Solar Imaging Radio Array *(SIRA)*

Flight Dynamics

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Agenda

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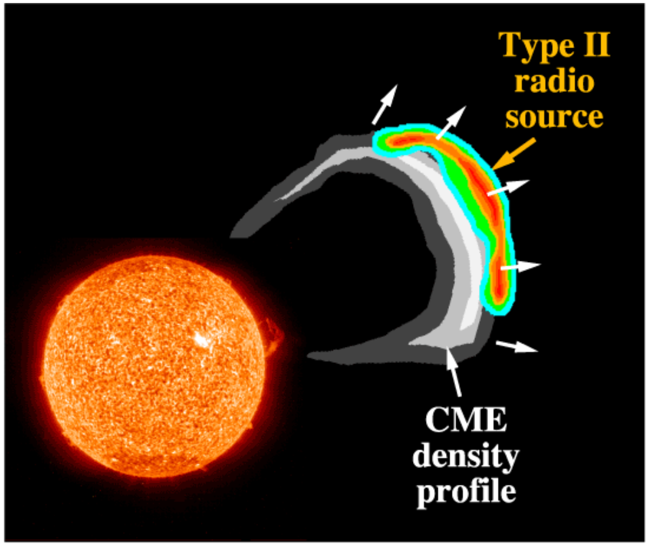
- Orbit Trades
  - Orbit Options
  - Shadows
  - Coverage
  - Launch Options
- Formation Control
- Summary
- Other Orbits



Two dimensional radio imaging of the CME-driven shock front and the CME density profile is critical for predicting the space weather effects of CMEs

SIRA Metrics

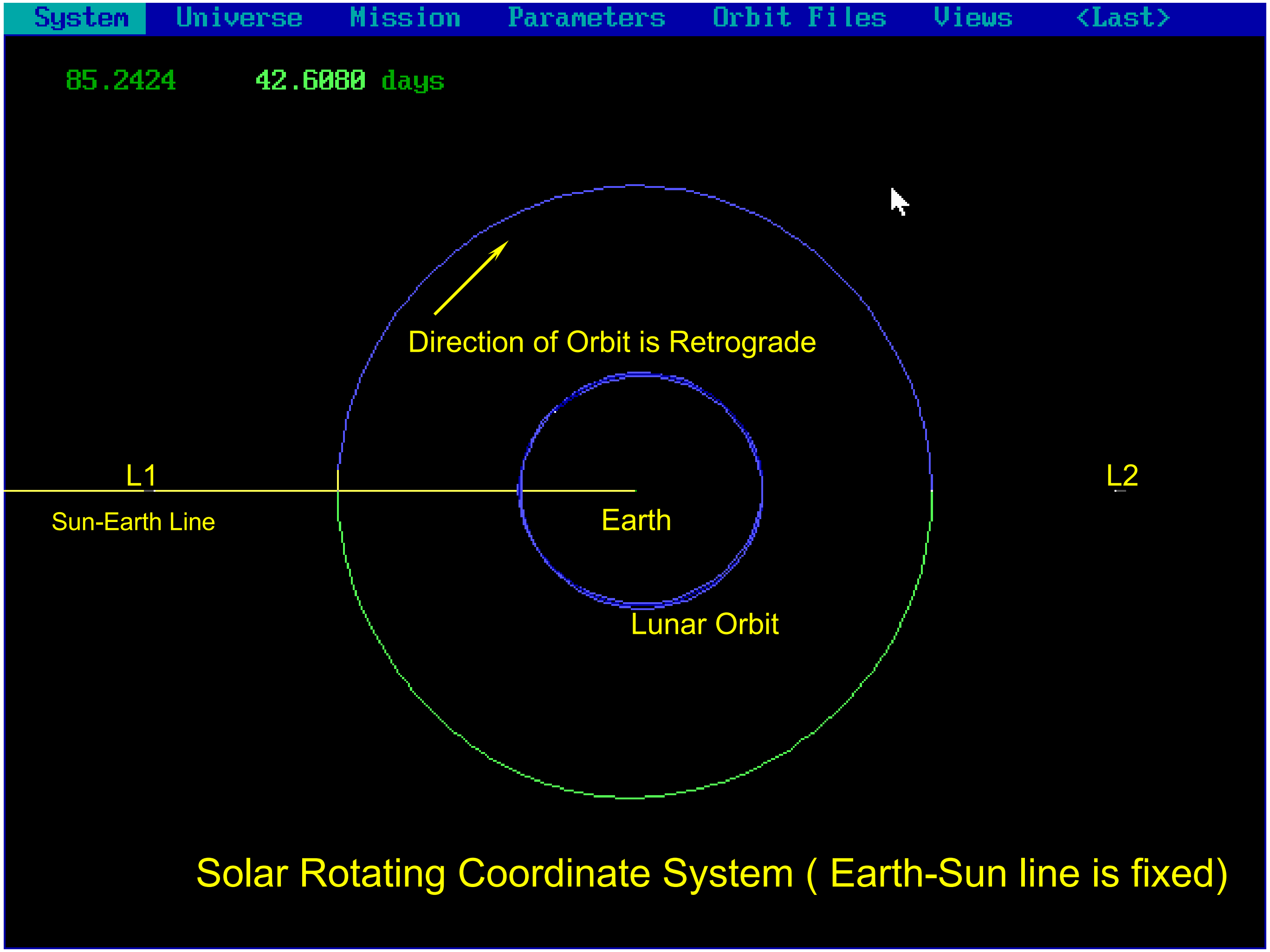
- Earth-constellation distance: > 50 Re (less interference) and< 100 Re (link margin).
  - **Closer than 100 Re would be desirable to improve the link margin requirement**
  - **A retrograde orbit of <160 Re (10^6 km), for a stable orbit would be ok**
- The density of "baselines" in the u-v plane should be uniformly distributed. Satellites randomly distributed on a sphere will produce this result.
- Formation diameter: ~25 km to achieve desired angular resolution
- The plan is to have up to 16 microsats, each with it's own "downlink".
- Satellites will be "approximately" 3-axis stabilized.
- Lower energy orbit insertion requirements are always appreciated.
- Eclipses should be avoided if possible.
- Defunct satellites should not "interfere" excessively with operational satellites.

SIRA Orbit Selection Trade

	DRO-TB	DRO-Lunar	Earth-Moon Lib	Sun-Earth Lib
Launch C3 Energy (km^2/s^2)	-0.1	-0.1	-1.8	-0.67
Mission Orbit Insertion ΔV (m/s)	3 to 200	416	700	~10
Orbit Maintenance ΔV/year (m/s)	0	0	5	5
Formation Maintenance ΔV/month (m/s) per spacecraft Strict (S) & Loose (L), Assuming 0.1mN	S – 1.32 L – 0.70	S – 1.32 L – 0.70	S –1.30 L - 0.69	S – 0.052 L – 0.024
Min / Max Distances to Earth (10^6 km)	0.5 to 7.0	0.5 only	0.25 to 0.5	1.2 to 1.7
Shadows	None	None for 3 years 9 min lunar penumbra in 4th year	None	None
Angle variation between Spacecraft-Earth and Spacecraft-Sun vectors over one orbit period (degrees)	360.	360.	360.	+/-37.0

TB= Three Body Dynamics

SIRA Retrograde Orbit



Why RO?

- Stable Orbit
- No Stationkeeping Delta-V
- Not as distant as L1
- Multiple Transfers
- No Shadows?
- Good Environment

✓Really a Lunar Periodic Orbit

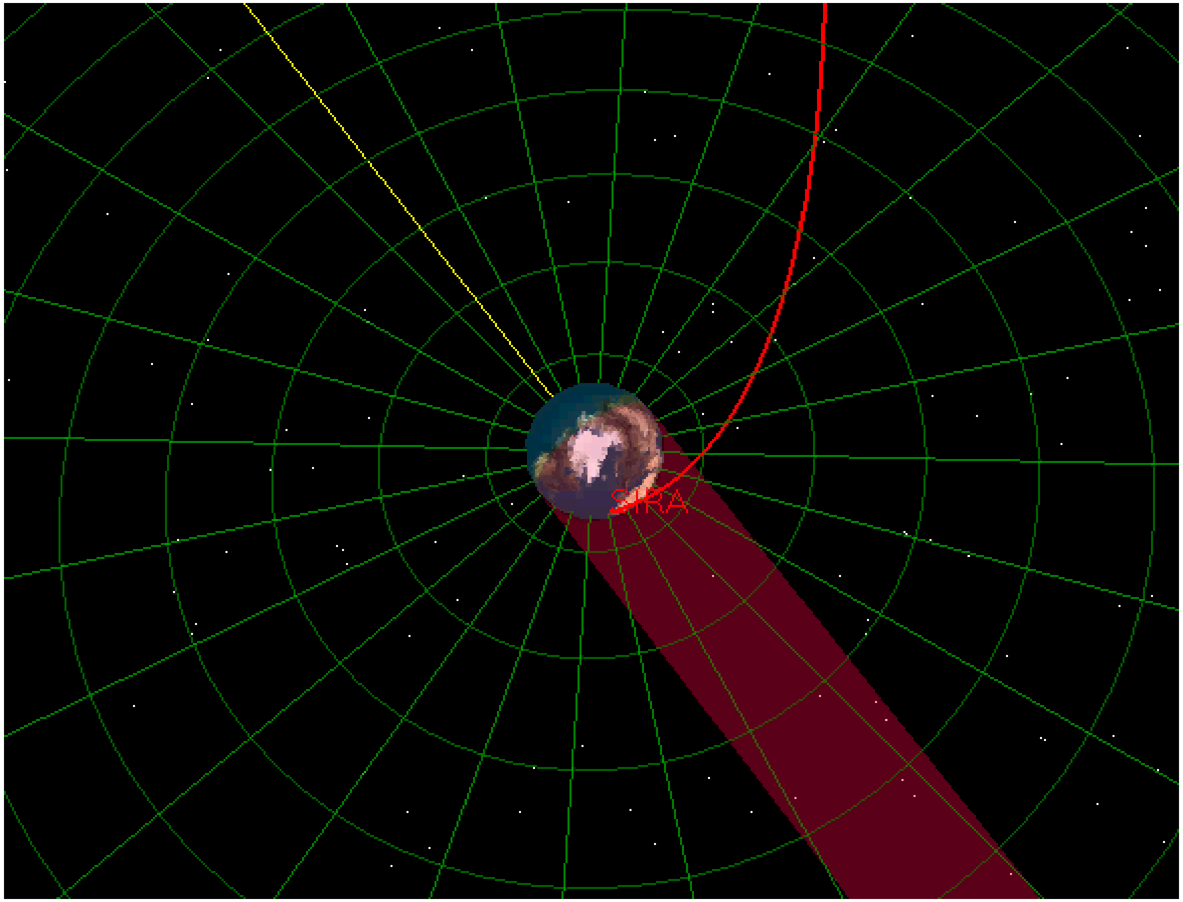
✓Classified as a Symmetric Doubly Asymptotic Orbit in the Restricted Three-Body Problem

