**The Whitepaper**

**SpaceMap**

SPACEMAP INC. ([www.spacemap42.com](http://www.spacemap42.com))

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1. INTRODUCTION

We are watching the beginning of New Space Age. A careful look at Morgan Stanley’s projection of the U$1T market in 2040 reveals a market segment named “Second Order Impacts,” which has a size larger than 1/3 of the entire market, is not born yet [R1]. SPACEMAP Inc. aims to be one of the leaders of the segment “the internet from space.”

The material presented here is available at the official web site: [www.spacemap42.com](http://www.spacemap42.com). The five YouTube movies are informative. 42 is the number from Deep Thought as the answer to “The Ultimate Question of Life, The Universe, and Everything” in “The Hitchhiker’s Guide to the Galaxy” by Douglas Adams. We want to be “The Satellite’s Guide to the Galaxy.”

* 1. Mission & Vision

We aim to provide best-possible solutions in real-time or near real-time in order to support customers’ decision-making in hard space problems. We will contribute to keeping the space safer, more sustainable and useful. We believe what we are doing is invaluable for humankind in New Space Age and thereafter, particularly with the surge of space objects.

2. OVERVIEW

SpaceMap is the first realization of the mission of SPACEMAP INC. Please refer to the SpaceMap homepage ([www.spacemap42.com](http://www.spacemap42.com)) and server page (platform.spacemap42.com).

2.1. Input & Preprocessing

SpaceMap produces solutions of a variety of decision-making problems in space based on a space catalogue as an input. The catalogue is currently Space-Track’s Space Catalogue which contains the spatiotemporal information of resident space objects (RSOs) [R2]: We plan to incorporate more diverse sources of input data in the near future. We preprocess the catalogue to transform the spatiotemporal information of individual RSOs to another form of perfectly fused spatiotemporal information of the entire catalogue [R3,R4]. We store the preprocessing result in a compact and concise data format in order to use it in the solution process of diverse queries. The preprocessing result is the Voronoi diagram of RSOs, particularly its dynamic version for moving RSOs [R5,R6,R7]. So, we do some preparation work before we solve queries: This is similar to search engines doing preprocessing in order to quickly react to users’ queries.

2.2. Beyond Traditional Approach

SpaceMap solves spatiotemporal problems as spatiotemporal ones: We do not solve a spatiotemporal problem as spatial problems of multiple snapshots of consecutive time steps. The conventional approach is based on the classical three-filters method which in principle decomposes timelines to get the snapshots corresponding to consecutive, distinct moments and attempt to relate them. While this approach is intuitive and easy to comprehend, it has several issues to be carefully examined. Firstly, and most importantly, it is designed to solve spatial problems between two objects: Be aware that many forthcoming problems in New Space Age involve more than two objects in spatiotemporal space. Even for two-object problems, it is time-consuming because a file-inversion, in one way or another, is necessary to associate distinct moments. In addition, it is coordinate-dependent and requires many parameters to be tuned carefully. We believe the conventional approach will expose its clear limitation soon, particularly with the rapidly increasing RSO count. Most popular commercial products are based on the three-filters approach. SpaceMap’s method solves all these challenges at once.

3. SPACEMAP FEATURES

3.1. Two-object Problems

3.1.1. Conjunctions

SpaceMap answers the queries related to conjunctions in real-time. Be aware that conjunction is a problem between two objects and thus we refer to it as a two-object problem. See YouTube-1 below. There are different types of conjunction queries. The conjunctions about the entire catalogue for a given threshold distance, abbreviated as an all-on-all (AOA) query, during the prediction window (PW) of seven days is reported in real-time. A query related with an object-of-interest (OOI) query, which is about the conjunctions of a particular asset, can be obviously reported faster. Any combination between these two types of queries can be answered in real-time. We verified that the solution quality of the SpaceMap’s conjunction output is comparable to that of the public CDM and no worse than popular commercial programs. Conjunction prediction can be freely accessed at the SpaceMap server while our current policy remains effective. If it is not desirable to use the SpaceMap server for any reason at all, we can develop an intranet version for user’s need.

See YouTube-1 [<https://youtu.be/7Wn9HwDwmpU>].

Conjunction between a Starlink satellite and a debris

3.1.2. Advanced Features of Two-object Problems: Statistics of constellations

SpaceMap takes advantage of its computational speed to present various advanced features of two-object problems. Given a preprocessing result, statistical analyses of all or some RSO-pairs in the current catalogue about diverse spatiotemporal conditions in timeline can be defined and efficiently performed. Another critical feature, particularly valuable in this constellation-increasing New Space Age, is to analyze the consequence of a new constellation from the conjunction or collision point of view. Given the proposal of a new constellation, we can produce reports on various types of spatial reasoning including conjunctions very efficiently: For instance, the self-conjunction between own satellites belonging to the new constellation, the conjunction between the new constellation and all existing RSOs, the one between the new constellation and another constellation in the current catalogue, etc. Here a conjunction may have hundreds or thousands of satellites with their orbital definition. This feature can be used by owners/operators (OO) of constellations for fine-tuning their orbit parameters for both design and operation. This feature can also be useful for mandating organizations such as FCC and ITU, insurance companies, etc. for the evaluation of proposed constellations.

