Airplanes for Planetary Exploration

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Outline

- Science From an Aerial Vehicle
- Mission Implementation Context
- ARES Overview
- Mars Airplane Technical Influences
- Mars Airplane Evolution
- Entry, Descent, Deployment Analysis, Simulation, and Testing
- Atmospheric Flight Analysis, Simulation, and Testing
- Other Considerations
- High Altitude Flight Testing
- Future Efforts
- Other Destinations

Science From a Mars Airplane

- Science interest has evolved as new measurements are obtained
  - Global scale from orbit
  - Local scale from landers/rovers
- Aerial vehicles fill a critical and unique niche between orbiters and landers
  - Aerial vehicles can obtain in-situ and remote measurements of terrain and geologic features inaccessible to landers and rovers
  - Aerial vehicles can perform precision high resolution surveys covering hundreds of kilometers - difficult for orbiters to perform
- Interactions between the surface and the atmosphere are best measured within the first scale height of the atmosphere
  - Mars – Understanding the water cycle and the Search for gases of biogenic and volcanic origin
  - Titan – Understanding the methane/ethane cycle and the Search for organic compounds, the precursors of living systems
- Surveys of magnetic fields on a regional-scale
- Investigation of near surface radiation levels on a regional-scale
- Prepare and support the human exploration of Mars

Mission Implementation Context

Primary mission emphasis is return of high-value science data

Key Constraints:

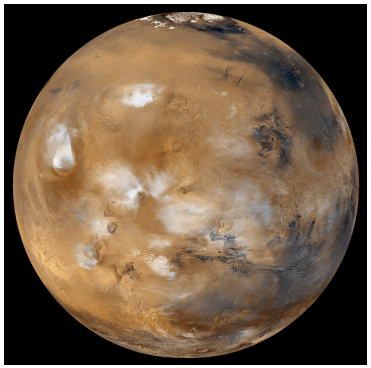
- **Cost** – Total mission cost limits
- **Schedule** – typical 4 year implementation schedule (from mission selection to Launch)
- **Launch Vehicle** – environments, packaging (diameter, CG)
- **Other** - Biologically sterile (Planetary Protection guidelines)

Reduce Mission Risk:

- Mission emphasis is return of science data
- Simplify systems to reduce complexity and increase reliability
- Ensure "on-time" delivery for launch opportunity (*Mars - 45 days every 26 months*)

Implementation strategy balances science needs and mission constraints

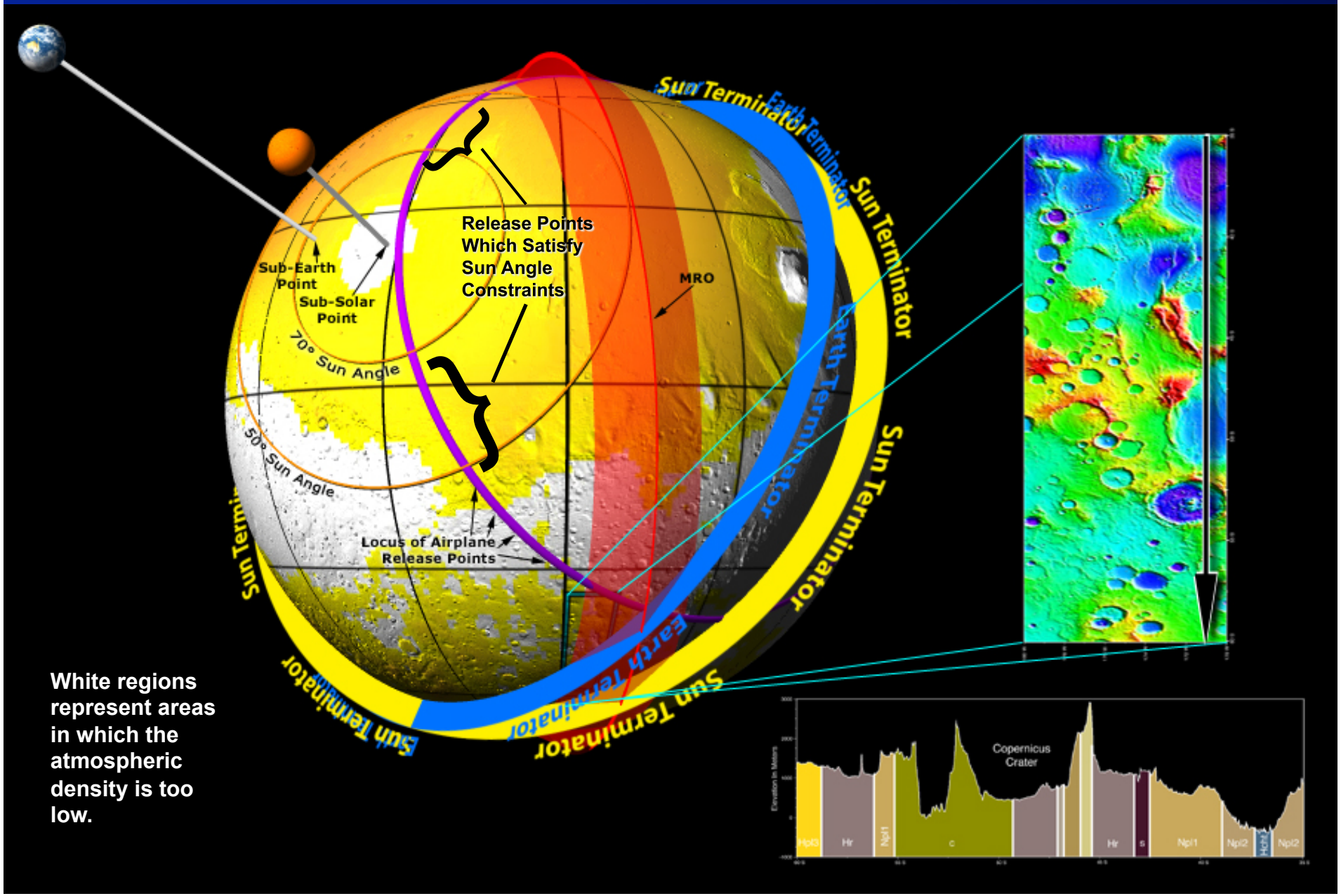
Earth-Mars Comparison



Diameter = 7917 miles
Gravity = 1 g
Surface Pressure = 1000 mbars
Topographic Variability = 12 miles
Atmos. = 79% N_2; 21% O_2

Diameter = 4213 miles
Gravity = 0.38 g
Surface Pressure = 6.4 mbars
Topographical Variability = 18 miles
Atmos. = 95.3% CO_2; 2.7% N_2;1.6% Ar

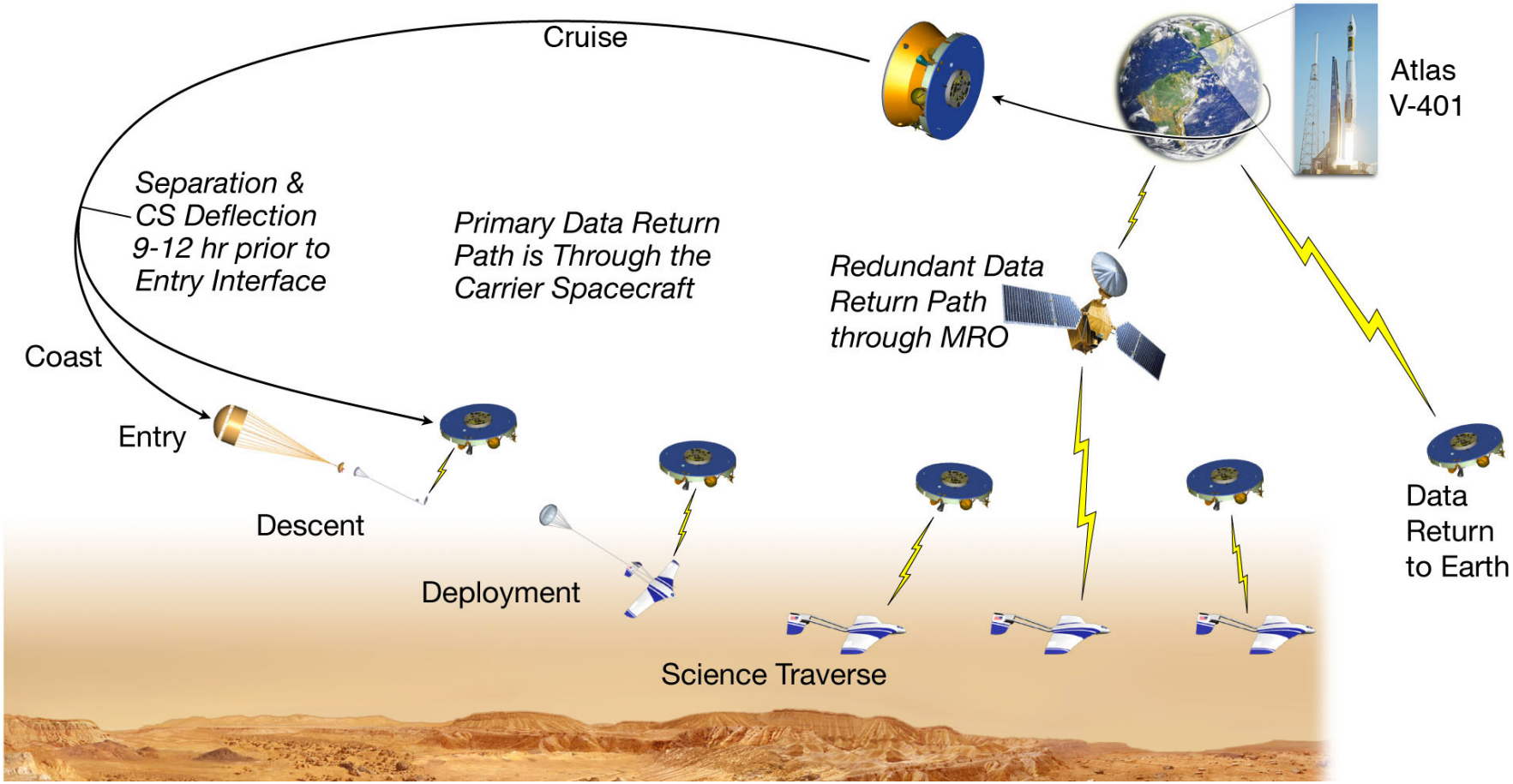
Development of Reference Flight Paths



White regions represent areas in which the atmospheric density is too low.

