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CONCEPTUAL PROJECT OF A SPACE SURVEILLANCE AND TRACKING SYSTEM (SST): A CASE STUDY FOR THE ITA SPACE CENTER

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CONCEPTUAL PROJECT OF A SPACE SURVEILLANCE AND TRACKING SYSTEM (SST): A CASE STUDY FOR THE ITA SPACE CENTER

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This work is dedicated to my wife Anna and to my son Leonardo, who are my reason for everything. Also, to my parents who I most admire and have as an example for life.

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*"Talent is cheap,
dedication is expensive."*
— Unknown

Resumo

O crescente número de Objetos Espaciais Residentes em Órbitas Próximas à Terra (NEO), especialmente em Órbitas Terrestres Baixas, colocam em risco a segurança das operações tripuladas e aumentam a probabilidade de danos e degradação da infraestrutura espacial instalada atualmente. O risco de possíveis colisões em efeito cascata pode trazer sérios prejuízos econômicos e afetar consideravelmente a sustentabilidade de futuras missões espaciais. Consequentemente, muitas empresas e agências estão buscando a capacidade de alcançar e manter altos níveis de Consciência Situacional do Espaço (SSA) por meio de seus próprios Sistemas de Vigilância e Rastreio de Objetos Espaciais (SST) buscando, especialmente, maior customização e transparência no gerenciamento dos dados produzidos pelo sistema comparativamente à soluções comerciais prontas. Neste contexto, um *framework* de *Model-Based Systems Engineering* (MBSE) utilizando a Metodologia ARCADIA é desenvolvido e implementado, neste trabalho, para um sistema conceitual envolvendo os sensores disponíveis para aplicações SST do Centro Espacial ITA. O *framework* proposto inclui, inicialmente, uma Análise Operacional na qual a questão do monitoramento de Objetos Residentes no Espaço (RSO) é estruturada em relação aos principais atores envolvidos e suas interações, a fim de identificar as principais interfaces e recursos a serem explorados e incorporados no modelo em uma representação ontológica. No Domínio da Solução, será proposta uma análise das Necessidades do Sistema e uma Arquitetura Lógica, descrevendo como o sistema funcionará para atender as expectativas do usuário por meio de componentes lógicos, integrando restrições não funcionais evidenciadas durante a Análise Operacional. Além disso, também são discutidos aspectos relacionados à definição da arquitetura do sitema, influenciada pelos tipos de observação que devem ser realizadas, tipos de dados a serem extraidos, algoritmos de determinação de órbitas e de propagadores orbitais utilizados. Aspectos que vão além do Gerenciamento de Sensores também são discutidos, uma vez que o sistema conta com fontes adicionais de informação, como dados de observações prévias e de outras bases de dados colaborativas. No presente trabalho, a metodologia ARCADIA foi implementada no software Capella®, uma solução de software Open-Source produzida pela empresa Thales.

Abstract

The increasing number of Resident Space Objects in Near-Earth Orbits (NEO), especially in Low Earth Orbits, jeopardize the safety of manned operations and increase the probability of damage and degradation of the current installed space infrastructure. The risk of possible collisions in a cascade effect can bring serious economic losses and considerably affects the sustainability of future space missions. Consequently, many companies and agencies are pursuing the capability to achieve and maintain high levels of Space Situational Awareness (SSA) through their own Space Surveillance and Tracking (SST) Systems seeking, especially, for more customization and transparency for data products than traditional commercial solutions available in the market, usually offered as a black-box system. In this context, a Model-Based Systems Engineering (MBSE) framework using ARCADIA Methodology is developed and implemented in this work for a conceptual system involving the available sensors for SST applications at the ITA Space Center. The proposed framework includes an Operational Analysis used to trace the main stakeholder's needs in a Solution Neutral environment. The issue of monitoring Resident Space Objects (RSO) is structured in regard to actors and how they interact with each other, in order to identify the main interfaces and features to be explored and incorporated in the model in an ontological representation. In the Solution Domain, an analysis of the System Needs and a Logical Architecture will be proposed, describing how the system will work to fulfill the user's expectations through logical components and integrating non-functional constraints evidenced during the Operational Analysis. Along this work, some aspects related to several architectural options trades, influenced by available orbit determination algorithms, observation techniques and propagators are also discussed, as well as aspects that go beyond Sensor Management, since the system relies on other sources of information, such previous observations and other collaborative databases where the uncertainty associated with each observation is a very sensitive information and an important parameter to be considered, especially in support for decision making. In the present work, the ARCADIA methodology was implemented in the software Capella®, an Open-Source software solution released by Thales.

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List of Abbreviations and Acronyms

AEB	Brazilian Space Agency
ARCADIA	Architecture Analysis and Design Integrated Approach
ASCOM	Astronomy Common Object Model
BC	Ballistic Coefficient
CCD	Charged-coupled
CCSDS	Consultative Committee for Space Data Systems
CEI	Aeronautics Institute of Technology Space Center
CGEM	Computadorized German Equatorial Mount
CJCS	Chief of Joint Command Staff
CMOS	Complementary Metal-oxide Semiconductor
CNES	French Space Agency
CNSA	China National Space Administration
COE	Classical Orbital Elements
COMMS	Communications
CONOPS	Concept of Operations
COPE	Brazilian Air Force Space Operations Center
COSPAR	Committee on Space Research
CPWI	Celestron™ Plane Wave™ Instruments
CSpOC	Combined Space Operations Center
DCTA	Department of Science and Technology of Brazilian Air Force
DEC	Declination
DoD	Department of Defense
DSI	Deep Sky Imager
ECI	Earth-centered Inertial reference frame
ESOC	European Space Operations Center
FAB	Brazilian Air Force
FOV	Field of View
GEO	Geostationary Orbit
GLONASS	Russian Global Navigation Satellite System

GMAT	General Mission Analysis Tool
GP	General Perturbations
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit
HEO	Highly Elliptical Orbit
IDA	Institute for Defense Analysis
INPE	Brazilian National Institute for Space Research
IR	Infra-red
ISO	International Organization for Standardization
ITA	Aeronautics Institute of Technology
ITRF	International Terrestrial Reference Frame
JSpOC	Joint Space Operations Center
LA	Logical Architecture
LAB	Logical Architecture Blank
LEO	Low Earth Orbit
MBSE	Model-based System Engineering
MCC	Mission Control Center
MEO	Medium Earth Orbit
MSM	Modes and States Machine
NASA	National Aeronautics and Space Administration
NEO	Near Earth Orbits
NORAD	North American Aerospace Defense Command
OA	Operational Analysis
OAB	Operational Architecture Blank
OAIB	Operational Activity Interaction Blank
OCB	Operational Capability Blank
ODM	Orbit Data Message
OEM	Orbit Ephemeris Message
OES	Operational Entity Scenario
OI	Object of Interest
OMM	Orbit Mean-Elements Message
OPM	Orbit Parameter Message
PESE	Strategic Program of Space Systems
RA	Right Ascension
RMS	Root Mean Square
RSO	Resident Space Object
RSOI	Resident Space Object of Interest
SA	System Analysis
SAB	System Architecture Blank

SDFB	System Data flow Blank
SDP	Simplified Deep Space Perturbations
SES	Scenario Entity Structure
SFBD	System Functions Breakdown
SGP	Simplified General Perturbations
SNR	Signal-to-Noise Ratio
SPORT	Scintilation Prediction Observation Research Task
SSA	Space Situation Awareness
SST	Space Surveillance and Tasking
SVOM	Space Variable Objects Monitor
SWI	Software Interface
SySML	System modeling Language
TLE	Two-line Element Set
UML	Unified Modeling Language

List of Symbols

A	scalar constant
B	scalar constant
C_i	scalar constant for ith time of observation
f_i	Lagrange coefficient for ith time of observation
$F_n\|_{t=t_0}$	General series expanded term for Lagrangian f_i evaluated in time $t = t_0$
g_i	Lagrange coefficient for ith time of observation
$G_n\|_{t=t_0}$	General series expanded term for Lagrangian g_i evaluated in time $t = t_0$
$\vec{h}$	specific angular momentum
$\hat{\mathbf{L}}_{\mathbf{i}}$	Unitary line-of-sight vector of dimension 3 in ith time of observation
$\vec{r}_i$	Position vector of dimension 3 expressed in ECI frame in ith time of observation
$\vec{r}_{site_i}$	Site's position vector of dimension 3 expressed in ECI frame in ith time of observation
t_i	ith time of observation
u_i	squared mean motion of satellite evaluated at ith time
$\vec{v}_i$	Velocity vector of dimension 3 expressed in ECI frame in ith time of observation
α_i	Right-ascension in ith time of observation
δ_i	Right-ascension in ith time of observation
μ	Earth gravitational parameter
ρ_i	scalar distance between RSO and the observatory in ith time of observation
τ_i	time interval related to the difference between ith time and central time $t = t_2$

Contents

1 Introduction

In this chapter, a contextualization of the issue of detecting and tracking Resident Space Objects (RSO) in Near-Earth orbits is made and, in addition, motivations, objectives and the general structure of this work is presented.

1.1 Contextualization and Motivation

According to the Institute for Defense Analyses (IDA) (LAL et al, 2018), 3000 new satellites are expected to be launched by 2026. Two-thirds of them are developed by private companies for commercial purposes applications, and the remaining third belongs to the government, academic and military agencies from over 60 different countries. Considering that, according to the U.S. Department of Defense (DoD) there are currently 23,000 objects larger than 10 cm in diameter in the Earth orbit, and other 500,000 larger than 1 cm are estimated and not being tracked. Around 95% of these objects are debris. It means that they do not have any means of control. Figure 1.1 is an out of scale representation of the orbit environment. Each dot represents a Resident Space Object (RSO), and, colors are attributed according to the propagated TLE's age, going from green ($0 - 5$ days) to red (> 30 days) (KELSO, 2022).

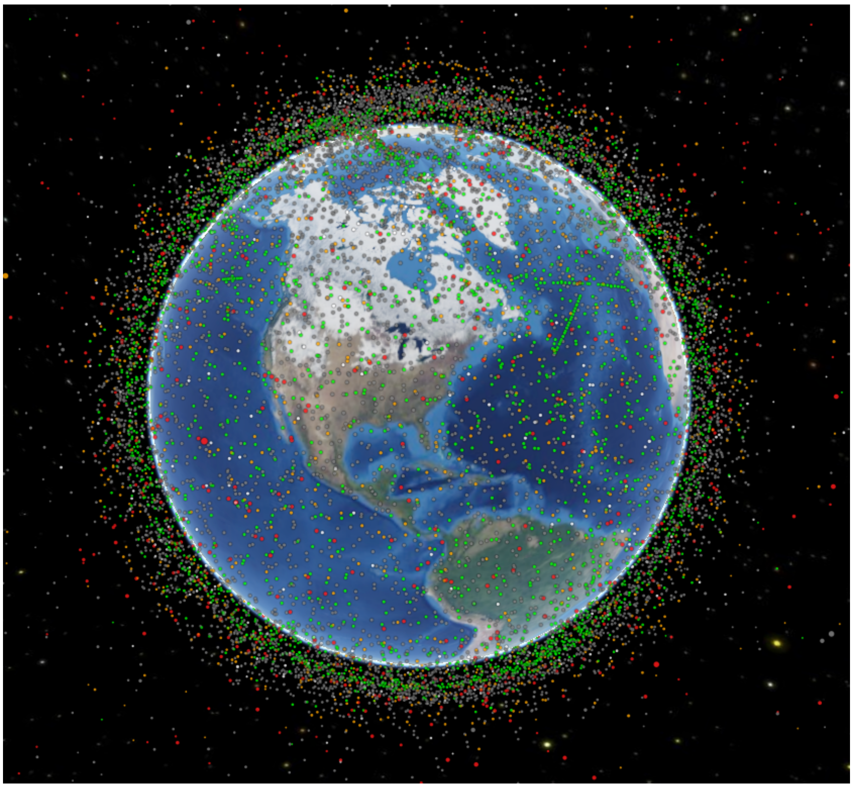

FIGURE 1.1 – CELESTRAK®visualization of Orbital-Enviorement in Nearth-Earth orbits.

Those numbers represent a great risk for safe space operations, bringing a higher probability of economic losses caused by damage or degradation of the currently installed space infrastructure. They also represent a risk for future space missions, since the debris generated by the collision of two debris might increase exponentially the quantity of debris generated and, consequently, the probability that new collisions might occur (OLTROGGE; ALFANO, 2019).

Affected by this scenario, companies and government agencies are pursuing the capability to achieve and maintain high levels of Space Situational Awareness (SSA) (LAL et al, 2018). Considering that a Resident Space Object (RSO) is any artificial or natural object orbiting another body (WILKINS *et al.*, 2014), in the Earth-orbit scope, although SSA involves a large number of activities, that are not limited to RSO detection and tracking, like space weather monitoring and forecasting (SPACE..., 2018), a Space Surveillance and Tracking System (SST) still arises as the main capability desired by operators. The main reason for that is that it represents an enabling system to all subsequent SSA activities and its development provides not only more customization and transparency about data products and generated information, but also provides crucial information for data analysis and data-quality management when performed in the context of a decision-making scenario (LAL et al, 2018).

The Space Operations Center of the Brazilian Air Force (COPE) is in charge of all activities related to the operation and management of Brazilian military assets in space.

In support for SSA, Space Surveillance and Tracking (SST) activities are operated by COPE, such that it works as an hybrid of commercial and in-house developed solutions. Although, traditionally reliable and with extensive client support, as mentioned before, commercial products expose concerns in regard to lack of transparency and customization. In this context, the development and study of a SST System could, not only positively contribute in better understanding the issue of Resident Space Objects (RSO) Monitoring, but could also contribute to the development of new processes and technologies related to the subject, which is highly desirable when considering the Strategic Program of Space Systems (PESE) guidelines and responsabilities accredited to the Aeronautics Institute of Technology (ITA), and, consequently, the ITA Space Center.

Considering that a Space Surveillance and Tracking System is a general term representing a group of activities and capabilities performed by different subsystems, in some cases from different domains (CJCS, 2020), and, usually, the user already has some limited or partial SST capability provided, or by a legacy of sensors, or by the access to some collaborative database maintained by third parties. There is a considerable quantity of candidate possible solutions to be analyzed. In this context, the main concern of this study was to, according to ISO 14300-1 (ISO 14300-1, 2011), perform studies related to the Pre-Phase A, using a top-down approach, to develop a conceptual architecture in order to provide support for architectural, functional and sensor configuration trade-off analyses without compromising system requirements, that will be validated through the model and will be derived from user's needs and expectations.

That is the context that enables Model-based System Engineering (MBSE) to play a key role in a top-down approach for the development of new products and systems (CRAWLEY, 2016), in the sense that it represents a systematic approach to deliver solutions, providing meaningful insights, especially, for interface management in complex systems when compared to traditional approaches (DORI, 2016) (WALDEN, 2016).

According to ARCADIA reference book (VOIRIN, 2018), the MBSE approach consists in the utilization of a formal digital language to formalize the process of specification, design, analysis and verification of a system. In this sense, although ARCADIA method is based on SysML concepts (HOLT, 2018), it goes beyond graphical representations by the optimization of the design process of systems architectures without compromising the traceability of the user's needs and constraints along with the product development. Figure 1.2 represents all ARCADIA's perspectives, and, how layers are internally linked in the model. Considering a top-down approach (CRAWLEY, 2016), where the system is built without any preconceptions, the ARCADIA method involves five different perspectives, going from general to specific - Operational Analysis, System Analysis, Logical Architecture, System Architecture, and Building Strategy. The Capella tool is an open-source software, developed by Thales, that enables the implementation of models following

ARCADIA methodology (ROQUES, 2018).

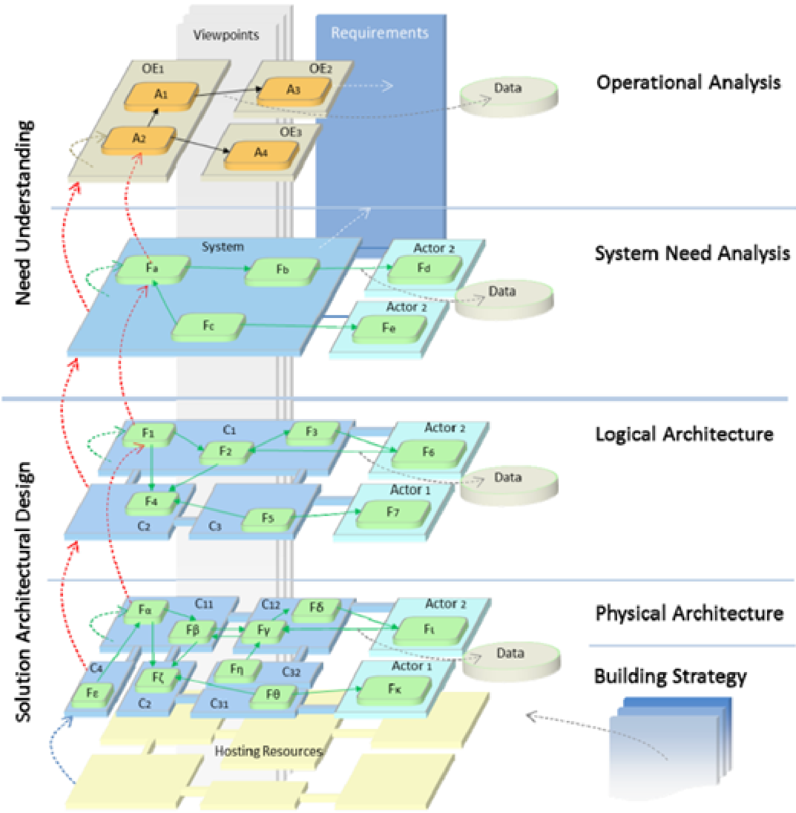

FIGURE 1.2 – ARCADIA Perspectives (VOIRIN, 2018).

Considering the aforementioned context, this study has the purpose to apply system engineering methodologies and best practices to deliver the capabilities desired by the ITA Space Center and, also, to describe the behavior of the system through functional analysis considering the influence of aspects related to different architectures of system and intrinsic characteristics of the sensor owned by CEI. It is expected that this work provides a basic and general framework for a SST System for the ITA Space Center, corresponding to the first three perspectives of ARCADIA methodology - Operational Analysis (OA), System Analysys (SA) and Logical Architecture (LA), that could be used as a starting point in the development of a definitive system.

1.2 General and specific objectives

The general objective of the present study is to develop a conceptual architecture for a Space Surveillance and Tracking (SST) System for meeting the needs of the ITA Space Center. This research is based on the hypothesis that it is feasible to perform basic SST activities, such as detection, and, identification of Objects of Interest (OI) in Near-Earth

Orbits, with the current installed infrastructure, regarding to acquisition hardware at ITA Space Center - Celestron 11 inch Telescope and MEADE Instruments CMOS Camera.

The specific objectives can be described as:

- Define and characterize the Objects of Interest (OI) to be monitored by the ITA Space Center in regard to mass, dimensions and orbit parameters;
- Define the capabilities associated to SST that are of interest to the ITA Space Center;
- Identify, by comparison with similar scope systems, the actual capacity of the ITA Space Center to perform SST activities with the current installed infrastructure regarding to software, sensors, and, other hardware;
- Define criteria of observations associated to orbit determination algorithms;
- Define a Concept of Operations (CONOPS) for the system;
- Define a Logical Architecture for the proposed SST system using the ARCADIA method implemented in the Capella Tool™.

1.3 Similar projects or iniatives

A complex system is defined as a system who exhibits one or more properties not exhibited by its parts when individually considered (LADYMAN *et al.*, 2013). Much of the complexity of those systems is associated to the great number of interfaces to be mapped and managed and, consequently, to insufficient information to perform behavior modeling and prediction of the system. In addition, those systems are characterized by numerous stakeholders from different backgrounds who needs a common background and unified source of true to validate and analyse system requirements, trade-off analyses, among others.

Considering the aforementioned context, similar studies exploring different aspects of SSA Systems or different aspects related to MBSE approach were found in literature. For example, Reference (ROVETTO, 2017) developed an ontology architecture concept for Europe's SSA program. Basically, the main ontology was divided in three principal instances - Space Surveillance and Tracking Ontology, Space Weather Ontology, and Near-Earth Object Ontology. The main purpose in working with ontologies was creating the foundations to manage data sharing and data integration across different systems in ESA SSA program. In Reference (LIEBSCHWAGER *et al.*, 2013), it was proposed a framework of homogeneous ground-based sensors for SSA applications. Other references, such as Reference (CHEN; LI, 2014) used Paralell Control Theory to model and simulate the behavior of a SSA System. In regard specifically to ARCADIA methodology, Reference (BONNET *et al.*, 2017) propose a methodological approach for studying and integrating the impact of modes and states on the architecture definition of systems in general and, Reference (LASALLE *et al.*, 2020) use the Capella Tool to design the Space Variable Objects Monitor (SVOM), a space-based system developed by the China National Space Administration (CNSA) in association with the French Space Agency (CNES) to make in situ measurements of gamma-rays in space. In the latter case, although the mission objective differs from SSA Detection and Tracking Systems, in common, both systems rely on autonomous or task-based observations performed by a network of sensors whose data are processed in real-time.

1.4 General Structure

The main characteristics of satellites and Object of Interest (OI) for the ITA Space Center, such as mass, physical dimensions and orbital parameters are presented in Chapter 2. Additionally, the main features of the optical sensor owned by CEI are presented as well the standards of orbital data transmission, such as Two-line Element Set (TLE) and CCSDS protocols are reviewed. In Chapter 3, the foundation theories associated to the logic of the system such as Initial Orbit Determination algorithms using angles-only observations are reviewed and analyzed. Next, in Chapter 4, the general methodology, and, ARCADIA method are discussed, and, finally, in Chapter 5 the developed system's architecture is presented and discussed.

2 Background and Legacy Hardware

Objects of Interest, legacy hardware, and, subjects that affected the system's architecture are presented and discussed in regard to their contribution and complementarity to the proposed study.

