



Section 4B

Lunar Orbit Insertion (LOI)

Lunar Orbit Loiter Trade: Parts 1 & 2



Appendix 4B (Part 1) – Lunar Orbit Insertion (LOI) - Lunar Orbit Loiter Trade



Lunar Mission Extension Risk Change When the Mission is Extended

The lunar mission risk scenarios us a nominal mission of 24 hours in lunar orbit prior to Lunar Surface Access Module (LSAM) descent to the surface, and 96 hours on the surface. For post-ascent the nominal mission assumes an immediate return to Earth. Additional scenarios for mission phase extension are shown in the following three figures:

- Extending the pre-landing lunar orbit phase by 0, 1, and 2 days,
- Extending the surface phase by 0, 1, and 2 days, and
- Extending the post landing lunar orbit phase by 0, 1, and 2 days.

In the post ascent phase to lunar orbit, it is assumed that the LSAM is expended and that the Crew Exploration Vehicle/Service Module (CEV/SM) is providing all of the crew survivability functions. Also, the values in these analyses do not include the demand related values of the launch vehicle and propulsion systems, nor is lunar rendezvous included since it is also equivalent for all mission scenarios. Extending the mission in lunar orbit prior to landing raises the risk of Loss of Mission (LOM) and Loss of Crew (LOC) above the other mission extension scenarios, simply because an additional vehicle is still attached (the LSAM, albeit powered down). While on the surface, the LSAM will be active but the CEV/SM will be quiescent and post ascent, the CEV/SM will be the only vehicle active. The risk does not change very much, just noticeable enough to show the slight differences in risk. Overall, the analysis reflects the combinations of mission elements (CEV, SM, and LSAM) in varying stages of operation (active, quiescent).



Lunar Mission Extension Pre-Surface Mission in Lunar Orbit Mission Extensions of 0, 1, and 2 days Prior to Landing

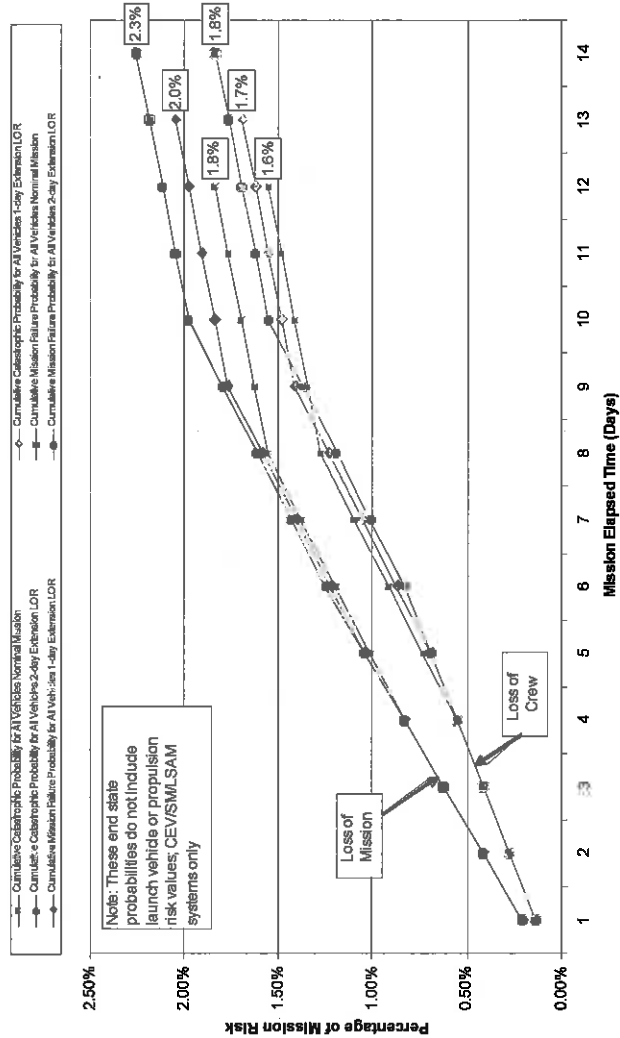


Figure 1 - Pre-landing loiter in lunar orbit



Lunar Mission Extension Surface Mission in Lunar Orbit Mission Extensions of 0, 1, and 2 days Surface Extension