What Is ARES?

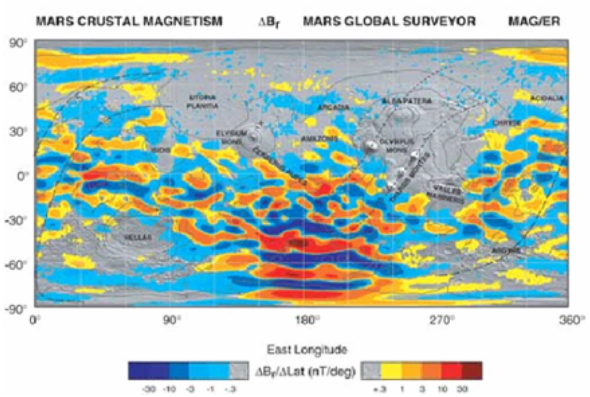
- ***ARES*** - Aerial Regional-scale Environmental Survey of Mars
- ARES - a science-focused Mars mission to perform a survey of remnant crustal magnetic regions and sub-surface water, while characterizing the surface and atmosphere chemical interactions and dynamics



Science Summary

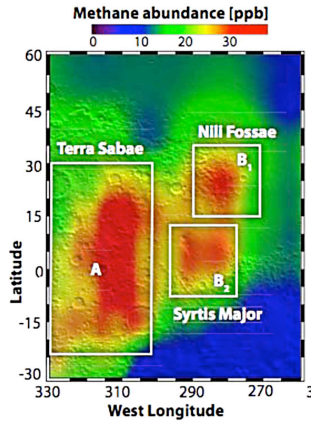
Crustal Magnetism

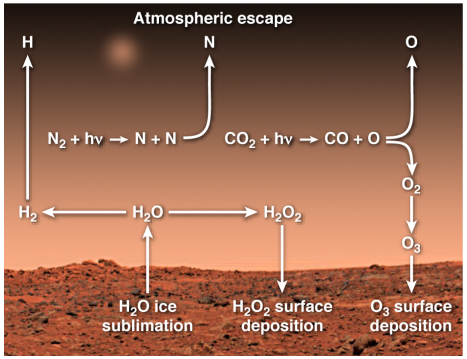
Crustal magnetic fields measured by MGS at 400 km. ARES will measure detailed crustal magnetic source structure 100x better than MGS to aid in the understanding of Mars geologic evolution.



Measurements of crustal magnetism are only accomplished with a near-surface controlled aerial traverse over regional-scale distances.

Atmospheric Composition & Chemistry

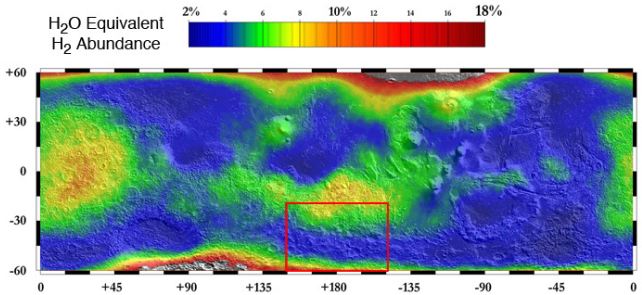




Atmospheric composition and chemistry objectives are uniquely accomplished with an aerial platform:
- ***determine regional-scale diversity***
- ***locate potential sources and sinks***
- ***assess boundary layer gas diffusion processes***

Sub-Surface Water & Hydrous Mineralogy

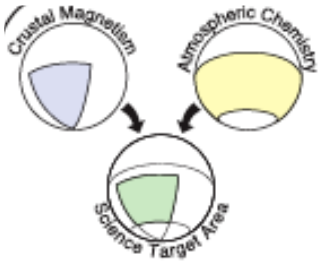
Water-equivalent Hydrogen abundance measured by Odyssey at 300 km.



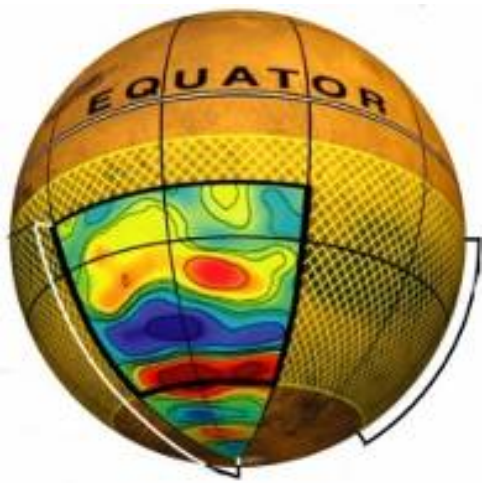
Can verify if sub-surface water deposited during periods of high obliquity is undergoing sublimation, thus constraining the climate change cycle.

Sub-surface water science objectives are uniquely accomplished with an aerial platform:
- ***resolve water features to <2km scale (100x over Odyssey)***
- ***Allows ground-truthing of Odyssey data and correlation of water features with geologic features on the same scale***
- ***measure simultaneous water vapor to deduce sublimation rates***

Science Target Area



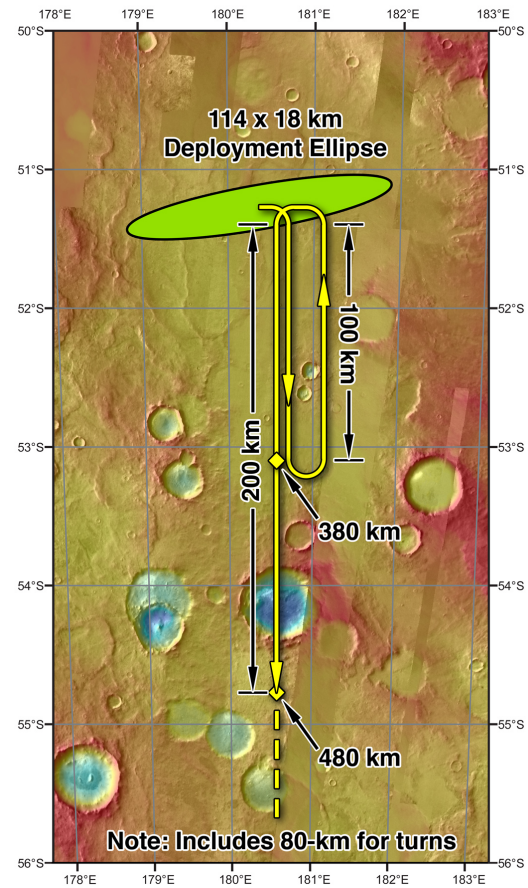
- Science Target Area (STA), the ancient highland of Mars, a region of great importance as identified in the SSE Report
- The STA is a confluence of science objectives satisfied with MAG, MS, and NS measurements



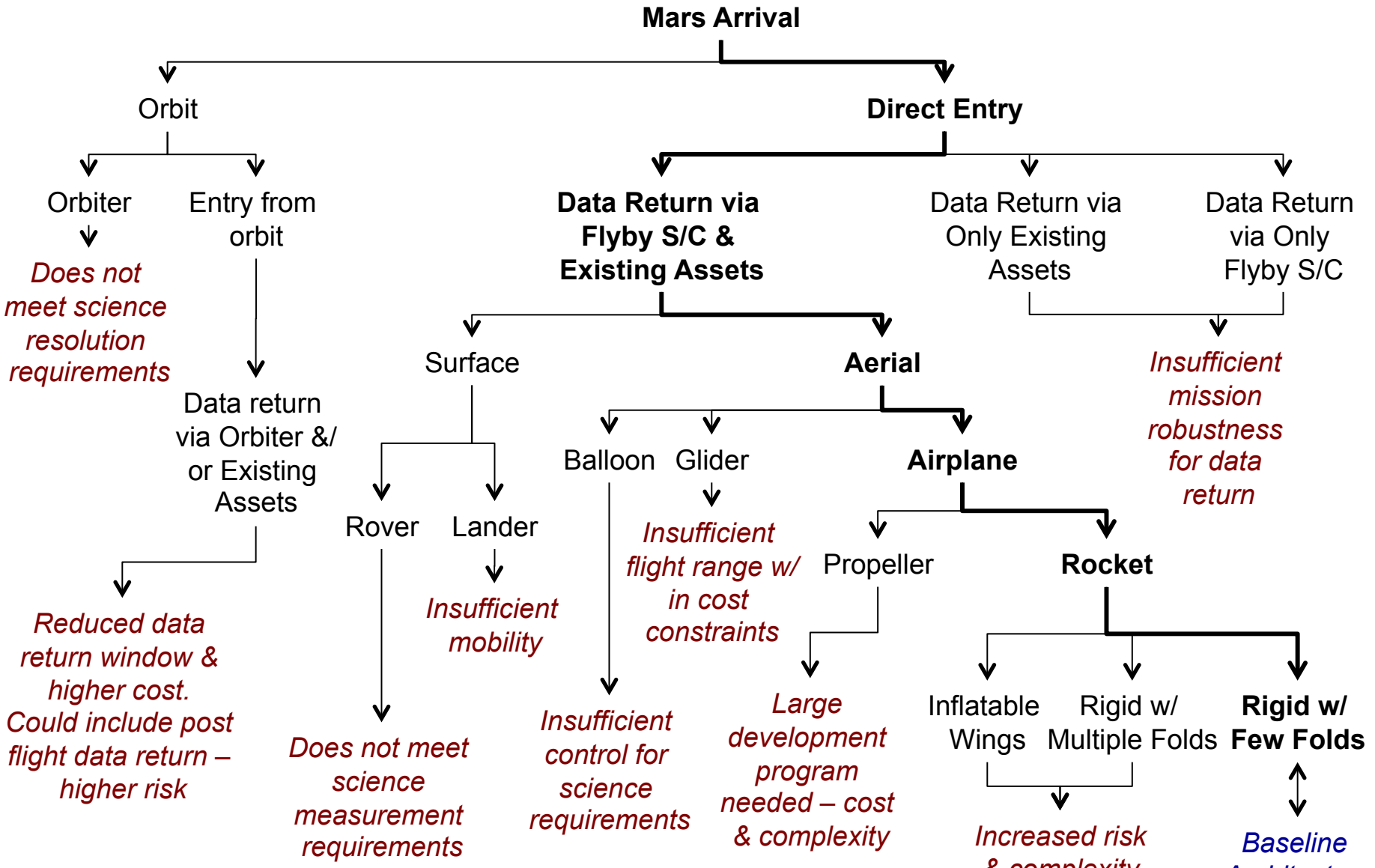
Science Target Area
-20 to –75 Latitude
180 Long (+/- 30 deg)