2.1 Objects of Interest (OI) for ITA Space Center

The Aeronautics Institute of Technology (ITA) owns the satellite ITASAT, currently in operation in LEO orbit, and, expects, to launch a second satellite, named SPORT, developed in cooperation with NASA, and, other American companies, and, universities, also in LEO orbit in the second semester of 2022. In this context, those satellites are considered Objects of Interest to ITA Space Center. The reason is simple, they have well known orbital parameters, telemetry data is available, and, especially, their physical properties are well known.

Those information are useful to calibrate the optical system, to have a better estimation on the performance of the system in providing orbital parameters using angles-only observations, and, to a series of other activities if the physical system is real implemented in the future. In practical terms, Optical sensors actually make measurements of apparent brightness of a RSO, that are expressed in astronomical magnitudes. This quantity, although, depends on the distance between the observer and the observed object, and, on the illumination conditions (SCHILDKNECHT, 2007).

In the aforementioned context, ITASAT and SPORT satellites *a priori* attitude behaviour and physical features information are used to provide a more realistic spectral model, used in the image processing, that is a process to convert angular data extracted from image analysis into an element set of state vector (position, velocity), and, finally produce orbital parameters to be correlated into a catalogue (SCHILDKNECHT, 2007). Figure 2.1 expresses in an ontological representation the main spectral and physical features, and, also, kinematics properties of an RSO that are explored in an SST system.

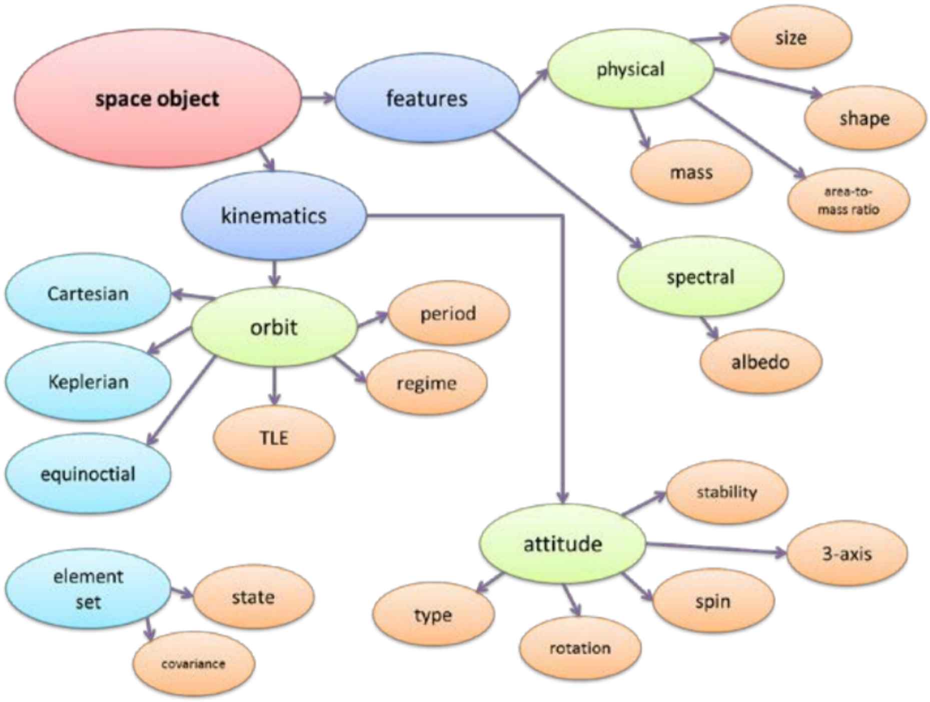

FIGURE 2.1 – Ontological Representation of a RSO (RALEY *et al.*, 2016).

Additionally, it is important to identify intrinsic characteristics of the main types of orbit that are observable from ITA Space Center location, since they have impacts on the observation techniques, sensor allocation, and, sensor configuration (CURIEL, 2020).

2.1.1 ITASAT

The ITASAT, shown in Figure 2.1, was co-developed by the Aeronautics Institute of Technology (ITA) and the National Institute of Space Research (INPE), and, funded by the Brazilian Space Agency (AEB) and the Brazilian Air Force (FAB). The satellite is able to regularly transmit beacons and re-transmit messages, providing a communication channel with amateur radios over the globe (SATO *et al.*, 2019). The Mission Control Center (MCC) of the satellite is located at the Aeronautics Institute of Technology (ITA), in São José dos Campos, São Paulo, Brazil.

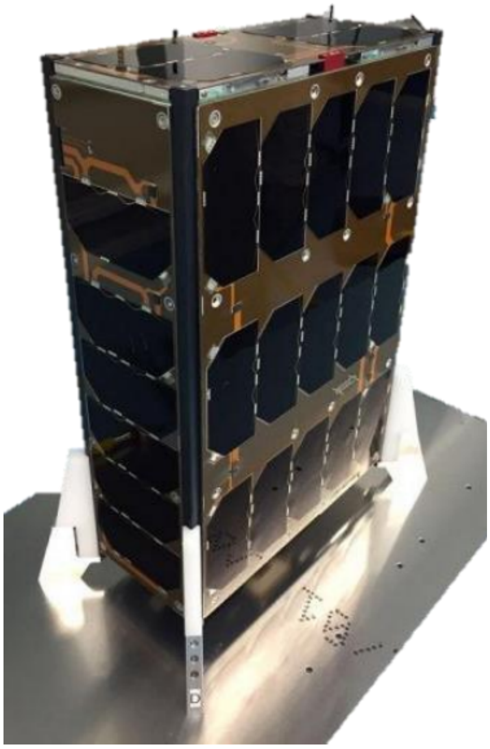

FIGURE 2.2 – ITASAT Protoflight Model (SATO *et al.*, 2019).

TABLE 2.1 – ITASAT Parameters of Interest

Classification	Value
NORAD ID	43786
COSPAR ID	2018-099AE
Orbital Parameters	**Value**
Altitude	573 km x 592 km
Inclination	97.613°
Eccentricity	0.00135
RA ascending node	23.053h
Argument perihelion	248.081°
Mean anomaly	111.898°
Orbital period	96.191min
Epoch of osculation	08 Oct 2022, 10:18
Physical Parameters	**Value**
COMMS and Telemetry	UHF (Uplink), VHF/S band (Downlink)
Dimension	6U
Weight	5.2 kg
External Structure	Al7075-T6
Solar Panels Composition	Polyimide with Kapton coverlay
Ballistic Coefficient (BC)	0.012 [m^2/kg]

2.1.2 SPORT Satellite

The main objective of the Scintillation Prediction Observations Research Task (SPORT) Mission is to use a 6U CubeSat platform, shown in Figure 2.2, to perform measurements in the ionosphere, in order to better understand the preconditions that leads to equatorial plasma bubbles formation. The project is an international cooperation between the National Aeronautics and Space Administration (NASA), the Brazilian National Institute for Space Research (INPE), and the Aeronautics Institute of Technology (ITA) under the Brazilian Air Force (FAB) Department of Science and Technology (DCTA), and, encouraged by U.S. Southern Command. (SPANN *et al.*, 2017).

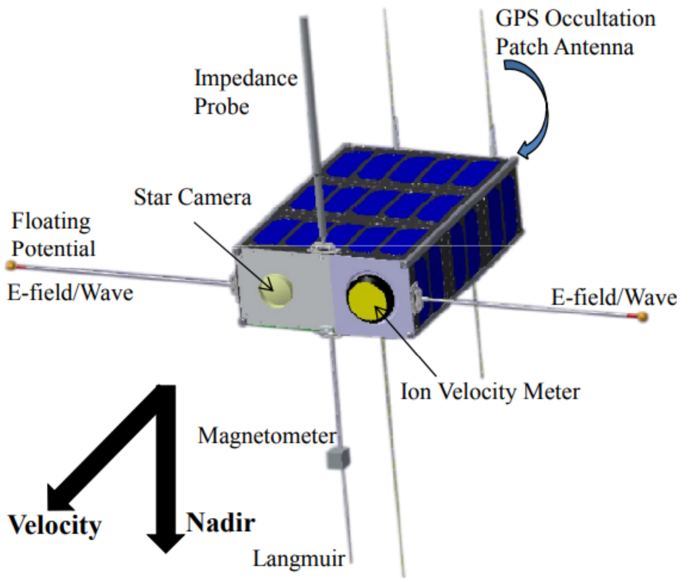

FIGURE 2.3 – SPORT Artistic representation (SPANN *et al.*, 2017).

TABLE 2.2 – SPORT Parameters of Interest

Classification	Value
NORAD ID	(TBD)
COSPAR ID	(TBD)
Orbital Parameters	Value
Altitude	400 km
Inclination	51.64°
Eccentricity	0.0002
RA ascending node	305.87°
Argument perihelion	103.049°
Mean anomaly	46.41°
Orbital period	95min
Physical Parameters	Value
COMMS and Telemetry	VHF (Uplink), UHF (Downlink)
Dimension	6U
Weight	9.2 kg
External Structure	Al7075-T6
Solar Panels Composition	Polyimide with Kapton coverlay
Ballistic Coefficient (BC)	0.001 [m^2/kg]

2.1.3 Orbit environment considerations

Orbit families can be grouped considering different parameters. The altitude criteria is widely used in the context of SST Systems, since it provides insightful patterns about RSO behaviour, predominant orbit perturbation effects, and, techniques of observation. Considering the class of higher orbits, with altitude above 2000 km, there is the family of Geostationary orbits (GEO), with altitudes in the order of 36,000 km. Objects in these orbits are stationary, considering an Earth fixed frame, or librating around an equilibrium position, when not hovering exactly above the Equator. Usually, this orbit is used for Communication Satellites (SCHILDKNECHT, 2007).

Additionally, also in the group of higher orbits, there are the families of High Eccentric Orbits (HEO) and Medium-Earth Orbits (MEO). Inside the group of HEO Orbits, it is important to consider two different families; the Geostationary Transfer Orbits (GTO) and Molniya Orbits. GTO orbits are characterized by perigees in LEO, and, apogees in the GEO altitude. Typical RSO in GTO orbits are spent upper rocket stages, payload adapters, and, debris produced along the mission. On the other side, typically occupied by Russian communication satellites, Molniya Orbits have perigees at a specific portion in LEO Orbit - 400 km to 600 km in the southern hemisphere, and, apogees above 40,000 km in the northern hemisphere (SCHILDKNECHT, 2007). Finally, MEO orbits have orbital periods of 12 h - 14 h, and, altitudes between 20,000 km and 22,000 km. These orbits are mainly occupied by Navigation Satellites Systems, such as GPS, Galileo, GLONASS, and, part of the Chinese BeiDou Constellation (LI *et al.*, 2015).

According to Reference (CURTIS, 2020), Low-Earth orbits have a maximum altitude of 2000 km. In consequence, differently from the class of satellites previously mentioned, orbital periods for LEO orbits usually lie in the interval between 80 min to 120 min. A practical effect in observing this class of satellites is that, usually, their predictions are valid for shorter period of time, since drag, as the main type of perturbation, have strong effect in orbital parameters, especially inside the orbital plane, as semi-major axis, and, eccentricity. In this sense, it is recommended that, to plan observations, TLE no longer than 3 days are used to this class of satellites (SCHILDKNECHT, 2007). This portion of Near-Earth orbits is the most relevant to ITA Space Center scope, since all of its assets are in this orbit, and, additionally, this orbit is the most suitable orbit type to perform observations using telescopes with relative low aperture diameters, which is the case of the Celestron‘s 11 inch owned by CEI (SCHILDKNECHT, 2007).

Satellite observation from ground-based optical sensors requires the utilization of orbit propagators, mainly, for two reasons: (*i*) To have an accuracy estimation of their own algorithms of orbit determination; and, (*ii*) To propagate orbits from a given TLE to the time of planned observations, in order to determine Right Ascension and declination angles of the target‘s visible path.

Propagators are, in reality, orbital models used to calculate orbital state vectors of RSO that take into considerations different type of orbit perturbations that are relevant to a given portion of space. Simplified General Perturbations (SGP) models are a class of propagators most widely used, since its utilization is compatible with Two-line Element (TLE) Set, which is the format usually adopted for data sharing as NORAD‘s, and NASA‘s catalogues (VALLADO, 2006).

Examples of perturbations that are considered to this class of models is Non-sphericity of Earth, drag, third body effects, and, others. Simplified General Perturbations (SGP) are suited to satellites with an orbital period of less than 225 minutes. On the other hand, Simplified Deep Space Perturbations (SDP) models refers to RSO with an orbital period greater than 225 minutes (VALLADO, 2006). Although, SDP has a simplified drag model, when compared to SGP, it includes Lunar–Solar gravity perturbations, and Earth ressonance effects, that are relevant to 24-hour geostationary and 12-hour Molniya orbits (HOOTS; ROEHRICH, 1980).

2.2 Sensors available at ITA Space Center

In this section, legacy hardware from ITA Space Center are presented. It consists of a Celestron™ 11 inch Telescope (complete optical assembly), and, a Deep Sky Imager Color IV from Meade Instruments™.

2.2.1 Celestron™ 11 inch Telescope and CGEM™ Mount

The actual optical system owned by ITA Space Center, presented in Figure 2.4, is an Aplanatic Schmidt Celestron™ EDGEHD 1100 11”. It has a catadioptric design, consisting in a zero power corrector plate, a spherical primary mirror, and a secondary mirror along with a set of field flattening lens integrated into the baffle tube. Inside the optical tube, a black tube extends out from the center hole in the primary mirror. This is the primary baffle tube and it prevents stray light from passing through to the eyepiece or camera (CELESTRON™, 2009a). The Optical Tube is assembled in a computerized German Equatorial Mount, also provided by Celestron™, model CGEM™ II (CELESTRON™, 2009b), and, controlled by CPWI™ software. This program is responsible to directly control the mount and alignment processes, the observations itself are managed by ASCOM and SkyCapture™ softwares (CELESTRON™, 2020).

FIGURE 2.4 – Optical System - Celestron EDGEHD 1100 11" and CGEM" II Mount (CELESTRON™, 2009b).

TABLE 2.3 – Celestron EDGEHD 1100 11” specifications (CELESTRON™, 2009a)

Specification	Value
Aperture	280 mm / 11”
Optical Design	Aplanatic Schimdt
Focal Lenght	2800mm
Focal Ratio	f/10
Eyepiece	23mm / 2” (122x)
Highest useful magnification	660x
Lowest useful magnification	14x
Limiting Stellar Magnitude	14.7
Resolution - Rayleight	0.50 arcsec
Resolution - Dawes Limit	0.42 arcsec
Light Gathering Power	1593x unaided eye
FOV: Standard eyepiece	0.67°
Linear FOV (@1000yds)	35 ft
Optical coatings - Standard	Starbright XLT coating
Secondary Mirror obstruction	3.75”
Secondary Mirror obstruction by Area	12%
Secondary Mirror obstruction by Diameter	34 %
Optical Tube lenght	24 inches

2.2.2 Deep Sky Imager Color IV Meade Instruments™

The Meade Deep Sky Imager (DSI) IV, presented in Figure 2.5, is a camera for astrophotography, that operates a thermoelectric cooled 16MP CMOS sensor, the monochrome Panasonic 4”/3” MN34230PLJ. The camera is operated by SkyCapture software, or by other software, interfaced through ASCOM with the CPWI software that controls the mount(MEADE™, 2018).

FIGURE 2.5 – Deep Sky Imager Color IV Meade Instruments™ (MEADE™, 2018).

TABLE 2.4 – Deep Sky Imager Color IV Meade Instruments™ Specifications (MEADE™, 2018)

Specification	Value
Imaging Sensor	Panasonic MN34230PLJ
Imaging Sensor Size	4”/3”
Pixel array	4640 x 3506
Pixel size	3.8μm x 3.8μm
Imaging chip	Single Shot Color
Video frame rate	23
Exposure range	0.15 ms - 3600 s
A/D Conversion	12 bits
Thermoelectric cooling	Yes
IR filter	Yes
Mounting	2” barrel
Read Noise (RMS)	1.2e @30db gain

2.3 Standards of Orbital Data communication

The protocols used in message transmission have great influence in limiting or not the usefulness of the produced data. Data processing techniques always imply in loss of a certain amount of the original generated data, but, on the other side, it would be impractical to share information, or, produce useful and timely data products using only raw data. In this sense, the utilization of standardized protocols allows not only data sharing between organizations, but, it is an effective way to generate data products, since patterns and standards of organization were customized considering the application given to data (OLIVEIRA *et al.*, 2022).

2.3.1 The Consultative Committee for Space Data Systems Protocols (CCSDS)

The CCSDS proposed a common framework and provided a common basis for the interchange of Orbit Data Messages (ODMs), specifying three standard message formats, including sets of requirements and criteria that these message formats were designed to meet, to be used when transmitting orbit information data between space agencies, and, commercial or governmental spacecraft operators - the Orbit Parameter Message (OPM), the Orbit Mean-Elements Message (OMM), and the Orbit Ephemeris Message (OEM) (CCSDS, 2009). Definitions of time systems, reference frames, planetary models, maneuvers and other fundamental topics related to the interpretation and processing of state vectors and spacecraft ephemerides are provided in aforementioned CCSDS documentation (CCSDS, 2019).

2.3.1.1 Orbit Parameter Message (OPM)

An OPM specifies the position and velocity of a single object at a specified epoch. Optionally, osculating Keplerian elements may be provided. This message is suited to exchanges that involve automated interaction, although can be human interpreted, and, do not require high-fidelity dynamic modeling (CCSDS, 2009).

OPM allows for modeling maneuvering assessments (finite or instantaneous events), and, simple modeling for perturbations such as solar radiation pressure and atmospheric drag. Additionally, it contains an optional covariance state matrix, representing the uncertainty of the orbit state. But, to determine position and velocity at times different from the specified epoch, requires software implementation to the utilization of propagation techniques (CCSDS, 2009).

An OPM file example is presented in Figure 2.6. It is composed by a header with labeling information like date and time of reference parameters, followed by the author of the message. Then, a subsequent block of information about including object's identification (ID), reference frame, and, reference time system used to generate data. Finally, object's information are listed, sequentially: (*i*) Epoch of measured data; (*ii*) State vector in Cartesian coordinates referenced in ECI system; and, (*iii*) Relevant physical parameters of the object (CCSDS, 2009).

```
CCSDS_OPM_VERS = 2.0
CREATION_DATE  = 1998-11-06T09:23:57
ORIGINATOR     = JAXA

COMMENT          GEOCENTRIC, CARTESIAN, EARTH FIXED
OBJECT_NAME    = SPACECRAFT 5
OBJECT_ID      = 1998-057A
CENTER_NAME    = EARTH
REF_FRAME      = ITRF-97
TIME_SYSTEM    = UTC

EPOCH =          1998-12-18T14:28:15.1172
X =              6503.514000
Y =              1239.647000
Z =              -717.490000
X_DOT =            -0.873160
Y_DOT =             8.740420
Z_DOT =            -4.191076
MASS =           3000.000000
SOLAR_RAD_AREA =   18.770000
SOLAR_RAD_COEFF =   1.000000
DRAG_AREA =        18.770000
DRAG_COEFF =        2.500000
```

FIGURE 2.6 – OPM File Example (CCSDS, 2009).

2.3.1.2 Orbit Mean-Elements Message (OMM)

An OMM specifies the orbital characteristics of a single object at a specified epoch, expressed in mean Keplerian elements. This message is similarly suitable to automated exchange of data, and, that do not require high-fidelity dynamic modeling (CCSDS, 2009). An interesting feature of the OMM is that it can be used to generate canonical NORAD Two Line Element Sets (TLE), in order to accommodate the needs of heritage users (VALLADO, 2006). The OMM also contains an optional covariance matrix which reflects the uncertainty of the mean Keplerian elements. This message is suited for directing antennas and planning contacts with satellites, and, not recommended for propagating precisely the orbits of active satellites, inactive man made objects, and, near-Earth debris fragments, since it is not suitable for numerical integration of the orbital dynamics equations (CCSDS, 2009).

An OMM file example is presented in Figure 2.7. The first two blocks of information are label information like: (*i*) Date/time of the message; (*ii*) Author; (*iii*) Reference frame, and, propagator used. Next, the third block, corresponds to the same information presented in a TLE message. In sequence, the fourth block lists some relevant physical, and, object's dynamics related parameters, such as mean motion and, its first derivative. Finally, fifth block presents the object's covariance matrix information (CCSDS, 2009).

```
CCSDS_OMM_VERS = 2.0
CREATION_DATE  = 2007-065T16:00:00
ORIGINATOR     = NOAA/USA

OBJECT_NAME    = GOES 9
OBJECT_ID      = 1995-025A
CENTER_NAME    = EARTH
REF_FRAME      = TEME
TIME_SYSTEM    = UTC
MEAN_ELEMENT_THEORY = SGP/SGP4

EPOCH              = 2007-064T10:34:41.4264
MEAN_MOTION        = 1.00273272
ECCENTRICITY       = 0.0005013
INCLINATION        =   3.0539
RA_OF_ASC_NODE     =  81.7939
ARG_OF_PERICENTER  = 249.2363
MEAN_ANOMALY       = 150.1602
GM                 = 398600.8

EPHEMERIS_TYPE     = 0
CLASSIFICATION_TYPE = U
NORAD_CAT_ID      = 23581
ELEMENT_SET_NO = 0925
REV_AT_EPOCH       = 4316
BSTAR              = 0.0001
MEAN_MOTION_DOT    = -0.00000113
MEAN_MOTION_DDOT   = 0.0

COV_REF_FRAME = TEME
CX_X =  3.331349476038534e-04
CY_X =  4.618927349220216e-04
CY_Y =  6.782421679971363e-04
CZ_X =  -3.070007847730449e-04
CZ_Y =  -4.221234189514228e-04
CZ_Z =  3.231931992380369e-04
CX_DOT_X =  -3.349365033922630e-07
CX_DOT_Y =  -4.686084221046758e-07
CX_DOT_Z =  2.484949578400095e-07
CX_DOT_X_DOT =  4.296022805587290e-10
CY_DOT_X =  -2.211832501084875e-07
CY_DOT_Y =  -2.864186892102733e-07
CY_DOT_Z =  1.798098699846038e-07
CY_DOT_X_DOT =  2.608899201686016e-10
CY_DOT_Y_DOT =  1.767514756338532e-10
CZ_DOT_X =  -3.041346050686871e-07
CZ_DOT_Y =  -4.989496988610662e-07
CZ_DOT_Z =  3.540310904497689e-07
CZ_DOT_X_DOT =  1.869263192954590e-10
CZ_DOT_Y_DOT =  1.008862586240695e-10
CZ_DOT_Z_DOT =  6.224444338635500e-10
```

FIGURE 2.7 – OMM File Example (CCSDS, 2009).

