Project Plan: Tracking Window Optimization for LiAISON-based Cislunar Smallsat Missions

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Space Flight, Space Engineering

1. Introduction and Relevance of the Project

Smallsats have become increasingly popular for a variety of space applications due to their low cost, compact size, and versatility. However, the growing amount of satellites pose a challenge to existing ground networks [1]. Additionally, there are challenges related to the lower radio power budgets for smallsats and large operational costs attached to the use of ground stations [2, 3]. Additionally, future lunar missions will be located at sites on the Moon where direct communication links to Earth are not possible and require a relay satellite [4, 5].

One way to accommodate these challenges is by exploring autonomous orbit determination (AOD) techniques that can enable smallsats achieve precise positioning without the direct need for a ground station [6]. One such technique is called Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) [7]. It is one of the effective techniques for smallsats because it is straightforward and uses existing radio communication technologies [2, 6]. To enable smallsats to autonomously navigate through space, LiAISON utilizes at least one satellite-to-satellite (SST) measurement type to obtain its relative position to another satellite where at least one of the satellite orbits has a unique size, shape, and orientation due to an asymmetric gravity field [4]. As direct-to-Earth navigation gets more difficult as a satellite gets further away from Earth, AOD could also be useful for satellites further than the Earth-Moon system [8]. However, available literature suggests the largest relevance for cislunar missions [6]. This study considers the navigation of cislunar smallsat missions only such as the Lunar Meteoroid Impact Observer (LUMIO) [9] and Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) [10]. Precise navigation is critical for a multitude of applications, such as remote sensing, station-keeping (S/K), and even for allowing human space travel [8]. While LiAISON can provide accurate state estimates, the effectiveness of a set of SST navigation measurements could be improved through a variety of factors [4]. These parameters might lead to an optimal set of time windows throughout which the satellites should perform orbital determination measurements while maintaining proper accuracy. The goal of this proposed thesis work is to find this optimum.

The layout of this proposal starts by addressing the state-of-the-art in section 2. From this follows the research questions in section 3. Then, the work will describe the methodology, setup and will propose a hypothesis starting from section 4. Since the thesis work will continue for a considerable time it was suggested to conform to a predefined planning. In section 7, this will be covered. Finally, the conclusions are elaborated upon in section 8.

2. State-of-the-art/Literature Review

A new era of small satellites for space exploration comes with a demand for autonomous deep-space navigation. This will decrease the reliance on ground-based tracking and provide a substantial reduction in operational costs because of crowded communication networks [6]. First, a general overview of the trends of those types of missions is given in subsection 2.1. This is then followed by an explanation of the principles behind LiAISON and OD in subsection 2.2 and subsection 2.3. Finally, subsection 2.6 aims to lay out a framework for ways in which this research work could contribute to the field.

2.1. Trends and challenges in cislunar smallsat missions

The availability of low-cost and low-volume commercially-of-the-shelf (COTS) spacecraft subsystems have enabled the miniaturization in the space sector and commercial viability for missions using small-scale products with applications that we considered impossible before [11]. With the current developments in the field of spacecraft miniaturization, more players have entered the satellite industry [12]. Turan et al. [6] looked at a total of 64 missions and concluded that, as of April 2022, most deep-space missions are focused on the Moon. The majority of the 64 missions aim to characterize the surface or atmosphere of a body. 34 out of the 64 missions incorporate inter-satellite links for telemetry, telecommand, or navigation purposes. Of these 34 there are 22 operating in cislunar space. For the sake of a proper delineation of the topic of the thesis work, it was chosen to only look at cislunar missions. Below one can find an overview of smallsat cislunar missions [6].