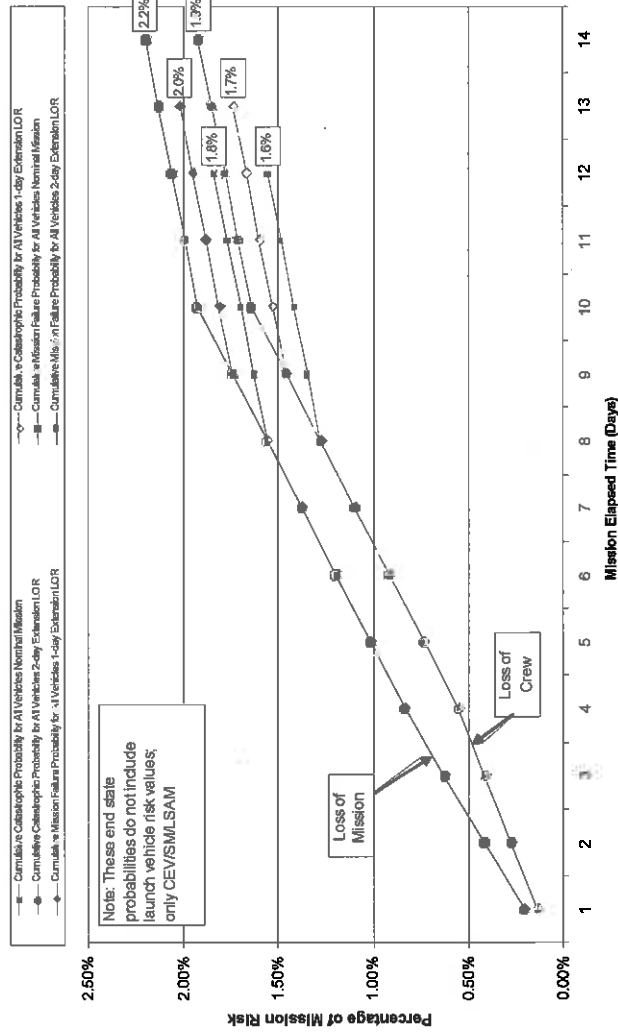


Figure 2 - Extension of the surface mission



Lunar Mission Extension Post-Surface Mission in Lunar Orbit Mission Extensions of 0, 1, and 2 days Post Ascent