2.3.1.3 Orbit Ephemeris Message (OEM)

An OEM specifies the position and velocity of a single object at multiple epochs contained within a specified time range. Differently from OPM and OMM, it is suited to data exchange applications that involve automated interaction, for example, frequent computer-to-computer communication, fast automated time interpretation, and, when processing is required. Additionally, it is also adequate when higher fidelity or higher precision dynamic modeling, in comparison with OPM, is required. The reason is that OEM allows for dynamic modeling of any number of gravitational and non-gravitational accelerations. To interpret the position and velocity at times different from the tabular epochs, requires an interpolation technique. In this standart, the covariance matrix is also optional, when used it represents the uncertainty of the orbit solution used to generate states in the ephemeris (CCSDS, 2009).

An OEM file example is presented in Figure 2.8. The first block of information are label information such as Object's ID, Reference frame used, times of reference, and, degree of the interpolation used. Next, the second block of information brings a set of state vectors, each line corresponding to each referenced time, and, each column corresponds, respectively, for (x,y,z) coordinates, and, then, its derivatives. The last block regards to covariance matrix information (CCSDS, 2009).

```
CCSDS_OEM_VERS = 2.0
CREATION_DATE = 1996-11-04T17:22:31
ORIGINATOR = NASA/JPL

META_START
OBJECT_NAME          = MARS GLOBAL SURVEYOR
OBJECT_ID            = 1996-062A
CENTER_NAME          = MARS BARYCENTER
REF_FRAME            = EME2000
TIME_SYSTEM          = UTC
START_TIME           = 1996-12-28T21:29:07.267
USEABLE_START_TIME   = 1996-12-28T22:08:02.5
USEABLE_STOP_TIME    = 1996-12-30T01:18:02.5
STOP_TIME            = 1996-12-30T01:28:02.267
INTERPOLATION        = HERMITE
INTERPOLATION_DEGREE = 7
META_STOP


COMMENT  This block begins after trajectory correction maneuver TCM-3.

1996-12-28T21:29:07.267 -2432.166 -063.042 1742.754  7.33702 -3.495867 -1.041945
1996-12-28T21:59:02.267 -2445.234 -878.141 1873.073  1.86043 -3.421256 -0.996366
1996-12-28T22:00:02.267 -2458.079 -683.858 2007.684  6.36786 -3.339563 -0.946654

   < intervening data records omitted here >

1996-12-30T01:28:02.267 2164.375 1115.811 -688.131  -3.53328 -2.88452 0.88535


COVARIANCE_START
EPOCH = 1996-12-28T21:29:07.267
COV_REF_FRAME = EME2000
 3.3313494e-04
 4.6189273e-04  6.7824216e-04
-3.0700078e-04 -4.2212341e-04  3.2319319e-04
-3.3493650e-07 -4.6860842e-07  2.4849495e-07  4.2960228e-10
-2.2118325e-07 -2.8641868e-07  1.7980986e-07  2.6088992e-10  1.7675147e-10
-3.0413460e-07 -4.9894969e-07  3.5403109e-07  1.8692631e-10  1.0088625e-10  6.2244443e-10

EPOCH = 1996-12-29T21:00:00
COV_REF_FRAME = EME2000
 3.4424505e-04
 4.5078162e-04  6.8935327e-04
-3.0600067e-04 -4.1101230e-04  3.3420420e-04
-3.2382549e-07 -4.5750731e-07  2.3738384e-07  4.3071339e-10
-2.1007214e-07 -2.7530757e-07  1.6870875e-07  2.5077881e-10  1.8786258e-10
-3.0302350e-07 -4.8783858e-07  3.4302008e-07  1.7581520e-10  1.0077514e-10  6.2244443e-10
COVARIANCE_STOP
```

FIGURE 2.8 – OEM File Example (CCSDS, 2009).

2.3.2 Two Line Element Set (TLE)

The US government provides general perturbations (GP) orbital data to the rest of the world since the 1970s. These data are produced by observations data from the US Space Surveillance Network (SSN) used to produce Brouwer mean elements using the SGP and

SDP orbit propagators (KELSO, 2022).

The format of the aforementioned data is known as Two-Line Element Set (TLE), and, it was conceived under the concept of providing the minimum data necessary to propagate the orbit of a resident space object (RSO), requiring relative low computational cost to be interpreted, shared, and, manipulated (KELSO, 2022).

A TLE file example is presented in Figure 2.9. In the first line, information such as NORAD ID, International Designator, and, referenced Epoch are listed. Next, also in the first line, Mean Motion's first, and, second derivatives, and, ballistic coefficient are also presented. Additionally, in the second line, orbital elements are presented. It is important to note that the mean motion is expressed in terms of revolutions per day. Both lines are ended by a checksum number, to mitigate computational errors (KELSO, 2022).

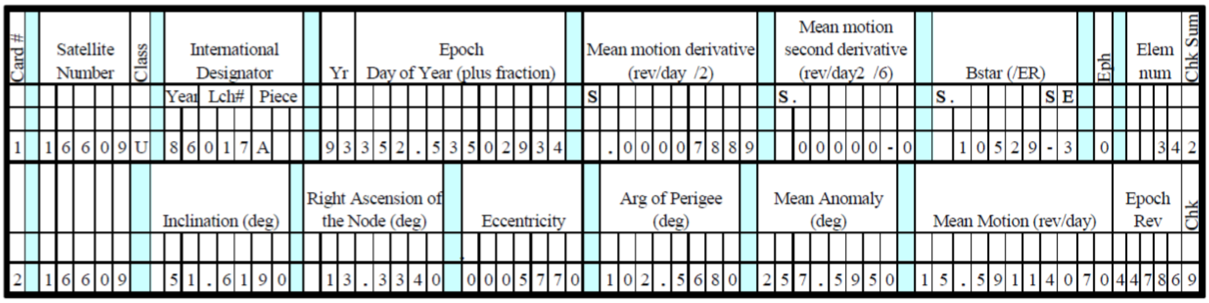

FIGURE 2.9 – TLE File Example (VALLADO; CEFOLA,).

Considering the scenario of exponential increase of the RSO population to be monitored, and, more demanding applications of data products, such as, conjunction analysis, maneuver assessment, and, a necessity of more customization in data processing techniques by users, there is a tendency in migrating to the Orbit Mean-Elements Message (OMM) standard (KELSO, 2022), that is part of the Orbit Data Messages (ODM) Recommended Standards CCSDS 502.0-B-2 (CCSDS, 2009). Consistently, Celestrak is recommending the utilization of the XML format of Version 2.0 of the OMM (CCSDS, 2019), to ensure future compatibility and interoperability (KELSO, 2022).

As mentioned before, TLE messages can be generated from OMM Messages by a simple conversion script, especially if the XML OMM format is used. Figure 2.10, brings an example of a TLE message generated from the OMM Original Message, presented in Figure 2.7. It is important to notice that, although the exposed and partial limitations of the TLE format, it is still widely used, especially to non-commercial and non-military applications, especially because the open catalogue provided by the CSpOC uses the TLE format, additionally, it has a low computational cost to be manipulated, are easy to interpret, and, are compatible with many commercial orbital propagators, with an extensive open-access repository with a variety of implementations (VALLADO; CEFOLA,).

```
GOES 9 [P]
1 23581U 95025A   07064.44075725 -.00000113  00000-0  10000-3 0  9250
2 23581   3.0539  81.7939 0005013 249.2363 150.1602  1.00273272 43169
```

FIGURE 2.10 – TLE generated from an OMM Message (CCSDS, 2009).

3 Theoretic Formulation

In this section, the foundation theories associated to the logic of the system such as orbit determination algorithms, conversion between different frames of reference,types of propagators and formats of data sharing useful for the proposed system are reviewed and analyzed.

3.1 Algorithm and formulation used for Orbit Determination

The exclusively utilization of Optical sensors to perform astrometric observations requires the utilization of angles-only techniques to the estimation of orbital parameters, when processing data products. Optical sensors produce images from regions of interest in the sky, in consequence, angular data is usually obtained by correlation with known stars in the background of the produced image (VALLADO, 2013). The visibility of the RSO is essentially determined by illuminating conditions, distance, size, and, its apparent brightness in terms of reflectance in the optical spectrum. Additionally, nowadays, the most common type of sensors used to produce the aforementioned images are charged-coupled devices (CCD) conjugated to telescopes (SCHILDKNECHT, 2007).

An orbit is completely specified in terms of six independent variables - the six classical orbital parameters or a set of the six components of position and velocity vectors in a given epoch (FERNANDES; ZANARDI, 2018). In general, angles-only methods are concerned with the determination of the orbital parameters from a given RSO based, at least, in three sets of two angular information about the object - right ascension and declination, when considering a Topocentric Equatorial coordinate system, or the corresponding angles in other coordinate systems. Figure 3.1 illustrates an example where the optical site provides angular data from, at least, three line-of-sight ($\hat{\mathbf{L}}_{\mathbf{i}}$) unity vectors (VALLADO, 2013).

Among several orbital determination algorithms from angles-only observations, this work will focus in the Gauss iteration method (FERNANDES; ZANARDI, 2018). Laplace's method, although of incontestable historical importance, is more suited to interplanetary

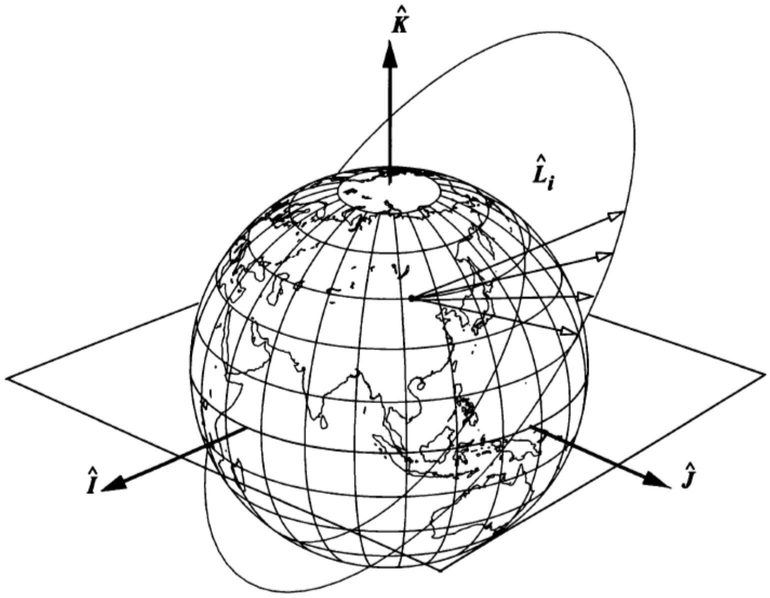

FIGURE 3.1 – Geometry of angles-only observations (VALLADO, 2013).

operations, working poorly for Near-Earth satellites (ESCOBAL, 1965), and, for this reason, will not be covered in this work. As mentioned before, the proposed method rely on angular measurements taken in a Topocentric reference frame ordered, respectively, in pairs of right ascension and declination ($[\alpha_{t_1}, \delta_{t_1}], [\alpha_{t_2}, \delta_{t_2}], [\alpha_{t_3}, \delta_{t_3}]$), and, times ($t_i$) (VALLADO, 2013).

Angular measurements are extracted from the images by comparison with the star background. In this context, it is important to notice that, commonly, the stars right ascensions and declination are catalogued in geocentric coordinates, and, the satellite's measurements are in a topocentric reference frame. All processing must rely in a common reference frame. Usually, observations are obtained in a Earth-fixed frame (ITRF), and, calculations are proceeded in a common inertial frame, including old ones, such as J2000 (VALLADO, 2013).

As mentioned earlier, for the proposed method explanation, it will be assumed that angular measurements data taken from a line-of-sight unit vectors ($\hat{\mathbf{L_i}}$) that are already in a topocentric inertial reference frame, at each observation time (FERNANDES; ZANARDI, 2018). Each component of $\hat{\mathbf{L_i}}$ can be easily decomposed in term of sines, and, cosines of right ascension (α), and, declination (δ).

$$\hat{\mathbf{L_i}} = \begin{bmatrix} \cos(\delta_i)\cos(\alpha_i) \\ \cos(\delta_i)\sin(\alpha_i) \\ \sin(\delta_i) \end{bmatrix} \tag{3.1}$$

The position of the RSO could be vectorially represented by Equation 3.2, where $\vec{r}_{site}$

is known and refers to the observer's site location, expressed in Cartesian coordinates in the Geocentric Equatorial reference frame, and, ρ is the slant-range, which is expected to be determined by both methods, using angles-only information of right ascension and declination in a topocentric coordinate frame (VALLADO, 2013).

$$\vec{r}_i = \rho\hat{\mathbf{L}_\mathbf{i}} + \vec{r}_{site_i}, i = 1, 2, 3, ... \tag{3.2}$$

3.1.1 Gauss Method

When using this method to initial orbit determination of RSO in Near-Earth orbits, it is recommended that each set of observations must be of no more than 10° apart for a better performance of the algorithm. For LEO orbits, this translates to observations taken, at most, five to ten minutes apart (VALLADO, 2013).

Considering a set of three position vectors, where slant range (ρ) and $\vec{r}_{site}$ are known, as expressed in Equation 3.2, and the fact that, considering the two-body dynamics, $\vec{r}_1$, $\vec{r}_2$ and $\vec{r}_3$ vectors are assumed to be coplanar, $\vec{r}_2$ can be expressed as a linear combination of $\vec{r}_1$ and $\vec{r}_3$, where C_1 and C_3 are multiplication scalar constants (FERNANDES; ZANARDI, 2018). The assumption that the three vectors lie on the same plane is reasonable, because the orbital plane parameters will not vary significantly over the period of the three observations (CURTIS, 2020).

$$\vec{r}_2 = C_1\vec{r}_1 + C_3\vec{r}_3 \tag{3.3}$$

Considering the expressions for $\vec{r}_1$, $\vec{r}_2$ and $\vec{r}_3$ in Equation 3.2, and, in Equation 3.3, yields to a system of three algebraic equations dependant upon five variables to be determined - ρ_1, ρ_2, ρ_3, C_1 and C_3, expressed in Equation 3.4 (VALLADO, 2013).

$$\vec{r}_{site_2} - C_1\vec{r}_{site_1} - C_3\vec{r}_{site_3} = C_1\rho_1\hat{L}_1 + C_3\rho_3\hat{L}_3 - \rho_2\hat{L}_2 \tag{3.4}$$

The main principle behind Gauss's method consists in the determination of two equations for C_1 and C_3, considering the time interval between observations and the radial distance in the intermediary position ($\vec{r}_2$) (FERNANDES; ZANARDI, 2018).

In order to obtain the constant C_1, a cross product with $\vec{r}_3$ is applied in both sides of Equation 3.3.

$$\vec{r}_2 \times \vec{r}_3 = C_1(\vec{r}_1 \times \vec{r}_3) + C_3(\vec{r}_3 \times \vec{r}_3) = C_1(\vec{r}_1 \times \vec{r}_3) \tag{3.5}$$

Then, a dot product with $(\vec{r}_1 \times \vec{r}_3)$ is applied in both sides of Equation 3.5, and, C_1 is isolated.

$$C_1 = \frac{(\vec{r}_2 \times \vec{r}_3) \cdot (\vec{r}_1 \times \vec{r}_3)}{\|\vec{r}_2 \times \vec{r}_3\|^2} \tag{3.6}$$

Analogously, is proceeded to determine C_3.

$$C_3 = \frac{(\vec{r}_2 \times \vec{r}_1) \cdot (\vec{r}_3 \times \vec{r}_1)}{\|\vec{r}_1 \times \vec{r}_3\|^2} \tag{3.7}$$

At this point, it is useful to express $\vec{r}_1$ and $\vec{r}_3$, in terms of the middle position $\vec{r}_2$ and the velocity vector in time t_2,expressed by vector $\vec{v}_2$, using Lagrange coefficients - f_i and g_i (VALLADO, 2013).

$$\vec{r}_1 = f_1\vec{r}_2 + g_1\vec{v}_2 \tag{3.8}$$

$$\vec{r}_3 = f_3\vec{r}_2 + g_3\vec{v}_2 \tag{3.9}$$

Substituting the relations presented in Equation 3.8 and Equation 3.9 in the C_1 and C_3 expressions, presented in Equation 3.6 and Equation 3.7, it‘s possible to obtain a new expression for the aforementioned constants (C_1,C_3), explicitly dependent on just terms of the first and third observations, where $\vec{h}$ represents the specific relative angular momentum of the satellite, calculated in time t_2 (FERNANDES; ZANARDI, 2018).

$$C_1 = \frac{g_3\vec{h} \cdot (f_1g_3 - g_1f_3)\vec{h}}{(f_1g_3 - g_1f_3)^2\vec{h} \cdot \vec{h}} = \frac{g_3(f_1g_3 - g_1f_3)h^2}{(f_1g_3 - g_1f_3)^2h^2} = \frac{g_3}{(f_1g_3 - g_1f_3)}, \vec{h} = (\vec{r}_2 \times \vec{v}_2) \tag{3.10}$$

$$C_3 = \frac{g_1\vec{h} \cdot (g_1f_3 - f_1g_3)\vec{h}}{(f_1g_3 - g_1f_3)^2\vec{h} \cdot \vec{h}} = \frac{g_1(g_1f_3 - f_1g_3)h^2}{(f_1g_3 - g_1f_3)^2h^2} = -\frac{g_1}{(f_1g_3 - g_1f_3)}, \vec{h} = (\vec{r}_2 \times \vec{v}_2) \tag{3.11}$$

As mentioned earlier, Gauss‘s method requires that the time between observations is small enough to meet convergence criteria of the Lagrange coefficients (BATE *et al.*, 1971). They are represented by Equation 3.12 and Equation 3.13, until the second term in an expanded series o n terms, where $\tau_1 = t_1 - t_2$ and $\tau_3 = t_3 - t_2$ are the time interval related to t_2 and $u_2 = \frac{\mu}{r_2^3}$ (FERNANDES; ZANARDI, 2018).

$$f(\vec{r}_2, \vec{v}_2, t) = \sum_{n=0}^{\infty} \frac{\tau^n}{n!} F_n|_{t=t_0} \approx f_1 = 1 - \frac{1}{2}u_2\tau_1^2, f_3 = 1 - \frac{1}{2}u_2\tau_3^2 \tag{3.12}$$

$$g(\vec{r}_2, \vec{v}_2, t) = \sum_{n=0}^{\infty} \frac{\tau^n}{n!} G_n|_{t=t_0} \approx g_1 = \tau_1 - \frac{1}{6}u_2\tau_1^3, g_3 = \tau_3 - \frac{1}{6}u_2\tau_3^3 \tag{3.13}$$

Applying Equation 3.12 in Equation 3.10, and, retaining just terms until third order, it is possible to determine a new expression for C_1, where $\tau = \tau_3 - \tau_1$.

$$C_1 = \frac{g_3}{(f_1 g_3 - g_1 f_3)} \approx \frac{\tau_3 - \frac{1}{6}u_2\tau_3^3}{\tau - \frac{1}{6}u_2\tau^3} \tag{3.14}$$

Expanding Equation 3.14 in terms of τ, and, considering just terms until second order, it is possible to have a new, and, sufficiently approximate relation for C_1, in terms of the time intervals between observations and the radial distance.

$$C_1 \approx \frac{\tau_3}{\tau}[1 + \frac{1}{6}u_2(\tau^2 - \tau_3^2)] \tag{3.15}$$

Similarly, it is proceeded for C_3.

$$C_3 \approx \frac{-\tau_1}{\tau}[1 + \frac{1}{6}u_2(\tau^2 - \tau_1^2)] \tag{3.16}$$

Next, also a new expression for ρ_1, ρ_2, and, ρ_3 in terms of time intervals between observations and radial distance is determined. It is performed a dot product by $(\hat{L_2} \times \hat{L_3})$ in both sides of Equation 3.4, and, considering that $\hat{L_2} \cdot (\hat{L_2} \times \hat{L_3}) = \hat{L_3} \cdot (\hat{L_2} \times \hat{L_3}) = 0$, we have a new expression for the aforementioned variables (ρ_1, ρ_2, and, ρ_3), that were previously expressed in Equation 3.4 (FERNANDES; ZANARDI, 2018).

$$C_1\rho_1\hat{L_1} \cdot (\hat{L_2} \times \hat{L_3}) = \vec{r}_{site_2} \cdot (\hat{L_2} \times \hat{L_3}) - C_1\vec{r}_{site_1} \cdot (\hat{L_2} \times \hat{L_3}) - C_3\vec{r}_{site_3} \cdot (\hat{L_2} \times \hat{L_3}) \tag{3.17}$$

Denoting with $D_0 \neq 0$:

$$D_0 = \hat{L_1} \cdot (\hat{L_2} \times \hat{L_3}) \tag{3.18}$$

$$D_{11} = R_1 \cdot (\hat{L_2} \times \hat{L_3}) \tag{3.19}$$

$$D_{21} = R_2 \cdot (\hat{L_2} \times \hat{L_3}) \tag{3.20}$$

$$D_{31} = R_3 \cdot (\hat{L_2} \times \hat{L_3}) \tag{3.21}$$

Substituting the aforementioned relations (3.18), (3.19), (3.20), and, (3.21) in Equation 3.17, yields to:

$$\rho_1 = \frac{1}{D_0}(-D_{11} + \frac{1}{C_1}D_{21} - \frac{C_3}{C_1}D_{31}) \tag{3.22}$$

Then, again, similarly is proceeded in Equation 3.4. Except for, instead of applying the dot product $(\hat{L_1} \times \hat{L_3})$, the same process is performed using $(\hat{L_1} \times \hat{L_3})$, and, then, $(\hat{L_1} \times \hat{L_2})$. At the end of the process, expressions for ρ_2 (Equation 3.23), ρ_3 (Equation 3.24), and, D (Equations from 3.25 to 3.30 (FERNANDES; ZANARDI, 2018).

