



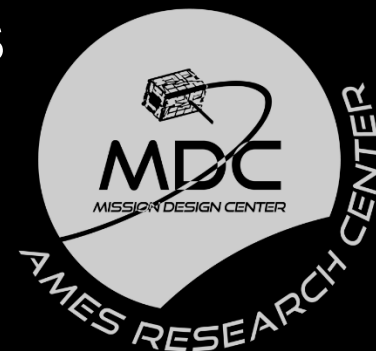
National Aeronautics and
Space Administration

Ames

Discovery • Innovations • Solutions



Mission Design for Deep Space CubeSats



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Butler Hine – Chief Technologist for Engineering
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NASA Ames' CubeSat Missions

NASA Ames has the oldest NASA effort in CubeSats

- Peer-review Science with its CubeSat Missions since 2006
- 21 Mission flown (31 CubeSats) or in active development
- Deployed NASA's first 1U and 3U CubeSats from ISS (2012, '14)
- Developed the first CubeSat Science Swarms (Oct 2015, '16)
- Developing the first Beyond LEO Bio-nanosat (Biosentinal 2018)

Ames CubeSats have been supporting the goals of:

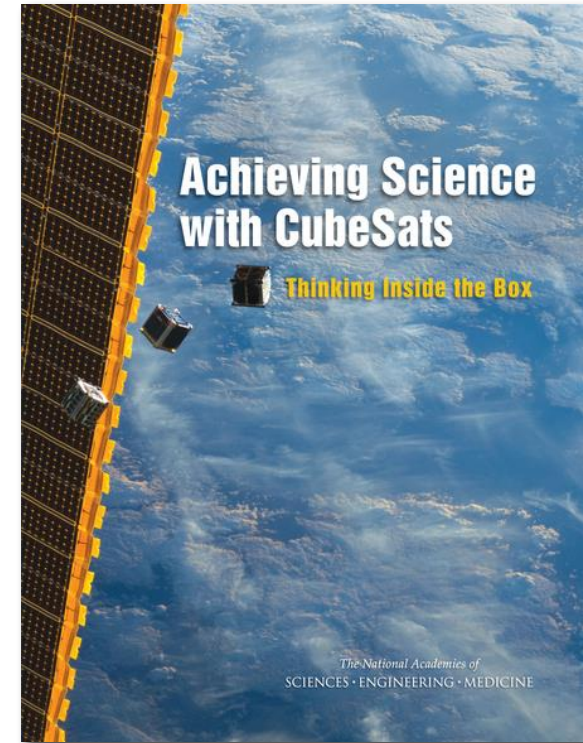
- Space Biology Science,
- Swarm Science, and
- Technology Development.

Current State-of-the-Practice

Domain:	Low Earth Orbit
Deployment:	Secondary Payload Hosted Payload ISS
Lifetime:	Weeks to Years (limited by orbital altitude)
Trajectory:	Passive Differential Drag Propulsion (in development but not yet routine)
Tracking:	GPS Transponders (in development)
Communications:	UHF, S-band and X-band Networked (Iridium, GlobalStar) (in development) Optical (in development)
Applications:	Education Technology Demonstrations/Maturation Space Biology/Life Sciences Earth Science

The Future Need

- **Solar and space physics, Earth science and applications from space—Exploration of Earth's atmospheric boundary region.** CubeSats are uniquely suited because of their expendability to explore the scientific processes that shape the upper atmospheric boundary using short-lifetime, low-altitude orbits.
- **Earth science and applications from space—Multi-point, high temporal resolution of Earth processes.** Satellite constellations in low Earth orbit could provide both global and diurnal observations of Earth processes that vary throughout the day, such as severe storms, and are currently under-sampled by Sun-synchronous observatories.
- **Planetary science—In situ investigation of the physical and chemical properties of planetary surfaces or atmospheres.** Deployable (daughter-ship) CubeSats could expand the scope of the motherships with complementary science or site exploration.
- **Astronomy and astrophysics, solar and space physics—Low-frequency radio science.** Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution in ways not accessible from Earth.
- **Biological and physical sciences in space—Investigate the survival and adaptation of organisms to space.** CubeSats offer a platform to understand the effects of the environment encountered in deep space, such as microgravity and high levels of radiation.



Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, 2016, Committee Chair: Thomas Zurbuchen

The 2016 NAS/SSB report describes example science application areas for CubeSat-class missions.

Challenges of Deep Space Applications

The Deep Space environment can be much more challenging than LEO in terms of:

Radiation

Thermal

Deep Space Communications are much more difficult than LEO:

Range

Antenna Size

Transmit Power

Ground Networks

Power:

Spacecraft are physically small, so require large area/mass SA

Deep Space Missions frequently require active trajectory control:

Propulsion needed either:

(1) to maintain the desired science orbit, or

(2) to get from the secondary payload drop-off to the desired destination

Use of propulsion implies:

(1) tracking

(2) orbit determination

(3) scheduled communications passes, and

(4) maneuver planning and execution

Deployment:

Hosted payload accommodation to destination

Transit from secondary payload drop-off to desired trajectory

Lots of impulsive dV or Low Thrust (high transit time in radiation belts)

Challenges of Deep Space Applications

The low-cost LEO CubeSat operations model does not apply to Deep Space

LEO operations can utilize simpler passive operations and GPS tracking



Deep Space operations require a more complex and active operations approach because of distance and trajectory management.



Deep Space mission operations do not change based on the size or cost of the spacecraft!



Mothership Concept

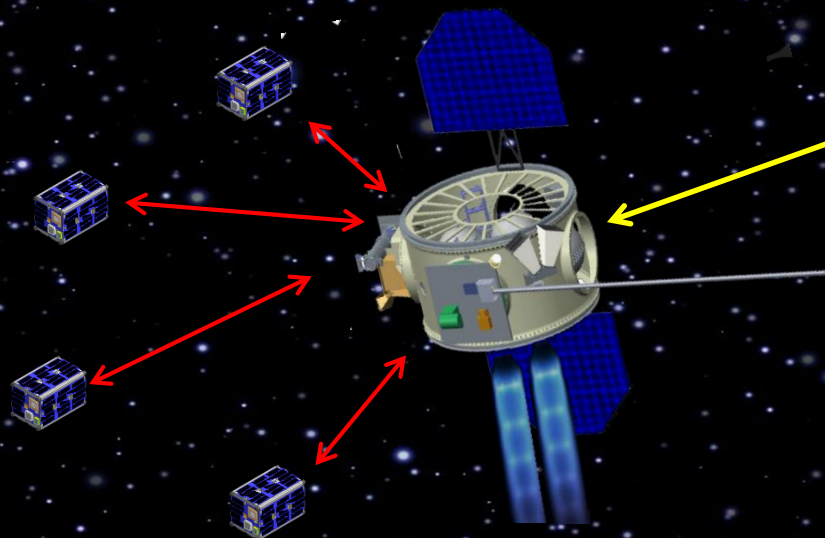
A larger spacecraft carries the CubeSats to their destination orbit, deploys them, and then supplies communications relay functions to Earth:

Propulsion is only required to maintain trajectory, not get them there

Communications becomes short range to the mothership

Less communications power results in smaller solar arrays

Relative navigation between CubeSats and Mothership



Mission Design Center (MDC)

Provide Mission Concept and Spacecraft Design Support for NASA, Academia, other Government agencies.

