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# COLLISION AVOIDANCE MANEUVER CALCULATION AND VISUALIZATION TOOL FOR LEO SATELLITES

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## ABSTRACT

*In this study, a computer software so called “ColAvo” is introduced along with the developed algorithms. The “ColAvo” can parse the Conjunction Data Messages, illustrates the possible conjunction between two earth orbiting objects and computes the collision avoidance maneuver. The main objective of this study is to help the satellite operators to reduce the decision time of the collision avoidance maneuver, since the conjunction assessment operations require quick actions. The software initially let the user to understand the possible collision by visualizing the provided Conjunction Data Message via Visualization Tool For Space. Afterwards, the developed targeting algorithm is used to calculate the collision avoidance maneuver according to the user inputs. The software development is done by using OREKIT 10.0 library in JAVA. Furthermore, the algorithm tests are done with the GMAT and the FreeFlyer software.*

## INTRODUCTION

The increasing demand of space missions yielding to new assets for countries, yet controversially contributing to the space debris environment. Every human-made object on space regardless of their current situation, especially on Low Earth Orbits (LEO), threaten each other in the sense of collision. In 2009, massive orbital debris is formed because of Cosmos-2251 and Iridum-33 collision. From 2009, at least 10 satellites collision observed, and yet the trend may be differing in a bad way for next decade since the debris density is increasing every year [NASA Office of Inspector, 2021]. However, Cosmos-2251 and Iridium-33 collision is a special case due to the fact that Cosmos-2251 is actually a rocket stage, while Iridium-33 is an active satellite. Consequently, roaming objects at LEO encourages the satellite operators to taking precautions such as avoiding the collision by making orbital maneuvers. In addition, satellite operators require prior information about the possible collisions in order to take precautionary actions. Authorities such as Combined Space Operation Center (CSpOC) provide these kinds of prior information. The possible collisions calculated by CSpOC is shared with the satellite operators under the format of Conjunction Data Massage (CDM) [CCSDS 508.0-B-1, 2013].

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CDM consists of the prior information of the potential collision, for instance, the orbital parameters of the objects, probability of collision, time of the closest approach and the miss distance. The satellite operators are performing a collision avoidance maneuver by using these messages. In nominal conditions, CDMs are sent 3 days before the possible conjunction epoch, and yet in some cases, these messages may be sent 10-12 hours before the collision epoch. As a result of that, the messages that are sent just before the collision epoch put the satellite operators under pressure. The rate of the send may be differing, but in average, it is 6 hours for per CDM. Moreover, all the new CDMs that have major change in the parameters resulting to new maneuver planning operation for the satellite operators. In this case, the maneuver planning operations are highly time dependent, and every tool that can ease the burden of computation time may help the operators. Hence, the main objective of this study is aimed to introduce the tool named “ColAvo” that can parse the CDMs, performs an orbital maneuver, and illustrates the orbits of the objects before and after the assessment.

In literature, there is one specific tool named ZIRCON that is developed by Geo-Informatics and Space Technology Development Agency (GISTDA) for Thailand Earth Observation Satellite (THEOS), which is used for collision risk assessment and orbit visualization [Channumsin at all, 2019]. ZIRCON calculates the new probability of collision after the collision avoidance maneuver and analyzes the possible collisions. The ColAvo is similar to the ZIRCON in purpose, since both applications are related to collision avoidance.

ColAvo can parse CDMs and let the user to decide what kind of maneuver need to be performed. This decision can be done by using the orbit visualization option of the tool. Afterwards, the user needs to decide the type of maneuver in order to start the targeting algorithm, which calculates the collision avoidance maneuver by using the user specified miss distance. The solution of this problem is based on Two Point Boundary Value Problem [Chapra and Canale, 2015, s. 151-157; 782-789]. In order to observe the impact of the maneuver on miss distance, 10 minutes of forward and backward propagation is done with respect to the time of closest approach, which clearly shows the new relative geometry. Satellite dynamic model and the propagation are simulated with OREKIT library [Maisonobe at all, 2010]. Consequently, the data format such as Orbit Ephemeris Message (OEM) is generated by ColAvo [CCSDS 502.0-B-2, 2009]. Then, it sent to the Visualization Tool for Space (VTS) by using TCP-IP protocols [Centre National D’etudes Spatiales, 2015]. Thus, the visualization is done.

## METHOD

This study intends to illustrate possible collisions of two Earth orbiting satellites, and let the user to decide the maneuver type as effortless as possible. The execution of the decided maneuver type is done via targeting algorithm and the resulting maneuver is displayed with the help of VTS.

The developed tool requires the CDM file as an input from the user. Furthermore, the given CDM file must be coherent with Consultative Committee for Space Data System (CCSDS) standards [CCSDS 508.0-B-1, 2013]. It must contain the necessary information at the time of closest approach such as miss distance, probability of collision and the orbital parameters of these two objects.

The algorithm starts with parsing the CDM. Moreover, the given CDM file is checked by the “ColAvo” to ensuring that the format of the CDM is whether compatible or not with respect to the CCSDS Standards. In addition, the CDM file contains the Time of Closest Approach (TCA), miss distance, relative speeds, Probability of Collision (PoC), position and velocity vectors for two objects, which are defined in International Terrestrial Reference Frame (ITRF) and the covariance matrices are included in this file.

As a second step, the state vectors are obtained with respect to the ITRF after the CDM parser. The orbits of the objects that are subjected to the collision are generated from the state vectors and the orbital states are propagated about 10 minutes back and forth from the TCA. Thereafter, obtained state vectors are written in an OEM file with a UTC time stamp, then this file is sent to VTS. Afterwards, the VTS can parse the OEM file and executes the visualization process with respect to this file [Centre National D’etudes Spatiales, 2020].

Spacecraft operator shall perform the collision avoidance maneuver if it is necessary according to the probability of collision. In order to perform the collision avoidance maneuver, one must decide the type of the maneuver and the desired miss distance that is constrained to the new TCA.