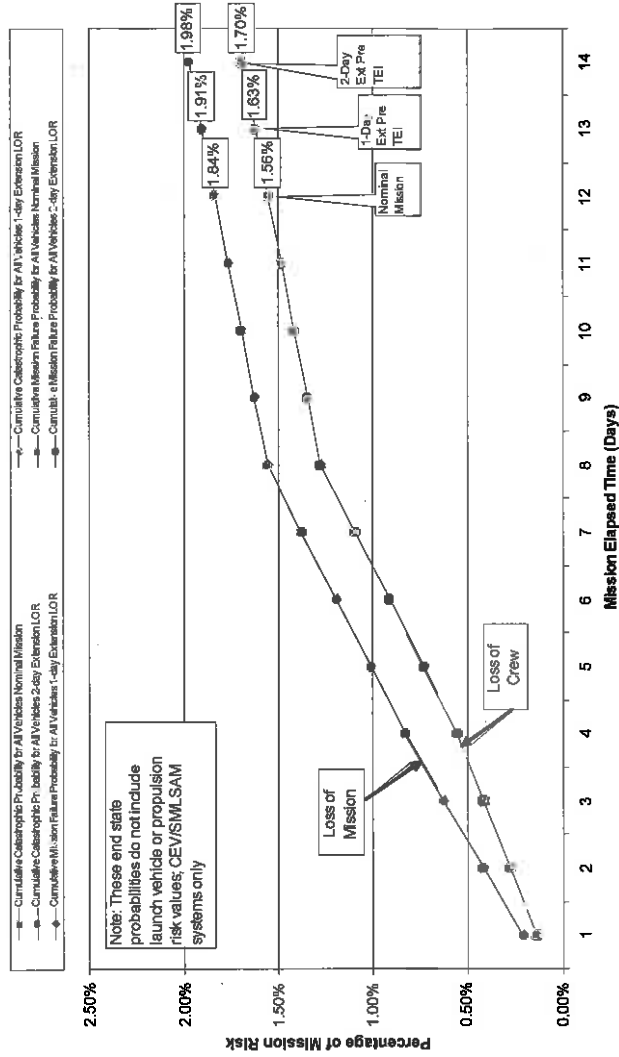


Figure 3 - Post ascent loiter in lunar orbit



The lunar surface stay time will affect the total mission risk in terms of how long the LSAM and the CEV/SM remain in standby for the return trip. The LSAM is launched prior to the CEV/SM and loiters until the CEV/SM arrives and docks. Given an initial checkout prior to Trans-lunar Injection (TLI), the LSAM will likely be powered down to a quiescent or semi-dormant state. For a typical sortie mission, the pressurized LSAM will become active just prior to undocking from the CEV/SM, which will in turn become quiescent as the crew leaves to burn to the surface.

For expediency and urgency (to complete a top-level model), the system probability of failure inputs were assumed as a λ failure rate with the system probabilities as simply a summation of the probability of failure per hour for all systems involved in the mission (see the list of system probability values in the CEV/SM and LSAM system probability of failure per hour sections). Since the probability values are relatively low, the λ gives an adequate approximation.



Appendix 4B (Part 2) – LOI-Lunar Orbit Loiter Trade

Lunar Mission Design Data TLI, LOI Delta-V Loiter Delta-V Cost

Supporting Analysis Requests For
The Exploration Systems Architecture Study (60-Day Study)

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Glossary

BTS	Broad Trade Study - conducted parallel to LDRM-2 by LaRC and GRC
CEV	crew exploration vehicle
COPERNICUS	multi-spacecraft, multi-gravity, multi-propellant system mission and trajectory design and optimization system (Cesar Ocampo's Program Employing Revolutionary and New Ideas In Common and Uncommon Sense)
EM	Earth-Moon
EDS	Earth departure stage
EOD	Earth orbit departure
FLO	First Lunar Outpost project (1992-1993)
IMLEO	Initial mass in low Earth orbit
L1	Earth-Moon cis-lunar libration point
LAN	Longitude of the ascending node
LDRM-2	Lunar Design Reference Mission 2 conducted 2004-2005
LEO	low Earth orbit
LLO	low lunar orbit
LOA	lunar orbit arrival (same as LOI)
LOD	lunar orbit departure (same as TEI)
LOI	lunar orbit insertion
LOR	lunar orbit rendezvous - mission mode
LPR	libration point rendezvous - mission mode
LS	landing site
LSAM	lunar surface access module
ME	Moon-Earth
S/C	spacecraft (could refer to CEV/LSAM combination or individual, depending on context)
TEI	trans-Earth injection
TLI	trans-Lunar injection



Introduction

- A specific data request was made for a global map (latitude and longitude-based) of TLI and LOI data for an outbound-only mission
- Data and contour plots were generated for a nominal outbound mission, for a 3-impulse LOI arrival at the Moon
- Data for variations to the nominal mission were also generated
 - Extended loiter in low lunar orbit after LOI, but prior to lunar landing
 - Variations in LOI epochs
 - At time of lunar maximum inclination
 - At time of lunar minimum inclination



Assumptions: Lunar Mission Performance

- Outbound mission only - TLI to LOI
- 3-Impulse LOI
- 4-day nominal TLI to LOI (1st maneuver of 3-impulse sequence)
- 1 day nominal loiter before LSAM landing for checkout
- Earth departure conditions
 - LEO parking orbit altitude = 407 km circular
 - Inclination = 28.7°
 - Earth departure RAN is free and can be adjusted to minimize DV cost
- TLI DV limit of 3150 m/s imposed
- Lunar orbit arrival conditions
 - Inclination and LAN specified for each landing site latitude and longitude
 - Based on minimum departure wedge angle requirement
- Results
 - Global map of TLI and LOI DV vs lunar latitude and longitude in 10° increments



Methodology

- EOLO modified
 - Selects Earth departure RAN for minimum DV
 - Limits TLI DV (to specified 3150 m/s value)
 - Batch processor
 - Speed improvements
 - Apopase maneuver of 3-impulse LOI sequence employs a “fail-safe” burn which prevents periapse of orbit from being reduced below 100 km (a crew safety consideration)

* Developed by Sam W. Wilson (retired, consulting with JSC/EG)
+ HYP1IMP used to generate LOI and TEI 3-impulse sequences with no fail-safe plain change allowance



