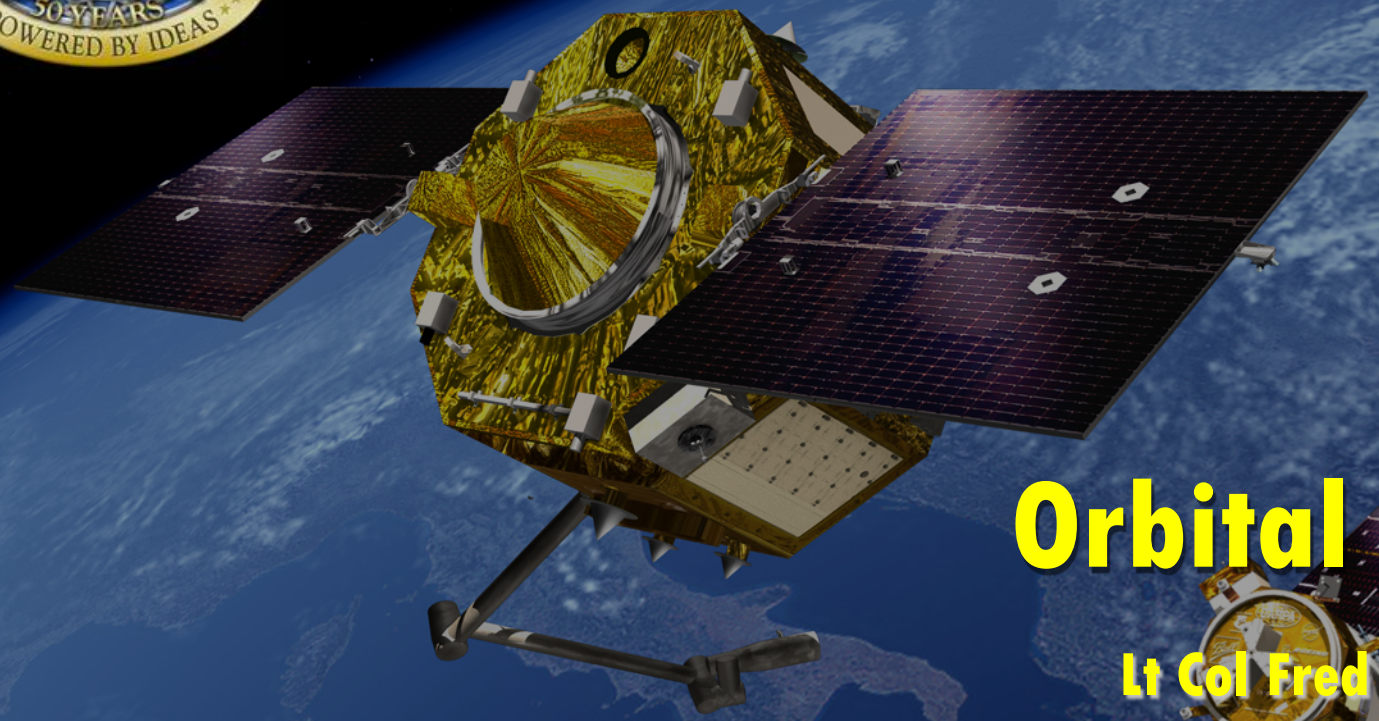


Orbital Express

Lt Col Fred Kennedy, USAF
Tactical Technology Office
Defense Advanced Research Projects Agency

Sensors and Systems for Space Applications Conference
Orlando, Florida
17 March 2008

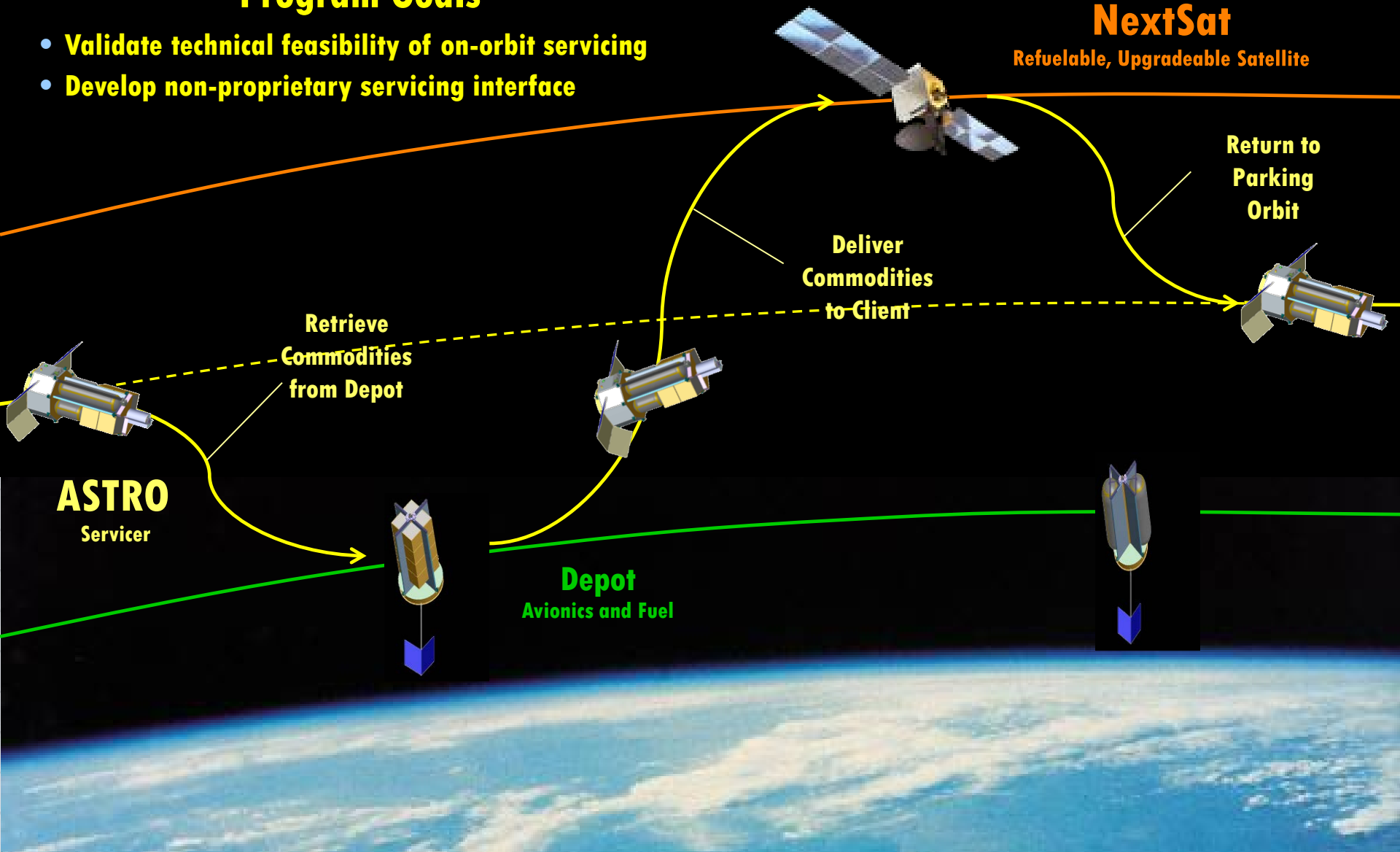
Approved for Public Release, Distribution Unlimited

On-Orbit Servicing System CONOPS

Architecture to Support Operations in Space

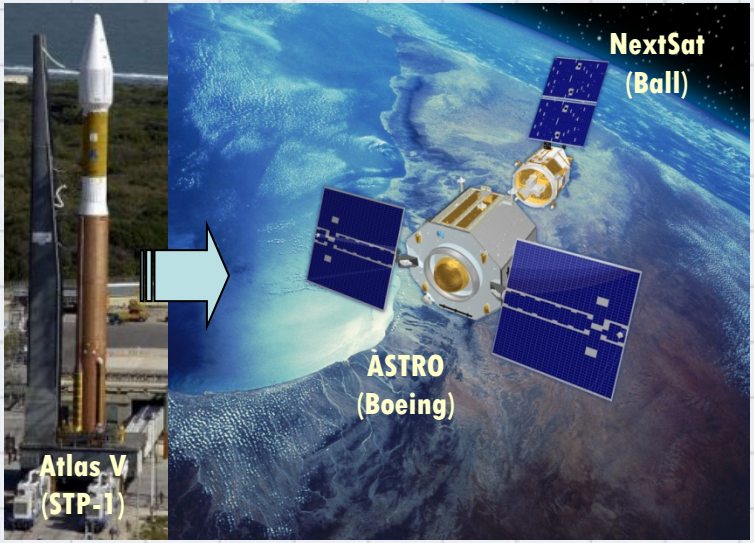
Program Goals

- Validate technical feasibility of on-orbit servicing
- Develop non-proprietary servicing interface

