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UltraSail

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UltraSail is a complete sail system for the launch, deployment, stabilization and control of very large solar sails enabling reduced mission times for interplanetary and deep space spacecraft. UltraSail is an innovative, non-traditional approach to propulsion technology achieved by combining propulsion and control systems developed for formation-flying microsatellites with an innovative solar sail architecture to achieve km^2-class controllable sail areas, sail subsystem area densities of 1 gm/m^2, and thrust levels equivalent to 400 kW ion thruster systems used for comparable deep space missions. UltraSail can conceivably even achieve outer planetary rendezvous, a deep space capability now reserved for high-mass nuclear and chemical systems. Ultrasail is a Delta IV-launched multi-blade spin-stabilized system with blade lengths as long as 50 km, reminiscent of the MacNeal Heliogyro. The primary innovation is the near-elimination of sail supporting structures by attaching the sail tip to a rigid formation-flying microsatellite truss which deploys the sail blade, and which then articulates the blade to provide attitude control, including spin stabilization and precession of the spin axis. These tip microsatellites are controlled by a solar-powered 3-axis microthruster system (electric or cold gas) to maintain proper sail film tension during deployment and spin-up. The satellite mass also provides a stabilizing centrifugal force on the blade while in rotation.

Understanding the dynamics of individual blades is key to the overall dynamics of UltraSail. Forces and torques that must be modeled include those due to solar pressure, those generated by the microsatellite at the blade tip and by torques applied at the blade root. Centrifugal forces also play a significant role in the deployment and maintenance of the sail configuration. To capture the dynamics of the overall system, the equations of motion for the blades have been derived. Using these differential equations, a control law will be derived to maneuver UltraSail. This law involves the pitching of the individual blades thereby moving the distribution of the radiation pressure on each individual blade and inducing a resultant torque on the system. The direction of the angular momentum vector and its rate of precession can be controlled through the pitch angle of the blades.

The UltraSail trajectory is also being studied. Optimal or near-optimal trajectories are being generated to showcase UltraSail performance. Various missions, e.g. outer planet and solar polar missions for observation of the Sun, are currently being investigated to demonstrate the performance enhancements generated by UltraSail technology. Calculus-of-variations-based optimization software is used to produce optimal UltraSail trajectories. The performance of these trajectories is being compared to optimal results generated with other propulsion models, including chemical propulsion, ion propulsion, and competing solar sail concepts. Results of these studies will quantify the performance of UltraSail compared to existing solar sail concepts for high energy missions.

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UltraSail -- Phase I Status

TITLE PAGE

Personnel

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John W. Hartmann	*Trajectories Optimization & Payload Performance (AAE)*
John Westerhoff	*Structural Dynamics (AAE)*
Nathan R. Richardson	*Graphics (AAE)*
Carl C. Burton	*Animation (UIUC Beckman Institute)*

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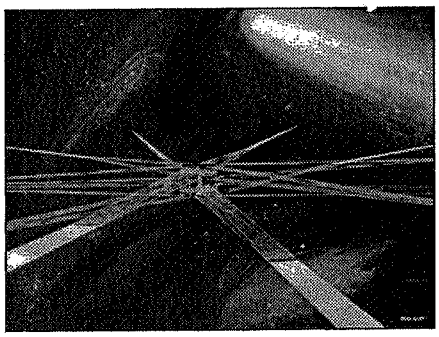
Solar Sail Concepts



All previous Solar Sail concepts use hub-based deployment and control

Heliogyro of MacLean (JPL 19XX) uses spin-up and centrifugal force to extend blades

Square Sail concepts use extending masts, e.g. inflatables; size limited by column buckling

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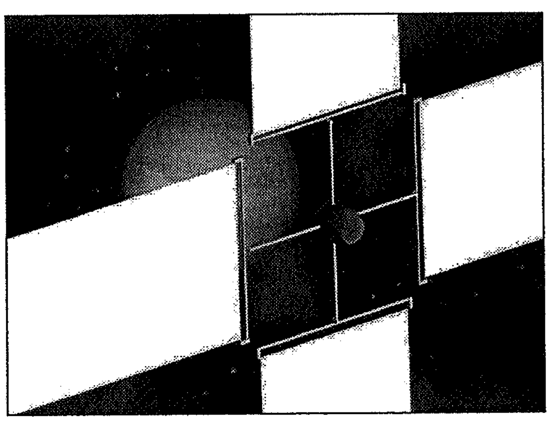
UltraSail Concept



