Space-Object Identification Satellite (SOISat) Mission

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ABSTRACT

This paper presents the mission design, concept of operations, and systems design for a Canadian Space Situational Awareness system called Space Object Identification Satellite, SOISat. With the increasing congestion of man-made objects in all orbital regimes around Earth, detection, classification, recognition, and identification of these resident space objects have become increasingly important to spacefaring nations such as Canada and her allies. The proposed SOISat spacecraft is intended for the surveillance of resident space objects in low-Earth, medium-Earth, and geostationary orbits. In particular, SOISat can be utilized for a) maintenance of the Space Situational Awareness catalogue for particular space assets, b) detection and identification of "DarkSats", i.e., satellites designed to be covert/invisible to the traditional means of detection, c) detection and characterization of unexpected propulsive events, and d) inspection and identification of space objects of interests such as debris objects. Current approaches to space object tracking and identification have significant limitations, especially in the geostationary orbit. An overview of some of the current commercial and non-commercial Space Situational Awareness systems is presented, some of the limitations associated with these systems are described, and SOISat capabilities in addressing these issues are explained. Leveraging the flight heritage of off-the-shelf SmallSat components integrated with the novel payloads envisioned for SOISat, it is expected that the resultant technology brings an unparalleled capability to Space Situational Awareness which does not currently exist. There are two state-of-the-art payload instruments onboard SOISat, namely, a synthetic aperture LADAR and an optoelectronic synthetic aperture processor. The preliminary theoretical results suggest that, at a range of 1000 km, the proposed space-object identification system is capable of imaging objects at a 1-cm resolution. Use of an optoelectronic sensor processor produces a human-readable image in a fraction of the time it would take to digitally process the synthetic aperture LADAR data using conventional techniques. The SOISat system can put forth significant technology development in the synthetic aperture LADAR systems, and meets a critical operation need in improving the understanding of resident space objects. Simulation scenarios are included in order to verify the performance of SOISat in detecting and tracking the resident space objects of interest.

1. INTRODUCTION

With the ongoing proliferation of small and maneuverable space objects, countries are expanding their capabilities for detection, classification, recognition, and identification (DCRI) of unknown space objects including DarkSats, i.e., satellites designed to be covert or less visible to the traditional Space Situational Awareness (SSA) sensors. For Canada, maintaining a leading edge in SSA is critical to ensure its continued prominence as a valued space partner, and more importantly, to provide Canada with the necessary capabilities to promote a secure and peaceful use of outer space. This paper introduces a Space-Object Identification (SOI) system that is believed to be one of the first space-borne systems with an advanced, novel payload instrument that can scan resident space objects (RSOs) in a level of detail that allows for a detailed identification of RSOs of interest. The project is currently undertaken by two Canadian partners, namely, Space Strategies Consulting Ltd. (SSCL) and Institut National d'Optique (INO). The project lead, SSCL, was established in 2014 to assist Canadian space companies and national security organizations with product development, commercialization, support for the development of concepts of operations (ConOps), and market analysis. INO is the largest centre for research and development of optics and photonics in Canada, providing advanced capabilities in electro-optical technologies and supporting Canadian businesses in several key industries through five

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business units including biomedical technology, advanced manufacturing, energy, resources and environment, security, defence, and aerospace.

The SOI project, under the Innovation for Defence Excellence and Security (IDEaS) programme by Department of National Defence (DND), has the primary objective of evaluating, both qualitatively and quantitatively, the potential of a SmallSat equipped with a Synthetic Aperture LADAR (SAL) and an Optronic Synthetic Aperture processor (OSAp) [1, 2] payload for SSA applications. The overarching objective of SSA is to know the location of every object orbiting the Earth, to know why it is there, what it is doing now, and predict what it will be doing in the future [3]. It is the ability to track and understand what exactly is in orbit from either space or from the ground. This capability is needed for nations to protect their extensive investment in space assets for weather, reconnaissance, navigation, and communications. These systems represent hundreds of billions of dollars worth of public and private investment [4] and play a key role in the national economy, prosperity, and wealth creation.

There are certain orbital regimes that have higher priority for SSA. Satellites launched into space generally cluster in these high-priority regions: LEO (low-Earth orbit) for weather and reconnaissance, MEO (medium-Earth orbit) for cellular telephone communication and navigation, GEO (geostationary orbit) for communications, meteorology, and navigation, as well as HEO (highly elliptical orbit) or Molniya orbits for communications services and other uses at high northern latitudes. These preferred orbits are currently cluttered with spent rockets, dysfunctional satellites, and thousands of other bits of debris that are hazards to space operations. By charting and tracking, SSA helps protect space assets and ensure safe operations by providing warnings of potential hazards (natural or manmade, and intentional or unintentional) in a timely manner to allow preventive actions to be taken.