As a third step, the "ColAvo" calculates the selected collision avoidance maneuver. There are two different maneuver types for the collision avoidance. These are in-plane-rising and in-plane-braking maneuvers. Since the "ColAvo" calculates the maneuver by using targeting algorithm, it is required to define a threshold value for the optimization variable so called the miss distance. Even though the maneuver start time affects the optimum maneuver results, it is left to the operator's decision. In addition to the maneuver start time, the user enters the thrust force, specific impulse, and satellite mass as input than targeting algorithm computes the required thrust duration. The thrust duration describes how long the thruster system will be on duty in terms of second. Moreover, the maneuver time is a number that defines the execution time of the maneuver in terms of satellite on orbit position before the TCA.

As a last step, the user can see the consequences of the calculated maneuver within a period of 10 minutes before and after the TCA. From this point, unless the first step, the calculated maneuvered orbit is propagated until the new TCA. The user can examine either the original orbits or the maneuvered orbit as their wishes.

The following subsections are related to the definitions of the key parts of the algorithm. Firstly, the satellite dynamic model parameters are introduced as well as the propagation technic. Secondly, the basic types of collision avoidance maneuver and their effect on the orbit is introduced. Subsequently, the targeting algorithm is clarified with a test case. At last, the user interface is introduced.

## Definition of Conjunction Data Message

Time of Closest Approach:

The time of closest approach (TCA) is one of the key elements inside the CDM. It points the possible collision epoch. The satellite states are given with respect to this epoch. One of the most time consuming events during the conjunction assessment is to determine the TCA. It requires vast amount of orbital states to propagate, and filter the possible collision epoch out. In addition, the TCA epoch is in UTC scale with a precision of milliseconds which brings the precise time calculations. The string format for the TCA instance is given as "YYYY-MM-DDTHH:mm:SS.sss".

Miss Distance:

One of the most important fields included in the CDM is called "Miss Distance". It defines the distance between satellites at the TCA. This field can be used to constrain the collision avoidance maneuver. In this study, the miss distance value is set as the optimization parameter for the targeting algorithm. The targeting algorithm is trying to find the desired miss distance (Maximum Miss Distance) by perturbing the thrust duration at given maneuver epoch within 10 minutes of collision window.

In Figure-1, two orbits are illustrated. Satellite 2 is defined as orbital debris while Satellite 1 is an active one. The miss distance can be calculated as the norm of the relative vector of these two satellites. It

is defined as $\boldsymbol{\Delta d}$ and given as follows;

$$\overrightarrow{\boldsymbol{r_1}} - \overrightarrow{\boldsymbol{r_2}} = \overrightarrow{\boldsymbol{r_{21}}} = \boldsymbol{\Delta d} \tag{1}$$

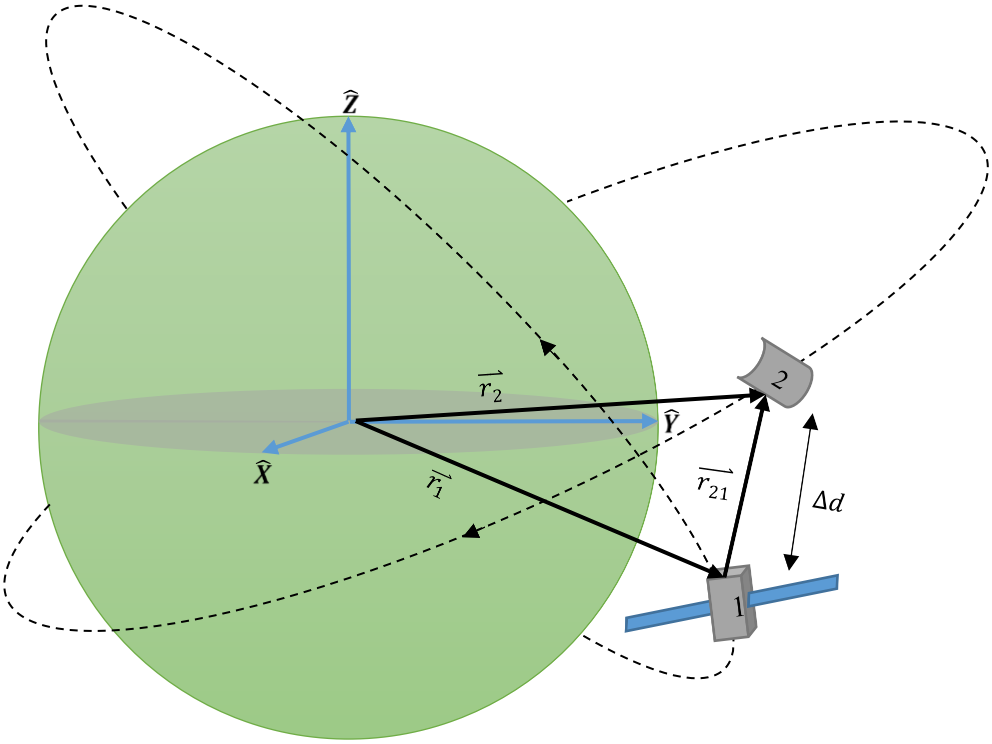


Figure 1: Definition of the miss distance

Probability of Collision (PoC):

One of the well-known mathematical outcomes of the orbit determination process is the positional uncertainty, which is called the Covariance Matrix. Covariance matrices are consisted of the uncertainties related to the position and the velocity namely the satellite state. The uncertainties in the orbit determination process affects the prediction of the future collisions. Hence, the uncertainties convert the deterministic problem into a stochastic one, which results to "Probability of Collision" (PoC). The PoC field inside the CDM is calculated by unique methods such as "FOSTER-1992", "CHAN-2003", "MCKINLEY-2006" and etc. It is important to relate the covariance to the PoC, yet the covariance matrices are not used in this study since the PoC value after the avoidance maneuver is not considered.

In Figure-2, the covariance matrices are illustrated as covariance ellipsoids. Satellite-1 is defined as the active while Satellite-2 is the debris one. Usually, the covariance matrix of the debris is elongated through velocity direction, since it is the most uncertain axis. That is why the covariance ellipsoid of the debris is larger than the active satellite. The PoC values can be used as a threshold value for the satellite operators. It can be used to decide whether a maneuver is needed or not. In space systems, the probabilities that are in the order of 1e-4 is considered as risky. Therefore, most of the satellite operators around the world plan a collision avoidance maneuver when the PoC is greater than 1e-4.

