Real-time Geosynchronous Collision Risk Management by using a Service Vehicle

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Space Situational Awareness is defined as the knowledge and characterization of all aspects of space. SSA is now a fundamental and critical component of space operations. Increased dependence on our space assets has in turn led to a greater need for accurate, near real-time knowledge of all space activities. With the continued growth of the orbital debris population, high-risk conjunction events are occurring more often. Consequently, satellite operators are performing collision avoidance maneuvers more frequently. Since any type of maneuver expends fuel and reduces the operational lifetime of the spacecraft, using fuel to perform collision avoidance maneuvers often times leads to a difficult trade between sufficiently reducing the risk while satisfying the operational needs of the mission. Thus the need for new, more sophisticated collision avoidance methods must be implemented. This paper presents a concept of operations for improving operational collision risk management through use of service vehicle. Once a high-threat conjunction event has been identified, the servicing vehicle will collect additional tracking information to improve the orbital information for the conjunction event. If a collision avoidance maneuver is deemed to be necessary, the servicing vehicle will rendezvous and dock with the operational spacecraft, perform the avoidance maneuver, and then un-dock once the collision risk has been reduced.

1. INTRODUCTION

Space Situational Awareness (SSA) is defined as the knowledge and characterization of all aspects of space. SSA is now a fundamental and critical component of space operations. The increased dependence on our space assets has in turn led to a greater need for accurate, near real-time knowledge of all space activities. Key areas of SSA include improved tracking of small objects, determining the intent of maneuvering spacecraft, identifying all potential high risk conjunction events, and leveraging non-traditional sensors in support of the SSA mission.

As the size of the space object population grows, satellite operators are required to spend more time evaluating close approach prediction results. Consequently, satellite operators are performing collision avoidance maneuvers more frequently. Since any type of maneuver expends fuel and reduces the operational lifetime of the spacecraft, using fuel to perform collision avoidance maneuvers often times leads to a difficult trade between sufficiently reducing the risk while satisfying the operational needs of the mission.

This paper demonstrates the operational feasibility of providing near real-time SSA to an operational spacecraft. The real-time SSA support consists of collision risk management, object tracking for improved orbit knowledge, and Mated Maneuver Operations (MMO) as a means of performing Collision Avoidance. We present the planning and execution details required to successfully execute a maneuver; given the traditional conjunction analysis timelines. Development of the collision avoidance strategy is created using SpaceNav's collision risk management tool suite. Orbit updates for both the operational satellite and the secondary are generated using observation data collected from the servicing vehicle.

The following sections present the details of our Geosynchronous Earth Orbit (GEO) collision avoidance analysis. The concept of a space-based servicing vehicle is introduced in Section 2. Detailed mission timelines are presented in Section 3. Sample mission scenarios are presented in Section 4. GEO constellation design considerations are discussed in Section 5. Conclusions and a discussion of future work are presented in Section 6.

2. CONCEPT OF A SPACE-BASED SERVICING VEHICLE

In this paper we introduce the notion of an on-orbit Servicing Vehicle (SV) that is capable of traveling about the GEO Belt in order to provide mission enabling and extending services. Many efforts are underway in the defense, civil, and commercial aerospace sectors to develop on-orbit servicing, with the most emphasis on the GEO mission [1,2]. The GEO Belt is home to high value civil, commercial and defense assets, for communication and remote sensing of the earth and space environments. Various approaches and motivations exist for planning such a mission. Services may include inspection, consumable replenishment (propellant), maneuvering for satellites that have exhausted all propellant, and component replacement. Common to all approaches is the need to rendezvous, approach, and dock or berth with an on-orbit satellite in order to provide services.

Providing near real-time SSA support to an operational spacecraft. The real-time SSA support consist of collision risk management, object tracking for improved orbit knowledge, and Mated Maneuver Operations (MMO) as a means of performing Collision Avoidance. Our typical mission profile includes a vehicle capable of performing rendezvous at GEO, a cooperative service client satellite, advance notification of a conjunction event, and related metrics describing the risk associated with the conjunction event.

The SV will be tasked to provide Mated Operations Services by owners of satellites in GEO when appropriate on predetermined schedules. For MOCOLA, we assume that mechanical interfaces are compatible, owner/operator supplied ephemerides and health and safety data are available, and that the Client Vehicle (CV) is commanded to shut down operations that would adversely affect docking, or is dormant in this regard.

In order to provide accessibility to as many on-orbit clients as possible, a parking orbit, or near-GEO trajectory is established that imparts longitudinal drift relative to GEO satellite stations, or slots. In the simplest case, an orbit lower than the GEO Belt will impart an Eastward drift at a few degrees per day. A trade to consider in designing the parking, or drift, orbit will be the propellant required to transfer to GEO and back versus the rate or travel and accessibility of the GEO Belt. As we will show, the timelines associated with identifying and mitigating collision risk on-orbit are challenging to accommodate for such a service.

Our notional SV will have the following characteristics: Rendezvous and Proximity Operations (RPO) sensors, high efficiency propulsion to carry out multiple energy consuming missions, docking hardware, and Guidance, Navigation, and Control systems to carry-out closed loop autonomous docking at the terminal phase of RPO.

3. MISSION EVENT TIMELINE & CONOPS

This section presents a notional mission timeline that captures the major events that are performed by the satellite operator, the servicing vehicle navigation team, and the collision risk management team. We present the major events in terms of mission phases; showing the required tasks for each of the mission stakeholders. The different mission events are organized in terms of discrete mission phases. Once the activities are described, a notional mission timeline that is tied to the time of closest approach (TCA). Our operations concept assumes a collision avoidance maneuver near the TCA – 2 day point.

In section 3.1 we present the details of our Concept of Operations. In section 3.2 we provide additional details to the collision risk management process. Section3.3 contains the rendezvous and orbit-capture details performed by the servicing vehicle.

3.1 Concept of Operations (CONOPS)

Once the request for SSA services has been made, the servicing vehicle mission planning team begins developing a mission plan that contains different mission phases. The early phases consist mostly of analysis that is performed to determine how the service vehicle provider can best support the satellite owner/operator. Table **1** lists the mission phase definitions.

Table 1: Mission Phase Definitions

Mission Phase	Mission Phase Definition
Phase 0 – Establishment of the Collision Risk by the Collision Risk Management Team	In Phase 0, the collision risk between the primary mission satellite and another 'secondary' object in the space object catalog is established. Establishment of the collision risk is determined by processing conjunction event data that is provided by JSpOC. This includes computing collision probability and probability forecasting information for the event.
Phase 1 – Determine Service Vehicle Availability	In Phase 1, after the collision risk has been established, the satellite owner/operator makes a formal request to the servicing vehicle provider to examine what SSA services are available. The service vehicle provider will examine if there is an available vehicle to 1. Collect tracking data on the secondary object and 2. Plan and perform a collision avoidance maneuver. The service vehicle provider will build a mission plan that shows a timeline with go-no-go decision points.
Phase 2 – Construction of baseline RPO trajectory and mission plan	In Phase 2, the servicing vehicle navigation team develops a detailed RPO trajectory sequence and subsequently a detailed mission plan. The mission plan includes all of the major activities for each mission stakeholder.
Phase 3a –Finalize Mission Plan	In Phase 3a, the decision to deploy the service vehicle will be made. The entire mission stakeholder team will meet & agree on the plan that will be executed.
Phase 3b –Mission Plan Execution	In Phase 3b, the decision to deploy the service vehicle has been made. The mission plan is executed.

