SPACEMAP: Real-time Web Server for Safer, more Sustainable and Efficient Space

Shawn Seunghwan Choi
SPACMAP Inc, School of Mechanical Engineering, Hanyang University, Korea
Peter (Joonghyun) Ryu
SPACEMAP Inc., Voronoi Diagram Research Center, Korea
Chanyoung Song
School of Mechanical Engineering, Hanyang University, Korea
Minwoo Ji
School of Mechanical Engineering, Hanyang University, Korea
Jaedong Seong
Korea Aerospace Research Institute, Korea
Misoon Mah
M&K Research & Development, USA
Roberto Furfaro
University of Arizona, USA
Douglas Deok-Soo Kim
SPACEMAP Inc., Voronoi Diagram Research Center,
School of Mechanical Engineering, Hanyang University, Korea

Abstract

The Earth orbit is becoming even busier. This phenomenon rapidly increases collision probability between resident space objects (RSOs). As RSOs fly fast, the consequence of collision is catastrophic. However, the accurate and efficient prediction of conjunctions and their optimal avoidance have long been a challenge even with the space catalogue of moderate size. It will surely remain so with anticipated extreme object count in the New Space Age. Here we present a web server SPACEMAP which can solve conjunction assessment and optimal maneuver planning in (near) real-time. SPACEMAP overcomes the challenging computational requirement by presenting the best candidate of maneuver alternatives by quickly evaluating the side-effects of secondary and tertiary conjunctions. A tertiary conjunction, which is defined between an object-of-interest (OOI) and other fast-flying RSOs in the neighborhood, is of particular importance and is solved by taking advantage of computationally powerful, new geometric construct called the Voronoi diagram. SPACEMAP provides a variety of critical intelligence and optimization functions in timeline as well: Predict adversarial satellites that can monitor me while I will drive; Predict adversarial satellites that will be within, e.g., 10km of own asset; Predict adversarial satellites that can cause spectrum interference on own asset; Find the optimal data transmission route of own asset under predicted interference; Find the optimal data transmission schedule between pairs of cities through a constellation or through multiple constellations in multiple orbits; Find the optimal schedule to monitor a hot spot either on the ground or in space. SPACEMAP currently uses the TLE data from Space-track. Incorporating other data types such as telemetry data (e.g. GPS), measurement data (e.g. radar), ADS-B, AIS, etc. is rather straightforward. The SPACEMAP web server runs on Amazon Web Services (AWS).

1. Introduction

There are many RSOs in the Earth orbit and there will be many more including spaceplanes in near future, not to mention debris and RSOs [1-2]. The rapidly growing number of objects will necessarily meet serious challenges such as safety and efficient utilization of space assets. These are definitely two most critical challenges.

In this paper, we primarily present space decision-making problems related to the safety issue including the collision between space objects. Conjunction assessment (CA) is to predict the events of potential collisions in timeline and has been one of core efforts for this research and development. Once a conjunction is predicted, it is desirable or necessary to avoid the collision in an optimal manner. However, existing methods for such decision-making has been expensive, inconvenient, and/or computationally slow. In this paper, we introduce SPACEMAP (www.SPACEMAP42.com) and its accompanying service page (platform.SPACEMAP42.com), a web server which will contribute to a more democratized space for human by facilitating real-time or near real-time access to critical decision-making methods of all kinds for space assets. SPACEMAP aims to provide such services with extremely low barrier to all stakeholders in space industry. We also introduce some other SPACEMAP features such as launch conjunction assessment (LCA) and WatcherCatcher.

2. Safety Challenge of Space Decision-making Problems

Fig. 1 shows the landing page of the SPACEMAP web server. The Earth is visualized using Cesium JS with green payloads and red debris with the menu buttons for the five available services shown in top-left. The basic CA is freely available while the four advanced services can be accessed after a simple "Sign In" using individual users' Google account. SPACEMAP currently uses the TLE data For the details of system access, refer to the online manual.

