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Attached for your information and use is the final report for Task 16, On-Orbit Asset Management Study. The Final Briefing was provided directly to the Air Force at Phillips Laboratory.

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FINAL REPORT

LOCKHEED MARTIN ASTRONAUTICS

P.O. BOX 179

DENVER, CO 80201

ON-ORBIT ASSET MANAGEMENT SYSTEM (OOAMS)

SEPTEMBER 1995

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TABLE OF CONTENTS

1.0 Executive Summary	1
2.0 Introduction	3
2.1 Background And Study Definition	3
2.2 System Groundrules And Assumptions	3
3.0 Mission Analysis	7
3.1 Mission Selection Process	7
3.2 Description Of Selected Missions	8
3.3 Mission Analysis Groundrules	8
3.4 Mission Maneuvering Scenarios	9
4.0 Utility Assessment	11
4.1 Increased Orbital Lifetime	11
4.2 Reduced Constellation Size	14
4.3 Improved Responsiveness	16
4.4 Increased Mission Capability/Tactical Advantage	18
4.5 Cost Assessment	19
5.0 Performance Goals Definition	26
6.0 Conclusions	29
Appendix	31
Bibliography	32
List Of Acronyms And Abbreviations	33

LIST OF FIGURES

Figure 1	Mission identification methodology.	7
Figure 2	Station-keeping lifetimes based on 5-yr N ₂ H ₄ propellant load.	11
Figure 3	Station-keeping lifetimes based on 10-yr N ₂ H ₄ propellant load.	12
Figure 4	Longitudinal (E/W) movement propellant comparison.	13
Figure 5	Improved lifetime analysis summary.	14
Figure 6	Example restart analysis for reduced constellation size.	15
Figure 7	Summary for reduced constellation size analysis.	16
Figure 8	Funding profiles.	20
Figure 9	Peak annual funding requirements.	21
Figure 10	Learning curve sensitivity.	23
Figure 11	DDT&E and unit cost sensitivity to program stretchout.	24
Figure 12	Cost distribution by program element.	25
Figure 13	Available missions by operational altitude.	27
Figure 14	Total impulse delivered vs. propellant consumed.	28

LIST OF TABLES

Table 1	Key study performance goals.	4
Table 2	Goals for future on-orbit asset management study efforts.	5
Table 3	Proposed system requirements.	6
Table 4	Mission summary information.	8
Table 5	Mission analysis groundrules.	9
Table 6	On-orbit maneuverability benefits and operational scenarios.	10
Table 7	Maneuver types by mission scenario.	10
Table 8	Mission scenario applicability.	10
Table 9	Improved responsiveness - restart analysis.	17
Table 10	Restart analysis for tactical advantage.	18
Table 11	Ten year break-even analysis.	22
Table 12	Performance goal summary.	26

1.0 EXECUTIVE SUMMARY

This study was sponsored by the U.S. Air Force Phillips Laboratory's Bimodal Power and Propulsion Program to determine if on-orbit maneuvering using bimodal power and propulsion technology would be useful in meeting the evolving role of space assets in military operations. Military operations are being pressured by both declining budgets and changing emphasis. The changing emphasis, most recently noted during Desert Storm, have included requests for rapid deployment of satellites, rapid redeployment on orbit, improved coverage, and increased sensor resolution. Declining budgets have prompted the need to decrease launch cost, increase satellite lifetime, and accomplish more with each satellite.

This study evaluates an On-Orbit Asset Management System (OOAMS) with respect to its ability to: 1) Lengthen lifetime of on-orbit assets, 2) Decrease the number of satellites required to perform a mission, 3) Increase responsiveness, and 4) Provide increased mission capability/tactical advantage.

The study started with development of a mission model. The 1994 National Mission Model was screened to identify candidate satellite systems for an OOAMS. The OOAMS is defined as an integral part of the payload in that it provides the power, propulsion, and guidance, navigation, and control (GN&C) functions to the payload. Because many of the satellite systems in the National Mission Model are existing and it was not known if it would be cost effective to modify these specific systems for use with the OOAMS, the selected missions were considered representative of those types of missions which may benefit from an OOAMS. A resultant set of 10 representative missions was used in conjunction with an initial set of conceptual performance goals and derived system requirements to perform the study analyses.

Four major conclusions were derived from the mission analyses and associated utility assessments for the nuclear bimodal OOAMS. First, the lifetime analysis suggested that the larger satellite systems (representative of NASA and Military communication systems, surveillance satellites and earth observing satellite systems) would benefit most from a nuclear bimodal OOAMS. Second, an evaluation of satellite constellations indicated that a modest reduction in the number of satellites could be realized using the OOAMS if the thermal restart capability was at least ten. Third, an OOAMS could provide significant improvements in responsiveness (relative to launching new assets) using on-orbit reconstitution of assets. For geostationary assets, an existing satellite could be repositioned in 1.5 to 4 days depending on the constellation and moving an asset from an orbital

depot to an operating orbit could be done in 3 to 5 days. Also, an in-plane reconstitution of Global Positioning System (GPS) type assets could be accomplished in 3 to 3.5 days. Finally, the study also suggests that a nuclear bimodal OOAMS could provide maneuvers totaling 1000 m/s of ΔV (including return to operating orbit) for threat evasion, a one-way $\Delta V = 128$ to 129 m/s for limited plane change capability, up to four roundtrips for debris collision avoidance, and four to six roundtrips for improved viewing capabilities.

A top level utility assessment was performed to address system cost issues relating to funding profiles, first unit cost, and break-even analysis. Peak funding requirements are directly proportional to total design, development, test, and evaluation (DDT&E) costs. Analysis indicates that for a peak funding requirement of \$50 million, a level similar to that funded on the nuclear SP-100 program, the total DDT&E cost must not exceed \$250 million. This appears to represent quite a challenge, but needs to be re-evaluated when design details are available to develop an estimate. Using the initial performance goal of < \$25 million for each unit after the 5th unit, first unit costs were derived using a series of cost improvement curves. The nominal projected first unit costs of \$30-\$35 million appear low for this type of system, but cannot be fully evaluated until the concept design matures. Hypothetical scenarios were created to show annual cost savings which must be realized to provide a break-even of various DDT&E costs over a 10 year period. The annual cost savings required to achieve the 10-yr break-even range from \$ 57 to \$81 million for a DDT&E cost of \$500 million and from \$180 to \$245 million for a DDT&E cost of \$1.5 billion.