The operations concept employed by the servicing vehicle mission operation team is to have the collision risk, and subsequent collision avoidance planning, be established by SpaceNav personnel. We leverage SpaceNav's collision risk management software to process JSpOC data, quantify the collision threat, and generate collision avoidance maneuver plans that will be executed by the servicing vehicle. Table **2** lists the major activities, for each phase, for each mission stakeholder.

Table 2: Major Activities & Events per Mission Phase

Mission Phase	Satellite Owner/Operator	Servicing Vehicle Navigation & Mission Operations Team	Collision Risk Management Team
Phase 0 – Establishment of the Collision Risk	• Provide the collision risk management team with conjunction event data	• Review existing ICD; ensure satellite O/O knows what vehicle specific information is required • Preliminary development of the RPO maneuver sequence	• Process conjunction event data to establish and quantify the collision risk • Initial collision avoidance strategy development
Phase 1- Determine Service Vehicle Availability	• Begin providing ICD-specific information to Servicing Vehicle Team • Continue to provide updated conjunction event information to the Collision Risk Management Team	• Perform coverage & tracking analysis for the primary • Perform coverage & tracking analysis for the secondary • Create trade space of possible SSA support options for the satellite O/O	• Refinement of the collision avoidance strategy based on inputs and mission constraints provided by the satellite O/O
Phase 2 – Construction of baseline RPO trajectory and mission plan	• Continue to provide updated conjunction event information to the Collision Risk Management Team	• Created detailed RPO trajectory plan	• Provide JSpOC with baseline trajectory plan • Process JSpOC data to perform collision risk analysis for the servicing vehicle • Continue to process satellite conjunction event data in order to re-compute the collision risk
Phase 3 – Mission Plan Execution	• Continue to provide updated conjunction event information to the Collision Risk Management Team • Provide satellite trajectory information to the Servicing Vehicle Team	• Execute mission plan	• Process JSpOC data to perform collision risk analysis for the servicing vehicle • Continue to process satellite conjunction event data in order to re-compute the collision risk

Figure 1 provides a flow of the major activities that constitute the deployment and use of the service vehicle. Decision points exist at the end of phases 0 – 2 that must be made to pass to the next phase. Phase 3 shows the re-plan activities that take place with the addition of information from the service vehicle tracking capability.

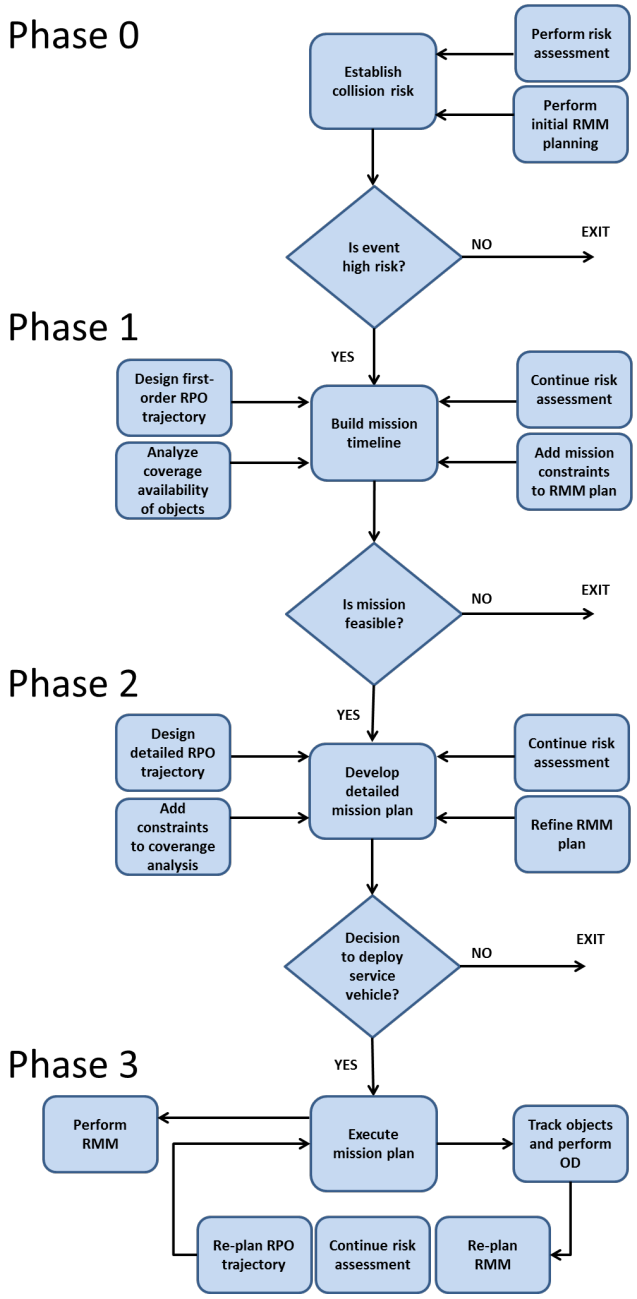
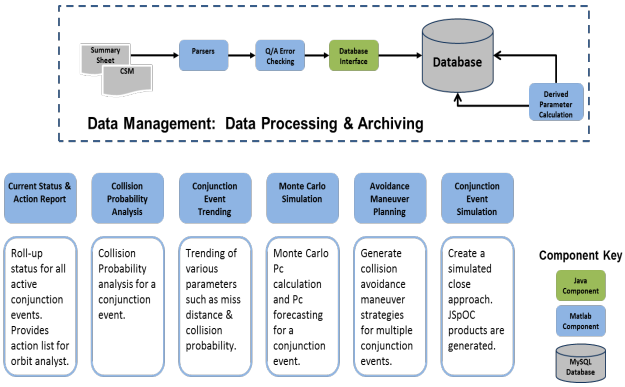


Figure 1: Flow chart of major activities of the service vehicle mission

3.2 Collision Risk Management Process



Operational collision risk management starts with the generation of close approach predictions and ends with an action/no-action decision from mission stakeholders. The step-by-step process consists of:

1. Reporting all conjunction events that are predicted to violate a specific separation distance threshold over some future time span,
2. Assessing and quantifying the collision threat for each conjunction event that is identified,
3. Developing and executing collision avoidance maneuvers when necessary.

Typical procedures have personnel at the Joint Space Operations Center (JSpOC) performing step 1, and the satellite operator performing steps 2 and 3. If two objects are predicted to come within some separation threshold, JSpOC personnel will issue a warning report and notify the appropriate satellite operator. Additionally, the JSpOC will provide various supplementary data products to the operator so that the collision threat can be established. Mission analysts must make sense of the JSpOC data by producing trends, comparing data for statistical consistency, and eventually quantifying the risk of collision [3].