	Inter-Satellite Link (ISL)	**Direct-to-Earth Link (DTE)**	**Inter-Satellite Link (ISL) + Direct-to-Earth Link (DTE)**
Cislunar Missions	LUMIO, VMMO, CLE*, MoonCare*, NanoSWARM	Lunar Flight Light, Lunar Ice Cube, LunaH-Map, LunIR, ArgoMoon, OMOTENASHI, Cislunar Explorers*, EQUULUES, HALO, WATER, IMPEL, CubeX	MiLuV, BOLAS*, OLFAR**, DSL**, CAPSTONE
Total	5	12	5

Table 1: Overview of communication link configurations for different cislunar smallsat missions. (*) = constellation of two satellites and (**) = constellation of more than two satellites. Source highlighting all mission references: [6].

The majority of the issues related to the use of smallsats navigation for deep-space missions are:

- Limited power: only a limited amount of power is budgeted to communication in general [6]. This naturally leads to limited power availability for navigation.
- Limited contact time: more spacecraft could be tracked at only a limited contact time. This is related to the ground station "visibility problem" which is about the communication conflicts that occur when multiple satellites try to communicate with ground stations in the visible range. As the amount of satellites increases, the more challenging the visibility problem becomes. The degree depends on the altitude and antenna parameters [13]. The communication time could affect the accuracy of station-keeping (S/K) maneuvers and thus the degree to which a spacecraft is at its intended location [14].

- Ground station delays: commands from ground stations cause delays. There is a certain downtime between signal from satellite causing a deviation from the true and target states. SOURCE
- Mission event schedule: body to communicate with might not be available due to their own internal communication scheduling [14].

Spacecraft autonomy can lead to decreased costs if ground control operations or hardware are reduced or eliminated [3, 4]. Since most navigation is based on a radiometric Earth-satellite link, there is a possibility to use this existing technology to automate the navigation aspect by performing satellite-to-satellite tracking (SST) [6]. This could also be beneficial because the relatively lower power signal of smallsat is not obscured by Earth's atmosphere and there is no direct-to-Earth (DTE) contact for all satellites that are not the relay. Another benefit might be that increased navigation will lead to a decreased quantity of ΔV required for S/K maneuvers.

2.2. Fundamentals of LiAISON-based navigation

There exists a variety of navigation methods, those that store data on-board and those that send data to a ground station to be analyzed and get feedback [6]. It is the former that provides the autonomous capabilities. There are two types of navigation:

- Absolute: Information on the orbit states is known with respect to a fixed reference point.
- Relative: Information on the orbit states is defined with respect to a moving reference point such as another satellite. To obtain the absolute information one needs knowledge of the absolute position of the moving reference point.

While the advantages of cross-link radiometric navigation are that the accuracy is large and it can be used by existing systems, its disadvantage is that this method needs to employ radiometric signaling between spacecraft [2]. Hence the name "liaison", which stands for "mutual understanding". When one has knowledge on the absolute position of one satellite, one can also determine the position of the other spacecraft [4]. The level of effectiveness for LiAISON depends on the level of asymmetry of the gravity field in the spacecraft's environment. Relative measurements, in a two-body problem, do not provide the absolute orientation of the orbital planes but only the relative orientation because the orbits cannot be fully unique [15]. That is, the absolute states of one spacecraft cannot be known as a particular initial condition can lead to multiple trajectory outcomes. A region in three body systems where the force due to a perturbing third body is relatively large are a good candidate for LiAISON as this leads to uniqueness in the respective orbit [16]. In that case, at least one of the satellite orbits has a unique size, shape, and orientation due to an asymmetric gravity field [4, 17]. That means that the absolute orientation of the orbit is known with certainty when the initial conditions are known. The impact of the asymmetric acceleration field on the spacecraft's trajectory must outweigh the noise from observations and the impacts of unmodeled accelerations by a large margin [4]. For that reason, libration points are a good choice, especially the unstable collinear Langrange points (L1, L2 and L3) [18].

2.3. Fundamentals of orbit determination

The OD consists of three sub-models: the dynamical model, measurement model, and estimation model. This subsection will cover all three of them. One should note that especially the dynamical and estimation model can be applied to systems other than those that are LiAISON-based navigation. The estimation model, however, contains information on the observables with are dependent on the navigational measurement technique.