Current SOI systems are to a great extant ground-based, and can provide radar images of space objects, while simultaneously estimating the motion state of the object. A historical overview of optical systems used for SOI applications can be found in [5]. There are various shortcomings that are associated with the ground-based, optical and radar tracking systems of RSOs. For instance, once an object is tracked and identified, it is currently not possible to consistently maintain this knowledge [6] due to several reasons such as object's orbital maneuver or object breakups. There are also challenges associated with the tracking and identification of objects in higher orbits (e.g., MEO and GEO), and the rotational motion of the objects can create inconsistencies and seriously hinder their identifications. In a nutshell, there is a technology gap for tracking and identification functions, as well as safe keeping high-value assets in space. The conceptual payload system that is under development by SSCL for SOI has the capability to scan a target at a range of 1000 km and produce a detailed image (2D and 3D) of the object at a 1-cm resolution. This level of unprecedented precision will provide decision makers and operators with the degree of intelligence they need, within the context of the evolving space environment, to evaluate the threat hazards of RSOs, be they space junk or hostile DarkSats.

The organization of this paper is as follows: Section 2 describes the preliminary conceptual design of SOISat. Section 3 provides an overview of the payload intended for the spacecraft. Section 0 presents a number of mission scenarios as well as the ConOps for SOI mission. Section 5 briefly describes the orbital and attitude maneuvers of the SOI spacecraft in each mission scenario. as well as the simulation parameters for two case studies. Section 6 presents the results, and a discussion on the capabilities of SOISat in light of the results. Lastly, Section 7 provides some concluding remarks.

2. SOI SPACECRAFT DESCRIPTION

With the continuing advancement in miniaturization of electronics and computer systems in the past couple of decades, there is a need for agile, SmallSat-based tactical spacecraft that can be tasked to perform DCRI in near real time, which can be produced and implemented within a much shorter time frame, on a much smaller financial budget than the traditional large satellites developed by major space organizations such as NASA and ESA required. A key design driver for the SOI spacecraft is that the satellite should utilize a Smallsat form factor and all subsystem elements should use commercially-available components with proven flight heritage (with the exception of the payload subsystem). In addition, there is a keen interest in utilizing a Canadian-built spacecraft platform due to national security considerations. As such, a number of Canadian spacecraft buses were evaluated in early phases of the project, and the DAUNTLESS platform (by Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies) was selected as a potential candidate for the SOI mission. A summary of the DAUNTLESS bus specifications is listed in Table 2. Component selection for the spacecraft is mainly inspired by mission scenarios, availability of the components, and their flight heritage and technology readiness level (TRL). Since SOISat must be capable of controlling its attitude during the mission, a three-axis attitude determination and control system (ADCS) is imperative.

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Table 2: Specifications and performance parameters of the DAUNTLESS platform [8].

Parameter	Value/description
Mass	Up to 500 kg
Volume	1 m ×1 m ×1 m (scalable)
Payload volume	Up to 0.80 m^3
Payload power	Up to 260 W·h per orbit; 800 W peak
ACS stability	Up to 1 arcsec (with a rate sensor, a star-tracker, and reaction wheels) in 10 seconds
ACS modes	Inertial, nadir tracking, and target tracking
Downlink rate	Up to 400 megabits per second (Mbps)
Propulsion	Optional
Orbit determination	GPS, 5—10 m accuracy
Launch interface	Separation system
Mission heritage	1 mission (LEO2)

Table 1: Initial Payload Parameters

Payload Component	Dimensions [m]	Mass [kg]	Power [W]
SAL	0.6 × 0.56 × 0.27	43	860 (with an additional 300 W to 1500 W for cooling)
OSAp	0.26 × 0.21 × 0.12	5.6	68
Total Payload Best Estimates:	-	~50	~2500

The proposed ADCS hardware onboard SOISat consists of six sun sensors (one on each side of the spacecraft), one three-axis magnetometer (to measure the ambient magnetic field in orbit, for attitude determination purposes), one three-axis rate sensor, three reaction wheels (for fine pointing), and three magnetic torquer rods, better known as magnetorquers (for detumbling maneuver as well as desaturating the reaction wheels). The candidate reaction wheels for SOISat can produce a maximum torque of 0.25 N·m while consuming less than 10 W of power. Also, for orbit determination, a global navigation system (GPS) is included.

Since the spacecraft is expected to perform a number of orbital transfer maneuvers to arrive at the target orbit, a propulsion system is needed. Currently, both chemical thrusters and low-thrust propulsion systems are deemed viable for SOISat, and further investigation into the amount of required delta-v is needed in order to better characterize the appropriate type of propulsion system for SOISat and the amount of required propellant. Ideally, the propulsion system must have a high specific impulse (typically, over 1000 s) to allow for longer mission durations and multiple orbital maneuvers if needed. Electric propulsion systems, in particular plasma-based thrusters, can provide much higher specific impulse values when compared to chemical thrusters. Propulsion systems with high specific impulse allow SOISat to perform station-keeping and orbital transfer maneuvers for extended periods of time, while consuming much less propellant than their chemical counterparts. One such plasma-based thruster is currently being developed by Baryon Dynamics Inc. [7] called Hybrid Electric Thruster. It is a gridded-ion thruster with an afterburner feature to provide an increase in thrust if needed. Ideally, the thruster would consume less that 60 W of power and have a cruising thrust of 1.5 mN.