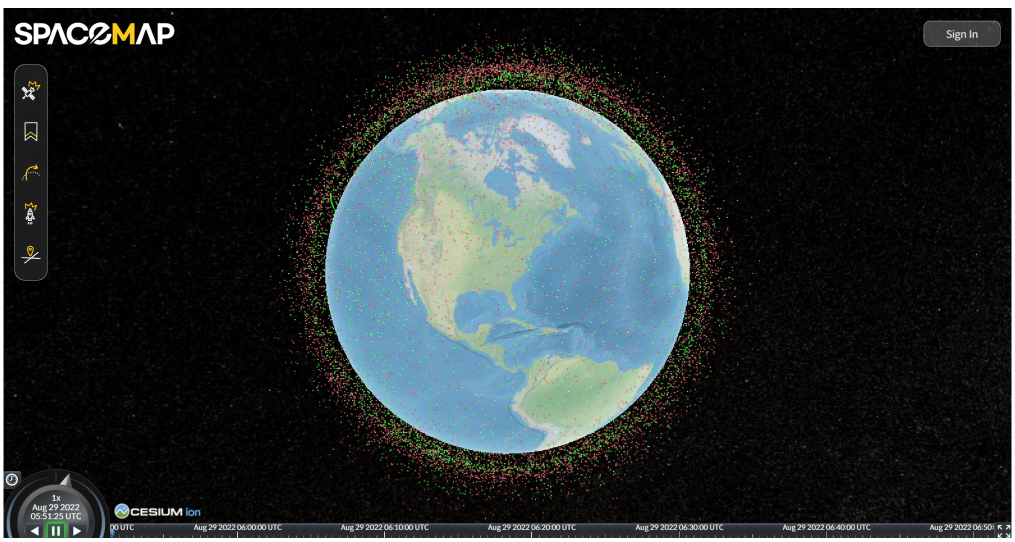

Fig. 1. The landing page of the SPACEMAP platform

2.1. Conjunction Assessment (CA)

Fig. 2 shows the real-time response after the CA function is executed by clicking the first button in the menu. The "Conjunction Table" in top-right shows the CA output which is displayed after it is sorted according to Time of Closest Approach (TCA, most recent first) or Distance of Closest Approach (DCA, closest first). Three different time formats are employed: UTC, local, and remaining time. Each tuple in the Table reports the conventional conjunction data: the primary and secondary objects of the conjunction together with the TCA/DCA data. Clicking the view-icon in the "View" immediately takes user to the 3D visualization of the corresponding conjunction event. The "Camera View" button contains different viewport options that can be used to track entities-of-interest in the visualization. Note that each entity is also associated with an ellipsoid which will be annotated by covariance.

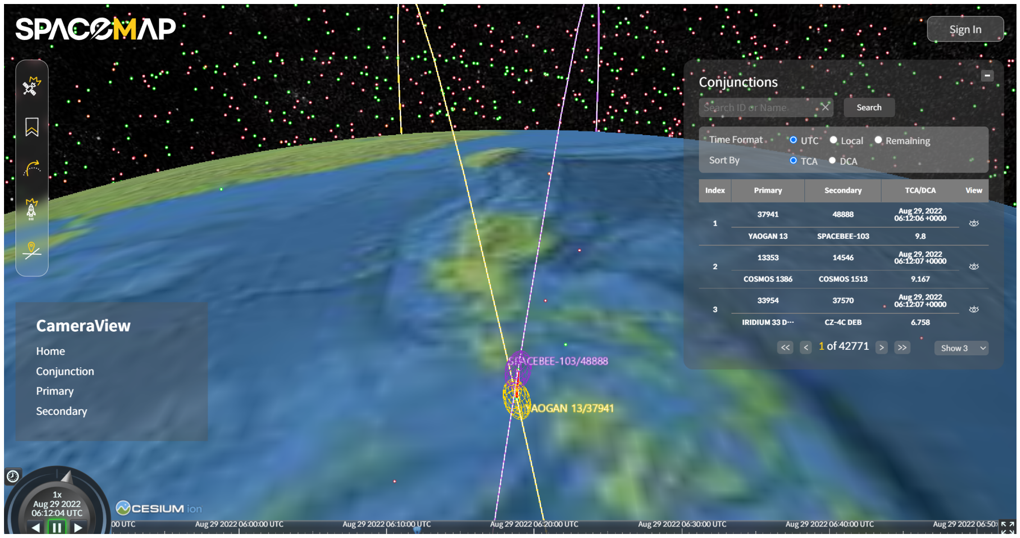

Fig. 2. CA output between two satellites. Curves and ellipsoids correspond to their orbits. The red line segment corresponds to the distance at DCA/TCA. This function is freely open to everyone.