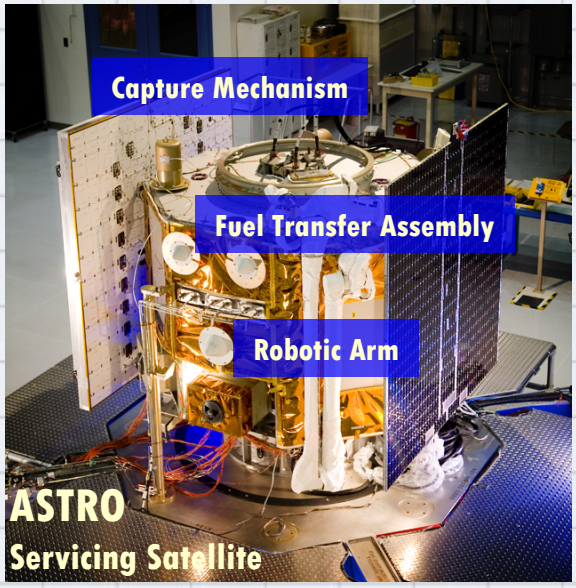


Orbital Express Space Demonstration

- **Objectives and Payoff**
  - Two satellite demonstration in Low Earth Orbit (492 km)
  - Will permit mission planners to consider autonomous satellite servicing in their spacecraft/constellation design
  - Orbital Express demo validated key technologies:
    - Fully autonomous rendezvous and proximity operations
    - Satellite grappling with a robotic arm, soft capture/docking
    - Propellant replenishment, battery and computer replacements
    - Establishes a non-proprietary servicing interface



- **Mission Accomplishments**
  - Both satellites shipped to Cape in Fall 2006
  - Final Rehearsals completed in February 2007
  - Launched on Atlas V AV-013, 8 March
  - Resolved major attitude anomaly
  - 1st fluid xfer 1 Apr, 1st battery xfer 6 Apr
  - Vehicles separated, remated on 17 April
  - 10-, 30-, 60 x 120 m, 4, 7, 300+ km RPOs

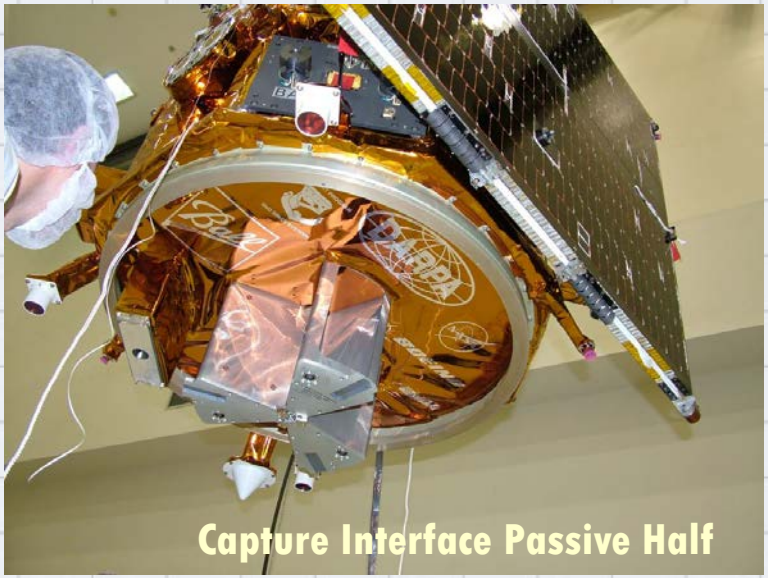


- **Results**
  - Proven autonomous rendezvous from distances exceeding 300 km
  - Nearly 20 hydrazine propellant transfers, pump/pressure fed
  - Battery, computer transfers, arm captures executed flawlessly

Key Demonstrations of Autonomy

- **All Orbital Express Scenario Operations are designed to be conducted autonomously**
  - Level of autonomy is selectable by mission operations
  - "Level 1" is lowest level of autonomy and demands numerous "authority to proceed"
  - Higher levels of autonomy permit the ASTRO vehicle to conduct scenarios with little or no intervention
  - Ground controllers are still able to intervene if they detect an anomalous situation
- **Autonomous Operations include:**
  - Battery and Computer Orbital Replacement Unit Transfers between ASTRO and NextSat
  - Propellant transfers
  - Rendezvous and Soft Capture

Capture Clip



Capture Interface Passive Half

Capture Interface Active Half

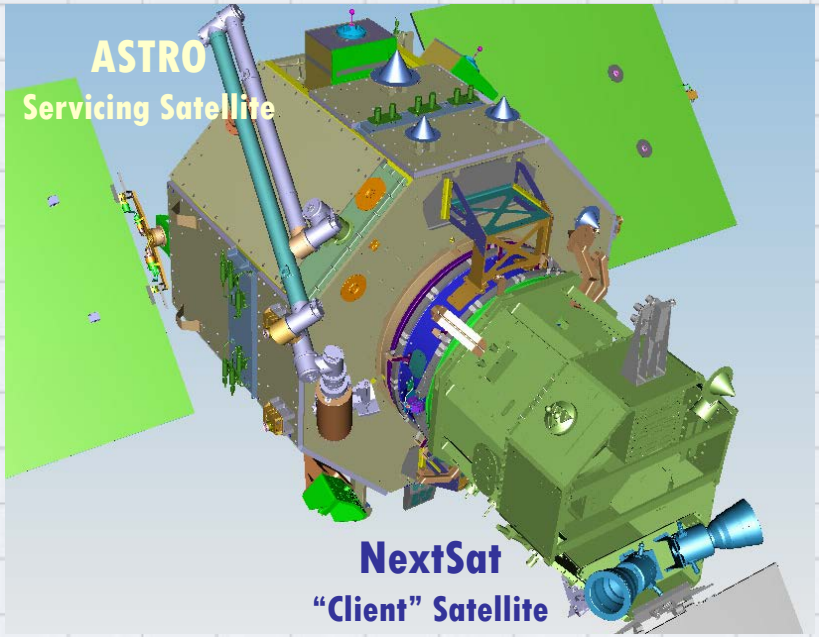
ORU Transfer Components – OEDMS Overview

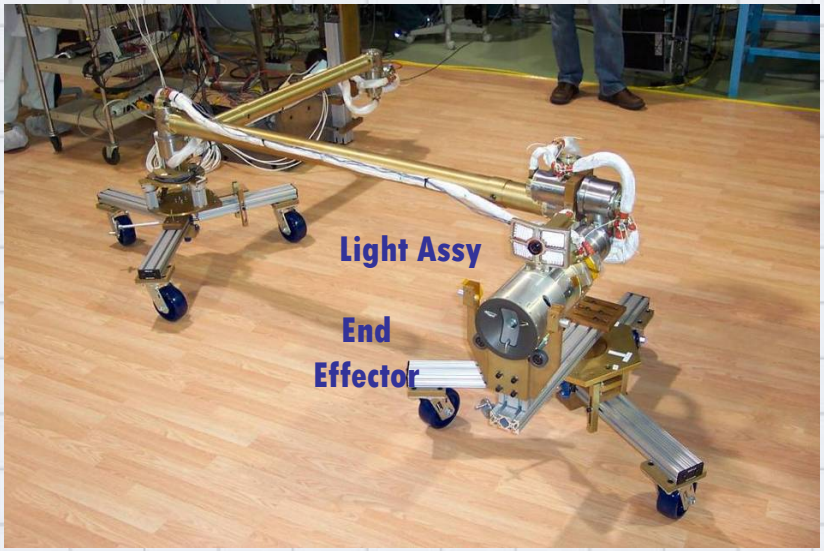
Overall View of ASTRO with AC-3 Installed and Battery ORU Removed

- ORU Transfer is executed via the OEDMS – Orbital Express Demonstration Manipulator System
  - MCU – Manipulator Control Unit
  - MA – Manipulator Arm
  - ORU – Orbital Replacement Unit
  - OIA – ORU Interface Adapter
  - OCA – ORU Container Assembly
  - MGS – Manipulator Ground Station
- ASTRO can accommodate Battery and Computer ORUs
- NEXTSat only accommodates the Battery ORU

Arm Operations

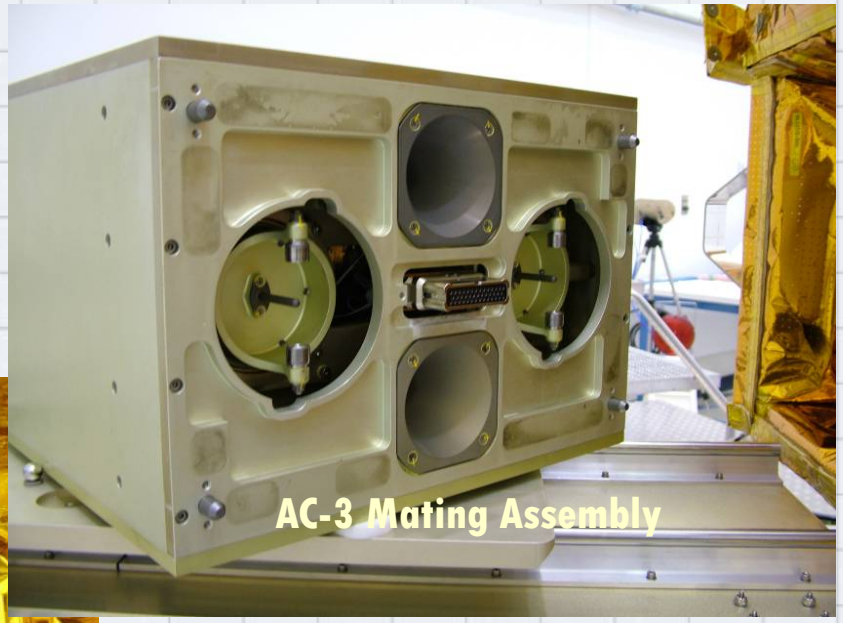
- MDA's manipulator arm fully "flat floor" tested
- ORU Grapple
  - Demonstrated movement of arm tip to ORU probe fixture
  - Demonstrated arm grapple to ORU
- ORU Removal
  - Demonstrated unlatch operations of ORU
    - Baseline WR software current limited torque yields 525% margin for unlatch torque range
  - Demonstrated straight line removal of ORU from OIA
- ORU Insertion
  - Demonstrated straight line insertion of ORU into OIA
  - Demonstrated micro-switch status (Ready-to-Latch) and branching conditions based on micro-switch feedback
  - Demonstrated latching operations and transition from Ready-to-Latch to Latched
    - Baseline WR software current limited torque yields 25% margin for latch torque range
- ORU Release
  - Demonstrated reset of ORU
    - Baseline WR software current limited torque yields 525% margin for reset torque range
  - Demonstrated release of ORU
- Characterized ORU insertion misalignment