$$\rho_2 = \frac{1}{D_0}(-C_1 D_{12} + D_{22} - C_3 D_{32}) \tag{3.23}$$

$$\rho_3 = \frac{1}{D_0}(-\frac{C_1}{C_3}D_{13} + \frac{1}{C_3}D_{23} - D_{33}) \tag{3.24}$$

Where D‘s are defined as follows:

$$D_{12} = R_1 \cdot (\hat{L_1} \times \hat{L_3}) \tag{3.25}$$

$$D_{22} = R_2 \cdot (\hat{L_1} \times \hat{L_3}) \tag{3.26}$$

$$D_{32} = R_3 \cdot (\hat{L_1} \times \hat{L_3}) \tag{3.27}$$

$$D_{13} = R_1 \cdot (\hat{L_1} \times \hat{L_2}) \tag{3.28}$$

$$D_{23} = R_2 \cdot (\hat{L_1} \times \hat{L_2}) \tag{3.29}$$

$$D_{33} = R_3 \cdot (\hat{L_1} \times \hat{L_2}) \tag{3.30}$$

Applying Equation 3.15 and Equation 3.16 in the expression of ρ_2 (Equation 3.23), a new expression for ρ_2 is obtained (FERNANDES; ZANARDI, 2018).

$$\rho_2 = A + Bu_2 \tag{3.31}$$

where:

$$A = \frac{1}{D_0}[-D_{12}\frac{\tau_3}{\tau} + D_{22} + D_{32}\frac{\tau_1}{\tau}] \tag{3.32}$$

$$B = \frac{1}{6D_0}[D_{12}(\tau_3^2 - \tau_2^2)\frac{\tau_3}{\tau} + D_{32}(\tau^2 - \tau_1^2)\frac{\tau_1}{\tau}] \tag{3.33}$$

Applying the modulus operator in both sides of Equation 3.3, an alternate expression for ρ_2 is obtained, as follows.

$$r_2^2 = \rho_2^2 + 2\rho_2\hat{L}_2 \cdot \vec{r}_{site_2} + \vec{r^2}_{site_2} \tag{3.34}$$

Taking into consideration the expression for ρ_2, presented in Equation 3.31, in the latter expression, in Equation 3.34, a simplified expression for r_2^2 is obtained, as follows.

$$r_2^2 = (\rho_2 = A + Bu_2)^2 + 2(\rho_2 = A + Bu_2)\hat{L}_2 \cdot \vec{r}_{site_2} + \vec{r^2}_{site_2} \tag{3.35}$$

Expanding the previous relation in Equation 3.36, and, rearranging the terms, the following expression is obtained, a polynomial equation of eighth grade, where μ is gravitational constant of the Earth (FERNANDES; ZANARDI, 2018).

$$r^8 + a_6r^6 + a_3r^3 + a_0 = 0 \tag{3.36}$$

where:

$$a_6 = -(A^2 + 2A\hat{L}_2 \cdot \vec{r}_{site_2} + \vec{r^2}_{site_2}) \tag{3.37}$$

$$a_3 - 2\mu B(A + \hat{L}_2 \cdot \vec{r}_{site_2}) \tag{3.38}$$

$$a_0 = -\mu^2 B^2 \tag{3.39}$$

The solution of Equation 3.36 is determined numerically, by an iterative process, such as Newton-Raphson's. In this context, this solution requires an initial guess to start the iterative process. In the case of catalogued objects, which is the case in this project, the initial guess would be provided from the most recent TLE acquired from the target satellite, during preparation phase.

Having determined r, ρ_1, ρ_2 and ρ_3 from Equations 3.22 to 3.24 with C_1 and C_3 calculated from Equation 3.15 and Equation 3.16. In sequence, through Equation 3.3, $\vec{r_1}$, $\vec{r_2}$ and $\vec{r_3}$ are calculated, and, the orbit can finally be determined by Gibbs Method (FERNANDES; ZANARDI, 2018).

The velocity vector in position $t = t_2$ is determined by Equation 3.40, obtained from Equation 3.8 and Equation 3.9.

$$\vec{v}_2 = \frac{1}{f_3 g_1 - f_1 g_3}(f_3 \vec{r}_1 - f_1 \vec{r}_3) \tag{3.40}$$

4 Methodology

This section was splitted in two subsections - General Methodology, and, ARCADIA methodology. The first is concerned with the general process behind the validation of the general and specific objectives used to confirm the initial hypothesis. Secondly, the ARCADIA methodology, concerned specifically with the modelling technique was explored.

In this context, in the latter section, the ARCADIA method and its implementation through the Capella tool are discussed and presented. Additionally, how the methodology was used to validate the model consistency, explore bahaviors, define scenarios, and, criteria of success are also presented.

4.1 General methodology

The general objective was proposed by the ITA space Center (CEI), and, as mentioned in Chapter 1 (Introduction), it consisted in developing a conceptual architecture for a SST System for CEI, using legacy hardware - an 11 inch Celestron telescope. Based on the proposed general objective, the hypothesis, and, specific objectives were derived to guide the development of the system.

It is also important to mention that, considering the domain of SST activities in ITA, the aforementioned optical system is the only legacy component to be integrated in the future system, additionally, regarding to concept of operations, and, activities developed, the proposed system is the first of its kind. In this sense, the present work also explored some foundational concepts of astrodynamics and astro observation related to the system, such as reference frame transformations, angles-only methods for Initial Orbit Determination, astrometry methods for image processing, and, formats of data sharing, because, actually, these were the aspects that guided, or, in some sense, constrained the logical architecture development.

Considering the aforementioned context, and, the wide scope of activities performed by SST systems, commonly supported by a legacy of sensors and systems, such as radars, telescopes, and, data centers, it was proposed to divide the system's development in three phases, referencing the capabilities that define SST. Figure 4.1 represents the aforementioned phases - (*i*) Identification; (*ii*) Tracking; (*iii*) Surveillance; and, the respective capabilities that are associated to each of them. Identification refers to the capability of performing observations using pre-existing catalogs, managed by third parties. On the other hand, Tracking phase requires the capability of refining orbital data from catalogues. It implies in using Initial Orbit Determination data, fused with propagated TLE from catalogues, to refine the pointing accuracy of the telescope, in order to follow-up RSO operations. This capability requires a great number of observations, in this context, online processing is highly desirable, in order to progressively refine measurements along subsequent passages. Tracking activities are largely performed by radar systems, especially for LEO orbits. Surveillance related activities are related to providing some major capabilities - (*i*) Autonomously detect uncatalogued RSO; (*ii*) Provide Conjunction alerts; (*iii*) Support Rendez-Vouz Operations; and, (*iv*) Manage own catalogue. This phase requires a network of sensors, and, a complex data processing architecture, that uses information from different sources (OLIVEIRA *et al.*, 2022).

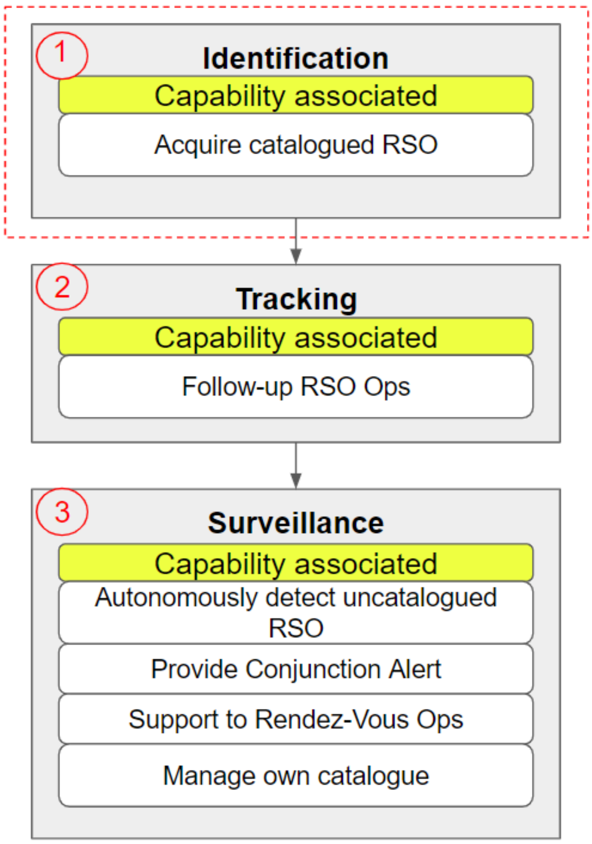

FIGURE 4.1 – Proposed steps to System's development.

Considering that Tracking activities, and, Surveillance activities are preceded and enabled by Identification, and also involve a network of heterogeneous sensors (OLIVEIRA *et al.*, 2022), the scope of this work is focused in developing the logical architecture of the first phase, allowing future implementations and contributions. In the Capella Model, Identification activities are referenced as *basic activities of SST*.

Having defined the system's scope, the general strategy used is presented in Figure 4.2. There were different approaches available to perform Model Development: Top-down or Bottom-up approach. In the first case, the system is derived from the desired capabilities defined by the stakeholder, and, from them, all the system functions, and, components are derived, and, refined iteratively. In the second, component level parts are specified in details, and, integrated to form larger components. The Top-Down approach was chosen considering that the system should be developed considering high-level, and, desired SST capabilities. This approach is also more flexible to incorporate future implementations, and, updates, based on a framework of reference.

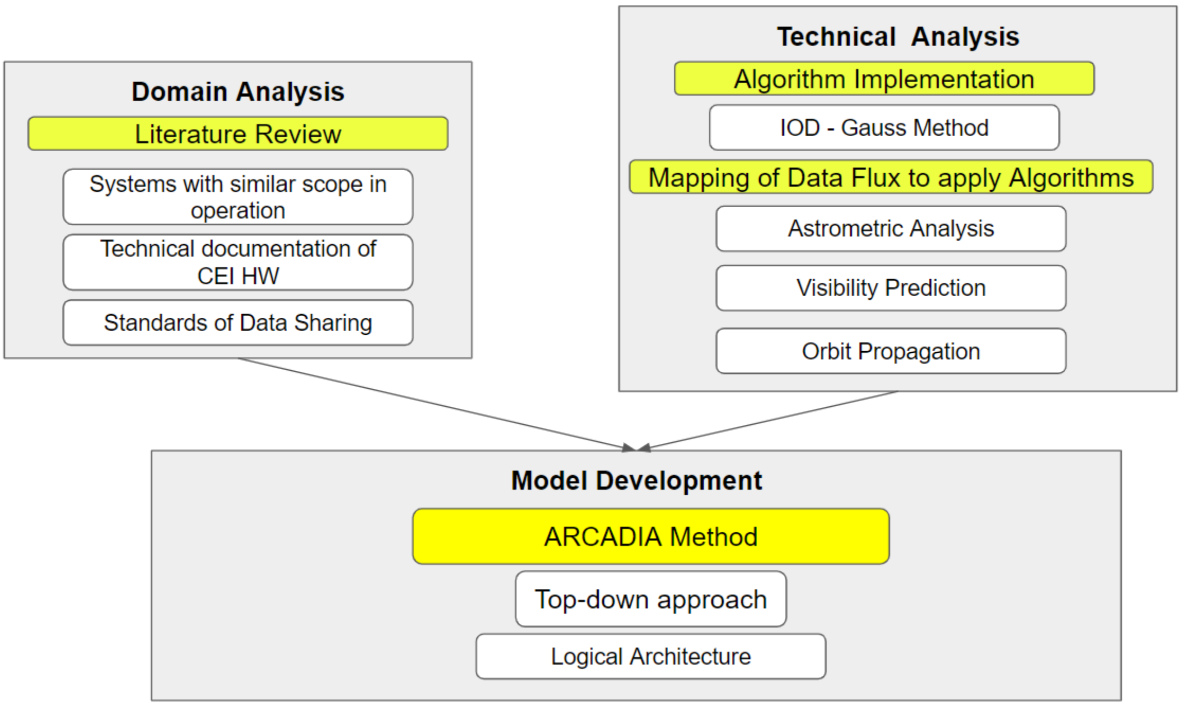

FIGURE 4.2 – General Methodology.

The Model development was supported by Domain Analysis, and, Technical Analysis. Domain Analysis consisted in scoping down to ITA Space Center domain of actuation. In this sense, through literature review, operating system's comparable to CEI® in terms of size, institutional objectives, and, budget were considered. Also, technical documentation of CEI hardware was considered, in order to identify limitations and different configurations between functional exchanges. Additionally, protocols and standards of data sharing were considered, since they provide the external interface of the system, and, are rationalized in terms of minimum amount of information required to run the system.

On the other hand, Technical Analysis was concerned with the mathematical models, and, methods that enable the activity of RSO observations through optical observations.

Since all the proposed system functions, in reality, were created to deliver information, or, receive information from IOD method, and, consequently, the logical architecture depends on the chosen method, and, its implementation, the Gauss method was implemented in MATLAB, using the Newton-Raphson's method of convergence, and, an initial guess for the semi-major axis provided by TLE. Other implementations, or, methods, would require a different flux of information. Other aspects of technical analysis, such as Astrometric analysis, Visibility Prediction, and, Orbit Propagation, although not implemented, were used in order to map the data flux necessary for system operation.

4.2 ARCADIA methodology

In accordance to ARCADIA methodology, the development of the Conceptual Architecture in the Capella tool (ROQUES, 2018) involved the implementation of three perspectives - Operational Analysis, System Analysis, and Logical Architecture.

The first four ARCADIA perspectives are presented in Figure 4.3 - Operational Analysis (OA); System Analysis (SA); Logical Architecture (LA); and, Physical Architecture. It represents how the system's functional requirements are progressively derived, and, refined along subsequent iterations towards the physical architecture.

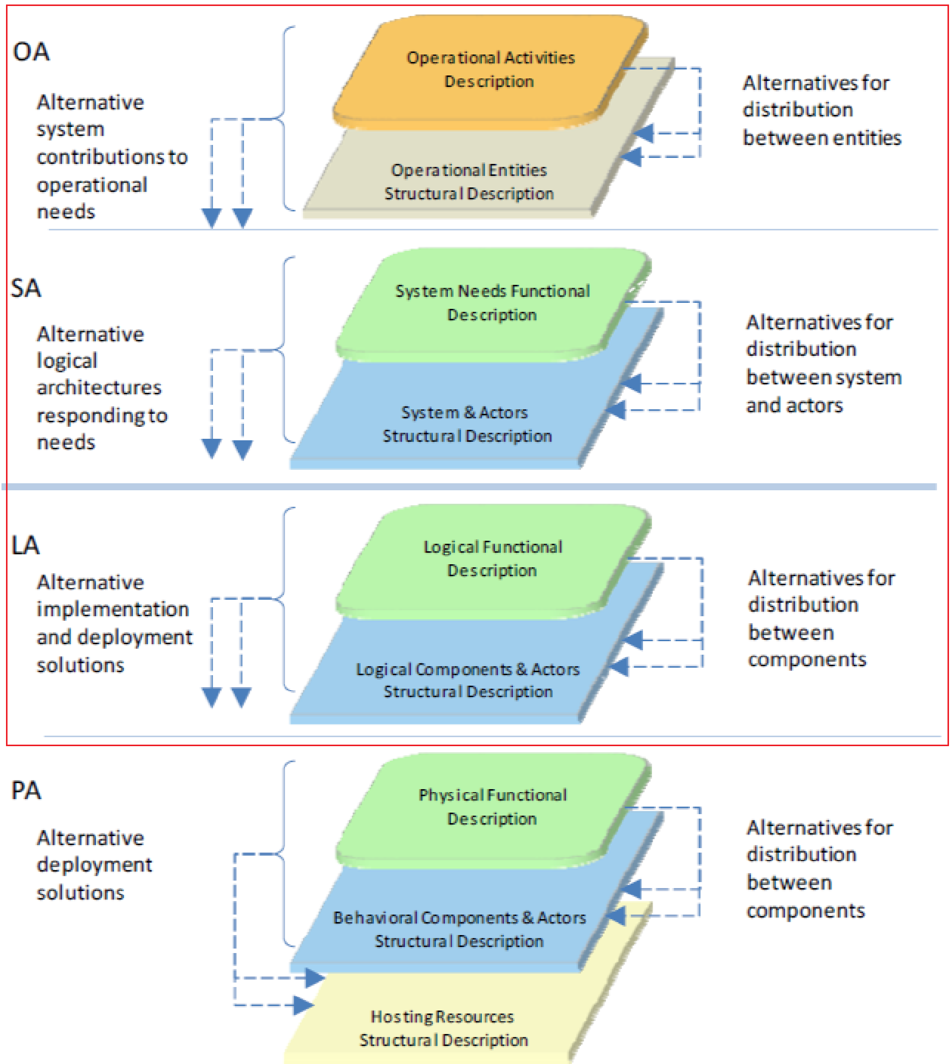

FIGURE 4.3 – ARCADIA‘s perspectives (VOIRIN, 2018).

Figure 4.4 represents the archetype of Operational Analysis. An Operational Mission requires capabilities to be performed. On the other hand, those capabilities are implemented through Operational Processes, and, Operational Activities, that can have its interactions described by Operational Activities Scenarios.

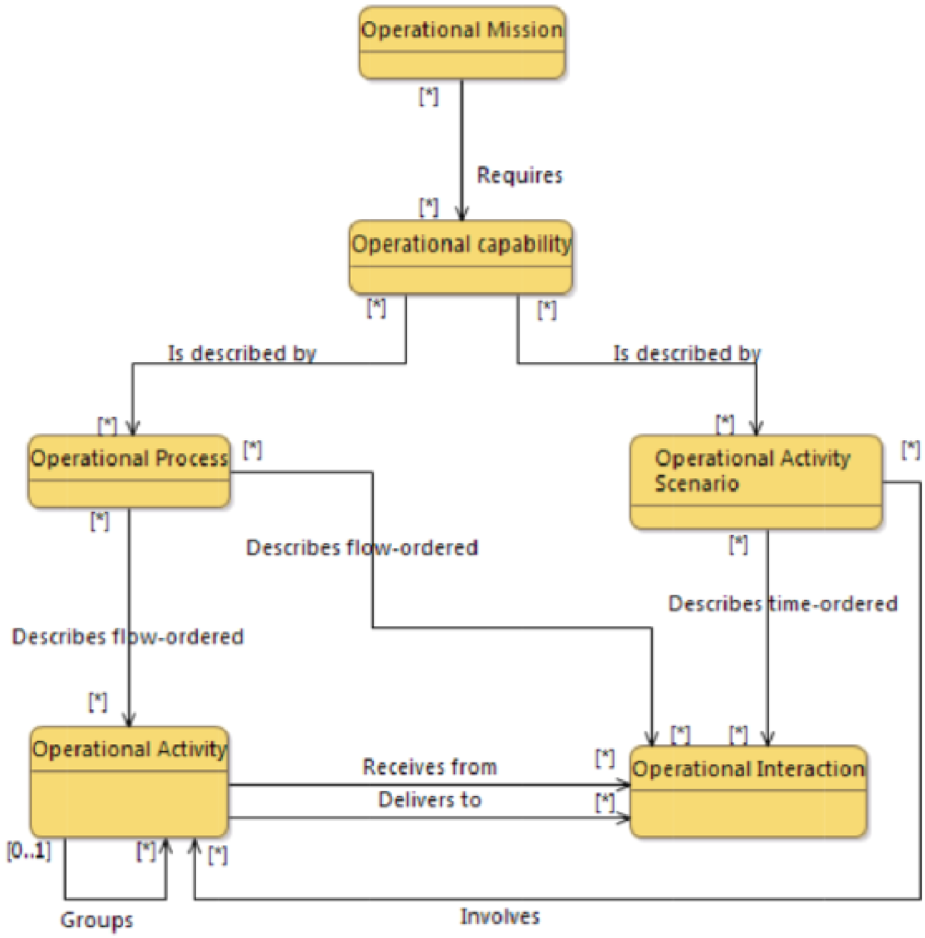

FIGURE 4.4 – Archetype of Operational Analysis (VOIRIN, 2018).

In this context, in Operational Analysis (OA), the problem was structured and defined considering a solution-free environment (CRAWLEY, 2016). During this phase, costumer needs and goals were identified and represented in the Operational Capability Diagram, as well as missions and activities that deliver Operational Capabilities desired by the stakeholders were mapped and represented in the Operational Activity Diagram. According to the method, Operational Processes were derived as the interface between different Operational Activities and, in the model developed in the Capella Tool, they were linked and related to a capability previously defined in the Operational Capability Diagram, as presented in Figure 4.4.

In consequence, OA is mainly concerned in creating a domain model, independently of the future system to be realized, creating a level of abstraction from the system under study, in order to better identify real needs of stakeholder‘s preventing anticipation, and, exclusion of comprehensive possible solutions by contamination of a non-intentionally biased or limited perspective provided by stakeholders. Additionally, it allows opportunities to be identified for subsequent system‘s versions, updates or implementations with different constraints (ROQUES, 2018).

A Space, Surveillance and Tracking (SST) System is usually defined as a system of systems because it requires the interaction between systems of different domains like mechanical, informational, and electrical. In this context, after deriving stakeholder needs and expectations, the boundaries of the system were defined. Boundary definition was performed not only to identify external interfaces, but also to clearly define the system's scope.

The archetype of System Analysis (SA) is presented in Figure 4.5. It represents that, similarly to OA, the System Mission is supported by a set of capabilities delivered by Functional Chains that are chronologically described by functional Scenarios. Ports are physical or logical entities to provide interface between functions.