The study concluded with performance goal definition. The three primary recommendations are associated with mission related vehicle performance capabilities. First, the addition of a conceptual performance goal (CPG) for operational altitude is recommended. Using mission capture and orbital lifetime criteria, the recommended minimum orbital altitude is 900 km. Next, in order to support reduction in constellation size, improved responsiveness, and enhanced mission capabilities, the on-orbit thermal restart capability should be increased from five to ten. And finally, an analysis of total impulse as a function of propellant consumed for the selected missions suggests that the total impulse be increased from 40 million Newton-seconds to approximately 48 million Newton-seconds.

2.0 INTRODUCTION

2.1 BACKGROUND AND STUDY DEFINITION

Benefits of on-orbit maneuverability are not clearly understood at this time. The U.S. Air Force Phillips Laboratory has sponsored this study to determine if on-orbit maneuvering using bimodal power and propulsion technology would be useful in meeting the evolving role of space assets in military operations. Military operations are calling for rapid deployment of satellites, rapid redeployment on orbit, improved coverage, and increased sensor resolution. In addition to evolving roles, there is increased emphasis on affordability as declining budgets have prompted the need to decrease launch cost, increase satellite lifetime, and accomplish more with each satellite.

The bimodal technology employs a single system to generate electrical power, direct thermal thrust, and potentially electric propulsion. The energy source may be either nuclear or solar. The main body of the study addresses the nuclear bimodal system. The appendix addresses solar system mission capabilities. For purposes of this study, the technology is employed to move a space asset subsequent to placement in its mission orbit. The lift phase, defined as the Earth-to-LEO and the LEO-to mission orbit phase, is being investigated in a complementary study, W.J. Schafer's Launch Vehicle Step-Down Study.

Study results are presented in terms of Mission Analysis (Section 3.0), Utility Assessment (Section 4.0), and Performance Goals Definition (Section 5.0).

2.2 SYSTEM GROUNDRULES AND ASSUMPTIONS

The Bimodal System Conceptual Performance Goals defined by Phillips Laboratory provided an initial set of guiding parameters for the study. Table 1 is a subset of key goals influencing results of this study. Many of the original CPGs were applicable to the system, but did not directly influence the study results. These goals, shown in Table 2, for completeness, could impact future assessments of an OOAMS. Table 3 defines a set of derived system level requirements which were necessary to clarify the scope and intent of the OOAMS.

Table 1 Key study performance goals.

On-Orbit Thermal Propulsion Operations	
Category	Value
Thrust	At Least 60 N
Specific Impulse	≥ 600 Sec
Lifetime	3.63×10^6 N-s
Restartability	Minimum of 5
Electrical Power System	
Category	Value
Power to User	10 kW _e
Electric Power Lifetime	10 Years
Startup & Housekeeping	Provide for Startup of Bimodal Power System & Operation of Satellite Prior to Bimodal Power Output
Schedule	
Category	Value
Flight Dem/Val	5-7 Years After Start (1.5 year system lifetime)
IOC	6-8 Years After Start (5 year system lifetime)
FOC	8-10 Years After Start (10 year system lifetime)
Cost	
Category	Value
Unit Cost	< \$25M From 5th Unit on

Table 2 Goals for future on-orbit asset management study efforts.

Physical Parameters	
Category	Goal
Medium/Intermediate Launch Vehicles	Atlas IIAS Shall Boost More Than 70% of Titan IV/Centaur Instrumented Payloads to GEO
Shielding	Radiation Attenuated at the 3.7 m Diameter Payload Shall Not Exceed 1×10^{13} nvt, 1×10^6 rads
Volume Constraints	Must Be Compatible With Potential Atlas IIAS Payload Fairings (Max. 3.65 m diameter)
Dynamic Envelope	
Category	Goal
Launch Config.	Should Be Compatible With Delta, Atlas, Titan III and IV
Deployed Spacecraft	Deployed Power Plant Shall Have No Resonant Structural Frequency Under 1 Hz and the Number of Resonant Frequencies Under 10 Hz Shall Be Minimized
Undeployed Spacecraft	System Shall Be Compatible With LV Environments and Meet Structure Stiffness Requirement of LV When Employed With Maximum Anticipated Instrumented Payload
Design Reliability	
Category	Goal
Reliability	The Probability of Meeting the Electrical Power and Thermal Propulsion Performance Requirements for the Life Times Specified Shall Be > 0.95
Single Point Failure	The System Shall Have No Credible Mission Ending Single Point Failures. Credible Failures Have a Probability of Occurrence of Greater Than 1×10^{-4}
Start and Restart	If System Is Operationally or Accidentally Shutdown on Orbit for Any Reason Other Than Final Shutdown, It Must Be Restartable
Cost	
Category	Goal
Transportation Cost	System Shall Be Fuelable at Launch Site to Minimize Costs of New Facilities and Shipping
Qualification and Testing	
Category	Goal
Qual. Non-Nuclear Testing	System Must Be Able to Be Tested As a Unit Using Non-Nuclear Heating Both for Development and Acceptance Testing of Both Power and Propulsion Subsystems
Nuclear Criticality Testing	System Shall Be Tested for Nuclear Criticality of Flight Hardware As Part of Acceptance Verification
Reliability Analysis and Testing	Reliability Shall Be Demonstrated Using Analysis and Test
Flight Qual/ Accept.	Testing Shall Meet MIL-STD-1540.
Facilities	Testing To Be Conducted in Existing Facilities (If possible)
Facilities	Facility Modifications Shall Be Minimized

Table 3 Proposed system requirements.

Category	Requirement
System Design	The On-Orbit Asset Management System Will Be Fully Integrated With the Payload
System Design	The System Will Provide Power, Propulsion, and GN&C Functions to the Payload
Payload	The System Will Be Based on a Design Which Minimizes Redesign of the Instrumented Payload
Reentry	The System Shall Prohibit Reentry Into the Earth's Atmosphere/Biosphere

3.0 MISSION ANALYSIS

3.1 MISSION SELECTION PROCESS

In order to assess the benefits of an OOAMS, a mission model was established. The model, which identifies missions potentially benefiting from an OOAMS, was created by screening the 1994 Air Force Space Command National Mission Model. Because the nuclear bimodal OOAMS will take several years to develop and will be an integral part of the payload providing the power, propulsion, and GN&C functions, specific missions could not be identified. Thus, the missions in the OOAMS mission model are to be considered "representative" of the types of missions that could be flown in the future. The OOAMS mission model development process and screening criteria are highlighted in Figure 1.