To generate, store, and distribute electrical energy that is required for mission operations, a power subsystem must be accommodated on the spacecraft, which includes solar cells, batteries, wiring harnesses, and a power board. Given the amount of power required for the operations of the SAL-OSAp system (discussed in Section 3), it is highly likely that deployable solar panels should be accommodated on DAUNTLESS to improve the power generation capabilities of the spacecraft. Lastly, to communicate with the ground segment and potentially for an intersatellite link with other satellites, a communications subsystem is included onboard SOISat, allowing for receiving and transmitting mission and science data.

3. SOI PAYLOAD DESIGN

As one of the main deliverables of the SOI project, INO has started working on the preliminary design of SAL and OSAp engineering models, which, when integrated together, will form the SOI payload instrument. INO has

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developed initial size, mass, and power estimates, which are listed in Table 1. As the design of the system becomes further mature in future milestones of the project, the allocated values for each design parameter will be revised accordingly to obtain a more refined mass, power, and size budgets.

It should be noted that the maximum allowable payload volume on the DAUNTLESS bus is 0.8 m^3 [8]. Even though the current size of the SAL and OSAp system is significantly smaller, thermal regulation components are expected to occupy a considerable volume within the payload bay. A solution that has been identified for the thermal regulation of the payload onboard SOISat is through the utilization of thermoelectric coolers. As many components of the SAL-OSAp payload are highly sensitive to thermal fluctuations, the subject of SOISat thermal regulation is critical and will be closely investigated in future milestones. Further, the total required payload power (i.e., up to 5 kW including a factor of 2 margin) has been identified as a potential obstacle with respect to integration into a SmallSat bus, in particular DAUNTLESS. Accordingly, INO is actively developing mitigation strategies to reduce the power and thermal requirements without compromising the performance and integrity of the system.

Through investigation of the storage and transmission requirements of data and images generated by the payload, it has been determined that each imaging campaign of SOISat will generate about 6.4 gigabytes of raw data, which would need to be stored on the spacecraft computers. However, after processing of the data by OSAp, the final image is only 8 megabytes. To successfully transmit the entire stored data during each pass over a ground station, at least 256 megabits per second of communication bandwidth would be required, while to transmit the final image, only 320 kilobits per second of bandwidth would be required. Several scenarios of data storage and transmission have been also investigated. In the first scenario, all raw data and final processed images are transferred to both the on-board computer and a dedicated ground station. This case has high storage and downlink capability requirements. In the second scenario, all raw data and final images are transferred to the onboard computer, but only final images are transmitted to the ground, either automatically or after operator's command. Raw data is kept in the onboard computer but can be transmitted to the ground upon request. This could potentially alleviate the stringent downlink requirements but may increase the amount of storage required onboard SOISat, depending on the time delay between receiving the final image and operator's command to transfer or discard the raw data. In the third scenario, the final image analysis is performed by the onboard computer, which determines whether to transfer a given image and the associated raw data to the ground. This scenario may reduce storage and downlink requirements, assuming that some data is discarded, however would require a much more powerful computer to complete the analysis within the time interval of imaging campaign (typically, 200 seconds).

4. CONCEPT OF OPERATIONS

A number of nominal operations scenarios have been envisioned for SOISat mission concept, which will be discussed in this section. In the first scenario, SOISat performs the DCRI task on a suspected DarkSat in LEO that is operating in close proximity to a Canadian asset, e.g., RADARSAT-1. The scenario is known as the LEO-watch mission (LWM). In this scenario, the SOI spacecraft is placed in a sun-synchronous orbit near the asset, from where SOISat scans the target asset, and potentially other targets of interest (including DarkSats) in close proximity of the asset. Given the