2.3.1 Dynamical model

The degree of the fidelity of the dynamical model depends on the number of accelerations that one takes into consideration. The easiest, and most commonly employed, model is the circular-restricted three-body problem (CRTBP) [4, 8, 16, 17, 19]. The CRTBP is defined by the following EOMs:

$$\begin{aligned}
\ddot{x} &= x + 2\dot{y} - \frac{(1-\mu)(x+\mu)}{r_1^3} - \frac{\mu(x+\mu-1)}{r_2^3} \\
\ddot{y} &= y - 2\dot{x} - \frac{(1-\mu)y}{r_1^3} - \frac{\mu y}{r_2^3} \\
\ddot{z} &= -\frac{(1-\mu)z}{r_1^3} - \frac{\mu z}{r_2^3}
\end{aligned} \tag{1}$$

Here, x, y, and z represent the spacecraft states with respect to the Earth-Moon barycenter in a rotating reference system. The system contains three bodies, assigned the following properties: Earth (P_1 and m_1), Moon (P_2 and m_2), and the spacecraft (P_3, assumed no mass). Equation 1 makes use to dimensionless parameters: $\mu = m_2/(m_1+m_2)$ represents the dimensionless mass distribution, $r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2}$ is the distance between the P_3 and P_1, and $r_2 = \sqrt{(x+\mu-1)^2 + y^2 + z^2}$ is the distance between the P_3 and P_2. This model assumes that perturbations from external bodies and the effect due to the mass of the spacecraft are negligible.

In reality, the dynamical model is a more complex process. This is what happens in the first line of Equation 3. Solar system ephemerides are not required in the CRTBP, but high-fidelity models do require information on the relative dynamics of all bodies and thus state histories. The JPL DE405 planetary ephemerides are a good source [20]. These ephemerides have been used in high-fidelity models before [4, 5, 16]. For position and velocity information of two spacecraft, Equation 2 represents the state vector. ϵ_i is a white-noise observation error and ℓ is the total amount of observations.

$$\mathbf{X} = \begin{bmatrix} x_1 & y_1 & z_1 & \dot{x}_1 & \dot{y}_1 & \dot{z}_1 & x_2 & y_2 & z_2 & \dot{x}_2 & \dot{y}_2 & \dot{z}_2 \end{bmatrix}^T \tag{2}$$

$$\begin{aligned}
\dot{\mathbf{X}} &= F(\mathbf{X}, t) \qquad \mathbf{X}(t_k) \equiv \mathbf{X}_k \\
\mathbf{Y}_i &= G(\mathbf{X}_i, t_i) + \epsilon_i \qquad i = 1, \ldots, \ell
\end{aligned} \tag{3}$$

A number of powerful methods from the domain of linear estimation theory may be employed to solve the OD issue if the state vector and the observation vector can be related linearly instead [21]. Instead of estimating the state and measurement vector, the deviations with respect to a reference is determined.

$$\mathbf{x}(t) = \mathbf{X}(t) - \mathbf{X}^*(t) \qquad \mathbf{y}(t) = \mathbf{Y}(t) - \mathbf{Y}^*(t) \tag{4}$$

$$\begin{aligned} \dot{\mathbf{x}}(t) &= A(t)\mathbf{x}(t) \\ \mathbf{y}_i &= \widetilde{H}_i \mathbf{x}_i + \boldsymbol{\epsilon}_i \qquad i = 1, \ldots, \ell \end{aligned} \tag{5}$$

Equation 5 is the result of linearizing Equation 3 employing the definitions of Equation 4. $\mathbf{x}(t)$ is called the state deviation vector and $\mathbf{y}(t)$ represents the observation residuals. An asterisk indicates that the values of $\mathbf{X}$ and $\mathbf{Y}$ are derived from a particular solution to the dynamical model equation in Equation 3 that is generated with the initial conditions $\mathbf{X}(t_0) = \mathbf{X}^*(t_0)$. The connection between the nonlinear system in Equation 3 and the linear system in Equation 5 is then made by using the A and $\widetilde{H}_i$ matrices [21].