- Dedicated team of experienced SMEs in all aspects of mission design with the capability to reach out to specialized areas for specific concept requirements.
- Integrated end-to-end mission design and simulation tools with ongoing development efforts to enhance current version and create new tools
- Extensive database of heritage flight hardware, instruments, and mission concepts to leverage for current and future concepts and spacecraft designs.
- Authors of the NASA SSTP State Satellite State of the Art Report imbedded in the concept teams to provide leading edge knowledge of spacecraft technology.
- Collaborative facilities and software tools which enhance the cooperative design environment of the MDC.
- Rapid prototyping capability with the Ames Space Shop (3D printing, CNC, laser cutting, etching, Raspberry Pi, Arduino, and other prototyping tools and systems.



MDC provides comprehensive integrated end-to-end mission design to win proposals

PI Concept Development

Science Instrument Development

Technology Development

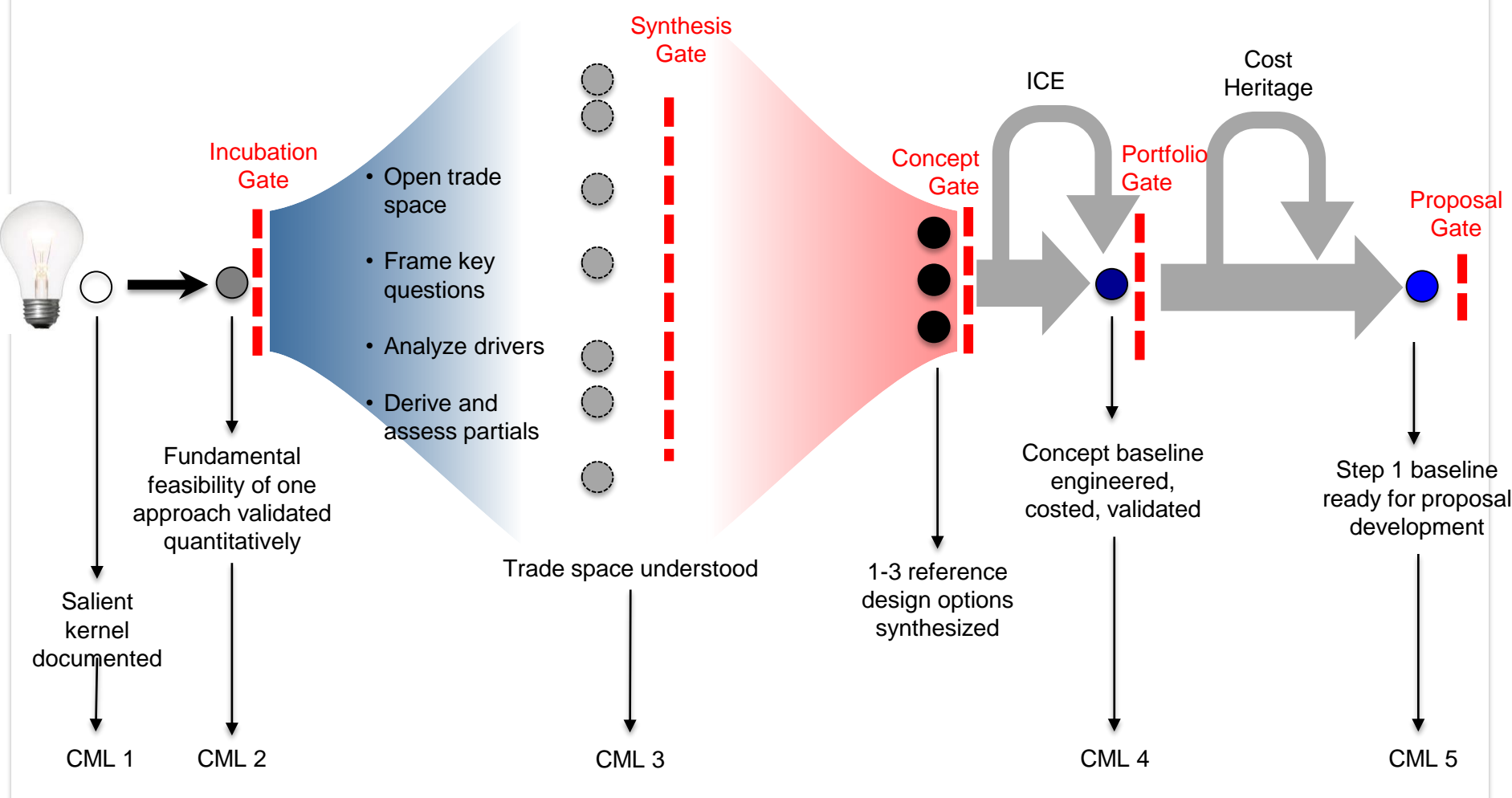
Constellations Designs

Geographic Region Coverage

Swarm Formation & Communications

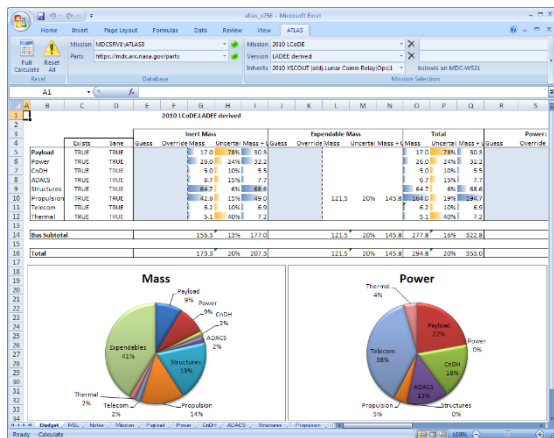


Ames' MDC supports concepts throughout development process





Proposal and Project Development Support



The MDC develops marketing material for concepts through standard products and services

Feasibility Evaluation - for quick decision-making

Conceptual Whitepaper - key technical considerations

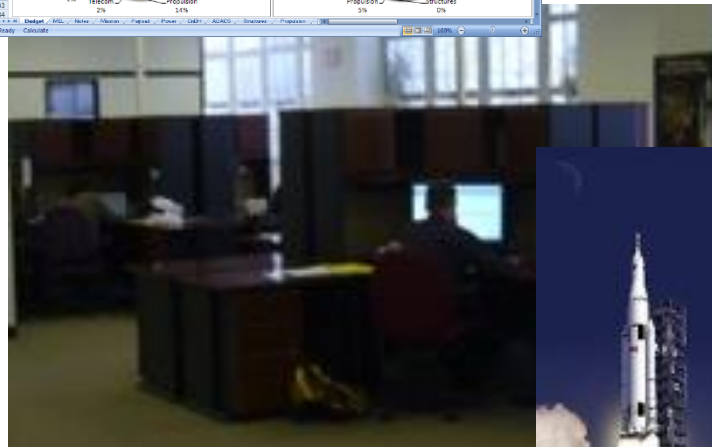
Technical Proposal – lays out credible solutions

MDC is also a shared, prioritized resource for all projects at any development phase.