2.2. Collision Avoidance (COLA)

Suppose that a conjunction is predicted in Fig. 2. Then, this critical event must be avoided if collision probability is sufficiently high and the avoidance maneuver needs to be optimal in terms of tertiary conjunctions, propellant usage, and mission continuity.

Given a predicted conjunction, the left of Fig. 3 shows five maneuver candidates of the primary object shown as the solid yellow curve (which we assume the only maneuvable one). These candidates can be either SPACEMAP-generated or user-supplied. The purple horizonal low-curvature curve denotes the secondary. The right of Fig. 3 shows the CA output of the five maneuver candidates: The five maneuver trajectories happen to create no new conjunction with the secondary in the given example. Some maneuvers, however, may create new conjunctions, called tertiary conjunctions, with other RSOs. In this example, SPACEMAP found seven tertiary conjunctions. SPACEMAP can evaluate dozens of or hundreds of maneuver candidates against all LEO RSOs (which currently counts >20,000 objects) in near real-time if moderate computation resource is employed.

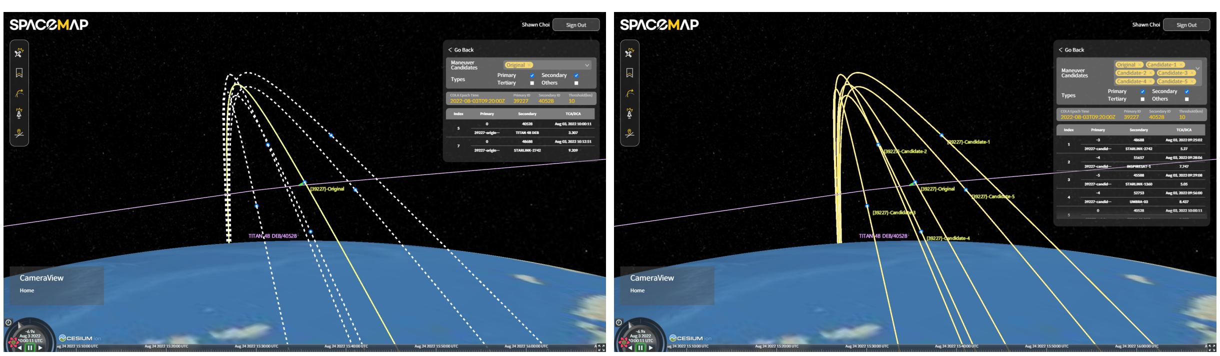

Fig. 3. Collision avoidance (COLA) with five maneuver candidates of the primary. The yellow and purple are the primary and secondary, resp. Conjunctions are reported in the Conjunction Table. (Left) The solid and dashed are the original and maneuver candidates, resp. (Right) After the five candidates are evaluated. No new conjunctions found with the original secondary object. However, several new tertiary conjunctions found.

Fig. 4 shows the tertiary conjunctions between the primaries-on-maneuver and the entire Space Catalogue. The left-figure shows one of the seven tertiaries, i.e. the red line segment, which is defined between the green curve (which corresponds to another RSO in the catalogue) and one of the maneuvers of the primary object. SPACEMAP allows to focus on a tertiary-of-interest by clicking a few buttons. The right-figure shows all the seven tertiaries, reported in the

Conjunction Table, which are produced by the five maneuver candidates. The Table can be sorted by TCA or DCA. Note that the computation requirement for no missing tertiary is in principle prohibitively huge and has been considered non-practical for ordinary users [3]: SPACEMAP can provide the optimal solution in near real-time with the guarantee of no missing tertiaries to any users.