$$A(t) = \left[\frac{\partial F(t)}{\partial \mathbf{X}(t)}\right]^* \qquad \widetilde{H}_i = \left[\frac{\partial G}{\partial \mathbf{X}}\right]^*_i \tag{6}$$

2.3.2 Measurement model

The number of rows of $\widetilde{H}_i$ is dependent on the amount of measurement types that are included. This could be range, range-rate and line-of-sight (LOS) [2]. For the LUMIO mission (in an L2 halo orbit) it was shown that range-only measurements provide better accuracy than range-rate measurements only [17]. If range-only measurements are included, $\widetilde{H}_i$ would look like Equation 7 [5].

$$\tilde{H}_i = \left[\begin{array}{cccccccccccc} \frac{\partial \rho}{\partial x_1} & \frac{\partial \rho}{\partial y_1} & \frac{\partial \rho}{\partial z_1} & \frac{\partial \rho}{\partial \dot{x}_1} & \frac{\partial \rho}{\partial \dot{y}_1} & \frac{\partial \rho}{\partial \dot{z}_1} & \frac{\partial \rho}{\partial x_2} & \frac{\partial \rho}{\partial y_2} & \frac{\partial \rho}{\partial z_2} & \frac{\partial \rho}{\partial \dot{x}_2} & \frac{\partial \rho}{\partial \dot{y}_2} & \frac{\partial \rho}{\partial \dot{z}_2} \end{array}\right]_i. \tag{7}$$

The range ρ in Equation 7 is calculated using Equation 8. ρ_{bias} represents statistical errors due to the clock states.

$$\rho = \sqrt{(x_1 - x_2)^2 + \left(y_1 - y_2\right)^2 + (z_1 - z_2)^2} + \rho_{\text{bias}} + \rho_{\text{noise}} \tag{8}$$

Then, the value of $\mathbf{x}(t)$ is then converted to the initial time t_k is found by propagating $\mathbf{x}(t)$ by the state transition matrix (STM) $\Phi(t, t_k)$. For that $\Phi(t, t_k)$ itself is also the result of another ODE as shown in Equation 10 [4, 21]. Also, $\widetilde{H}_i$ is transferred to H_i through Equation 11.

$$\mathbf{x}(t) = \Phi(t, t_k)\mathbf{x}_k \tag{9}$$

$$\dot{\Phi}(t, t_k) = A(t)\Phi(t, t_k) \tag{10}$$

$$H_i = \tilde{H}_i \Phi(t_i, t_k) \tag{11}$$

2.3.3 Estimation model

A common way to combine the states of the dynamical model with the measurements is to use a sequential filter like the Extended Kalman Filter (EKF) [4, 5, 8, 17].

There exist a variety of adaptions on the EKF [22]. The EKF is heavily influenced by poorly predicted values for components in the process noise matrix which might lead to low performance of the EKF. For example, the Adaptive Extended Kalman Filter (AEKF) aims to improve the filter performances by adaptively estimating Q and W based on innovation and residual [23]. To account for measurement biases the Consider Kalman Filter (CKF) can be used as well [17]. Because the EKF is very sensitive to initial conditions, it must be carefully characterized [24]. A solution to this could be to use another estimating technique called the "batch filter" [21, 25]. Its advantages with respect to the sequential estimation techniques are that the batch filter is less susceptible to initial errors.

2.3.4 Observability effectiveness

To assess navigation performance quickly, linear covariance analysis is used [14]. It is based on linearization about a pre-defined (nonlinear) nominal trajectory and propagation and updating of covariance matrices. The degree to which radiometric measurements provide information on the states can be derived from eigenvectors and eigenvalues resulting from the information matrix, or Λ, as shown in Equation 12. It represents the sum of "observation effectiveness", or $\delta\Lambda(t_i)$, at observation i with $\Lambda \in \mathbb{R}^{12x12}$ [4]. Below, $\tilde{H}_i$ represents the observation geometry, Φ is the state transition matrix, W is the observation noise. ℓ is the number of measurements per time window t_k.