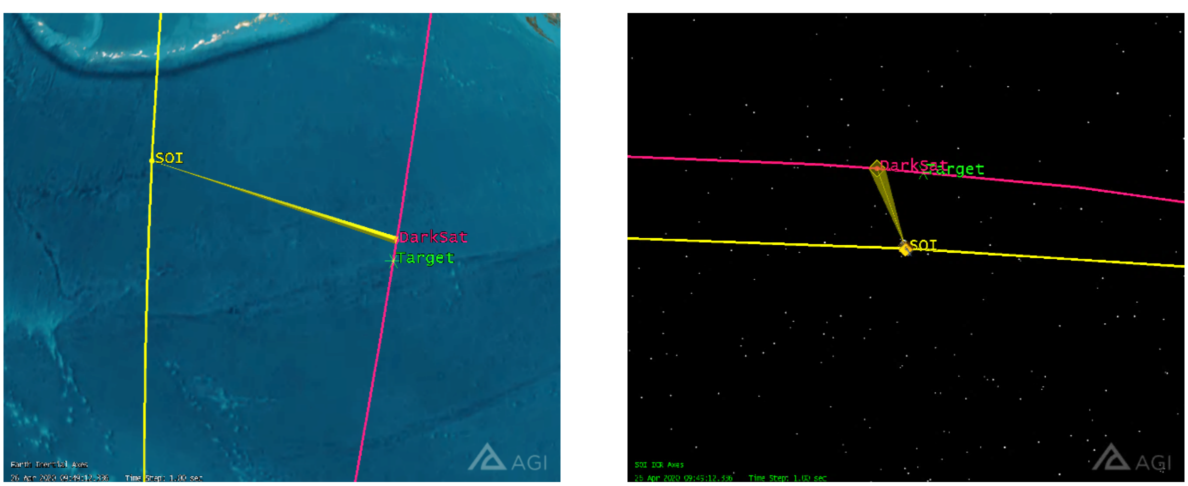

Fig. 1: LEO-watch Mission simulated in STK.

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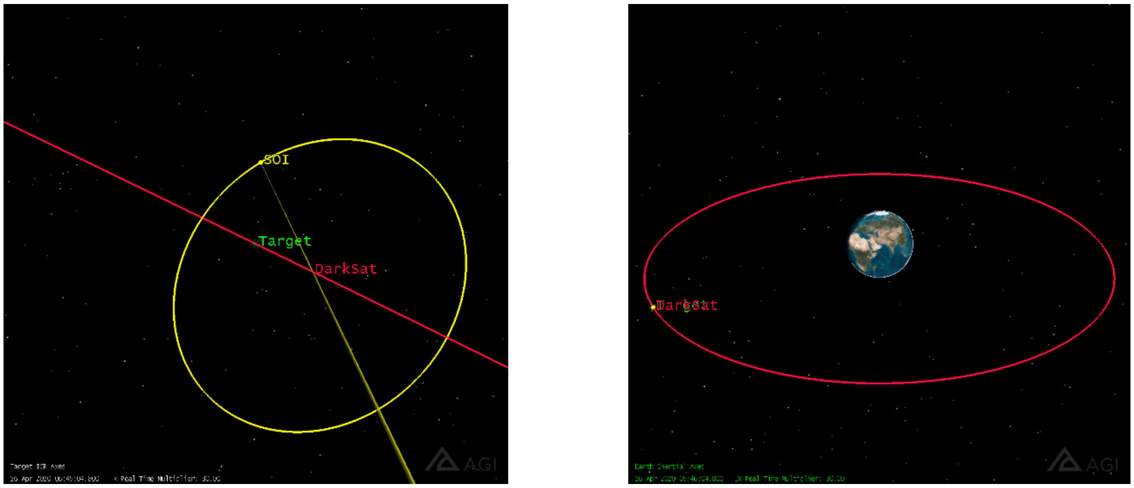

Fig. 2: GEO-watch Mission simulated in STK.

current limit on the operational range of the SOI Payload, it is postulated that SOISat can only detect a DarkSat when the relative distance between the two spacecraft (i.e., SOISat and DarkSat) falls below 1000 km. Further, it would take the SAL-OSAp system at least 200 seconds to successfully scan the target in sufficient detail. Fig. 1 shows some snapshots of the LWM scenario simulated in Systems Tool Kit (STK). The red line indicates DarkSat's orbit, and the yellow line indicates SOISat's orbit.

The watch mission concept is further adapted to a scenario in the MEO orbital regime (called MEO-watch mission, MWM), whereby a GPS satellite is chosen as the threatened high-value asset. In this instance, the SOI satellite flies in formation with the approaching DarkSat at a relative distance of 100 km, providing imagery from various angles and facets of the target DarkSat. While still under investigation, it is theorized that the SOI payload would achieve sub-centimeter resolution at the 100-km relative distance.

Finally, a watch mission is conceived for SOISat in GEO, whereby the SOISat performs DCRI on a suspected DarkSat flying in close proximity to a high-value, operational GEO satellite. The high acuity scans provided by the SOI payload can be used to either identify possible problems that the asset may be experiencing or perform DCRI operations on a possible DarkSat flying in close proximity to that asset. For the purpose of the GEO-watch mission (GWM) considered in this paper, the latter case is considered as an important operations scenario. In this case, SOISat is tasked to fly in formation in a near-circular orbit around the suspected DarkSat, at a relative distance of several hundreds of kilometers. Fig. 2 shows snapshots of the GWM scenario simulated in STK. The red line indicates the GEO orbit of the DarkSat, and the yellow line indicates the orbit of SOISat. While in its orbit around the DarkSat, the SOI payload is able to make frequent images of the target, thereby determining potential capabilities (and possibly intent) of the intruder.