Results

Nominal Mission LOI ΔV

Nominal LOI Completion Epoch - December 25, 2034

Extended loiter used to reduce LOI ΔV

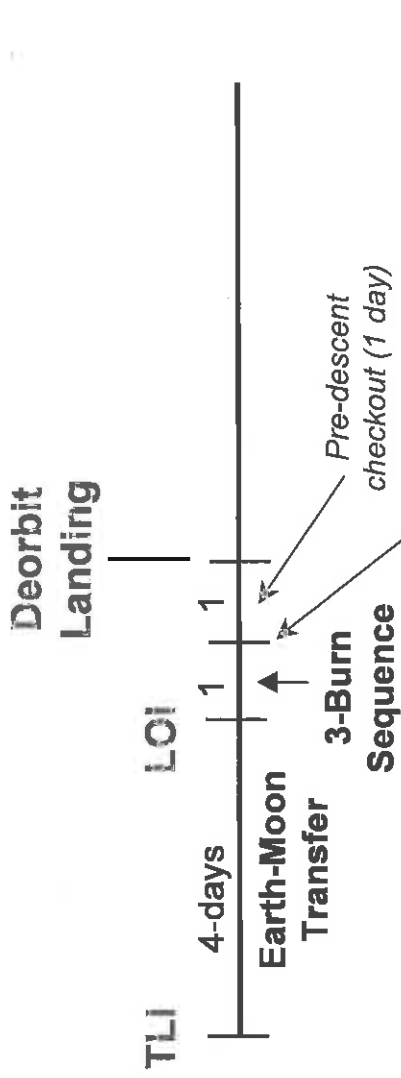
Nominal lunar loiter prior to landing – 1 day