AFSPACECOM 1994 National Mission Model

OOAMS Screening Criteria

- Government Missions
- Titan II Class or Larger
- No Space Station Payloads
- No Interplanetary Payloads
- At Least Two Satellites in the Constellation

OOAMS Candidate Satellites

Name	Function	Weight (kg)	Estimated Lifetime (Years)	Orbit	Constellation Size	Current Launch Vehicle
DSO-1	Area Broadcast Satellite	1000	10/15	SSO 10° P	4 phases of 1	Space Shuttle
DSO-2	Navigation, Surveillance, and Search Satellite	1000	10/15	SSO	1 phase of 1	Space Shuttle
DSO-3	Military Communications	1170	10/15	SSO	1 phase of 1	Atlas 5
DSO-4	Military Communications	1000	10/15	SSO	1 phase of 1	Atlas 5
DSO-5	Military Communications	1000	10/15	SSO	1 phase of 1	Atlas 5
DSO-6	Military & Civil Search, Rescue, and Communications	1000	10/15	SSO 10° P	1 phase of 1	Atlas 5
DSO-7	Search, Rescue, and Communications	1000	10/15	SSO 10° P	1 phase of 1	Atlas 5
DSO-8	Search, Rescue, and Communications	1000	10/15	SSO 10° P	1 phase of 1	Atlas 5
DSO-9	Search, Rescue, and Communications	1000	10/15	SSO 10° P	1 phase of 1	Atlas 5
DSO-10	Search, Rescue, and Communications	1000	10/15	SSO 10° P	1 phase of 1	Atlas 5

Figure 1 Mission identification methodology.

3.2 DESCRIPTION OF SELECTED MISSIONS

After the mission selection process was completed, 10 missions, six defense and four civil, were identified as potential beneficiaries of a nuclear bimodal OOAMS. These missions are summarized in Table 4.

Table 4 Mission summary information.

Name	Function	Current Spacecraft Mass (kg)	Estimated Adjusted Mass* (kg)	Orbit	Constellation Size	Current Launch Vehicle
DoD-1	Jam Resistant Military Communication	4535	3175	GEO @ 5°	4 planes of 1	Titan IV/Centaur
DoD-2	Survivable Surveillance of Missile and Space Launches	2268	1587	GSO	1 plane of 4	Titan IV/Centaur
DSCS	Military Communications	1179	825	GSO	1 plane of 7	Atlas II
UHF F/O	Military Communications	1325	928	GSO	1 plane of 9	Atlas II
GPS	Military & Civil Space Based Earth Navigational Aid	1134	794	20187 km @ 55°	6 planes of 4	Delta II
DMSP	Military Weather Satellite	825	578	833 km @ 98.7°	2 planes of 1	Titan II
GOES	Civil Weather Satellite	980	686	GSO	1 plane of 3?	Atlas II
TDRS	NASA Communications	2224	1557	GSO	1 plane of 3	Atlas II
EOS	NASA Earth Observation System	5578	3905	706 km @ 98.2°	4 planes of 1	Atlas II
NOAA	Civil Weather Satellite	1023	716	852 km @ 98.7°	2 planes of 1	Titan II

* Estimated Adjusted Mass Is the Estimated Mass of the Spacecraft after the Power, Propulsion, and GN&C Functions Have Been Removed (Estimated Adjusted Mass = 70% of the Current Spacecraft Mass)

3.3 MISSION ANALYSIS GROUND RULES

The mission and vehicle performance analyses were based on the groundrules and assumptions, shown in Table 5. Values for the first category, ΔV 's and Propellant Groundrules, were based on Lockheed Martin standard design practices. Similarly, the tank mass value in the second category of Vehicle Masses, is also considered a standard design value. The bimodal stage mass was derived based on design data provided by Phillips Lab. All of the reactor performance characteristics as well as the usable power for the electric propulsion system were provided by Phillips Lab at the beginning of the study. The Arcjet Isp and efficiency values were based on data obtained from Rocket Research.

Table 5 Mission analysis groundrules.

ΔV 's & Propellant Loads Calculated by Payload and Maneuver Scenario

Flight Performance Reserve	= 2% of Total ΔV
Unusable Propellant	= 1.5% of "Usable" Propellant
LH ₂ Boiloff	= 0.25% per Month

Vehicle Masses

Bimodal Stage	= 2900 kg for NEBA-1 & NEBA-3
OOAMS Tanks	= 20% of Total OOAMS Propellant

Reactor Performance Characteristics

NEBA-1	826 sec Isp
	2200 N Thrust
NEBA-3	820 sec Isp
	88N Thrust

Electric Propulsion Performance Characteristics

Usable Power	= 5 kWe
Arcjet Isp	= 1000 sec
Arcjet Efficiency	= 35%

3.4 MISSION MANEUVERING SCENARIOS

Using the defined groundrules, each of the candidate missions was evaluated to determine if on-orbit maneuverability would provide benefits in terms of 1) Lifetime of on-orbit assets, 2) Reduction in the number of satellites required to perform a mission, 3) Increased responsiveness (relative to launching new assets), and/or 4) Increased mission capability/tactical advantage. The operational scenarios and corresponding maneuvers for each of the four areas are defined in Tables 6 and 7, respectively. Potential applicability of each benefit is correlated to the specific mission types in Table 8. Basically, each mission, with the exception of GPS, could potentially realize benefits in all four categories. Reduction in the number of satellites for the GPS type mission was not possible because the geometric coverage requirements dictate the number of satellites. The utility assessments, section 4.0, quantify benefits which could be realized by the representative missions.

Table 6 On-orbit maneuverability benefits and operational scenarios.

Potential On-Orbit Maneuverability Benefit	Operational Scenarios
Increased Lifetime	<ul style="list-style-type: none"> •Reboost •Station-Keeping
Reduction in the Number of Satellites	<ul style="list-style-type: none"> •Plane Change •In-Plane Position Change
Improved Responsiveness	<ul style="list-style-type: none"> •Replace Failed Satellite •New Satellite Coverage
Increased Mission Capability or Tactical Advantage	<ul style="list-style-type: none"> •Change in Overflight Time or Position •Threat Evasion •Improved Viewing •Debris Collision Avoidance

Table 7 Maneuver types by mission scenario.