- Performance
- Control
- Deployment
- Potential Missions
- Propulsion
- Key Technical Issues

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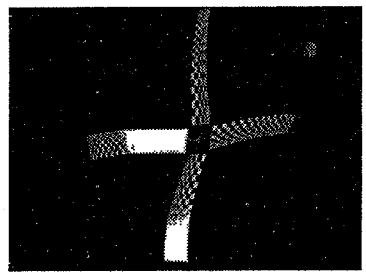
Combining Several Technologies

- Build on previous spin stabilized concept
  - MacNeal Heliogyro
- Deploy using Satellites for rotor tip control
  - Use formation flying technology
- Very large area possible -- several km^2?
- Advanced films for high acceleration
- Torque on sails precesses spin axis



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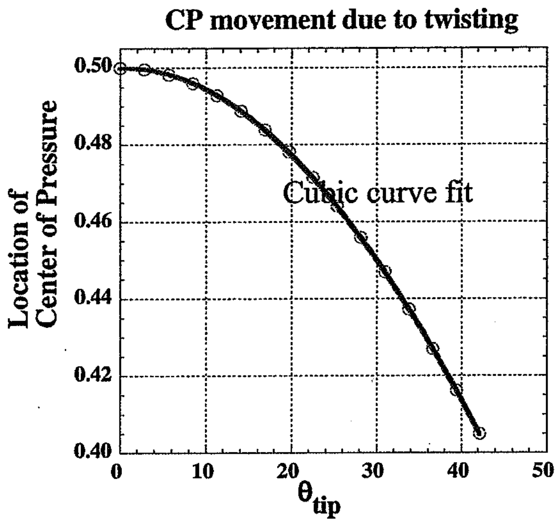
Scenario of Events

- LAUNCH
- DEPLOYMENT
- SPIN-UP
- TRAJECTORY

CUAerospace — Center of Pressure as a Function of θ_{tip}



- Found as a function of θ_{tip} (θ at $x = R$), ζ, and R for an individual blade
- ζ assumed constant
- θ varies linearly from blade root to tip
- Closed form solution found
  - Cubic curve fit

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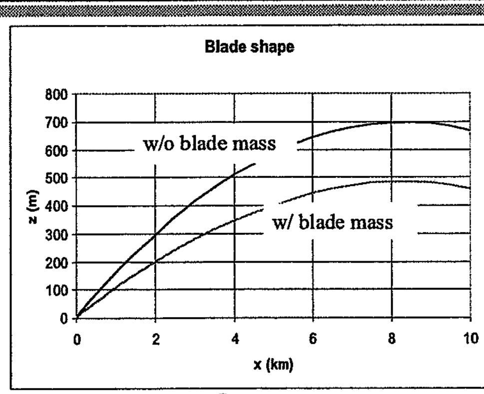
CUAerospace — Catenary Solution of Blade Shape

Parameters:
R=10 km
c=10 m
ρ=1 g/m^2
M/N=500 kg
m_{sat}=100 kg
m_{blade}=100 kg
ω=0.00212 rad/s
p_o=9.01e-6 N/m^2



$$z(x) = \frac{p_o}{\omega^2}\left[\frac{c x_m \operatorname{arctanh}\left[x\left(\frac{\rho c}{2m_{sat}R + \rho c R^2}\right)^{1/2}\right]}{\left[\frac{\rho c R}{2}\left(m_{sat} + \frac{?cR}{2}\right)\right]^{1/2}} + \frac{\ln\left[\omega^2\left(m_{sat}R + \frac{\rho c R^2}{2} - \frac{\rho c x^2}{2}\right)\right]}{?}\right] - z_0; \quad x_m = R\left[1 - \frac{m_{sat}}{M/N - m_{sat}}\right]$$