SIRA Orbit Options- Near Retrograde Orbit Lunar Transfer

Transfer Type	Lunar Gravity Assist	Lunar Gravity Assist	Lunar Gravity Assist	Lunar Gravity Assist
Transfer Time to Mission Orbit (days)	6	7	4.5	8
Inclination to Ecliptic Plane (deg)	23	18	8	2
Initial Orbit Radius (km)	460,000	495,000	425,000	553,000
Initial Period (days)	36.0	40.1	31.9	47.3
Final Orbit Radius (km)	445000 x 510,000	475000 x 515,000	425000 x 481,000	530000 x 583,000
Final Period (days)	38.0	40.2	35.1	47.8
Transfer Injection C3 (km^2/s^2)	0.046	0.135	-0.291	-0.230
Mission Orbit Injection ΔV (m/s)	403	416	495	520

Note: Lunar Gravity Assist distance approx 3200km from lunar center
No Stationkeeping maneuvers required for NRO

SIRA Orbit Options – Lunar Transfer and Final Orbit



SIRA Orbit Options –Shadow and Coverage

Shadow

Orbit Radius (km)	460,000	495,000	425,000	553,000
Inclination to Ecliptic Plane (deg)	23	18	8	2
Final Orbit Period (days)	38.0	40.2	35.1	47.8
Shadow in Mission Orbit	None for 4 years	None for 3 years 9 min lunar penumbra in 4th year	0.5 hr. lunar umbra in 1st year 2 hr. Earth umbra in 3rd year Multiple penumbra events	No umbra for 1st 2 years 2-3 1-2 hr. umbra in 3rd and 4th year Multiple penumbra events

Coverage

Initial Orbit Radius (km)	460,000	495,000	425,000	553,000
Inclination to Ecliptic Plane (deg)	23	18	8	2
Final Period (days)	38.0	40.2	35.1	47.8
DSN Coverage Gaps in Mission Orbit	215 hours over 4 years	110 hours over 4 years	8 hours over 4 years	Continuous Coverage

SIRA Navigation

Navigation

- Traditional ground orbit determination for the carrier and for each spacecraft. X-band Downlink
- Additional measurement data of inter-spacecraft range information
- Anticipated accuracies of ~ 3 m inter-spacecraft range and < 100 m absolute position.

Tracking data coverage requirements:

- Launch and early orbit: 12 hrs
- Cis-lunar: 8 hours every day to perilune
- Post-lunar: 12 hrs for insertion maneuver plan
- Deployment: TBD
- Mission Orbit and formation maintenance: several hrs per day on each spacecraft for 1st week.
- Several hours per week thereafter

SIRA Formation Analysis

- Formations are all baselined to maintain a sphere of 25 km radius.
  - Center of sphere was placed onto orbit
  - Constant low thrust control assuming 0.1mN
  - Simple PD controller to hold position

- A sphere was used for initial placement of formation spacecraft.
  - A uniformly distributed sphere was computed using Robert Bauer's "Uniform Sampling of SO3" algorithm from 2001 Flight Mechanics Symposium"
  - Spacecraft location on sphere held with respect to each other
  - A strict and a loose formation control was then applied.

How much ΔV to initialize, maintain, and resize?

Phase	Max [m/s]	Mean [m/s]	Min [m/s]	Std [m/s]
a	0.635	0.607	0.592	0.014
b	1.323	0.792	0.392	0.293
c	0.757	0.674	0.541	0.069
d	0.679	0.616	0.582	0.031
e	1.201	0.721	0.367	0.263
f	0.679	0.608	0.503	0.056

Phase Description

a) Init 25km sphere
b) Maintain 25km sphere (strict PD control) one month
c) Maintain 25km sphere (loose control) one month
d) Resize from 25km to 50km
e) Maintain 50km sphere (strict PD control) one month
f) Maintain 50km sphere (loose control) one month

Examples:

Initialize & maintain 2 yr:
= 33 m/s

Initialize, Maintain 2yr, & four resizes:
= 36 m/s

SIRA Trade Summary

- Given mission metrics and assumptions, analysis shows feasibility of SIRA mission with a spherical formation

- Chosen lunar transfer ΔV is < 500 m/s and is dependent upon orbit distance and lunar assist conditions

- Formation Initialization, maintenance, and resize in general is not a driver; possible ΔV requirement of ~ 36 m/s
  - **Formation Maintenance ΔV/month (m/s) < *1.5 m/s***
  - **Initialization ΔV (m/s) < *1m/s***
  - **Resize ΔV (m/s) < *1m/s***
  - **Additional analysis required for maneuver type and system engineering aspects**

- Orbit selection dependent upon mission metrics, launch mass capability, system engineering

Considerations for Future Orbit Analysis

- Shadows are seasonally dependent
- Final mission orbit is geometry dependent on cis-lunar trajectory, epoch, parking orbit, and lunar inclination
- Launch windows of approximately 5 days with moon perpendicular to Sun-Earth line
- Launch vehicle error correction of approx 50 m/s
- Re-contact analysis
- Selection of natural dynamics to minimize formation control effort
- Navigation on each s/c after deployment
- Navigation for post launch (12 hrs), post gravity assist / pre-insertion (12 hrs), and deployment (TBD hrs)
- Formation deployment / initialization and maintenance maneuver modeling - Initialization and control effort combined with finite maneuver planning / propulsion design
- Inter-spacecraft timing transfer synchronization

Backup

SIRA Orbit Selection Trade

- A brief orbit trade was performed for the SIRA mission based on metrics

- Three orbits were reviewed,
  - ✓ Earth-Moon L4 Libration orbit
  - ✓ Earth Centered Retrograde orbits (lunar transfer and three body transfer)
  - ✓ Sun-Earth L1 Libration orbit

- All orbit trades used high fidelity perturbation modeling and precision integrators

- A moon centered circular orbit at about 30,000km was also analyzed, but was eliminated due to the high insertion ΔV cost of over 1km/s.

SIRA Orbit Options – Distant Retrograde Orbit Three-body Transfer

Transfer Type	Three-body	Three-body	Three-body	Three-body	Three-body
Final Orbit Radius (km)	500,000	750,000	900,000	1,050,000	1,200,000
Transfer Time to Mission Orbit (days)	151	231	253	282	304
Inclination to Ecliptic Plane (deg)	0 / 5	0	0	0	0 / 5
Max Transfer Distance (km) (10^6)	2.5	4.5	5.3	6.5	7.3
Initial Period (days)	39	67	86	105	122
Transfer Injection C3 (km^2/s^2)	-.13	0.02	0.10	0.15	0.26
Mission Orbit Injection ΔV (m/s)	210 / 256	43	23	7	3 / 28

SIRA Orbit Options –Shadows

Three Body Option

Final Orbit Radius (km)	500000	750000	900000	1050000	1200000
Final Orbit Period (days)	39	67	86	105	122
Shadow in Mission Orbit (no lunar shadows)	Penumbra: 5 hrs Umbra: 2 hrs [5 deg: None]	Penumbra: 6 hrs Umbra: 2 hrs	Penumbra: 7 hrs Umbra: 2 hrs	Penumbra: 7 hrs Umbra: 1 hr	Penumbra: 8 hrs Umbra: None [5 deg: None]

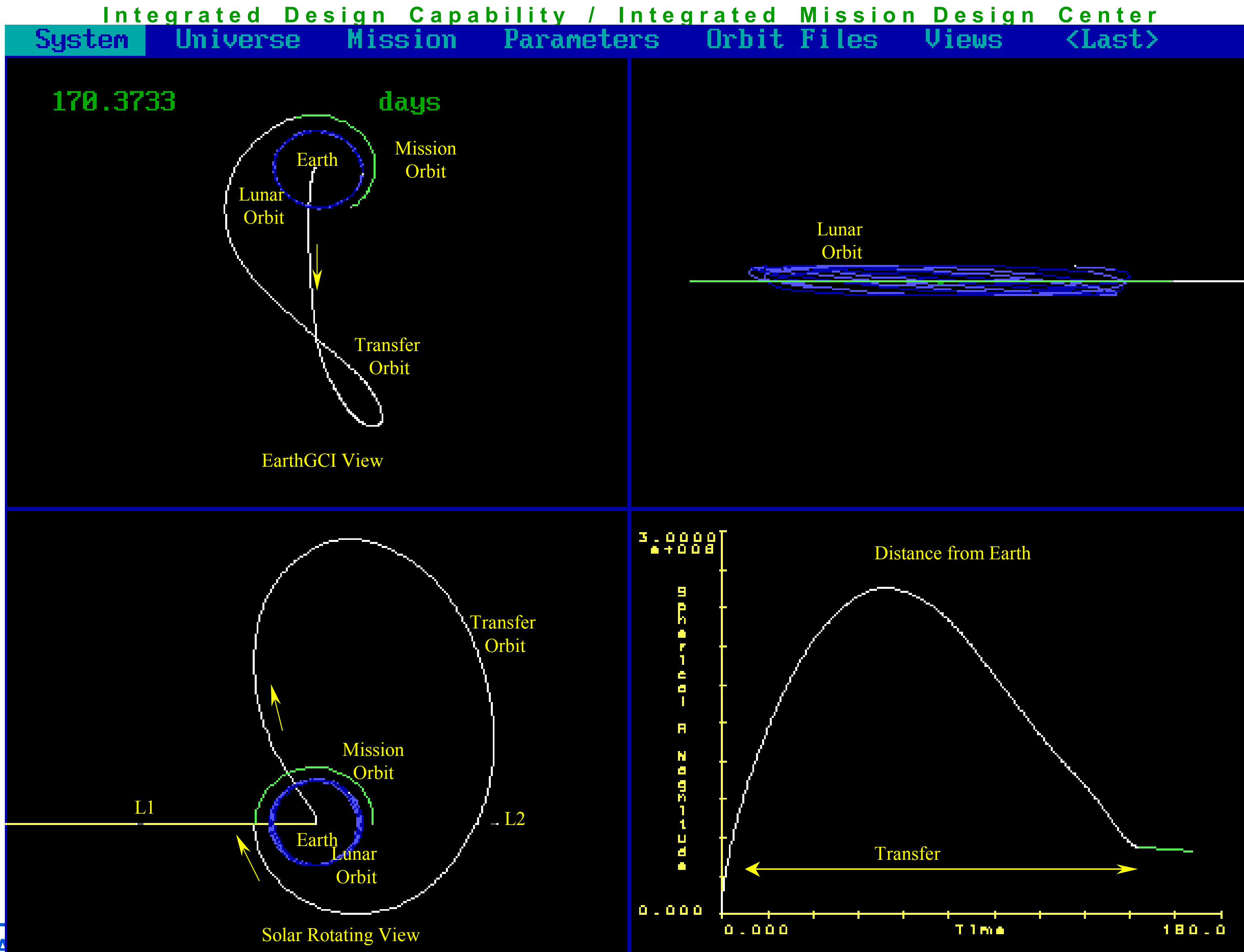
Lunar Orbit Option

Orbit Radius (km)	460,000	495,000	425,000	553,000
Inclination to Ecliptic Plane (deg)	23	18	8	2
Final Orbit Period (days)	38.0	40.2	35.1	47.8
Shadow in Mission Orbit	None for 4 years	None for 3 years 9 min lunar penumbra in 4th year	0.5 hr. lunar umbra in 1st year 2 hr. Earth umbra in 3rd year Multiple penumbra events	No umbra for 1st 2 years 2-3 1-2 hr. umbra in 3rd and 4th year Multiple penumbra events