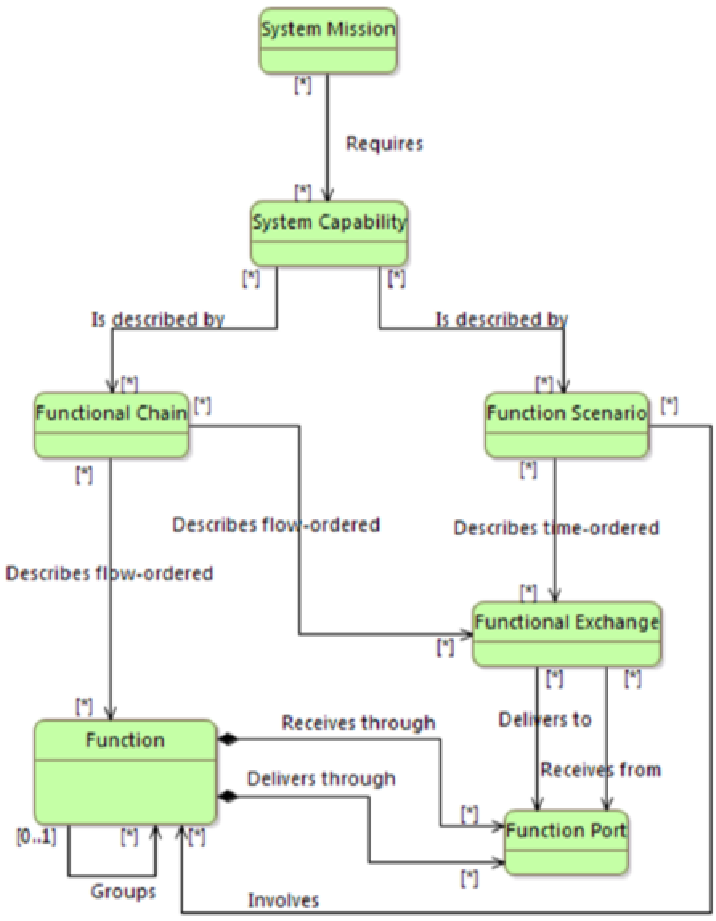

FIGURE 4.5 – Archetype of Functional Description in System Analysis (VOIRIN, 2018).

The process of defining the boundaries of the system was performed during the SA, and, according to ARCADIA method (VOIRIN, 2018), the System Analysis Diagram represents the formalization of system requirements. SA delivered the system functional needs description in terms of functional chains and use case scenarios, expressed in terms of Data Flow diagrams, and, tied to a System's capability. Also, in this perspective, non-functional requirements were defined as constraints and, transitioned, in the Capella Tool, from the capabilities derived during OA.

The transition between different levels of abstraction in Capella, as from OA to SA, or, from SA to LA, for example, can be performed using three different systematic approaches (ROQUES, 2018):

- Entirely: All activities becomes System‘s functions of the same name allocated to the System;
- Partially: The activities must broken-down to more specialized functions, and the allocation is performed manually by the modeler, that can choose between actors, entities, or, the proposed system itself;
- Not at all: Activities are renamed as Functions with the same tag name, but all allocation to model must be performed manually.

In this project it was used the Partially systematic approach, since it provides more flexibility to define system‘s scope, without loosing the advantage of maintaining parentality with upper layers of higher level of abstraction. The advantage is that it permits to validate new functions, and, components created along the project, by parent capabilities, defined in OA, that represent stakeholder‘s needs, and, expectations about the system. In this context, the decision to realize a given Activity, mapped in OA, into deep layers is a project decision influenced by the costumer requirements, budget, schedule, and, technical feasibility (ROQUES, 2018). Consequently, all transitions proposed by Capella use the top/down approach, going to deeper level‘s of abstraction iteratively, and, incrementally in order not to lose traceability (VOIRIN, 2018).

Accordingly, all entities used in SA were transitioned from Operational Analysis, preventing the creation of system elements that do not have any correspondence to the system capabilities previously defined during OA. In this study, it was considered that the System's scope was the interface between RSO and the final User. Additionaly, ARCADIA rules impose that only "leaf" functions can have input/output ports (ROQUES, 2018). In consequence, whenever a layer is transitioned to lower levels, and, basic functions are broken down into more specific ones, functional exchanges, and, interfaces must also be refined to keep coherence in terms of level of specification along the model (VOIRIN, 2018). It is a good practice in Capella, to change the color of the diagram to white, whenever a function is broken down, in order to have a properly differentiation between parent and child functions (ROQUES, 2018). Figure 4.6 clearly specifies the process incrementally, and, iteratively going to deeper engineering level‘s of abstraction in order not to lose traceability, and, consistency along the model.

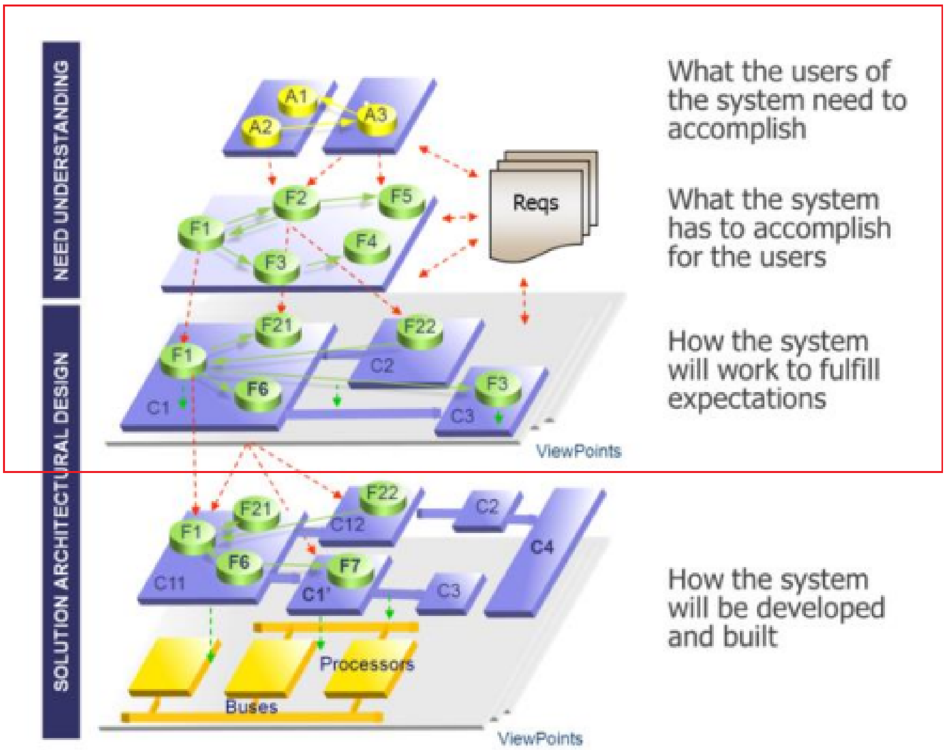

FIGURE 4.6 – ARCADIA engineering levels (ROQUES, 2016).

Logical Architecture (LA), also known as Principle Architecture, implemented the major aspects related to the design guidelines of the solution. The System Functions defined during SA were transitioned to the Logical Domain, in doing so, logical functions were linked to a parent function defined during System Analysis. After the transition, the Logical Components of the system were created, and the System Functions were allocated to them. The interface between Logical Components was implemented by functional exchanges. These components will later be implemented as subsystems, mechanical parts, assemblies, software, etc, when transitioned to the physical architecture (VOIRIN, 2018).

The allocation of functions to Logical Components basically consisted in grouping together, behavior functions previously defined based on criteria such as functional coherence or strong interaction between complex interfaces. In addition, this process also lead to segregation of functions of different levels of criticality or the distribution of high-consuming functions into a group of more specialized functional exchanges. This was an iterative process that required multi-view points and several trade-off analyses, and, evidenced diverse candidate architectures. The methodology imposed that this perspective was represented in a high-level of abstraction permitting that trade-off analyses were made without compromising compliance to system requirements.

The basic notation of Mode and States Machine (MSM) in the ARCADIA method is presented in Figure 4.7. The Capella tool permits to model System's Modes and States as graphical representations of State Machines inspired from UML/SysML. In UML/SysML, a State is situation during the lifetyme of a component where it satifies a certain condition, executes a certain behavior, or, expects a certain event. States are linked together by Transitions. As presented in Figure 4.7, the basic idea in this representation is that a Transition contains a source State, a Trigger, and, a target State. When it is the case, it can also contain a Guard Condition (ROQUES, 2018). Additionally, in the system is always subjected to two pseudo-states - Initial, and, Final States. They correspond to the creation, and, destruction of the element in a certain context.

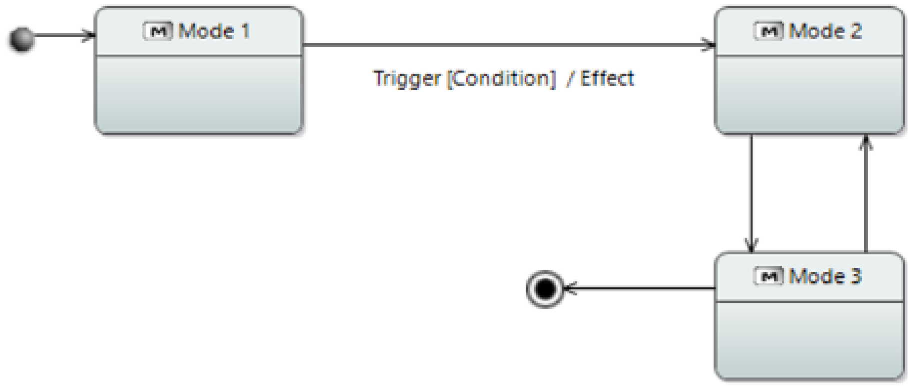

FIGURE 4.7 – Basic notation of Mode and State Diagram (MSM) (ROQUES, 2018).

Every time a system switches to a new mode or state, there is an effect resulted from an emergent behavior of the system. As Capella Tool works with concepts that come from UML/SysML, three possible effects can be modeled (ROQUES, 2018):

- Entry: Executed each time the Mode/State is entered into. It is used when a same effect is set off by all of the transitions that enter into the Mode/State;
- Do activity: On the contrary that Effects that are instantaneous, durable activities have a duration, can be interrupted, and, are always allocated to a specific Mode/State;
- Exit: Executed every time the Mode/State is exited. Generally used when a same effect is set off by all of the transitions that exit the Mode/State.

Accordingly to UML/SysML, a trigger in Capella can therefore also be a Time Event, or a Change Event. The first is modeled using the word ”after” followed by an expression that defines duration, counted from the entrance into the Current State, or by the word ”at”, followed by an expression that represent absolute time. On the other hand, Change Events are modeled using ”when”, followed by a Boolean expression. When modeling the State Machine, all the transitions between modes are automatically transitioned to the model, an can be comprehensively visualized in the Scenarios Diagram (ROQUES, 2018).

Finally, ARCADIA methodology provides model checking rules in several categories, mainly expressed by: integrity, design, completeness, and, traceability inside the model-context. In this sense, predefined validations profiles can be used, or, customized ones can be developed, focusing on different aspects that are of interest to be validated (ROQUES, 2016). In this context, and, considering that all elements in lower architectures are parent-related to the capabilities defined in upper layers, as OA and SA, part of model validation in Capella is performed concurrently to design modeling, considering self-consistency, correctness, and, completeness in regard to capabilities to be delivered by the modeled system (ROQUES, 2018).

5 Results and Discussion

In this section, the first three perspectives of ARCADIA methodology developed for the SST System for ITA Space Center are presented and discussed - Operational Analysis(OA), System Analysis (SA) and Logical Architecture (LA). Additionally, it is presented how the mathematical models discussed in the Theoretic Formulation were incorporated in the digital model and how they influence the behavior of the system, especially in the context of different scenarios such as the orbits of the Objects of Interest (OI) of ITA and, also, in regard to different orbit parameters in general, such as semi-major axis and inclination relative to the equator.

5.1 Operational Analysis (OA)

The first activity of OA consisted in identifying the main Operational Capabilities needed by the user. The aforementioned Operational Capabilities condenses the high-level objectives of the ITA Space Center in the domain of Resident-Space Objects (RSO) monitoring: (*i*) Produce Orbital Data from Resident Objects of Interest; and, (*ii*) Make Orbital dynamics related Analysis and Research.

The final iterated version of the Operational Capability Diagram of OA is depicted in Figure 5.1. This diagram shows the correlation between Actors, Operational Entities, and the mentioned capabilities. Those capabilities are a representation of how to achieve the user's motivations, expectations, and goals.

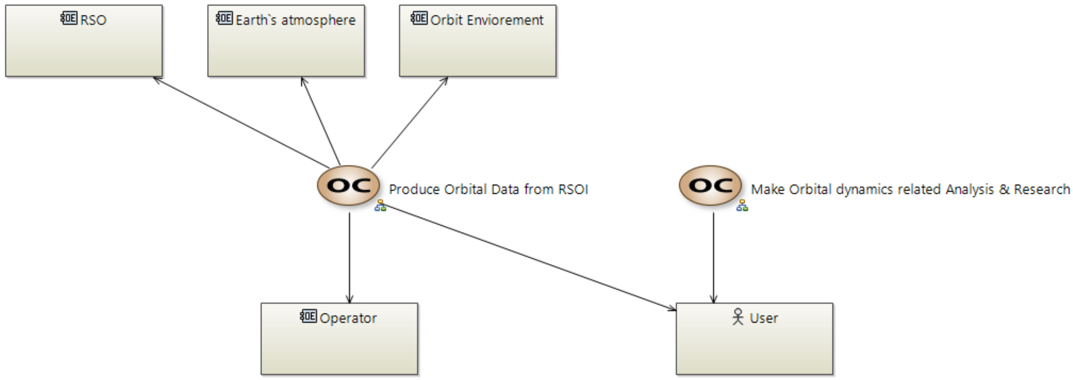

FIGURE 5.1 – Operational Capabilities Diagram (OCB).

The Data Flow diagram presented in Figure 5.2 depicts the general process involved in delivering the capabilities represented by the "OC" symbol. In this process, it is evident that the Capability of *Making Orbital Dynamics Analysis and Research* depends on, firstly, *Producing Orbital Data from RSOI*, since the inputted information about Orbital Parameters were derived from State Vectors obtained through some kind of generic data collection and processing technique. In this step of analysis, it is not recommended to specify which data collection or processing technique will be used, in order not to limit possible architectures. In the level of abstraction considered, the Operational activities encapsulate a group of activities that will be necessary to it is implementation. The activity *Collect Data* involves collect orbital data from a given RSOI from an existing catalog, prepare the observation identifying visible times, apparent magnitudes of OI and sensor pointing information, collect, and, manage the collected data. Similarly, *Produce Orbital Parameters* involve generating Keplerian Orbital Elements, Covariance matrix, when applicable for analysis, data formatting, sharing, and, padronization, for example.

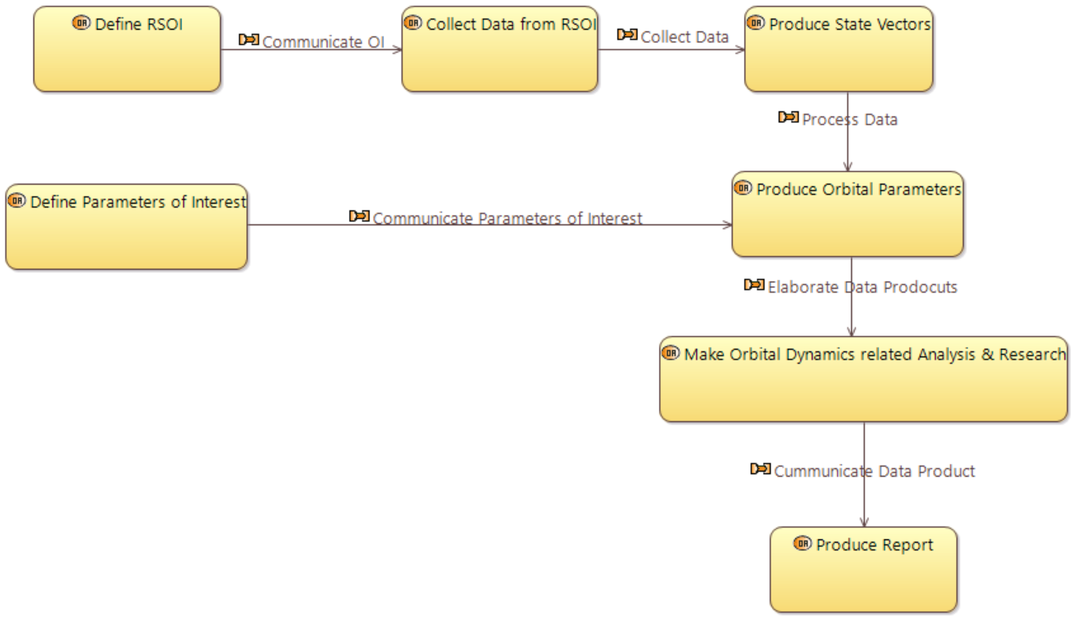

FIGURE 5.2 – Global view of activities (OAIB).

Figure 5.3 presents the Simplified Operational Context of the system. In this diagram, Operational Activities and data flux, mapped in the diagram of Figure 5.2, were allocated to Operational Actors and Entities in order to contextualize the operational scenario, representing the domain of actuation of the future system that still needs to be proposed, delimited, and, developed in further steps of analysis.

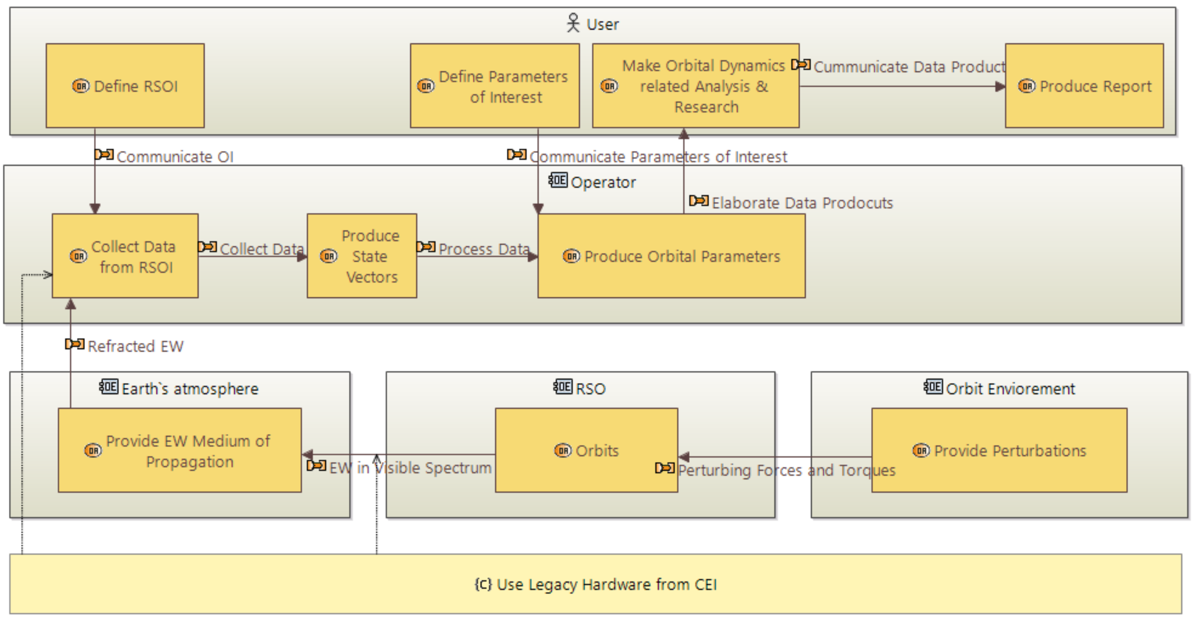

FIGURE 5.3 – Simplified Operational Context (OAB).

The proposed Operational Context of Figure 5.3 involves a User, representing a student or a researcher, who needs, for some reason, to study aspects related to the dynamics of an RSO of Interest (RSOI) using its own produced information. In this sense, he must identify which object he/she is interested in collecting data, and, especially, what kind of analysis he/she needs to perform, and, he/she must communicate it to the Operator, because these information will affect how data is collected, and, what kind of output data will be offered. The Operator, representing ITA Space Center, is responsible to collect that data and process it.

The Orbit Environment, and, consequently Perturbing Forces and Torques were included in the model because they strongly affect the validity of the data obtained, and, especially, the models and considerations used to process data and plan observations, such as visibility prediction models, apparent magnitude models, and, others. For the same reason the Earth‘s atmosphere has been considered in the model, because the atmosphere medium of propagation seriously affects the process of collecting data. Just for example, humidity has strong influence on the opacity of the image and pixel signal-to-noise ratio (SNR), when operating in the optical spectrum. These relations will be more explored in the SA and LA, but are worth to be considered since upper layers of the model, like the Operational Context domain.

Additionally, it is important to note that, in the Operational Activity diagram, presented in Figure 5.3, the activity of *Collecting Data from RSOI* is constrained to the utilization of legacy hardware of ITA Space Center. This implies that data collection must be performed in the optical spectrum. It is interesting to note that, although using just the optical portion of spectrum obviously affects on how State Vectors will be obtained, the general process of extracting state vectors from the data collection process, and, produce orbital parameters from them, is independent from hardware implementation. This is an important remark, since this general framework is still valid for future, more comprehensive implementations.

The process that accomplishes the capability *Produce Orbital Data from RSOI* is better expressed in terms of Scenarios. Figure 5.4 represents an Operational Entity Scenario. It gives a chronological and sequential understanding on how actors and entities exchange information, affects, and, are affected by each other in the domain of analysis. In this level of abstraction technical implementations were not considered yet.