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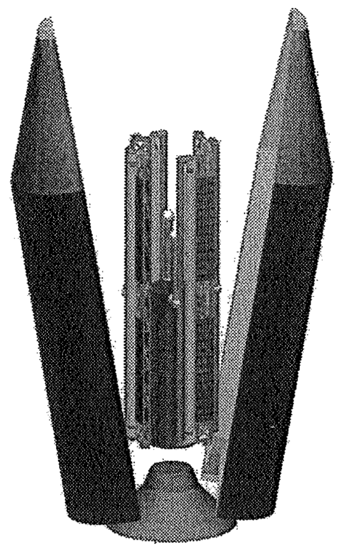
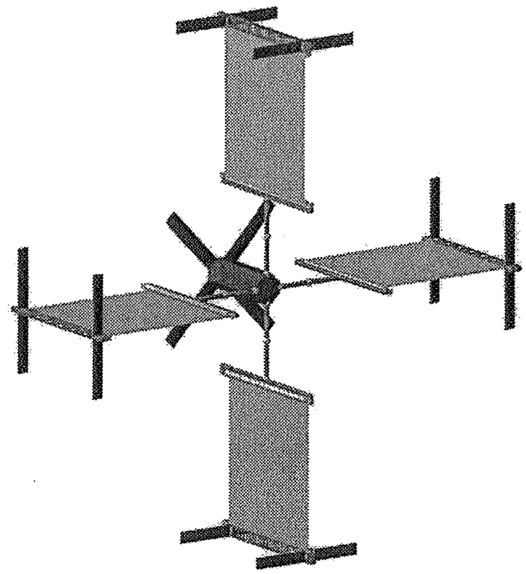
Deployment





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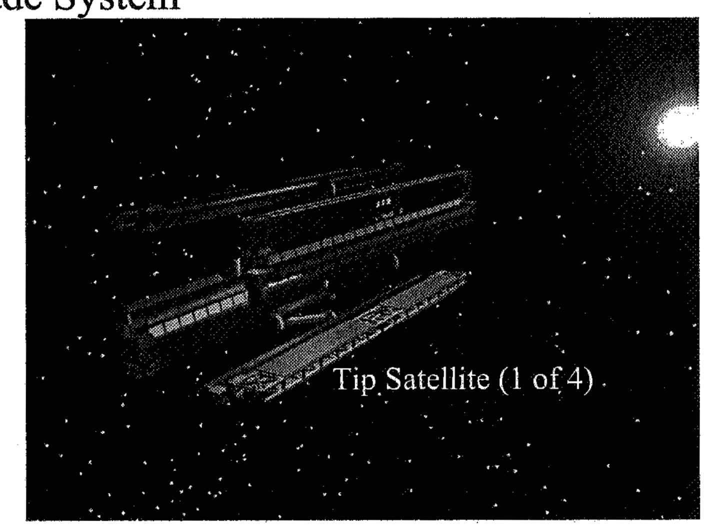
Deployment

- 4 Blade System



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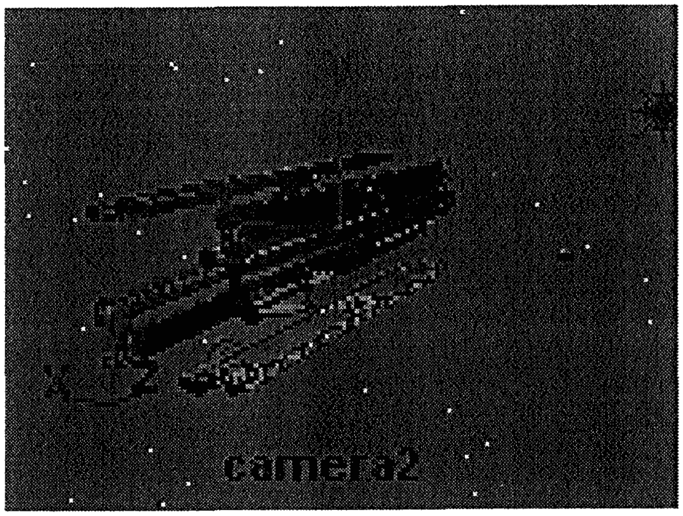
Phase I Animation