Science-driven Flight Requirements:

Altitude: 1.5 km AGL
(+/- 0.5 km 3-sigma)
Velocity: 145 m/s (nominal),
180 m/s (max)
Range: 480 km (baseline)
380 km (threshold)
Duration: 55 min (baseline)
43 min (threshold)
Navigation: +/- 10 deg North/ South
+/- 5 deg parallelism



Systematic Approach to Final Architecture



Mars Airplane Technical Drivers

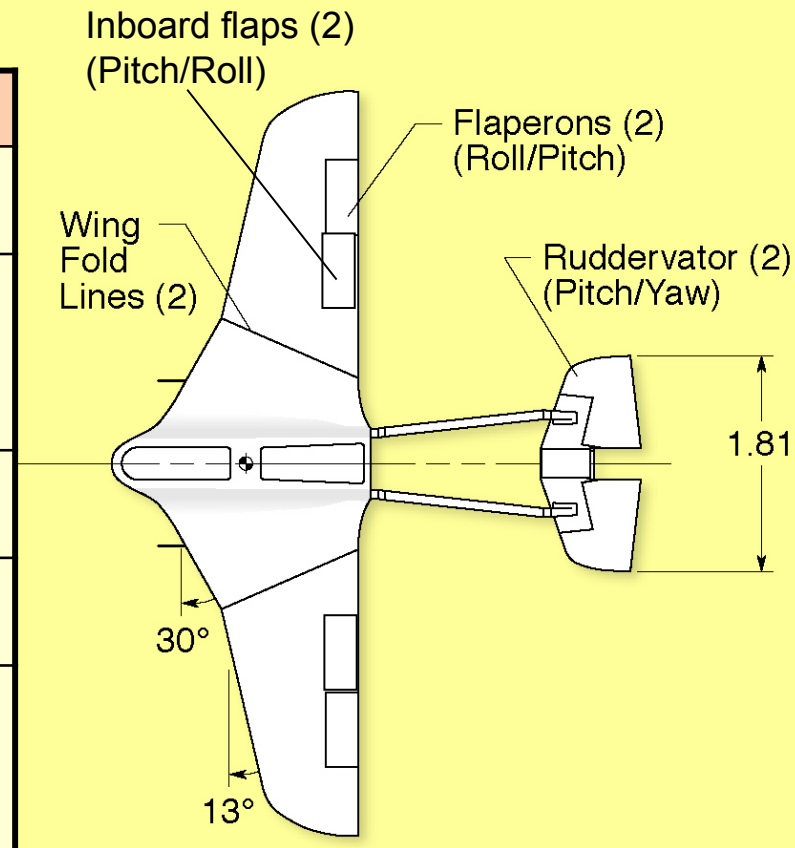
Atmospheric Density - Low w/ Large Variability	***Influences Reynolds No. & Dynamic Pressure***	**Resolved via** ***Increasing Flight Speed*** ***Increasing Wing Area*** ***Sensitivity to Flight Mass***
Low Temperature & CO_2 Atmosphere	***Influences Reynolds No. & Mach No.***	**Resolved via** ***Increasing Wing Chord*** ***Decreasing Wing Thick.*** ***Airfoil Selection***
Launch & Entry Loads - Packaging in Entry Aeroshell	***Influences Airplane Size & Configuration***	**Resolved via** ***Folding Airplane*** ***Airframe & Support Stiffness*** ***Sensitivity to Configuration*** ***Operations Planning***
No magnetic poles, stars not visible	***Influences Guidance & Nav. – Science & Safety***	**Resolved via** ***IMU & flight duration within calibration time*** ***Additional nav. sensors***

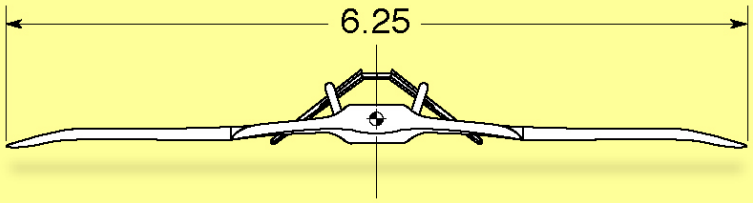
Influence Of Science Measurements

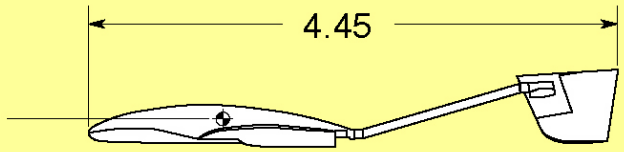
Measurement	Vertical	Lateral				Other		
	Altitude	Rel. Nav.	Abs. Nav.	Speed	Stability	LTST	Flight Range	Mag. Clean.
Imaging	X			X	X	X		
Spectroscopy	X			X	X	X		
Mass Spectrometer	X		X			X	X	
Gas Chromatograph	X		X			X	X	
Magnetometer	X	X					X	X
Neutron Spectrometer	X		X				X	
SAR	X		X	X			X	
Gravity Meter	X	X					X	X
Meteorology	X			X		X	X	

ARES Airplane Configuration

Parameter	Value	Benefit
Reference Area	**7 m^2**	**Enable STA access through pullout margin**
Mean Aerodynamic Chord	**1.25 m**	**Allows credible aerodynamic determination because Reynolds number is in a validated, predictable regime**
Propulsion	**Pulsed Rocket**	**Low risk, proven propulsion for low density applications**
Number of Folds	**3**	**Few folds increases deployment reliability**
Stability	**Naturally Stable**	**Static stability allows use of traditional flight control system and simplifies flight software**