$$\Lambda = \sum_{i=1}^{\ell} \delta\Lambda(t_i) = \sum_{i=1}^{\ell} H_i^T W H_i = \sum_{i=1}^{\ell} \Phi^T(t_i, t_k)\,\tilde{H}_i^T W \tilde{H}_i \Phi(t_i, t_k) \tag{12}$$

The size of the eigenvectors derived from Λ are an indication of the amount of useful information gathered from an observation of a particular state. If the information matrix has full rank, one can observe all position and velocity states [15]. Full rank does not assess the degree of observability [26]. Λ can be split into an element related to the position states of spacecraft 1 and 2, leading to $\delta\Lambda_1 \in \mathbb{R}^{3x3}$ and $\delta\Lambda_2 \in \mathbb{R}^{3x3}$ respectively [4]. The effectiveness of the measurement for a particular position state (so x, y or z) is the eigenvalue belonging to the eigenvector of the respective state and is defined as Equation 13. i refers to the first three columns of $\delta\Lambda$.

$$\sqrt{||\lambda_i||} \qquad \forall i \in 1,2,3 \tag{13}$$

The eigenvectors define the principle dimensions of the $\Phi\Phi^T$ error ellipsoid. Integration the STM in the case when a nominal trajectory is periodic gives the monodromy matrix and gives special eigenvalue properties [4, 27]. Two of its eigenvalues indicate the stable and unstable manifolds or, in other words, the principle axis in the ellipsoid that have $||\lambda_i|| \leq 1$ and $||\lambda_i|| > 1$ respectively [28]. If the STM is propagated over other times scale than one orbit period, one obtains "local" manifolds. An unstable manifold refers to the direction in the error ellipsoid in which state uncertainty builds up over time. A more effective observation senses along the wide axis of the uncertainty ellipsoid. The more perpendicular the observations are with respect to the unstable manifold, the worse the observation effectiveness. At particular relative orbit geometries, the observations influence the measurement effectiveness. This can be seen by the timing and extent of "blackout periods" in a plot of $\sqrt{||\lambda_i||}$ over time by K. A. Hill [4]. A clear example of the time change of $\delta\Lambda$ can be seen in the research done on the LUMIO/LPF mission by Turan et al [17]. Again, the blackout periods can be observed from which optimal tracking windows can be derived.

2.4. Cislunar orbit types

The Earth-Moon system offers a variety of orbits for cross-link radiometric navigation. Next to Lunar and Earth orbits (such as LEO, GEO, polar, ELFO) there are also halo orbits [16, 19]. Halo orbits are located at the collinear libration points (L1, L2 and L3) [19]. One of the advantages of L2 halo orbits is that some of these can provide great coverage of the lunar far-side and polar regions without blocking the visibility to Earth [29]. When a halo orbit is derived from the CRTBP, the orbit can be called periodic for a reasonable length of time. However, high-fidelity models (n-body dynamical systems) allow such an orbit to deviate from the periodic case in a relatively short time frame motion due to perturbations of external bodies. For that reason, it is called "quasi-periodic" [4, 14]. The geometry of a halo orbit depends on the Jacobi energy of the spacecraft, C_j [19]. The smaller C_j, the larger the orbit [30].

Turan et al. [17] performed analysis specific to the LUMIO (L2 halo)-LPF(Elliptical Lunar Frozen Orbit (ELFO)) constellation and showed that the best position observability occurs at moments when LPF is in the high-velocity region, so periselene of its ELFO. K. A. Hill [4] simulated a large variety of constellation geometries and concluded that Halo-Moon constellations provide the best observability effectiveness $\delta\Lambda$ when relative distances are large, the S/C are not in the same plane and the halo orbits have a relatively small orbit.

2.5. Station-keeping

Before a spacecraft is in orbit, a nominal orbit is defined. Although many perturbations can be modeled, a satellite will still drift away from the nominal position, causing state deviations as shown in Equation 9.

