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PRELIMINARY ANALYSIS OF THE BENEFITS DERIVED TO US AIR FORCE SPACECRAFT FROM ON-ORBIT REFUELING

PRESENTED TO

SOAR 92

BY

SCOTT SMITH
SA-ALC/TIEO
KELLY AFB, TX 78241

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INTRODUCTION AND DESCRIPTION OF ANALYSES

This analysis was undertaken during FY 91 as a joint effort of SSD/XRP and SA-ALC/TIE as a preliminary step to identify potential benefits from refueling Air Force satellites on orbit. Both economic and operational benefits were included. Operational benefits were related in economic terms to allow evaluation. All economic comparisons were made using FY 91 costs. An additional purpose of the effort was to identify the preferred mission parameters, for an on-orbit refueling system.

A companion study was being concurrently conducted by SSD/XRP and NASA/JPL (JPL Pub D-8240) to develop a hardware concept for an on-orbit refueling system. The mass estimates for refueling missions obtained from the companion study were used in conducting the economic analyses of this benefits study.

For this study, on-orbit refueling was based on the concept developed in the companion JPL study. The concept involves launching an S/C carrying fuel that would be transferred to another "target" S/C which is already in orbit. The two S/C would then rendezvous, dock and transfer fuel. Another fluid, such as a cryogenic, might be included if needed by the target S/C.

The hardware concept for refueling was intended to minimize costs. The re-fueler S/C was designated to be expendable and would contain only the minimal capabilities. It would be launched into the orbit plane and altitude of the target S/C(s). The re-fueler S/C would rendezvous and dock with the target S/C and the fluid transfer would occur. When the refueling mission was completed, the re-fueler S/C would be ejected from the orbit. In order to optimize launch costs, some missions involved launching two re-fueler S/C on one LV. In this case the second re-fueler S/C would be placed in a storage orbit until needed.

The effort covered all Air Force S/C and launch programs that were active during the period of this project. To provide the most realistic results possible, the analyses were based on the generation of S/C in development at the time of this study. The following S/C programs were included in the study:

- Defense Meteorological Satellite Program
- Defense Satellite Communication System
- Defense Support Program
- Global Positioning System
- Space Based Radar System

The Follow-On Early Warning System and MILSTAR were not included since the requirements for these programs were being significantly revised during the time of this study. For each analysis an On-Orbit Cost was calculated which included non-recurring, recurring and failure costs up to the point of S/C activation. For each S/C program, four analyses were conducted as described below:

Fuel Transfer Analysis

This portion of the study identified the maximum S/C fuel capacity and type, an initial two year fuel supply and an amount to be transferred during a refueling mission. Planned refueling missions would be timed so that the target S/C would not go below a two year fuel quantity.

Operational Analysis

Improving the function and performance of the S/C mission through on-orbit resupply was evaluated in this section. The value of this improvement was quantified and an economic analysis was conducted using the estimated costs of the refueling system. The main areas considered were weight additions to the payload obtained by launching the S/C with less than a full load of fuel and maneuver for either survivability or constellation maintenance. Weight additions to the payload were used to either add performance capacity or increase redundancy and reliability.

Launch Cost Analysis

Possible economic benefits from launching with smaller or larger LV as well as combined launches were identified. The smaller LV alternative included off-loading fuel at launch to allow use of a smaller LV and then refueling on-orbit. Larger LVs were evaluated to determine benefits from including additional fuel and payload on the original S/C launch and not refueling. Combined payloads were evaluated to determine benefits from larger LVs capable of launching two or more S/C.

Lifetime Extension Analysis

Economic benefits were evaluated where refueling could extend the service life of a S/C. In cases where fuel was the first life limiting item, an on-orbit refueling capability was considered as the improvement. In cases where another subsystem was the first life limiting item, the improvement was to off-load fuel at launch and use the weight savings to add redundancy to the life limiting item. This second case also included refueling on-orbit to replace the fuel off-loaded at launch. Economic benefits were determined by estimating the added life gained until the next subsystem failed.

RESULTS

The results of the analyses for each system are summarized in the following sections.