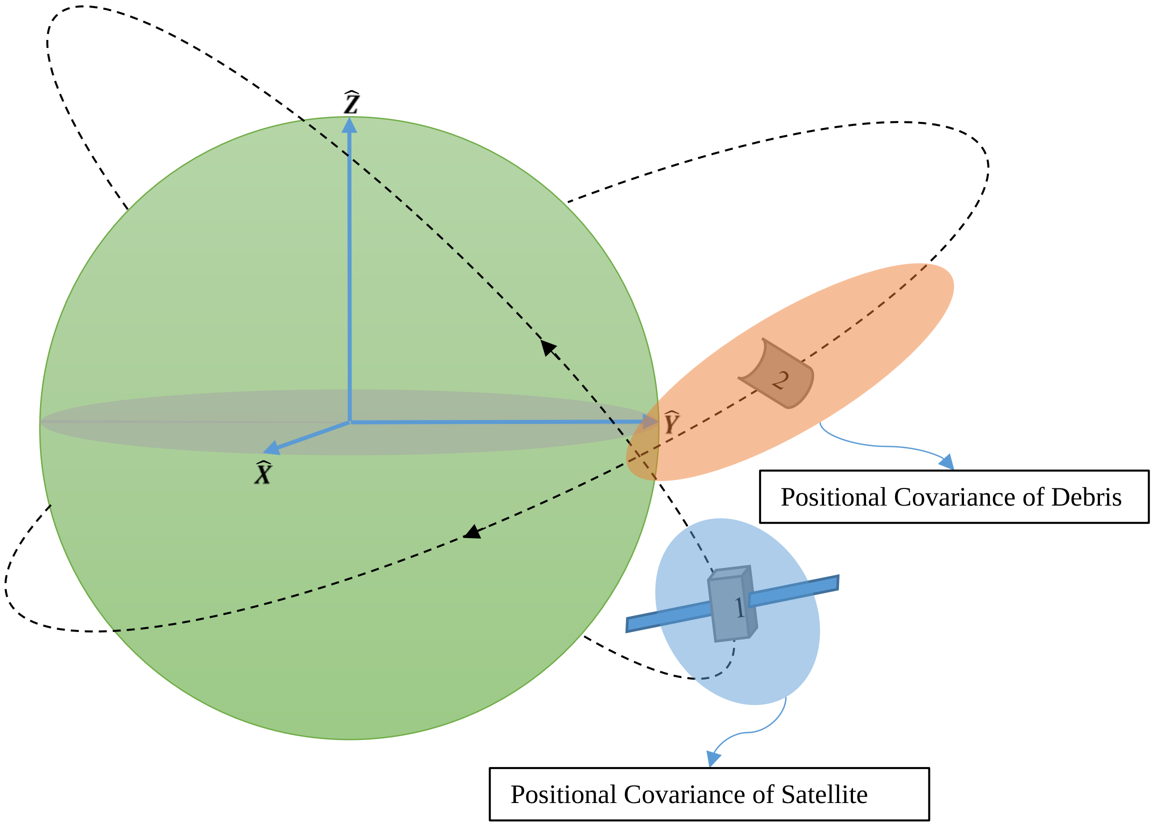


Figure 2: Probability of Collision Geometry

Satellite State:

The CDM file contains the orbital parameters of the two objects. These parameters are given in the Cartesian coordinate system in the form of position and velocity. In addition, the states are defined at the TCA epoch in International Terrestrial Reference Frame (ITRF).

These position and velocity vectors are used as initial state for the orbit propagation. Therefore it is mandatory to convert the states into non-accelerating reference frame such as Earth Centered Inertial Frame (EME2000). Also, the satellite force model that is used during orbit determination is provided within the CDM.

In Figure-3, part of a CDM is given as an example. As seen from the Figure-3, there is too much parameters inside the CDM, and yet some of the parameters have the same element name. Hence, specific information for both objects has separated with the “OBJECT” element. For instance, primary object data is placed after “OBJECT = OBJECT1” and secondary object data is placed after “OBJECT = OBJECT2” lines.

Position data are represented with X, Y, and Z elements and velocity data are represented with X_DOT, Y_DOT, and Z_DOT.

```
CCSDS_CDM_VERS          =1.0
CREATION_DATE           =2021-05-09T18:10:17
ORIGINATOR              =CSPOC
MESSAGE_FOR             =TUSAS-SAT
TCA                     =2021-05-12T04:20:34.629
MISS_DISTANCE           =342            [m]
RELATIVE_SPEED          =5067           [m/s]
RELATIVE_POSITION_R     =148.9          [m]
RELATIVE_POSITION_T     =291.3          [m]
```

```
RELATIVE_POSITION_N          =101.3                [m]
RELATIVE_VELOCITY_R             =80.5                  [m/s]
RELATIVE_VELOCITY_T            =-1722.9                [m/s]
RELATIVE_VELOCITY_N             =4765.2                [m/s]
COLLISION_PROBABILITY           =0.00000007066145
COLLISION_PROBABILITY_METHOD      =FOSTER-1992
REF_FRAME                                 =ITRF
GRAVITY_MODEL                             =EGM-96: 36D 36O
ATMOSPHERIC_MODEL                         =JBH09
N_BODY_PERTURBATIONS                     =MOON,SUN
SOLAR_RAD_PRESSURE                       =YES
EARTH_TIDES                               =YES
INTRACK_THRUST                           =NO
OBJECT                   =OBJECT1
X                      =-651.523341           [km]
Y                      =-4022.346444           [km]
Z                      =-5777.787638           [km]
X_DOT                      =-1.161775208           [km/s]
Y_DOT                      =6.206723161            [km/s]
Z_DOT                      =-4.192426361           [km/s]
OBJECT                   =OBJECT2
X                      =-651.470549           [km]
Y                      =-4022.187545           [km]
Z                      =-5778.086358           [km]
X_DOT                      =3.742974861            [km/s]
Y_DOT                      =4.951401494            [km/s]
Z_DOT                      =-3.970108465           [km/s]
```

Figure 3: An example of CDM File

### Definition of the Satellite Dynamic Model

Satellite force model consist of the followings;

$$\vec{a} = \vec{a}_{\oplus} + \vec{a}_{G} + \vec{a}_{\odot} + \vec{a}_{T} \qquad (2)$$

Parameters consisting in Equation-2 is Keplerian acceleration ($\vec{a}_{\oplus}$), gravitational potential acceleration ($\vec{a}_{G}$), third body acceleration ($\vec{a}_{\odot}$) and thrust acceleration ($\vec{a}_{T}$) respectively.