3.2. Optimizations (Many-object Problems)

3.2.1. Data Transmission Optimization

Beyond two-object problems, there are important many-object problems, particularly for the internet data business such as Starlink, OneWeb, and Kuiper. The optimized utilization of constellation satellites is critical to the success of business. For example, if a 5% of utilization can be improved by optimization from a non-optimized constellation consisting of 2,000 satellites in LEO, U$100M can be saved (We assume that the manufacturing and deploy cost U$1M/each: A satellite weighs 250kg, its manufacturing cost is U$25K, and its deploy costs U$3K/kg). If the satellites are designed to function 5 years, U$20M is saved annually. This example may apply to Starlink. The YouTube-2 below shows a simple example of such optimization problems: Find the shortest paths between three pairs of cities at every moment within a time window of future. Here, the shortest path has the minimum number of satellites for data hops: This path corresponds to the fastest data transmission path between the cities. The three cities are Seoul, San Francisco, and Sydney and the three inter-city paths represent a parallel, diagonal, and vertical w.r.t. the equator, respectively.

See YouTube-2 [<https://youtu.be/kiMpmL0NRns>].

Paths : Seoul 🡪 San Francisco 🡪 Sydney 🡪 Seoul;

Distance threshold : 1,000km; Data set : Starlink

However, an optimization about communication satellites, particularly in LEO, is a challenge because their spatiotemporal dynamics is extremely high: We are not aware of any good methods. Here SpaceMap answers queries related with many-objects very efficiently, frequently near real-time depending on problem-definition. Several optimization queries and search queries belong to this category.

3.2.2. Maneuver Optimization (Collision Avoidance)

Suppose that a primary conjunction is predicted, and the owner/operator wants to perform an avoidance maneuver. It is desirable to find a collision-avoiding maneuver which is safe enough without causing any dangerous secondary and tertiary conjunctions yet saves a capacity-limited propellant as much as possible. We want to find the optimal maneuver plan under the dual consideration of safety and budget. The problem is known as NP-hard if we want to consider all neighbor objects in timeline. So, in such a case, it seems that the generate-and-test approach might be reasonable by discretizing the timelines for the moment of maneuver start and the duration of propulsion. SpaceMap can take a set of maneuver alternatives from owner/operator and quickly evaluate them. SpaceMap evaluates sufficiently large alternatives by taking advantage of its accurate yet fast speed of each evaluation. The scores of alternatives are stored in a matrix form, called Maneuver Reward Matrix, from which satellite operator can make an optimal choice for a given measure.

3.3. Launches

3.3.1. Launch Conjunction Assessment (LCA)

Launch count will increase very fast in forthcoming years and collisions between launch vehicles and RSOs are more likely unless launches are carefully planned and closely monitored. Launch conjunction assessment (LCA) is a conjunction assessment of a launch vehicle which will follow a planned fixed trajectory after the launch. See YouTube-3 below. RSOs within a threshold distance are visualized: Observe that the Starlink train is correctly captured. We consider LCA has not been sufficiently addressed in launch procedures yet. This might be because there were not too many launches and because people had a misconception of big-enough space. Space is ‘no longer’ big enough!

See YouTube-3 [<https://youtu.be/cCg_Nb2yHf8>].

We find two technical challenges for the not-sufficiently-addressed LCA. First, there exists no good computational method to replace the traditional, classic three-filters method which assumes orbital motions. Second, there exists no mathematical model to represent the spatiotemporal error of launch vehicle’s location and velocity to cope with RSOs’ high speed. SpaceMap completely solves the first challenge. SpaceMap will help resolve the second challenge: The error model might be developed soon using the SpaceMap concepts and techniques. Launchers might already use in-house error models.

In LCA, the time-of-launch (ToL) and location-of-launch (LoL) are both fixed. SpaceMap solves LCA-problems in real-time just as it solves ordinary CA-problems. Hence, this function of SpaceMap easily applies to early-orbital motions, de-orbit motions, inter-orbital motions, end-of-life motions, etc. The classical three-filters approach, on the other hand, is not attractive for LCA-problems because it is designed for orbital motions.

3.3.2. Real-time LCA-in-the-Loop (LitL)

The actual flight trajectory of a launch vehicle is always associated with a spatiotemporal error: It might be sometimes significant, or sometimes ignorable. The projection of a flying vehicle’s trajectory in near timeline can be easily calculated using the telemetry data of the vehicle, i.e. GPS data. If the SpaceMap’s realtime LCA is used together with the trajectory projection during propulsion, the LCA result can be automatic feedback to flight control system in order to find the safest trajectory, i.e. lowest probability of collision. This feature is invaluable for manned spacecrafts: Is it possible to imagine the SpaceX’s StarShip with hundreds of passengers cruising space without this capability? SpaceMap already has the solution.

