.

As mentioned, both levels of intervention may be applied on a local basis (i.e. country-wide) or internationally, with the involvement of institutions such as the UN, given that such entities possess the authority to impose such regulations.

Alternatively, one of the drivers that could possibly leverage the use of tracking technologies is the insurance cost. Allowing discounts for those who grant tracking capabilities for their platforms (or, the other way around, rising the costs for insurance for those who don't) may encourage the use of such technologies for any future mission, under the obvious condition for insurances to be mandatory for the launch of any platform.