Almost all spaceflight concepts are supported by the MDC at some point in planning or implementation

LCROSS, LADEE, IRIS, O/OREOS, TES 1-6, BioSentinel, NLAS, and other projects have all received MDC support

Concepts to Flight



MDC Supports Missions from Proposal to Operations



Concurrent Engineering

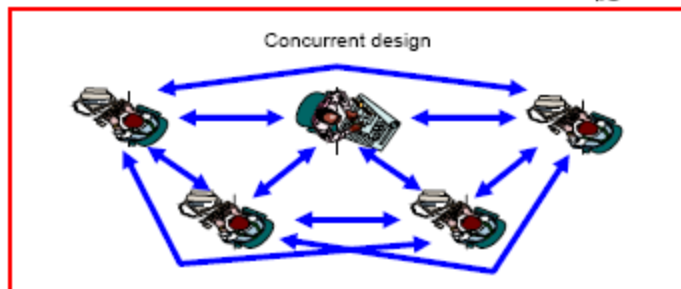
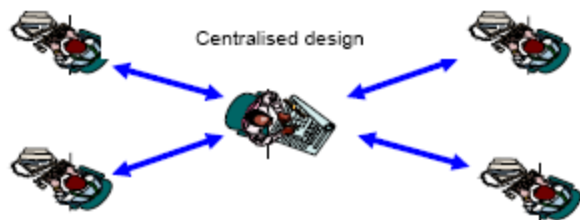


The ARC Mission Design Center is a concurrent engineering facility

- “War Room” environment for design teams
- Similar to Team X (JPL), COMPASS (GRC), MDL (GSFC), MDF (ESA), and several in industry, such as CIEL (Boeing)
- Uses small multi-disciplinary core team augmented with support from other specific subject matter experts

Leverage IT Product Development to Space Mission Design

- Searchable database of previous mission designs
- Database of COTS hardware components and characteristics – Small Sat State of the Art Report
- Custom-built and commercial software tools comprise an Integrated Concurrent Engineering (ICE) environment





Category	Item	Total Software Capability*												
		Atlas (custom ARC tool)	STK, SOAP, GMAT	MAiE	Copernicus, Malto, Mystic	SPENVIS, Trajpad	SolidWorks	Thermal Desktop	NICH, SSCM, NAFCOM	DOORS	MS Project	Sharepoint, NSCKN, MINX	Matlab/Simulink	Microsoft Office
Mission	Orbit and Operational Analysis	■	■	■	■							■	■	■
	Radiation Dosage				■							■	■	■
	Trajectory Optimization (impulsive)	■	■	■	■							■	■	■
	Trajectory Optimization (finite/ low thrust)		■		■							■	■	■
Subsystems	ADACS	■	■				■				■	■	■	
	Telecom	■	■	■	■						■	■	■	
	Power	■	■	■	■			■			■	■	■	
	Thermal	■	■				■				■	■	■	
	Structures	■	■		■	■	■				■	■	■	
	C&DH	■	■								■	■	■	
	Propulsion	■	■	■	■						■	■	■	
System Engineering	Hardware Equipment Lists	■				■					■	■	■	
	Requirements Management	■						■			■	■	■	
	Mass Budgets	■		■		■					■	■	■	
	Spacecraft Configurations	■				■					■	■	■	
Project Management	Task Tracking								■	■		■	■	
	Collaboration	■								■	■	■	■	
	Knowledge Management	■								■	■	■	■	
	Schedule						■			■	■	■	■	
	Cost Estimates							■		■	■	■	■	
	Documentation	■								■	■	■	■	

Legend	
■	Detailed Analysis
■	First-Order / Engineering Estimate
■	Some Utility
■	Not Applicable
■	Non-Standard / Specialized

*Note: First Order software analysis is supplemented with mission design experience to produce detailed results

Ongoing Development is Focused on Providing High Fidelity Day-in-the-life Mission Simulations

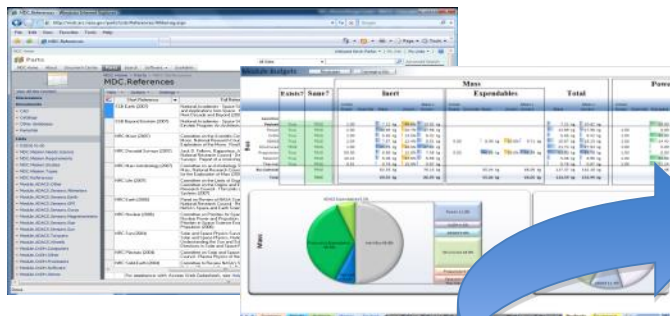
Integrated Design & Simulation Tools

Current Toolsets

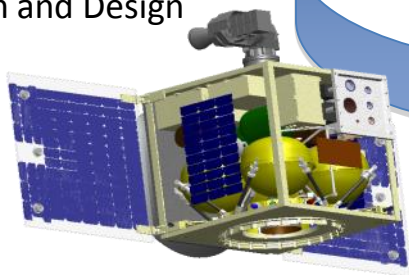
- Atlas and ICEicle – Internal integrated concurrent engineering
- SharePoint – Database, project storage
- STK / SOAP – Trajectories, coverage
- Solidworks – CAD, Mechanical Designs
- Matlab/Simulink – GNC / ADCS modeling and analysis
- Thermal Desktop – Thermal Analysis
- MSC Nastran – FEA modeling

Toolsets in Progress

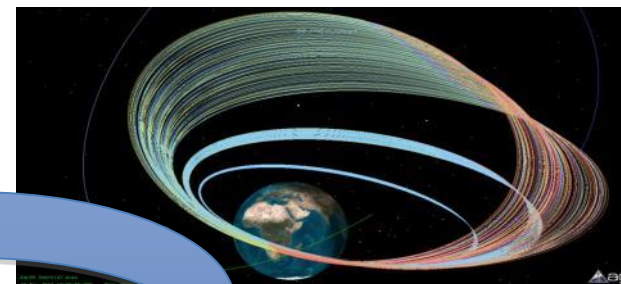
- Generation of xTEDS from database designs
- Integration of plug-and-play software into mission modeling
- Autocode of ConOps software
- Full simulation based design validation
- Autocoded control software