SIRA Orbit Options – Coverage

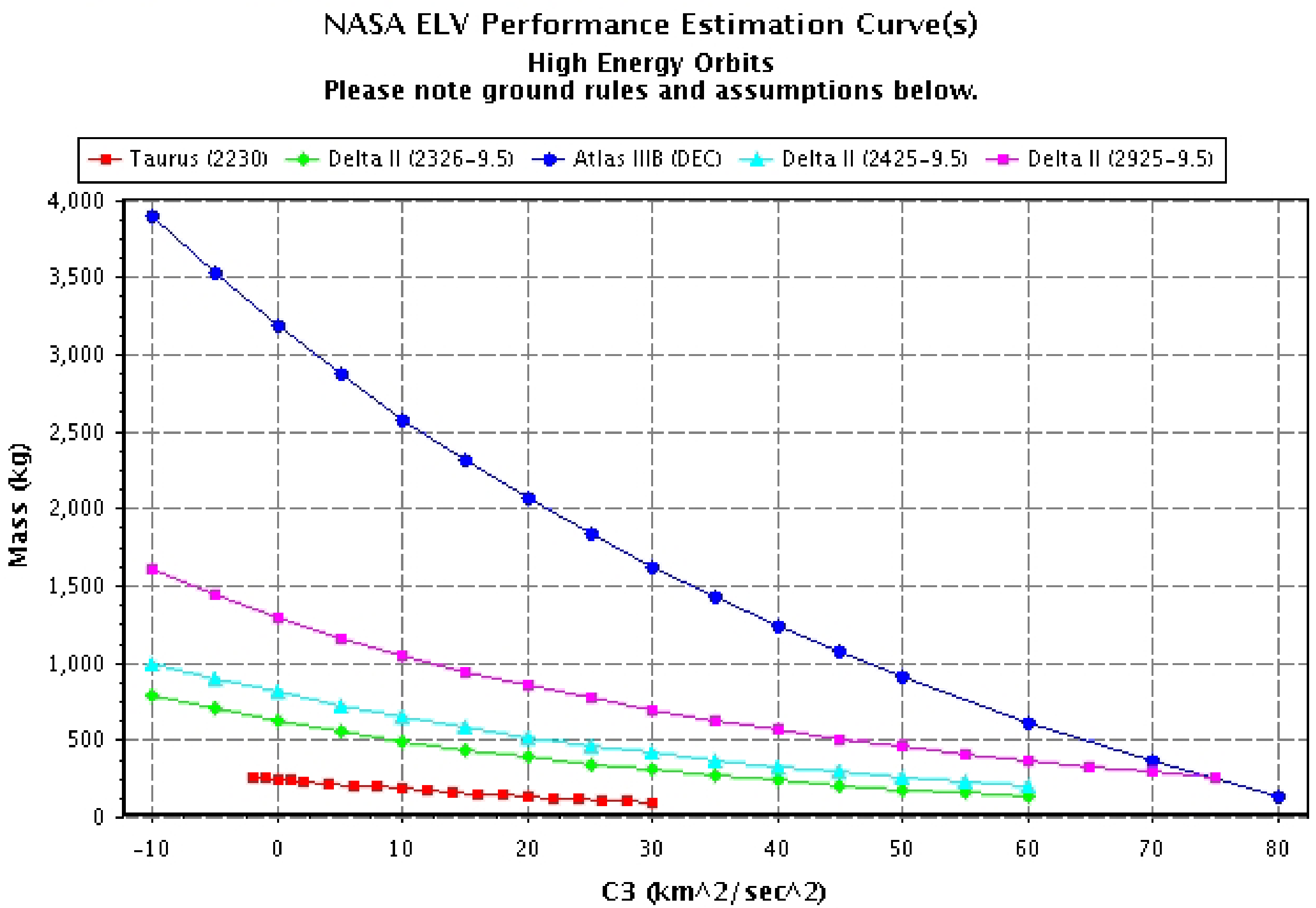
Initial Orbit Radius (km)	460,000	495,000	425,000	553,000
Inclination to Ecliptic Plane (deg)	23	18	8	2
Final Period (days)	38.0	40.2	35.1	47.8
DSN Coverage Gaps in Mission Orbit	215 hours over 4 years	110 hours over 4 years	8 hours over 4 years	Continuous Coverage

SIRA Orbit Options – Three Body Transfer and Final Orbit



SIRA Orbit Options – Launch

Important Note: The data contained in these curves are based on ground rules and assumptions located below the plot. Please read this information carefully. This information is intended for NASA customers only.



SIRA Orbit Options – Launch

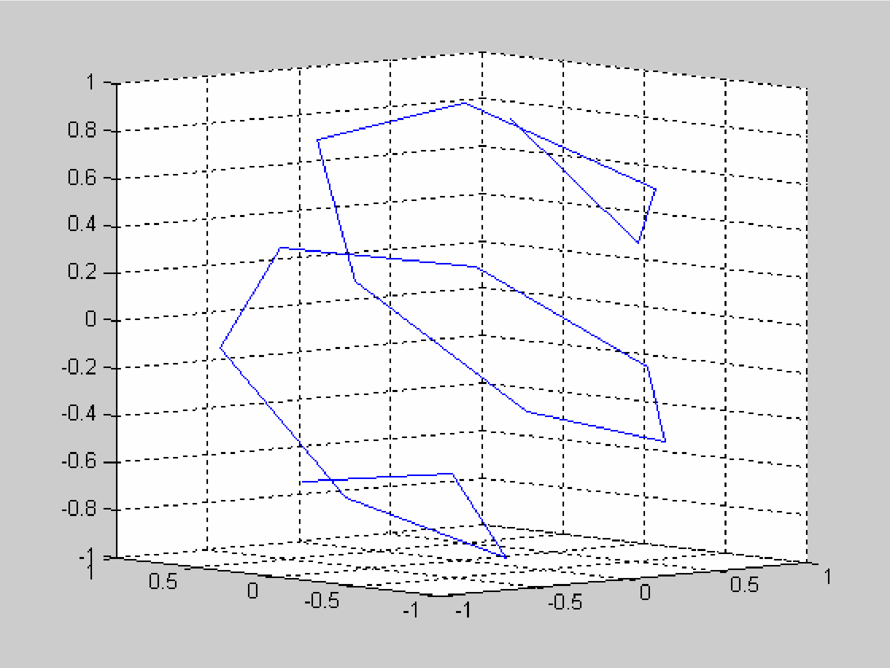
Launch vehicle payload mass capabilities for a C3 ~ 0 km^2/sec^2, from ELV web site

Taurus (2230)	245.0		
Taurus (2130)	295.0	Delta II (2926-9.5)	1140.0
Delta II (2326-10)	600.0	Delta II (2925-10L)	1225.0
Delta II (2920-10L)	620.0	Delta II (2925-10)	1240.0
Delta II (2920-10)	625.0	Delta II (2925-9.5)	1290.0
Delta II (2326-9.5)	625.0	Delta II (2926H-10L)	1305.0
Delta II (2920-9.5)	690.0	Delta II (2926H-10)	1315.0
Delta II (2426-10)	695.0	Delta II (2926H-9.5)	1345.0
Delta II (2426-9.5)	715.0	Delta II (2925H-10L)	1480.0
Delta II (2425-10)	790.0	Delta II (2925H-10)	1495.0
Delta II (2425-9.5)	810.0	Delta II (2925H-9.5)	1525.0
Delta II (2920H-10L)	860.0	Delta III (3940-11)	2625.0
Delta II (2920H-10)	875.0	Atlas IIIB (SEC)	2975.0
Delta II (2920H-9.5)	905.0	Atlas IIIB (DEC)	3180.0
Delta II (2926-10L)	1075.0		
Delta II (2926-10)	1085.0		

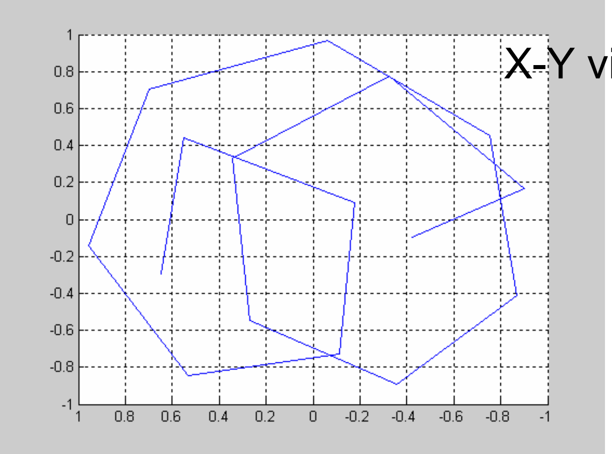
SIRA Formation Analysis

- Matlab generated sphere based on S03 algorithm
  - ✓ Uniform distribution of points on a unit sphere
  - ✓ 16 points at vertices represents spacecraft locations