SpaceNav's Collision Risk Management software solution enables mission stakeholders to analyze and qualify high interest conjunction events. The software solution is comprised of a set of analysis tools, a database, and supporting infrastructure. The services of the Collision Risk Management software suite are described below.

- *Data Management: Data Processing & Archiving*: The Data Management service processes and archives all conjunction event data products. All data is stored in a database.
- *Current Status & Action Report*: The Current Status & Action Report service generates a summary status for all active conjunction events. The service is designed to be run at any time, and provides analyst with a complete threat characterization picture.
- *Collision Probability Analysis*: The Collision Probability Analysis service computes miss distance and collision probability for given Conjunction Summary Message (CSM). Probability analysis is performed for a single primary and a single secondary at time of closest approach.
- *Conjunction Event Trending*: The Conjunction Event Trending service produces time history trends for a given conjunction event. Relevant parameters such as the collision probability, combined position uncertainty and sigma level ratios are plotted over time.
- *Monte Carlo Simulation*: The Monte Carlo Simulation service provides a stochastic model of a conjunction event. A collision probability value & forecasting results are calculated from the model.
- *Avoidance Maneuver Planning*: The Avoidance Maneuver Planning service generates a delta-V maneuver that reduces the collision probability for one or more conjunction events
- *Conjunction Event Simulation*: The Conjunction Event Simulation service generates a conjunction event when provided with primary object state information. The risk can be controlled by the user through separation geometry & covariance inputs.

3.3. Proximity Operations, Rendezvous and Docking Sequence

For this study, we assume the SV can achieve a co-planar, co-elliptic orbit with the CV as a pre-requisite for rendezvous. Any notional SV will be required to change inclination, as potential clients will include satellites unable to perform North-South station-keeping. We assume the SV will be capable of changing inclination in free-flight and during mated operations.

3.3.1 RPO Trajectory

The SV approach to the client at GEO is defined by a trajectory that includes a series of maneuvers and free motion segments [4]. Table 3 shows the typical RPO trajectory phases and Table 4 outlines nominal maneuver plan for the servicing vehicle. Our study modeled the Far and Near Rendezvous Phases that employed low thrust, high efficiency propulsion and trajectory design. The Proximity and Docking phases employ closed loop guidance and will exercise a different propulsion system.

Table 3: Typical RPO Trajectory Phases for the service vehicle

RPO Trajectory Phase	Distance to Client	Definition
Far Rendezvous	2000 km to 25 km	Relative Angle Measurements
Near Rendezvous	25 km to 1 km	Angles + Range Measurements
Proximity Phase	<1 km	Closed Loop Guidance, Navigation and Control
Docking Phase	< 10 m	Mechanical interaction (Docking/Berthing/Grappling)

Our notional rendezvous sequence begins with an initial drift orbit below the GEO altitude such that the SV is traveling at 2 degrees per day eastward. Our SV begins 2000 km west of the CV and 155 km below in altitude. At this distance, on board visible sensors determine the relative bearing of the CV. Figure 2 provides a diagram of the typical trajectory of the service vehicle.

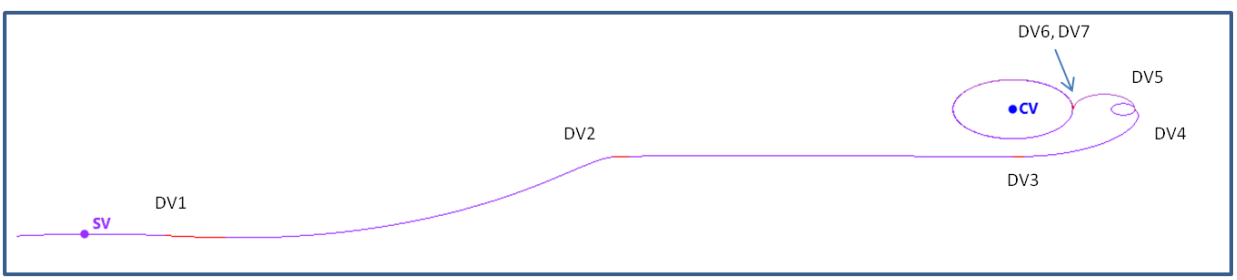


Figure 2: Typical service vehicle trajectory for the service vehicle relative to the client vehicle (CV)

3.3.2 Far Rendezvous

The Far Rendezvous Phase begins after acquisition of the CV by on board sensors, marking the transition from ground based navigation to relative tracking navigation. Far Rendezvous is characterized by the availability of relative angle tracking from sensors on the SV. The acquisition of an on-orbit GEO satellite by an optical sensor will depend on many factors including the CV bus size, the visible reflectance properties, sun angle, field of view of the SV sensor, orbit position uncertainty of the CV, and distance. For our study we assume that the SV optical sensor has the necessary qualities to acquire a GEO size satellite bus at a range of 2000 km. The SV pointing knowledge and control are assumed sufficient to extract angle data observations from the sensor.

Two or more sets of Hohmann maneuvers raise the SV orbit during the approach to the CV. In our scenario, the first Hohmann Maneuver Pair (DV1 , DV2) raises the orbit from GEO-155 km to GEO-35 km. At this time the drift rate relative to the client (CV) slows to 0.5 deg/day. The SV drifts below the CV, passing the +RBar. This fly-by vantage is a good opportunity to take tracking observations including bearing angle data from the SV to the

Client. The next pair of Hohmann maneuvers (DV3, DV4) raise the SV orbit to GEO, at a distance ahead of the client along the +Vbar.

Hohmann maneuver pairs offer fuel efficient means of achieving orbit raising, but require elapsed times of 12 hours between them, equal to the half period of the reference GEO orbit. This presents a challenge on the timeline to reach the CV, as the time required by fewer Hohmann Pairs must be traded against SV pointing and slewing requirements to maintain visible sensor acquisition over the approach. More Hohmann Pairs offer more control authority to phase timing and to achieve a particular approach slope for the SV attitude. A trajectory approach that provides a constant slope is favorable for SV sensor tracking of the CV. For our notional approach, we use 2 Hohmann Maneuver pairs to save time.

DV4, normally a circularization burn, is planned with a small eccentricity post-maneuver ($e<0.0001$) such that tracking of the client includes some dynamic variance, which is favorable for relative navigation estimation. The SV will dwell on the Vbar for some time, allowing for relative state estimation, maneuver planning updates, and favorable lighting before the Near Rendezvous phase.

3.3.3 Near Rendezvous

The Near Rendezvous Phase begins when the RPO sensors aboard the SV can determine relative range to the SV in addition to the angles. For the purposes of this study, we define the distance of 25 km as the Near Rendezvous boundary.

A CW hop along the Vbar to establish the final close approach is performed by a radial burn, DV5. A complementary radial burn, DV6, is used to stop the motion on the Vbar at a fixed distance of 50 km. Another dwell period follows DV6. Finally, an insertion burn to a Circumnavigation Ellipse is performed, DV7. At this point the SV is in a relative motion ellipse, with a close approach distance of 25 km.

This maneuver sequence has 3 dwell periods designed to provide operational flexibility for planning observations of the secondary, favorable lighting conditions, orbit determination updates and maneuver re-planning.