The propagation is done numerically by integrating the acceleration differential equation. It is done by using Prince-Dormand(853) method. All the state vector integration is calculated in the Earth Centered Inertial (ECI) Frame. Consequently, the OEM files are generated with respect to this dynamic model.

### Definition of the Maneuver Types

The collision avoidance maneuvers are divided into two categories, which are in-plane raising and in-plane braking. The satellite operator must decide to which kind of maneuver must be performed. This can be done by the differencing the norms of the position vectors at TCA. The operator shall define a threshold value for this difference, and hence decide whether the maneuver needed to be performed or not according to this threshold value.

The In-plane raising maneuvers are the cases where norm of the primary object position is greater than norm of the secondary object position. The purpose of this maneuver is increasing the altitude, which actually effects the miss distance, of primary object to avoid collision. This can be done by applying a thrust along the velocity direction. Since the thrust must be applied in a finite time, one must find the thrust duration that satisfies the required miss distance, by using targeting algorithm.

The In-plane braking maneuvers are the type of maneuvers which is opposite of the raising one. Namely, norm of the primary object position is less than norm of the secondary object position. The purpose of this maneuver is reducing the altitude of primary object to avoid collision. This can be done by applying thrust opposite of the velocity direction which reduces the spacecraft velocity resulting to decrease in altitude. Again, one must find the thrust duration for it, which satisfies the required miss distance, by using targeting algorithm.

## Definition of the Targeting Algorithm

Targeting algorithm was developed to reach the desired orbit by perturbing the thrust duration. This algorithm based on the solution of “Two Point Boundary Value Problem” by shooting method.

Assume that, $f''(x, f(x), f'(x))$ function is nonlinear differential equation and $f(x) \in \mathcal{R}$. As a result, one can define the boundaries as $f(x_0) = f_0$ and $f(x_1) = f_1$. In this study, $f_1$ is the desired miss distance and $x_1$ is the searching parameter. We may convert the boundary problem to the initial value problem as follows;

$$\boldsymbol{f''\left(x, f(x), f'(x)\right), \qquad f(x_0) = f_0\,, \qquad f'(x_0) = f'_0} \tag{3}$$

One can say that $x$ value is the thrust duration. The external function may be defined to reach $f_1$ at boundary values;

$$\boldsymbol{G(A) = f(x) - f_1 = 0} \tag{4}$$

$f(x)$ function is the solution of $f''\left(x, f(x), f'(x)\right)$ with given $x$ value which satisfies $x_1$ boundary condition for initial value problem. It is easy to see that with $G(A)$ function, the targeting problem is reduced to the root-finding problem. Since the equations are not linear, one of the numerical root finding method Newton-Raphson may be used. From this point, the Newton-Raphson iterative process is defined as follows;

$$\boldsymbol{A_{i+1} = A_i - \frac{G(A_i)}{G'(A_i)}} \tag{5}$$

Note that the $G'(A)$ must known in order to apply the Newton-Raphson method. The differential equation in initial value problem is non-linear function and depend on thrust duration, which makes it an implicit function. Consequently, $G'(A)$ shall be calculated as numerically and to do that one need to apply differential correction method such as “Forward Difference”. So, $G'(A)$ may be described in terms of forward difference as follows;

$$\boldsymbol{G'(A) = \frac{G(A+h) - G(A)}{h}} \tag{6}$$

In Eq-4, “h” is called as “perturbation step size”. For this study it was selected as 1e-6.

Targeting algorithm is iterative process and sometimes it may not converge and at these situations, an error message appears on screen. Reason of non-converged situation may depend on bad initial guess and poor differentiation. In addition, the user can decide maximum iteration number via the user interface, and if maximum iteration number is reached a warning message appears on the screen and algorithm will stopped. As a result of that, the user will see the last iteration result.

Targeting algorithm structure is summarized in Figure-4.