ORU and ORU Interface Assemblies

ORU Transfer Test Clip

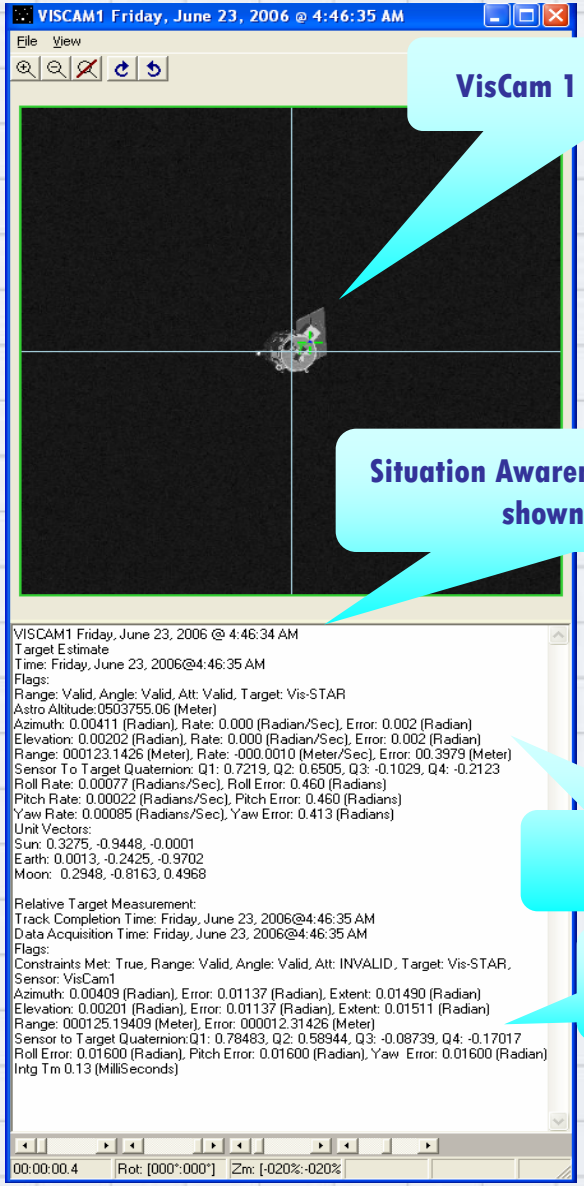


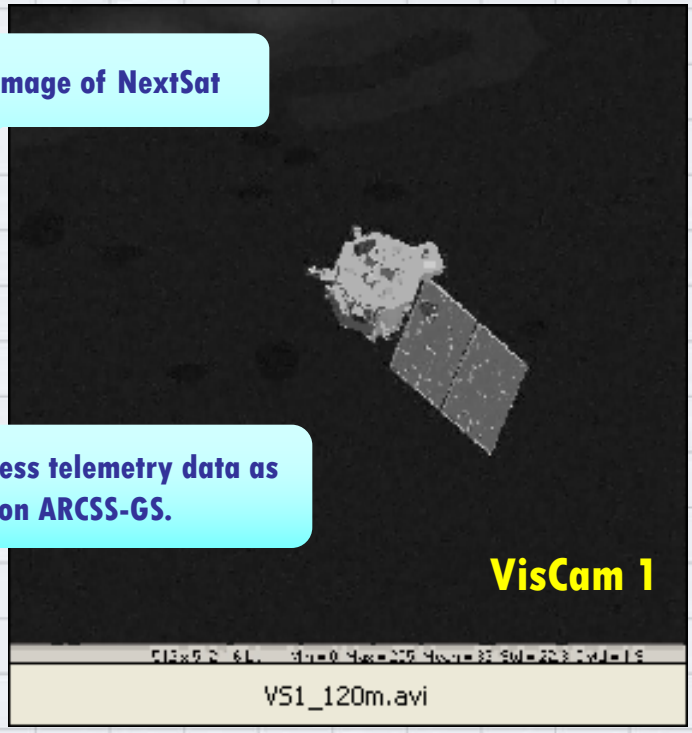
AC-3 Mating Assembly

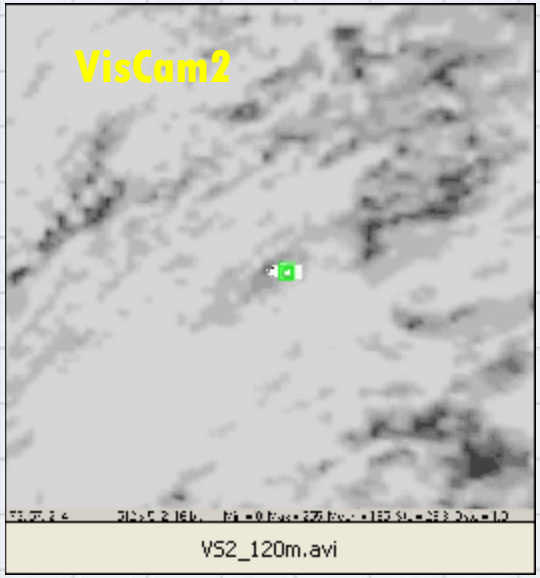
AC-3 OIA Final Closeout

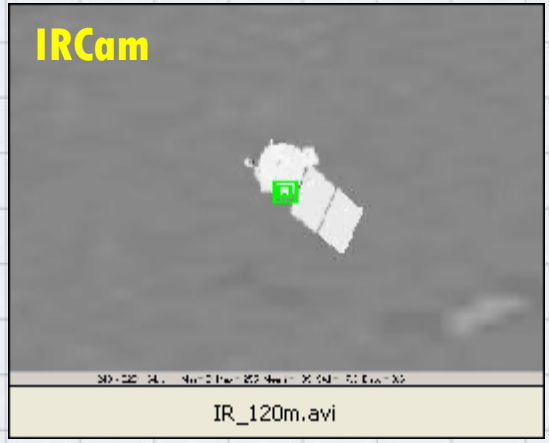
ASTRO Battery OIA Final Installation
(After Radiator Tape Installation)

Autonomous Rendezvous and Capture Sensor Subsystem (ARCSS)









AVGS

Target Estimate (from G&RN)

Sensor Measurement (Output of AC-2)

ARCSS and AC2 (Sensor Computer) software are being readied to support autonomous rendezvous and capture operations in May

"Rainbow Table": ASTRO Response to Guidance & Navigation Anomalies

Single Component Failure	Abort Region														
	Outbound					Inbound									
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Mate to Demate	Demate to Sep Corridor End	Sep Corridor End to TI –11 min ---- *1 km Scens*	Sep Corridor End to 7 km ---- *>1 km Scens*	7 km to NR1 –1 min (~35 km)	NR1 –1 min to NR2 –11 min (~35 to ~10 km)	NR2 –11 min to 4 km –11 min (~10 to ~5 km)	4 km –11 min to TI –11 min (~5 to ~2 km)	TI –11 min to FI (~2 km to ~120 m)	FI to Approach Corridor Start (~120 to ~60 m)	Approach Corridor Start (~60 m) to 5 m	5 m to Capture Init (.17 m)	Direct Capture Init (~.17 m) to Captured	Captured to Mate	Free-Flyer Capture Init to Mate
VisCam1	Abort Demate	Degrded Rel Nav	Transfer to 1 km, Stndoff, TTPL	Transfer to 7 km, Stndoff, TTPL	Transfer to V-Bar, Stndoff, TTPL	Transfer to 7 km, Stndoff, TTPL	Transfer to 4 km, Stndoff, TTPL	Degrded Rel Nav	Degrded Rel Nav	Degrded Rel Nav	Degrded Rel Nav	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact
VisCam2 – *AVGS-Only Scenarios*	Abort Demate	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	Not Applicble
VisCam2 – *Vis-STAR-Only Scenarios*	Abort Demate	Degrded Rel Nav	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	Transfer to 120 m, Stnkeep, TTPL	No AR&C Impact	Degrded Rel Nav	Transfer to ±120 m, Stnkeep, TTPL	No AR&C Impact	No AR&C Impact	Degrded Rel Nav
VisCam2 – *AVGS Plus Vis-STAR Scenarios*	Abort Demate	Degrded Rel Nav	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	No AR&C Impact	Degrded Rel Nav	Degrded Rel Nav	No AR&C Impact	No AR&C Impact	Degrded Rel Nav