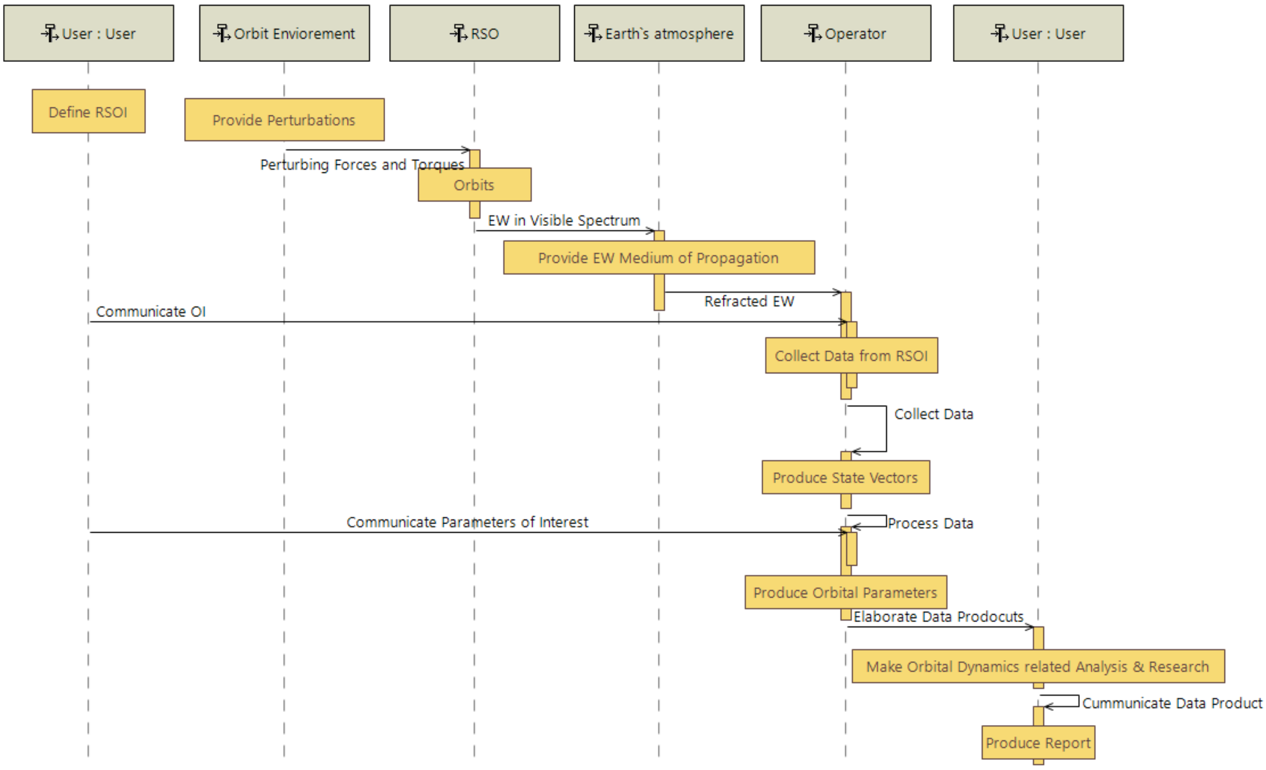

FIGURE 5.4 – Produce orbital Data from RSOI (OES).

5.2 System Analysis (SA)

Figure 5.5 represents the System Architecture for CEI SST System (SAB). The system was named as CEI SST System, represented by a dark blue box. All functions are presented in green boxes, and, Functional Chains in colored sequence of arrows. The constraint is of using legacy sensors are affecting the spectrum in which observations are made, and, it is represented as an orange box.

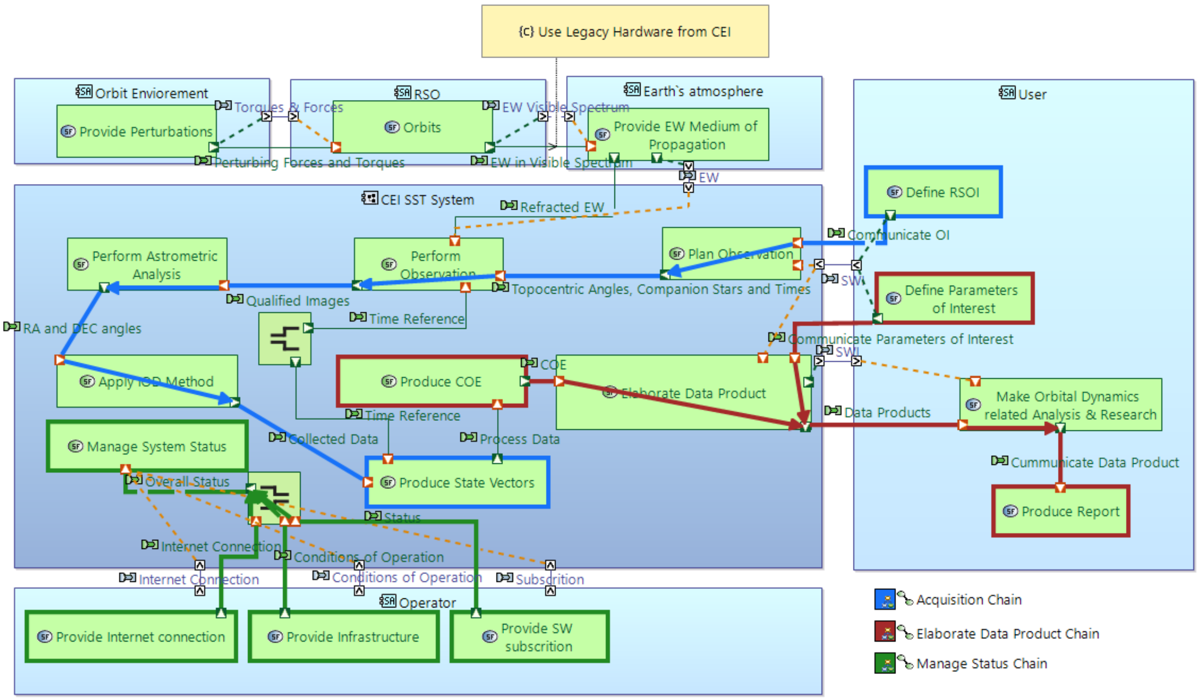

FIGURE 5.5 – System Architecture for CEI SST System (SAB).

In the process of transitioning the OA architecture down to system level, the partially transitioning approach was chosen. In this sense, as shown in Figure 5.5, the boundaries of the system, and, its scope were defined through the allocation of functions that specify and realize the Operational Activities previously derived in OA to actors, entities, and, specially, to the proposed system - CEI SST System. Basically, all three activities previously assigned to the Operator - Collect data from RSOI, Produce State Vectors, Produce Orbital Parameters, were allocated to CEI SST System and realized by 10 basic functions. On the other hand, in this new context, the operator, representing ITA Space Center, is meant to provide the physical infrastructure, internet connection, and, software subscription. In this level of abstraction, which software, and, for which activity it will be necessary is not meant to be specified yet.

The CEI SST System's scope is described in terms of two capabilities - *Produce Orbital Data from RSOI* and *Provide Data Products for Orbital dynamics related analysis and research*, more specific than the previously two mapped in OA. The first capability, *Produce Orbital Data from RSOI*, is realized by two functional chains, the *Acquisition*, represented in a blue flow of system functions in Figure 5.5, and, *Manage Status*, represented in green. On the other hand, the latter capability, *Provide Data Products for Orbital dynamics related analysis and research*, is realized by the *Elaborate Data Product* chain. In this level of abstraction, physical components are not specified. In consequence, component exchanges that define physical interfaces between components were already mapped, but, in accordance to best practices of ARCADIA method, were tagged by generic names such as SWI (Software Interface), or by the name of the information it carries.

Figure 5.6 represents the Global Data flow from CEI SST System. In this diagram, functions that are performed by the system are represented in green boxes, on the other hand, functions that represent an input or output for the system, are represented in blue.

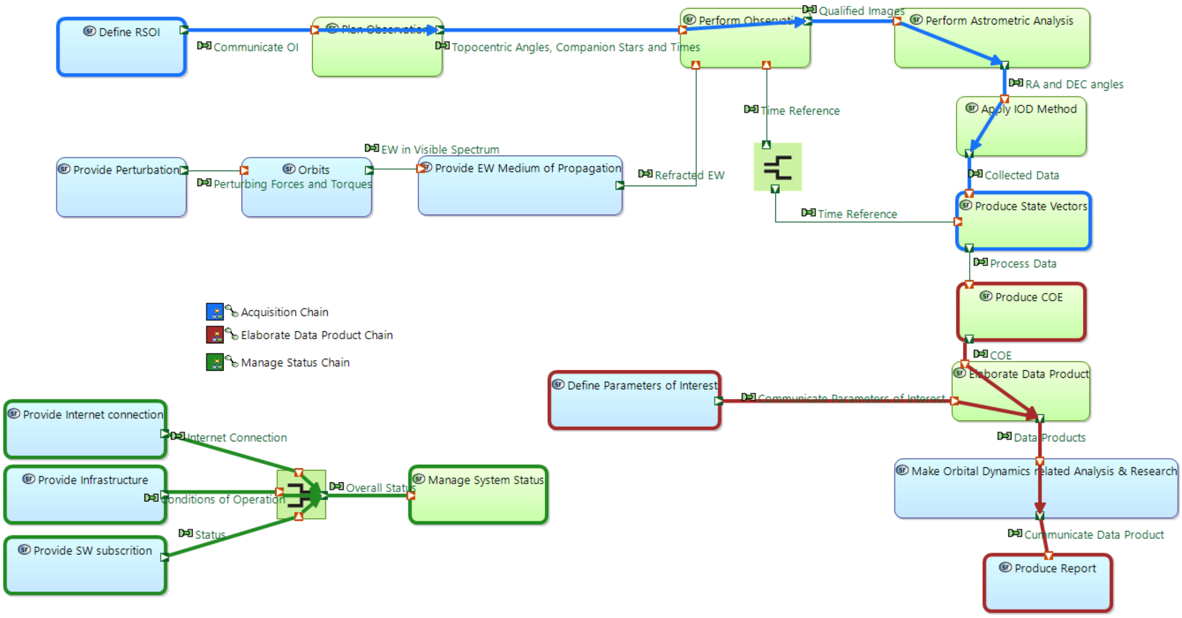

FIGURE 5.6 – Global data flow from CEI SST System (SDFB).

The way functions are sequentially correlated and what information they are expected to deliver are better represented in a Global data flow from the System, represented in Figure 5.6. The seed function is provided by the user, who communicates the OI to be analyzed. With this input information, the system is able to plan the observation identifying visible times, Topocentric angles, and, Companion Stars, further used in Astrometric Analysis, and, use this information to perform observations. Then, useful images submitted to a qualifying process are inputted in the Astrometric Analysis process, and, next, Initial Orbit Determination algorithms are used to extract state vectors from a set of Right Ascensions (RA) and Declinations (DEC) angles, in order to produce Classical Orbital Elements (COE) to be outputted with other parameters of interest that must defined by the user. In parallel, the system must be able to share a precise and common time reference signal to enable the processes of data collection and processing. Additionally, the system is managing the status of other enabling activities, provided by the operator, such as internet connection, software subscription and aspects related to infrastructure.

System-level scenarios were also developed in order to provide a comprehensive representation of the behavior of the system. Acquisition and Manage Status scenarios are associated to *Provide Orbital Data from RSOI* capability, in its turn, Elaborate Data Product scenario is associated to *Provide Data Products for Orbital dynamics related analysis and* *research*. In the present discussion, the System-level analysis was used to better expose interfaces and how information transit along the system, and, provide emergent behaviors. Technical aspects such as methods of observation, formats of data and the justification of some architectural implementations are explored in the Logical Architecture.

Figure 5.7, Figure 5.8, and, Figure 5.9 represent, respectively, the Acquisition, Manage Status, and, Elaborate Data Product scenarios. Grey ellipses represent the system modes, and, green boxes are system functions. The arrows represent the chronological data flux between system's functions.

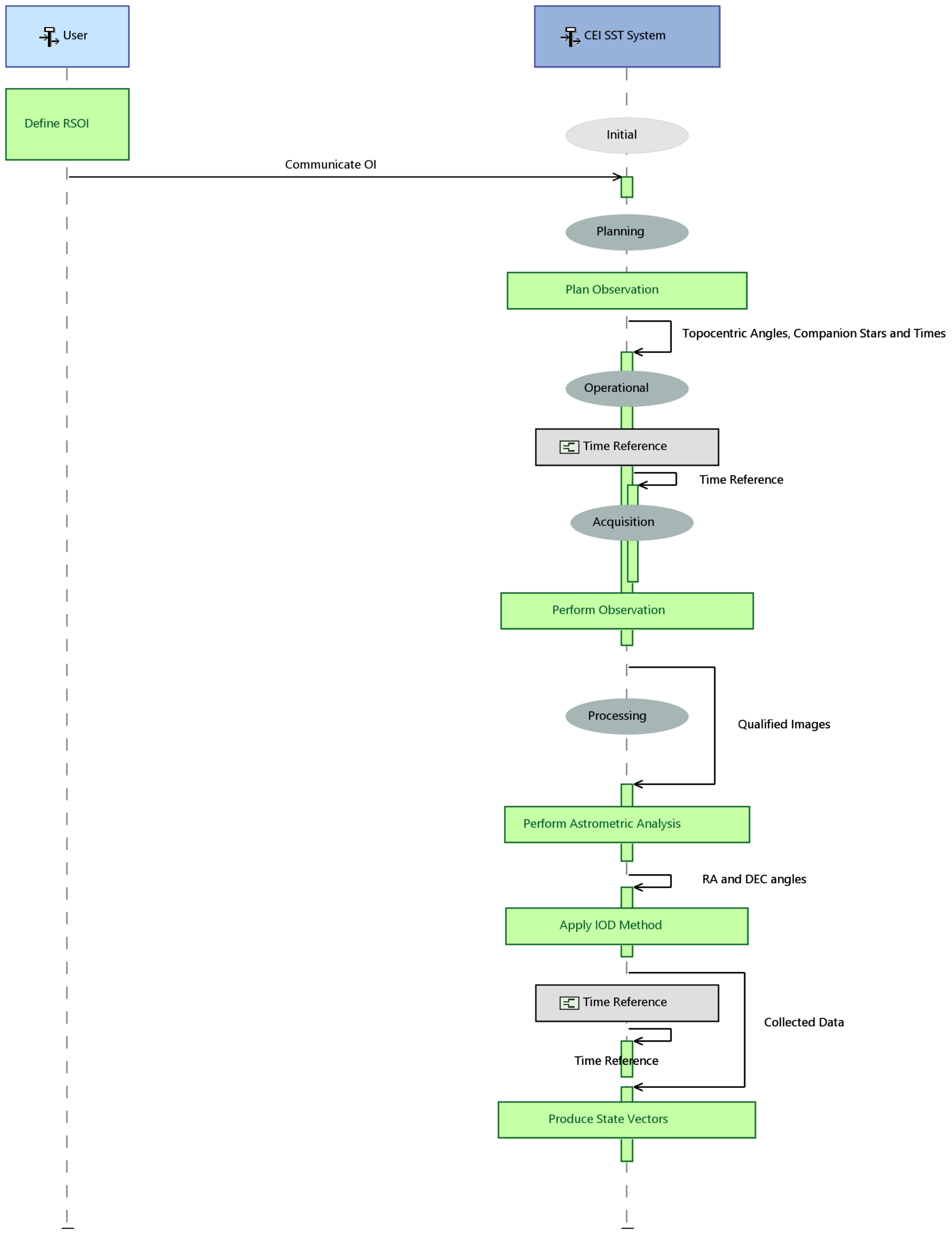

FIGURE 5.7 – Acquisition Scenario (SES).

In Figure 5.7, *Define RSOI* is a seed function provided by the user, that triggers the transition from *Initial* to *Planning* mode. Plan Observation is, actually, a root function to a group of lower level sub functions that will be explored in details in further diagrams. *Operational* Mode is triggered by Topocentric Angles, Comparison Stars and Times of observation set of data. It is characterized as a Stand-by Mode when the system is ready to collect data that is exclusively performed by the *Acquisition* Mode. Next, *Processing*

Mode requires some process of qualifying useful images for analysis, and, then, data will be processed and correlated according to the times observations were made. Acquisition Scenario ends with a set of correlated and formatted state vectors from the all the period of observations, in coherence to the implementation choice of running acquisition and data processing sequentially, and, not in parallel, mainly because of simplicity.

As presented in Figure 5.8, the Manage Status scenario, also associated to the capability *Provide Orbital Data from RSOI*, is performed continuously during operation, and, basically, involves enabling activities to perform observations.

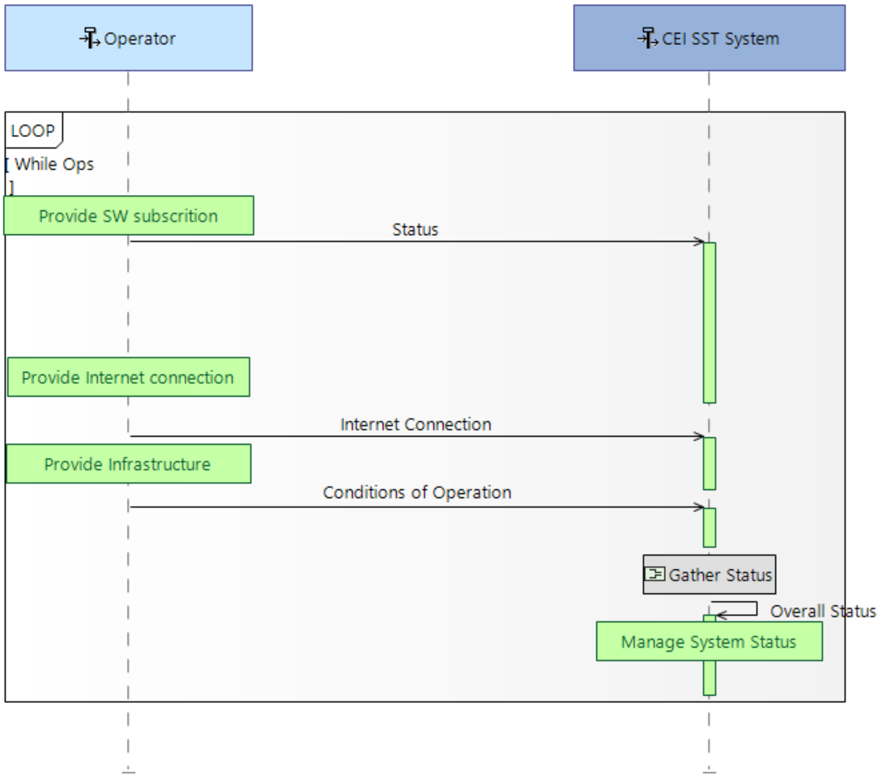

FIGURE 5.8 – Manage Status Scenario (SES).

At last, *Elaborate Data Product* Scenario starts during *Processing* Mode, when Classical Orbital Parameters are obtained from the set of state vectors, and, more inputted specifications provided by the user, in order to provide the final processing and Data Product delivery, from where the final user will extract data input in his own analyses and report.

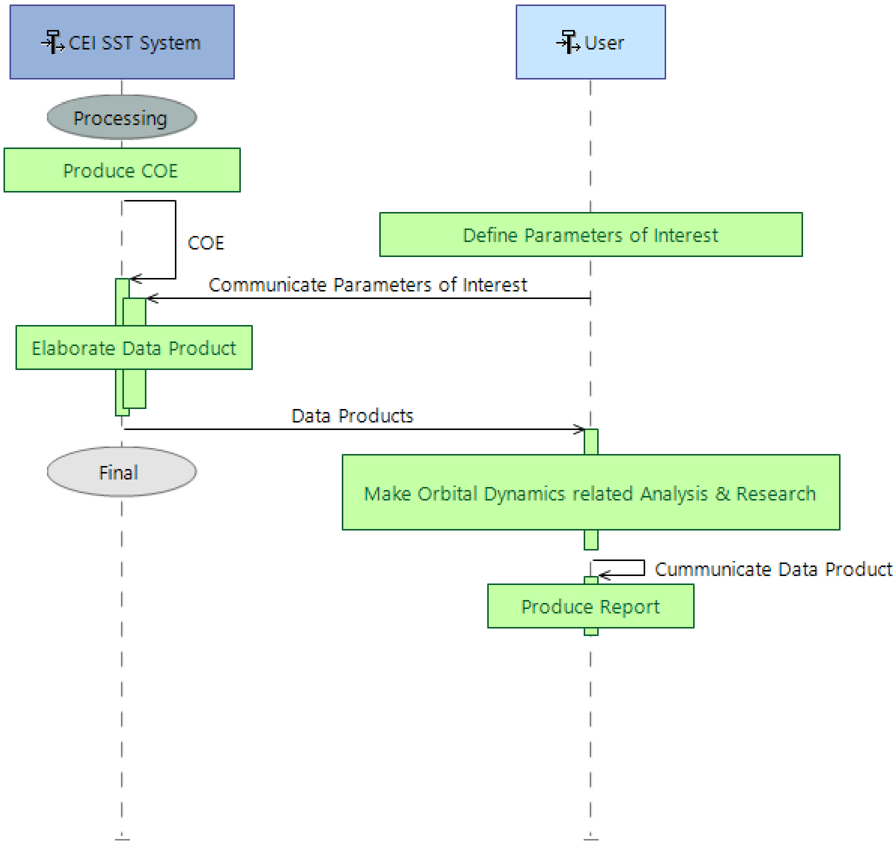

FIGURE 5.9 – Elaborate Data Product Scenario (SES).

Figure 5.10 represents a consolidated representation of system modes. Each mode, as well its respective functions, are allocated to a grey box. In this diagram, *Initial* state is transitioned to *Planning* when triggered by the OI definition. In the upper portion of grey boxes System Modes are specified. Inside those boxes, Entry, Do, and, Exit functions are displayed, as well the triggering conditions or realization of information transfer, that are responsible for triggering transitions between system modes. As presented in the MSM diagram, *Acquisition* Mode is only accessed by *Operational* Mode. The condition *Satellite is not visible* compasses the case in which the satellite exits de FOV of the sensor, as well, the case in which the contact is not obtained. In both cases, if the scheduled observations were not fully accomplished, the sensor points to the next target on the list. If not, *Processing* Mode is triggered, and, when completed, provide transition to Final state.