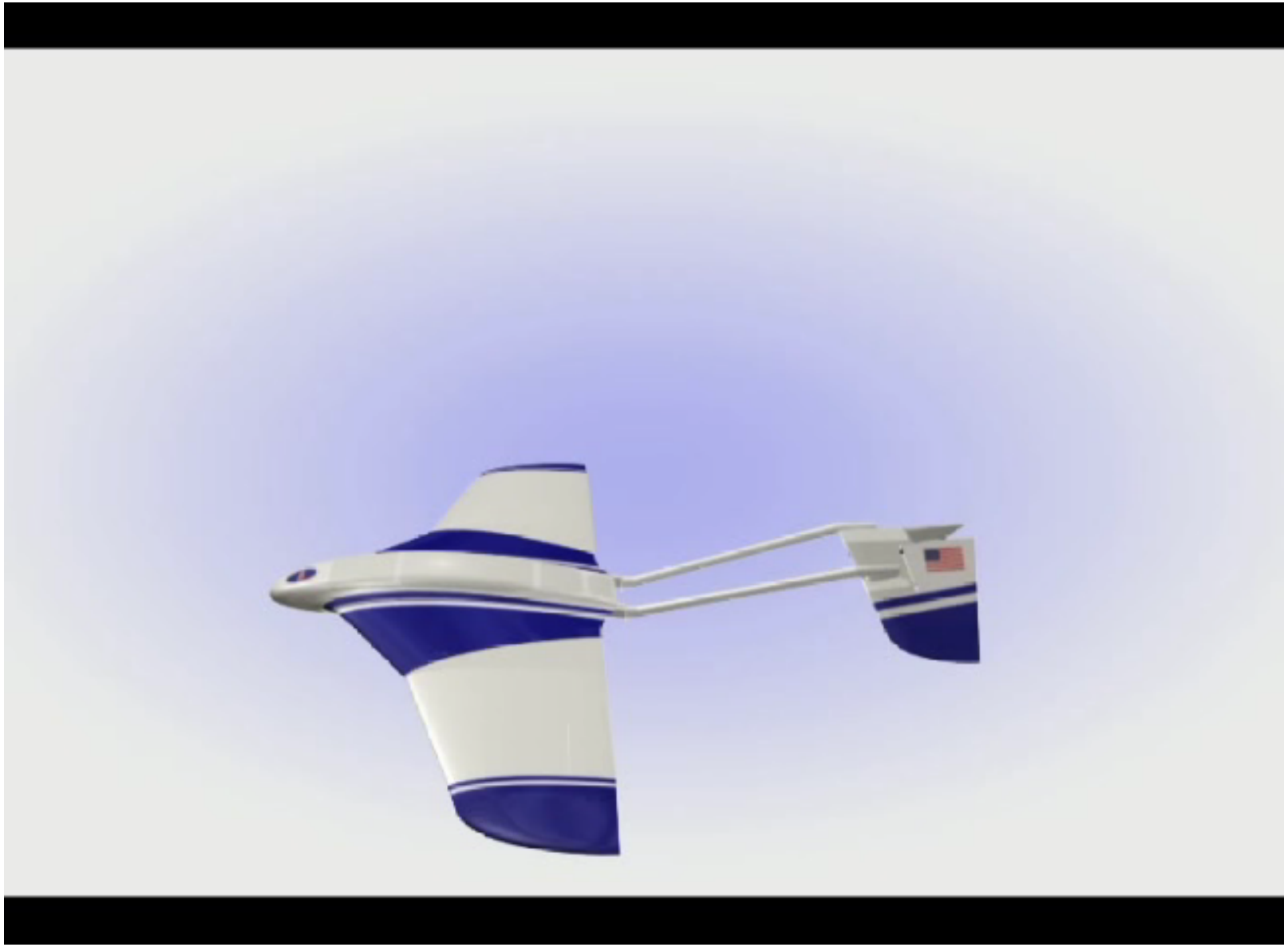




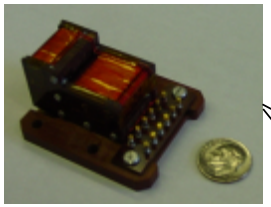


Dimensions in meters

Aeroshell Packaging Influences Configuration

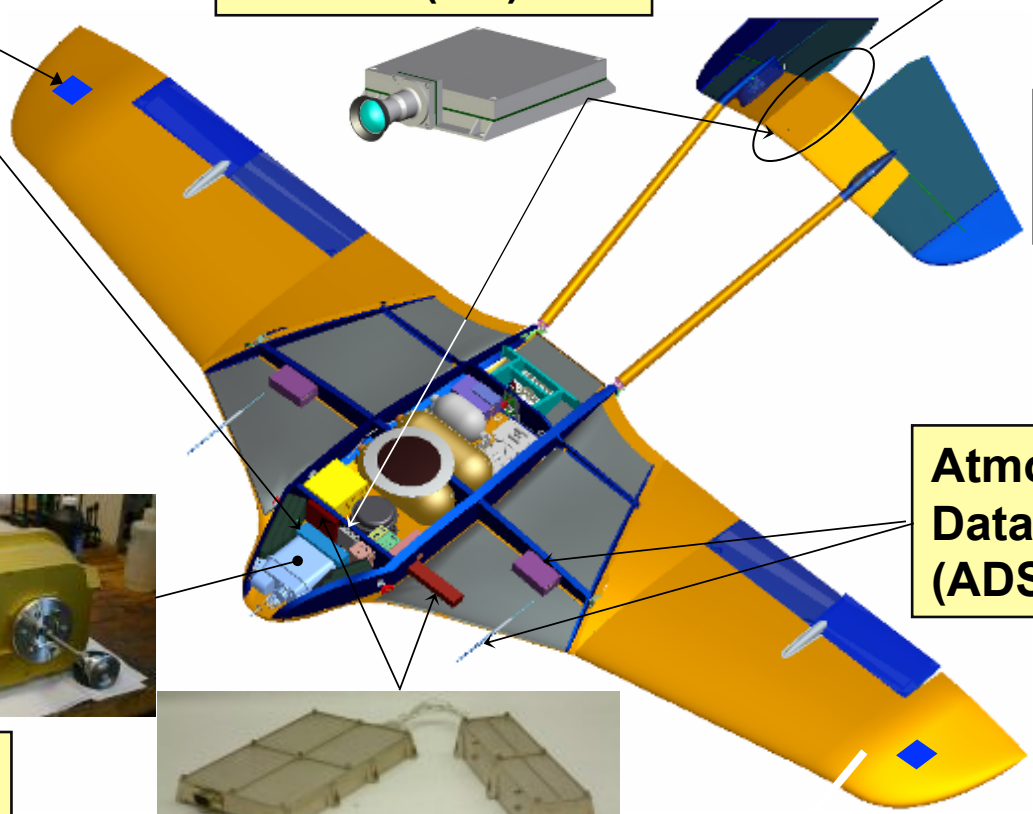


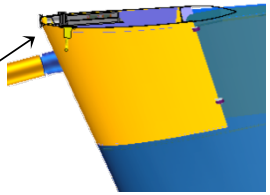
ARES Science Payload



Magnetometer (MAG)

Video Camera (VC) and Context Camera (CC)

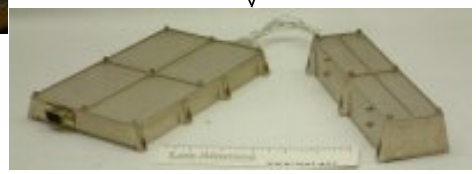




VC accommodated in tail

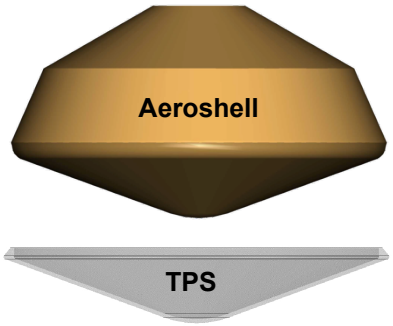
Atmospheric Data System (ADS)

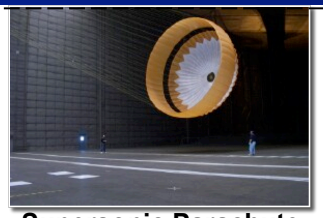
Mass Spectrometer (MS)



Neutron Spectrometer (NS)

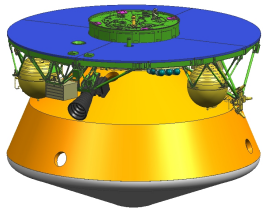
ARES Overview – System Implementation



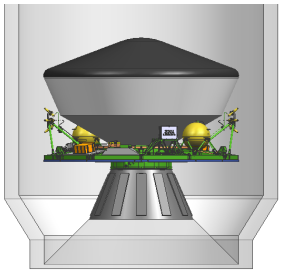


Supersonic Parachute Disk-Gap Band

Entry Flight System

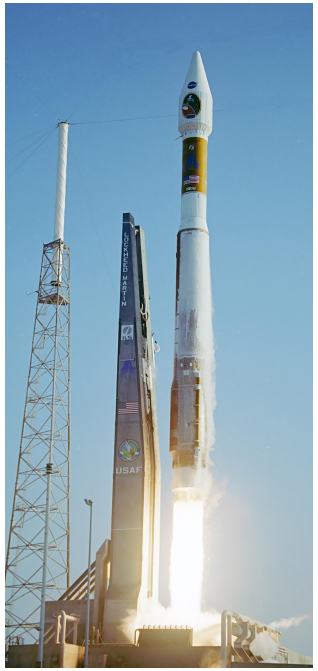


Interplanetary Cruise

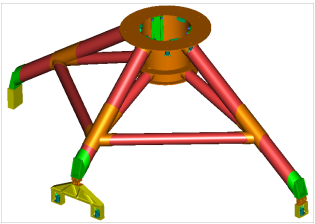


Launch

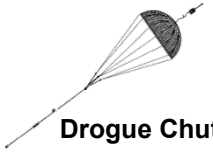
ARES Spacecraft



Launch Vehicle

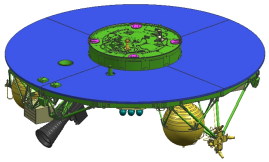


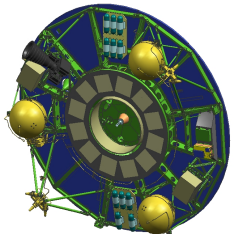
Airplane Extraction Subsystem



Drogue Chute

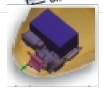
Deployment System





Carrier Spacecraft Flight System

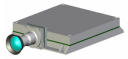
MAG



MS

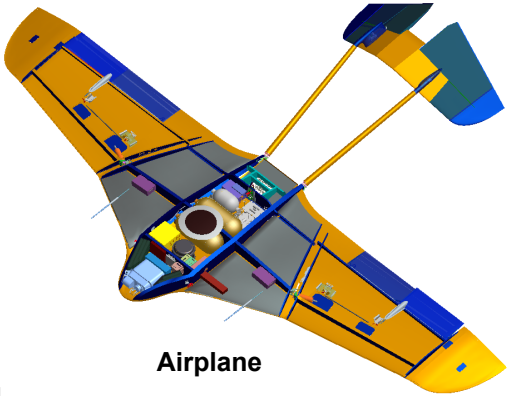
NS

CC



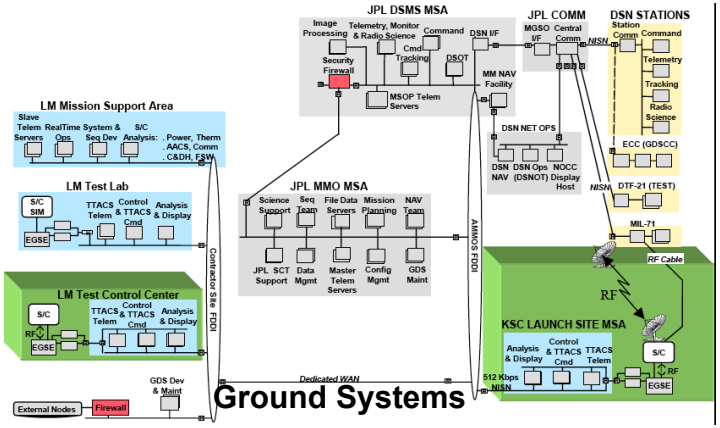
VC

Science Payload



Airplane

Atmospheric Flight System

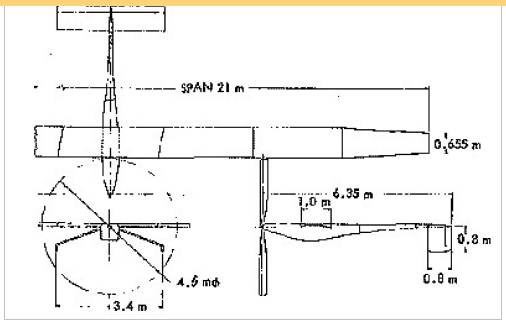


Ground Systems

Evolution of Mars Airplanes

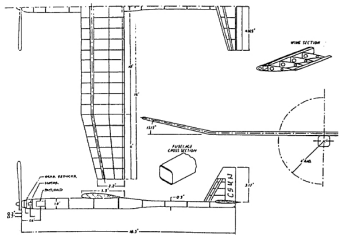
Packaging in Aeroshell better understood
Reduced mission implementation risk (propulsion, systems, data return)
Increased focus on Science Needs