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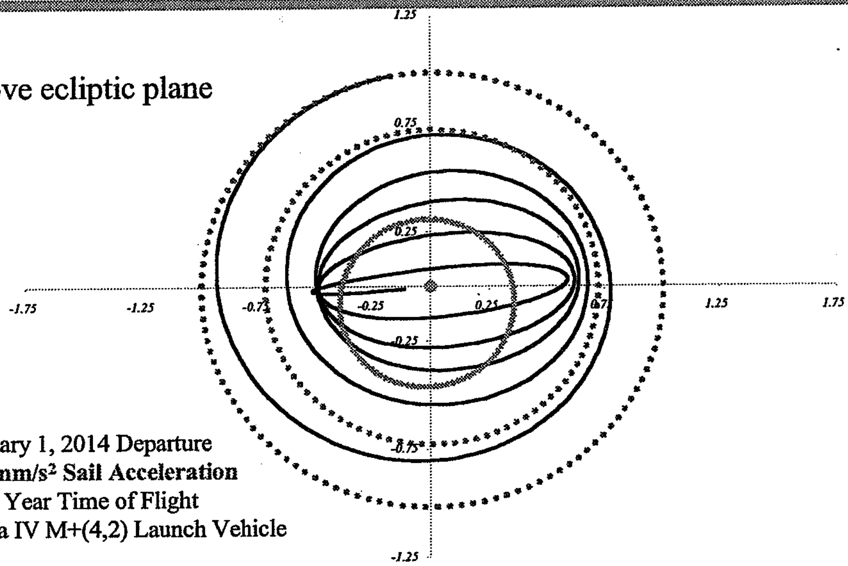
Trajectory Studies

- Optimized Sail Trajectories
- Assume high acceleration, $a_o > 1$ mm/s^2
- Trajectories investigated
  - Solar Polar
  - Outer Planet Flyby
  - Outer Planet Flyby with Venus Gravity Assist
  - Outer Planet Rendezvous
    - Commonly thought to require NEPS or Aerocapture

CU Aerospace — Mission to 0.48 AU Solar-Polar Orbit - 1

Above ecliptic plane



January 1, 2014 Departure
1.0 mm/s² Sail Acceleration
2.84 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

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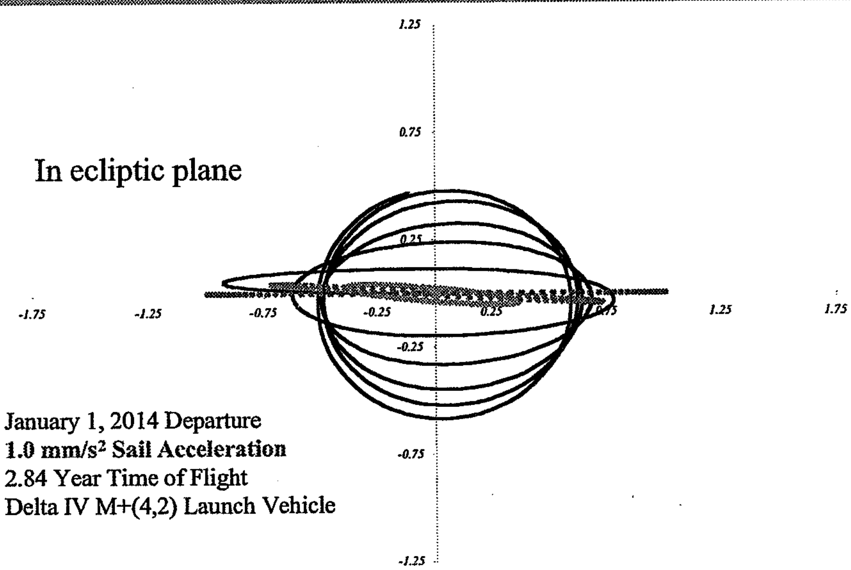
CU Aerospace — Mission to 0.48 AU Solar-Polar Orbit - 2

In ecliptic plane



January 1, 2014 Departure
1.0 mm/s² Sail Acceleration
2.84 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

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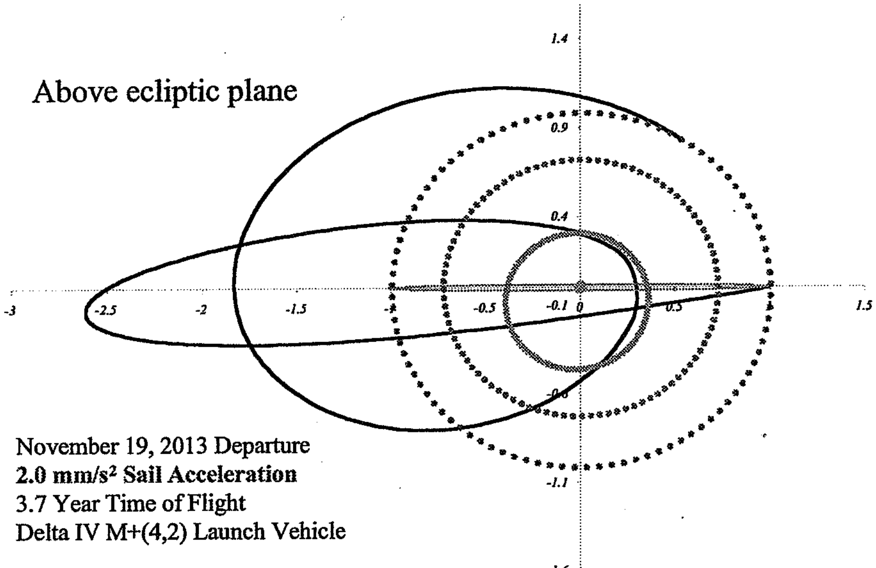
CU Aerospace — Mission to 1.0 AU Solar-Polar Orbit - 1