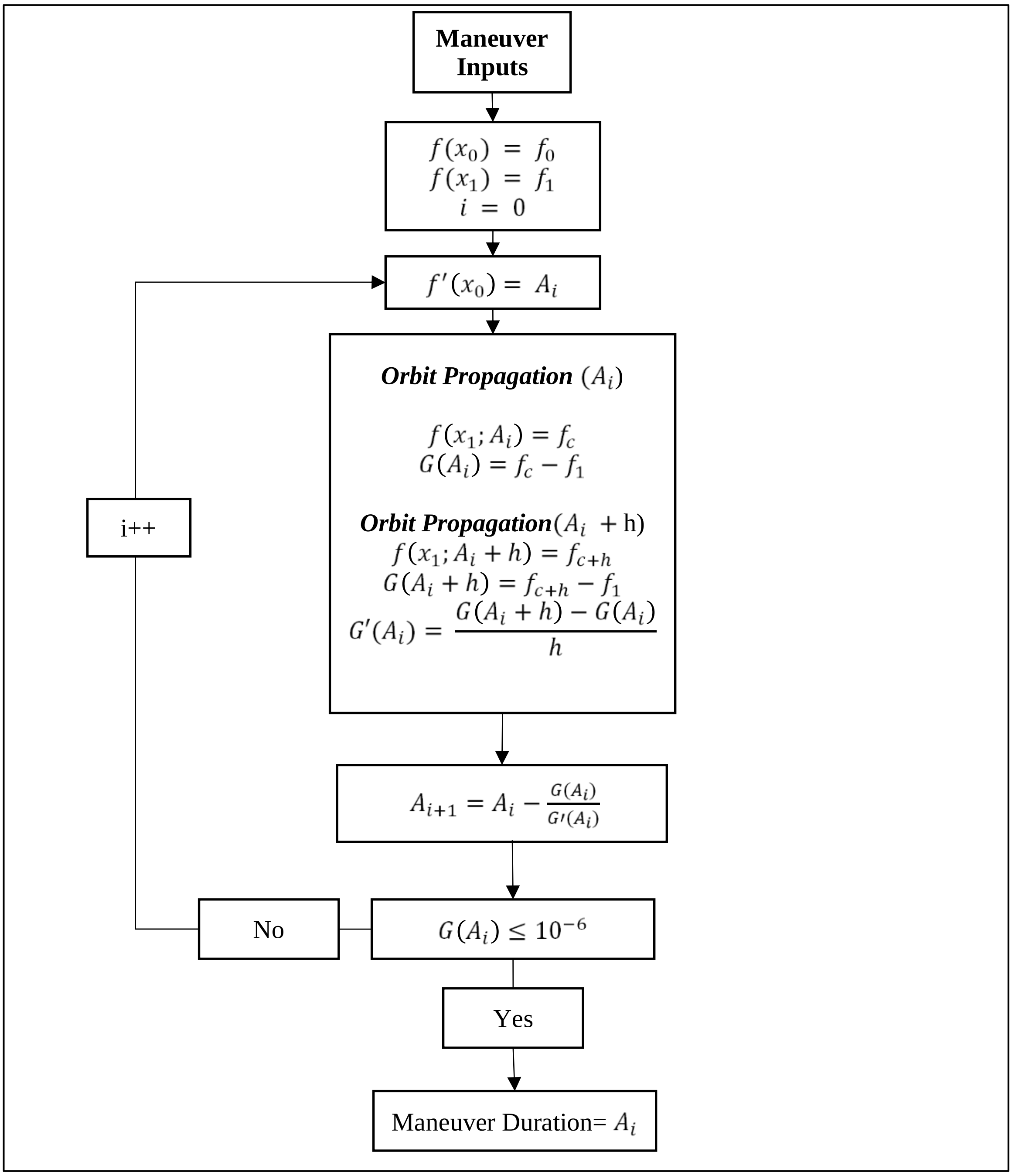


Figure 4: Targeting Algorithm

The developed algorithm was tested with optimization algorithms inside the GMAT and the FreeFlyer. The test case is required to rise the apogee of a spacecraft to 12000 km after a tangential burn at the perigee.

In order to compare the targeting algorithm, the spacecraft force models has simplified in a way that it consists only the Keplerian acceleration (two-body problem). For this case, the initial orbit and the maneuver inputs are given in Table-2 while the initial state is given in Table-1.

Table 1 Test Orbit, Cartesian Coordinates defined in ECI

| | X | Y | Z |
|---|---|---|---|
| **Position (km)** | 7100 | 0 | 1300 |

| | | | |
|---|---|---|---|
| **Velocity (km/s)** | 0 | 7.35 | 1 |

Table 2 Maneuver Inputs for Apogee Targeting.

| | **Thruster Force(N)** | **Specific Impulse(s)** | **Target Apogee(km)** | **Initial Guess(s)** |
|---|---|---|---|---|
| **Maneuver** | 1000 | 300 | 12000 | 200 |

Results of GMAT and FreeFlyer targeting algorithms are given in the Table-3;

Table 3 Results of the Targeting Algorithms

| | **FreeFlyer** | **GMAT** | **Targeting Algorithm** |
|---|---|---|---|
| **Thrust Duration(s)** | 1212.04600 | 1212.04617 | 1212.04618 |
| **Apogee(km)** | 11999.99842 | 11999.99999 | 12000.00000 |
| **Mass** | 1194.01901 | 1194.01895 | 1194.01895 |

Hence, targeting algorithm has verified with GMAT and FreeFlyer. Error threshold for the targeted apogee is selected as 1e-6 for all targeting algorithms. Yet, FreeFlyer reached to the maximum iteration. Consequently, the results that are given by FreeFlyer is on the order of 1e-3. Thus, improved targeting algorithm for this visualization tool has succeed to rise the apogee altitude to 12000km with an error of 1e-6.

### Definition of the OEM and the VTS Time Transformations

The VTS application is actually a broker between package of programs. It is the preferred broker for “ColAvo” since it is very powerful and flexible. It can handle common orbit-attitude file formats as well as 3DS models easily, which makes it useful for the socket applications.

There are lots of ephemeris formats, yet one of the most common orbit ephemeris file format is OEM. In Figure-5, an example of OEM file is given. This file contains position and velocity of the orbiting objects along with its defined frame with a time stamp. The object states must be in a Cartesian form with a unit of km. In addition to that, the object states must be defined in non-accelerated frames such as J2000. The time stamp of the states is referenced to two different date type namely the Julian Date of 1950 (JD1950) and Modified Julian Date (MDJ). More over to this, JD1950 is defined as the number of days count from 1 January 1950 00:00:00.000 UTC to the current epoch while MJD is defined from 17 November 1858 00:00:00.000 UTC. In this study, OEM files are created with the time stamp of MJD. The OEM file hold the time stamp in two different columns by dividing the day part and day fraction part.

MJD can be calculated using the definition of Julian Date. The Julian Date is starting from B.C 1 January 4713 12:00:00.000. One can find the days count from this date to current epoch and to the definition of MJD. Afterwards, one can subtract these day counts, which yields to number of days passed from MJD reference.