Mission Scenario	Corresponding Maneuver Types					
	Reboost	Station-Keeping	Plane Change	In-Plane Position Change	Argument of Perigee Change	Altitude Change
Improved Lifetime	X	X				X*
Reduction in Number of Satellites			X	X	X*	
Improved Responsiveness			X	X	X*	X
Increased Mission Capability			X		X*	X

* Not Evaluated

Table 8 Mission scenario applicability.

Name	Improved Lifetime	Reduction in Number of Satellites	Improved Responsiveness	Improved Mission Capability
DoD-1	X	X	X	X
DoD-2	X	X	X	X
DSOS	X	X	X	X
UMF-FU	X	X	X	X
GPS	X		X	X
LMSP	X	X	X	X
GOES	X	X	X	X
TDPS	X	X	X	X
EOS	X	X	X	X
VOAA	X	X	X	X

4.0 UTILITY ASSESSMENT

4.1 INCREASED ORBITAL LIFETIME

The two aspects of lifetime considered in the analyses were on-orbit station-keeping and satellite maneuvering within a nominal operating plane. The analyses compared the nuclear OOAMS propellant requirements to conventional N_2H_4 propellant requirements. Figure 2 shows the lifetime of the 10 representative missions based on a nuclear bimodal OOAMS propellant load equivalent to the conventional propellant load required to provide a five year lifetime. Figure 3 displays lifetime data, similar to figure 2, for a nuclear bimodal OOAMS propellant load equivalent to the conventional propellant load required to provide a 10 year lifetime.

Figure 2 Station-keeping lifetimes based on 5-yr N_2H_4 propellant load.

Figure 3 Station-keeping lifetimes based on 10-yr N_2H_4 propellant load.

Improved lifetime was also analyzed from the perspective of movement within the satellite's operational plane, assuming the use of the thermal propulsion system. The analysis evaluated the propellant requirements of moving the satellites longitudinally (East/West) at rates of five and 10 degrees per day. Of the 10 representative missions, only the six geostationary missions would require longitudinal movement. The analysis also parameterized the number of maneuvers executed to determine the effects of differing numbers of maneuvers. Again, the nuclear bimodal OOAMS propellant requirements were compared to the requirements for a conventionally propelled satellite. The results of this analysis are shown in Figure 4.

Satellite	Propellant (kg)			
	5 x 5 deg/day Maneuvers		10 x 5 deg/day Maneuvers	
	Bimodal	Conventional	Bimodal	Conventional
DoD-1	120	200	240	400
DoD-2	90	140	180	290
DSCS	80	70	160	150
UHF F/O	80	70	160	150
GOES	70	60	140	130
TDRS	90	140	180	290

***DoD-1, DoD-2, and TDRS
Benefit from Bimodal E/W Movement***

Satellite	Propellant (kg)			
	5 x 30 deg/day Maneuvers		10 x 30 deg/day Maneuvers	
	Bimodal	Conventional	Bimodal	Conventional
DoD-1	780	1390	1720	3450
DoD-2	570	990	1270	2460
DSCS	500	520	1100	1280
UHF F/O	500	520	1100	1280
GOES	500	430	1000	1070
TDRS	570	990	1270	2460

Figure 4 Longitudinal (E/W) movement propellant comparison.

The results of the lifetime analysis, summarized in Figure 5, indicate that the larger geostationary satellites DoD-1, DoD-2, TDRS, and EOS, benefit most from the nuclear bimodal OOAMS.

Satellite	5-yr Benefit*	10-yr Benefit*	
DoD-1	Yes	Yes	Larger Spacecraft (DoD-1, DoD-2, TDRS, EOS) Benefit Most from Bimodal Orbit Maintenance
DoD-2	Yes	Yes	
DSCS	Yes	No	
UHF F/O	Yes	No	
GPS	Yes	No	
DMSP	No	No	DMSP & GOES Do Not Benefit from Bimodal Orbit Maintenance
GOES	No	No	
TDRS	Yes	Yes	
EOS	Yes	Yes	
NOAA	Yes	No	

* Compared to N_2H_4 Mono-Prop ACS

Figure 5 Improved lifetime analysis summary.

4.2 REDUCED CONSTELLATION SIZE

The analyses performed to determine if a nuclear bimodal OOAMS could reduce the number of satellites in a constellation focused on coverage geometry, maneuver ΔV required to maintain proper satellite coverage, and the number of restarts required to execute the maneuvers. GPS was the only mission incapable of constellation reduction due to coverage geometry. Figure 6 shows an example of the restart analysis that was performed for the DoD-1 and DoD-2 missions. The graph shows the number of allowed restarts per year (on average) as a function of the restart capability of the nuclear bimodal OOAMS, lifetime of the satellite, and constellation size reduction. For example, for a restart capability of 10, a 10 year lifetime, and constellation reduction of one, the allowed number of restarts per year would be approximately three. This result means that a DoD-1 satellite would be able to reposition (to provide the coverage of the missing satellite) an average of once per year and a DoD-2 satellite an average of three times in two years. The remainder of the results from the restart analysis and the entire ΔV analysis can be found in the appendix.

*This Type of Analysis Was Completed
for Each Satellite Evaluated*

Figure 6 Example restart analysis for reduced constellation size.

The results of the constellation reduction analysis are summarized in Figure 7. The results assume only one repositioning maneuver is required per year to accommodate the removed satellite(s). One conclusion that can be drawn from the restart analysis is that the reduction in constellation size will drive the nuclear bimodal thermal restart requirement to a value higher than the CPG value of five.

Satellite	Potential of Reducing the Number of Satellites
DoD-1	Possibly Reduced by 1 - Satellite Must Stay on TIV, Thermal Restarts ≥ 10 , $\sim 5^\circ/\text{day}$ East/West Movement
DoD-2	Possibly Reduced by 2 - Satellite Must Stay on TIV, Thermal Restarts ≥ 10 (7, if only reduced by 1), $\sim 30^\circ/\text{day}$ East/West Movement
DSCS	Possibly Reduced by 2 - Satellite Must Stay on Atlas, Thermal Restarts ≥ 4 (3, if only reduced by 1), $\sim 30^\circ/\text{day}$ East/West Movement
UHF F/O	see DSCS
GPS	Not Possible - Satellite Number Is Driven by Coverage Geometry
DMSP	Not Likely - Massive Propellant Requirements
GOES	see DSCS
TDRS	see DoD-2
EOS	Not Possible - Unique Functions of Satellites
NOAA	Not Likely - Massive Propellant Requirements

Assumes Only One Repositioning per Year Is Required to Accomodate Removed Satellite(s)

Reduction of Constellation Sizes Will Drive Thermal Restart Requirement to Greater than the CPG of 5

Figure 7 Summary for reduced constellation size analysis.