Algorithms will have to be incorporated to define the direction, magnitude, and timing of an impulsive ΔV maneuver. The LUMIO and EQULEUUS missions use an algorithm based on the target points method (TPM) [30, 31]. This method performs a Monte-Carlo simulation including random errors on orbit injection, determination and maneuver execution processes on the nominal orbit determined while subjected to all sorts of perturbations. The state deviation is calculated with optical instruments for LUMIO. The worst-case 1-year operational S/K ΔV for LUMIOs chosen orbit is 4.3 [m/s] (3σ). [9].

2.6. Contribution of this proposal

Although LiAISON can offer precise state estimations, a number of variables affect how well a collection of SST navigation measurements perform. Many factors, including measurement type, precision, interval, inter-satellite distance, number of spacecraft, orbital size, shape, and orientation, have been researched before [6]. In subsubsection 2.3.4 it was stated that there exist blackout periods that influence the effectiveness of the OD. From the found literature the OD measurements are assumed to take place at a certain frequency [4].

From an operational perspective, this constant connection with the other satellite might not be feasible. From this, tracking windows at specific locations in orbit can be planned. There might also be other factors that could affect whether tracking at a certain moment is possible. In other words, there might be a set of ideal time windows for the satellites to conduct observations that take into account a variety of factors in a spacecraft mission. Finding this optimal is the aim of this research by looking into the following parameters:

- Relative orbit geometry between satellites [4, 17]
- Type of utilized estimation filter [21]
- Type of ranging technique with resulting measurement errors [17, 30]
- Communication availability between satellites due to event scheduling [14]
- Radio requirements [9, 17]
- Power and accuracy requirements [17, 32]
- Level of fidelity of utilized dynamical model [4]
- Measurement frequency [25]
- Clock bias and drift [17]

An aspect to consider is that most researchers use the dynamics of the CRTBP. K. A. Hill [4] did an extensive analysis by comparing a large range of orbit combinations using CRTBP. A high-fidelity environment might give a more accurate description of the dynamics and allows for a better representation of the navigation errors. Also, with information on S/K, the dynamics over a longer period than 14 days could be considered. Turan et al. [17] did this with LUMIO over a period of 14 days. Finally, one could also consider novel tricks such as using simple ultra-low rate signals (semaphores) to communicate basic needs. This way a satellite could quickly assess the status of the mission and serve it upon request. This should be done while still adhering to the requirements of the satellites shown in Table 1.

3. Research Question(s)

Considering the conducted literature study, the thesis work will aim to conduct research concerning the following research objective and questions:

Research objective

"To investigate the ability to increase the accuracy of satellite autonomous navigation of existing LiAISON-based cislunar smallsat missions by scheduling satellite-to-satellite tracking sessions as efficiently as possible."

Main research question

"What is the most optimal satellite-to-satellite tracking schedule for LiAISON-based cislunar smallsat missions to increase navigation accuracy?"

Sub questions

1. What are the working principles behind LiAISON?
2. What parameters influence the effectiveness of autonomous navigation observations?
3. How can parameters that influence measurement effectiveness be related to the tracking schedule?
4. What are the discrepancies in the improved navigation accuracy for the different cislunar missions?
5. What are the discrepancies in navigation accuracy between using the CRTBP and a high-fidelity model as the dynamical system?

4. Theoretical Content/Methodology

This research work has the nature of a causal study and will follow deductive reasoning philosophy. This section will discuss the main steps that will be performed. The work will not include certain lab or field experiments, but aims to look at the extent to which there is a causal effect of the before mentioned parameters on navigation accuracy. From a practical perspective, this work is close to the supervisor's work which allows for efficient cooperation and information exchange. Details might adjust over time. The goal will be to optimize the observation accuracies by minimizing the blackout periods in the effectivenesses plots, see subsection 2.3. This is to remove the effectiveness dips and the overall magnitude as much as possible by means of adjusting a variety of variables shown in subsection 2.6. Separate CTBRP and high-fidelity dynamical models are propagated using the same initial states. S/K methods from subsection 2.5 will be used. As input for the estimation filter, the estimation model requires the initial states and the range measurements. The final accuracy results from a Monte-Carlo simulation to obtain a mean and confidence interval. A RMS value based on Monte-Carlo values calculated at each epoch determines the accuracy at a moment in time.