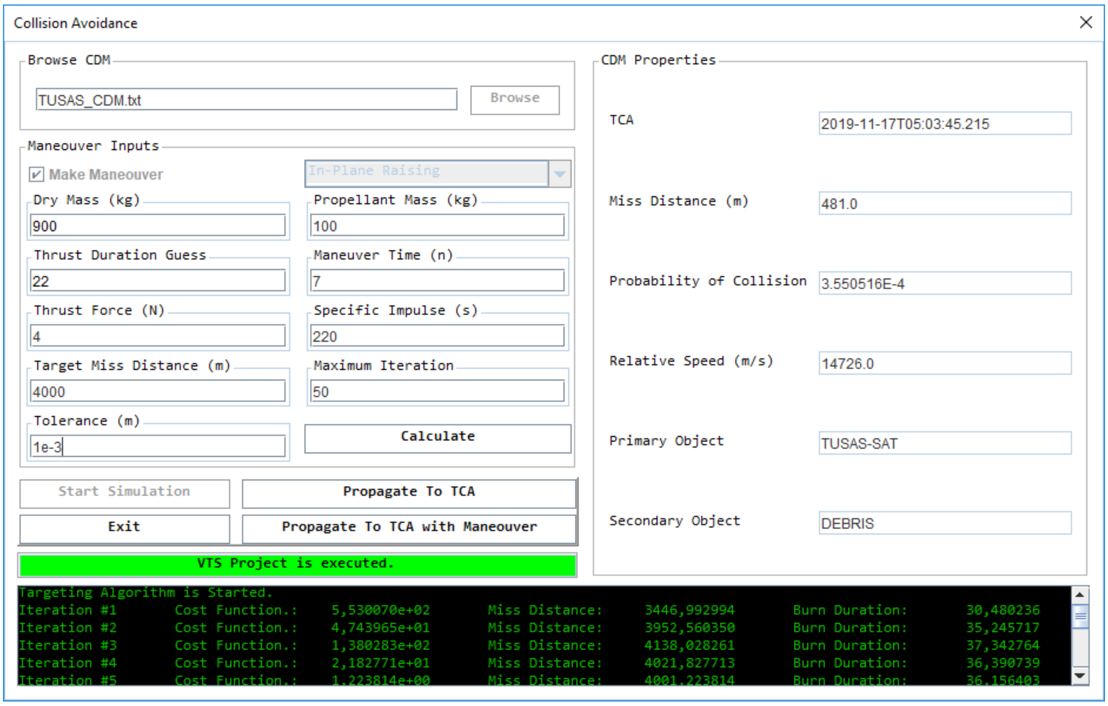
```
CIC_OEM_VERS   = 2.0
CREATION_DATE  = 2021-02-04T10:44:17.7767621
ORIGINATOR     = TUSAS
META_START
OBJECT_NAME = TuSAT
OBJECT_ID   = TuSAT
CENTER_NAME = EARTH
REF_FRAME   = EME2000
TIME_SYSTEM = UTC
META_STOP
58804     17062.21490     3181.05453     -385.61017     -6302.44035
```

```
58804    17122.21500    2779.61531    -477.72750    -6483.43592
58804    17182.21500    2366.94274    -567.91399    -6638.15988
58804    17242.21499    1944.70735    -655.80579    -6765.99317
```

Figure 5: An Example of OEM File

### Definition of the User Interface

"ColAvo" application has an interface that had been developed in JAVA. This interface can be used to navigate through VTS and other sub-programs. Initially, the user is required to give the CDM to the application. "ColAvo" can parse the given CDM, and show the important properties of it such as TCA, miss distance, relative speed and etc. Afterwards, the user can analyze the geometry of the orbiting bodies in order to determine the maneuver type by starting the simulation without maneuver calculation. Subsequently, the user must provide the visual analysis result as a maneuver type, where they defined as raising or braking, as well as the initial guess for the burn duration that is sufficient enough to satisfy the target miss distance. Furthermore, one can start the maneuver computation while monitoring the iterations and overall results from the log screen. After the calculation is done, "ColAvo" will automatically recognize the calculated maneuver and updates the VTS project, which will have both pre-maneuver and post-maneuver ephemerides. In the Figure-6 developed interface is shown. At the left-hand side, one can see the maneuver inputs are given while at the right-hand side, CDM properties are shown. In Figure 7, an example of simulation is shown through VTS application that is called Celestia. The overall conjunction assessment algorithm is shown in Figure-8.



Browse CDM: TUSAS_CDM.txt

☑ Make Maneouver: In-Plane Raising

Dry Mass (kg): 900

Propellant Mass (kg): 100

Thrust Duration Guess: 22

Maneuver Time (n): 7

Thrust Force (N): 4

Specific Impulse (s): 220

Target Miss Distance (m): 4000

Maximum Iteration: 50

Tolerance (m): 1e-3

VTS Project is executed.

TCA: 2019-11-17T05:03:45.215

Miss Distance (m): 481.0

Probability of Collision: 3.550516E-4

Relative Speed (m/s): 14726.0

Primary Object: TUSAS-SAT

Secondary Object: DEBRIS

```
Targeting Algorithm is Started.
Iteration #1    Cost Function.:    5,530070e+02    Miss Distance:    3446,992994    Burn Duration:    30,480236
Iteration #2    Cost Function.:    4,743965e+01    Miss Distance:    3952,560350    Burn Duration:    35,245717
Iteration #3    Cost Function.:    1,380283e+02    Miss Distance:    4138,028261    Burn Duration:    37,342764
Iteration #4    Cost Function.:    2,182771e+01    Miss Distance:    4021,827713    Burn Duration:    36,390739
Iteration #5    Cost Function.:    1,223814e+00    Miss Distance:    4001,223814    Burn Duration:    36,156403
```

Figure 6: Application Interface.