Defense Meteorological Satellite Program

Although DMSP block 6 is expected to be at an altitude that would otherwise make on-orbit refueling attractive, the small 55-75 pound expected fuel capacity does not provide an opportunity for benefits. The expected fuel capacity is approximately the same as the estimated 50 pound weight impact to the target S/C to add on-orbit refueling capability. The historically short time to failure of DMSP subsystems and payloads might offer potential benefits for on-orbit maintenance if a low cost capability could be developed.

Defense Satellite Communications System

DSCS SHF Replenishment, if launched on the Atlas II LV, has potential benefits from both life extension by on-orbit refueling and from operational improvements gained by off-loading fuel to add communications transponders. Potential savings may also be achieved by using a larger LV without on-orbit refueling. The SPO was considering the use of bipropellant for SHF Replenishment S/C. This would negate many of the benefits. Results of the analyses are shown in the following tables.

The lowest cost alternative is to upgrade to the Atlas IIAS LV and include the additional fuel and/or transponders on the SHF Replenishment S/C at launch.

DSCS SHF REPLENISHMENT
MONOPROPELLANT
ALTAS II LV
$302.3 MILLION ON-ORBIT COST

	NO REFUELING	REFUELING ONLY	ONE ADDL TRANSPONDER	TWO ADDL TRANSPONDERS
S/C LIFETIME	10.0 YRS	13.0 YRS	12.5 YRS	13.0 YRS
REFUELING	N/A	7.1 YRS	3.2 YRS	0[1]/6.5 YRS
ANN COST PER TRANS	$5.04 M	$4.88 M	$4.41 M	$4.47 M
NET SAVE PER S/C	N/A	$12.6 M	$42.5 M	$29.2 M

DSCS SHF REPLENISHMENT
BIPROPELLANT
ATLAS II LV
$302.3 MILLION ON-ORBIT COST

	NO REFUELING	REFUELING ONLY	ONE ADDL TRANSPONDER	TWO ADDL TRANSPONDERS
S/C LIFETIME	13.0 YRS	13.0 YRS	13.0 YRS	13.0 YRS
REFUELING	N/A	N/A	4.4 YRS	0[2]/9.1 YRS
ANN COST PER TRANS	$3.88 M	N/A	$4.25 M	$4.48 M
NET SAVE PER S/C	N/A	N/A	$(33.6) M	$(62.6) M

DSCS SHF REPLENISHMENT
NO REFUELING
ATLAS IIAS LV
$319.1 MILLION ON-ORBIT COST

	LIFE EXTEND ONLY	ONE ADDL TRANSPONDER	TWO ADDL TRANSPONDERS
S/C LIFETIME	13.0 YRS	13.0 YRS	13.0 YRS
ANN COST PER TRANS	$4.08 M	$3.57 M	$3.17 M
SAVE PER MONOPROP S/C	$76.0 M	$118.8 M	$164.2 M
SAVE PER BIPROP S/C	N/A	$28.2 M	$73.6 M

DSCS SHF REPLENISHMENT

	ANN COST PER TRANS	SAVE (M) MONO	BIPROP	REFUEL
ATLAS IIAS TWO ADDL TRANSPONDERS	$3.17 M	$164.2	$73.6	N
ATLAS IIAS ONE ADDL TRANSPONDER	$3.57 M	$118.8	$28.2	N
ATLAS II BIPROP NO REFUEL	$3.88 M		$00.0	N
ATLAS IIAS LIFE EXTENSION ONLY	$4.08 M	$73.8	N/A	N
ATLAS II BIPROP ONE ADDL TRANS	$4.25 M		$(33.6)	Y
ATLAS II MONO ONE ADDL TRANS	$4.41 M	$42.5		Y
ATLAS II MONO TWO ADDL TRANS	$4.47 M	$29.2		Y
ATLAS II BIPROP TWO ADDL TRANS	$4.48 M		$(62.6)	Y
ALTAS II MONOPROP REFUEL ONLY	$4.88 M	$12.6		Y
ATLAS II MONOPROP NO REFUEL	$5.04 M	$0.0		N

Additional potential savings may be possible if re-fueler S/C launches can be combined with DSP-1 S/C on the Titan IV SRMU IUS LV. This possibility will only exist if DSP-1 is chosen as the concept for FEWS.