Table 4: Nominal maneuver plan for the servicing vehicle

RPO Trajectory Maneuver	Maneuver Start (Days from TCA)	Delta-V (m/s)	Description
DV1	5.6	1.671	Hohmann Pair 1, Raise Apogee
DV2	5.2	1.320	Hohmann Pair 1, Raise Perigee
DV3	3.9	0.733	Hohmann Pair 2, Raise Apogee to GEO
DV4	3.5	0.719	Hohmann Pair 2, Raise Perigee to GEO
DV5	2.0	0.562	VBar CW Hop to +50 km
DV6	1.5	0.908	VBar Stop at +50 km
DV7	1.3	1.833	CircumNav Ellipse Insertion

3.3.4 Proximity and Docking Phase

The proximity phase is defined for the transition between open loop and closed loop Guidance, Navigation, and Control. At ranges less than 1 km, the GN&C algorithms on-board the SV determine the approach trajectory suitable for docking safely. Within 10 meters, the relative motion is stable and controlled such that mechanical interactions, whether grappling, berthing, or docking, may proceed. For this paper, these phases were not modeled in detail.

4. GEO CONJUNCTION EVENT CASE STUDIES

We now consider two different GEO conjunction events; demonstrating the utility of the servicing vehicle in the context of improved, near real-time collision risk management. The first conjunction event scenario is a close approach between EchoStar 17 and a piece of debris. The collision risk for the EchoStar 17 event is initially high, and remains high throughout. We present the entire end-to-end process, starting with a change to the service vehicle drift rate and ending with execution of a collision avoidance maneuver.

The second conjunction event scenario is a close approach between AMSC 1 and a piece of debris. The collision risk for the AMSC 1 event is high when it's first identified (at TCA – 10 days). As the orbital knowledge of the piece of debris is improved, the collision risk is reduced. We present tracking data collection details and show how the orbit updates attribute to the reduction in the collision probability.

The timelines and risk assessment methodologies described in Section 3 are now applied to both of the conjunction events. We present the major activities and analysis performed for each mission phase.
Both simulations consist of:

- Daily conjunction event reporting and subsequent collision risk analysis
- Daily state vector updates for the secondary that are based on tracking data collected from the servicing vehicle
- Daily state vector updates for the primary that are based on tracking data collected from the servicing vehicle
- Planning and re-planning of the avoidance maneuver and RPO maneuver sequence

4.1 Conjunction Event Scenario #1 – EchoStar 17

A conjunction event was simulated for the geosynchronous satellite EchoStar 17. The orbit of a secondary object, denoted in the following by Object A, was designed so that a high-risk conjunction event was predicted to occur on 1 Feb 2014 02:32. Event details are provided in the following subsections. We present the information in terms of mission phases. Simulated JSpOC Conjunction Summary Messages (CSMs) were generated for this event.

4.1.1 Initial Conditions

The orbital elements and physical parameters of both objects at TCA are shown in Table 5. Both objects are in geosynchronous orbits with low eccentricity. Object A has an inclination of 15.5 deg, while EchoStar 17 is nearly equatorial.

Table 5: Orbital parameters and physical characteristics for EchoStar 17 and Object A

Parameter	**EchoStar 17**	**Object A**
epoch	1 Feb 2014 02:32:00.004	1 Feb 2014 02:32:00.004
semi-major axis (km)	42163.591	42158.693
eccentricity	0.000126	7.526334e-10
inclination (deg)	0.532	15.493
argument of perigee (deg)	315.808	359.239
RAAN (deg)	82.897	61.192
true anomaly (deg)	21.754	359.999
radial cross section (m^2)	24.0	0.143

4.1.2 Initial Close Approach Prediction Results

The close approach between EchoStar 17 and Object A was first reported to the satellite O/O at TCA – 10 days. This is the typical screening time for objects in GEO. Risk analysis was performed using data from the JSpOC CSM product. The results provided in Table 6 indicate that the collision risk is high.

Table 6: Initial risk assessment for EchoStar 17 vs. Object A

Days to TCA	Collision Probability	Miss	Radial	In-track	Cross-track
10	1.04E-02	69.8	33.0	61.0	8.0

4.1.3 Event Details

The major activities of the planning and execution of the service vehicle mission will be presented here. Table 7 presents the activities broken down by phase and time relative to TCA. Phases 0 – 2 contain steps to determine whether the service vehicle option is feasible for the close approach and phase 3 contains the execution and iterative planning steps.

Table 7: Timeline of major activities with corresponding phases

Phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**
Days to TCA	**9 - 10**	**9**	**8**	**0 - 8**
Major Activities	• Receipt of initial event notification • Establish collision risk • Generate initial avoidance maneuver plan	• Generate first-order RPO maneuver sequence • Perform coverage analysis of both objects • Include mission constraints in avoidance maneuver planning	• Generate detailed RPO maneuver sequence • Add constraints to coverage analysis • Continue risk assessment	• Decide to deploy service vehicle • Track both objects & perform OD • Continue risk assessment • Iteratively re-plan RPO maneuvers based on latest state data • Iteratively re-plan avoidance maneuver based on latest state data

4.1.3.1 Phase 0 – Establishment of the Collision Risk

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*
• Received initial event notification at TCA-10 days • Additional CSM received at TCA-9 days • Products provided to collision risk management team	• Request vehicle specific data from satellite O/O	• Processing of first two CSMs shows event is high risk • Initial avoidance maneuver planning shows maneuver of +/- 0.002 m/s at TCA-2 days will mitigate risk

The collision risk management team initially performs risk assessment when notified by the satellite O/O that a service vehicle may be requested. In this phase, two event predictions have been received from the JSpOC in the form of CSMs. The initial event notification was dated 22 Jan 2014. The Pc for this update was 1.04E-02 and the miss distance was 69.8 m.

Avoidance maneuver planning is performed in Phase 0 to aid in the determination of the feasibility of using a service vehicle to perform the maneuver. The initial maneuver planning step is run without regard to the satellite's mission constraints. It was found that a maneuver of +/- 0.002 m/s performed approximately 2 days prior to TCA would effectively mitigate the collision risk.

4.1.3.2 – Phase 1 – Service Vehicle Availability

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*

• CSM received at TCA-8 days provided to collision risk management team
• Provide mission constraints
  o Maneuvers should counter natural eastward drift
  o Eccentricity growth should be minimized
	• First-order RPO trajectory shows that service vehicle can dock at approximately TCA-2 days
	• Initial coverage analysis shows percentage of time objects are visible
	  o EchoStar 17: 58%
	  o Object A: 49%
		• Processing of third CSM shows risk remains high
		• Avoidance maneuver planning shows maneuver of +0.002 m/s at apogee crossing ~TCA-1.5 days will mitigate risk and satisfy mission constraints

In Phase 2 a first-order RPO trajectory is designed for the service vehicle. This step is performed to determine if a service vehicle can reach the satellite with sufficient time to aid in the process of reducing the collision risk either through providing additional orbital knowledge through tracking of the objects or in the execution of an avoidance maneuver. It was determined that a service vehicle could reach the satellite and perform docking within approximately two days from TCA.