- ***JPL/DSI Astroplane represents the first large-scale integrated systems study.***
- ***Jason represents the first flight tests of aeroshell extraction and unfolding.***
- ***Airplane for Mars Exploration provided the first high altitude pullout.***
- ***ARES has provided the first high altitude unfolding with the follow-on pullout.***
- ***Evolution has progressed due to enhanced design tools to allow understanding of the low Reynolds number flow, increased focus on the aeroshell packaging strategies for deployment.***
- ***Embrace the science needs***

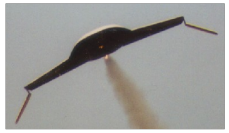


1978
JPL/DSI Astroplane

1992
Aurora Flight Sciences
Jason



1990 - 1992
Project ARES-III
Cal State Univ., Northridge

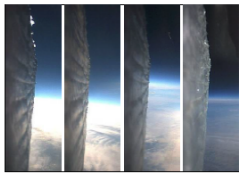


1999
Mars Micromission
Aurora Flight Sciences

1997 - 2002
Airplane for Mars Exploration
NASA ARC

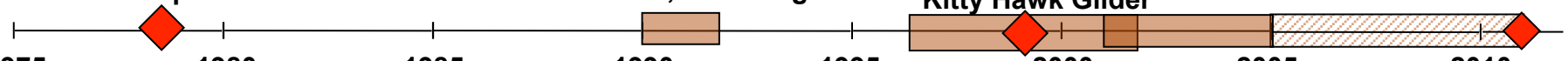
1997 - 2002
Aerovironment
Kitty Hawk Glider

2001 - Present
ARES
NASA LaRC



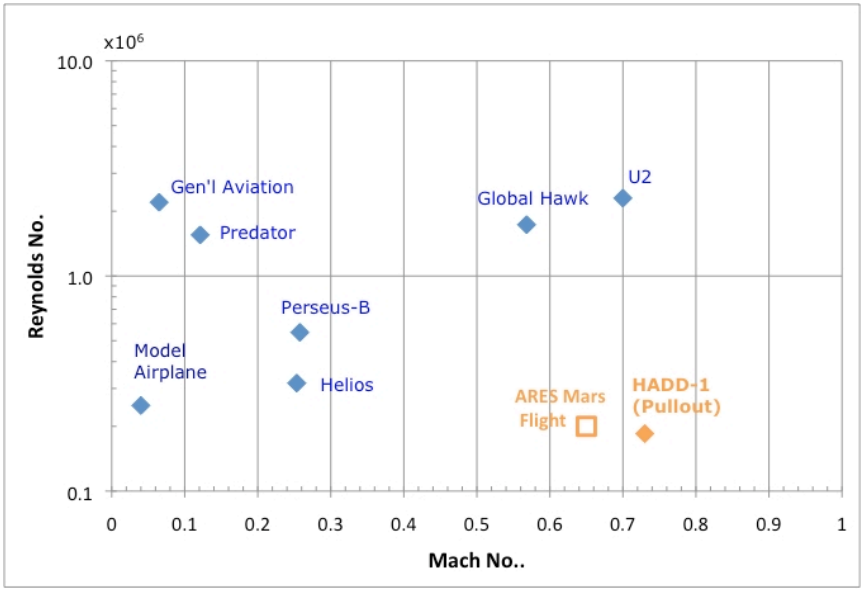
2004 - Present
Big Blue
Univ KY

2005 - Present
Low Re Mars Research
JAXA-Tohoku Univ



Aerodynamic Performance

- ARES cruise regime (Low Reynolds No. with high subsonic Mach No.) requires extensive testing and analysis to validate performance
- Limited flight experience at ARES combination of Mach and Reynolds Number



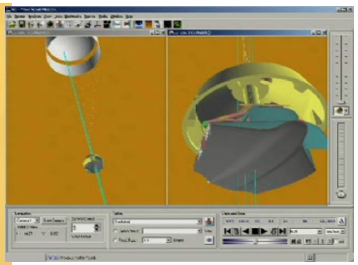
Comparison of Cruise Mach No. and Chord Reynolds No. for vehicles with similar aerodynamic conditions

Airplane	Cruise Alt.	Propulsion	Other
General Aviation	10 kft	Propeller - Engine	Crewed
Predator	25 kft	Turbo-Prop	Uncrewed-RPV
Perseus-B	60 kft	Propeller-Turbo Charged Piston	Uncrewed-RPV
Helios	96 kft	Propeller - Solar	Uncrewed-RPV
Global Hawk	60 kft	Turbo-Fan	Uncrewed-Auto.
U2	65 kft	Turbo-Jet	Crewed
HADD1	100 kft	Glider	Uncrewed-Auto. GHe balloon
ARES	105 kft (equiv)	Rocket	Uncrewed-Auto. L/V

Modeling, Simulation, & Testing Enable Rapid Design Process

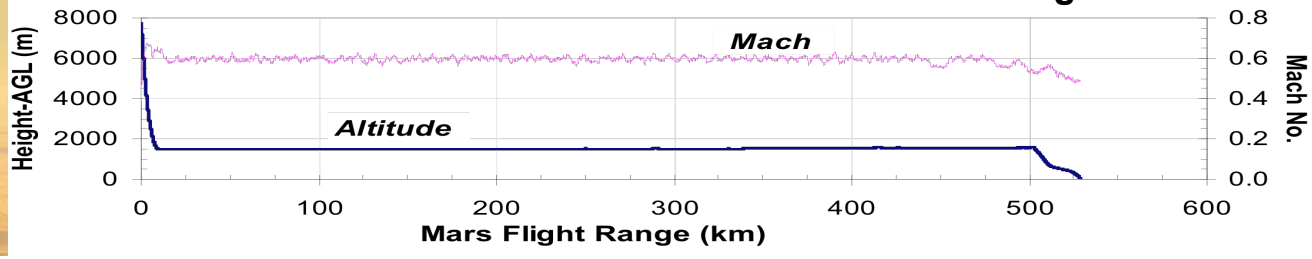
Multiple simulations enable rapid decision making regarding performance, content, cost, and risk reduction testing

Transition-Payload to Platform

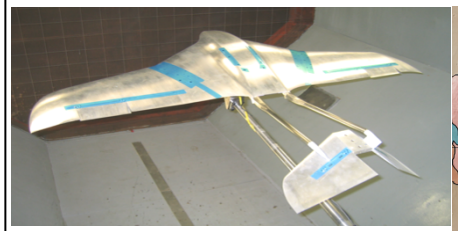


Extraction: Multi-Body Dynamics Sim.

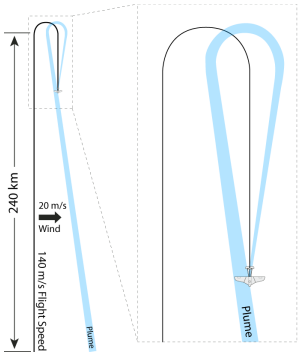
- Aerodynamics
- Entry & Descent
- Extraction Dynamics
- Flight Controls-Stability
- Guidance & Navigation
- Propulsion-Thrust, Transients
- Weather & Winds
- Data Collection
- Relay Link Performance
- Illumination
- Engineering Design/Analysis



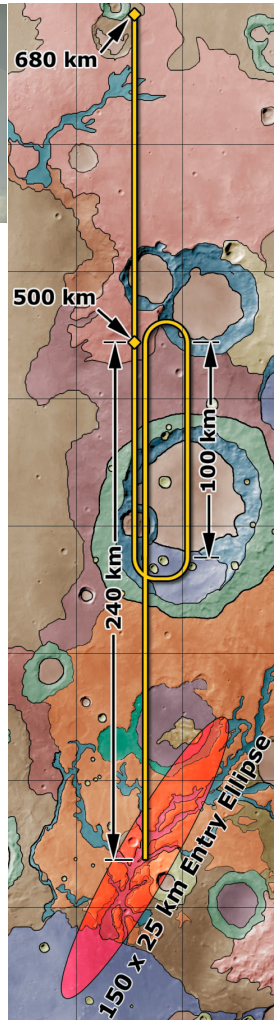
Science Traverse



¼-Scale Wind Tunnel Model



Rocket Plume Migration

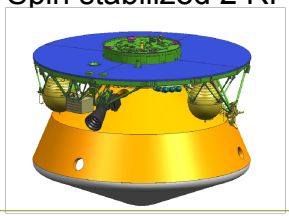


Increasing Confidence and Reducing Risk

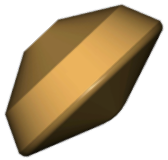
- A “hardware rich” development program ensures early demonstration of system performance leading to increased confidence in operational capability
- Entry, Descent, and Deployment (EDD) is viewed as the Number 1 risk
  - Focused effort includes analysis, ground testing, and flight testing
  - Relevant scales for testing is essential
- Performance in the unique aerodynamic regime of low Reynolds number and high subsonic Mach number requires appropriate validation
  - Extensive analysis
  - Extensive ground testing
  - Focused flight testing – unpowered and powered
- A stable platform for science data collection and data transmission
  - Traditional airplane performance via simulation and testing
  - Include significant environmental uncertainties – density, temperature, wind
  - Demonstrate end to end operations via flight testing - planned