Defense Support Program

Potential benefits were identified from off-loading fuel at launch and adding redundant Reaction Wheel Assembly bearings. Refueling would also offer enhanced maneuver capability. However, the technical difficulties of stopping rotation and then stabilizing the DSP-1 S/C for refueling as well as developing the redundant bearing assemblies appeared to be very large. Estimating the cost of overcoming these technical problems was beyond the scope of this study.

Separately, the concept of "piggy backing" DSP-1/FEWS/DSCS launches with other S/C appeared to offer significant potential cost savings. This potential should be evaluated in depth for all DoD systems using low inclination geostationary/geosynchronous orbits.

As noted above, the future of DSP-1 type S/C will depend on the concept selected for FEWS.

Global Positioning System

A potential savings for GPS IIR was identified from extending fuel lifetime to the 12.2 year MTBF for the S/C. However, results would be highly dependent on actual fuel expenditures for drift orbit maintenance and re-phasing which are much larger than station keeping in the fuel budget. The 0.6325 pounds of extra station keeping fuel would be less than the estimated 50 pound weight penalty for adding refueling equipment to the target S/C. Results of the analyses are shown in the following table.

GPS II R
MONOPROPELLANT

	DELTA 7925 LV		ATLAS IILV
	NO REFUEL	REFUEL	NO REFUEL
S/C LIFETIME	7.5 YRS	12.2 YRS	12.2 YRS
ON-ORBIT COST	$108.5 M	$108.5 M	$125.2 M
ANN COST PER S/C	$14.5 M	$14.0 M	$10.3 M
SAVE PER S/C	N/A	$5.65 M	$51.5 M

Unplanned weight increases could cause the GPS IIR to exceed the capacity of the planned Delta 7925 LV. In this event, utilizing an Atlas II LV would be $51.5 million less costly per S/C than off-loading fuel at launch and refueling on-orbit.

A previous study indicated an "active and spare" constellation maintenance strategy had potential to achieve the same performance with three fewer spare S/C on-orbit than presently planned. The offset would be the weight penalty to equip all GPS IIR S/C with refueling capability and the cost of refueling missions. This would negate the savings from fewer on-orbit spare S/C.

Space Based Radar

Significant potential cost savings were identified for a SBR S/C using either monopropellant or bipropellant. These included life extension by refueling alone and by refueling combined with off-loading fuel at launch to increase the number of battery packs on the SBR S/C. Potential savings were also identified for using a larger LV without on-orbit refueling. These savings were aided by several factors favorable to on-orbit refueling. First, SBR is at an orbit altitude which reduces the launch cost for a re-fueler S/C. Second, the SBR would periodically use fuel to re-boost the S/C due to drag effects of the atmosphere. Finally, the on-orbit cost of SBR is large compared to refueling cost.

The results of the analyses are shown in the following tables.

SPACE BASED RADAR
MONOPROPELLANT
ATLAS IIAS LV
$396.8 MILLION ON-ORBIT COST

	NO REFUEL	REFUEL ONLY	ONE ADDL BATTERY PK	TWO ADDL BATTERY PKS
S/C LIFETIME	7.0 YRS	12.6 YRS	15.2 YRS	18.6 YRS
REFUELING	N/A	5.0 YRS	3.3/8.3 YRS	1.6/6.6/11.6 YRS
ANNL COST PER S/C	$56.7 M	$38.2 M	$33.9 M	$30.8 M
NET SAVE PER S/C	N/A	$222.0 M	$346.1 M	$482.9 M

SPACE BASED RADAR
BIPROPELLANT
ATLAS IIAS LV
$396.8 MILLION ON-ORBIT COST

	NO REFUEL	REFUEL ONLY	ONE ADDL BATTERY PK	TWO ADDL BATTERY PKS
S/C LIFETIME	9.2 YRS	12.6 YRS	14.2 YRS	18.6 YRS
REFUELING	N/A	7.2 YRS	5.0 YRS	2.8/11.0 YRS
ANNL COST PER S/C	$43.3 M	$36.4 M	$32.6 M	$27.8 M
NET SAVE PER S/C	N/A	$86.7 M	$151.7 M	$288.4 M