5. ATTITUDE AND ORBITAL MANEUVERS

The primary constraint on SOISat's attitude motion during the target-tracking phase is that the payload line-of-sight must be pointing toward the target spacecraft's centre of mass as both spacecraft proceed in their orbits, as shown in Fig. 3. In order to evaluate the performance of SOISat in the LWM and GWM scenarios, a case study is created for each scenario. The orbital parameters of both spacecraft at epoch t_0 pertaining to each case study are listed in Table 3. In the table, the subscript "s" indicates SOISat, and the subscript "t" indicates target (i.e., DarkSat). As noted in Section 0, the SOISat spacecraft only tracks the target satellite when the relative distance between the two spacecraft is below 1000 km. Therefore, for the LWM scenario, the orbital states of SOISat and the target at the point in orbit where their relative distance falls below 1000 km are determined and reported in Table 3 using STK. In an effort to track the desired attitude, SOISat's attitude control system generates a control torque ($\boldsymbol{\tau}$) that, in this work, is modeled based on the quaternions feedback regulator. The gain values are selected such that the command torques do not exceed the maximum allowable torque by the reaction wheel (i.e., 0.25 N·m for the candidate reaction wheels), and that SOISat can point its payload at and track the target object within a short period of time from the beginning of the maneuver. For the GWM scenario, SOISat performs a formation maneuver around target spacecraft. To formulate the

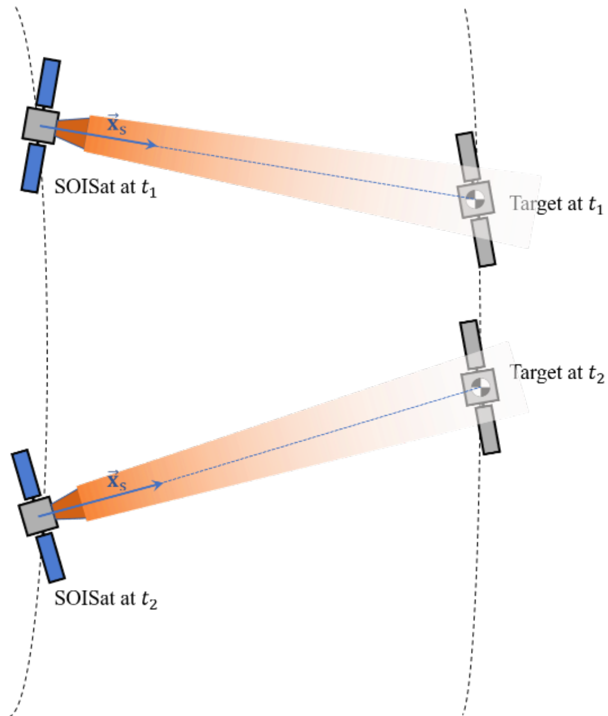

Fig. 3: SOISat tracking the target.

dynamics of SOISat's formation flying in the vicinity of the target spacecraft, the homogenous solutions of the Clohessy-Wiltshire equations are obtained, which allow for achieving an unforced formation (i.e., without consuming propellant) around the target spacecraft. Further, in terms of achieving a bounded formation trajectory, a projected circular orbit (PCO) has been considered for SOISat, where the projection of SOISat's orbital trajectory in the plane directly below the spacecraft appears as a circle. In terms of the spacecraft attitude, it is assumed that SOISat is initially tracking the inertial frame, i.e., $\mathbf{q}_s(t_0) = [0 \quad 0 \quad 0 \quad 1]^\top$, where $\mathbf{q}_s$ denotes SOISat's attitude quaternions. Lastly, in

Table 3: Simulation parameters pertaining to LEO- and GEO-watch mission scenarios. a: semimajor axis; e: eccentricity; i: inclination; Ω: right ascension of the ascending node; ϖ: argument of perigee; ϑ: true anomaly.

Scenario	Spacecraft	Classical orbital elements at t_0	Orbital position and velocity at t_0
LEO-watch mission	SOISat	$a = 8000.0$ km $e = 0.001$, $i = 88.0°$ $\Omega = 0$ $\varpi = 0$ $\vartheta = 3.6°$	$\mathbf{r}_s = [7977.09 \quad -17.99 \quad 487.89]^\top$ km $\mathbf{v}_s = [-0.43 \quad 0.25 \quad 7.05]^\top$ km/s
	DarkSat	$a = 8300.0$ $e = 0.001$ $i = 98.0°$ $\Omega = 0$ $\varpi = 0$ $\vartheta = 3.0°$	$\mathbf{r}_t = [8171.80 \quad 1341.27 \quad 418.6]^\top$ km $\mathbf{v}_t = [-0.18 \quad -1.01 \quad 6.86]^\top$ km/s
GEO-watch mission	DarkSat	$a = 42166.3$ km $e = 0.0$ $i = 0.0$	$\mathbf{r}_t = [-34876.66 \quad -23698.26 \quad 67.47]^\top$ km $\mathbf{v}_t = [1.73 \quad -2.54 \quad 0.00]^\top$ km/s