ARES Entry, Descent, Deployment Phases

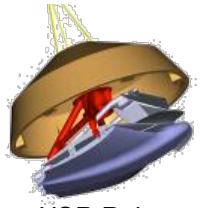
Pre-Entry Operations	Hypersonic Operations	Parachute Operations	Pullout Operations
• TCM-5 Ops • Pre-Entry Operations • Navigation Update • Separation: E-12 hours • Coast to EI • Spin stabilized 2 RPM	• Ballistic Entry • -12° FPA • Wait for Parachute • All devices energized	• Deploy Parachute • Release Heat Shield • Extract Airplane	• Deploy Drogue Chute • Release Drogue Chute • Complete Pullout • Initiate Powered Flight



Interface-EI:
Sensed g=0.03

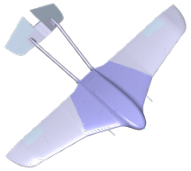


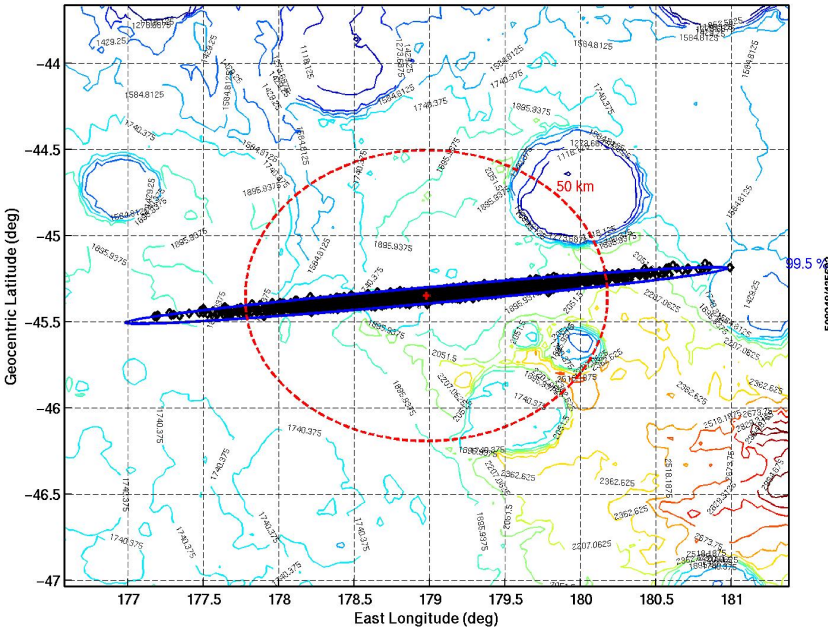
Interface-PD:
Navigated M=1.9
(V = 400 m/sec)



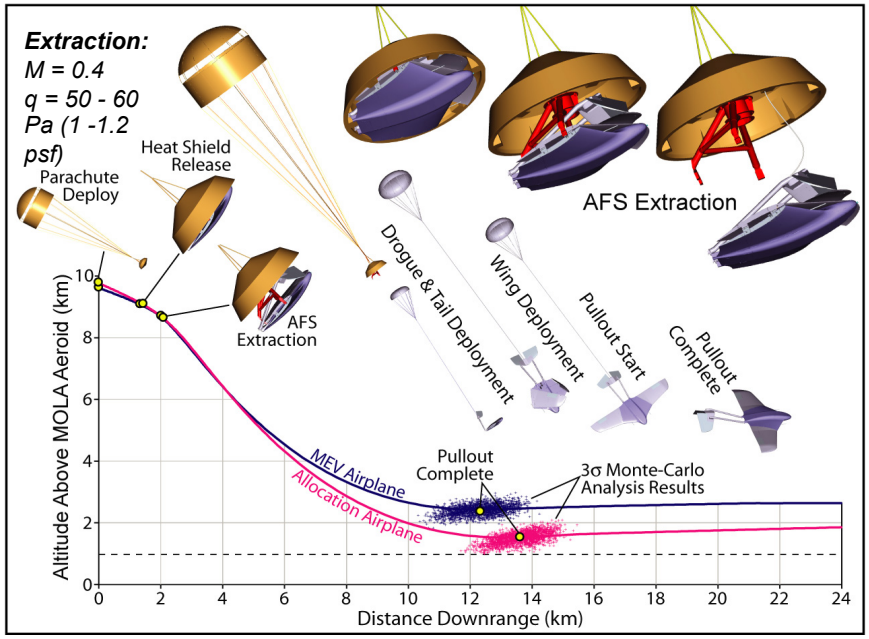
HSR Release:
Navigated M=0.8

Interface-Deploy.:
Timer 7 s
after HSR



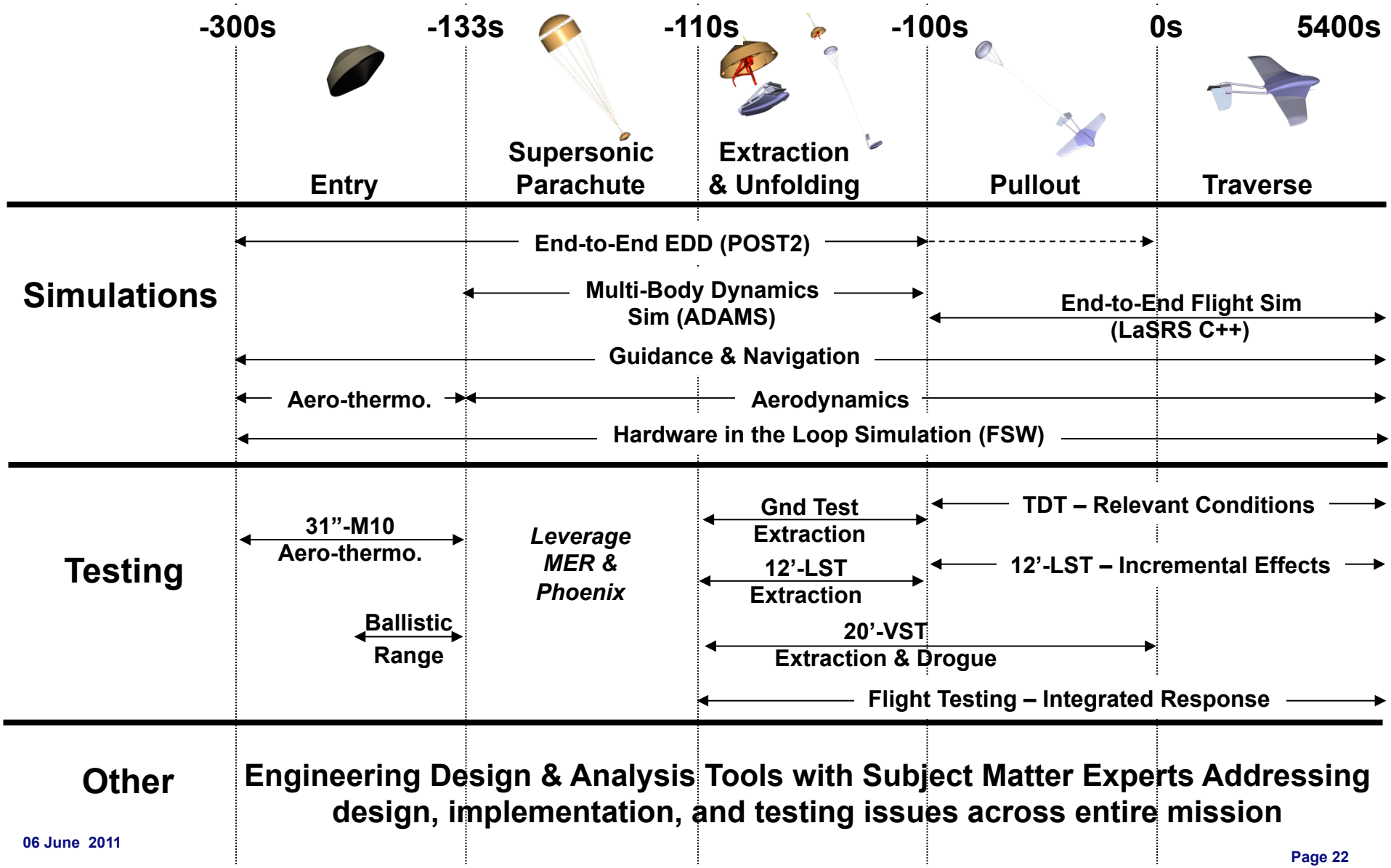


Delivery Footprint at Start of Extraction

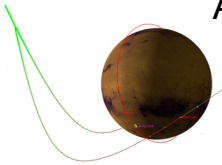


Extraction, Unfolding, and Pullout Sequence

EDD End-to-End: Design, Analysis, & Assessment

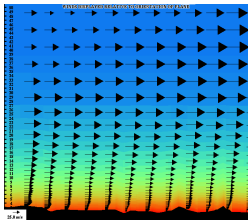


End to End EDD Assessment via POST2



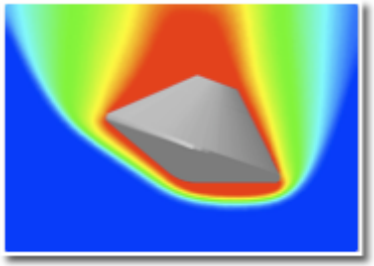
Approach Navigation, Entry Conditions

Mass Properties

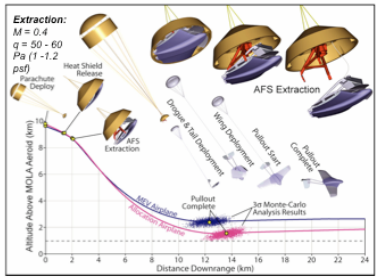


Meso-Scale Atmosphere Model

Aerodynamics & Aerothermodynamics



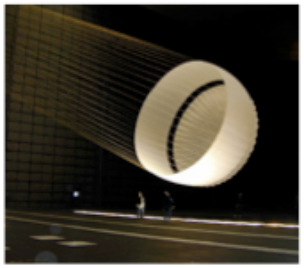
Subsystem models are integrated into an end-to-end EDL trajectory simulation