4.3 IMPROVED RESPONSIVENESS

The three parameters analyzed in the responsiveness analyses include constellation geometry, maneuver ΔV required to provide the increased responsiveness (shown in the appendix), and number of restarts required to execute the maneuvers. Two basic scenarios, replacement of a failed satellite and the new satellite coverage, were evaluated to assess responsiveness. Results of the restart analysis are shown in Table 9.

Table 9 Improved responsiveness - restart analysis.

Restarts - Replacement Needed

Satellite	from Another Plane	from Within Plane	On-Orbit Reconstitution
DoD-1	3	–	5(3)
DoD-2	–	2	4(2)
DSCS	–	2	4(2)
UHF F/O	–	2	4(2)
GPS	3	2	5(3)
DMSP	–	–	2
GOES	–	2	4(2)
TDRS	–	2	4(2)

(depending on phasing)

New Satellite Coverage

Satellite	Restarts
DMSP	1
NOAA	1
EOS	1

In the case of the replacement maneuvering scenario, replacement from within the orbital plane and from another orbital plane were analyzed depending on the constellation type. On-orbit reconstitution from an on-orbit spares depot was analyzed for all constellation types. The EOS and NOAA missions were not analyzed for replacement needs due to their civil, low responsiveness replacement needs.

In the case of the new coverage maneuvering scenario, the three LEO satellites in the OOAMS mission model were analyzed. The remaining seven missions are high Earth orbiting missions that currently provide the required coverage and are not driven by quick needs to provide new coverage. The civil (NOAA and EOS) missions were included in this case analysis to evaluate their potential needs to provide coverage of an Earth related crisis, i.e., natural disaster or severe weather.

The improved responsiveness analysis provides several conclusions. First, a nuclear bimodal OOAMS supports on-orbit reconstitution of geostationary assets (DoD-1, DoD-2, DSCS, UHF F/O, GOES, and TDRS) using either an “in-use” satellite temporarily or spares from an orbital depot. Temporarily redeploying an asset that is already in use takes from 1.5 and 4 days depending on the constellation, while moving an operational asset from an orbital depot to its nominal operating orbit takes from 3 to 5 days. Second, a nuclear bimodal OOAMS supports “in-plane” reconstitution of GPS assets in 3 to 3.5 days. Because GPS is composed of multiple orbital

planes, an orbital depot is not practical and several on-orbit spares would be required to accomplish the reconstitution. Lastly, LEO assets (DMSP, NOAA, and EOS) would gain only limited responsiveness benefits from a nuclear bimodal OOAMS. Spare LEO assets could be moved from higher LEOs, which have lower orbit maintenance requirements and reduced debris collision probability, into lower operational positions in approximately one hour. A nuclear bimodal OOAMS could also provide a limited plane change capability (128 to 129 meters per second per degree), enabling overflight time and position changes. Generally, each reconstitution maneuver, LEO or geostationary, requires two to five restarts.

4.4 INCREASED MISSION CAPABILITY/TACTICAL ADVANTAGE

Analyses performed to assess increased mission capability and tactical advantage focused on maneuver ΔV and the number of restarts required to execute the maneuvers. Five maneuver types that could provide tactical advantage were evaluated: Plane Change; Argument of Perigee Change; Threat Evasion; Improved Viewing; and Debris Collision Avoidance (reduced probability). The results of the restart analysis are shown in Table 10 as a function of the five maneuver types.

Table 10 Restart analysis for tactical advantage.

Maneuver	Number of Restarts Required
Plane Change	1
Argument of Perigee Change	1
Threat Evasion	≥ 2 (function of desired capability)
Improved Viewing	2 (with return)
Debris Collision Avoidance	4 (with return)

The maneuvering for tactical advantage analysis also provides several conclusions. First, a nuclear bimodal OOAMS could provide a considerable threat evasion capability. Maneuvers totaling 1000 meters per second of ΔV (including return to operating orbit) would be possible, but would require at least two thermal restarts of the nuclear bimodal OOAMS to complete the evasion maneuver and return to the operational orbit. Second, the nuclear bimodal OOAMS could provide a limited plane

change capability, with a one-way $\Delta V = 128$ to 129 meters per second and a single thermal restart requirement. Third, the nuclear bimodal OOAMS could provide a limited debris collision avoidance capability, with four roundtrips possible and each roundtrip requiring four thermal restarts. Finally, the nuclear bimodal OOAMS could provide an “improved viewing” capability, with four to six roundtrips possible and each roundtrip requiring two thermal restarts.

4.5 COST ASSESSMENT

This section addresses some preliminary on-orbit management cost issues. Without specific configuration(s) and mission model(s), a traditional life cycle cost estimate and analysis was not possible. There were, however, five top level cost areas examined to assess impacts and trends. This section presents results and data associated with funding profiles, cost improvement curves, break-even analysis, schedule sensitivities, and typical cost distribution graphs.

A range of DDT&E cost values was established to provide boundaries for the preliminary analysis. The selected values ranged from \$500 Million up to \$1.5 Billion. A preliminary estimate of \$880 M for a nuclear bimodal power and propulsion subsystem unit gathered from an earlier bimodal study was used as a starting point. In an analysis such as this, the absolute values are not as critical as the data trends. The trends will serve to focus future efforts in the appropriate areas. By establishing a wide range we were able to observe the sensitivity associated with the subsequent annual funding and hypothetical break-even analysis.

Using a 10 year FOC goal, DDT&E cost, and the desire for an IOC within 6-8 years of program start, funding profiles were constructed (Figure 8). Because of the need for operational units within 5 years of start, three distributions with relatively high spending in the early years were selected for use in the profiles. The distributions were established based on the percentage of the DDT&E expended by the estimated schedule mid point of 5 years.

Figure 8 Funding profiles.