Assumptions: 1) AVGS failure on AVGS-only scenarios in regions 10 through 14 results in hot switchover to AVGS plus Vis-STAR
2) Vis-STAR failure on Vis-STAR-only scenarios in regions 10 through 14 results in hot switchover to AVGS plus Vis-STAR
3) Autonomous switch (by AC2) from VS1 to VS2 when target is outside VS1 FOV and Range < 1km

- Blue: Good/Go Condition – Proceed with Existing AR&C Trajectory
- Green: Degraded/Go Condition – Proceed with Existing AR&C Trajectory
- Yellow: Degraded/Delay Condition – Trajectory Hold, AR&C Resumes Whether or not Recovered
- Red: Degraded/No-Go Condition – Trajectory Hold, AR&C Scrubbed if not Recovered
- Black: Loss of Vehicle Control – Vehicle Adrift, AR&C Scrubbed if not Recovered

Orbital Express Scenario Plan

"No plan survives contact with the enemy (i.e., space)"

0-1	Sun, 04/01/07	7091	2															F1	N	R	P	1	23	
0-2	Mon, 04/02/07	7092	1															F2	N	P	T	1	5	
0-3	Wed, 04/04/07	7094	2															F3	A	P	T	1	12	
0-4	Fri, 04/06/07	7096	2										O1	B	N	1	8							AT_LEO-06 Enable Reg Offset
COK	Sat, 04/07/07	7097	1																					AT_PL-06 ORU OLA Video Survey; AT_PL-01 MCU Data Txfr; AT_FSW-04 AC2 Dump
0-5	Mon, 04/09/07	7099	2															F4	N	P	FS	1	10	First use of flow sensors
0-6	Tue, 04/10/07	7100	1															F5	A	P	FS	1	5	
0-7	Wed, 04/11/07	7101	1															F6	N	P	FS	2	3	
0-8	Fri, 04/13/07	7103	2															F7	A	P	FS	1	12	
1-1	Mon, 04/16/07	7106	3	S1				188	Y	FF	N	A/V												NS data rate change to support ST test; NS Startracker Test; AT_PL-01 MCU Data Txfr; AT_FSW-04 AC2 Dump
COL	Tue, 04/17/07	7107	1																					AT_UTIL-25 Sensor Calibration
0-10	Thu, 04/19/07	7109	2															F8	N	P	FS	2	4	
0-11	Fri, 04/20/07	7110	1															F9	A	P	FS	2	5	
COM	Sat, 04/21/07	7111	1																					AT_PL-04 Capture Interface OLA Video Survey; AT_PL-01 MCU Data Txfr; AT_FSW-04 AC2 Dump
CON	Sun, 04/22/07	7112	1																					AT_LEO-05 OEDMS Reg C/O; AT_LEO-06 Enable Reg Offset; AT_PL-01 MCU Data Txfr; AT_FSW-04 AC2 Dump
1-2	Mon, 04/23/07	7113	1										O3	B	A	2	4							
1-3	Wed, 04/25/07	7115	2										O4	B	N	3	0							
COO	Thu, 04/26/07	7116	1																					(P) AT_LEO-13 FCS Modal
1-4	Sat, 04/28/07	7118	2															F10	N	P	FS	3	4	Thruster firing during fluid xfr; (P) AT_PL-05 Fluid Transfer Interface OLA Video Survey [conduct after mate, but before transfer]; (P) AT_PL-01 MCU Data Txfr; (P) AT_FSW-04 AC2 Dump
1-5	Sun, 04/29/07	7119	1															F11	A	P	FS	3	3	Thruster firing during fluid xfr
1-6	Tue, 05/01/07	7121	2															F12	N	P	FS	3	3	
1-7	Wed, 05/02/07	7122	1															F13	A	P	T	3	5	
M5	Thu, 05/03/07	7123	1																					I-Load Updates; (P) AT_PL-05 Fluid Transfer Interface OLA Video Survey; (P) AT_PL-01 MCU Data Txfr; (P) AT_FSW-04 AC2 Dump
2-1	Sat, 05/05/07	7125	2	U2	10m		SI		17	Y	DI	D	BL											
2-2	Sun, 05/06/07	7126	1															F14	N	P	FS	3	0	
2-3	Tue, 05/08/07	7128	2															F15	A	P	FS	3	0	
M6	Wed, 05/09/07	7129	1																					I-Load Updates; (P) AT_LEO-05 OEDMS Reg C/O; (P) AT_LEO-06 Enable Reg Offset; (P) AT_PL-01 MCU Data Txfr; (P) AT_FSW-04 AC2 Dump
3-1	Sat, 05/12/07	7132	3	U3	30m		SI		109	Y	FF	N	BL											
3-2	Sun, 05/13/07	7133	1											O5	B	A	3	0	F16	N	P	FS	3	0
3-3	Tue, 05/15/07	7135	2											O6	B	N	3	0	F17	A	P	FS	3	0
4	Wed, 05/16/07	7136	1	U4	60m		SI		109	N	DI	D	A											
5	Sun, 05/20/07	7140	4	U5	120m		-R	1x	307	Y	DI	D	BL											
0-9	Tue, 05/22/07	7142	2											O2	C		2	4						Transfer and AC3 funct check - not used as prime
COP	Wed, 05/23/07	7143	1																					AT_LEO-15 AC2/AC3 Self-Test
6-1	Sun, 05/27/07	7147	4	U6	1km	B	SI	1x	480	Y	FF	N	V	O7	B	A	3	0	F18	N	P	FS	3	0	NS ADCS C/O; RCS w/Fluid Xfr; Sim Prox Abort
6-2	Tue, 05/29/07	7149	2											O8	B	N	3	0	F19	A	P	FS	3	0	Thruster Firing during Fluid Xfr
7	Sat, 06/02/07	7153	4	U7	7km	F	+V		1426	Y	DI	D	BL											AT_CAL-01 LRF/Viscam Align
8-1	Sun, 06/03/07	7154	1											O9	C		3	0						
COQ	Mon, 06/04/07	7155	1																					AT_LEO-15 AC2/AC3 Self-Test
8-2	Fri, 06/08/07	7159	4	U8	7km	B	SI	3x	1426	Y	FF	N	BL	O10	B	A	3	0						AC3 primary for U8; Simulated 4km Hold
		7159												O11	B	N	3	0	F20	N	P	FS	3	0
8-3	Sat, 06/09/07	7160	1																F21	A	P	FS	3	0
8-4	Mon, 06/11/07	7162	2																F22	N	R	P	2	6
8-5	Wed, 06/13/07	7164	2																F23	A	R	P	2	7
8-6	Thu, 06/14/07	7165	1																F24				0	0	Final coupler mate, leak check and demate
EOL	Fri, 06/15/07	7166	1																					AT_EOL-01 End of Life; NS Decomm
Potential Scenarios Not in Current Baseline																								