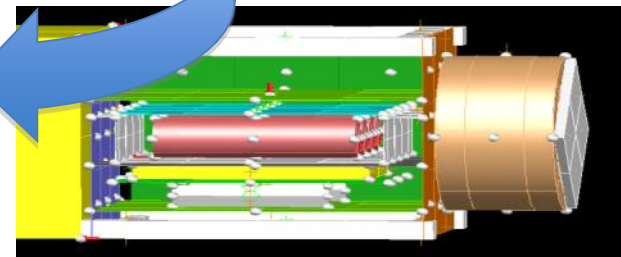
System and Design



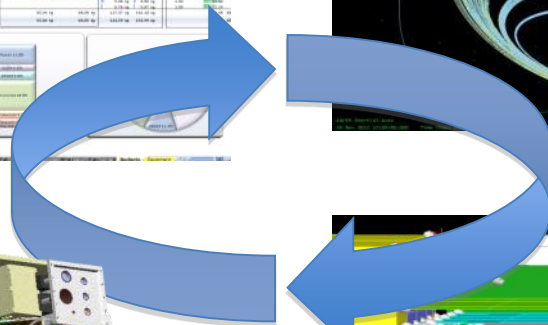
Mechanical



Dynamics

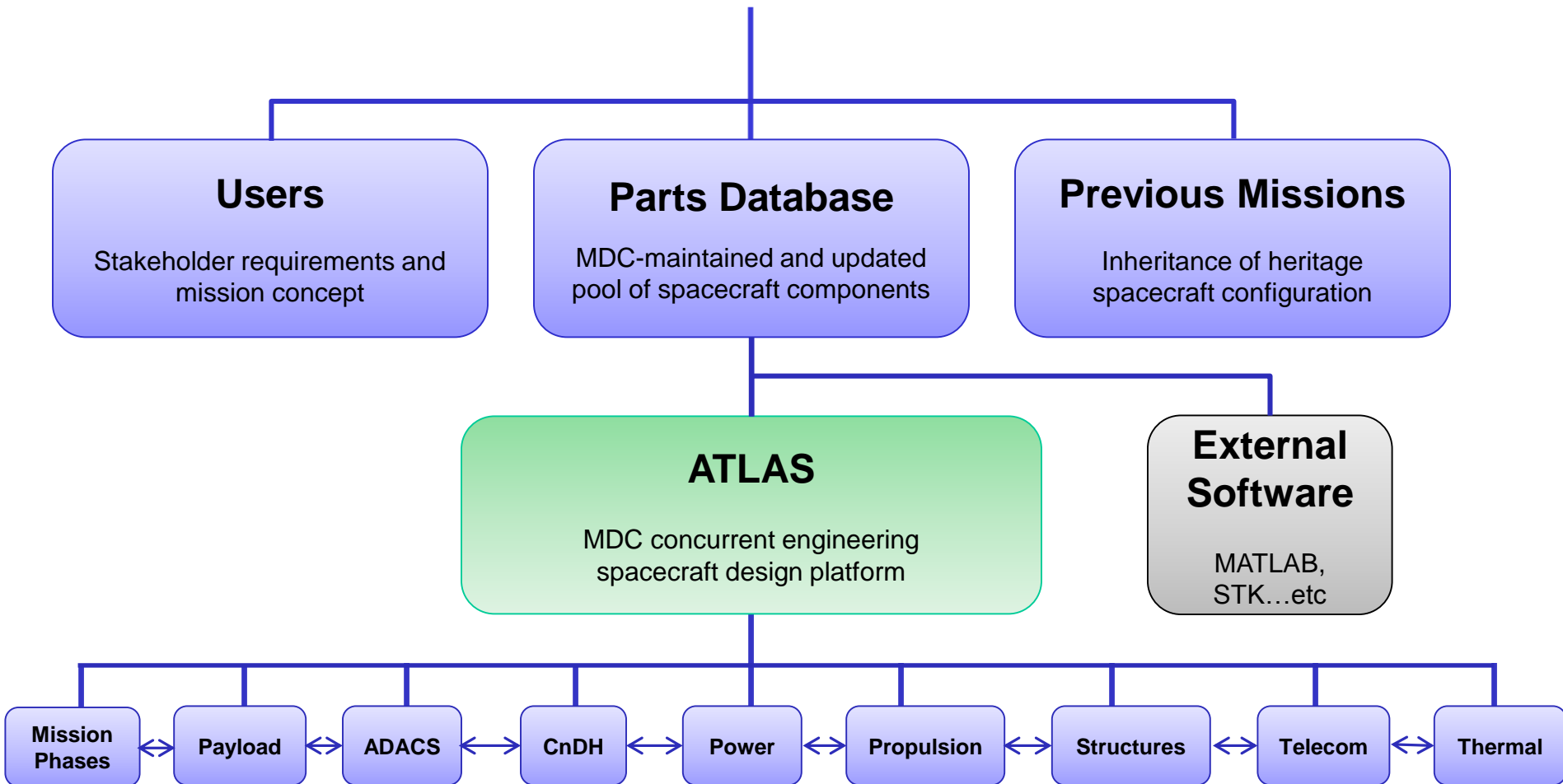


Thermal





Atlas Architecture





atlas_v256 - Microsoft Excel

Home Insert Page Layout Formulas Data Review View ATLAS

Mission: MDCSRV1\ATLAS3
 Parts: https://mdc.arc.nasa.gov/parts
 Database

Mission: 2010 LCoDE
 Version: LADEE derived
 Inherits: 2010 XSCOUT (old).Lunar Comm Relay(Ops)1
 Mission Selection: bslewis on MDC-WS21

A1

2010 LCoDE.LADEE derived														
	Exists	Sane	Inert Mass			Expendable Mass			Total			Power:		
			Guess	Override Mass	Uncertai Mass + U	Guess	Override Mass	Uncertai Mass + U	Mass	Uncertai Mass + U	Guess	Override		
5 Payload	TRUE	TRUE		17.0	78%	30.3				17.0	78%	30.3		
6 Power	TRUE	TRUE		26.0	24%	32.2				26.0	24%	32.2		
7 CnDH	TRUE	TRUE		5.0	10%	5.5				5.0	10%	5.5		
8 ADACS	TRUE	TRUE		6.7	15%	7.7				6.7	15%	7.7		
9 Structures	TRUE	TRUE		64.7	6%	68.6				64.7	6%	68.6		
10 Propulsion	TRUE	TRUE		42.6	15%	49.0	121.5	20%	145.8	164.0	19%	194.7		
11 Telecom	TRUE	TRUE		6.2	10%	6.9				6.2	10%	6.9		
12 Thermal	TRUE	TRUE		5.1	40%	7.2				5.1	40%	7.2		
14 Bus Subtotal				156.3	13%	177.0	121.5	20%	145.8	277.8	16%	322.8		
16 Total				173.3	20%	207.3	121.5	20%	145.8	294.8	20%	353.0		