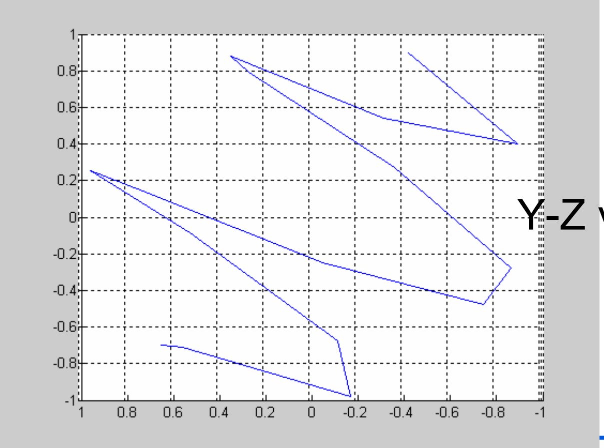
3-D view



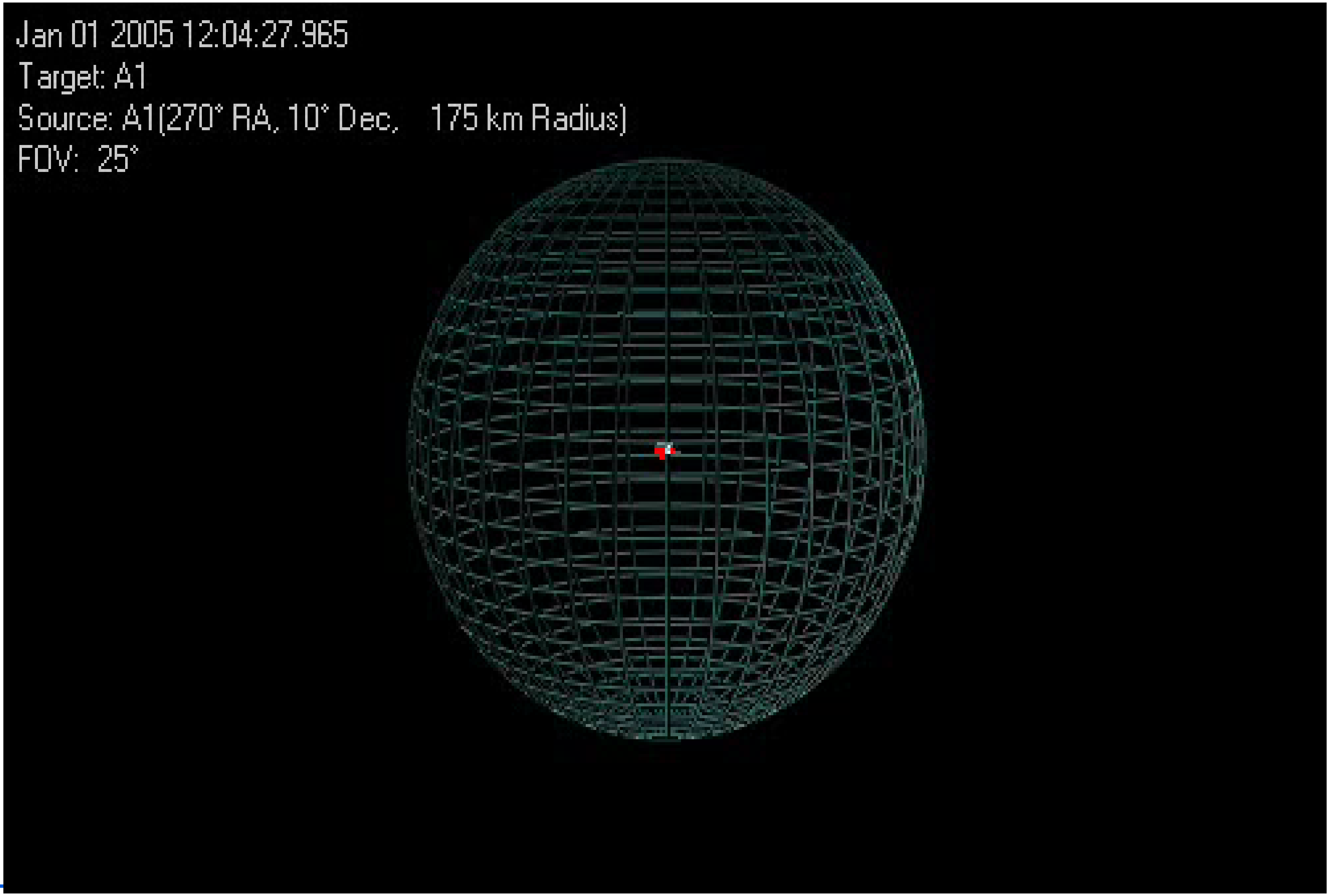
X-Y view



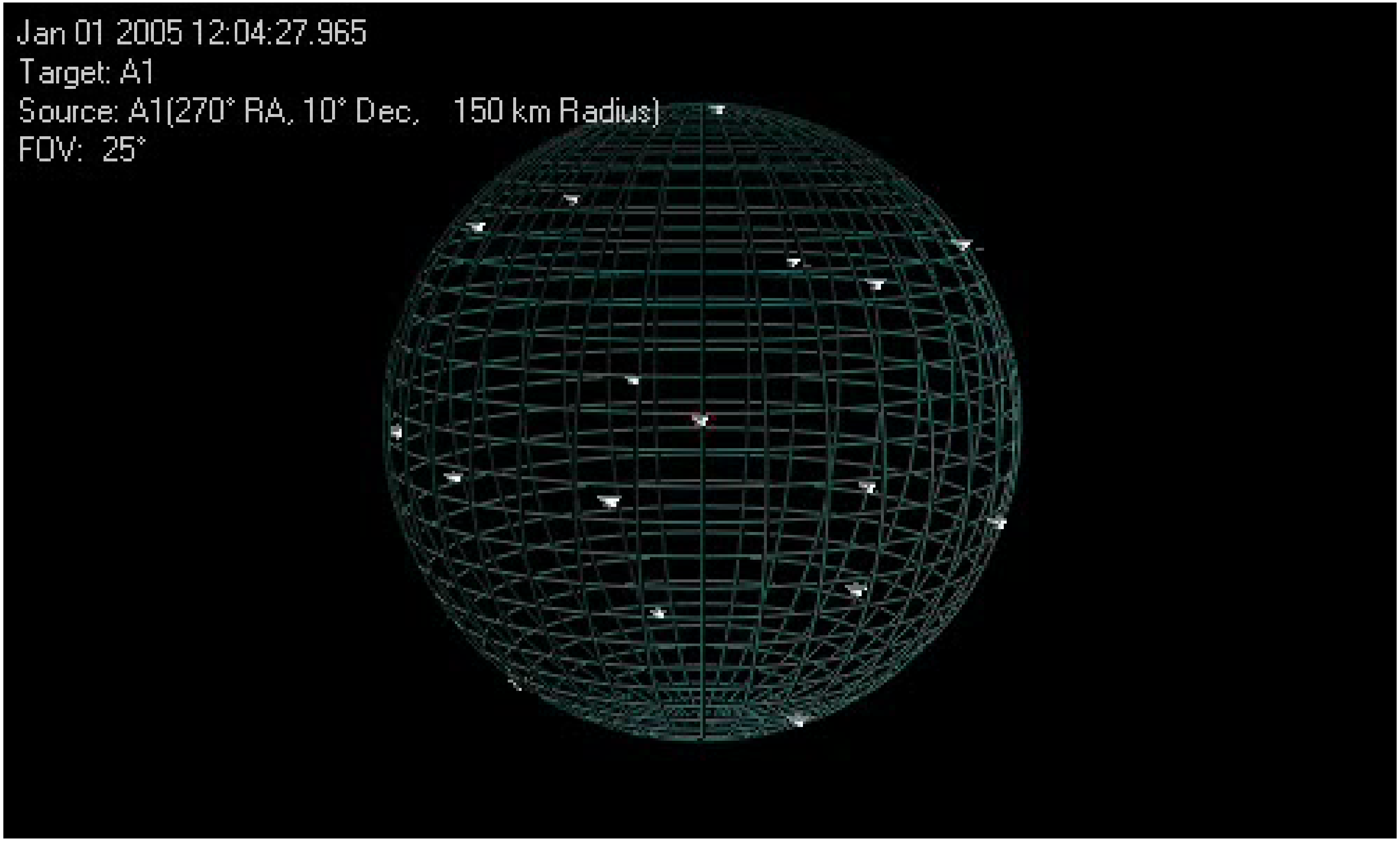
Y-Z view



SIRA Formation Control Analysis



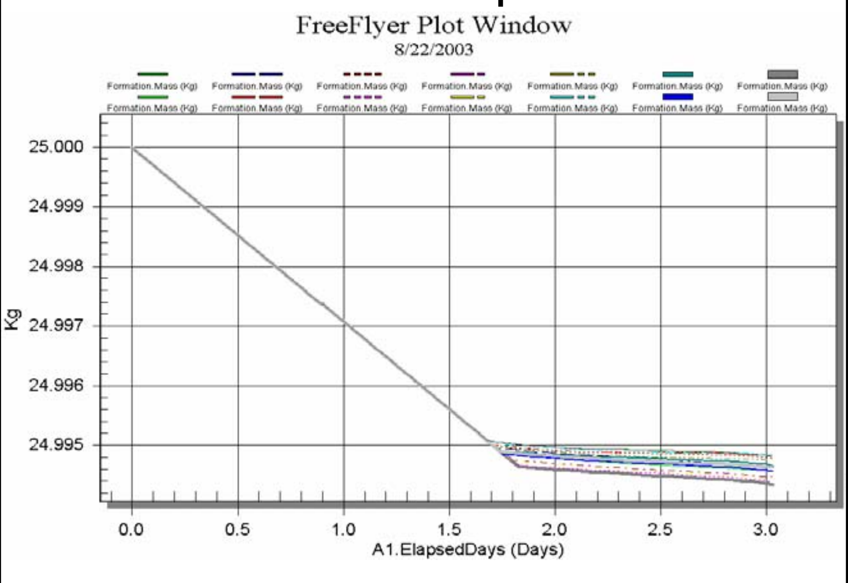
SIRA Formation Control Analysis



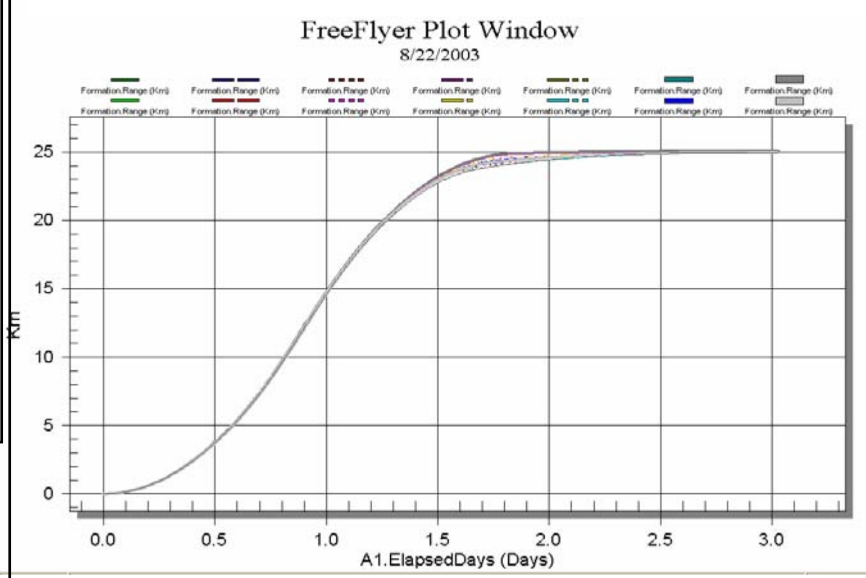
SIRA Formation Control Analysis

- Initialization and maintenance
- Spacecraft controlled to maintain only relative separations
- Plots show formation position and drift (sphere represent 25km radius)
- Maneuver performed in most optimum direction based on controller output