3.3.3. Launch Optimization & Blackouts

Launchers want to be as safe as possible during launches. One of the most critical considerations is the possibility of collision of launch vehicle with RSOs. However, it is often overlooked in launch preparation. Launch optimization is to find the best time-of-launch (ToL) in terms of conjunction between a launch vehicle and RSOs with two pieces of input: a trajectory-of-launch (TRoL) and a launch-time-window (LTW). We assume a location-of-launch (LoL) is fixed.

SpaceMap’s launch optimizer (LO) module can efficiently report the optimal time-of-launch (ToL) based on user-defined measure. If a launcher has a set of *N* trajectory alternatives, SpaceMap can find the optimal plan, i.e. the safest combination of trajectory and correspond ToL, very fast: In the time sublinear to *N*. This is possible due to the SpaceMap’s parallelization technology.

SpaceMap has a set of handles with which launcher can define own measurement by choosing appropriate one(s). The most straightforward, and perhaps naïve, measure would be to measure the distance to the closest approaching (CAD) RSO during the entire flight. The d1 in Fig. 1(a) shows the low-bound of such a CAD curve. We also call it as CAD-1 function. E.g. d1(100) = 18 which means that the closest-approaching RSO may approach to the vehicle as close as 18km after the vehicle is launched at 100sec after the beginning of LTW. Likewise, d2(T) and d3(T) denote the low-bounds of the distance to the second and to the third closest RSOs to the vehicle launched at T sec in LTW, respectively.

The horizontal black line segments on Y=0 denote the blackout BO(d1, 20) = { *t* | d1(*t*) < 20 }: i.e. It is not recommended to fire a launch during this interval, called blackouts, if the launcher wishes to maintain at least a 20km safety distance during flight. This idea works only on a critical assumption: A launch vehicle exactly follows a planned spatiotemporal trajectory from both time and location perspectives. This is too strong to be true but many commercial programs are based on this assumption. Note that BO(d1, 20) is immediately obtained once d1(t) is available: SpaceMap computes d1(t) fast. Many existing commercial programs only compute BO(d1, q) for some q.

SpaceMap, on the other hand, produces d2(x), d3(x), …, dk(x), where k is sufficiently big, with a tiny, ignorable amount of marginal computation in addition to that for d1(x). Its implication is profound. Once these multiple dk(x) functions are available, their weighted functions can be easily defined. Hence, if the spatiotemporal error (i.e. the location and velocity) of launch vehicle is appropriately modeled, the weighted functions of dk(x)’s may be used for the decision-making of safe launch schedule. Note BO(d1, q), BO(d2, q), …, BO(dk, q) can also be immediately obtained.



Fig. 1. The close distance approach (CAD) functions. d1(*t*) is the function of the distance to the closest RSO during the flight of a vehicle launched at *t*. d2(*t*), and d3(*t*) correspond to the second and third closest RSOs. The black line segments at Y=0 denote the blackouts corresponding to q = 20km.

3.4. Other Functions: Searches

Many other functions can be easily implemented in SpaceMap.

3.4.1. Trespasser Identification

If you want to know the satellites approaching to your space assets during its mission, you can rely on SpaceMap’s Trespasser Identification (TI) module. It finds and report all objects which approach your assets within the distance threshold you specified. A statistical analysis of the report may reveal critical information. The computation can be done near-realtime. See YouTube-4 below.

See YouTube-4 [<https://youtu.be/HX5jBrLPz0g>].

Trespasser identification. Find those who trespasses a Starlink satellite’s backyard.

3.4.2. Watcher Catcher

Watcher Catcher (WC) module identifies the RSOs which is within the field-of-view (FoV) at a given location. If the FoV is replaced by the photograph-angle of individual satellite, the satellites which can spy the location can be found. This function can be used for spectrum interference avoidance planning. The computation can be done near-realtime. See YouTube-5 below.

See YouTube-5 [<https://youtu.be/QLHo7KUKOuU>].

Watcher Catcher of Ottawa, Canada. Constellations: Starlink and OneWeb

3.5. Product Types

We have four product types. The first and primary method of service is the web service through SpaceMap ([www.spacemap42.com](http://www.spacemap42.com)). If it is not desirable for any reason, we can provide an intranet for users’ organization. This might apply to organizations related to national security or those maintaining relatively large constellations. Some of our services can be delivered as standalone applications, possibly as apps running on smartphones. The fourth is our library that can be licensed by application developers: We anticipate this is very useful for solving many critical space problems that we do not know yet. Our spatiotemporal databases and spatiotemporal analyses about current catalog together with a new hypothetical constellation would be useful services to the space community.

4. OUTLOOK

SpaceMap aims to solve decision-making problems of space objects in real-time or near real-time. Space objects move very fast, object count increases very rapidly, queries about more than two objects are becoming more frequent, and many problems are inherently NP-hard. Hence, our vision of real-time or near real-time is very challenging.

SpaceMap has just launched. We expect SpaceMap to be the global infrastructure for all stakeholders of New Space Age which will bring, in our wild guess and hope, a market of a size much larger than Morgan Stanley’s $1T in 2040. We welcome any questions, comments, collaborations, and challenges.

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