Mass

Category	Percentage
Expendables	41%
Structures	19%
Propulsion	14%
Payload	9%
Power	9%
CnDH	2%
ADACS	2%
Thermal	2%
Telecom	2%

Power

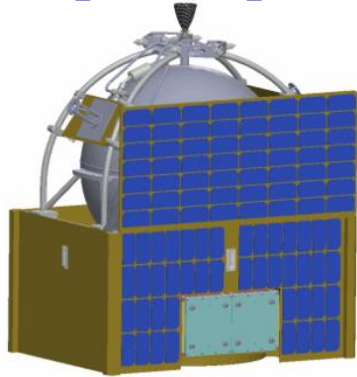
Category	Percentage
Telecom	38%
Payload	22%
CnDH	18%
ADACS	13%
Propulsion	5%
Thermal	4%
Structures	0%
Power	0%

Budget MEL Notes Mission Payload Power CnDH ADACS Structures Propulsion

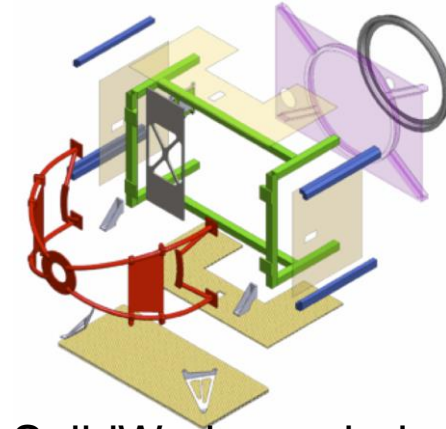
Ready Calculate 100%



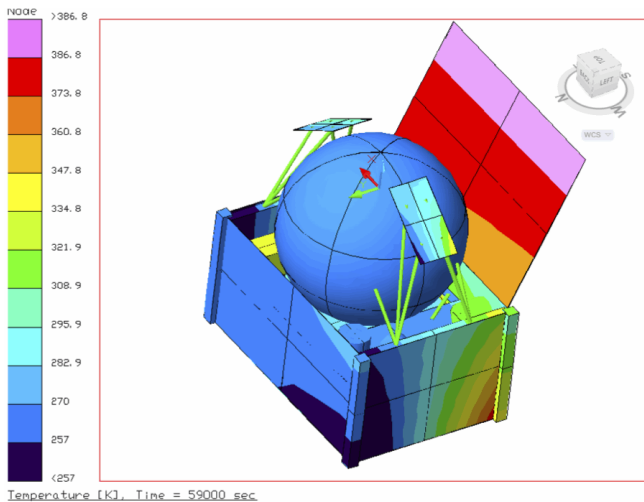
Example: Spacecraft modeling and analysis



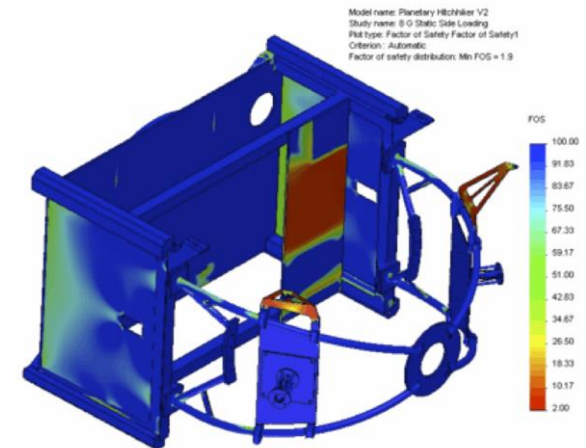
SolidWorks CAD model



SolidWorks exploded view



Thermal Desktop model



SolidWorks Finite Element Analysis



Example: MATLAB Solar Electric Power Script

AGESS Power Analysis

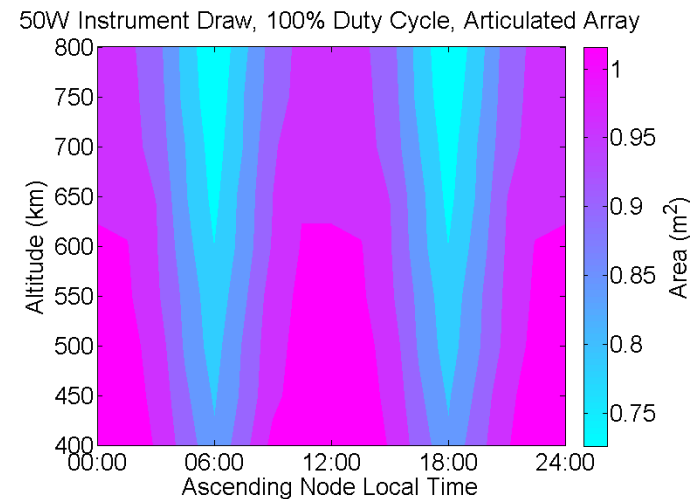
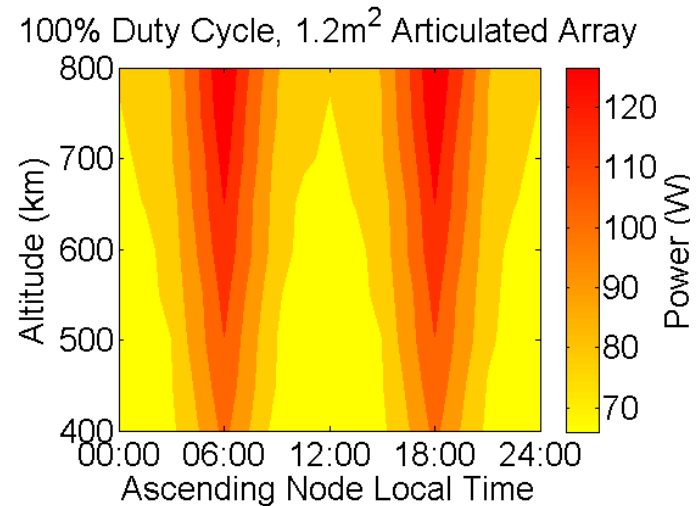
- MATLAB Attitude and Top Level Parameters
- STK Power and Orbit Propagation

```
Command Window
New to MATLAB? Watch this Video, see Demos, or read Getting Started.
Name
  2130
  2115
  poster graphics
  scripts
  attitudedemo.m
  controldemo.m
  DEMOS_READ
  powerdemo.m

Workspace
Name Value
A <9x17
B <9x17
P <9x17
X <2x189
alts [400,45
c 999.00
ect [1500.2
et <9x17
f 988.00
h <1x1
ia <9x17
inc [18.738
mlts <1x17
ot <9x17
pf <1065
sat <1x1

Command History
o.deg = 3
clear classes
o = Tank_
clear classes
o = Geom_3D_Asse
o.Volume = 10
o.Diameter = 2
o.cons
clear classes
o = Fluid_Fundam
o.I = 50
o.Z
o
o.P = 1e5
o.con

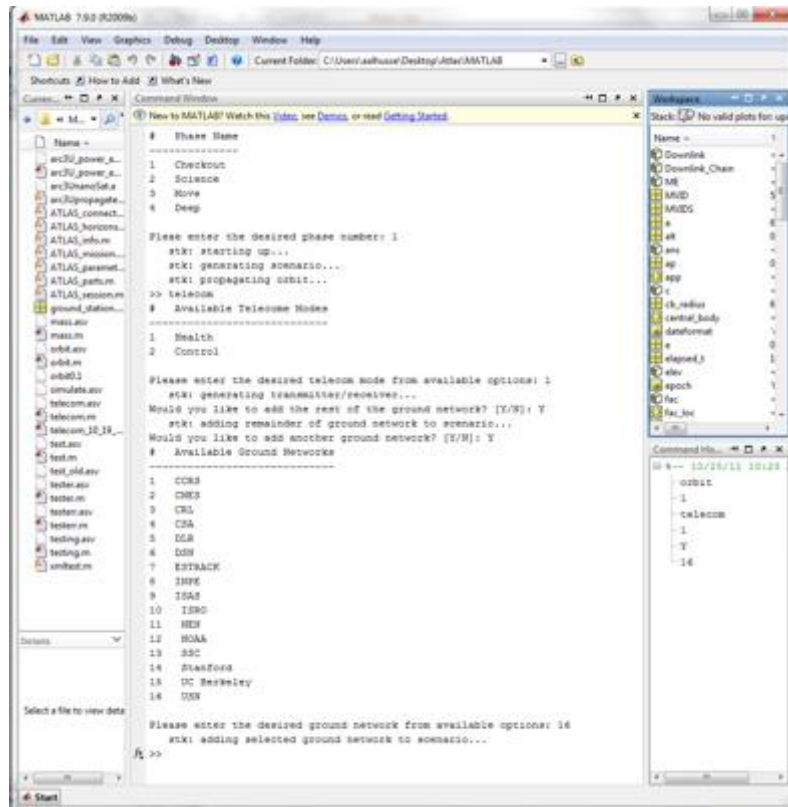
Choose altitudes to test at...
alts = [400 700]
Choose ascending node times to test at...
mlts = [6 12]
Run analysis...
[inc ect obt] = orbitpower(stk,alts,mlts,1,1)
400 km and 6
400 km and 12
700 km and 6
700 km and 12
Average incidence angles (deg) - inc:
    18.7382    45.7874
    19.8062    44.8449
Maximum eclipse times (sec) - ect:
    1500    2175
    1140    2130
Load data from previous work...
powercharts
```