Mass Depletion



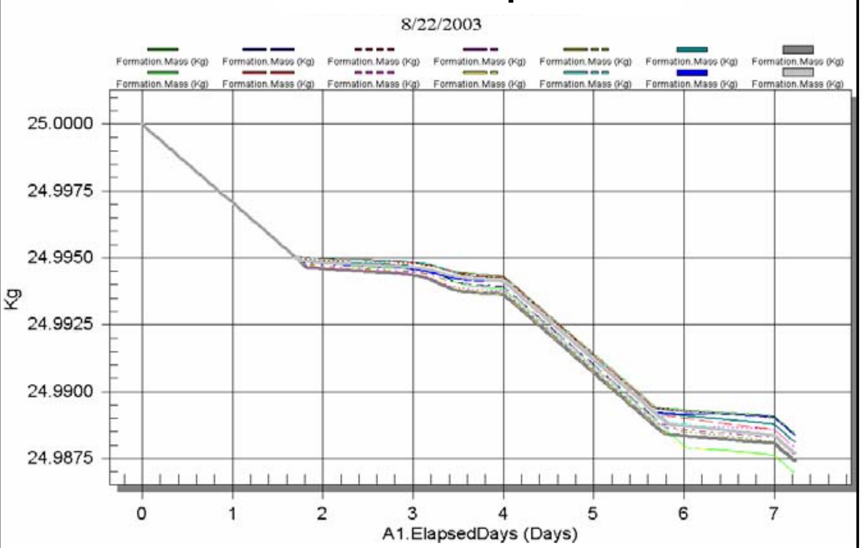
Radial Distance from Center



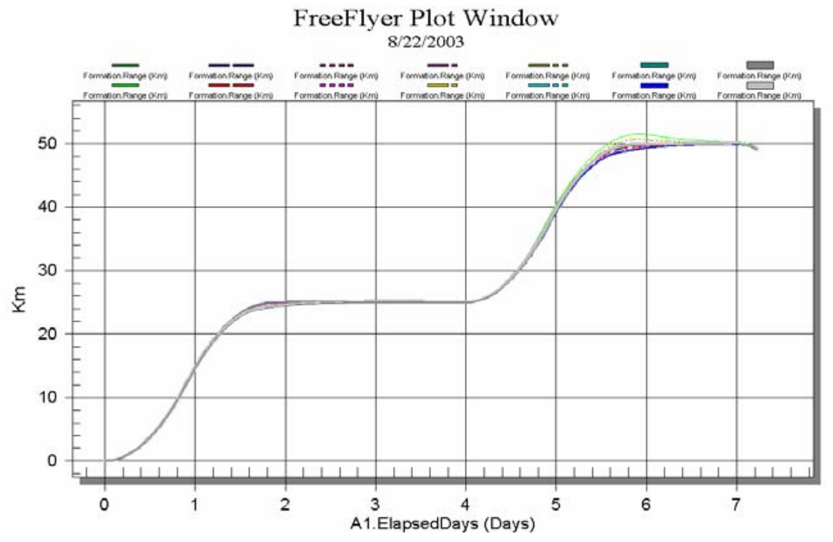
SIRA Formation Control Analysis

- Initialization, maintain, resize, maintain
- Spacecraft controlled to maintain only relative separations
- Maneuver performed in most optimum direction based on controller output

Mass Depletion

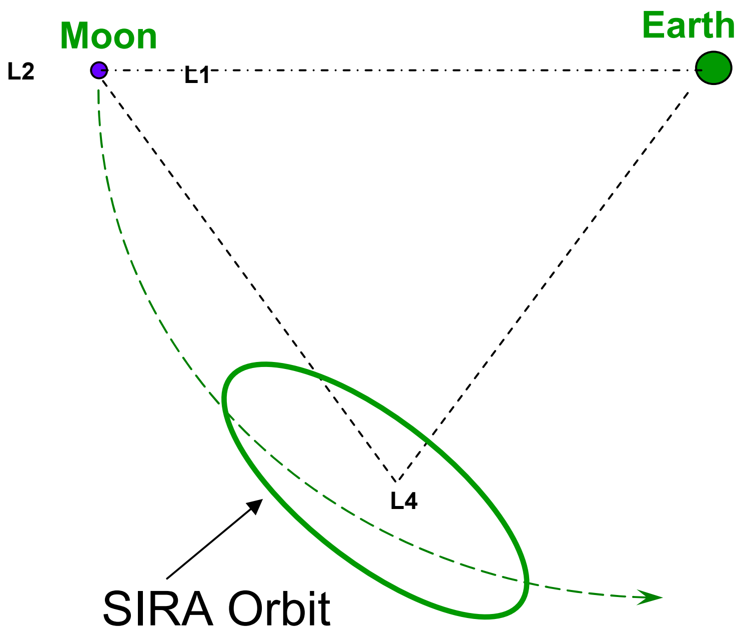


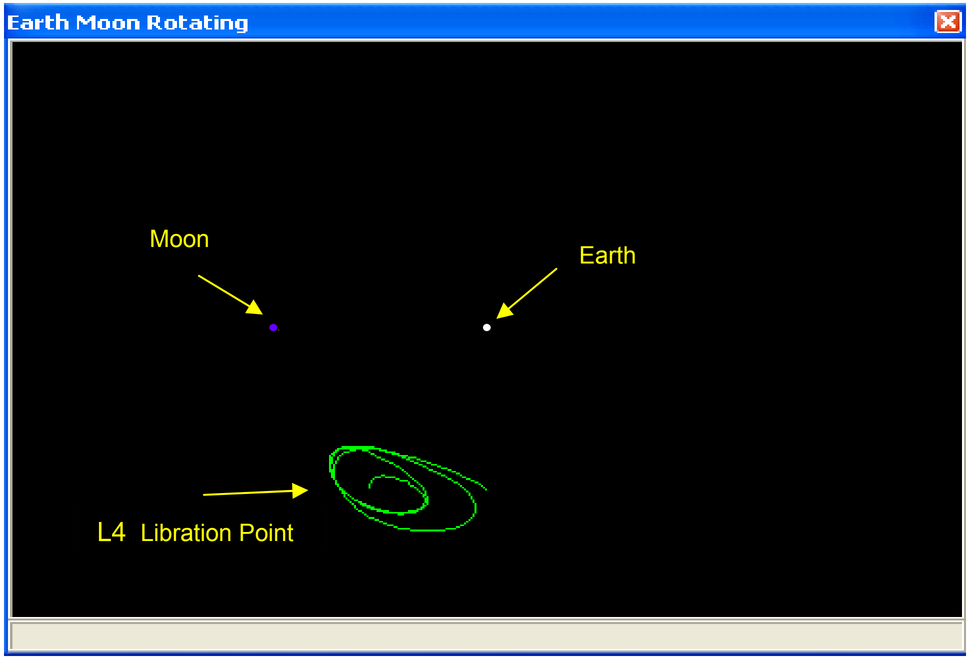
Radial Distance from Center



Earth - Moon L4 Libration Orbit

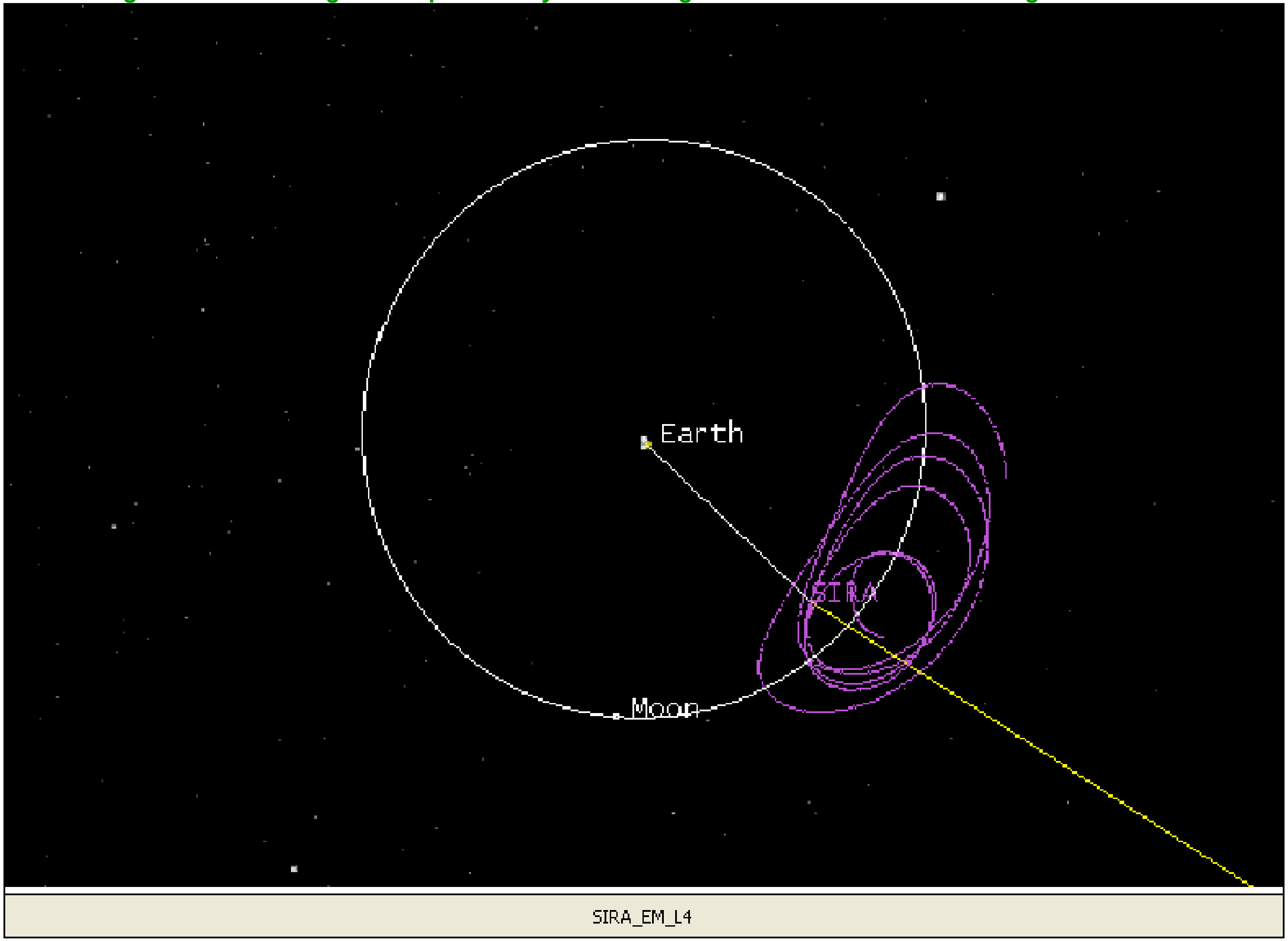
- Stable orbit in Earth - moon neighborhood
- L4 Location is at equal distances from Earth and Moon
- Requires insertion maneuver