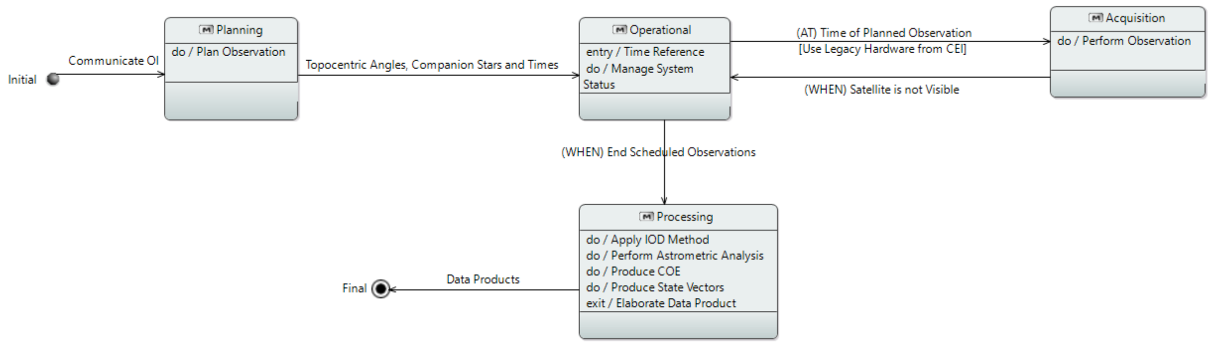

FIGURE 5.10 – System Level Modes and States Machine from CEI SST System (MSM).

Finally, a breakdown diagram representing all the system functions is shown in Figure 5.11. Green, grey, and, white boxes are System functions, and, blue are outside from the system functions that affect the system. As SA is actually, requires also, a refinement in regard to high-level activities mapped during OA, some more complex functions, represented in the white boxes, were better specified by new leaf functions, represented in green as child functions from the white ones.

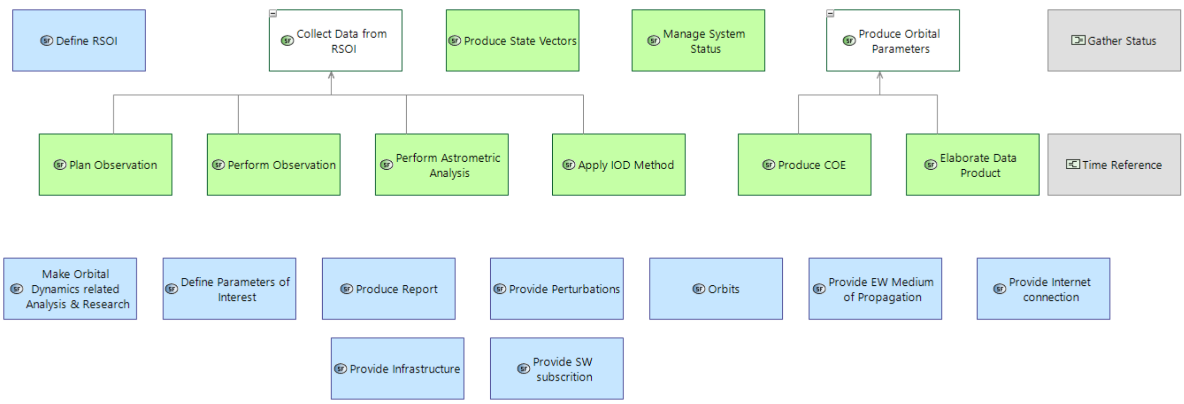

FIGURE 5.11 – System Level Functions (SFBD).

5.3 Logical Architecture (LA)

As previously presented, SA analysis was mainly concerned with the behaviour of the system, and, consequently, the system was modeled as a "black box". On the other side, the LA, initially transitioned from SA, is mainly concerned on how the systems logically works "inside the box", to deliver the expected outputs, from the previously mapped inputs. In this context, now a more detailed *Acquisition* Scenario is displayed in Figure 5.12. The SST System was divided in two main subsystems, one dedicated to data collection, named *Aquisition Subsystem*, and, the other dedicated to the overall Management of the

System, named *Management System*, mainly responsible to encapsulate Planning and Data Processing related activities.

It is important to notice that, in spite of the similarities with the *Acquisition* Scenario derived in SA, in LA some exchanges components and functions were refined. In consequence, after the definition of RSOI, the User must send an Acquisition Request to the Management subsystem. Details of the data structure of this request will be provided in the Logical Data-Flow Architecture Blank diagram of function *Plan observation*. Similarly, after planning the observation, the system will input a DataSet to the Acquisition Subsystem with all the information needed to perform observations and to be inputted in the Processing phase. Obviously, all the system must operate in coherently and precise time reference, calibrated to external references.

The latter remark is extremely important to avoid, for example, uncorrelated times of observation provided by inaccuracies in the internal clocks of computers that manage the system. Since LA is still not concerned with technical or physical implementations of the system, the logical function *Route a Time Reference Signal* and its subsequent allocation to a Logical component, prevents the occurrence of this undesired behavior of the system independently on further decisions that are meant to be taken during the project's implementation.

Examples of undesired behaviors caused by uncorrelated times of observation are: (*i*) Inconsistency between commanded angles to the Acquisition System and the actual position of the RSO; (*ii*) Incorrect prediction of apparent brightness of RSO; (*iii*) No correlation between the data produced with the intended observations; (*iv*) Additional complexity to validate the data produced and compared the obtained results with external sources of information and orbit propagators.

In this context, still considering the diagram depicted in Figure 5.12, after performing the observation, there is a process to register, share, and, store all the data produced during the observation period, before any processing activity is performed. The raw images must be labeled with basic information such as: (*i*) Name of the Observed Object; (*ii*) Name of Comparison Star; (*iii*) Date / Local time of observation. Additionally, general parameters used in all acquisitions for a given period of observation must always be registered, for example: (*i*) Telescope Model; (*ii*) Camera Model; (*iii*) focal-reduction set configuration; (*iv*) Exposure Time; (*iv*) FOV size; (*vi*) Pixel Scale, and, when applicable, additional information such as binning scheme.

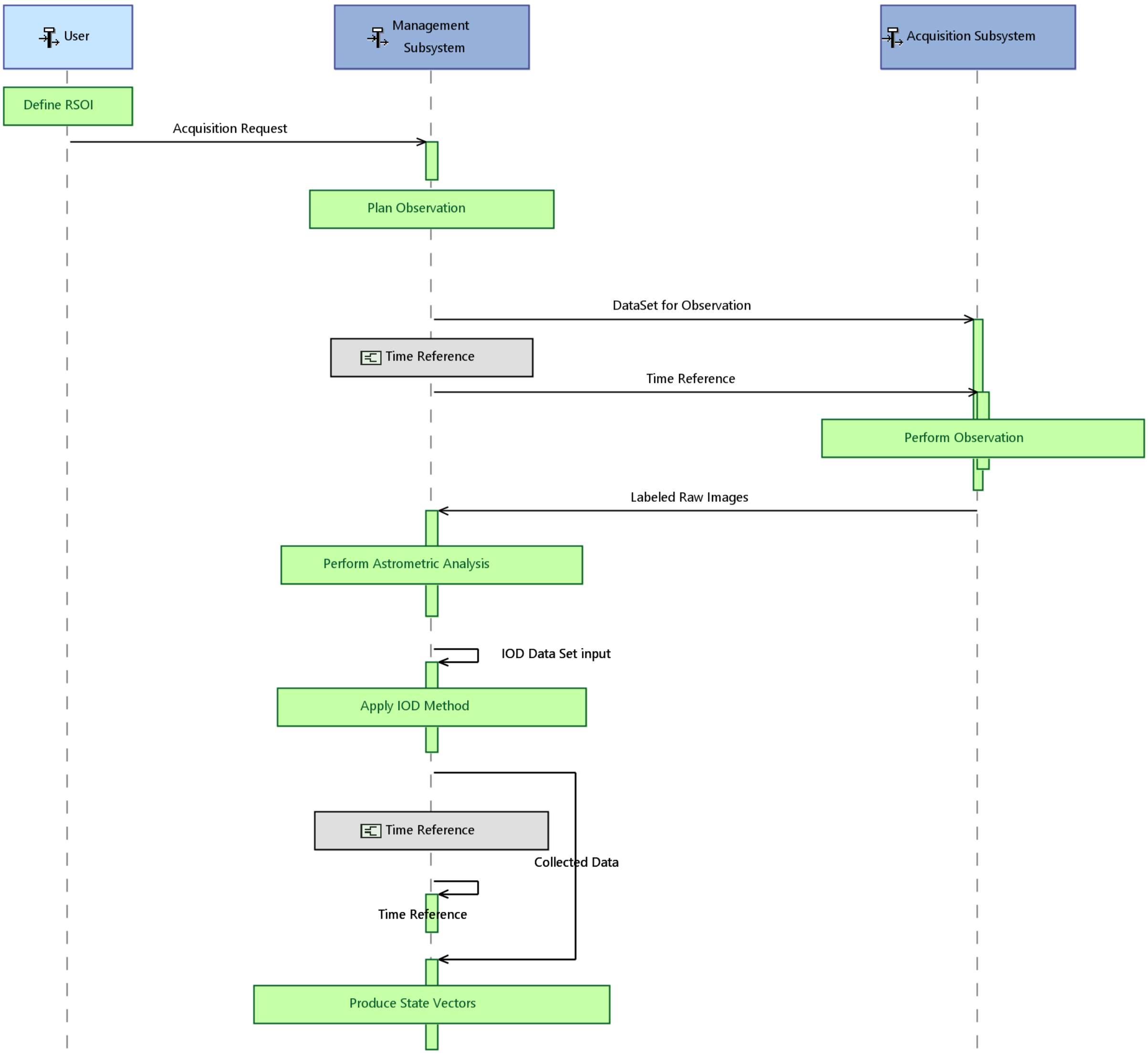

FIGURE 5.12 – Acquisition Scenario.

According to ARCADIA method, during LA some high-levels functions, derived during SA, were represented through more specific functions, as presented in Figure 5.13. The *Acquisition Request* provided by the User could be splited into two general cases: (i) Given a specific period of observation, find observable and suitable targets to be acquainted; (ii) Given an Object of Interest, find observable times and determine periods of observation. In consequence, for the first case, the *Acquisition Request* should minimally include: (i) Coordinates and Altitude of Observatory; and, (ii) Desired period of observation (date/local time). On the other hand, in the latter case: (i) Coordinates and Altitude of Observatory; and, (ii) NORAD ID or International Designator of OI.

The *Scheduling* function, also represented in Figure 5.13 basically consists in using the inputted data from the *Acquisition Request* to search in public-access catalogued data maintained by organizations such as the Joint Space Operations Center (JSpOC), European Space Operations Center (ESOC), or, Space Data Association, for example, to extract updated TLE. These messages contain useful information as orbit states and orbit parameters that will be further used during data processing, and, to determine visible times, Topocentric angles and apparent magnitude of the OI. Those information can also easily be obtained in public access databases, maintained by the aforementioned organizations.

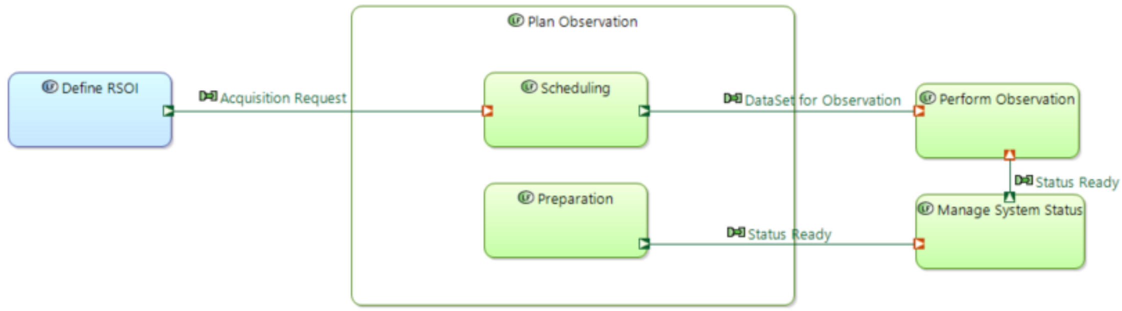

FIGURE 5.13 – Subfunctions from *Plan Observations*.

It is important to note that the *Scheduling* function delivers a Data set with the planned observations to the *Acquisition* System, responsible to perform observations. As mentioned earlier, the angles-only orbit determination indicated method is Gauss‘s method. Consequently, a minimum set of three observations is required to estimate the state vectors of the intermediary observation. Additionally, those observations must be in the same passage, and, are required to have low angular separation. In this sense, it is recommended to plan more than three acquisitions of each object, in the case of unsuccessful observations. Minimum information provided in the Scheduling Data set should contain: (*i*) NORAD ID; (*ii*) Apparent brightness; (*iii*) Time (hh:mm:ss) and Topocentric angles (Azimuth and Elevation) of Start Visibility Point, Highest Point in sky trajectory and End Visibility Point. In addition, an useful information would be a star chart with the projected trajectory against the star background, in order to optimize the process of identifying Companion Stars. Usually, commercial software to manage observations already have internal process of identifying companion stars during the acquisition.

The *Preparation* function depicted displayed in the diagram of Figure 5.13 involves Preparation activities that must be performed to enable observations, some of them are performed immediately before the period of observations, others the day before. Since the physical implementation of the system is out of the scope of this level of abstraction, these activities were just generically listed in a non-chronological order, as follows: (*i*) Check weather conditions; (*ii*) Check Observable conditions; (*iii*) Powering Hardware and Software; (*iv*) Calibrating the Telescope; (*v*) Aligning the Telescope; (*vi*) Time synchronization.

Figure 5.14 represents the logical data flow in terms of *Perform Astrometric Analysis* subfunctions.

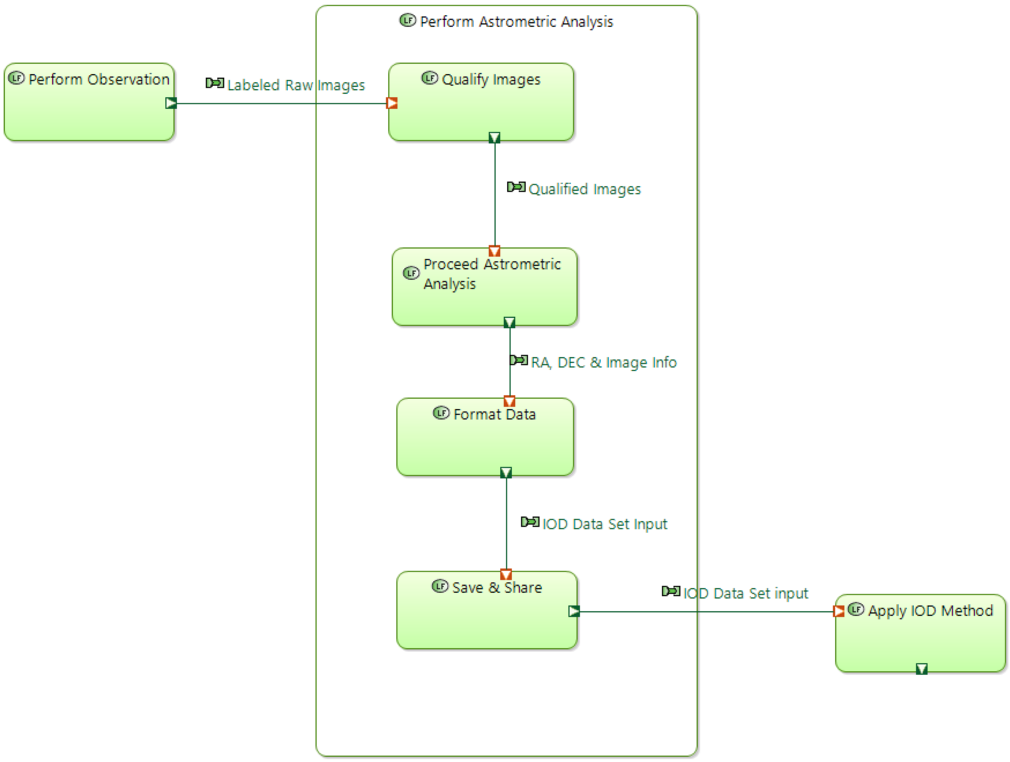

FIGURE 5.14 – Subfunctions from *Perform Astrometric Analysis*.

Similarly to *Plan Observation*, *Perform Astrometric Analysis* is actually decomposed in a sequence of 4 more specific functions - Qualify Images, Proceed Astrometric Analysis, Format Data, and, Save and Share Data. Basically, the qualification process consists in only keeping raw images that have the minimum amount of information necessary to perform astrometry. That is, each image must have, in the FOV, a known comparison star, and, the satellite streak beginning and ending.

Then, the qualified images are submitted to astrometric analysis, that essentially consists in extracting RA and DEC angles from the the image. In general terms, the process consists in correlating pixel locations on the image, with known RA and DEC angles obtained from open-access stars catalog's, such as Gaia's, maintained by ESA, and, with predicted RA and DEC angles for the OI, obtained by the propagated TLE, registered during the *Scheduling* process. An example of an accurate orbit propagator is the SGP4, for lower orbits, or, SDP4 for higher orbits. Those simplified perturbations models used in propagators could be implemented in MATLAB, or used, in commercial or open-source software, such as STK or NASA's GMAT. It's important to note that, commonly, stars's catalog, and, TLE are referenced in the J2000 (Julian dates), and the observations RA and DEC angles are in local time (Gregorian dates). So care must be taken to use a consistent epoch, along the analysis. In sequence, still referencing to Figure 5.14, data must be grouped, ordered in time, and, formatted accordingly to the IOD process. The resulting Data set from this process consists in a set of RA, DEC, and, an estimation of the orbit semi-major axis, obtained from TLE, to input an initial guess in the IOD method. The aforementioned initial guess is required to solve Newton's Raphson method, used to during the implementation of Gauss's method.

The scenarios for *Manage Status*, and, *Elaborate Data Products* are presented, respectively, in Figure 5.15, and, Figure 5.16. There was not a considerable necessity in refining them from SA, if not by the Logical Element *Management Subsystem*, incorporated in the model.

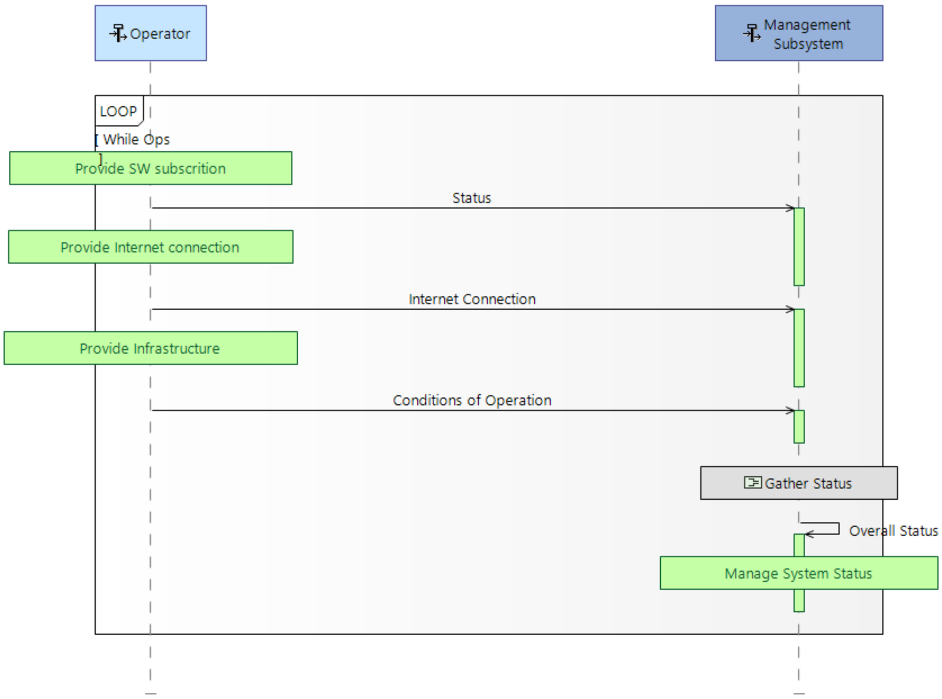

FIGURE 5.15 – Manage Status Scenario.

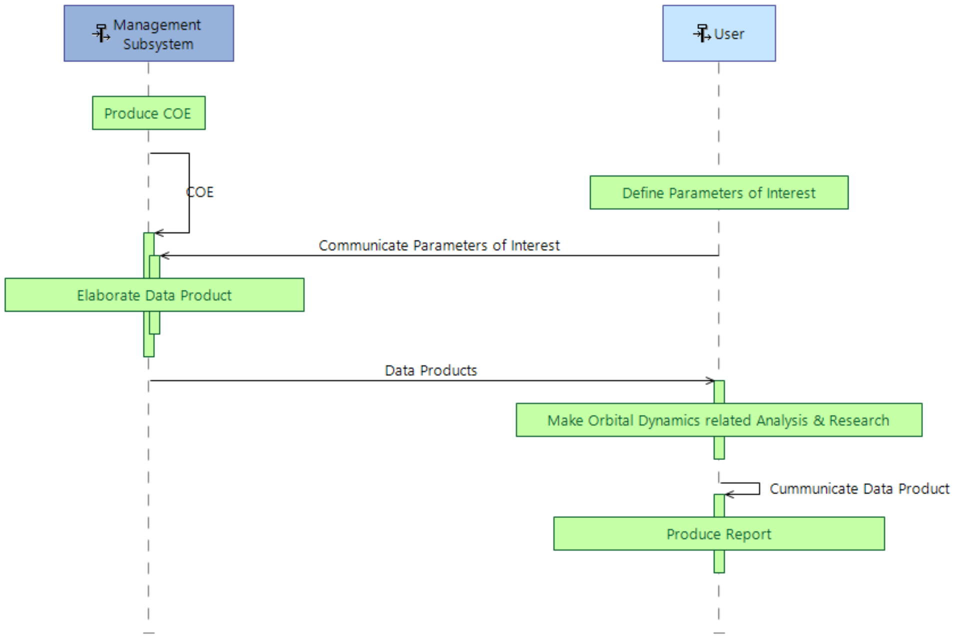

FIGURE 5.16 – Elaborate Data products Scenario.

Finally, the Logical representation of the CEI® SST System is consolidated in Figure 5.17. The interface with external entities, and, actors are consolidated by software interfaces (SWI), or, Refracted EW in optical spectrum, in the case of the Acquisition Subsystem. Although LA is not concerned with physical implementations, the proposed system is constrained to use legacy hardware from ITA Space Center. In consequence, it was possible to restrict the operation to the EW spectrum, and, also, to understand, in advance, some implications on the behavior of the modeled system provided by this limitation. For example, observations are restricted to night time, and, usually ideal illuminating conditions of the target are provided for a period of two hours before the sunrise, and, two hours past the sunset. Additionally, other limitations refer to environmental conditions.