The service vehicle navigation team used the preliminary RPO trajectory to perform coverage analysis of both EchoStar 17 and Object A. This analysis is performed to determine the extent to which additional tracking data may be collected while the service vehicle is drifting toward the primary object. This analysis only takes into consideration of the sun angle and a maximum range constraint. It was determined that EchoStar 17 would be in view 58% of the time and Object A would be in view 49% of the time. This indicated that track date could likely be collected for both objects during the RPO sequence.

Mission constraints are supplied by the satellite O/O to the collision risk management team at this point. This information is used to customize the avoidance maneuver for the satellite's mission. EchoStar 17 has constraints on its longitude and eccentricity that govern the maneuver's direction and timing. A positive burn will be performed to counter the satellite's natural eastward drift and the maneuver will take place at apogee to minimize eccentricity growth.

SpaceNav maneuver planning software was used to find the minimal magnitude maneuver that sufficiently reduced the collision risk by lowering the Pc value to an acceptable level. The target maneuver time was the time of the apogee crossing that occurred approximately 1.5 orbital periods prior to the TCA. This left sufficient time for orbit updates to occur to verify that the event had been successfully mitigated. The initial maneuver plan had a maneuver magnitude of 0.0021 m/s with a burn centroid of 30 Jan 2014 13:17.

4.1.3.3 – Phase 2 – Construction of the baseline RPO trajectory and mission plan

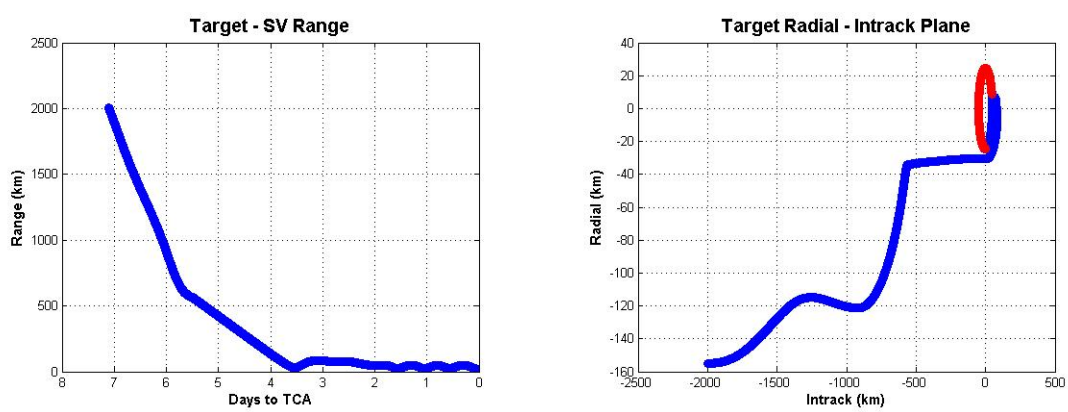
Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*
• Continue to provide conjunction event data to collision risk management team	• Detailed RPO trajectory created with series of 7 maneuvers o Total DV: 7.746 m/s • Constraints imposed on coverage analysis shows percentage of time objects are visible o EchoStar 17: 39.5% o Object A: 8.4%	• Continue risk assessment o Confer with JSpOC to ensure tracking of objects is sufficient

A detailed RPO trajectory was designed for the service vehicle to rendezvous with EchoStar 17. The maneuver plan is presented in Table 8. This places the service vehicle in a circumnavigation orbit around EchoStar 17 at TCA – 2.3 days. Refer to Section 3.3 for a detailed description of the RPO trajectory and maneuver sequence.

Table 8: RPO maneuver plan for rendezvous with EchoStar 17

Maneuver	Maneuver Time	Delta-V (m/s)
DV1	26 Jan 2014 02:00	1.671
DV2	26 Jan 2014 15:02	1.320
DV3	27 Jan 2014 13:12	0.733
DV4	28 Jan 2014 00:15	0.719
DV5	29 Jan 2014 00:44	0.562
DV6	29 Jan 2014 12:32	0.908
DV7	29 Jan 2014 18:32	1.833

Relative trajectory plots for the motion of the service vehicle relative to EchoStar 17 are shown in Figures 3. Figure 3b shows the motion of the service vehicle in the Radial-Intrack plane of the Radial, Intrack, Crosstrack frame centered on EchoStar 17. The final points in time are colored in red for Figure 3b.



(a) (b)

Figure 3: Relative trajectory of service vehicle relative to EchoStar 17.
(a) Range and (b) Relative Radial-Intrack plane

Simulated azimuth and elevation observations of both objects were generated for this scenario. Observation times were calculated based on the following set of criteria,

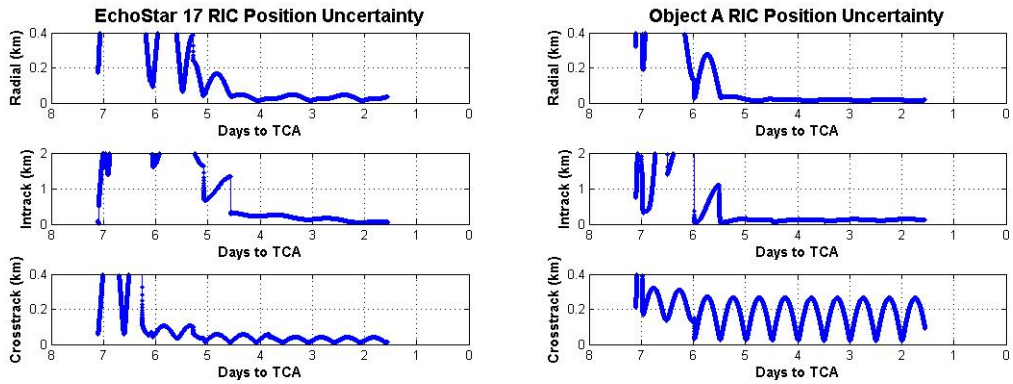
- Range from service vehicle to object is less than 1500 km
- Sun – object – sensor angle is less than 90 deg
- Observations cannot be taken during eclipse
- Observations cannot be taken while the service vehicle is maneuvering
- Track times are 30 minutes or less.

Based on this criteria it was found that EchoStar 17 would be visible 39.5% of the time and Object A would be visible 8.4% of the time.

4.1.3.4 – Phase 3 – Mission Plan Execution

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*
• Decide to deploy service vehicle with concurrence from service vehicle team that mission can be accomplished • Decide to proceed with service vehicle docking and avoidance maneuver due to continued high risk	• Execute RPO maneuver sequence • Tracks objects and perform OD o EchoStar 17: 11 tracks o Object A: 9 tracks • Re-plan RPO maneuver sequence with state data from OD o Change in DV from initial plan: -0.077 m/s • Execute avoidance maneuver o Maneuver time: 30 Jan 201413:17:08 o Maneuver Magnitude: 0.0018 m/s	• Processing of daily CSMs shows risk remains high o All Pc values > 1.0E-2 • Perform risk assessment with state data from OD o All Pc values > 1.0E-1 • Re-plan avoidance maneuver with state data from OD o Change in DV from initial plan: -0.0003 m/s • Perform collision risk assessment following avoidance maneuver o Pc < 1e-10 o risk successfully mitigated

Phase 3 begins with the decision to deploy the service vehicle. For this scenario the decision was made at TCA – 8 days following the receipt of three updates from the JSpOC for the close approach. The service vehicle began the RPO maneuver sequence with the first maneuver taking place at 26 Jan 2014 02:00. During this phase 11 tracks were collected on EchoStar 17 and 9 tracks were collected on Object A. An Unscented Kalman Filter (UKF) was used to process the observations and produce new state vector solutions for both objects. The a priori state vectors were taken from the latest available JSpOC products that were dated prior to the first observation time. Figures 4 provide the position uncertainties that were obtained from the UKF.