Extraction, Unfolding, and Pullout Sequence

POST2 - simulation for assessing ARES EDD performance

Parachute Model

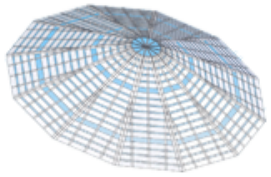


IMU Model

Extraction Model

Unfolding Aero Model

Drogue Chute Model



High Speed Aero Model

Extraction & Unfolding – Ground Testing

Unfolding Wind Tunnel Test
March 2002

Full-Scale Release Test
June 2006

Extraction Dynamics
Wind Tunnel Test
Jan 2006

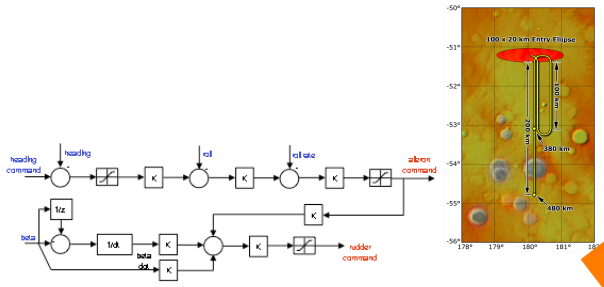
Extraction Test-Oct. 2003

Full-Scale Dynamic
Extraction Test-Nov. 2007

Extraction Drag
Wind Tunnel Test
Jun 2006

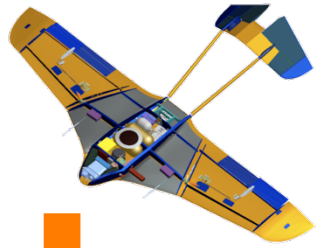
Extraction and transition requires extensive simulation, ground testing, and flight testing to bound performance - one of the key design features.

End to End Mission Assessment via LaSRS

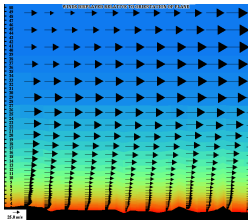


Control Algorithms

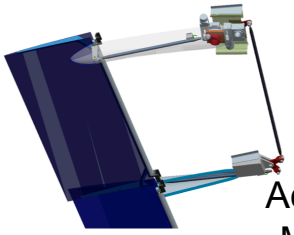
Way Points



Mass Properties

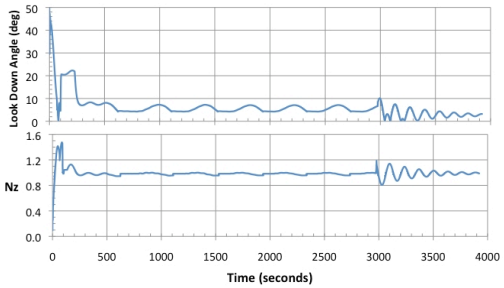


Meso-Scale Atmosphere Model



Actuator Models

Subsystem models are integrated into an end-to-end Mission simulation



LaSRS - simulation for assessing ARES Mission performance

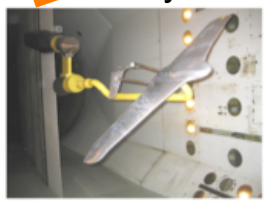
Extraction Model

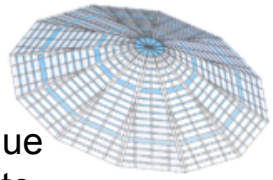
Nav Sensor Models

Propulsion Model

Unfolding Aero Model

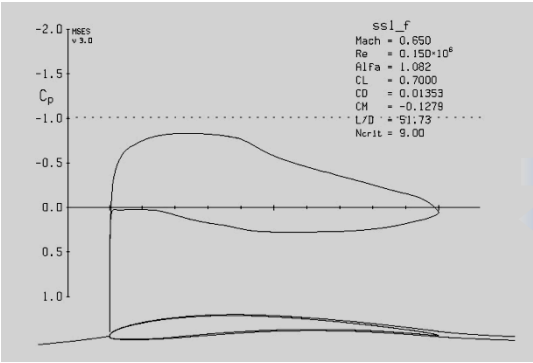
Aerodynamics & Dynamics





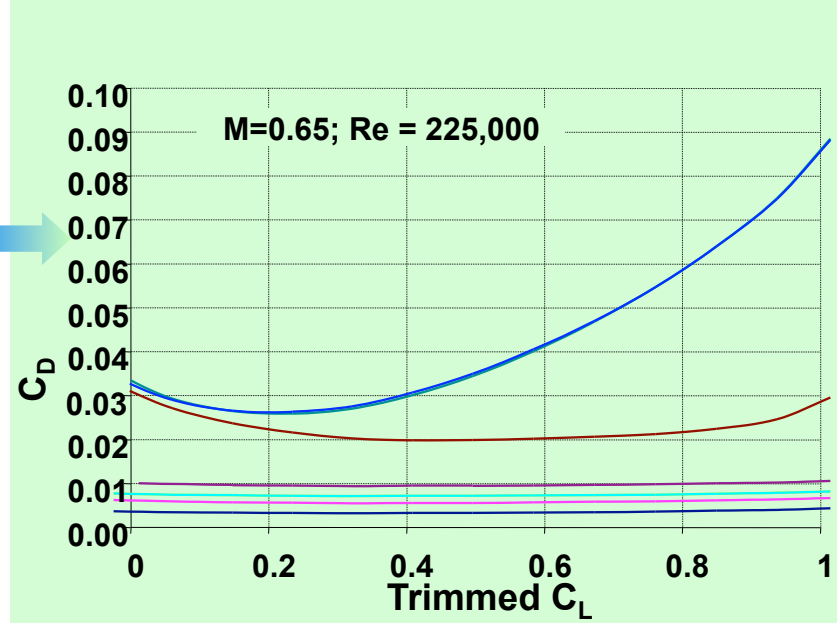
Drogue Chute Model

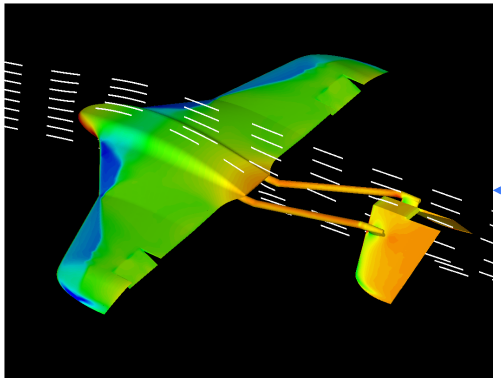
Predictive Capability Exists



Tailored Airfoil for Mars Environment

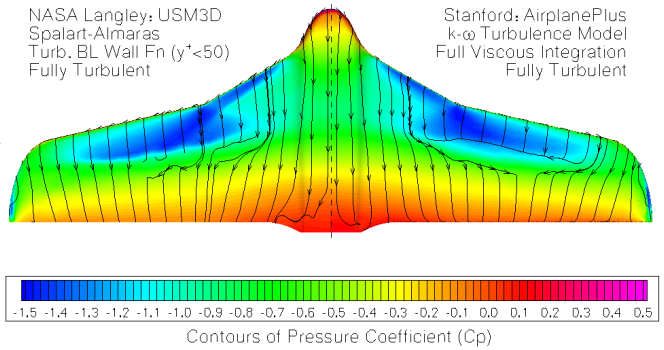
Analytical Tools
Vorview
VORLAX
AVL
PANAIR
MSES
Nonlinear Weissinger
Airplane Plus
Tetruss
FUN3D
PAB3D
USM3D





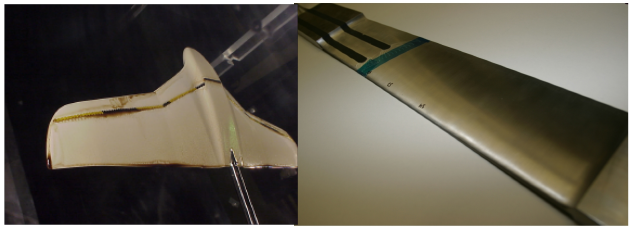
Flaperon Droop At Pullout

Comparison of N-S Solutions
ARES 2.2OML at Pullout: M=0.72 / α=5.5° / Re_C=150K



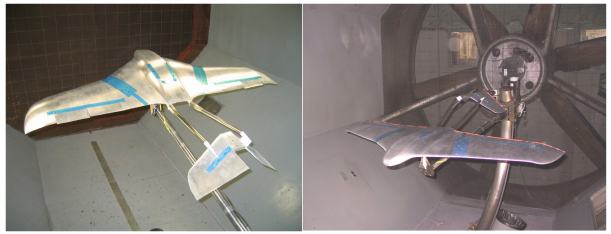
Independent Corroboration

Empirical Basis For Performance Predictions



13%-Scale 8%-Scale (2D)