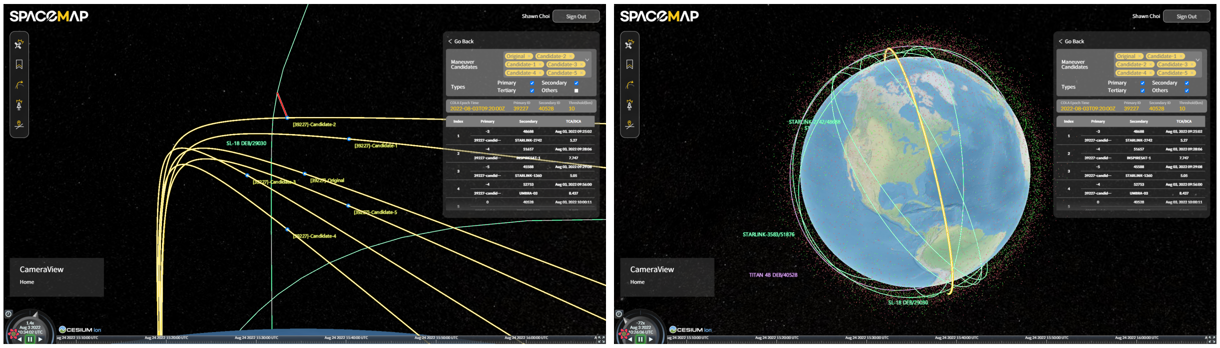

Fig. 4 Tertiary conjunctions detected. The green curves denote the new tertiary objects. A tertiary conjunction is a new conjunction occurred by a maneuver. (Left) One of the seven tertiary conjunctions in the red line segment. (Right) The seven tertiaries are identified by the five maneuver candidates during [-1H, +1H) maneuver time window (i.e., each maneuver has 2-hour flight duration, from before to after TCA).

3. SPACEMAP's Advanced Features

3.1. Launch Conjunction Assessment and Launch Optimization

Fig. 5 shows the CA and COLA capabilities can be easily and directly applied to solve the launch CA (LCA). Not to mention about the fast computation speed, we emphasize that SPACEMAP can model the uncertainty of launch vehicle's state vectors, i.e. the location and velocity uncertainties with a tiny additional computation. More importantly, SPACEMAP can produce the optimal (with respect to collisions) time-of-launch (ToL) for a given geometry of launch trajectory (GoL) with a moderate amount of computation time using a moderate computational resource. This implies that SPACEMAP can be used to find the optimal combination of ToL and GoL, simply by repeating the computation mentioned earlier. We aim to provide a platform which can solve these problems in near real-time.

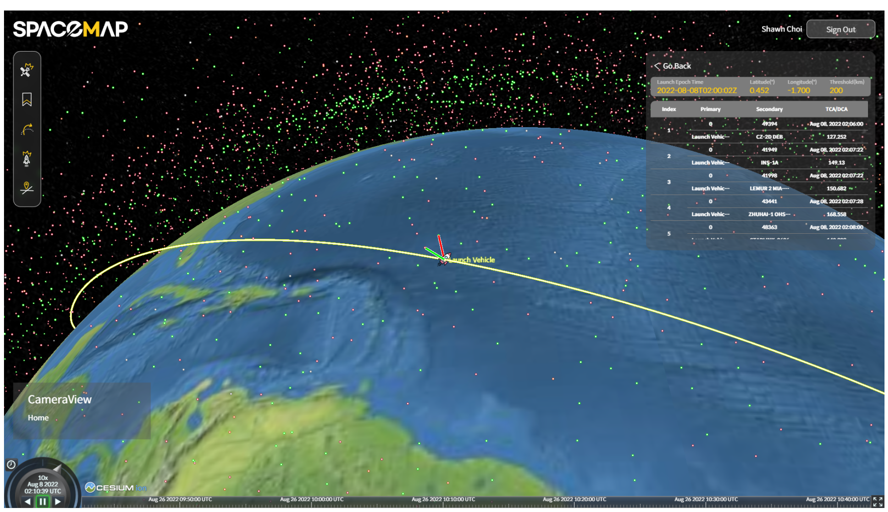

Fig. 5. Launch conjunction assessment (LCA) by SPACEMAP. The yellow curve is a launch trajectory from Boca Chica, TX. The red and green line segments denote the objects approaching to and going-away from the launcher. SPACEMAP can not only perform LCA in near real-time but also model the uncertainty of the launcher state vector, i.e., the location and velocity uncertainties.