Peak annual funding requirements were extracted from the funding profiles. Figure 9 illustrates these values by funding distribution and total DDT&E cost. The peak annual funding requirements are directly proportionally to the total DDT&E costs. For the three funding profiles shown above, the \$500M program has the lowest annual funding requirements and these values range from \$86 M - \$102 M. Even though these represent the smallest requirements, they may present quite a challenge in today's environment of declining budgets. As a point of reference for nuclear programs, the SP-100 program was funded at a peak level on the order of \$50 Million. In order to realize a peak annual funding requirement near \$50M, the total DDT&E cost must not exceed approximately \$250 Million, as shown in Figure 9.

Figure 9 Peak annual funding requirements.

The DDT&E cost values were also used in preliminary break-even analysis (Table 11). A range of annual cost savings was determined for each of the three investment cost levels such that a break-even point was achieved in 10 years assuming a 10% interest rate. Because the cost savings could begin at various times with respect to the on-orbit asset management life cycle, a range was applied to try and bound the annual cost savings requirement. The range was established by having savings begin at either program ATP or after the Dem/Val phase. Many different scenarios could result in the savings. Table 11 provides a few options to help provide a better understanding of what the savings might be in terms of satellite elimination. As discussed earlier, specific satellite

systems were not named as beneficiaries of the OOAMS since there were uncertainties in both the OOAMS development schedule and the cost effectiveness of modifying existing systems. The satellite unit cost values, ranging from \$100 million to \$650 million, are representative of existing systems which have been deployed. The analysis only considered satellite unit costs and assumed these were allocated in equal annual amounts over the ten year period.

Table 11 Ten year break-even analysis.

Non-Recurring Investment	Annual Cost Savings Requirement (10 Year Period)	Potential Scenarios to Realize Savings
\$ 1.5 Billion	Option 1 \$180M Option 2 \$245M	Option 1 (Savings begin with ATP) -Eliminate 1 satellite with unit cost of \$500M <i>and</i> -Eliminate 2 satellites with unit cost of \$200M <i>and</i> -Eliminate 2 satellites with unit cost of \$100M Option 2 (Savings begin after Dem/Val) -Eliminate 1 satellite with unit cost of \$600M <i>and</i> -Eliminate 3 satellites with unit cost of \$200M <i>and</i> -Eliminate 3 satellites with unit cost of \$100M
\$1.0 Billion	Option 1 \$115M Option 2 \$165M	Option 1 (Savings begin with ATP) -Eliminate 1 satellite with unit cost of \$400M <i>and</i> -Eliminate 1 satellites with unit cost of \$200M <i>and</i> -Eliminate 2 satellites with unit cost of \$100M Option 2 (Savings begin after Dem/Val) -Eliminate 1 satellite with unit cost of \$650M <i>and</i> -Eliminate 1 satellites with unit cost of \$200M <i>and</i> -Eliminate satellites with unit cost of \$100M
\$0.5 Billion	Option 1 \$57M Option 2 \$ 81M	Option 1 (Savings begin with ATP) -Eliminate 1 satellite with unit cost of \$150M <i>and</i> -Eliminate 2 satellites with unit cost of \$100M Option 2 (Savings begin after Dem/Val) -Eliminate 2 satellite with unit cost of \$200M <i>and</i> -Eliminate 1 satellites with unit cost of \$100M

The unit cost goal of < \$25M from the 5th unit on was used in conjunction with a series of unit cost improvement curves to project a first unit cost estimate. Figure 10 projects first unit cost estimates associated with 88%-95% curves. Based on the aerospace industry paradigm, the OOAMS unit cost improvement curve is expected to be in the range of 93%-95%. The unit cost improvement curve applies to the total unit, not just labor. It accounts for improvements in areas such as touch labor, material lot buys, statistical process control, and performance measurement teams. Using the expected curves, the first unit should cost between \$30M and \$35M. The first unit cost typically includes cost of material, labor, set-up, manufacturing, and overhead. Present estimates indicate this value may be unrealistically low. Although there is no point design estimate, this statement is made based on knowledge that a nuclear bimodal power and propulsion unit alone may cost \$20-27M. Even achieving a 88% or 90% unit cost improvement curve, the goal value of

\$25 M appears too low. Thus, at this time there appears to be a potential discrepancy between the unit cost performance goal and what has been observed on related studies.

Figure 10 Learning curve sensitivity.

Annual funding allocations for government programs often result in schedule stretchouts and as such schedule can adversely influence the program life cycle cost. Data based on the Titan IV program and the Advanced Launch System (ALS) Studies is presented in Figure 11. The analysis assumed that the stretchouts occurred after ATP. For the DDT&E curve, the manpower levels were managed to tasks rather than to the schedule. The unit cost curve assumes that the production skill levels must be maintained throughout the schedule. According to the figure, a 36 month stretchout has the potential to increase DDT&E cost by 18% and increase unit cost by 23%. It is important to incorporate data and trends of this nature into a program risk analysis early in the life cycle.

Figure 11 DDT&E and unit cost sensitivity to program stretchout.

Typical DDT&E and first unit cost distribution graphs, shown in Figure 12, were created based on an extensive database of upper stage studies and programs. These graphs indicate that propulsion is usually the single largest cost item in both estimates. Although the percentages may vary for a nuclear bimodal OOAMS, propulsion is likely to remain a driving element. Thus, early definition and understanding of the propulsion system requirements will be essential to providing a system which effectively reduces operational costs and provides an affordable system. Specific OOAMS cost distribution graphs should be developed as soon as sufficient design data is available.

Figure 12 Cost distribution by program element.

5.0 PERFORMANCE GOALS DEFINITION

Performance goals are often reflected as system requirements and are defined based on consideration of cost, risk, schedule and operational utility. The performance goals defined as a result of this study are summarized in Table 12. Three of the performance goals relate to mission capabilities and two are associated with cost. For the mission related goals, one new performance goal was added and two others were identified for revision: Operational Orbit (recommended new CPG), Total Thermal Impulse Capability (CPGs 3.1.1.3 and 3.1.2.3 from the Phillips Lab documentation), and Thermal Restarts (CPG 3.1.2.4 from the Phillips Lab documentation). A new performance goal was established for DDT&E cost and a revision in the unit cost goal is recommended.

Table 12 Performance goal summary.