Unmated Operations

Propellant Transfers

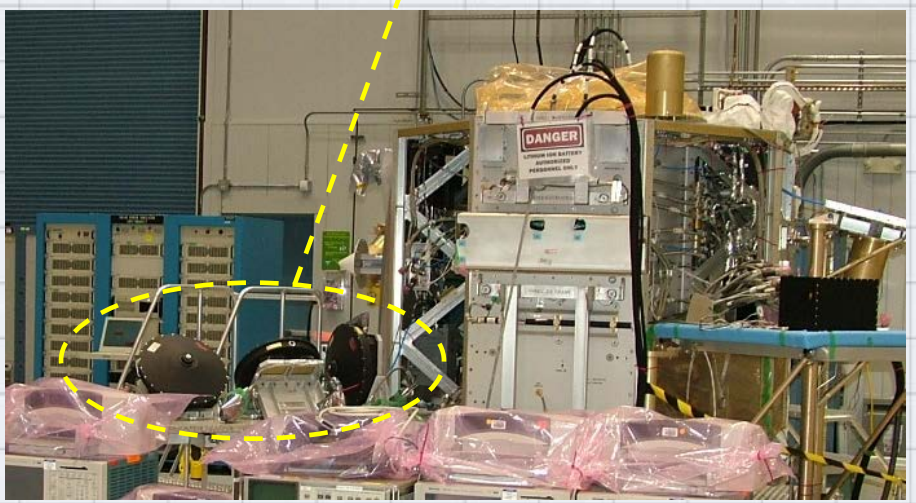
ORU Transfers

Launch and Early Orbit

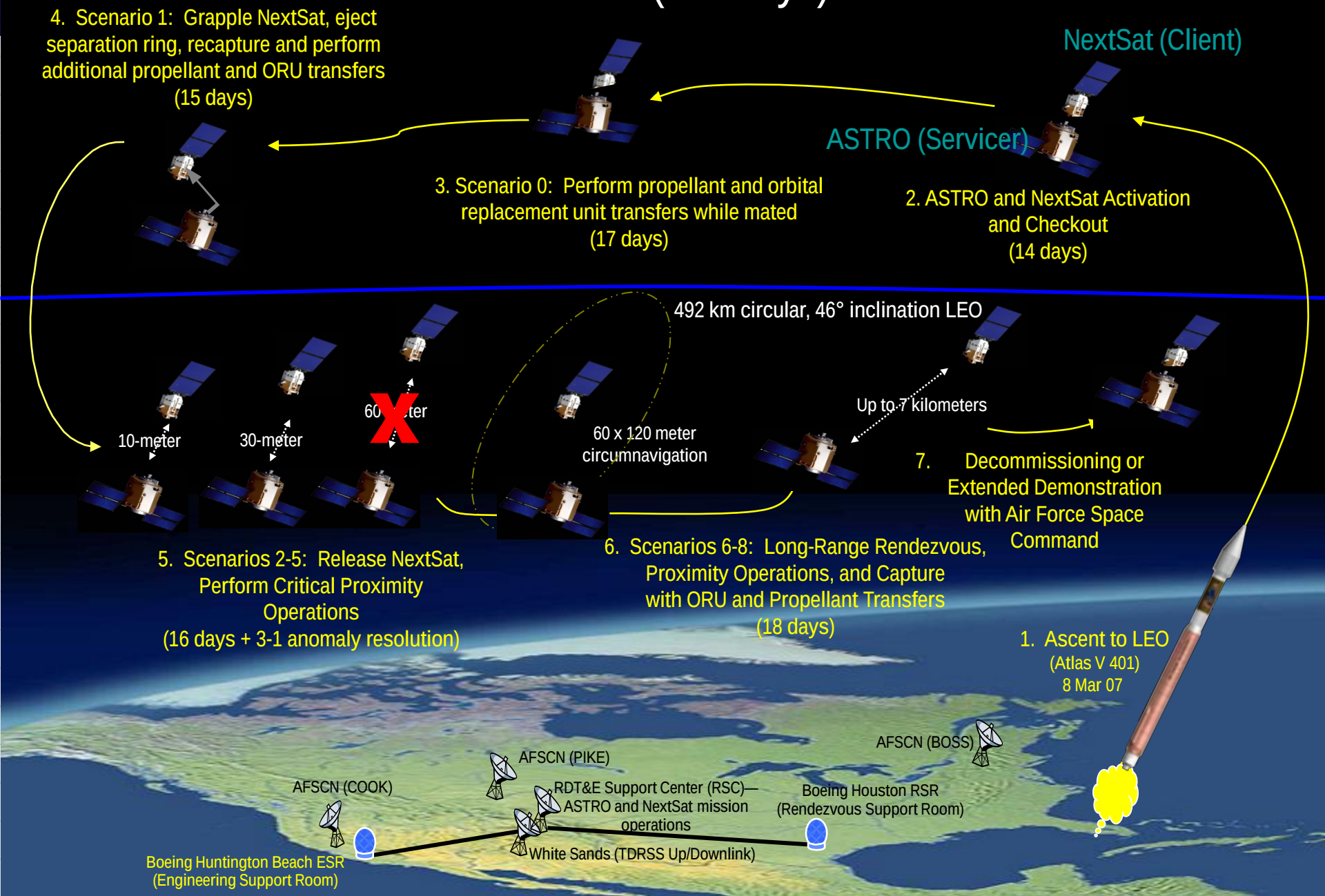
- **Nominal launch from Cape Canaveral at 2210 EST, 8 Mar 07**
  - Orbital Express spacecraft separated from Centaur 18 minutes after launch
  - First acquisition (TDRSS) T + 20 min
  - Solar arrays deployed, guidance systems initialized upon separation
- **Entered sun-safe mode T + 74 min**
  - Onboard guidance could not locate GPS satellites and establish position
  - ASTRO/NextSat stack experienced anomalous pitch rates (up to 5°/sec)
  - Pitch wheel saturated
- **ASTRO guidance turned on T + 18 hrs**
  - First indications all nominal
  - Later determined that vehicle was not target-tracking the sun; instead, it was coning around the anti-sun vector
  - ASTRO reached critical depth of discharge, bus shutdown T + 22 hrs

Recovery and Return to Checkout

- **ASTRO pitch wheel anomaly found to result from hardware/software disconnect on wheel polarity**
  - Flight software was commanding the wheel "backwards" from its installed orientation
  - Gross errors were fixed with gain sign change
  - A more comprehensive software update was required to reset magnetic torquers, resolve cross product issues
  - No further problems were encountered
- **GPS anomaly resulted from incorrect message information in Space Based GPS/INS Interface Control Document**
  - Resolved message problems with SIGI vendor, incorporated in software update
  - SIGI worked nominally thereafter
- **Checkout activities restarted**
  - ASTRO imaging systems initialized, characterized
  - Robotic arm initialized, global survey performed
  - NextSat checkouts completed

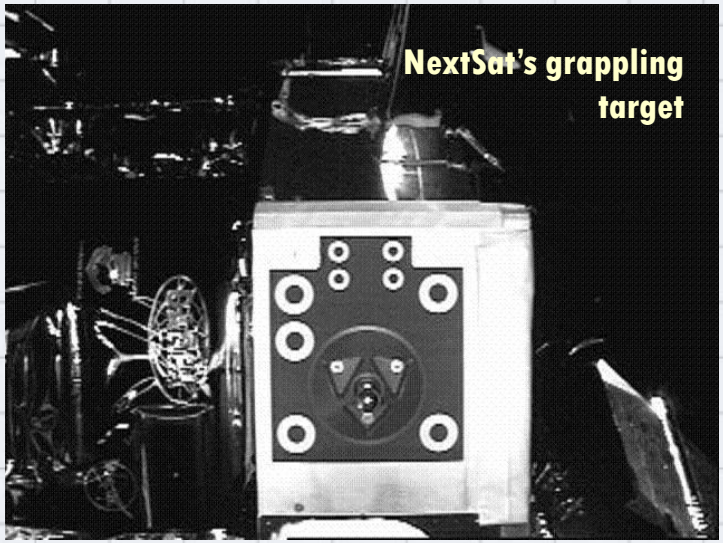


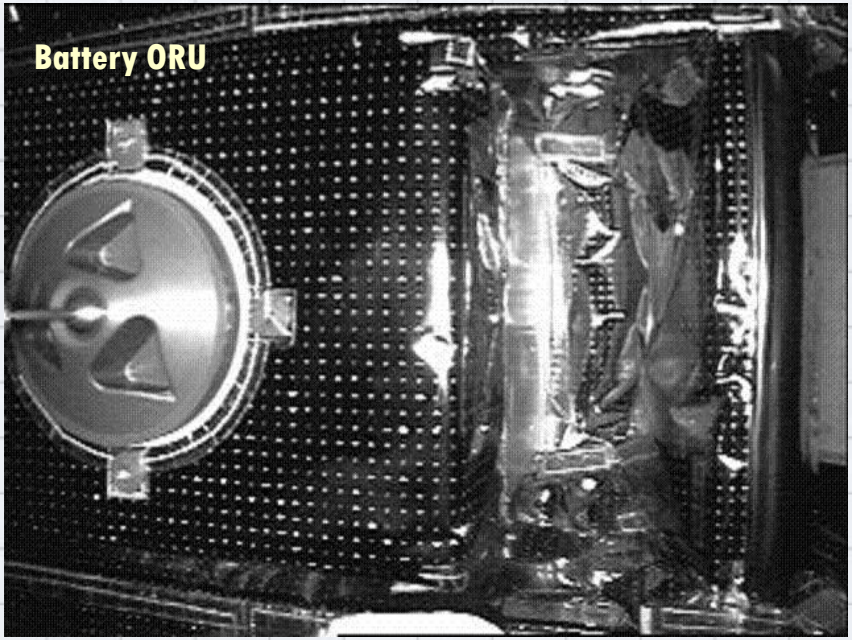
Orbital Express Demonstration Timeline (135 days)

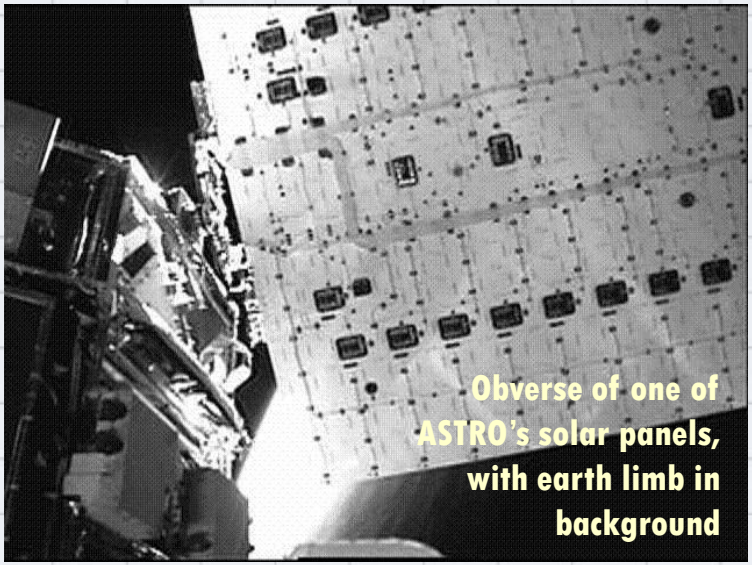


Results of Global Survey (28 Mar 07)