(a) (b)

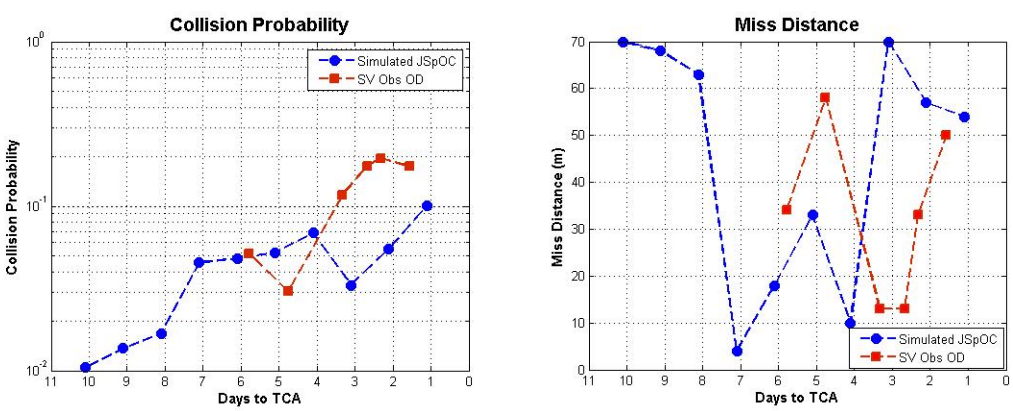
Figure 4: RIC position uncertainties from the UKF performed with service vehicle observations for (a) EchoStar 17 and (b) Object A

The results from these ODs provided a reduction in the position uncertainty as compared to the simulated JSpOC data. Comparisons were made after the data was propagated to TCA since that is how the covariance data on CSMs is presented. The average reduction of the total position uncertainty is shown in Table 9.

Table 9: Percent reduction in total position uncertainty gained through service vehicle tracking

	EchoStar 17	Object A
Percent Reduction in Total Position Uncertainty	36%	42%

Following each orbit determination the risk assessment process was performed. Figures 5 show a comparison of the Pc and miss distance from the two sources of state information. The results obtained with the use of the service vehicle observations are in good agreement with those from the simulated JSpOC results and reinforce the need for an avoidance maneuver to mitigate the collision risk. The reduction in position uncertainty did not have a large effect on the Pc for this close approach.



(a) (b)

Figure 5: Event trends for EchoStar 17 vs. Object A comparing simulated JSpOC results to those of state solutions using service vehicle observations. Trends of, (a) Pc and (b) miss distance.

Re-planning of the RPO maneuver sequence is also performed based upon the new state vector information. This step is necessary to ensure that the service vehicle is on-track to rendezvous with the target satellite properly. For this scenario the maneuver plan was re-planned three times resulting in a 0.077 m/s reduction in the total delta-V. The total delta-V used was 7.669 m/s.

As with the RPO maneuver sequence, the avoidance maneuver was re-planned based upon the new state vector information that was available. The maneuver is planned such that it creates sufficient separation between the position uncertainty ellipsoids at the TCA to reduce the collision risk; therefore, changes in both position and position uncertainty can drive changes to the avoidance maneuver. For this close approach there was little change to the maneuver time or magnitude. The final re-plan resulted in a maneuver time of 30 Jan 201413:17:08 and a maneuver magnitude of 0.0018 m/s.

Following the avoidance maneuver, the Pc value was 2.513e-11 and the miss distance was 833.0 m. No other close approaches between these objects posed a threat of collision. The service vehicle remained attached to EchoStar 17 until the TCA past so that additional risk was not imposed onto the problem by having three objects in the same vicinity at the TCA.

4.2 Conjunction Event Scenario #2 – AMSC 1

For scenario #2 a close approach was simulated for the geosynchronous satellite AMSC 1. A secondary object, Object B, was simulated with an orbit designed to create a high-risk close approach with AMSC 1 on 23 Aug 2013 15:39. The presentation of this scenario is similar to that of scenario #1. Simulated JSpOC CSMs were generated for this event.

4.2.1 Initial Conditions

The orbital elements and physical parameters of both objects at TCA are shown in Table 10. Both objects have nearly circular, geosynchronous orbits with non-zero inclinations.

Table 10: Orbital parameters and physical characteristics for AMSC 1 and Object B

Parameter	AMSC 1	Object B
epoch	23 Aug 2013 15:39:29.908	23 Aug 2013 15:39:29.908
semi-major axis (km)	42163.992	42152.789
eccentricity	0.000376	7.526e-10
inclination (deg)	7.966	14.501
argument of perigee (deg)	94.134	24.818
RAAN (deg)	54.213	79.145
true anomaly (deg)	315.190	0.000
radial cross section (m^2)	28.0	1.0

4.2.2 Initial close approach prediction results

The close approach between AMSC 1 and Object B was first reported to the satellite O/O at TCA – 9.6 days. Risk analysis was performed using data from the JSpOC CSM product. The results provided in Table 11 indicate that the collision risk is high.

Table 11: Initial risk assessment for AMSC 1 vs. Object B

Days to TCA	Collision Probability	Miss	Radial	In-track	Cross-track
10	6.32E-03	67.3	38.9	54.8	3.8

4.2.3 Event Details

The major activities of the planning and execution of the service vehicle mission will be presented here. The major activities are presented in Table 12. The sequence of events is similar to that of scenario #1, however, the mission goal of the service vehicle will change in this scenario.

Table 12: Timeline of major activities with corresponding phases

Phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**
Days to TCA	**9 - 10**	**9**	**8**	**0 - 8**
Major Activities	• Receipt of initial event notification • Establish collision risk • Generate initial avoidance plan	• Generate first-order RPO maneuver sequence • Perform coverage analysis of both objects • Include mission constraints in avoidance maneuver planning	• Generate detailed RPO maneuver sequence • Add constraints to coverage analysis • Continue risk assessment	• Decide to deploy service vehicle • Track both objects & perform OD • Continue risk assessment • Re-deploy service vehicle as SSA sensor and continue to track objects

4.2.3.1 Phase 0 – Establishment of the Collision Risk

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*
• Received initial event notification at TCA-9.6 days • Additional CSM received at TCA-8.6 days • Products provided to collision risk management team	• Request vehicle specific data from satellite O/O	• Processing of first two CSMs shows event is high risk • Initial avoidance maneuver planning shows maneuver of +/- 0.003 m/s at TCA-2 days will mitigate risk

The first two CSMs received for this indicated that the close approach had a high risk. The initial notification came on 14 Aug 2013. Risk assessment calculations resulted in a Pc value of 6.32E-03 and a miss distance of 67.3 m. The initial avoidance maneuver plan showed that a maneuver of +/- 0.003 m/s taking place 1.5 to 2 days prior to TCA would successfully mitigate the risk.