CPG	Existing Goal	Recommended Goal	CPG Driver
Operational Altitude	None	900 km	Operational Utility
On-Orbit Thermal Restarts	5	10	Operational Utility
Total Impulse	4.0×10^6 N-s	4.8×10^6 N-s	Operational Utility
DDT&E Cost	None	~ \$250M	Cost (Affordability) and Schedule
Unit Cost	< \$25 M from 5th unit on	TBD	Cost

The on-orbit thermal restart requirement stated in the July 1994 revision of the Bimodal System Conceptual Performance Goals is five. In order to support reduction in constellation size, improved responsiveness, and enhanced mission capabilities (see section 3.0), it is recommended that the on-orbit thermal restart capability be increased to ten.

Figure 13 shows the sensitivity of potential missions captured (from the OOAMS Mission Model, see section 3.2) by a nuclear bimodal OOAMS as a function of its operational altitude. From a mission capture perspective, the recommended minimum operational orbit would be approximately 700 kilometers to capture all possible missions. However, from an orbital lifetime perspective, 700 kilometers is probably too low and would have a worst case orbital lifetime of less than five years. As a result, we would recommend the minimum orbital altitude be set at approximately 900 km. Only eight missions are lost over the period from 1995 to 2006 and this altitude provides a longer orbital lifetime in the case of a catastrophic failure.

Figure 13 Available missions by operational altitude.

The two thermal impulse CPGs (CPG 3.1.1.3 and 3.1.2.3 from the Phillips Laboratory documentation) were found to be too low. Figure 14 depicts the total impulse delivered by a nuclear bimodal system as a function of propellant consumed by the thermal propulsion system. The shaded area on the graph represents the propellant consumed and total impulse delivered by the nuclear bimodal system's GEO reference mission. The latest CPG revision (July 1994) indicated a total (orbital transfer and on-orbit maneuvering) thermal impulse of approximately 40 million Newton-seconds, which translates to a propellant consumption of approximately 5000 kilograms. After the orbital maneuvering trades were completed, it was determined a total propellant consumption (orbital transfer and on-orbit maneuvering) of 6000 kilograms or approximately 48 million Newton-seconds of total impulse is more representative of the requirement derived from the set of missions identified in the OOAMS Mission Model (Section 3.2).

Figure 14 Total impulse delivered vs. propellant consumed.

Even though a formal cost analysis was not prepared, there was enough evidence to suggest that a DDT&E goal should be established and that the unit cost goal may require a revision. Overall budget constraints and peak annual funding requirements will impact the DDT&E goal. A reference value of \$250 million was identified in the table, but this number should be revised as more program information and cost data is available. A comparison of the \$25 million unit cost goal with data available from other studies and programs indicates this value may be low. This number should be updated as more data becomes available.

6.0 CONCLUSIONS

This study indicates that a nuclear bimodal OOAMS provides increased lifetime for certain on orbit assets, reduced size for selected constellations, increased responsiveness and increased mission capabilities. Because the benefits were derived from representative missions, it was not possible to quantify them for use in an affordability assessment.

For selected missions, the nuclear bimodal OOAMS provides an improved lifetime on orbit. The lifetimes of larger satellite systems were increased using LH2 arcjets to provide reboost and station-keeping. The assessment was made by providing the nuclear bimodal system with a propellant load equivalent to that required for a conventional monopropellant N_2H_4 system. Representatives of these larger satellites systems include jam resistant military communications (DoD-1), survivable surveillance satellites (DoD-2), NASA communications (TDRS), and NASA's Earth Observation System (EOS). Propellant loads were also evaluated for moving the satellites within their operational plane. Again, the larger geostationary systems benefited from the nuclear bimodal OOAMS.

Modest reductions, 1 or 2 satellites, are possible for satellite constellations representative of the DoD-1, DoD-2, and DSCS systems. The analysis assumed only one repositioning per year was required to accommodate the removed satellite(s). Using the nuclear bimodal OOAMS to reduce constellation sizes would require the restart CPG be increased from five to ten.

The level of increased responsiveness offered by the nuclear bimodal OOAMS varied with the mission types. On-orbit reconstitution of GSO assets (representative of DoD-1, DoD-2, DSCS, UHF F/O, GOES, and TDRS) required 1.5 to 4 days depending on the system. This involved moving an existing asset to provide a temporary replacement. Moving an asset from an on-orbit depot to an operational station, providing a permanent replacement capability, required 3 to 5 days depending on the system. The OOAMS also supported in-plane on-orbit reconstitution of systems similar to GPS in 3 to 3.5 days. Because this type of system is composed of multiple orbital planes, several on-orbit spares were required to accomplish the reconstitution. LEO assets realized limited benefits. Spare assets could be moved from higher LEOs, which required less orbit maintenance, into operational positions in about 1 hour. A plane change capability of 128-129 m/s per degree of plane change was also possible for the LEO assets. The plane change capability could be used to enable overflight time or position changes. Each reconstitution maneuver required two to five restarts.

A nuclear bimodal OOAMS can provide an increased mission capability/tactical advantage through threat evasion, plane change, debris collision avoidance, and "improved viewing" capabilities. A total of 1000 m/s of ΔV could be provided for threat evasions. Two thermal restarts are required to complete the evasion maneuver and return to the operational orbit. A limited plane change capability, 128 to 129 m/s per degree of plane change, is also possible for LEO assets. One thermal restart is required for each plane change maneuver. The OOAMS system could also provide up to 4 roundtrips for debris collision avoidance. Each round-trip would require 4 thermal restarts. And finally, there is also a benefit associated with improved viewing capability. The system could provide four to six roundtrips and each roundtrip would require 2 thermal restarts.

With respect to cost, the preliminary analysis suggests that meeting a system DDT&E cost which is low enough to ensure reasonable annual funding requirements may not be possible for a nuclear bimodal OOAMS. If, for example, the program DDT&E were \$500 million, the peak annual funding requirement would be near \$100 million. This level of funding may be difficult to obtain in the face of declining budgets. There is also evidence that the \$25 M unit cost goal may be too low.