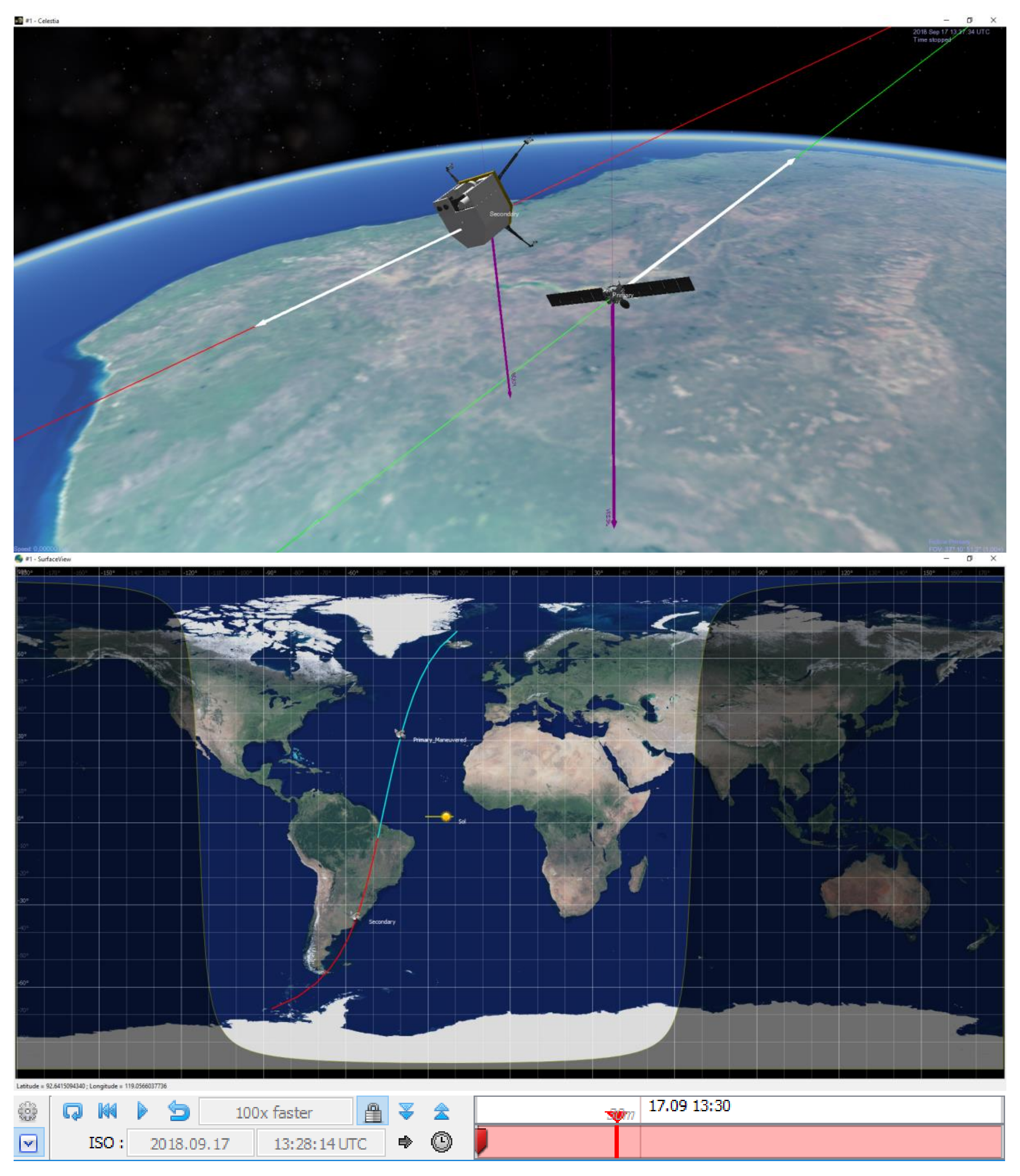


Figure 7: An Example of Simulation

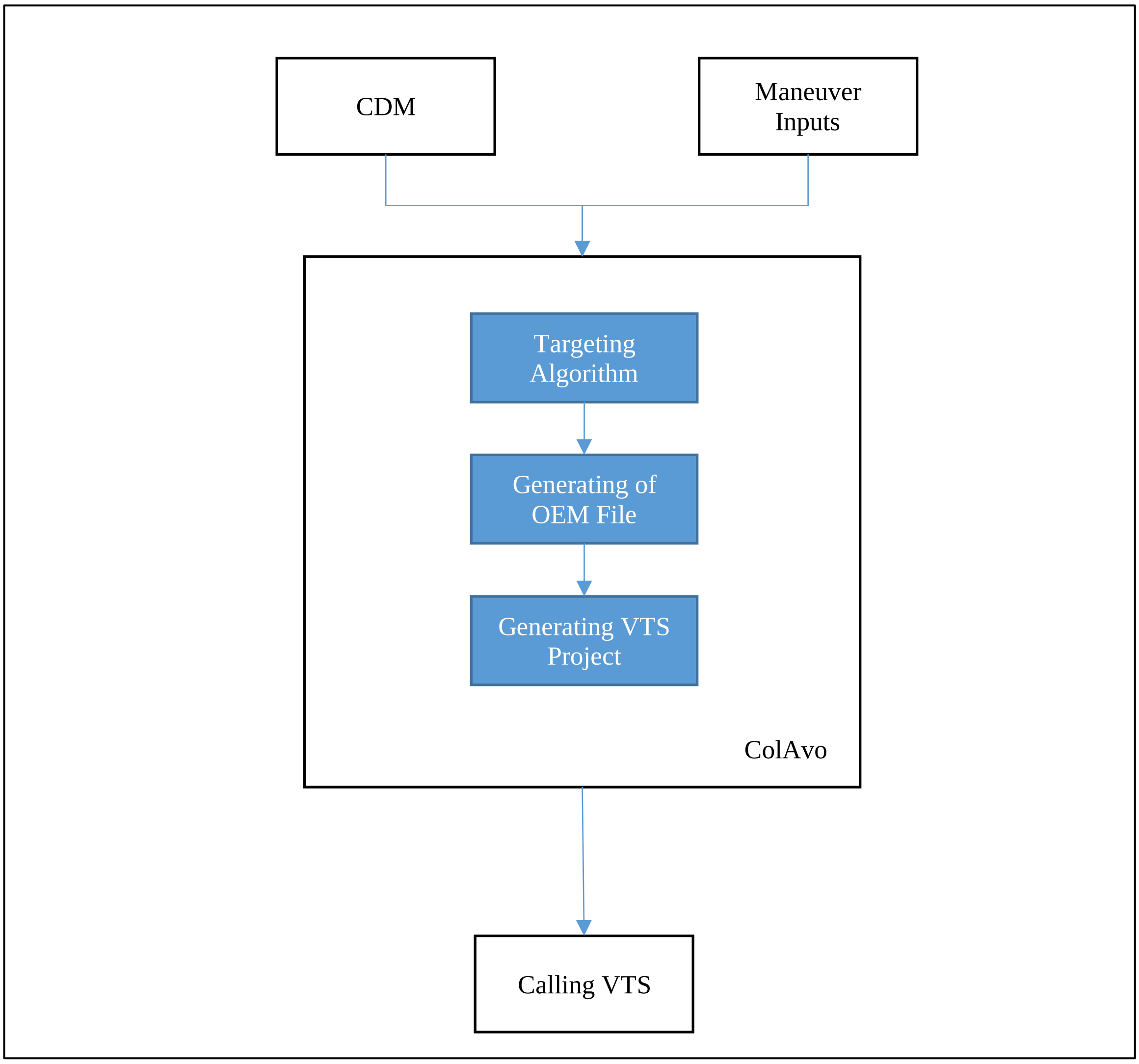


Figure 8: ColAvo Application Flow

## APPLICATIONS

In this section, two different test cases have explained. The inputs and maneuver outputs have given in the form of a table. For both test cases, generated CDM files have read and maneuver type has decided by the results of visualization.