SPACE BASED RADAR
NO REFUELING
TITAN IV NUS
$475.4 MILLION ON-ORBIT COST

	LIFE EXTEND ONLY	ONE ADDL BATTERY	TWO ADDL BATTERIES
S/C LIFETIME	12.6 YRS	15.2 YRS	18.6 YRS
ANN COST PER S/C	$37.7 M	$31.3 M	$25.6 M
SAVE PER MONOPROP S/C	$238.9 M	$386.3 M	$579.1 M
SAVE PER BIPROP S/C	$70.4 M	$182.7 M	$330.2 M

SPACE BASED RADAR

	ANN COST PER S/C (M)	SAVE MONO (M)	BI (M)	S/C LIFE (YRS)	RE FUEL
TITAN IV NUS TWO ADDL BATTERIES	$25.6	$579.1	$330.2	18.6	N
ATLAS IIAS BIPROP TWO ADDL BATT	$27.8		$288.4	18.6	Y
ATLAS IIAS MONO TWO ADDL BATT	$30.8	$482.9		18.6	Y
TITAN IV NUS ONE ADDL BATTERY	$31.3	$386.3	$182.7	15.2	N
ATLAS IIAS BIPROP ONE ADDL BATT	$32.6		$151.7	14.2	Y
ATLAS IIAS MONO ONE ADDL BATT	$33.9	$346.1		15.2	Y
ATLAS IIAS BIPROP REFUEL ONLY	$36.4		$86.7	12.6	Y
TITAN IV NUS ADDED FUEL ONLY	$37.7	$238.9	$70.4	12.6	N
ATLAS IIAS MONO REFUEL ONLY	$38.2	$222.0		12.0	Y
ATLAS IIAS BIPROP NO REFUEL	$43.3		N/A	9.2	N
ATLAS IIAS MONO NO REFUEL	$56.7	N/A		7.0	N

RECOMMENDATIONS

The cancellation of the SBR effort in the FY 91 DoD budget, left DSCS SHF Replenishment using monopropellant fuel as the remaining system with meaningful potential benefits from on-orbit refueling. Potential benefits for DSCS SHF Replenishment were also identified from using a larger LV without refueling.

Four sequential follow-on actions were recommended to advance on-orbit refueling to readiness for operational use. The first was to determine if SHF Replenishment would use monopropellant fuel. Second was a more in-depth benefits analysis that would add confidence to the major assumptions made in this preliminary study. This would be followed by an evaluation of whether non Air Force DoD S/C such as Fleet Sat would also benefit from on-orbit refueling. The final recommendation was a decision on committing funds to a technology demonstration of on-orbit refueling capability for DoD S/C.

TERMS AND ACRONYMS

ADDL	Additional
ALC	Air Logistics Center
ANNL	Annual
BATT	Battery Pack
BI	Bipropellant
BIPROP	Bipropellant
DMSP	Defense Meteorological System
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
FEWS	Follow-on Early Warning System
FY	Fiscal Year
GPS	Global Positioning System
IUS	Inertial Upper Stage
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LBS	Pounds
LV	Launch Vehicle
MILSTAR	Military Strategic and Tactical Relay System
MONO	Monopropellant
MONOPROP	Monopropellant
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NAVSTAR/GPS	Global Positioning System
NUS	No Upper Stage
PK	Battery Pack
PKS	Battery Packs
SA	San Antonio
SBR	Space Based Radar
S/C	Space Craft
SHF	Super High Frequency
SPO	System Program Office
SRMU	Solid Rocket Motor Upgrade
SSD/XRP	Space Systems Division/
SPO	System Program Office
TIE	Technology and Industrial Support Directorate Engineering Division
TRANS	Communications transponder(s)
YRS	Years