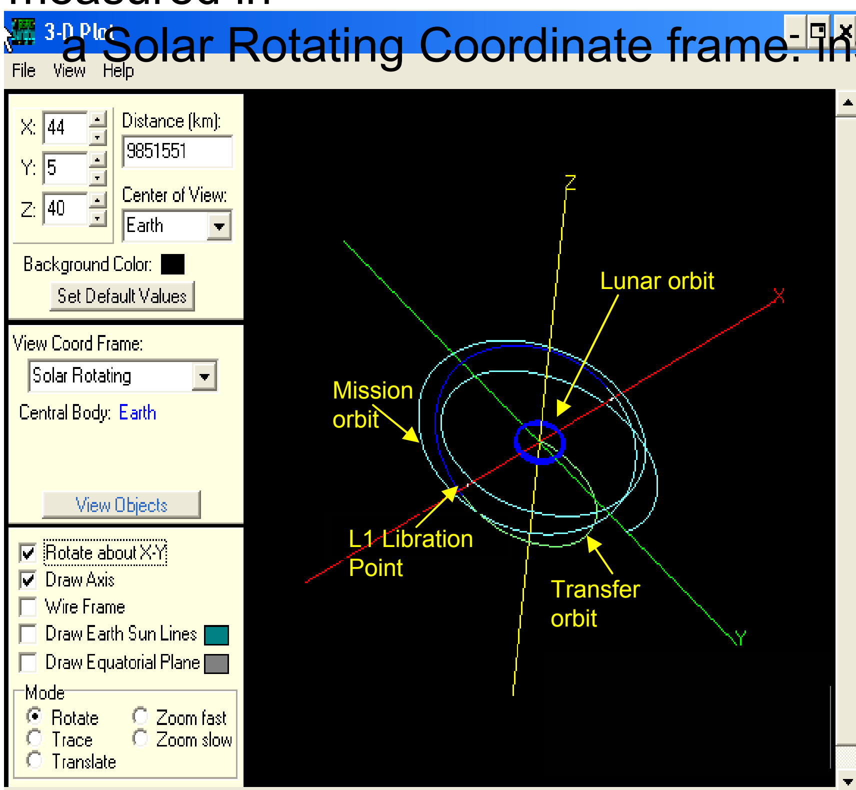
Shown in Earth-Moon Rotating System

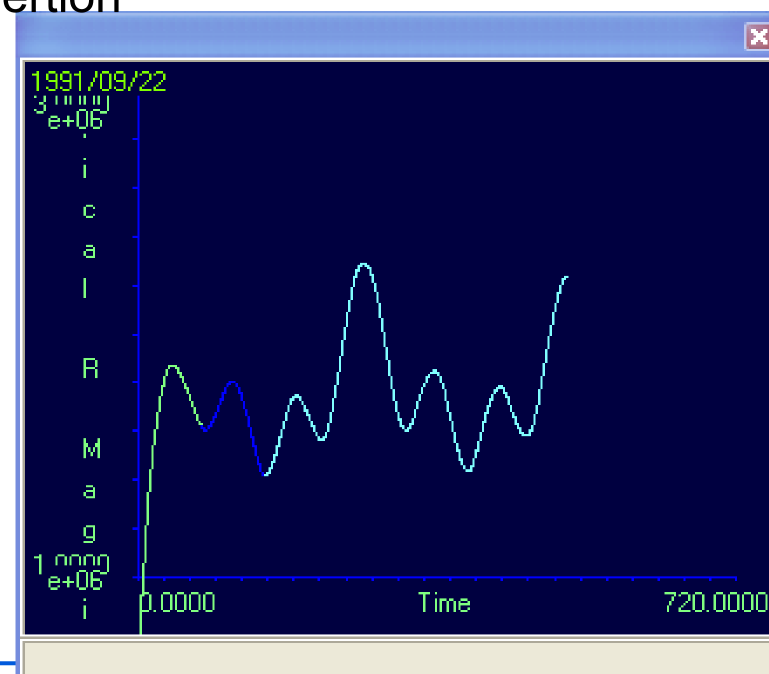
Earth - Moon L4 Libration Orbit



Distant Retrograde Orbit (DRO) Orbit

- DRO is really an orbit in heliocentric space
- Heliocentric orbit parameters chosen that have same period of Earth with slightly altered eccentricity
- Circular relative motion wrt Earth orbiting clockwise
- Needs an insertion maneuver, but is stable afterwards
- It has dimensions of ~ 1.7e6 km in x and <2.0e6km in y directions as measured in a Solar Rotating Coordinate frame. insertion

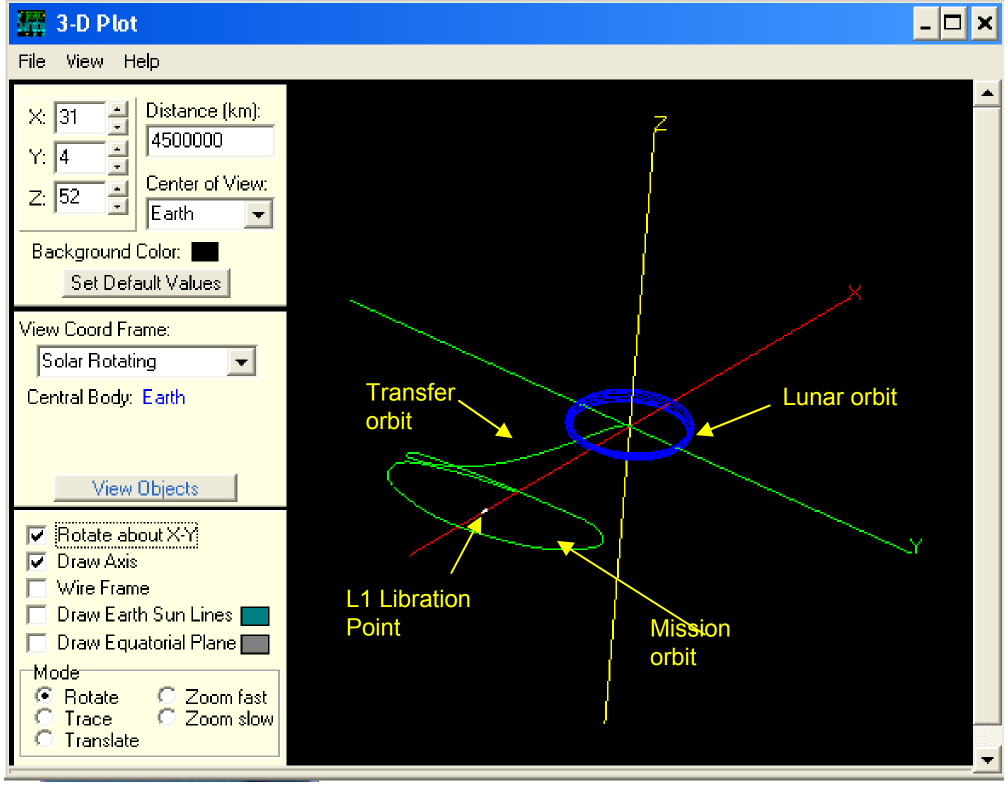


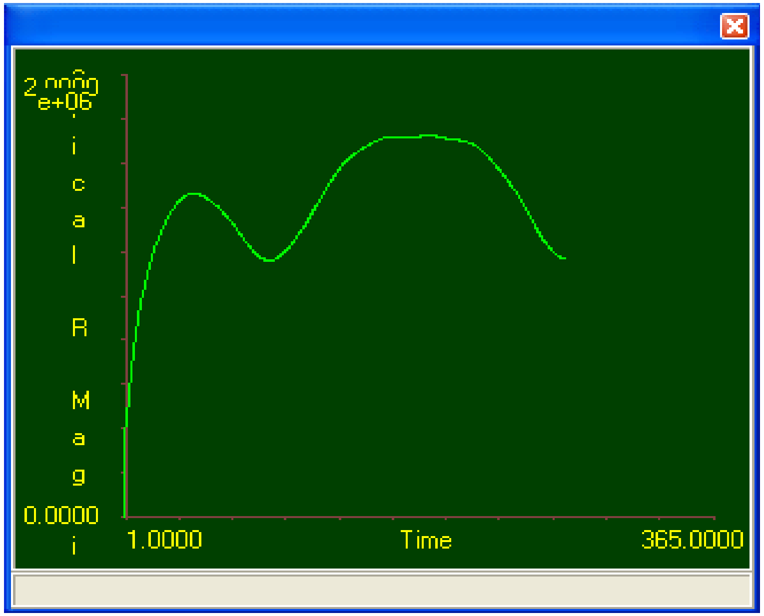


Earth Distant Retrograde Orbit (DRO) Orbit

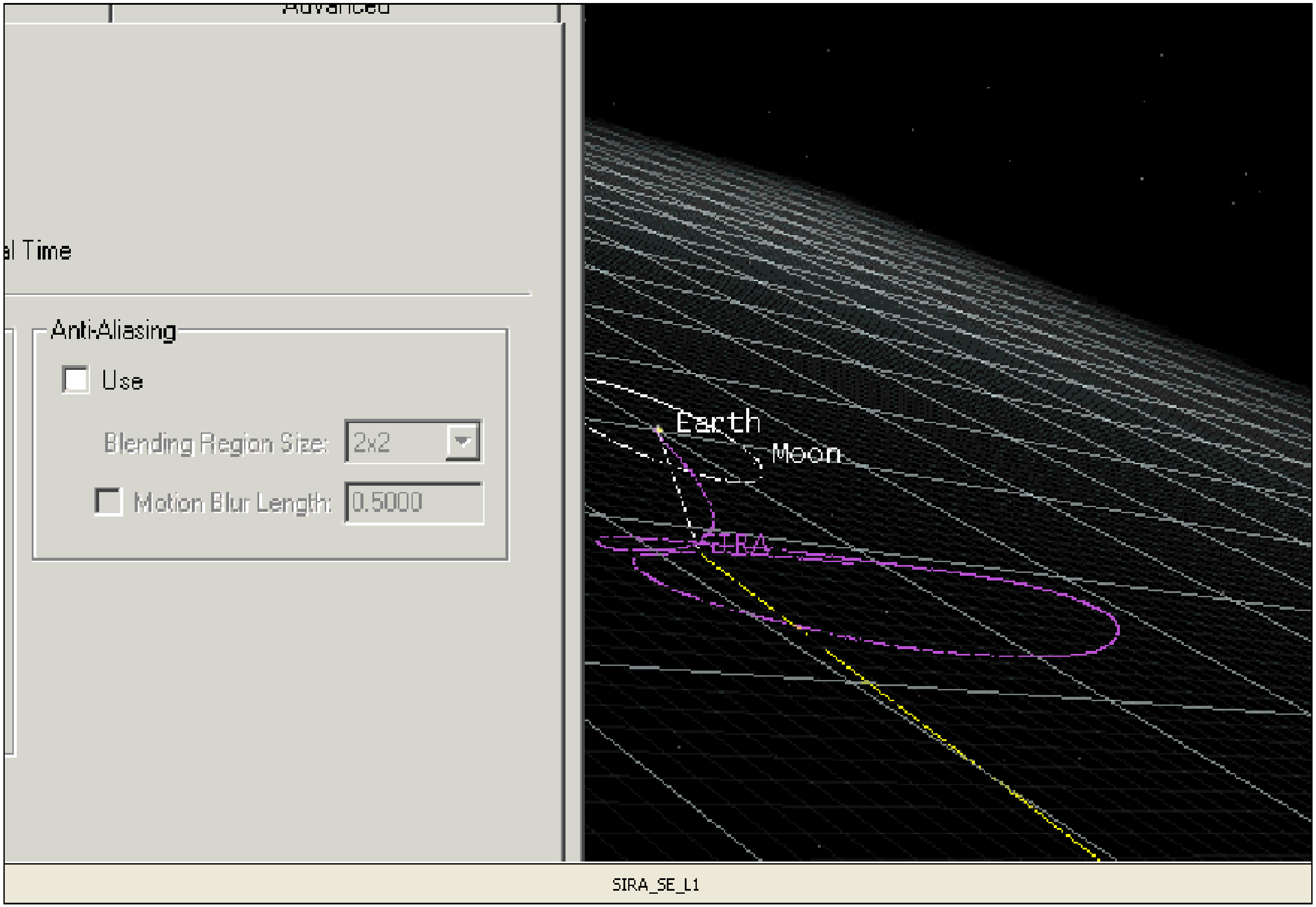
Libration Orbit

- This is a standard libration orbit about the co-linear L1 location (ISEE, SOHO, ACE)
- It has dimensions of about 1.6e6 km in ‘x’ and 1.9e6km in ‘y’ directions as measured in a Solar Rotating Coordinate frame.