For the first CDM, the miss distance inside the CDM has adjusted to be as 254m at closest approach and orbit information are given in Table 4. In this case, TuSAT was located above with respect to secondary object. Therefore, the resulting maneuver type is In-Plane Raising. In Table-5, the maneuver inputs are given, which are 6N of thrust force, 220s of specific impulse, 2500 meters of target miss distance, 1000kg of satellite mass, 7 orbits before TCA maneuver epoch and 55 seconds of initial guess for burn duration. Targeting algorithm was converged within 6 iterations. Moreover, Delta-V and burn duration values have been calculated as 0.04169 m/s and 8,68582 seconds respectively. Hence, 2500.00005m miss distance was obtained by the targeting algorithm.

For the second CDM, the miss distance is set to be 342m. Orbit information has given in Table 7. In this scenario, TuSAT was located below of the secondary object; thus, in-plane-braking maneuver is need to be performed. The maneuver inputs have given in Table 8 as 3.5N thruster force, 180 seconds specific impulse, 1500m target miss distance, 800kg satellite mass, 7 orbits before TCA maneuver epoch, 70 seconds initial guess for burn duration. Targeting algorithm was completed after eight iterations. Delta-V and burn duration values was obtained as 0.01544 m/s and 3.97166 seconds respectively. In addition, 1499.99967 meters miss distance was obtained by the algorithm with an error order of 1e-6.

Table 4 CDM Parameters for First Test Case

| | **Position (km)** | | | **Velocity (km/s)** | | |
|---|---|---|---|---|---|---|
| | **X** | **Y** | **Z** | **X** | **Y** | **Z** |
| **TuSAT** | -1695.62954 | -1049.66287 | 6766.4982 | 3.25832 | 6.60322 | 1.83723 |
| **Debris** | -1695.70966 | -1049.45569 | 6766.37506 | -7.3942 | 0.22802 | -1.75732 |
| **TCA** | 2019-06-14T23:26:55.083 | | | | | |
| **Miss Distance (m)** | 254.0 | | | | | |

Table 5 Decided Maneuver Type and Inputs for First Test Case

| | **Thrust Force (N)** | **Specific Impulse (s)** | **Target Miss Distance (m)** | **Dry Mass (kg)** | **Maneuver Time (n)** | **Initial Guess (s)** |
|---|---|---|---|---|---|---|
| **Maneuver** | 6 | 220 | 2500 | 1000 | 7 | 10 |
| **Maneuver Type** | In Plane Raising | | | | | |

Table 6 Targeting Algorithm Test Results for First Test Case

| | **Number of Iterations** | **Delta-V (m/s)** | **Burn Duration(s)** | **Miss Distance (m)** |
|---|---|---|---|---|
| **Results of Targeting Algorithm** | 4 | 0.041692 | 8.68582 | 2500,000050 |
| **New TCA** | 2019-06-14T23:26:54.783 | | | |

Table 7 CDM Parameters for Second Test Case

| | **Position (km)** | | | **Velocity (km/s)** | | |
|---|---|---|---|---|---|---|
| | **X** | **Y** | **Z** | **X** | **Y** | **Z** |
| **TuSAT** | -651.52334 | -4022.34644 | -5777.78763 | -1.16177 | 1.08498 | 6.20672 |
| **Debris** | -651.47054 | -4022.18754 | -5778.08635 | 3.74297 | 4.95140 | -3.97010 |
| **TCA** | 2021-05-12T04:20:34.629 | | | | | |
| **Miss Distance (m)** | 342.0 | | | | | |

Table 8 Decided Maneuver Type and Inputs for Second Test Case

| | **Thrust Force (N)** | **Specific Impulse (s)** | **Target Miss Distance (m)** | **Dry Mass (kg)** | **Maneuver Time (n)** | **Initial Guess (s)** |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| **Maneuver** | 3.5 | 180 | 1500 | 800 | 7 | 70 |
| **Maneuver Type** | In Plane Braking | | | | | |

Tablo 9 Results of Targeting Algorithm for Second Test Cases

| | **Number of Iterations** | **Delta-V (m/s)** | **Burn Duration (s)** | **Miss Distance (m)** |
|---|---|---|---|---|
| **Results of Targeting Algorithm** | 8 | 0.01544 | 3.97166 | 1499.99967 |
| **New TCA** | 2021-05-12T04:20:34.529 | | | |

## CONCLUSION

In recent years, number of satellites are growing seriously due to the increasing demand of satellite projects. Nowadays, Earth orbiting satellites are subjected to more conjunction possibilities. Associations like CSpOC may send conjunction data messages to the satellite operators to inform them in terms of possible conjunction. According to the collision probability, operators need to determine go or no-go decision for the maneuver.

The users can analyze satellite positions with the developed application and can decide the required maneuver. This tool can reduce the decision time for the maneuver, yet it needed to be improved for the future applications. In test case, the calculated maneuvers are aiming to keep the miss distance with respect to a threshold value. The precision of the targeting algorithm is in the level of 1e-6, and it ensures the target miss distance in micrometer consistency which is practically very hard to maintain. The Iteration numbers directly affect the calculation duration. It can be decreased by setting up the threshold value to 1e-3 which is indicating millimeter precision for miss distance.

For future applications, the user interface is planned to be improved. The targeting algorithm can be modified in a way that the user can select the optimization as well as the differential correction method. In addition, it is planned to modify the application to let the user define its own satellite parameters. Therefore, the user shall be define the force models, satellite frames and propulsion model. Also, further analysis will be covered the analysis of PoC after the executed maneuver.

Consequently, the interface of the software will be improved, as well as the inputs of the maneuver in the future studies. Even though the targeting algorithm calculates the desired maneuver in a precision of micrometer, it is not practically possible. Therefore, the threshold value for the miss distance can be set to lower values to decrease the decision time even more.

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