AFMC

SOAR 92

ON-ORBIT REFUELING

AN ANALYSIS OF POTENTIAL BENEFITS

SPACE OPERATIONS, APPLICATIONS AND RESEARCH SYMPOSIUM

SCOTT SMITH
SA-ALC/TIEO

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OVERVIEW

- DESCRIPTION OF REFUELER S/C
- DESCRIPTION OF ANALYSES
- RESULTS
  - SPACE BASED RADAR
  - DSCS
- SUMMARY

DESCRIPTION OF ANALYSES

- FUEL TRANSFER ANALYSIS
- OPERATIONAL ANALYSIS
- LAUNCH COST ANALYSIS
- LIFE TIME EXTENSION ANALYSIS

DESCRIPTION OF ANALYSES

- ALL AF SPACE SYSTEMS EXCEPT FEWS & MILSTAR
- FY 91 COST BASIS
- COSTS INCLUDED

	SPACE		LAUNCH	CONTROL		
	N/R	RECUR	RECUR	N/R	RECUR	OPER
TARGET	●	●	●			
REFUELER	●	●	●	●	●	●

RESULTS

SPACE BASED RADAR

- FUEL TRANSFER ANALYSIS
  - •• MONOPROPELLANT
  - •• BIPROPELLANT
- LAUNCH COST ANALYSIS
  - •• ATLAS IIAS LAUNCH VEH
  - •• TITAN IV NUS LAUNCH VEH
- LIFE TIME EXTENSION ANALYSIS
  - •• ADDED FUEL
  - •• ADDED BATTERY PACKS

RESULTS

SPACE BASED RADAR

LV	ADDL BATTERY	RE FUEL	ANN COST PER S/C MONO	ANN COST PER S/C BIPROP	S/C LIFE TIME
T IV NUS	2	0	$25.6 M	$25.6 M	18.6 YRS
A II AS	2	3/2	$30.7 M	$27.8 M	18.6 YRS
T IV NUS	1	0	$31.3 M	$31.3 M	15.2 YRS
A II AS	1	2/1	$33.9 M	$32.6 M	15.2 YRS
A II AS	0	1		$36.4 M	12.6 YRS
T IV NUS	0	0	$37.7 M	$37.7 M	12.6 YRS
A II AS	0	1	$38.2 M		12.0 YRS
A II AS	**0**	**0**		**$43.3 M**	**9.2 YRS**
A II AS	**0**	**0**	**$56.7 M**		**7.0 YRS**