- Arm camera shot 1,660 photos over 54-minute period
- Single command executed arm global survey script
- Assembled video indicates both vehicles were in good shape







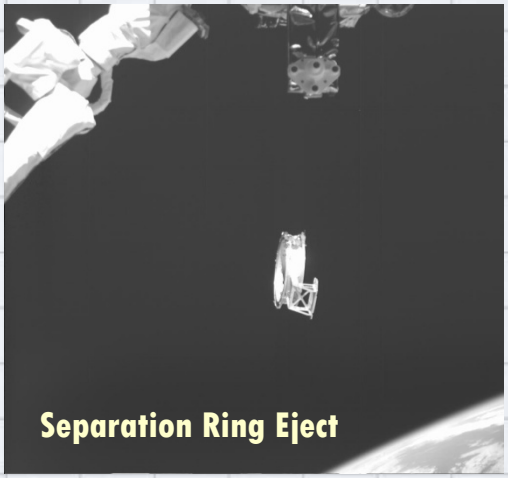
Global Survey Video

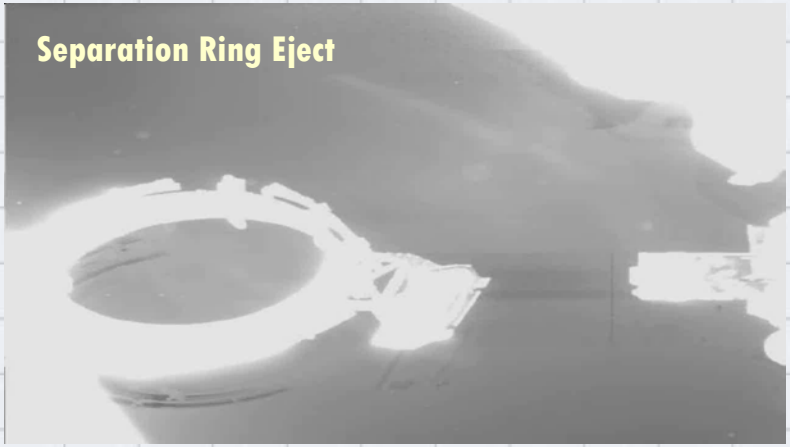
Early Ops

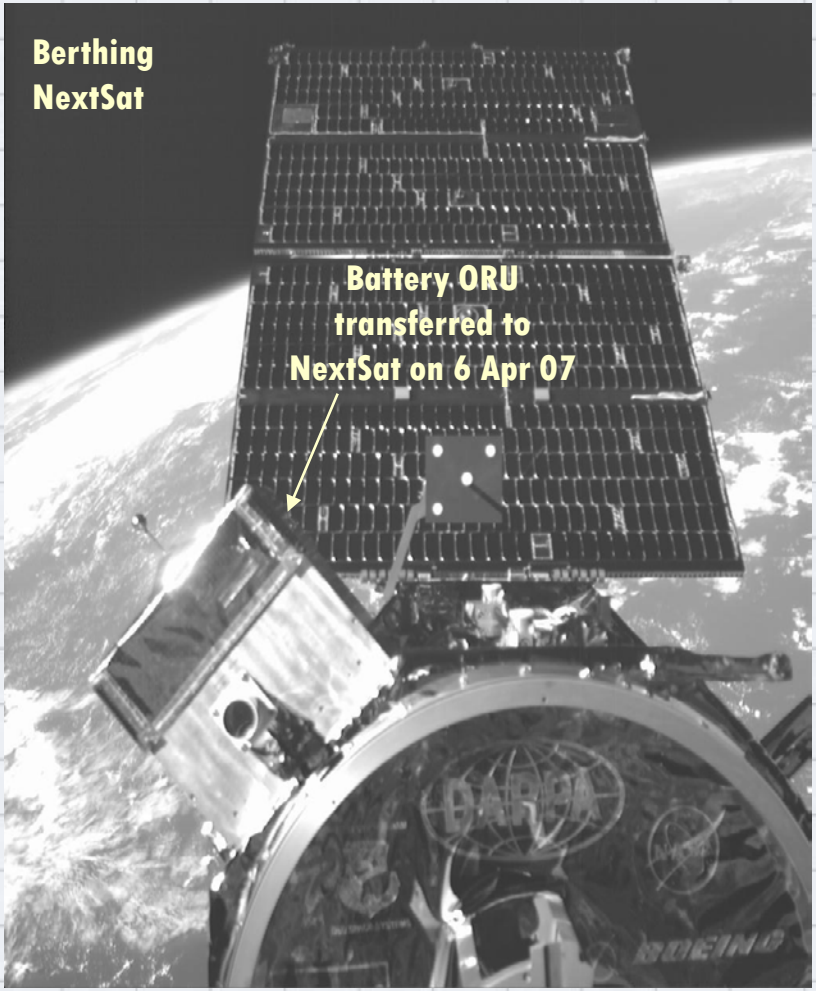
- Ring ejection and first separation on 17 Apr 07
- 10-meter Rendezvous and Capture Scenario: 5 May 07