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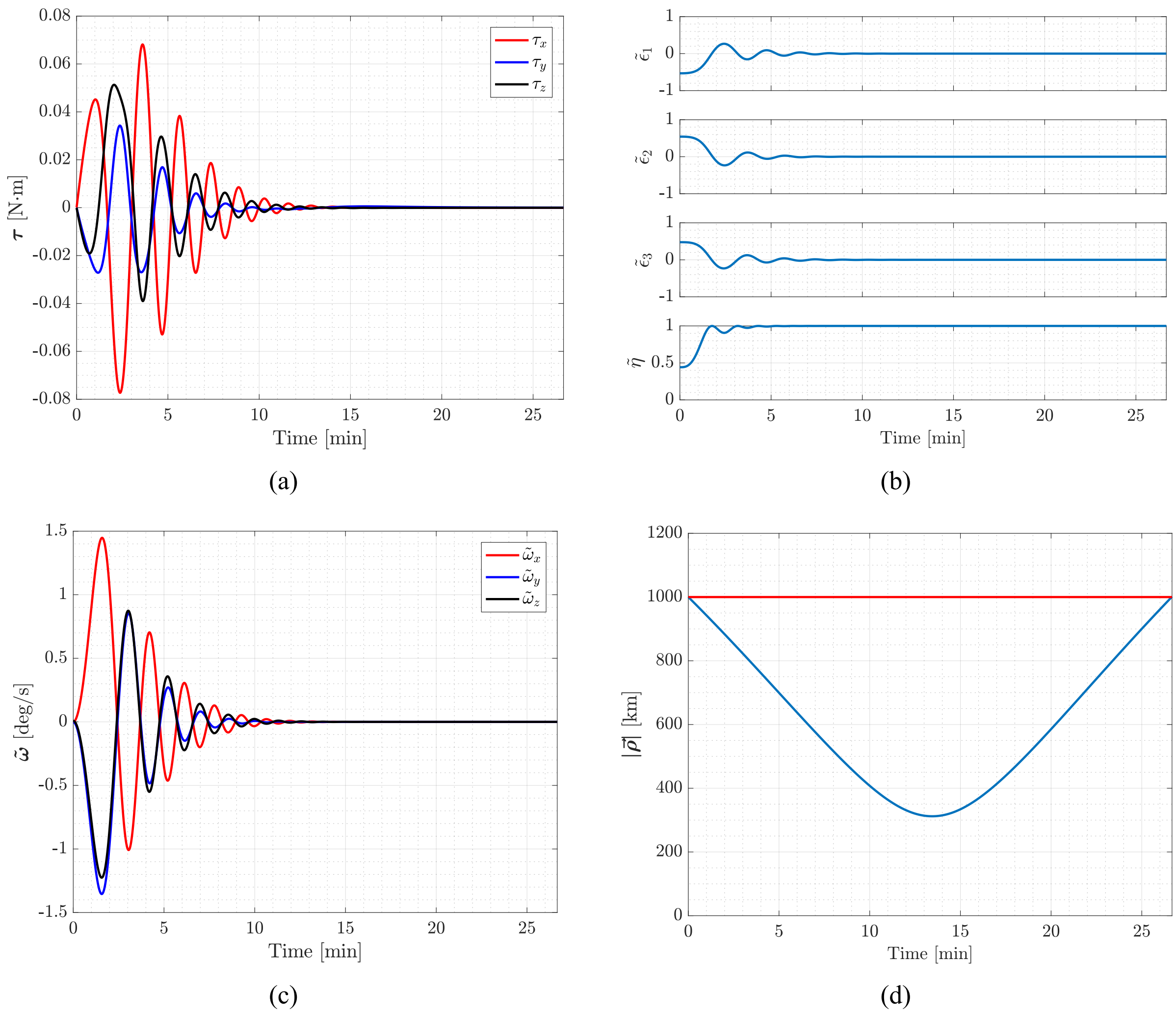

Fig. 4: Time histories of (a) the command torque, (b) error quaternions, (c) error in angular velocities, and (d) the range between SOISat and the DarkSat (bottom right) for the LWM simulation scenario.

order to improve the fidelity of simulation scenarios, two sources of disturbances are introduced to the dynamics of SOISat's attitude. They are the gravity-gradient disturbance torque and the magnetic disturbance torque.