For example, due to the extinction phenomena, the quality of images are hugely impacted by atmosphere opacity (SCHILDKNECHT, 2007). In general terms, extinction phenomena is mainly caused by two effects - absorption, mostly provided by humidity, and, scattering, mostly provided by small suspended particles in solid state, such as smoke, and, dry fog. In practical terms, this analysis should be performed *a priori* regarding the period of observations, and, were already considered in the discussion of Logical Functions *Plan Observation / Preparation* by the items check weather, and, observable conditions. In the case of weather conditions, all the needed information such as cloud coverage prediction, precipitation, and, humidity, can be obtained by REDEMET website (REDEMET, 2022), maintained by the Brazilian Air Force. On the other hand, observable conditions could be obtained by public access Bortle Scale map visualizations, such as Clear Outside website (FLO, 2022), or, by an equipment called Sky Quality meter, that measures the brightness of local sky in $mag/arcsec^2$, which is the most indicated technique. In this context, lower elevation angles in topocentric coordinates, provide images with lower SNR ratios, since observations are performed in a thicker layer of the atmosphere. In this context, some light filters could also be applied during the acquiring process. Negative aspects of filter utilization is that it limits the amount of light collected by the sensor, resulting in longer acquisition, and, processing periods, possibly affecting the next observations, if not sufficient time is allocated during the scheduling of observations.

As displayed in Figure 5.17 the function *Perform Observation* is provided by a software interface. According to Celestron™, the ASCOM software provides the interface between the software that controls the optical apparatus, including CCD or CMOS camera, and, observation management software, that could be a commercially offered solution, such as SkyCapture™, or a developed in-house software.

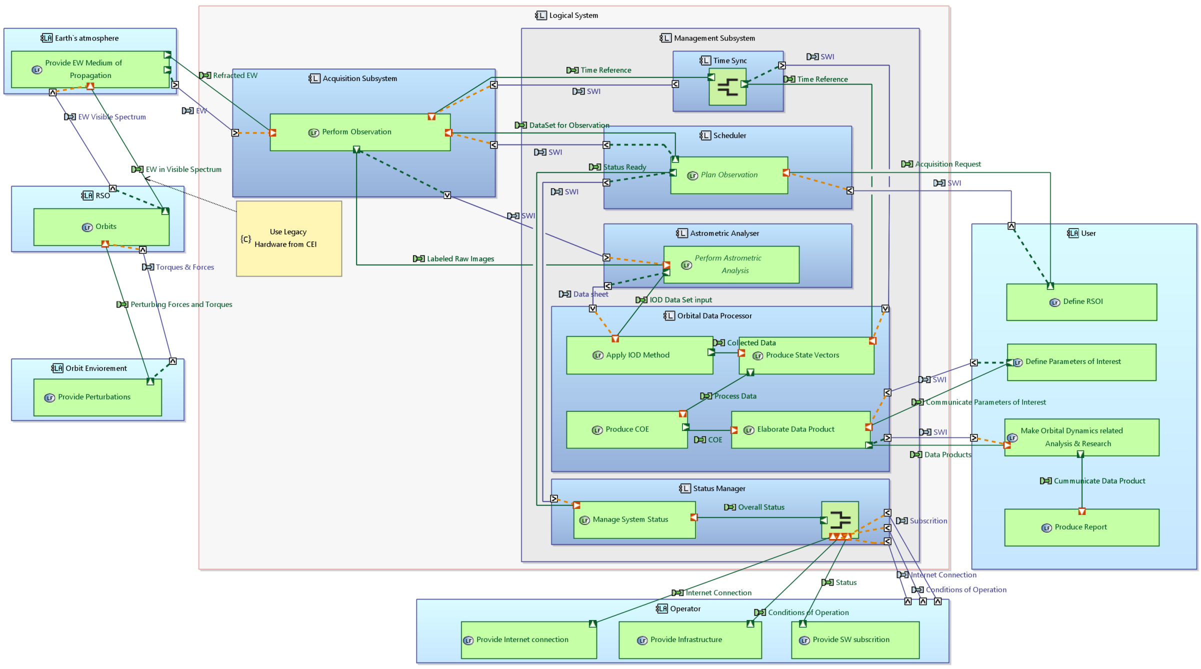

FIGURE 5.17 – Logical System (LAB).

During LA, all the functions provided by the *Management Subsystem* were allocated to more specific Logical Components, as indicated in blue boxes inside boundaries of the *Management Subsystem* in Figure 5.17. In this context, it is important to note that, although the majority of interfaces between external, and, internal components are provided by SWI, the LA already permits to identify 4 different possible domains of software intervention, when physical architecture is implemented: (*i*) General Management of activity, involving *Status Manager*, *Time Sync*, and, *Acquisition Subsystem*; (*ii*) Planning of Observations, involving the *Scheduler* component; (*iii*) Astrometry, involving an *Astrometric Analyser*; and, finally, (*iv*) General Data Processing, involving the *Orbital Data Processor*, representing a sequence of implemented algorithms from literature, responsible for transformation between local and inertial coordinate systems, IOD, and, Orbit Elements determination methods, such as Gauss's and Gibbs's, respectively, considering the context of the present work. Additionally, as mentioned before, the *Time Sync* logical component enables the correlation between scheduling, acquisition, and, data processing activities, and, *Plan Observation*, and, *Perform Astrometric Analysis*, were, respectively, allocated to Logical Components *Scheduler*, and, *Astrometric Analyser*.

At last, considering the Operator responsibilities, in the bottom part of the diagram presented in Figure 5.17, the function *Provide Infrastructure* is realized by the component exchange *Condition of Operation*. It means the all the information needed by the user to plan observations, such as environmental and weather conditions, will be provided by the Operator. Additionally, to Provide Conditions of Operation, a possible implementation in the physical domain can be also the consideration of a dome utilization. A Dome is extremely useful to limit artificial light pollution, and, to protect hardware from environmental conditions. Although not mandatory, an automated Dome is recommended, since it provides the possibility of fully integration, and, synchronization of the software's that manage the telescope.

A comprehensive visualization of all logical functions allocated to the CEI® SST System are presented in Figure 5.18. White box represent functions, broken down into more specialized functions in the model.

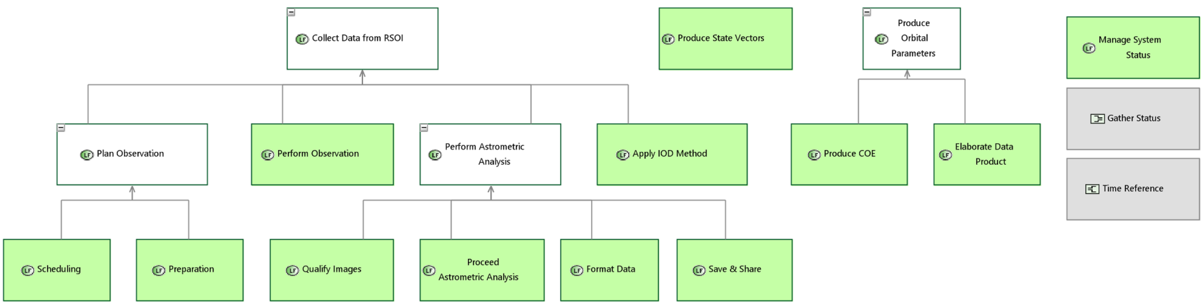

FIGURE 5.18 – Break-down diagram of Logical Functions allocated to CEI SST system.

6 Conclusion

This work proposed a basic framework for a SST System for CEI® Space Center in order to permit future implementations of the system, when budget, schedule, and, scope are defined. This framework includes all the logical components, functions to be performed, interaction, and, data that must be exchanged to perform RSO observations, using a semi-professional Celestron 11 inch Telescope, and, a CMOS camera. The architecture was intentionally developed until the logical architecture, to keep a level of abstraction in which the stakeholder can choose if in the physical implementation of the system, a commercial, an open-source, or, a in-house developed solution will be adopted, according to its interests and limitations. In this context, it is important to note that, independently of the implementation that will be chosen, the architecture presented will still be valid, and, could be reused in further implementations or scope extensions of the proposed system.

In Chapter 1, the domain of Space, Surveillance and Tracking (SST) systems was discussed, exploring aspects such as how it contributes to the context of Space Situation Awareness (SSA), and, highlighting its importance in the context of an enabling system supporting in-orbit operations, conjunction alerts, and, in general, safer space operations. Additionally, the main objective, proposed by the ITA Space Center was presented, then an hypothesis and specific objectives were determined to guide the process of model development. Finally, similar projects or initiatives were discussed, whether in the context of utilization of Model-based system engineering to develop conceptual projects using a top-down approach, or, in the case of similar scope system‘s that are already in operation, considering parameters as budget, scientific scope, and, hardware available.

In Chapter 2, all background information used in support to model development were presented, such as parameters of interest of the satellites owned by ITA, intrinsic characteristics of orbit environment that affect satellite observation, and, catalogue maintenance. Additionally, technical parameters available at the ITA Space Center were presented, as well, the standards of orbit communication, specially TLE. Exploring these protocols were necessary to define what data needed to be collected to the system, the methodology to extract them, in order not to lose information, and, the most efficient format do share them, considering computational cost, and, bandwidth utilization.

Chapter 3 explored the main characteristics of angles-only techniques of orbit determination, considering especially the case of Gauss's Method. Explore in detail the method‘s formulation was essential to define system‘s functions, differentiating between "Produce state vector" from a given epoch using an IOD method, to "Produce Classical Orbital Parameters", using Gibbs‘s method, and the aforementioned state vectors as an input, for example. Additionally, the method needed to be specified since it not only defines the concept of operations of the system, but, also constraints, and, operational limitations. In the case of Gauss‘s method, it is adoption requires that, at least, three angular measurements from the same target were made in the same passage, additionally, low angular spacing between them must be considered. Without implementing the algorithm, these limitations would difficultly be emerged.

In Chapter 4, the general methodology used to develop the model was explored, and, also the ARCADIA methodology was presented, since it defined all the processes, and, steps of model development. Considering the general methodology, first it was presented the scope of the proposed model, considering the capabilities associated to SST system‘s. It was exposed that the conceptual system proposed is concerned with the capability of acquiring orbital data from already catalogued RSO. Following this idea, model development was supported by a domain analysis, and, a technical analysis. The first was concerned in identifying similar scope system‘s, and, understanding legacy hardware integration feasibility, by consulting technical documentation, and, comparing to hardware of kindred systems in operation. On the other hand, technical analysis was concerned in identifying the functions and capabilities needed to deliver the desired emergent behavior of the system. As mentioned before, this analysis additionally provided information about operational concept, and, limitations.

In Chapter 5, all the process of model development was presented in detail and, also, project‘s decisions were justified, as the utilization of a component dedicated for time synchronization and it is implications. First in OA, needs and desires of stakeholders were represented by two capabilities: Produce orbital data from RSOI, and, Make orbital dynamics analysis and research. From these two capabilities, activities necessary to deliver them were identified, as well, what actors or entities were involved in this domain. Next, all this OA architecture was defined as a parent-architecture to SA. In this context, all the capabilities, and, functions defined in SA, are internally linked to an OA element. Doing so, the boundaries of the system were defined without losing traceability with the higher-level architecture. Additionally, in SA a Model-State Machine was developed, and, scenarios of operation were explored. These diagrams permitted to identify how activities are chronologically linked, and, what are the emergent behaviors provided by the system to the final user, and, operator.

At last, also in Chapter 5, a conceptual framework for CEI SST System was finally proposed. In this framework the CEI SST system is divided in two subsystem‘s: Acquisition, and, Management. The first, although physical architecture was not defined yet, as it the system is constrained to use CEI legacy hardware, it is already feasible to state that is the telescope, and, the CMOS camera. On the other hand, the Management subsystem was actually splitted into 5 components: (*i*) Tyme Sync; (*ii*) Scheduler; (*iii*) Astrometric Analyser; (*iv*) Orbital Data Processor; and, (*v*) Status Manager. These components, actually represent 4 domains of software‘s actuation, considering the future realization of physical architecture: (*i*) General Management of activity; (*ii*) Planning of Observations; (*iii*) Astrometry; and, (*iv*) General Data Processing. The scope of the present work was the define the minimum activities, and, data that carachterize wach domain of software realization.

Regarding to specific objectives, OI to be monitored by ITA were presented in Chapter 2, and, all the parameters that are necessary to be inputted in orbit propagators, or, to plan observations were presented. Secondly, the capabilities of interest to ITA were presented in OA, and, basically they refer to the capacity of producing orbital data, and, process it, in support to scientific, research, and, technical development activities. It is also important to mention that, this is the main reason why a fully commercial, and black box solution is not feasible to ITA, since it seriously limits educational and research scope. Criteria of observation, concept of operations, and, Logical Architecture were proposed in Chapter 5.

6.1 Contributions

This work provided ITA Space Center with a basic framework for the SST System using legacy hardware as the 11 in Celestron Telescope and Meade CMOS camera, in a context where managers can choose between commercial, open-source, or, in-house developed solutions, considering additional aspects such as budget, schedule, and, especially, scientific scope.

It is important to mention that, the scope of the proposed system is to perform Initial Orbit Determination (IOD) of already catalogued RSO. Additionally, in consequence of the strategy adopted in the IOD algorithm implementation, and, also, because of the Gauss method itself, the proposed system must acquire a minimum of three qualified sets of observations in the same passage, and, all the data produced is processed offline, in other words, after the end of the period of observations.

6.2 Future work

Future prospective works are suggested, as follows:

- Simulate the Concept of Operations using real TLE propagated Data in STK/EOIR or similar software;
- Implement other Initial Orbit Determination algorithms such as Double-r Iteration, and, Gooding Method;
- Implement in-house developed code for astrometry analysis;
- Implement in-house developed code for Visibility prediction;
- Create OI apparent brightness prediction models more realistic than lambertian sphere models;
- Implement a software interface (SWI) that integrates all software used for analysis;
- Implement physical architecture considering the budget available and scientific scope, and, interests of ITA Space Center;
- Define Concept of Operations to perform Orbit Determination with information from multiple passages.

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Appendix A - Gauss Method implementation

```
% AERONAUTICS INSTITUTE OF TECHNOLOGY
% ITA SPACE CENTER
% author: Carlos Eduardo de Sa Amaral Oliveira AESP22
% Ref: Fundamentos de Astronutica I. FERNANDES, S.S, ZANARDI, M.C.,2018
%%

clc;clear all;
format longg
mu = 398600;% Earth Gravitational parameter [km2/s2]

% Manually input follwinig data:
t = [0,300,600]; % Instants of observation, t=0 date/local time t1 [s]
% MUST input data from observations already converted to ECI
alfa = [301.25,318.4127,341.2413]; %right ascension set of observations[degree]
delta = [-1.1107,1.4354,1.8581]; %declination set of observations [degree]
theta = [45.,46.2534,47.5068]; %sideral local time [degree]
thetadot = 7.292115e-5; %Earth's angular velocity [rad/s]
H = 1; %Altitude of observatory [km]
ae = 6378; % Mean earth radious[km]
ee = 0.08199;% Earth's eccentriccity
phi = 40; %latitude of observatory [degree]
% Determine observatory coordinates
x = ((ae/sqrt(1-(ee*sind(phi))^2))+H)*cosd(phi)
z = (((ae*(1-ee^2))/sqrt(1-(ee*sind(phi))^2))+H)*sind(phi)

% Determine R, first and second derivatives for central time t=t2
R = zeros(3,3);
Rdot = zeros(3,3);
Rdotdot = zeros(3,3);
for i=1:3
```

```
    R(:,i) = [x*cosd(theta(i));x*sind(theta(i));z]; %coord in ECI system[i,j,k]
    Rdot(:,i) =
        [-x*thetadot*sind(theta(i));x*thetadot*cosd(theta(i));0];%[km/s]
    Rdotdot(:,i) =
        [-x*thetadot^2*cosd(theta(i));-x*thetadot^2*sind(theta(i));0]; %[km/s2]
end
R % matrix R = [R1,R2,R3] - [km]
Rdot % matrix Rdot = [R1dot,R2dot,R3dot] - [km]
Rdotdot %matrix Rdotdot = [R1dotdot,R2dotdot,R3dotdot] - [km]
L = [L1,L2,L3] % matrix L = [L1,L2,L3], times of observation divided by columns
% Determinants
D0 = dot(L(:,1),cross(L(:,2),L(:,3)));
D11 = dot(R(:,1),cross(L(:,2),L(:,3))); %[km]
D21 = dot(R(:,2),cross(L(:,2),L(:,3))); %[km]
D31 = dot(R(:,3),cross(L(:,2),L(:,3))); %[km]
D12 = dot(R(:,1),cross(L(:,1),L(:,3))); %[km]
D22 = dot(R(:,2),cross(L(:,1),L(:,3))); %[km]
D32 = dot(R(:,3),cross(L(:,1),L(:,3))); %[km]
D13 = dot(R(:,1),cross(L(:,1),L(:,2))); %[km]
D23 = dot(R(:,2),cross(L(:,1),L(:,2))); %[km]
D33 = dot(R(:,3),cross(L(:,1),L(:,2))); %[km]
% A and B determination
tau1 = t(1)-t(2);
tau3 = t(3)-t(2);
tau = tau3-tau1;
A = (1/D0)*(-D12*(tau3/tau)+D22+D32*(tau1/tau))
B = (1/(6*D0))*(D12*(tau3^2-tau^2)*(tau3/tau)+D32*(tau^2-tau1^2)*(tau1/tau))
% a0,a3 and a6 determination
a6 = -(A^2+2*A*dot(L(:,2),R(:,2))+(norm(R(:,2)))^2)
a3 = -2*mu*B*(A+dot(L(:,2),R(:,2)))
a0 = -(mu*B)^2
% Input data for Newton_Raphson
r =8471; %Initial Guess >> Input data extracted from TLE used in Planning
Frr = r^8+a6*r^6+a3*r^3+a0;
FR=0-Frr;
FRdot=-(-8*r^7-6*a6*r^5-3*a3*r^2);
i=0;
%Newton-Raphson algorithm
while abs(FR)>=1e-3 %stoppage criteria
i=i+1;
rn=r-Frr/FRdot;
```

```
r=rn;
Frr = r^8+a6*r^6+a3*r^3+a0;
FR=0-Frr;
FRdot=-(-8*r^7-6*a6*r^5-3*a3*r^2);
if(i>100)
    break
end
end
r
% If do not converge >> refine initial guess
% C1 and C3 determiantion
u2 = mu/r^3;
C1 = (tau3/tau)*(1+(u2/6)*(tau^2-tau3^2))
C3 = -(tau1/tau)*(1+(u2/6)*(tau^2-tau1^2))
% pho1,pho 2 and pho3 determination
pho1 = (1/D0)*(-D11+(D21/C1)-(C3/C1)*D31)
pho2 = (1/D0)*(-C1*D12+D22-C3*D32)
pho3 = (1/D0)*(-(C1/C3)*D13+(D23/C3)-D33)
% r1, r, r3 determination
r1 = R(:,1)+pho1*L(:,1)
r3 = R(:,3)+pho3*L(:,3)
%  Lagrange coefficinets determination f_i,g_i com i=1 e i=3
f1 = 1-0.5*u2*tau1^2
f3 = 1-0.5*u2*tau3^2
g1 = tau1-(u2*tau1^3)/6
g3 = tau3-(u2*tau3^3)/6
% Determine vector r and v for central time t2
r2 = R(:,2)+pho2*L(:,2)
v2 = (1/(f3*g1-f1*g3))*(f3*r1-f1*r3)
% use this output in Gibbs method do determine COE
```

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5. TÍTULO E SUBTÍTULO:

Conceptual project of a space surveillance and tracking system: a case study for the ITA space center.

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SSA, SST, Model-based System Engineering, ARCADIA, Capella

9.PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

Controle de satélites; Verificação de programas (computadores); Rastreamento de satélites; Engenharia de sistemas; Simulação computadorizada; Estudos de caso; Análise operacional; Engenharia aeroespacial.

10. APRESENTAÇÃO: **(X) Nacional ( ) Internacional**

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11. RESUMO:

The increasing number of Resident Space Objects in Near-Earth Orbits (NEO), especially in Low Earth Orbits, jeopardize the safety of manned operations and increase the probability of damage and degradation of the current installed space infrastructure. The risk of possible collisions in a cascade effect can bring serious economic losses and considerably affects the sustainability of future space missions. Consequently, many companies and agencies are pursuing the capability to achieve and maintain high levels of Space Situational Awareness (SSA) through their own Space Surveillance and Tracking (SST) Systems seeking, especially, for more customization and transparency for data products than traditional commercial solutions available in the market, usually offered as a black-box system. In this context, a Model-Based Systems Engineering (MBSE) framework using ARCADIA Methodology is developed and implemented in this work for a conceptual system involving the available sensors for SST applications at the ITA Space Center. The proposed framework includes an Operational Analysis used to trace the main stakeholder's needs in a Solution Neutral environment. The issue of monitoring Resident Space Objects (RSO) is structured in regard to actors and how they interact with each other, in order to identify the main interfaces and features to be explored and incorporated in the model in an ontological representation. In the Solution Domain, an analysis of the System Needs and a Logical Architecture will be proposed, describing how the system will work to fulfill the user's expectations through logical components and integrating non-functional constraints evidenced during the Operational Analysis. Along this work, some aspects related to several architectural options trades, influenced by available orbit determination algorithms, observation techniques and propagators are also discussed, as well as aspects that go beyond Sensor Management, since the system relies on other sources of information, such previous observations and other collaborative databases where the uncertainty associated with each observation is a very sensitive information and an important parameter to be considered, especially in support for decision making. In the present work, the ARCADIA methodology was implemented in the software Capella\textregistered, an Open-Source software solution released by Thales.

12. GRAU DE SIGILO:

(X) OSTENSIVO ( ) RESERVADO ( ) SECRETO