Space Transportation

On-Orbit Assessment Management Study Appendix

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Contents

Space Transportation

	<u>Page</u>
Integrated Solar Upper Stage (ISUS) Mission Analysis	A-2
Nuclear Bimodal System Mission ΔV 's	A-9
Reduced Constellation Size - Restart Analysis	A-15

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ISUS Mission Analysis Assumptions

Space Transportation

- **Baseline 12 hr “Molniya” Orbit**
 - 1000 x 39464 km
 - 63.4° Inclination
 - 270° Argument of Perigee
- **ISUS Engine Performance Characteristics**
 - 42N Thrust
 - 407 sec Isp

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ISUS Molniya LAN Changes

Space Transportation

- Δ LAN Completed in 3 Days
- Reduction in Net Payload Refers to Titan II SLV

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ISUS Molniya Argument of Perigee (W) Changes

Space Transportation

- ΔW Maneuver
- Reduction in Net Payload Refers to Titan II SLV

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Using Earth's Oblateness for Molniya ΔW

Space Transportation

- Perform Δi Maneuvers to Take Advantage of Earth's Oblateness
- Roundtrip ΔV Includes Maneuver to Restore Inclination to 63.4°

**Takes Too Much Time
or Too Much ΔV**

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ISUS Molniya RAAAN Changes

Space Transportation

ΔV (m/s)

RAAN Change (deg)

Reduction in Net Payload (kg)

RAAN Change (deg)

- Δ RAAN Maneuver
- Reduction in Net Payload Refers to Titan II SLV

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Using Earth's Oblateness for Molniya Δ RAAN

Space Transportation

- Allow Nodal Regression to “Perform” Maneuver

Takes Too Much Time

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Titan II/ISUS GEO Performance

Space Transportation

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DoD-1 ΔV 's

Space Transportation

Scenario	Maneuver ΔV s	
Increased Lifetime	Reboost + Station-Keeping	= 61 m/s per year
Reduction in Number of Satellites	Δ RAAN Between Planes = 45°	= 205 m/s
	East/West Movement within Plane	= 5.7 m/s per deg/day
Improved Responsiveness	Exisiting Satellite from Another Plane	= 205 m/s + E/W Movement
	Exisiting Satellite from within Plane	= NA
	New Satellite from Another Orbit	= 36 m/s (from 1000 km above) + E/W Movement + 380 (90° Δ RAAN)
	New Satellite Coverage	= NA
Increased Mission Capability or Tactical Advantage	Threat Evasion	= 0.04 m/s per km (apogee or perigee change & return)

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DoD-2, DSCS, UHF F/O, GOES, and TDRS ΔV 's

Space Transportation

Scenario	Maneuver ΔV s	
Increased Lifetime	Reboost + Station-Keeping	= 54 m/s per year
Reduction in Number of Satellites	Δ RAAN Between Planes	= NA
	East/West Movement within Plane	= 5.7 m/s per deg/day
Improved Responsiveness	Exisiting Satellite from Another Plane	= NA
	Exisiting Satellite from within Plane	= E/W Movement
	New Satellite from Another Orbit	= 36 m/s (from 1000 km above) + E/W Movement
	New Satellite Coverage	= NA
Increased Mission Capability or Tactical Advantage	Threat Evasion	= 0.04 m/s per km (apogee or perigee change & return)

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GPS ΔV 's

Space Transportation

Scenario	Maneuver ΔV s
Increased Lifetime	Reboost + Station-Keeping = 20 m/s per year
Reduction in Number of Satellites	Number of Satellites Driven by Coverage Geometry Required for Navigation $\Rightarrow$ Number of Satellites CANNOT Be Reduced with OOAM
Improved Responsiveness	Existing Satellite from Another Plane = 4487 m/s + 3.6 m/s/(deg/day) Existing Satellite from within Plane = 3.6 m/s per deg/day New Satellite from Another Orbit = 119 m/s (from 500 km above) + 3.6 m/s per deg/day + 3173 (60° Δ RAAN) or + 4487 m/s (90° Δ RAAN) New Satellite Coverage = NA
Increased Mission Capability or Tactical Advantage	Threat Evasion = 0.07 m/s per km (apogee or perigee change & return)

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DMSP ΔV 's

Space Transportation

Scenario	Maneuver ΔV s	
Increased Lifetime	Reboost + Station-Keeping	= 6 m/s per year
Reduction in Number of Satellites	Δ RAAN Between Planes	= 128 m/s per deg
	East/West Movement within Plane	= NA
Improved Responsiveness	Exisiting Satellite from Another Plane	= NA
	Exisiting Satellite from within Plane	= NA
	New Satellite from Another Orbit	= NA
	New Satellite Coverage	= 128 m/s per deg
Increased Mission Capability or Tactical Advantage	Improved Viewing	= 0.52 m/s per km (Δh_p or Δh_a & return)
	Threat Evasion	= see Improved Viewing
	Debris Collision Avoidance	= 950 m/s (roundtrip)
	Plane Change	= 128 m/s per deg

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EOS ΔV 's

Space Transportation

Scenario	Maneuver ΔV s
Increased Lifetime	Reboost + Station-Keeping = 24 m/s per year
Reduction in Number of Satellites	Each Satellite Performs a Different Function $\Rightarrow$ Number of Satellites CANNOT Be Reduced through the Use of OOAM
Improved Responsiveness	Existing Satellite from Another Plane = NA Existing Satellite from within Plane = NA New Satellite from Another Orbit = NA New Satellite Coverage = 129 m/s per deg
Increased Mission Capability or Tactical Advantage	Improved Viewing = 0.53 m/s per km (Δh_p or Δh_a & return) Threat Evasion = NA Debris Collision Avoidance = 1080 m/s (roundtrip) Plane Change = 129 m/s per deg

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NOAA ΔV 's

Space Transportation

Scenario	Maneuver ΔV s	
Increased Lifetime	Reboost + Station-Keeping	= 5 m/s per year
Reduction in Number of Satellites	Δ RAAN Between Planes	= 128 m/s per deg
	East/West Movement within Plane	= NA
Improved Responsiveness	Exisiting Satellite from Another Plane	= NA
	Exisiting Satellite from within Plane	= NA
	New Satellite from Another Orbit	= NA
	New Satellite Coverage	= 128 m/s per deg
Increased Mission Capability or Tactical Advantage	Improved Viewing	= 0.52 m/s per km (Δh_p or Δh_a & return)
	Threat Evasion	= NA
	Debris Collision Avoidance	= 930 m/s (roundtrip)
	Plane Change	= 128 m/s per deg

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Restart Analysis - DoD-1 & 2

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Restart Analysis - DSCS

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Restart Analysis - UHF F/O

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Restart Analysis - GOES & TDRS

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