Libration Orbit



Launch Vehicle Information

- Corresponds to a C3 of –0.5 km^2/s^2
- Mass to orbit ranges from 250 kg(Taurus) to 1510kg (Delta-

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Expendable Launch Vehicles
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Plot Curve (5 Max)	Vehicle	Max Payload (kg)
☐	Taurus (2230)	250.0
☐	Taurus (2130)	295.0
☐	Delta II (2326-10)	610.0
☐	Delta II (2920-10L)	630.0
☐	Delta II (2326-9.5)	635.0
☐	Delta II (2920-10)	635.0
☐	Delta II (2426-10)	700.0
☐	Delta II (2920-9.5)	705.0
☐	Delta II (2426-9.5)	720.0
☐	Delta II (2425-10)	795.0
☐	Delta II (2425-9.5)	820.0
☐	Delta II (2920H-10L)	880.0
☐	Delta II (2920H-10)	890.0
☐	Delta II (2920H-9.5)	920.0
☐	Delta II (2926-10L)	1085.0
☐	Delta II (2926-10)	1095.0

Flight Design Group

Web Site

☐	Delta II (2925-10L)	1240.0
☐	Delta II (2925-10)	1250.0
☐	Delta II (2925-9.5)	1305.0
☐	Delta II (2926H-10L)	1320.0
☐	Delta II (2926H-10)	1330.0
☐	Delta II (2926H-9.5)	1360.0
☐	Delta II (2925H-10L)	1495.0
☐	Delta II (2925H-10)	1510.0
☐	Delta II (2925H-9.5)	1540.0
☐	Delta III (3940-11)	2655.0
☐	Atlas IIIB (SEC)	3005.0
☐	Atlas IIIB (DEC)	3215.0

Launch Vehicle Information

Corresponds to a C3 of $-1.8\ km^2/s^2$

- Mass to orbit ranges from 260 kg(Taurus) to 1585kg (Delta-

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(5 Max)		
☐	Taurus (2230)	260.0
☐	Taurus (2130)	310.0
☐	Delta II (2326-10)	625.0
☐	Delta II (2326-9.5)	655.0
☐	Delta II (2920-10L)	670.0
☐	Delta II (2920-10)	675.0
☐	Delta II (2426-10)	725.0
☐	Delta II (2426-9.5)	745.0
☐	Delta II (2920-9.5)	745.0
☐	Delta II (2425-10)	820.0
☐	Delta II (2425-9.5)	845.0
☐	Delta II (2920H-10L)	925.0
☐	Delta II (2920H-10)	935.0
☐	Delta II (2920H-9.5)	965.0
☐	Delta II (2926-10L)	1120.0
☐	Delta II (2926-10)	1130.0
☐	Delta II (2926-9.5)	1190.0
☐	Delta II (2925-10L)	1275.0
☐	Delta II (2925-10)	1285.0
☐	Delta II (2925-9.5)	1340.0
☐	Delta II (2926H-10L)	1360.0
☐	Delta II (2926H-10)	1375.0
☐	Delta II (2926H-9.5)	1400.0
☐	Delta II (2925H-10L)	1535.0
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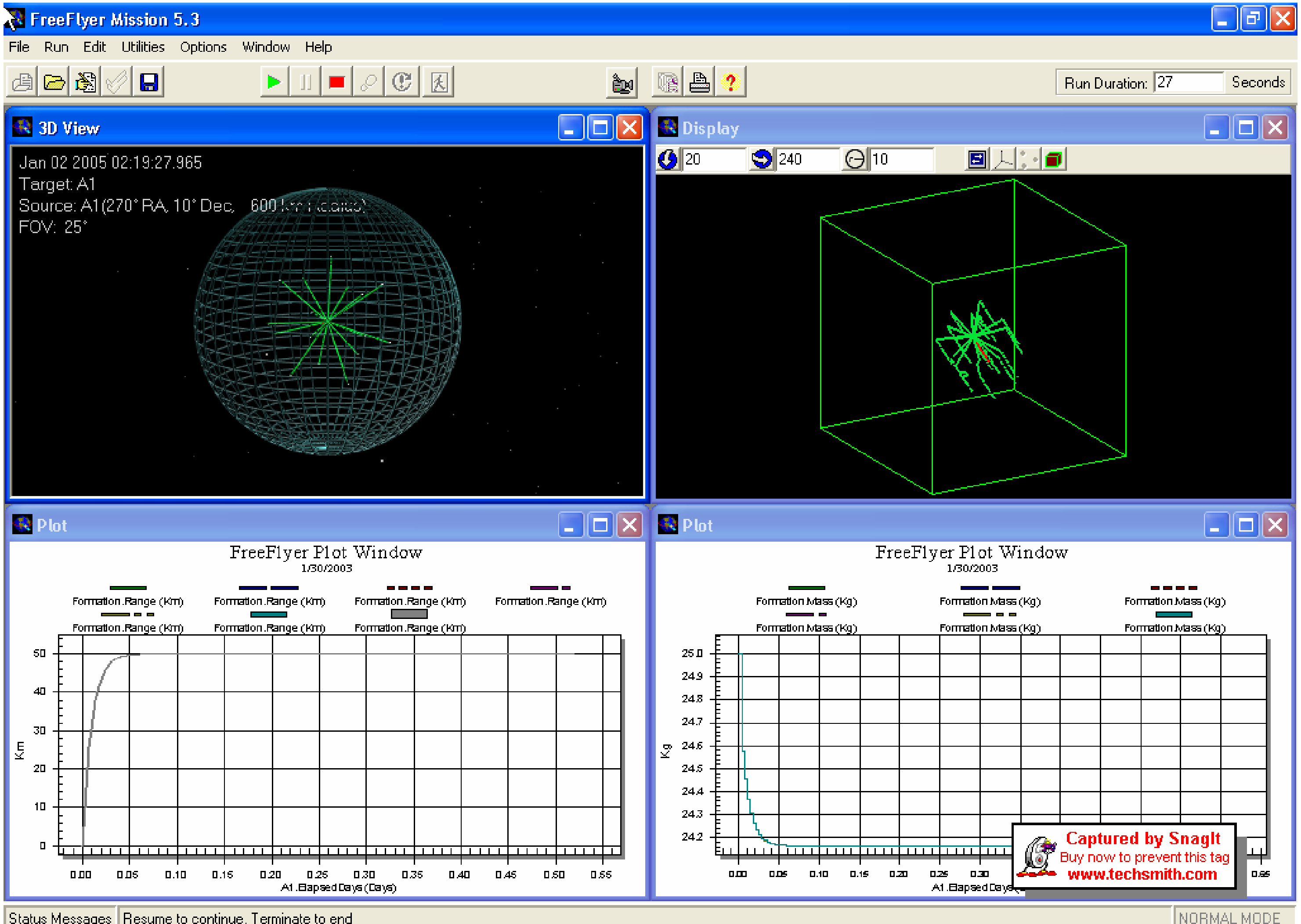
☐	Atlas IIIB (SEC)	3075.0
☐	Atlas IIIB (DEC)	3300.0