RESULTS

DSCS REPLENISHMENT

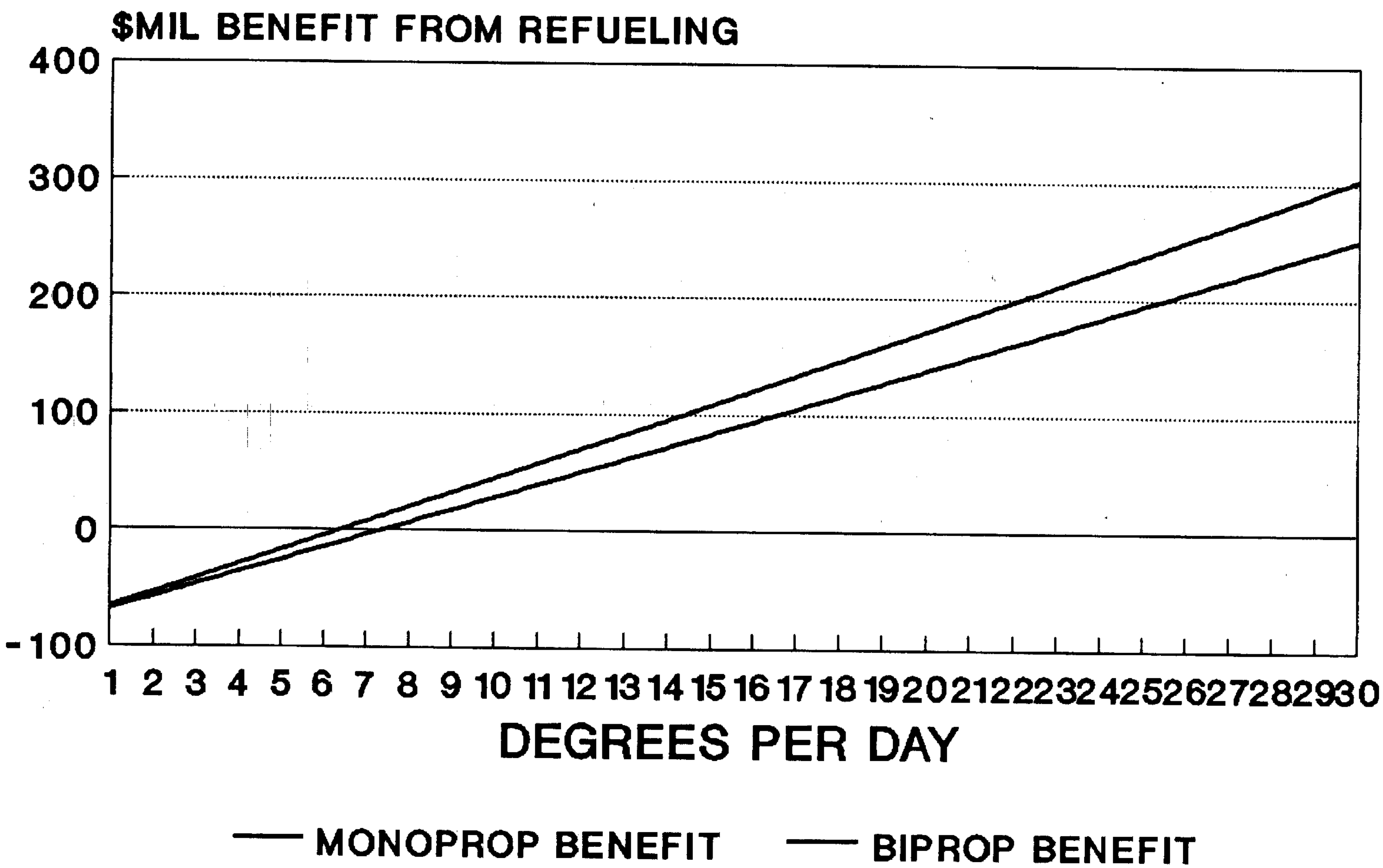
- FUEL TRANSFER ANALYSIS
  - MONOPROPELLANT
  - BIPROPELLANT
- OPERATIONAL ANALYSIS
  - ADDED TRANSPONDERS
  - REPOSITIONING
- LAUNCH COST ANALYSIS
  - ATLAS II LAUNCH VEH
  - ATLAS IIAS LAUNCH VEH
- LIFE TIME EXTENSION ANALYSIS
  - ADDED FUEL

RESULTS

DSCS REPLENISHMENT

LV	ADDL TRANS	RE FUEL	ANN COST PER TRANS MONO	ANN COST PER TRANS BIPROP	S/C LIFE TIME
A II AS	2	0	$3.17 M	$3.17 M	13.0 YRS
A II AS	1	0	$3.57 M	$3.57 M	13.0 YRS
A II	**0**	**0**		**$3.88 M**	**13.0 YRS**
A II AS	0	0	$4.08 M		13.0 YRS
A II	1	1		**$4.25 M**	13.0 YRS
A II	1	1	$4.41 M		12.5 YRS
A II	2	2	$4.47 M		13.0 YRS
A II	2	2		**$4.48 M**	13.0 YRS
A II	0	1	$4.88 M		13.0 YRS
A II	**0**	**0**	**$5.04 M**		**10.0 YRS**

DSCS REPOSITIONING



NO ADDED TRANSPONDERS
FUEL IS LIFE LIMITING

DESCRIPTION OF REFUELER S/C

- NOT A HIGH TECH S/C
- EXPENDABLE
- TAURUS LV FOR LEO
- 2 REFUELERS PER ATLAS II LV FOR GEO
- LOWER COST LV WILL IMPROVE BENEFITS

SUMMARY

- RESULTS ARE CASE DEPENDENT
- DSCS - POTENTIAL OPERATIONAL BENEFIT
- DSCS & SBR - POTENTIAL COST BENEFITS
- FUTURE MILSTAR AND FEWS ANALYSES

ON-ORBIT REFUELING: AN ANALYSIS OF POTENTIAL BENEFITS

Scott Smith
SA-ALC/TIEO
Kelly AFB, TX

Abstract unavailable at time of publication.