4.2.3.2 – Phase 1 – Service Vehicle Availability

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*

• CSM received at TCA-7.6 days provided to collision risk management team
• Provide mission constraints
  o Maneuvers should counter natural eastward drift
  o Eccentricity growth should be minimized
	• First-order RPO trajectory shows that service vehicle can dock at approximately TCA-2 days
	• Initial coverage analysis shows percentage of time objects are visible
	  o AMSC 1: 60%
	  o Object B: 53%
		• Processing of third CSM shows risk remains high
		• Avoidance maneuver planning shows maneuver of +0.003 m/s at apogee crossing TCA-1.4 days will mitigate risk and satisfy mission constraints

For scenario #2, only the initial RPO maneuver planning was performed. This planning showed that the service vehicle would arrive at the circumnavigation orbit about AMSC 1 at approximately TCA – 2 days. Coverage analysis of the objects showed that they would be visible a sufficient amount of time to allow for the collection of track data. The service vehicle will be able to view AMSC 1 and Object B, 60% and 53% of the time, respectively.

Mission constraints for the AMSC 1 satellite are similar to EchoStar 17. Both have a natural eastward drift and need to maintain a near-circular orbit. A positive burn will be performed to counter the satellite's natural eastward drift and the maneuver will take place at apogee to minimize eccentricity growth. The target maneuver opportunity for the avoidance maneuver was the apogee crossing that occurred 1 – 2 days prior to TCA. The resulting time of the maneuver was 22 Aug 2013 05:39 and the minimal burn magnitude to mitigate the collision risk was 0.0028 m/s.

4.2.3.3 – Phase 2 – Construction of the baseline RPO trajectory and mission plan

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*

• Continue to provide conjunction event data to collision risk management team	• Detailed RPO trajectory created with series of 7 maneuvers
	  o Not modeled in this scenario
	• Constraints imposed on coverage analysis shows percentage of time objects are visible
	  o AMSC 1: 42.5%
	  o Object B: 9.3%
		• Continue risk assessment
		  o Confer with JSpOC to ensure tracking of objects is sufficient

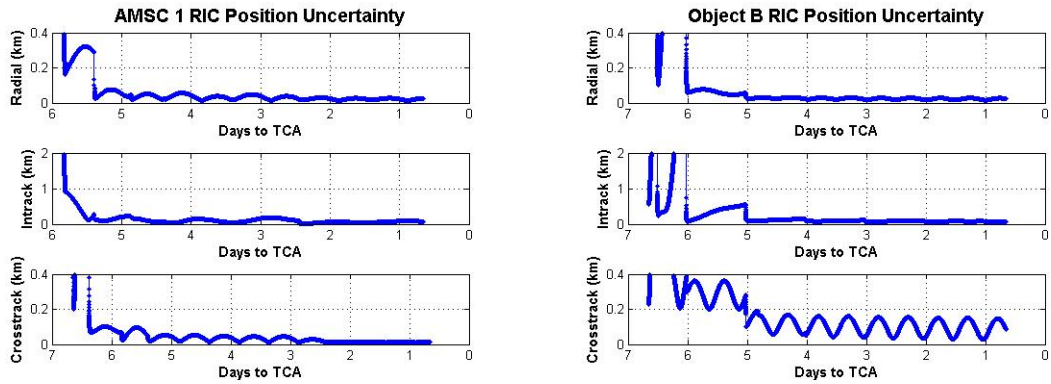
Simulated azimuth and elevation observations of both objects were generated using the same criteria as scenario #1. Coverage analysis confirmed that the objects were visible a sufficient amount of time to gather tracking data to aid in collecting observations to improve the orbit knowledge of the objects. Analysis showed that AMSC 1 would be visible 42.5% of the time and Object B would be visible 9.3% of the time.

4.2.3.4 – Phase 3 – Mission Plan Execution

Satellite owner/operator	*Servicing Vehicle Navigation and Mission Operations Team*	*Collision Risk Management Team*

• Decide to deploy service vehicle with concurrence from service vehicle team that mission can be accomplished
• Decide to abort service vehicle docking and avoidance maneuver
• Decide to redirect service vehicle to stay in vicinity and provide SSA support
	• Execute RPO maneuver sequence
	• Tracks objects and perform OD
	  o AMSC 1: 12 tracks
	  o Object B: 7 tracks
	• Re-plan RPO maneuver sequence with state data from OD
	  o Not modeled in this scenario
		• Processing of daily CSMs shows risk remains high
		  o All Pc values > 1.0E-2
		• Perform risk assessment with state data from OD
		  o Pc drops to zero

Phase 3 begins with the decision to deploy the service vehicle. For this scenario the decision was made at TCA – 7.4 days following the receipt of three updates from the JSpOC for the close approach. Tracking of both objects began at TCA – 6 days. While adhering to the tracking restrictions provided in scenario #1, 12 tracks were collected for AMSC 1 and 7 tracks were collected for Object B. All observations were processed with a UKF. The position uncertainties as determined by the UKF are presented in Figure 6 for both objects.



(a) (b)

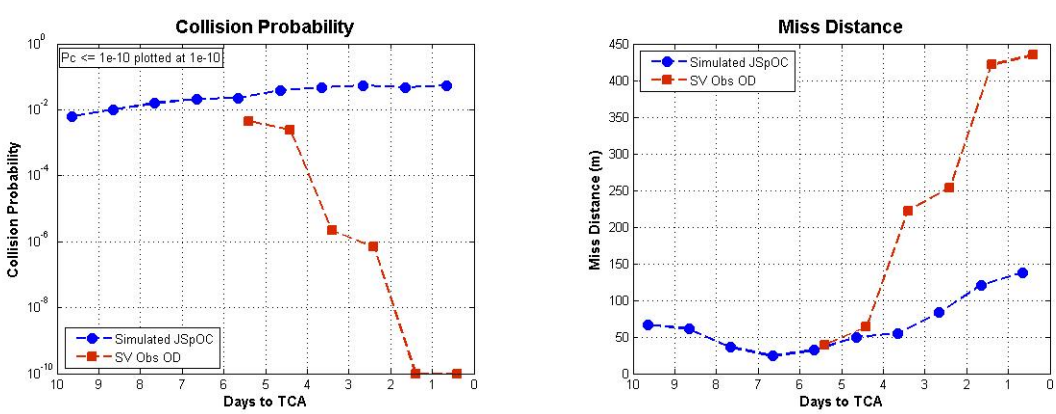
Figure 6: RIC position uncertainties from the UKF performed with service vehicle observations for (a) AMSC 1 and (b) Object B

The covariance from these ODs provided a reduction in the position uncertainty as compared to the simulated JSpOC data. Comparisons were made after the data was propagated to TCA. The average reduction of the total position uncertainty is shown in Table 13.