FreeFlyer Mission 5.3
File Run Edit Utilities Options Window Help
Run Duration: 27 Seconds
3D View
Jan 02 2005 02:19:27.965
Target: A1
FOV: 25°
Display
Plot
FreeFlyer Plot Window
1/30/2003
Formation.Range (Km)
A1.ElapsedDays (Days)
Formation.Mass (Kg)
Status Messages
Resume to continue, Terminate to end
NORMAL MODE
Captured by SnagIt
Buy now to prevent this tag
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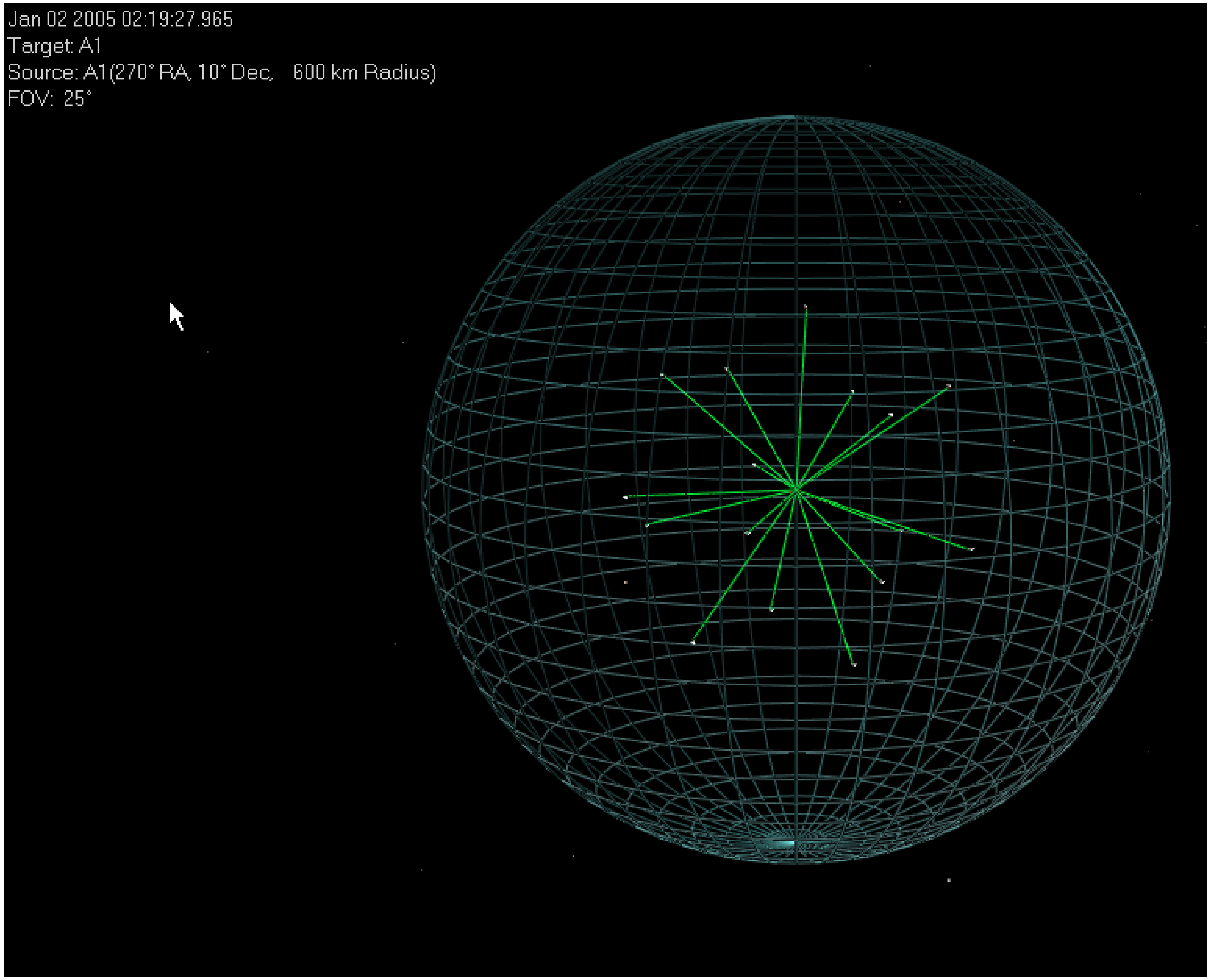
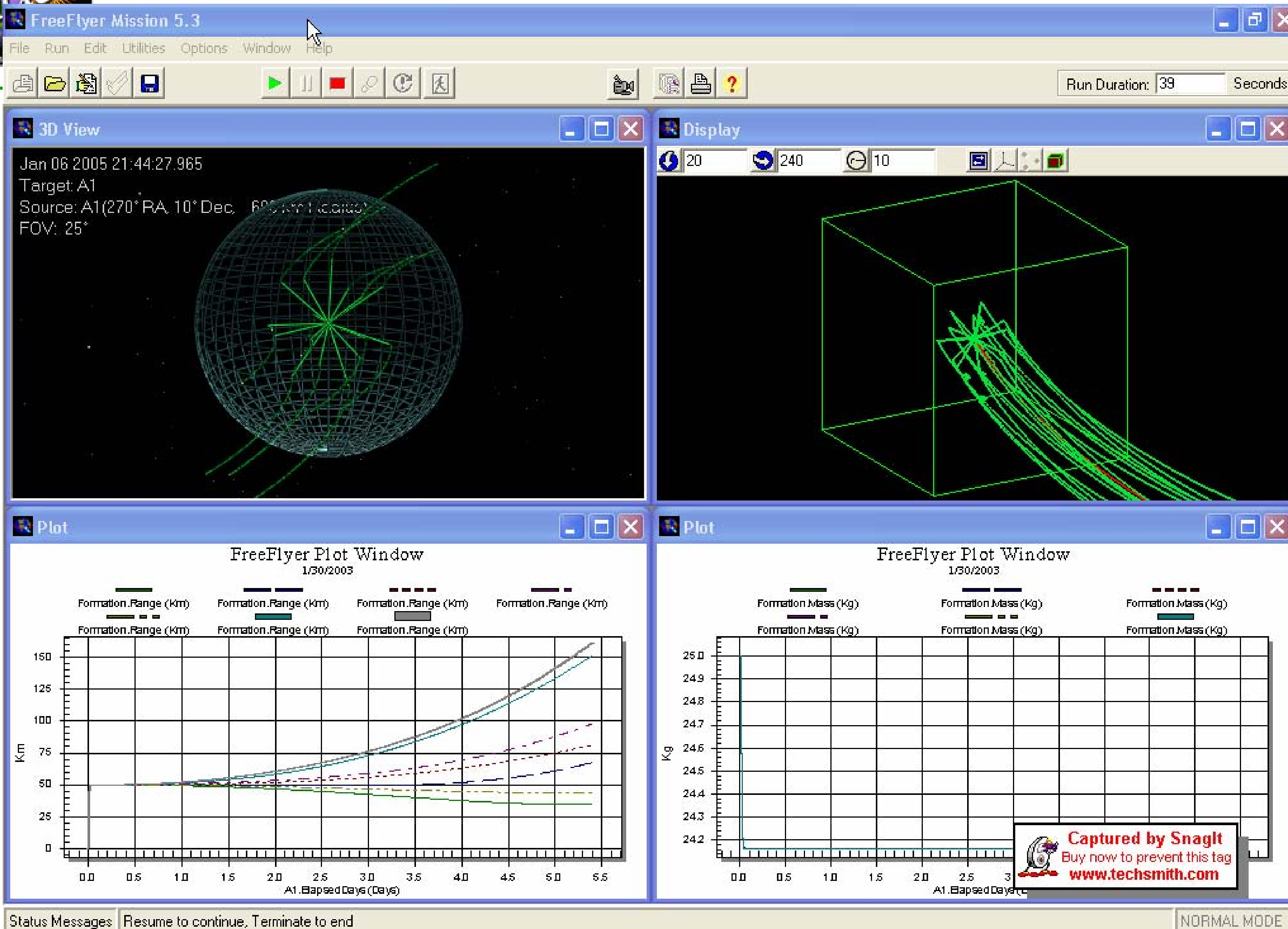

Jan 02 2005 02:19:27.965
Target: A1
Source: A1(270° RA, 10° Dec, 600 km Radius)
FOV: 25°


FreeFlyer Mission 5.3
File Run Edit Utilities Options Window Help
Run Duration: 39 Seconds
3D View
Jan 06 2005 21:44:27.965
Target: A1
Source: A1(270° RA, 10° Dec,
FOV: 25°
Display
20
240
10
Plot
FreeFlyer Plot Window
1/30/2003
Formation.Range (Km)
Km
A1.Elapsed Days (Days)
Plot
FreeFlyer Plot Window
1/30/2003
Formation.Mass (Kg)
Kg
Captured by SnagIt
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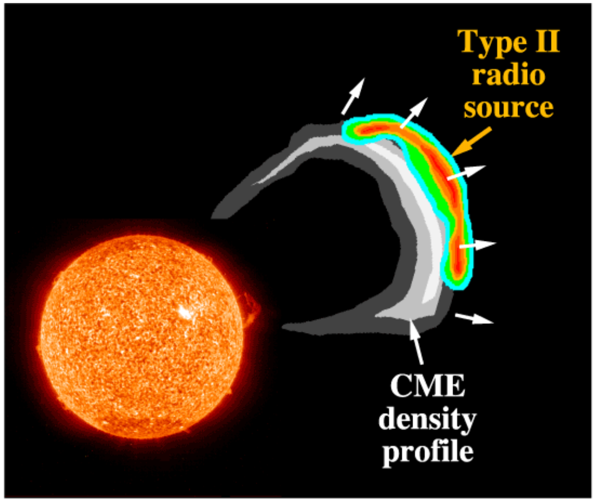
www.techsmith.com
Status Messages
Resume to continue, Terminate to end
NORMAL MODE

Solar Imaging Radio Array



Two dimensional radio imaging of the CME-driven shock front and the CME density profile is critical for predicting the space weather effects of CMEs

Technology Requirements:
- Intermicrosat ranging (to ~3 m)
- "Full-sky" aperture synthesis mapping algorithm development
- Onboard data cross-correlation desirable (for space weather snapshots)

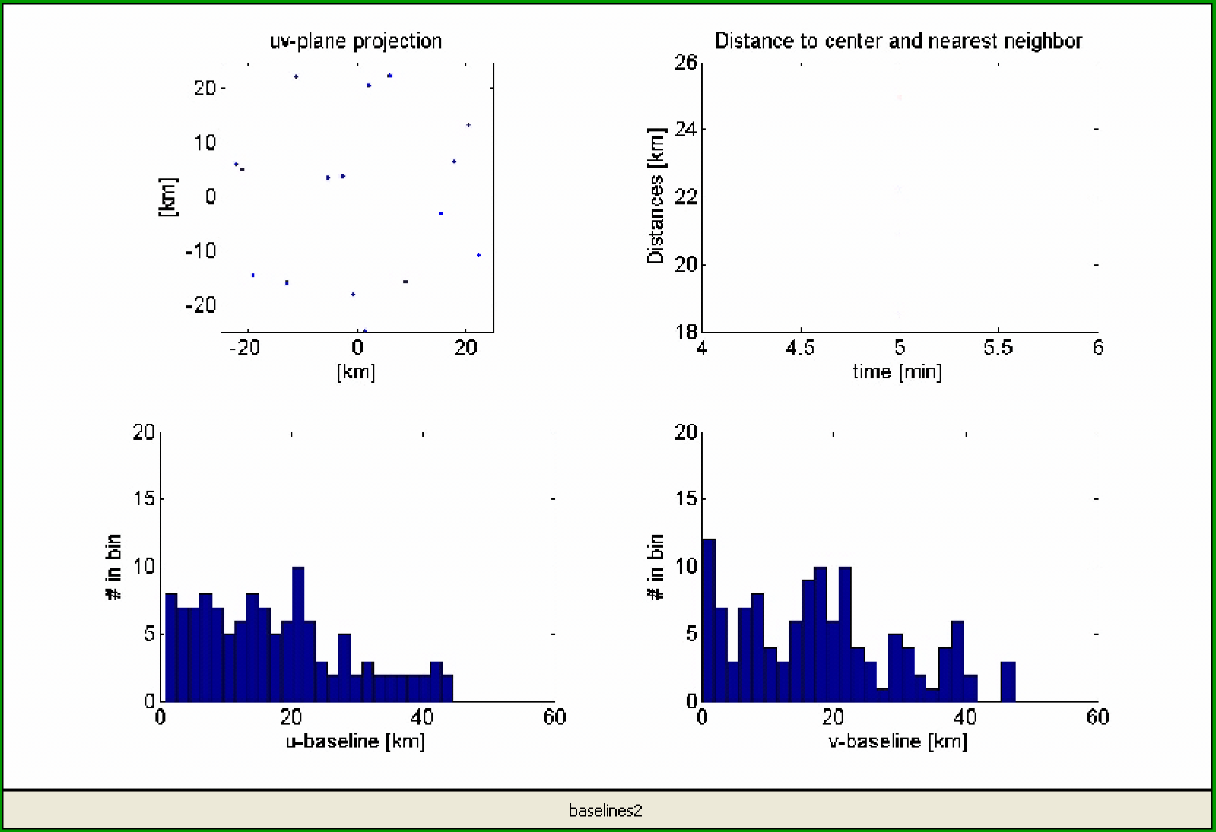
Science Objectives:
- Understand CME structure, propagation, and evolution from the Sun to 1 AU
- Apply solar radio burst images to mapping of solar wind density structures and magnetic field topology, providing a unique tool for solar wind analysis
- Enhance space weather prediction capabilities using radio images of CMEs
- Observe and analyze the global response of Earth's magnetosphere to CMEs and other space-weather-effective events from an external perspective
- Image the low-frequency (< 30 MHz) radio universe at high angular resolution and catalog and understand the objects found therein

Mission Description:
- Microsat constellation of 10 – 16 identical spacecraft
- Crossed dipole antennas and low frequency radio receivers
- Quasi-spherical constellation with <100 km diameter
- Nearly circular distant retrograde orbit (~10^6 km from Earth) or other terrestrial radio interference limiting orbit
- Individual microsat communication with ground stations

Measurement Strategies:
- High spatial and temporal resolution
- Frequency range from ~30 MHz to ~30 kHz
- Frequency spacing and time resolution optimized for solar burst analysis
- Rapid data processing for space weather prediction

SIRA Formation U-V Plane Analysis

- Spacecraft controlled to maintain only relative separations
- Plots show statistic of U-V plane and relative formation positions



Earth Distant Retrograde Orbit (DRO) Orbit

SIRA Orbit Options – Lunar Transfer