Example: Atlas-STK Interface

ATLAS/STK Telecom Add-on:

- Exports ATLAS telecom design rapidly to STK
- Populates ground stations from MDC database
- Allows quick trades between ground networks



MATLAB 7.9.0 (R2009b) Command Window

```

>> New to MATLAB? Watch this video, see Demos, or read Getting Started.
>> No valid plots for update.
>> Please enter the desired phase number: 1
>> Please enter the desired telecom mode from available options: 1
>> Would you like to add the rest of the ground network? [Y/N]: Y
>> Would you like to add another ground network? [Y/N]: Y
>> Available Ground Networks
>> Please enter the desired ground network from available options: 16
>>
  
```

Available Ground Networks:

1. CCRS
2. CNRS
3. CRG
4. CSA
5. DLR
6. DSN
7. ESTRACK
8. ISRE
9. ISAS
10. ISRO
11. IRI
12. MOA
13. SSC
14. Stanford
15. UC Berkeley
16. DSN



Scenario Name - STK 9 - 3D Graphics 1 - Earth

3D Graphics 1 - Earth

2D Graphics 1 - Earth

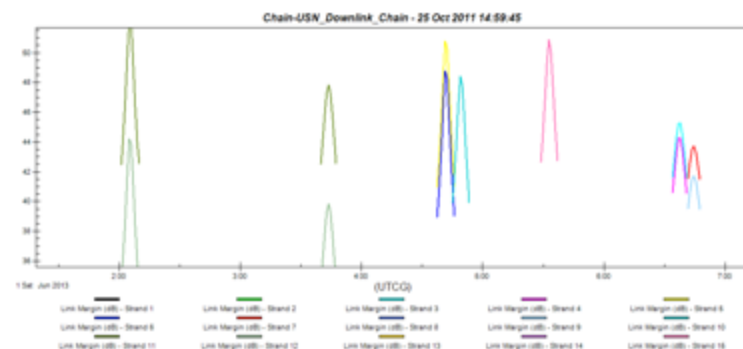
2D Graphics 2 - Earth

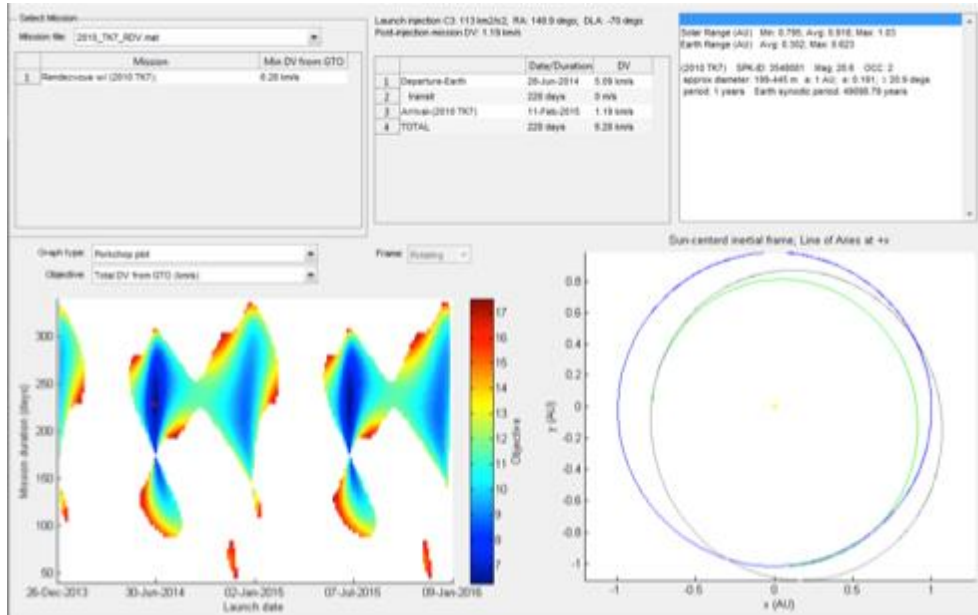
Chain-USA_Downlink_Chain - 25 Oct 2011 14:59:45