5. Set-up

5.1. Software usage

Producing and verifying results will become a qualitatively intensive process. To fulfill the objectives of this research, the results will come from Python and Matlab. N-body astrodynamics calculations are supported by the TU Delft Astrodynamics Toolbox (Tudat), a robust collection of libraries [33]. Tudat's functionality is built in $C++$, but its Python interface, Tudatpy, will be used. A toolkit called "SPICE kernels" will be used for the JPL DE405 ephermerides. A downside of TUDAT is that it is still in production and might require help from its developers. Additionally, inspiration is taken from the CRTBP Autonomous Orbit Determination application, built in Matlab by Erdem Turan from TU Delft (version 01/03/2023). Note that this does not have a built-in high-fidelity model.

6. Results and Outcomes

6.1. Results

The final results will be plots comparing initial and optimized observation effectiveness for position states. The state accuracy plots show the errors with 3σ over a time period of the mission lifetime, also for initial and improved results. A table or orbit plot will include an overview of the measurement time steps and the moment it occurs in orbit. The specific parameters from subsection 2.6 will be put in a table. Verification and validation has to be performed as well. Because TU Delft has close ties with the LUMIO mission, the simulated dynamics of the LUMIO mission can be compared to the computed LUMIO states used by the LUMIO team, ranging from March 21st to April 4th of 2024. These states are considered the "true" states as these have been verified before. The research by Turan et al. [17] provides plots of the RMS accuracies of the states for LUMIO and the LPF. This can be used to verify the measurement and estimation model code. Since other cislunar missions seem to not openly provide such information it could be the case that mid-study the focus is put on the LUMIO mission only. Regarding S/K, the 3σ ΔV value is consistent with those from LUMIO [30]. Regarding data management, files will be stored privately on GitHub. The LUMIO state files are confidential. This will be shared only with the supervisor.

6.2. Outcomes

With the statements from subsection 2.4 in mind, one could expect an overall decrease in blackout periods and increase in the accuracy plots. These periods will be due to a result of employing an OD window in the faster parts in orbit. A higher measurement frequency will be necessary at those regions. Accuracies will decrease again in non OD regions, but the slower dynamics lead to slower error propagations. The high-fidelity model will result in the best accuracies. The AEKF will result in a better positional estimation than EKF and lead to faster convergence. S/K likely should be performed outside of observation windows.

7. Project Planning

All work packages, key review points, milestones and deliverables have been put into a useful Gantt-chart in Figure 1. The goal is to graduate by the end of 2023. Figure 1 assumes that the literature study and main thesis report will be worked on while waiting for feedback. It also shows the current progress for certain tasks until the moment of writing. Moreover, the connections of milestones that occur in chronological order are shown. A miscellaneous section was added to account for aspects that are not necessarily related to the thesis work itself. The supervisor will be Stefano Speretta from the Space Engineering department.

8. Conclusions

This project plan proposes a study on an autonomous radiometric satellite-to-satellite navigation technique called LiAISON. Due to the rise of smallsats and the growing relevance of the cislunar regime, this work will solely look at smallsat missions in the Earth-Moon system. State-of-the-art suggests that there exist patterns, spatial and temporal, which decrease the observational effectiveness of OD measurements. The objective of the research will be to optimize the observational state accuracy of smallsats by considering a variety of parameters related to the spacecraft's mission. This study will be highly theoretical and shall employ Python and Matlab software to analyze models related to the dynamical, observational, and estimation aspects of a variety of known cislunar missions. Dynamics are verified by using previously verified state histories of the respective missions. Currently this information is only known for the LUMIO mission. Work on this thesis shall prove whether the focus will be on more cislunar missions or just LUMIO. The work could aid future smallsat mission designs regarding signal scheduling and might improve power budgets as well. Organizational wise, the goal is to finish this project by the end of the calendar year 2023. Stefano Speretta will supervise the project.