Transition Effects



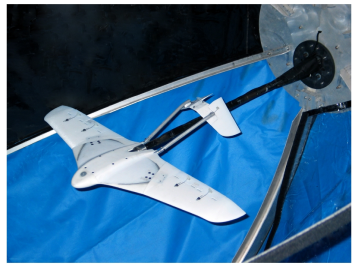
Delta Effects Damping

25%-Scale - Subsonic Testing

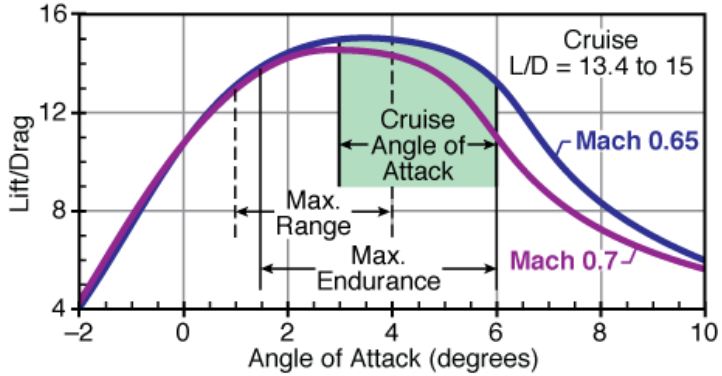
25% Scale - Transonic Testing

25%-Scale - Unfolding (Static Aero)

25%-Scale - Drogue (Proximity Aero)



14%-Scale - Dynamic (Rotary Balance)

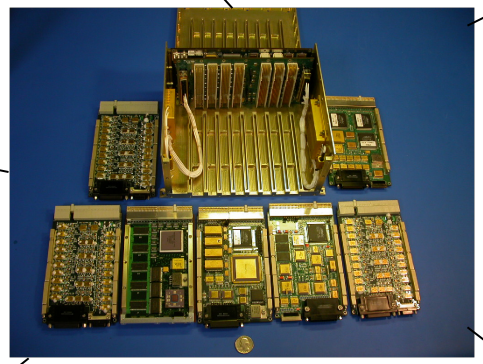


Flight Controls Considerations

Flight Controls Robustness:
Single String vs Block Redundant
Functional Redundancy
Fault Tolerance

Flight Software:
New vs Reuse
Real-Time Operating System
Development Environment
Software updates/uploads
Data collection and return
Redundancy Management

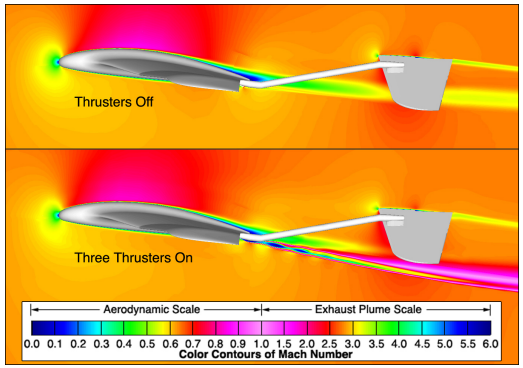
Flight Controls Strategy:
Autonomous vs Remote
Deployment flight initialization
High Speed Pullout
Cruise strategy
Recovery strategy



Navigation Strategy:
Rapid Deployment - Initialization
I-Loads Updates
Terrain recognition for position knowledge augmentation
Retasking during operations

Sensors:
Environments
Self-calibration
Reliability after long-term storage
Air Data in low pressure
Low drift IMU
Redundancy

Propulsion Trade



ARES Propulsion Trade Study
Bi-Propellant Rocket Propulsion

Propeller Driven:

Pros
- Most efficient for long range or endurance

Cons
- Packaging and unfolding increase complexity
- Efficiency will suffer at higher Mach no. (Supersonic tips?)
- Propeller wash over wing \reduces aero efficiency
- Pusher will shift CG aft
- Motor and gearbox heat rejection will be challenging
- Extensive development needed

Electric Motor

Battery:

Pros
- Existing technology

Cons
- Constant mass
- System mass grows as mission endurance increases
- Battery heat rejection
- Limited options for high current withdrawal

Fuel Cell:

Pros
- High fuel efficiency
- Benefits increase as mission endurance increases

Cons
- Heat rejection
- High current withdrawal

Engine:

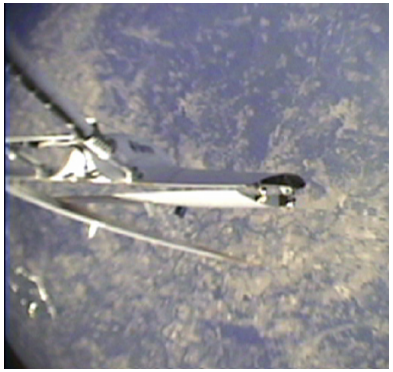
Pros
- Wide range of propellants
- Potential to use atmos as an oxidizer
- Lower system mass

Cons
- Heat rejection

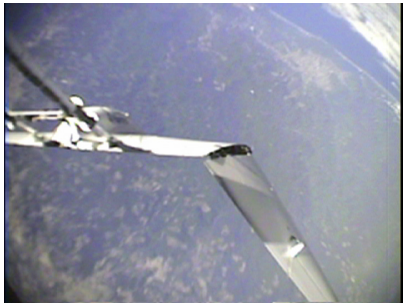
Validation Via High Altitude Flight Testing

Tail Deploy

High Altitude Deployment Test,
Sept. 19, 2002
103,000 feet



Left Wing Deploy



Right Wing Deploy

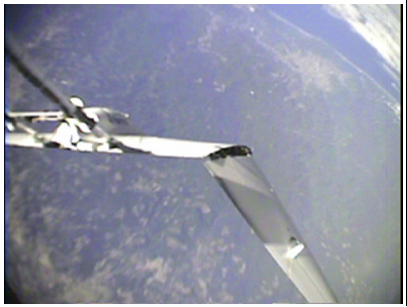
Autonomous Operation

Validation Via High Altitude Flight Testing

Tail Deploy

High Altitude Deployment Test,
Sept. 19, 2002
103,000 feet

Left Wing Deploy



Right Wing Deploy

Autonomous Operation

Half-Scale and Full-Scale Flight Test Mars Airplanes

Potential Developmental Areas

ARES Applicability

Aerodynamics – C_L & L/D

Increase Aerodynamic Performance – Higher L/D; Higher CL, Boundary Layer Suction;

Structure/Packaging – Rigid Airframe, 3 Folds, Traditional Subsystems

Increase Packaging Efficiency –folding; Inflatable Wings; Inflatable Aeroshells, Subsystem Miniaturization

Propulsion – Rocket

Improved Propulsive Efficiency–propeller design, High Energy Density Propellants, Jet development

Thermal – Sink thermal energy to structure, environment rejection

Improved Thermal Efficiency– Active cooling systems; regenerative heat rejection systems

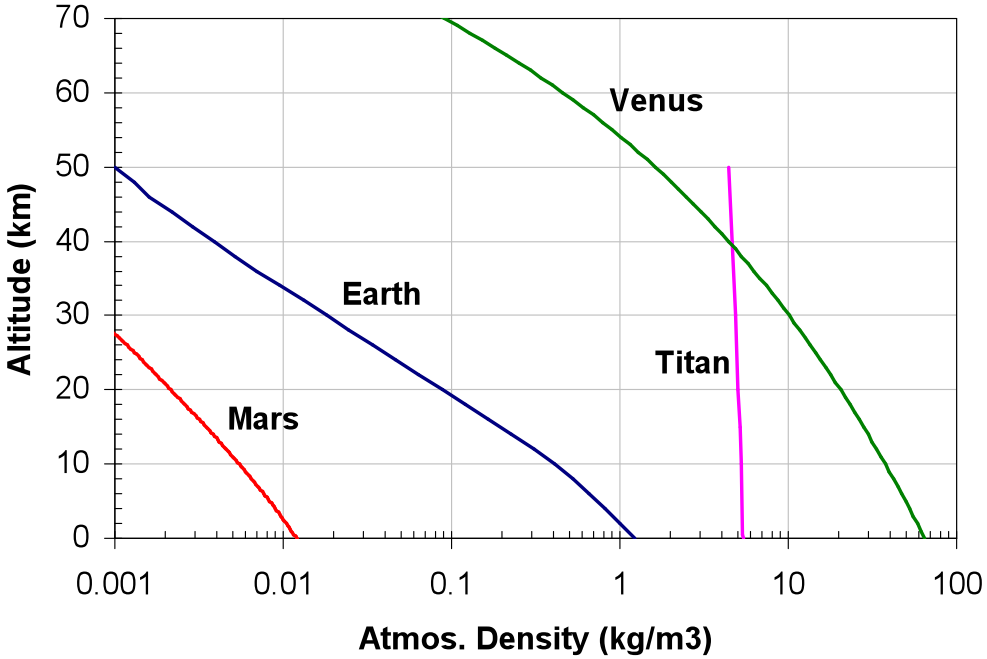
Payload Mass Fraction:
8 – 10%

Improved Payload Mass Fraction – Reduced avionics mass;

Other Destinations

Parameter	Earth	Venus	Mars	Titan
Distance from Sun (10^6 km)	149.6	108.2	227.9	1,433
Gravity (cm/s^2)	980	887	370	135
Surface Pressure (bars)	1	92	0.008	1.5
Primary Atmos. Constituents	78% N_2, 21% O_2	96% CO_2, 4% N_2	95% CO_2, 3% N_2, 2% Ar	>97% N_2, <3% CH_4

- Venus and Titan higher density means more amenable to flying than Mars
- But:
  - Venus – extreme environment – pressure, temperature, corrosive environment
  - Titan – extreme cold
- Titan mission design – data return - influences architecture



Summary

- Aerial platforms provide a unique measurement perspective
- Flying airplanes on Mars can be done with what we know and can design and test today.
- Integrating science requirements and measurement strategies with platform selection and performance requirements is essential for mission success
- Extensive analysis and testing is a key strategy for demonstrating system maturity

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ARES Website:
http://marsairplane.larc.nasa.gov

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