UTCO

1 Jun 2013 00:48:00.000 | Time Step: 60.00 sec

1 Jun 2013 00:48:00.000 | Time Step: 60.00 sec

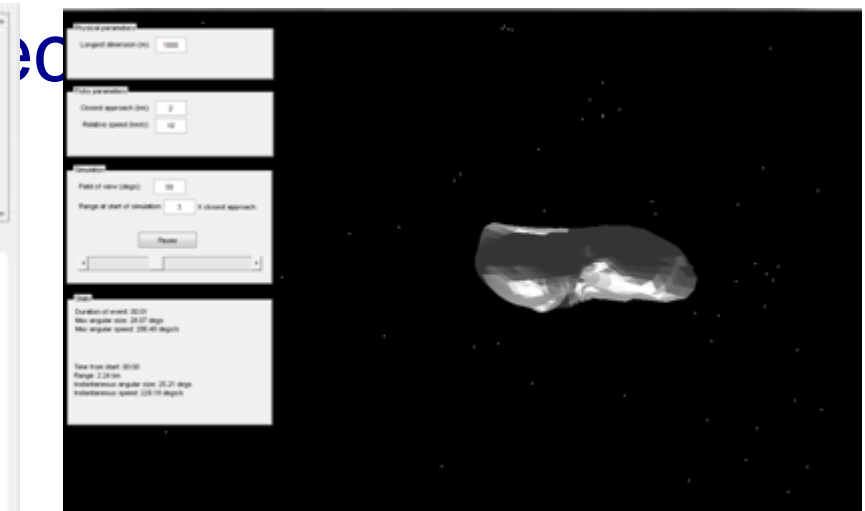




Interplanetary trajectory solver for NEOs and planets

In-House Trajectory Tools for:

- Solving patched conic and N-body interplanetary trajectories to NEOs and planets
- Obtaining low-energy transfers to the Moon
- Optimizing flyby encounter characteristics
- Optimizing EP thruster maneuvers and trajectories



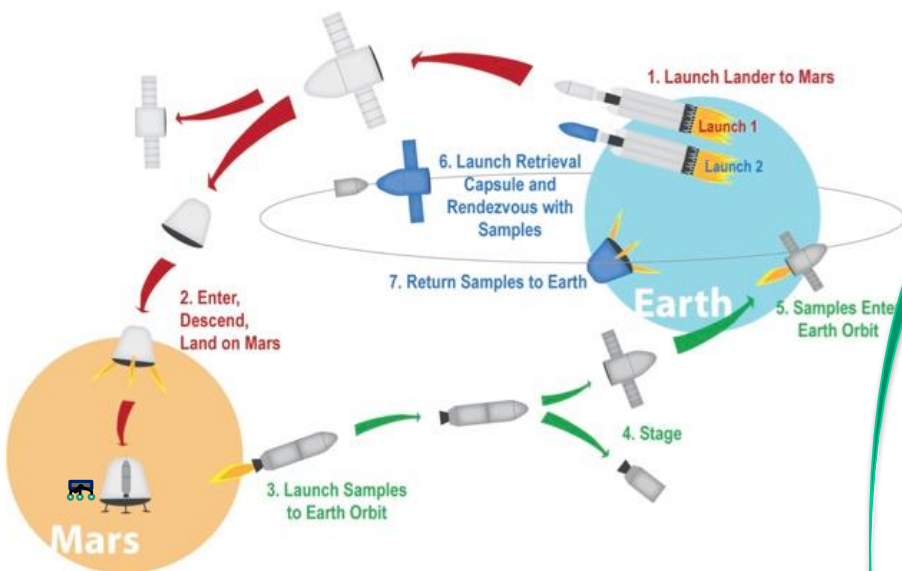
Flyby encounter optimizer



Secondary payload from GTO to the Moon transfer solver



Red Dragon Mars Sample Return Study



How much mass and volume is required for Earth return rocket and related subsystems?

- Conduct parametric optimization study for Earth return rocket using in-house computational tool, HAVOC

Will This

Determine sensitivity of design to: propellant choice, rocket motor design, staging Δv , aerodynamics, etc.

- Choose baseline design for Earth return rocket
- Perform bottom-up design of Earth return rocket and related subsystems

Fit Into

- Develop solutions for support equipment

How much mass and volume can Red Dragon deliver to Mars?

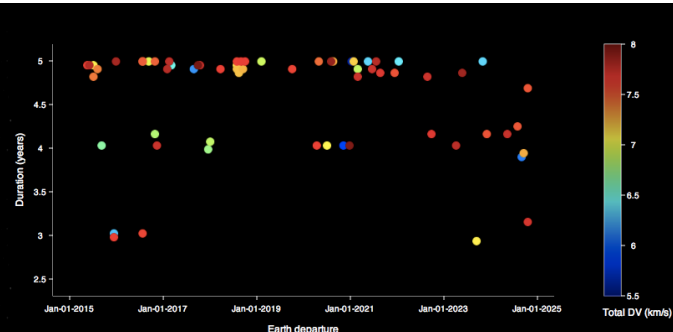
This ?

- Construct aerodynamic model of Dragon
- Include model of retro-propulsion system
- Compute EDL trajectories from entry interface down to surface
- Use in-house computational tool, TRAJ; commercially available tool, POST
- MARSGRAM atmospheric model
- Determine mass limit for successful EDL

Demonstrated that compact and efficient use of emerging commercial capabilities to perform a high priority science mission is feasible.

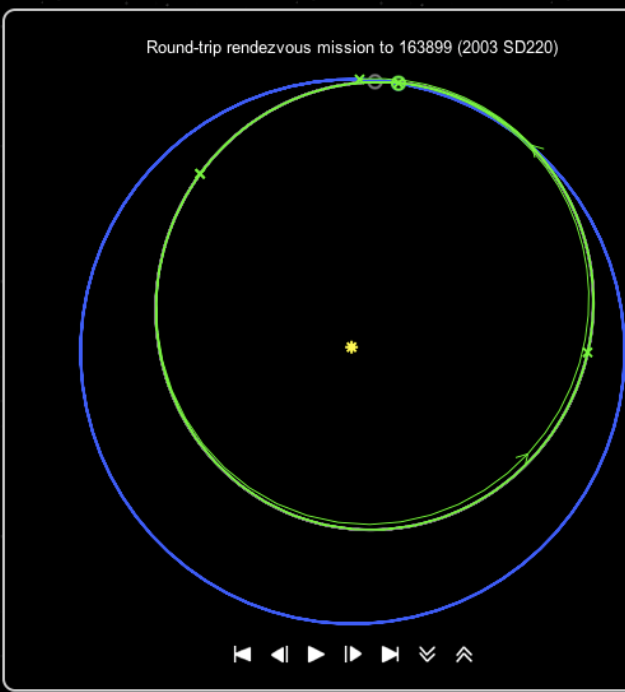
Capabilities of Mission Design Division used to augment analytical work from other Ames organizations

Yes!



Search Query took 1.1s, returned 64 trajectories.