6. RESULTS AND DISCUSSION

Fig. 4 shows the time histories of command torque (Fig. 4a), error in quaternions, $\tilde{\mathbf{q}}_s = [\epsilon_1 \quad \epsilon_2 \quad \epsilon_3 \quad \eta]^\mathsf{T}$ (Fig. 4b), error in angular velocities, $\tilde{\boldsymbol{\omega}}$ (Fig. 4c), and the range between SOISat and DarkSat, $|\vec{\boldsymbol{\rho}}|$ (Fig. 4d) during the LWM simulation scenario. Evidently, SOISat manages to successfully point the payload directly at the DarkSat and track the spacecraft using the onboard reaction wheels and the prescribed quaternion feedback regulator, after about 13 min into the simulation. As shown in Fig. 4a, the command torque never exceeds the maximum torque that can be produced by the candidate reaction wheels (i.e., 0.25 N·m), and that the required torque to continuously track the target DarkSat becomes negligible once SOISat successfully locks onto the target spacecraft (i.e., about 13 min into the simulation). As shown in Fig. 4b, the transient errors in the attitude quaternions vanish through the application of the quaternion feedback regulator control law; so do the transient errors in the angular velocities as evident in Fig. 4c. Further, as shown in Fig. 4d, there is a 27-min time span during which the relative distance between the two spacecraft is less than 1000 km, and so SOISat can be tasked to track the target DarkSat. As discussed in Section 0, each imaging campaign of SOISat takes about 200 s, and hence, given that it takes SOISat about 13 min to successfully track the target DarkSat, there is about 20 min of available time for SOISat to perform the desired DCRI operations.

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The results obtained for the GWM simulation scenarios are presented in Fig. 5 and Fig. 6. The SOISat spacecraft manages to successfully point the payload directly at the DarkSat and track the spacecraft using the onboard reaction wheels and the prescribed quaternion feedback regulator after about 12 min into the simulation, while flying in formation with the DarkSat spacecraft. Specifically, Fig. 5a shows that the command torques are almost negligible throughout the tracking maneuver, except for the beginning of the maneuver (as shown in Fig. 5b) where SOISat attempts to transition from an inertially-pointing mode to a target-tracking mode. But, as before, the required torques never exceed the 0.25 N·m-limit, even during the initial phase of the maneuver where the errors in SOISat's attitude are substantial. Similarly to the LWS simulation scenario, the required torques to continue tracking the target DarkSat become negligible after the initial phase of pointing at and tracking the target spacecraft. As shown in Fig. 5c and Fig. 5d, the transient errors in the angular velocities vanish through the application of the quaternion feedback regulator control law, even in the presence of the disturbance torques.

Lastly, Fig. 6 shows the orbital trajectory of SOISat around the target DarkSat during the formation flying in the GWM simulation scenario. As noted in Section 5.1, the maneuver is intended to be natural, i.e., SOISat would not need to utilize its onboard thruster to form the prescribed formation trajectory around the target debris. The plots show that the formation is bounded, i.e., the relative distance between the two spacecraft never becomes substantially large at any point during the simulation, and that the projection of orbital trajectory in the X-Y plane appears as a circle with a radius of 100 km. Such type of formation is particularly useful where SOISat would need to continuously access the