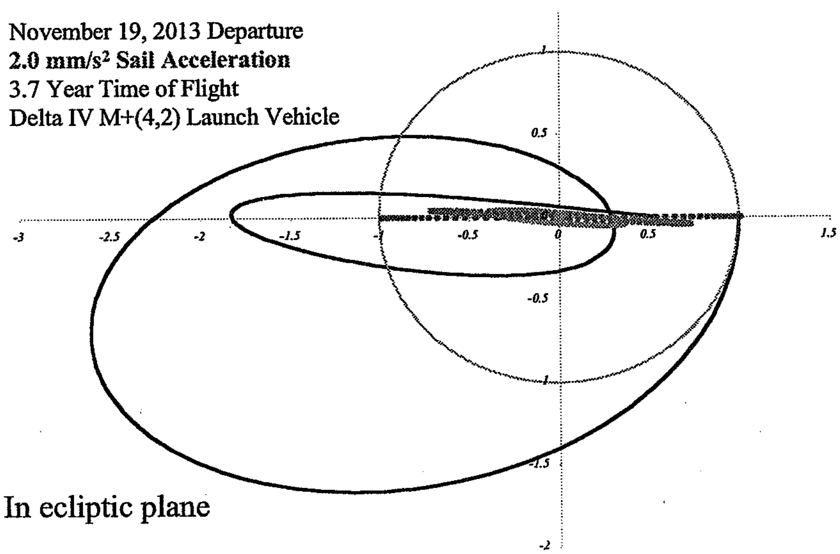
Above ecliptic plane



November 19, 2013 Departure
2.0 mm/s² Sail Acceleration
3.7 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

CU Aerospace — Mission to 1.0 AU Solar-Polar Orbit - 2

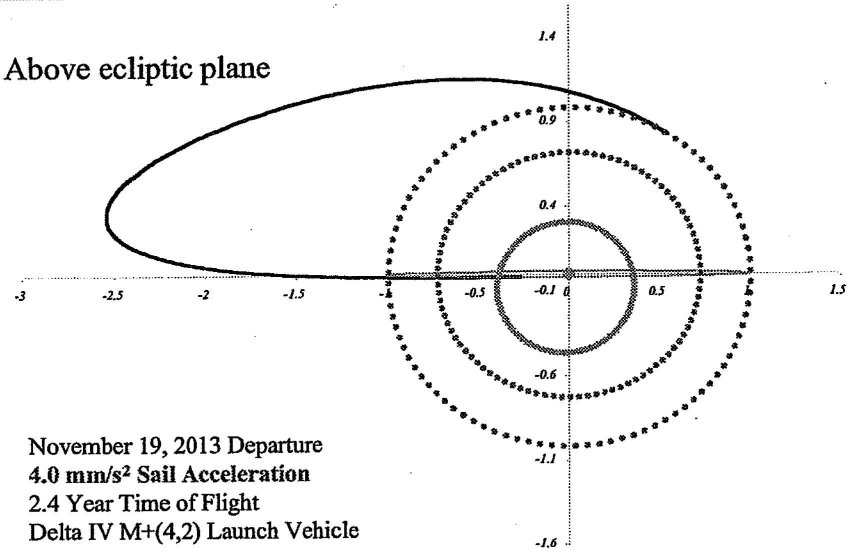
November 19, 2013 Departure
2.0 mm/s² Sail Acceleration
3.7 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle



In ecliptic plane

CUAerospace Mission to 1.0 AU Solar-Polar Orbit - 3

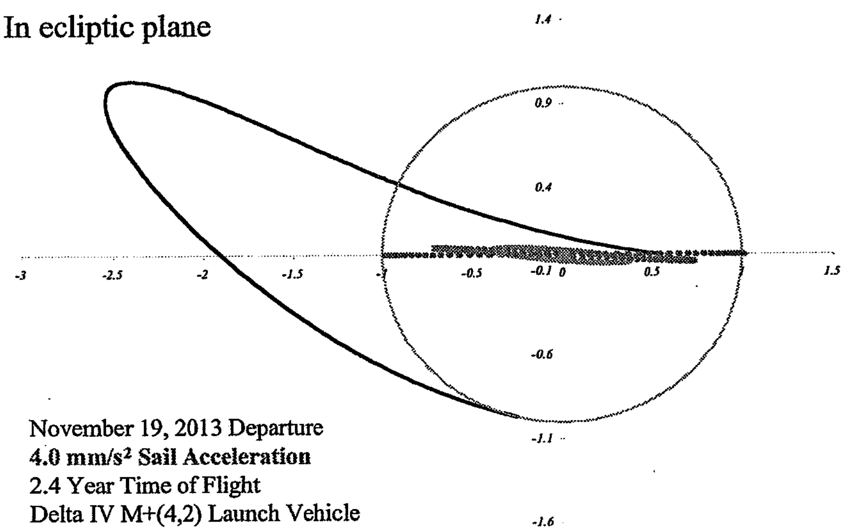
Above ecliptic plane



November 19, 2013 Departure
4.0 mm/s² Sail Acceleration
2.4 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

CUAerospace Mission to 1.0 AU Solar-Polar Orbit - 4

In ecliptic plane



November 19, 2013 Departure
4.0 mm/s² Sail Acceleration
2.4 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

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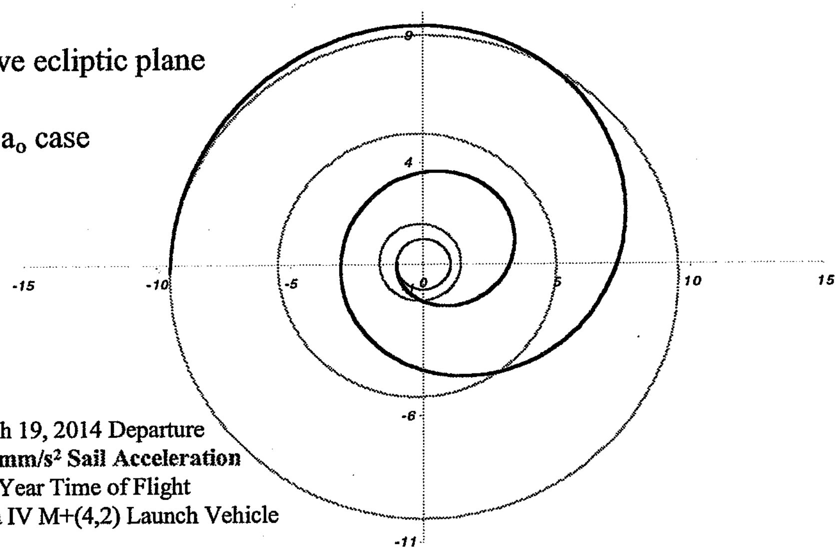
Earth-Saturn Rendezvous Mission

Above ecliptic plane

Min a_o case



March 19, 2014 Departure
1.14 mm/s² Sail Acceleration
25.5 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

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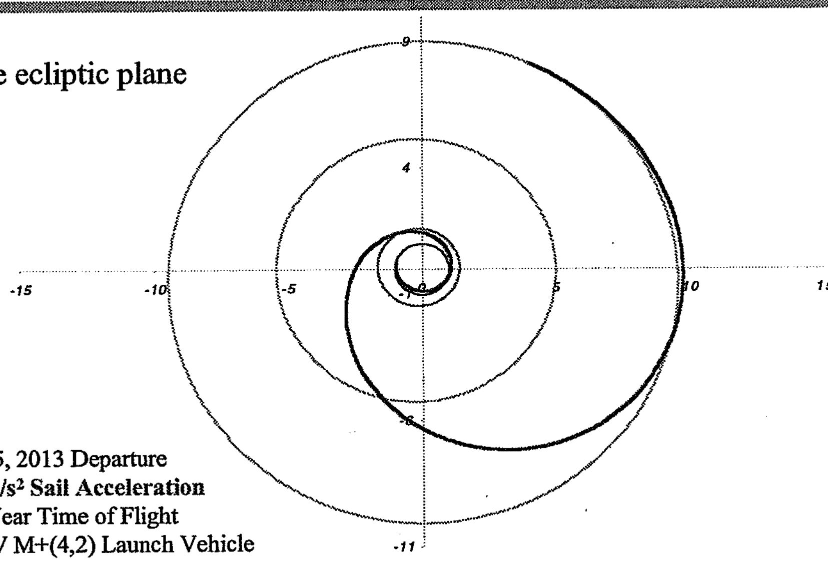
Earth-Saturn Rendezvous Mission