Ring Eject

NextSat Separation

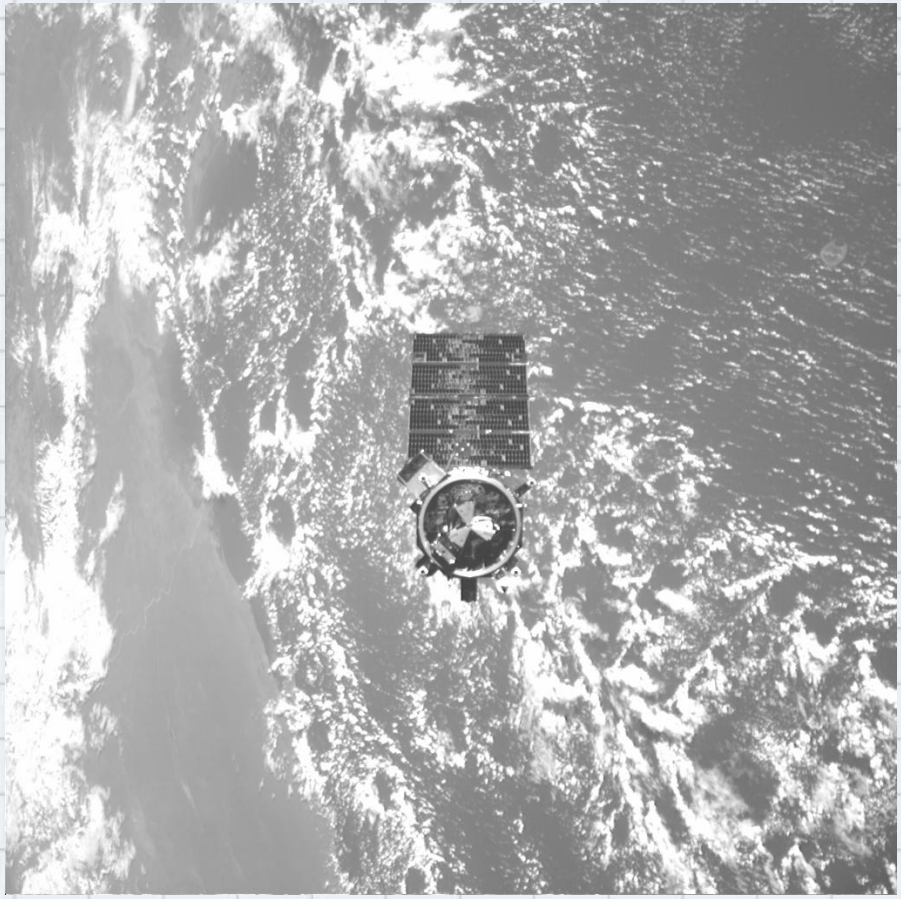


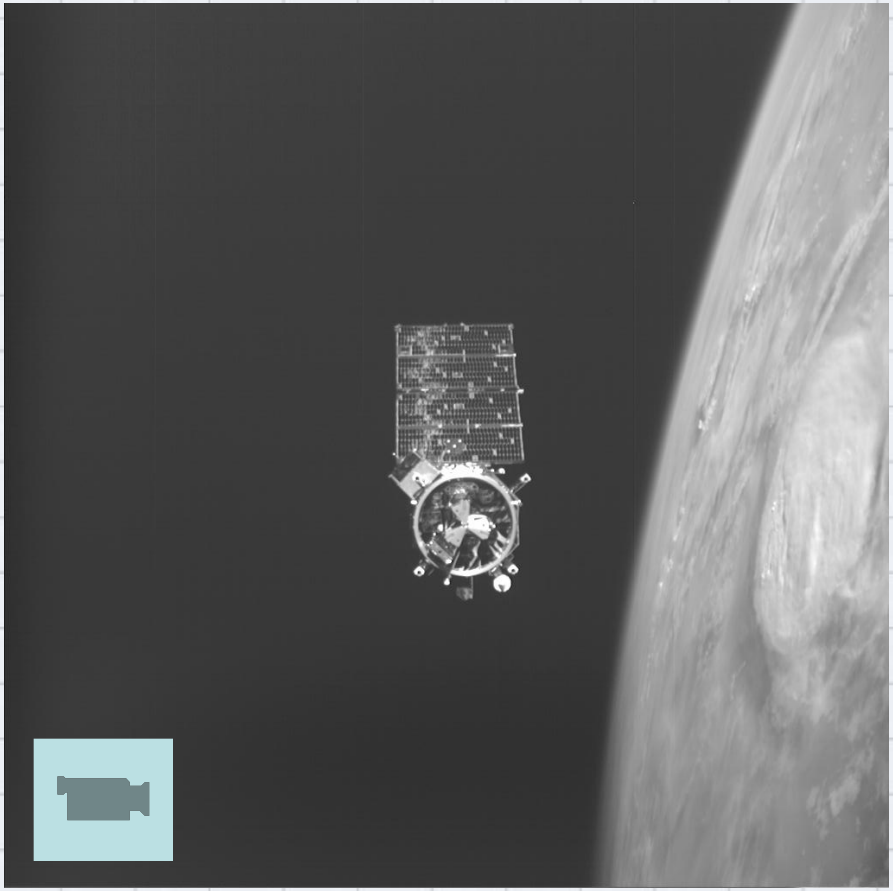




Everything looked good…

Scenario 2-1: 10-meter rendezvous/capture

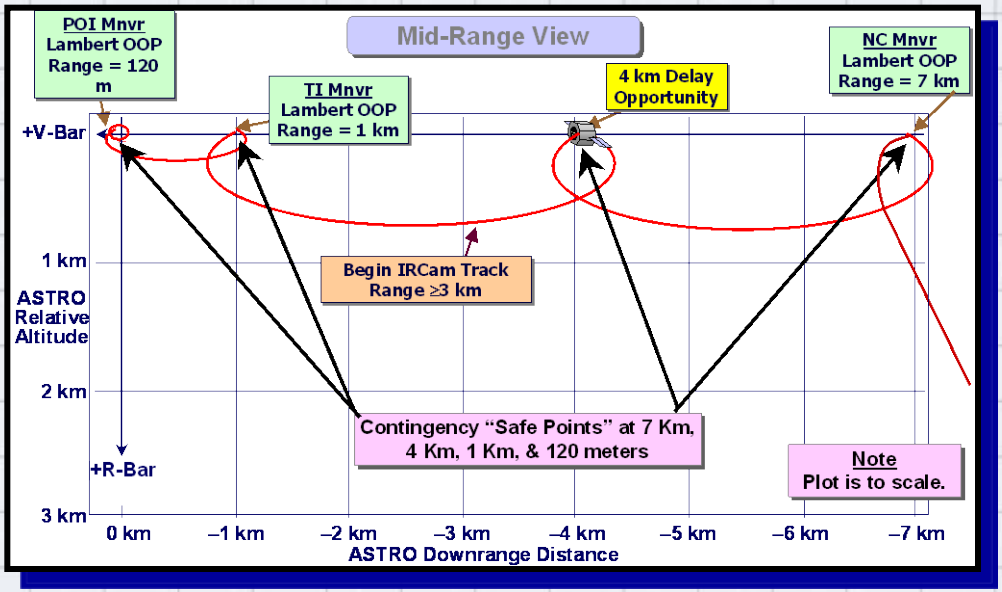


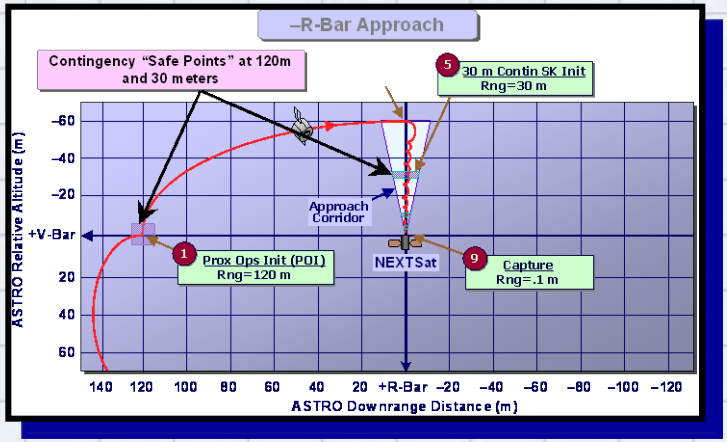


Fully successful

Accomplishments through Scenario 3-1

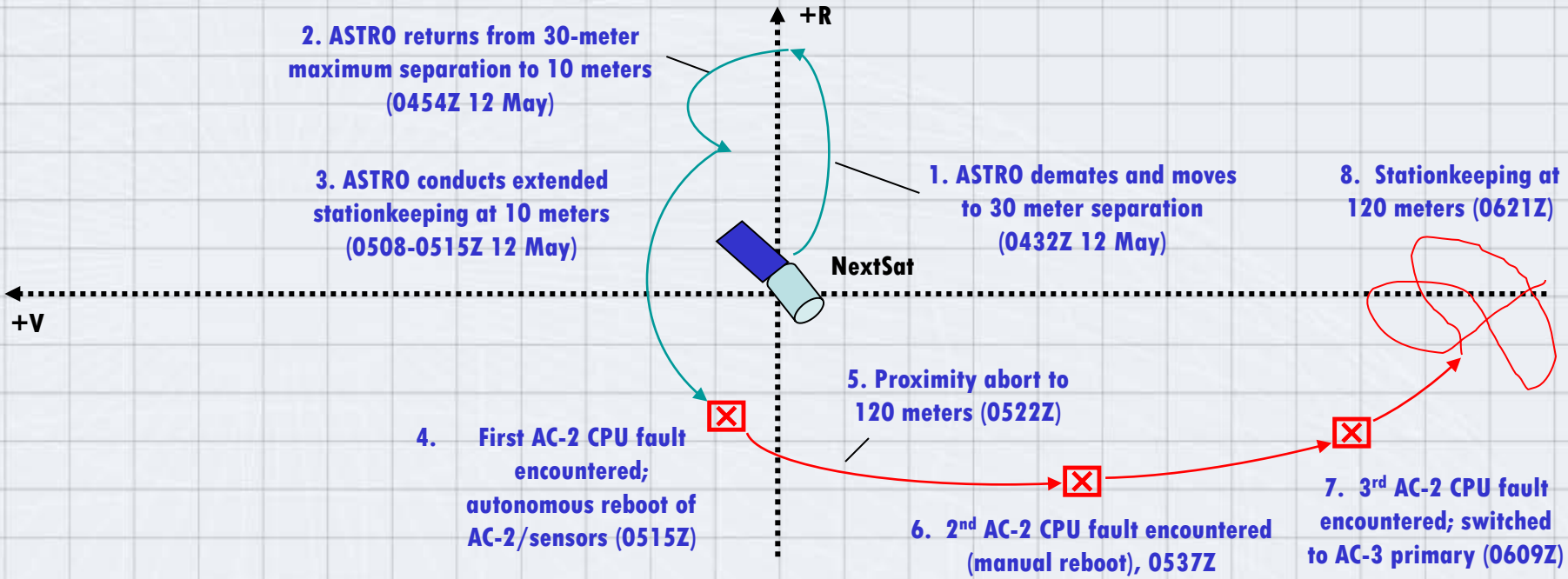
- First pumped transfer of hydrazine propellant : 2 Apr 07
- First battery ORU transfer from ASTRO to NextSat: 6 Apr 07
- Ring Eject, Separation of ASTRO and NextSat: 17 Apr 07
- 10-meter Rendezvous and Capture Scenario: 5 May 07
- 30-meter Scenario encountered an anomaly on 11 May 07
  - Troubleshooting and recovery operations required 8 days
  - Vehicles safely mated late in the evening of 18 May 07





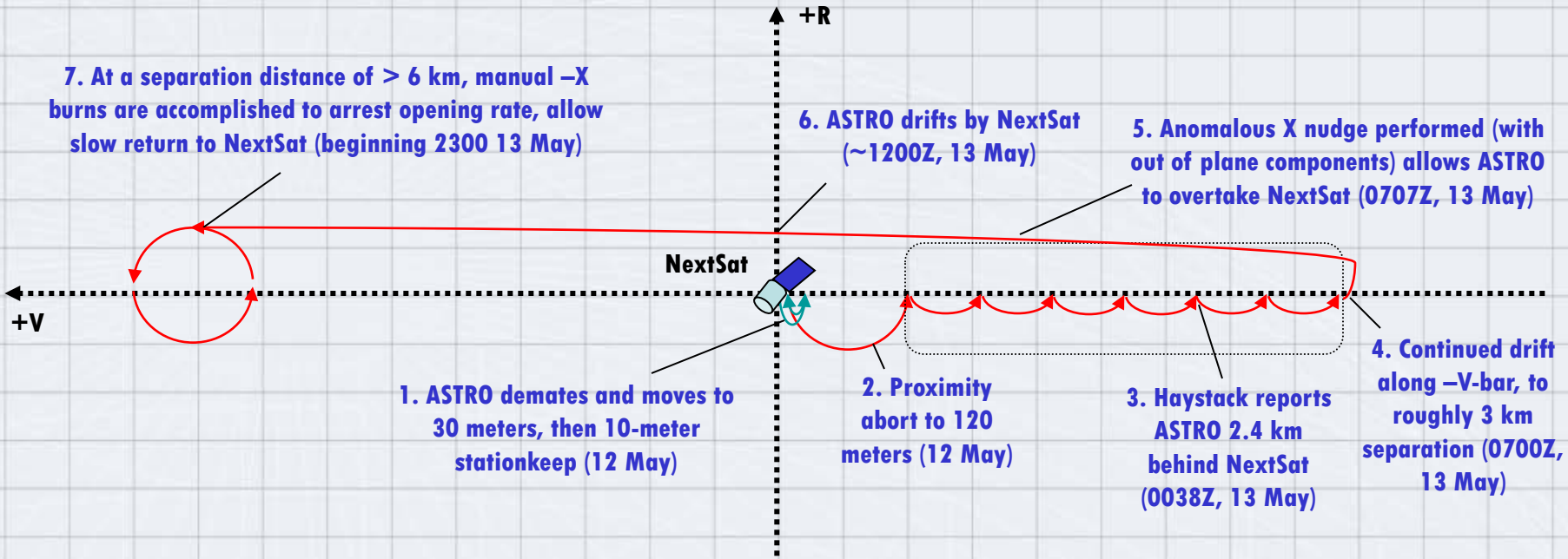
Scenario 3-1 surprised us!