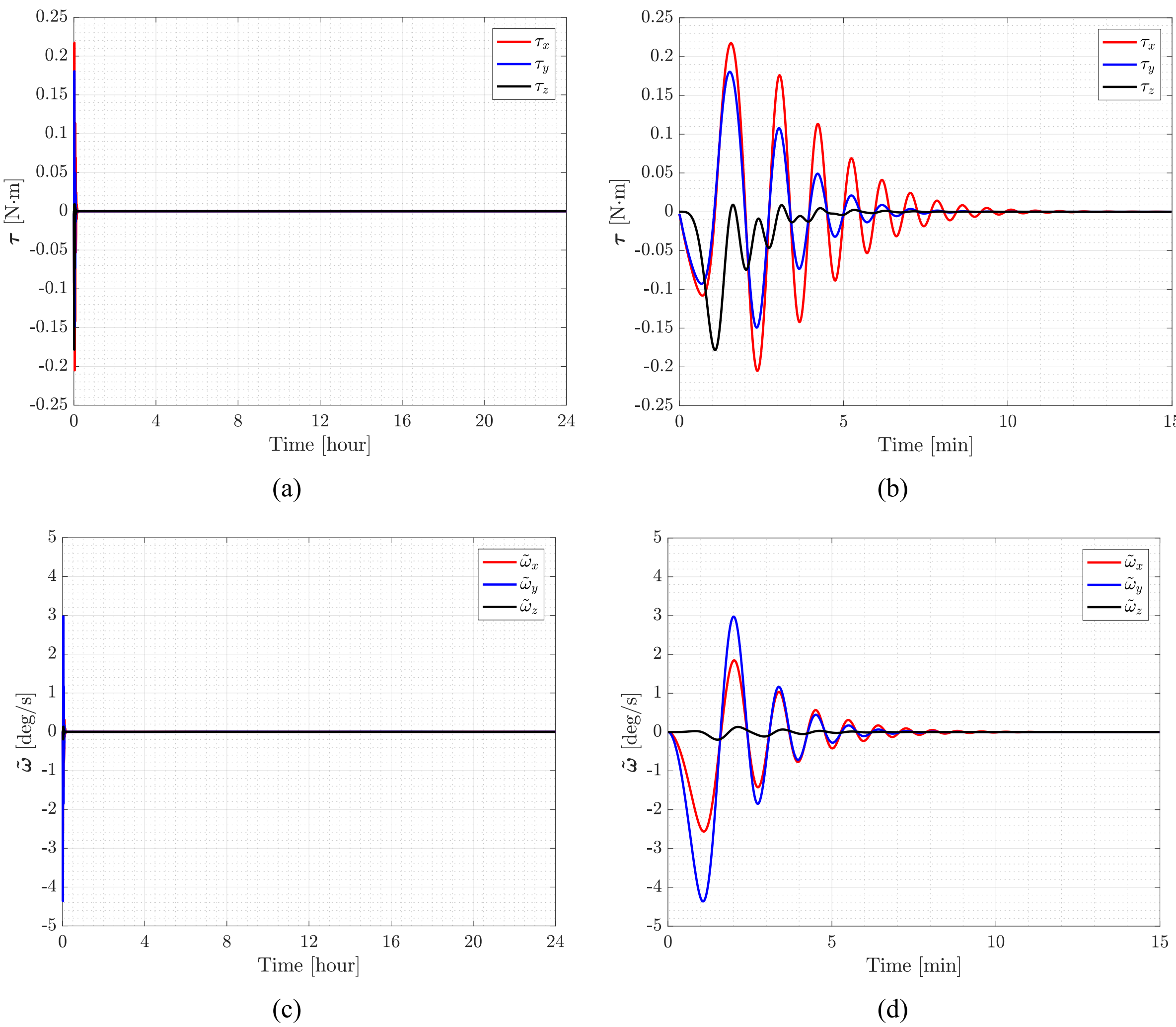

Fig. 5: Time histories of (a) and (b) the command torques, and (c) and (d) error in angular velocities for the GWM simulation scenario.

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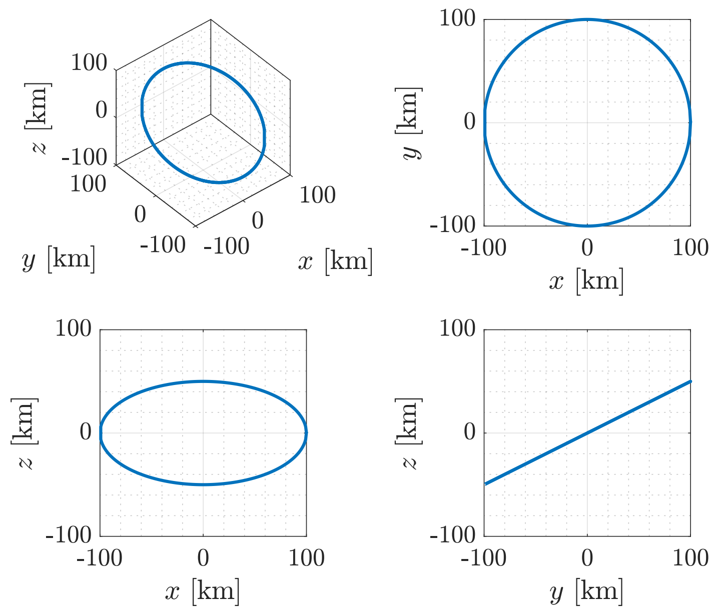

Fig. 6: Orbital trajectory of SOISat around the DarkSat spacecraft during the GWM simulation scenario, as viewed in the Hill reference frame.

ground station right below to transmit the payload data if such requirement exists. It is worth noting that the formation flying trajectory designed for the GWM scenario is natural, i.e., SOISat would not need to expend any propellant to maintain the formation, even though the gravitational perturbations are included in the orbital dynamics of both spacecraft.

7. CONCLUSIONS

In this paper, the mission design, concept of operations, and systems design for a Canadian Space Situational Awareness system called Space Object Identification Satellite called SOISat were discussed. The proposed SOISat spacecraft is intended for detection and characterization of resident space objects in low-Earth, medium-Earth, and geostationary orbits. In particular, SOISat can be utilized for maintenance of the space situational awareness catalogue for particular space assets, detection and identification of DarkSats in LEO, MEO, and GEO orbital regimes, detection and characterization of unexpected propulsive events, and inspection and identification of space objects of interests such as DarkSats and debris objects. Current approaches utilized for space object tracking and identification have significant limitations, especially in GEO. SOISat, however, can greatly improve the SSA capabilities owing to its novel payload. Future studies should investigate the systems engineering of SOI payload instruments as well as spacecraft bus. In addition, the formation-keeping maneuvers that SOISat would potentially need to perform during the mission should be formulated and the amount of required propellant should be determined.

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