Above ecliptic plane



March 5, 2013 Departure
2.0 mm/s² Sail Acceleration
17.65 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle

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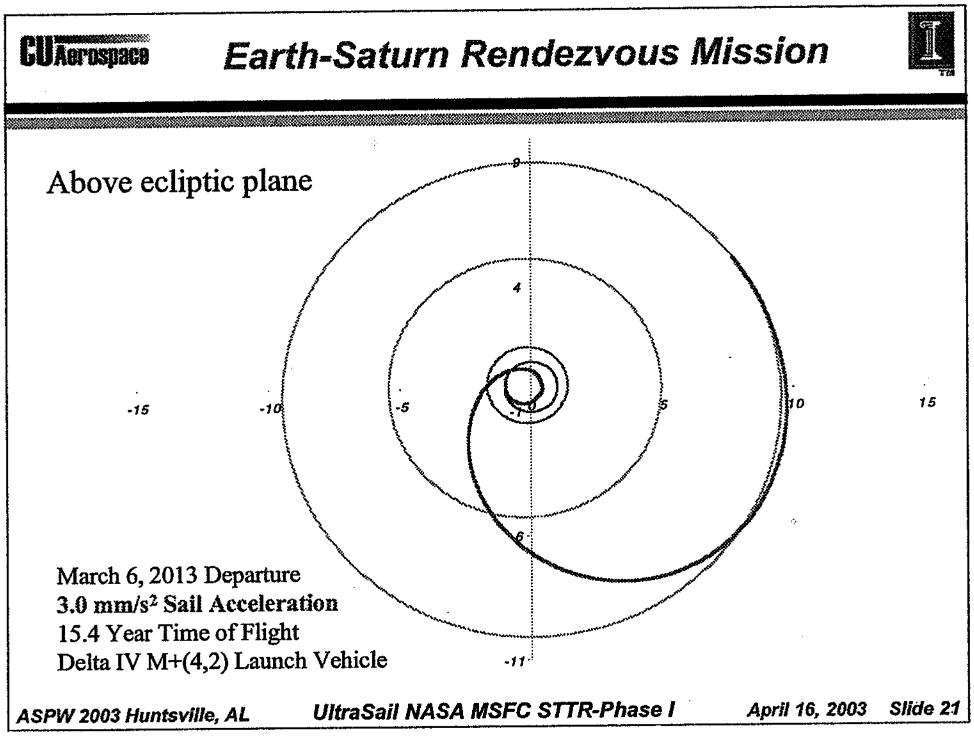
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Earth-Saturn Rendezvous Mission
Above ecliptic plane
9
4
-15
-10
-5
5
10
15
6
-11
March 6, 2013 Departure
3.0 mm/s² Sail Acceleration
15.4 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle
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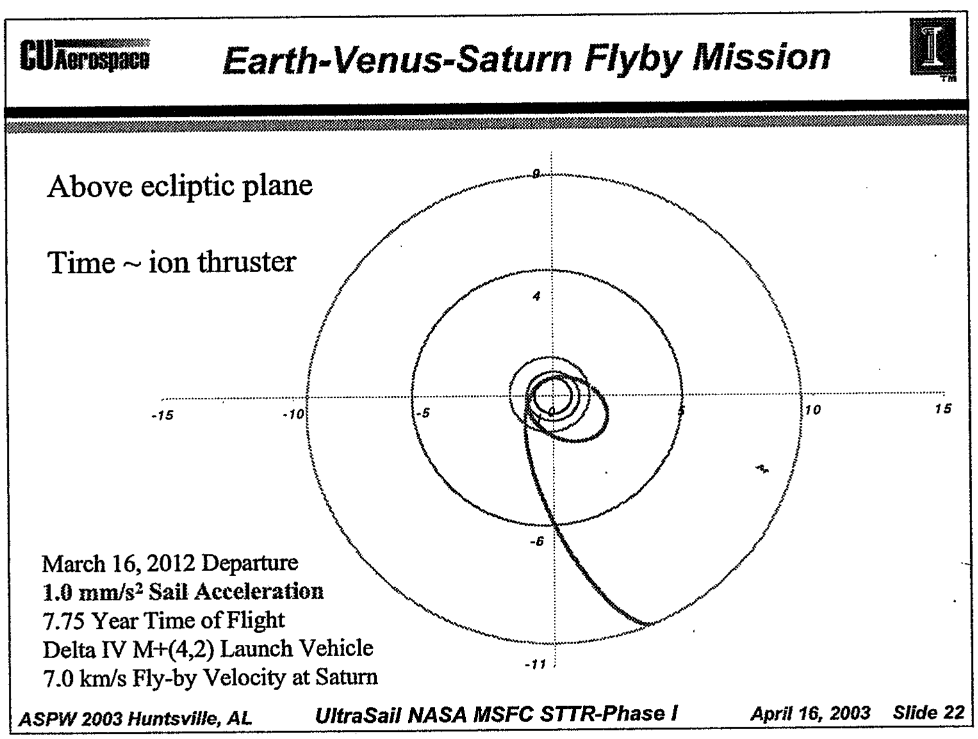
UltraSail NASA MSFC STTR-Phase I
April 16, 2003
Slide 21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Earth-Venus-Saturn Flyby Mission
Above ecliptic plane
Time ~ ion thruster
9
4
-15
-10
-5
5
10
15
-6
-11
March 16, 2012 Departure
1.0 mm/s² Sail Acceleration
7.75 Year Time of Flight
Delta IV M+(4,2) Launch Vehicle
7.0 km/s Fly-by Velocity at Saturn
ASPW 2003 Huntsville, AL
UltraSail NASA MSFC STTR-Phase I
April 16, 2003
Slide 22