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A. Gantt Chart

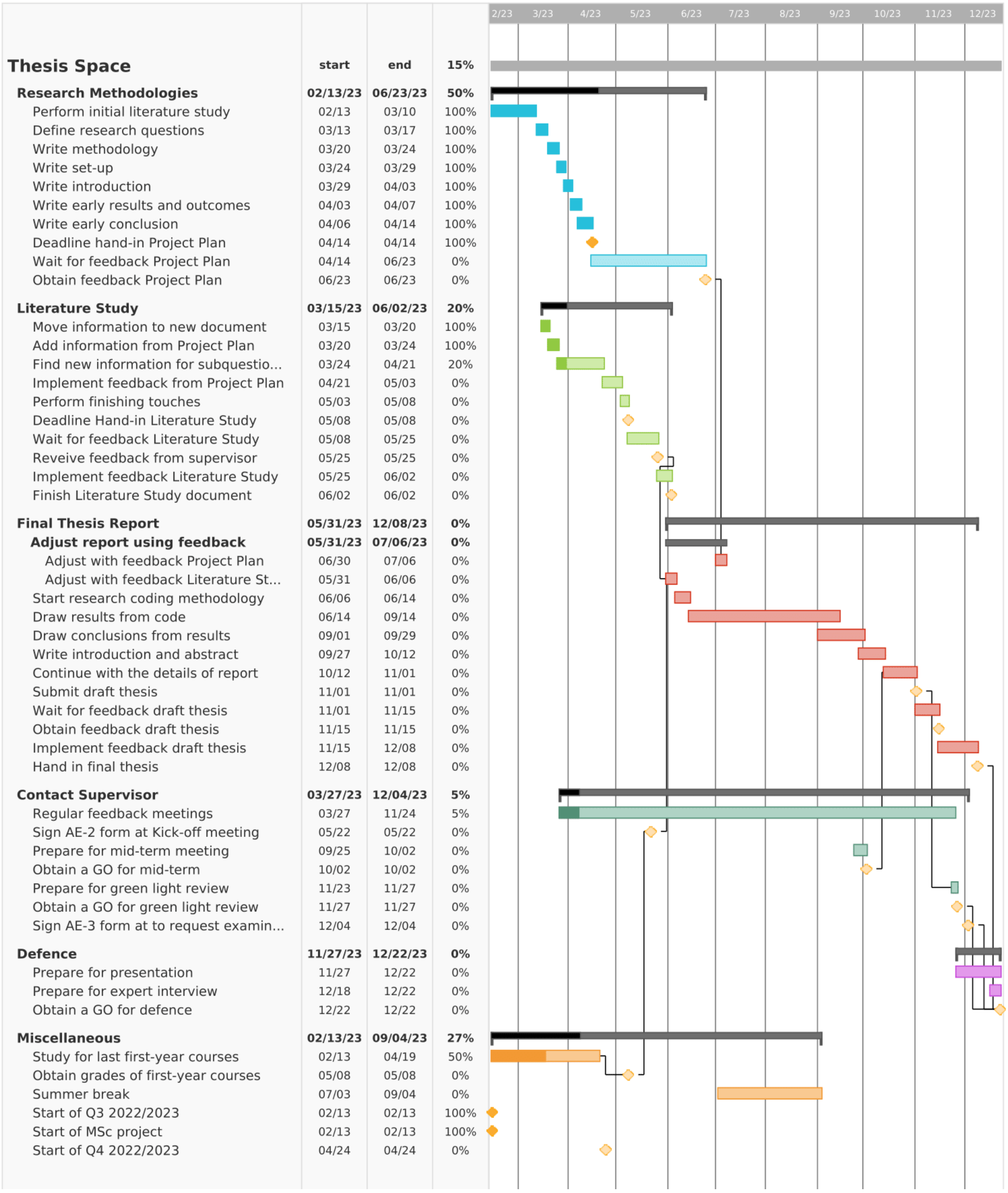

Figure 1: Gantt chart representing the planning of the research project