3.2. SPACEMAP for Spaceplane Transportation

Fig. 6 is a schematic diagram which emphasizes the significance of the (near) real-time CA and COLA for the transportation system using spaceplanes between cities. The transportation cost to LEO has been reduced to orders of thousand dollars due to Falcon9 and Falcon Heavy and is expected to soon be as low as orders of hundreds of dollars when Spaceship becomes practical [4]. When this happens, expectedly within a couple of years, the spaceplane transportation will become a practical means which could be complement of and supplement to, or possibly replacement of airplane transportation. To materialize such an application, the safety challenge must be resolved in addition to transportation cost: the endogenous and exogenous aspects of the safety. The endogenous safety refers to the one inherent to hardware engineering of rockets and vehicles: This will be resolved soon. The exogenous one is another complex challenge which consists of measurement, orbit determination, etc. The real-time CA and COLA is the "MUST" that must be secured before such an effort can be attempted. This is because (i) Space catalogue is almost always incomplete, (ii) the catalogue can be marginally updated around a spaceplane while it flies, (iii) the updated catalogue must be reflected for the CA of the flying vehicle in its neighborhood in real-time, (iv) the flying vehicle must maneuver, if necessary, considering the updated catalogue in real-time, and (v) the modified maneuver must be re-inserted into the Space catalogue for the re-evaluation of CA.

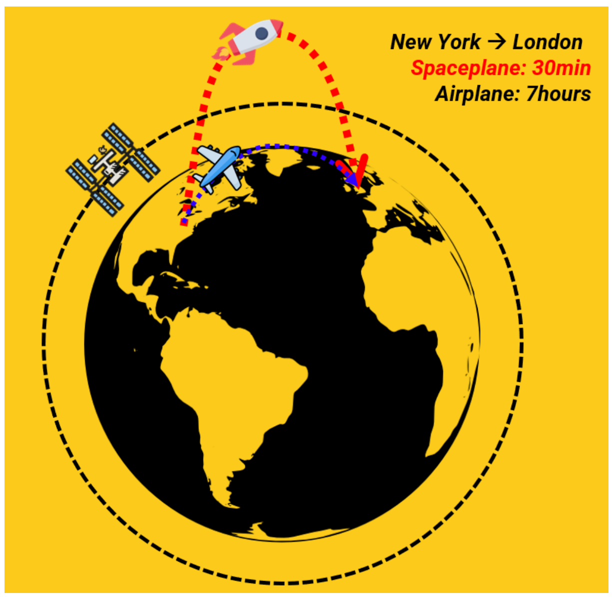

Fig. 6. Significance of the near real-time CA and COLA for future spaceflight between cities.

3.3. WatcherCatcher Service

Suppose that you want to observe some site on earth via satellite constellation in timeline. You may want to predict which satellites can take the picture of you in your preferred time. Suppose that you want to predict the satellites in a communication constellation, such as Starlink or OneWeb, which can uplink and downlink with your data terminal. SPACEMAP can provide real-time results to these problems via the WatcherCatcher service which requires the following parameters: latitude, longitude, altitude of your target site, field-of-view (FOV), prediction time window.

Fig. 7 illustrates snapshots of the WatcherCatcher result. A predicted result can be visualized using animation function if the problem contains a prediction time window of positive length. Fig. 7 shows a snapshot of the animation result. The yellow cone represents the FOV of 100 degrees. SPACEMAP predicts the satellites which will fly over an anchor site, Seoul (Left) and Ann Arbor (Right), and visualizes within this yellow cone. The green and red line segments correspond to going-away and approaching satellites, respectively. The table in the figure shows the list of satellites which will be within the cone during prediction time window. WatcherCatcher can also be used to determine the best satellite for uplinking and downlinking of transmitted data.

There are many more critical applications of WatcherCatcher. E.g., the rapid increase in satellite mission planning and mega-constellation inevitably lead to satellite scheduling system to optimally allocate user requests and to efficiently carry out communications between satellites and ground station. Variations of satellite scheduling formulations have been studied where the key issue is whether they can be efficiently solved to achieve best ground stations usage and to allow the largest number of mission planning requests [5]. However, it turns out that satellite scheduling problem with visibility window (time window) is NP-hard [5]. It is very challenging to find a feasible solution due to the complex constraints of the problem [6].

Whatever the target location or target moving object is given as an input, WatcherCatcher can help to find the best solution. Suppose that you want to predict adversarial satellites that might be able to monitor you while you are driving, assuming that the set of adversarial satellites is known a priori. The WatcherCatcher can quickly report you the candidate driving schedules which are safe from being monitored.