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Future Trajectories

- Currently working with Earth-Saturn rendezvous trajectories to relax rendezvous conditions, allowing for some minimal flyby velocity at Saturn, to see how much flight time can be reduced and attempt to bridge the gap between rendezvous and the 7 km/s EVS flyby case
- Also need to generate solar sail results using lower sail acceleration constants consistent with non-UltraSail technology (~0.3-0.5 mm/s^2 range)
- Will eventually begin to generate NEP and SEP trajectories that can be compared and contrasted against UltraSail results

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Future Tasks

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Conclusions

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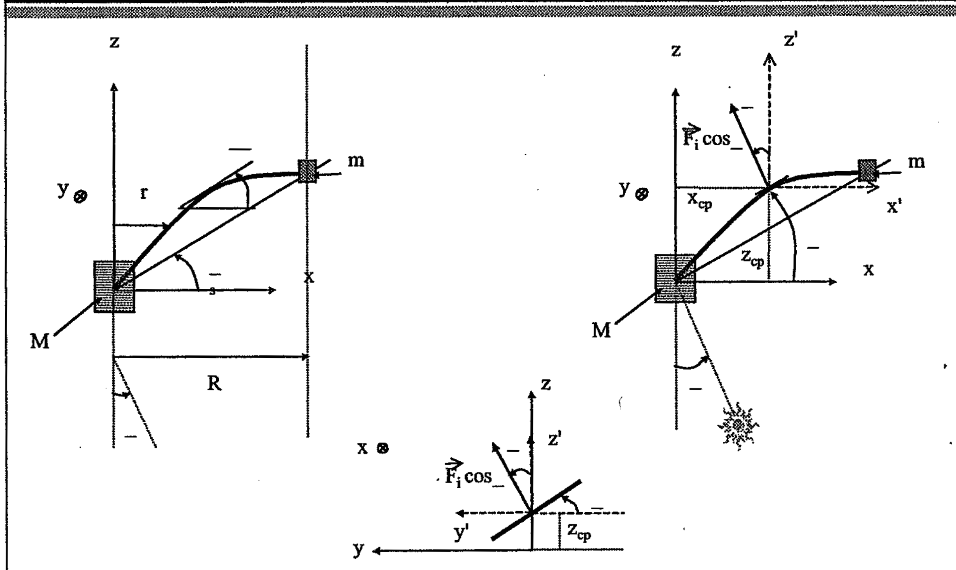
System Nomenclature



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