Scenario 3-1: 30-meter rendezvous/capture



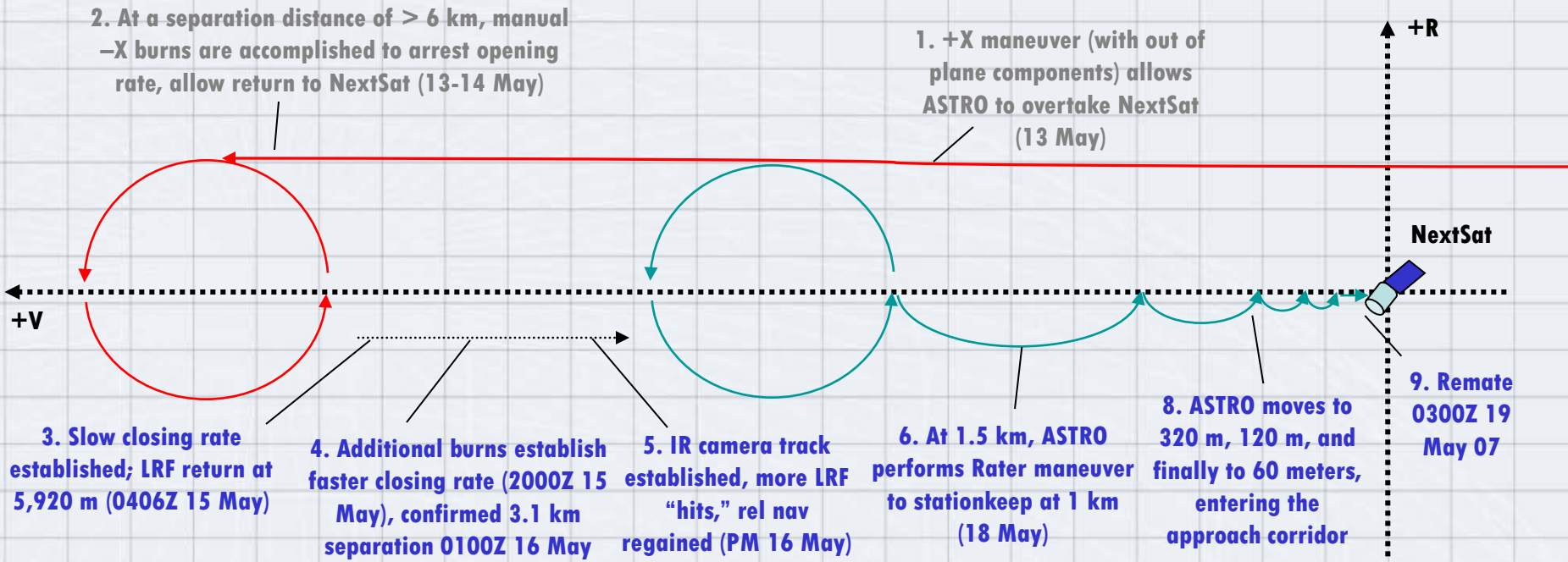
- **ASTRO demated nominally from NextSat late Friday, 11 May 07**
  - Retreated to 30 meters separation distance and recovered to 10-meter stationkeep
  - Encountered primary sensor computer CPU fault at 10 meters and executed abort
  - AC-2 and sensors power cycled following CPU fault; two additional AC-2 failures occur
  - On third AC-2 failure, mission ops selected AC-3 as primary sensor computer
  - ASTRO's autonomous abort took it to a 120-meter hold point and began stationkeeping
- **Relative navigation difficulties at 120 meters forced decision to coast, troubleshoot**
  - At 120 m, ASTRO began to expend significant propellant "keeping up" with navigation state

Scenario 3-1: 30-meter rendezvous/capture (2)



- **Initially, ASTRO slowly drifts backward along –V-bar…then moves forward, passes NS**
  - ASTRO was placed in a free drift with an unknown opening rate (NextSat was becoming noticeably smaller in situational awareness imagery)
  - Situational awareness imagery grew sparser, ops team turns off Viscam2, IR track
  - Haystack overflight indicates separation distance of 2.4 km (midnight, 13 May)
  - Six hours later, anomalous "X Nudge" burn performed
  - This maneuver imparted a high closing rate with Y/Z components (estimate 600 m/hr)
  - ASTRO passes NextSat in early morning hours of 13 May
  - Haystack confirms late on 13 May that ASTRO was now 6 km ahead of NextSat

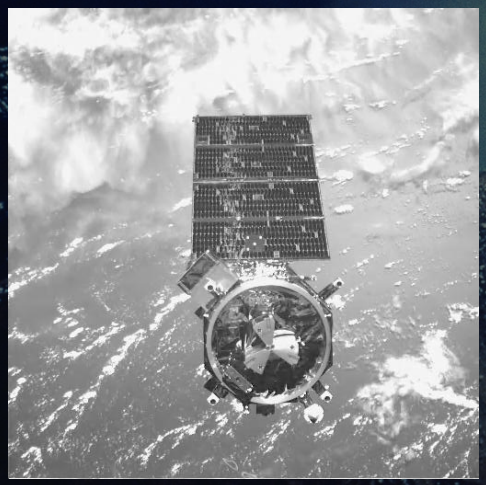
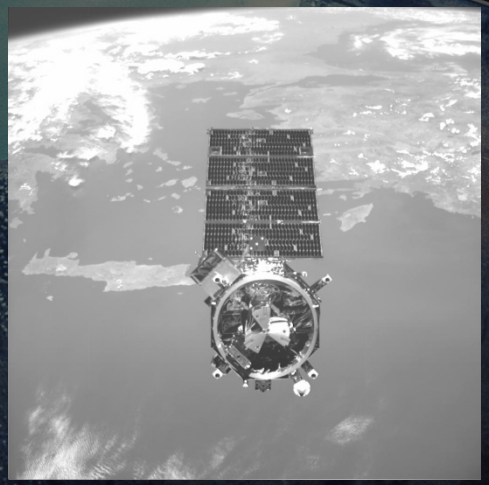
Scenario 3-1: 30-meter rendezvous/capture



- **Manual "test and checkout" burns were used to control inward drift towards NextSat**
  - Chance laser rangefinder hit confirmed Haystack separation estimates (~ 6 km)
  - Additional burns were used to establish faster closing rate, then slowed at 3 km
  - Navigation filter began processing IR camera inputs, then LRF inputs (16 May)
  - Guidance team constructed an ingress maneuver from an arbitrary point outside 1 km
- **Autonomous guidance engaged, ASTRO maneuvers to approach, mate with NextSat**
  - At 1.5 km separation, ASTRO performed a series of small burns to reach stationkeep at 1 km
  - Two additional maneuvers brough ASTRO to 320 meters, then 120 meters
  - Final burns puts ASTRO in NextSat's capture corridor (60 meters), followed by capture

Later Scenarios

- Scenario 5: 60 x 120 meter flyaround
  - -R-bar approach with direct capture
- Scenario 7: "4-km instantiation" with free-flyer capture
- Scenario 8-2: Design Reference Servicing Mission
  - Autonomous rendezvous from a range of 7 km
  - Standoff at 4 km
  - Flyaround inspection at 3x orbit rate
  - Free-Flyer Capture
  - Autonomous Fluid Transfer from ASTRO to NextSat
  - Autonomous Battery ORU Transfer from NextSat to ASTRO and back
  - Highest level of autonomy
- End of Life

Summary

- **What a wild ride!**
  - 100% of mission success criteria met
  - "Taken the technical excuse off the table for on-orbit servicing"
  - Demonstrated rendezvous capability from > 300 km
  -
- **Selected Lessons Learned**
  - 4-pi steradian radar or other sensor would vastly improve ability to find client when "lost in space"
  - Servicing and prox ops <u>demands</u> 24 x 7 communications
  - Don't let anyone convince you that a last-minute software fix is "just fine"