SPK ID	Name	Ale	Size	Orbit	Earth	Destination	Earth	Stay time	Injection	Ale	Injection	Post-	Total	Reentry	Route		
Year		Mass		eccen	Departure	Arrival	Departure	Duration	CD (km ² /s ²)	DA (km/s)	Injection	Injection	Injection	Injection			
216298	16298 (2001 SK162)	17.8	730-1533 m	0	Jan-10-2021	Sep-13-2022	Jan-03-2024	Jan-06-2026	112 days	4.90	25.9	2	4.74	0.07	6.51	12.86	EEAAE
2056803	6803 (2003 JG106)	17.8	685-1533 m	0	Nov-07-2020	Jun-22-2022	May-06-2023	Nov-18-2024	330 days	4.03	25.4	33*	4.45	1.38	5.83	13.21	EAAE
2136818	136818 (1994 CN2)	16.8	1-3 km	1	Aug-30-2024	Jul-18-2028	Dec-26-2028	Jul-24-2028	160 days	3.0	30.7	9*	4.54	1.55	6.09	13.23	EAAE
2141993	141993 (2002 FK12)	16	885-1528 m	0	Aug-27-2019	Mar-26-2020	Jan-18-2020	Jul-28-2022	112 days	4.91	25.3	7*	4.20	1.95	6.16	13.3	EEAAE
2142869	142869 (2003 SD220)	16.9	1-3 km	0	Dec-12-2015	Oct-27-2016	Sep-15-2018	Dec-20-2018	118 days	3.02	25.7	49*	4.34	1.95	6.29	12.91	EAAE
2001843	1843 (1993 EC)	15.8	2 km	0	May-18-2021	Mar-07-2024	Mar-10-2025	May-16-2026	1101 days	4.96	30.3	10*	4.53	1.81	6.34	12.92	EAAE
2003808	3808 (1980 PA)	17.4	1000 m	0	Oct-31-2023	Nov-21-2025	Oct-23-2028	Oct-28-2028	336 days	4.88	28.7	18*	4.78	1.58	6.34	12.95	EAAE
2007341	741 (1991 VG)	16.7	10 km	0	Jan-13-2022	Jan-26-2023	May-29-2025	Jan-11-2027	1183 days	4.99	42.6	9*	6.01	1.38	7.4	13.1	EAAE
2153951	153951 (2001 SA263)	16.9	2 km	0	Mar-04-2017	Nov-07-2020	Feb-27-2021	Feb-14-2022	112 days	4.95	31.2	13*	4.58	1.02	6.48	13.33	EEAAE
2005189	5189 (1990 LQ)	17.3	922-2061 m	0	Sep-07-2015	Mar-23-2018	Jul-13-2018	Sep-18-2019	112 days	4.03	25.7	11*	4.34	2.33	6.67	15.79	EEAAE
2007287	87287 (2000 LY27)	16.9	1-2 km	0	Dec-17-2017	Jan-21-2019	Jun-30-2019	Dec-12-2021	160 days	3.88	33.3	33*	4.65	2.1	6.75	12.33	EAAE
2004179	4179 (1993 RA)	15.3	1.8 km	0	Oct-01-2016	Feb-22-2018	Jun-14-2019	Dec-28-2020	112 days	4.18	35.3	19*	5.97	0.95	6.92	12.65	EAAE
2011394	11394 (1994 BE19)	17.8	722-1637 m	0	Jan-02-2018	Apr-13-2020	Oct-06-2020	Jan-26-2022	178 days	4.07	22.5	4*	4.2	2.86	6.88	12.37	EAAE
3141540	2002 VP89	17.8	722-1615 m	0	Feb-27-2021	May-10-2024	Sep-15-2024	Jan-24-2026	128 days	4.51	25.1	12*	4.31	2.58	6.87	14.07	EEAAE
2007390	7390 (1993 VG)	17.3	922-2061 m	0	Feb-06-2019	May-10-2021	Apr-06-2022	Feb-06-2024	1189 days	4.99	38.8	41*	4.79	2.12	6.9	12.78	EAAE
2012523	12523 (2003 JG106)	16.1	2-4 km	0	Sep-08-2018	Oct-12-2018	Dec-07-2019	Sep-07-2021	114 days	4.95	46.1	19*	5.95	1.13	6.99	14.68	EAAE
2008034	8034 (1992 LF)	17.8	698-1563 m	0	Jul-02-2020	Apr-03-2022	Sep-10-2022	Jul-13-2024	180 days	4.03	18.1	9*	4.02	3.05	7.07	12.4	EEAAE
2138117	138117 (1994 CC)	17.8	818-1821 m	0	Jul-05-2015	Jul-28-2017	Jan-02-2018	Jun-16-2020	180 days	4.95	42.7	10*	5.02	2.07	7.09	14.38	EAAE
2006239	6239 (1993 GF)	17.8	688-1563 m	0	Sep-13-2020	Aug-17-2022	Dec-07-2022	Aug-20-2024	118 days	2.83	24.9	19*	4.3	2.79	7.08	17.82	EEAAE
2019784	19784 (2000 NF5)	16	2-4 km	0	Jul-28-2018	May-18-2021	Sep-07-2021	Jan-11-2023	112 days	4.95	26.1	2*	4.35	2.76	7.11	13.1	EEAAE
2000433	433 (1988 DQ)	11.2	17 km	0	Jan-26-2021	Jan-26-2023	Mar-10-2025	Jan-24-2026	111 days	4.99	23.8	20*	4.28	2.92	7.17	13.14	EAAE
2239716	239716 (2007 FA2)	17.8	701-1688 m	0	Jul-29-2018	Apr-03-2022	Jul-24-2022	Jun-25-2023	112 days	4.81	28.4	2*	4.36	2.85	7.21	14.13	EEAAE
2005940	2011 (XZ)	17.4	847-1528 m	2	Aug-14-2018	Feb-27-2021	Dec-12-2021	Jan-26-2023	280 days	4.88	29	2*	4.25	2.88	7.21	15.14	EEAAE



163899 (2003 SD220) [Small-Body Database]

SPK-ID	2163899	Orbit Condition Code	0
Absolute Magnitude	16.9	Size	1-3 km
Semi-major axis	0.828 AU	Eccentricity	0.211
Inclination	8.46°		

Trajectory Itinerary

	Date	ΔV	
Earth Departure	Dec-12-2015	4.34 km/s	C3 = 25.7 km ² /s ² DLA = -48°
<i>320-day transfer</i>			
Asteroid Arrival	Oct-27-2016	1.46 km/s	
<i>1.88-yr stay</i>			
Asteroid Departure	Sep-15-2018	486 m/s	
<i>96-day transfer</i>			
Earth reentry	Dec-20-2018	-	12.51 km/s reentry total ΔV
<i>3.02-yr total mission</i>			
		1.95 km/s	post-injection ΔV
		6.29 km/s	total ΔV

Solar range: 0.64 - 1.01 AU Earth range: 0 - 2.01 AU

- Web application for searching and assessing candidate mission trajectories
- Originally developed for internal use
- Now publicly accessible at <http://trajbrowser.arc.nasa.gov>



Questions?