Table 13: Percent reduction in total position uncertainty gained through service vehicle tracking

	AMSC 1	Object B
Percent Reduction in Total Position Uncertainty	34%	55%

The risk assessment process was performed following each OD. The use of the increased orbital knowledge obtained through service vehicle tracking produced a dramatic change in this scenario. Figures 7 provides the Pc and miss distance trends for the risk analysis performed on the simulated JSpOC solution and state solutions from the UKF OD. Following the third OD at the TCA – 3.5 day point the Pc value dropped from 4.70E-02 to 2.20E-06 and the miss distance increased from 55.0 m to 223.6. Given the new risk assessment, a maneuver would not be required to mitigate the risk.



(a) (b)

Figure 7: Event trends for AMSC 1 vs. Object B comparing JSpOC results to those of state solutions using service vehicle observations. Trends of, (a) Pc and (b) miss distance.

At this point it was decided to forgo the docking of the service vehicle. The mission was redefined such that the service vehicle would be put to use solely as an additional sensor providing improved orbital knowledge for the objects. To accomplish this, the service vehicle was put into an orbital altitude of GEO+35 km. This moved the service vehicle from its position in front of AMSC 1 to a position that provided a drift rate of 0.5 deg/day westward. AMSC1 then drifted under the service vehicle and additional tracking took place on both objects. As seen in Figures 7 the Pc continued to go down and the miss distance increased; effectively reducing the collision risk to zero.

The service vehicle's primary utility in this scenario is that of a SSA sensor. The tracking of both objects and the corresponding orbit determination solutions provided improved information for the risk assessment process. The collision risk became sufficiently low such that an avoidance maneuver was not needed and the docking of the service vehicle was not required. Had the service vehicle not been deployed to provide improved knowledge of the close approach, an avoidance maneuver would have been required.

5. CONSTELLATION DESIGN CONSIDERATIONS

A key assumption in the preceding analysis is that the planning and execution of rendezvous and proximity operations for collision avoidance at GEO can occur within the framework of the current conjunction assessment advisory process. The timeline begins at TCA-10 days. The duration of the RPO maneuvers planned to be in the 3 to 4 day range, with some allocation for COLA planning and approval, the remaining question for an on-orbit service to mitigate collision risk is how to ensure that the SV can reach a CV in time to perform the service. In this section we consider the design parameters of interest.

The viability of on-orbit servicing has been demonstrated by the progress made by various government programs, past and present, including DARPA Orbital Express, NASA Hubble Servicing Missions, NASA Restore, DARPA Phoenix, and others [5]. With the increasing interest in commercialization of this industry, it seems inevitable that some technical solution shall emerge to meet the rising demand. With the number of high value GEO satellites in orbit numbering in the hundreds, it stands to reason that typical business case models for commercial missions will involve multiple servicer satellites in operation.

A first look at basic response capability of such a constellation must consider several factors. First, the number of SV's deployed is modeled. Second, how the SV's are distributed about the GEO Belt is defined. Next the CONOPS for the relative drift orbit when not in a tasked mode for mated operations must be defined. Finally, the delta-v required for a given drift transfer CONOPS derived to provide a first order look at feasibility.

The number of vehicles in an SV fleet will influence the coverage area within the GEO Belt for a given CONOPS. Assuming an evenly distributed fleet, the number of vehicles is modeled as 4, 6, and 8 for comparison. For a fleet of 4 evenly distributed SV's, the largest arc of longitude to traverse in response to a rendezvous tasking mission is 45 degrees, assuming SV capability to travel eastward and westward. In the simplest CONOPS, all SV's are drifting below the GEO belt (or all above it). Therefore the cost to accelerate along the nominal drift direction is lower than to the cost to raise the SV orbit above (or below) the belt and change drift rate for the same magnitude in the opposite direction.

Selection of the nominal drift orbit is another factor to consider. The delta-v cost to rendezvous with a client within the 10 day timeframe outlined in section 3.3 will vary based on drift rate necessary. Since larger relative drift rates are achieved with larger differences in orbit altitude, the delta-v cost to achieve the necessary drift rate must be balanced against the required response time. For this analysis GEO – 155 km is used as the notional drift orbit altitude for the SV fleet. Also, the drift orbit for the SV fleet is assumed to be the same for the entire fleet.

We assume that planning and execution of the RPO maneuvers requires 5 days. Therefore, the time remaining to respond to a rendezvous task at GEO for collision avoidance is 5 days. Using impulsive maneuver assumptions, the delta-V required to achieve full coverage of the GEO Belt is shown in Table 14. The maximum drift rate required for each fleet size is

$$\dot{\lambda}_{MAX} = \frac{360}{2nt_{trans}} deg/day$$

Where n = number of SV's in fleet, t_{trans} = 5 days.

Table 14: Delta-V required to achieve full coverage of the GEO Belt for different service vehicle fleet sizes

# SV's	MaxDrift Rate Required (deg/day)	Delta-V Eastward (m/s)	Delta-V Westward (m/s)	Average (m/s)
4	9	45.1	57.2	51.1
6	6	28.3	39.9	34.1
8	4.5	19.9	31.3	25.6

Using impulsive Hohmann transfer maneuver assumptions, the Delta-V required to achieve the maximum drift rate is calculated from GEO – 155 km. Note that Eastward drift rates require less Delta-V than westward drift rates, due to the additional altitude change above the GEO Belt required for Westward drift rates. Next, the conclusion of the transfer to max drift is a maneuver to relative altitude difference of 155 km, above or below the GEO Belt. From this point the RPO sequence shown in Section 3.3 may be modeled. Finally, the cost to return to GEO – 155 km is added. With no way of knowing where potential clients will require service, we model delta-v cost as an average of East and West values drift cost. Table 14 shows the cost in delta-v for a fleet size of 4, 6, and 8 SV's.

At first read the delta-v table may not convey any operational limitations to achieving total coverage of the GEO belt with a small constellation size as presented. However, the impulsive maneuver assumptions made for this analysis require some scrutiny. The high level of maneuver capability required for a servicing vehicle to perform multiple rendezvous and mated operations at GEO require high efficiency propulsion systems performance. Therefore high performance technologies such as Electric Propulsion are required, characterized by high specific impulse and low thrust. Low thrust will lead to very long maneuver durations. Investigation of the maximum delta-v delivered over one-half the transfer time, assuming constant thrust acceleration followed by constant thrust deceleration, will set the performance limit for a given SV design. Further investigation will improve the understanding of accessibility to the GEO Belt of various SV designs and CONOPS.

6. CONCLUSIONS & FUTURE WORK

Operational collision risk management requires spacecraft operators to perform daily evaluation of close approach predictions. Since the size of the orbital debris population continues to grow, the need for more frequent collision avoidance maneuvers is required. In order to save fuel and increase mission lifetime, the utilization of a servicing vehicle has been introduced. We demonstrated that use of a servicing vehicle is achievable given the timeline constraints imposed by operational conjunction analysis. Future work includes formal development of the constellation design trades that we introduced in Section 5. Additionally, we intent to explore optimal tracking collection schemes for the servicing vehicle.

7. REFERENCES

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