With the benefit of low latency for mega-constellation in LEO and development of inter-satellite link (ISL) technology, satellite internet is expected to have an important part of next generation global communication systems [7]. However, due to the high speed of satellites in LEO, communication network topology changes very fast and becomes more complicated than that of MEO and GEO. In this respect, routing optimization in satellite network with ISLs will be critical to developing satellite internet communications. SPACEMAP can help this optimization because SPACEMAP can identify neighbor satellites of each moving one very efficiently. Then the best one may be chosen among those neighbors so that the shortest route can be obtained.

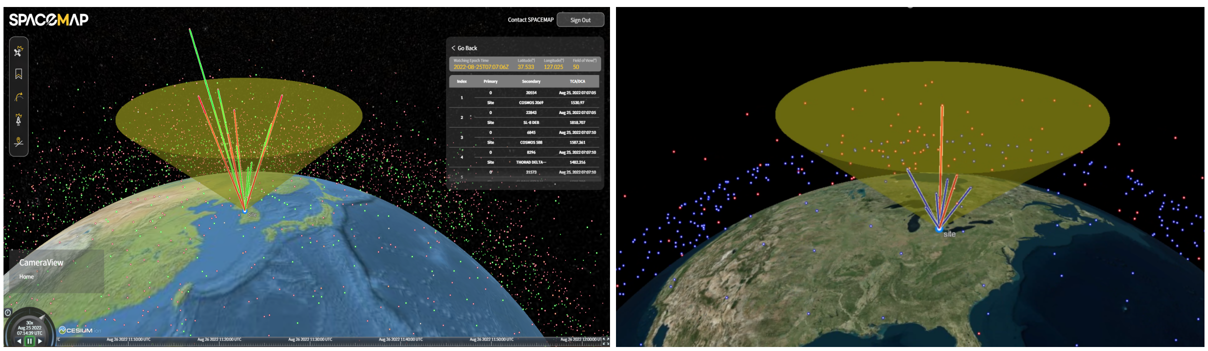

Fig. 7. WatcherCatcher, FOV: 100°. (Left) Green: Satellites, Red: Debris, Seoul, Korea,
(Right) Blue: Starlink, Red: OneWeb, Site: Ann Arbor, MI

3.4. How does SPACEMAP works?

SPACEMAP currently uses the TLE data downloaded from Space-Track website and preprocesses the data for a variety of, potentially all, queries from diverse stakeholders in space tech industry. The preprocessing is based on the Voronoi diagram of moving space objects according to our prior works [8-13]. The following business segments, if not all, can benefit from SPACEMAP: Constellation owners and operators, launchers, internet providers, debris-removing companies, in-orbit service providers, space tour companies, insurance companies, research institutes, academics, national defence organizations, etc. The platform runs on AWS [14, 15].

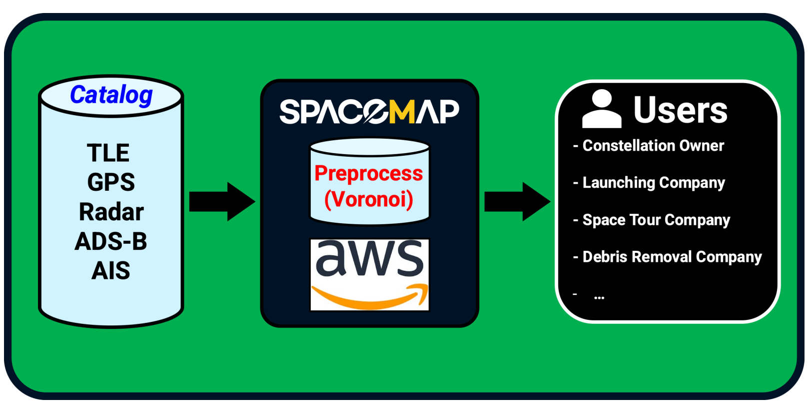

Fig. 8 SPACEMAP flow

4. Conclusions

Space is not sufficiently spacious enough to guarantee the safety of fast-moving space objects. In addition, the efficient use of space is critical for diverse applications in the coming New Space Age. Both safety and efficiency issues have been studied but remain as challenges.

Here we presented the safety issues of space decision-making problems, in particular conjunction assessment and collision avoidance in real-time under the umbrella of SPACEMAP (www.SPACEMAP42.com) and its accompanying service page (platform.SPACEMAP42.com). We also presented other advanced features such as launch conjunction assessment and WatcherCatcher. We believe that SPACEMAP will contribute to the safer, more sustainable and efficient space.

Acknowledgements

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