TLI \leq 3150 m/s, LOI ΔV minimized

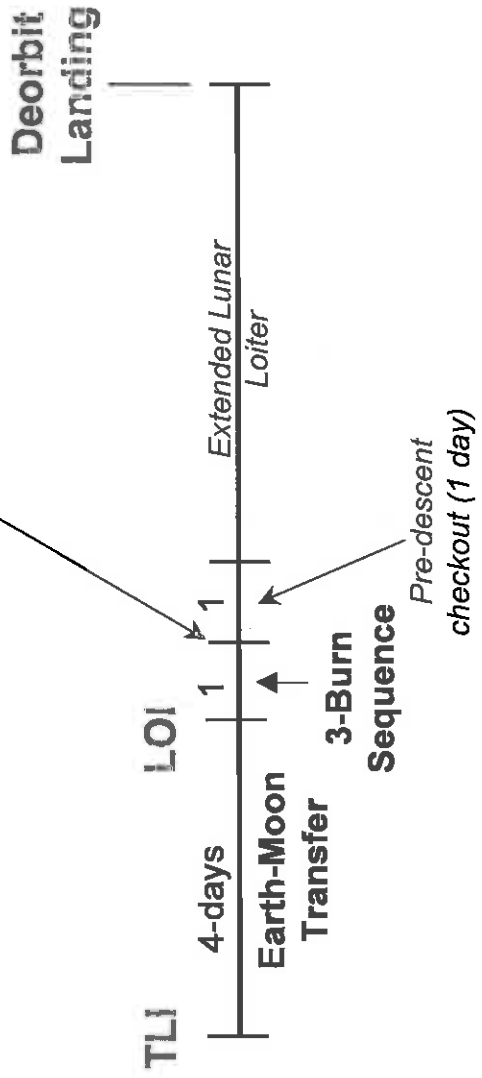


Mission Sequence

3-Burn Sequence Nominal

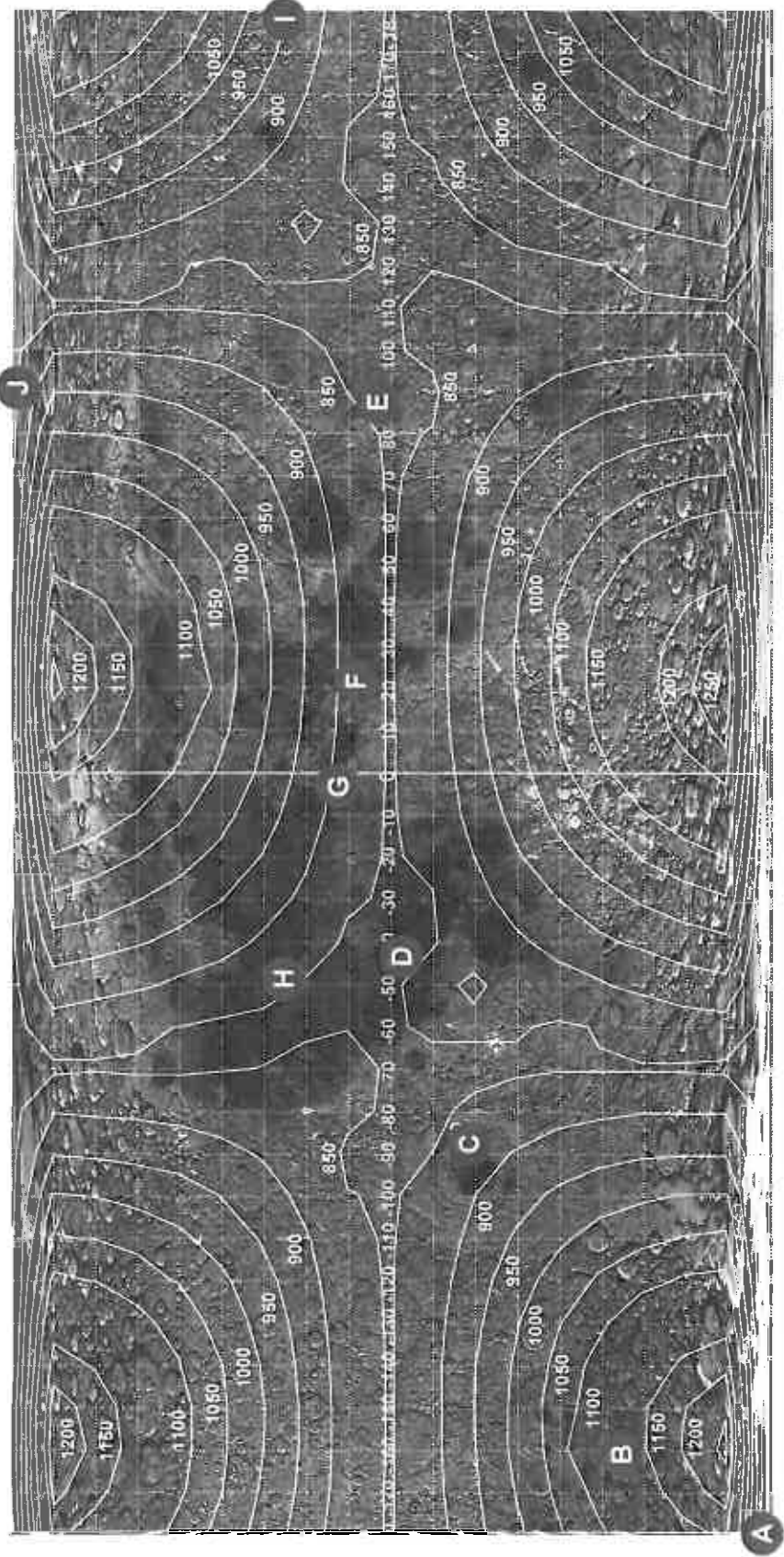


3-Burn Sequence Extended Lunar Loiter



Possible Lunar Landing Sites

Landing Site	Latitude	Longitude	Notes
A. South Pole	89.9 S	180 W	(LAC 144) rim of Shackleton
B. Far side SBA floor	54 S	162 W	(LAC 133) near Bose
C. Orientale basin floor	19 S	88 W	(LAC 91) near Kopff
D. Oceanus Procellarum	3 S	43 W	(LAC 75) inside Flamsteed P
E. Mare Smythii	2.5 N	86.5 E	(LAC 63) near Peek
F. W/NW Tranquilitatis	8 N	21 E	(LAC 60) north of Arago
G. Rima Bode	13 N	3.9 W	(LAC 59) near Bode vent system
H. Aristarchus plateau	26 N	49 W	(LAC 39) north of Cobra Head
I. Central far side highlands	26 N	178 E	(LAC 50) near near Dante
J. North Pole	89.5 N	91 E	(LAC 1) rim of Peary B





Results

Nominal Mission (with Extended Loiter) LOI ΔV Reduction with Extended Loiter in LLO

Nominal LOI Completion Epoch - December 25, 2034

Extended loiter used to reduce LOI ΔV

Nominal lunar loiter prior to landing – 1 day

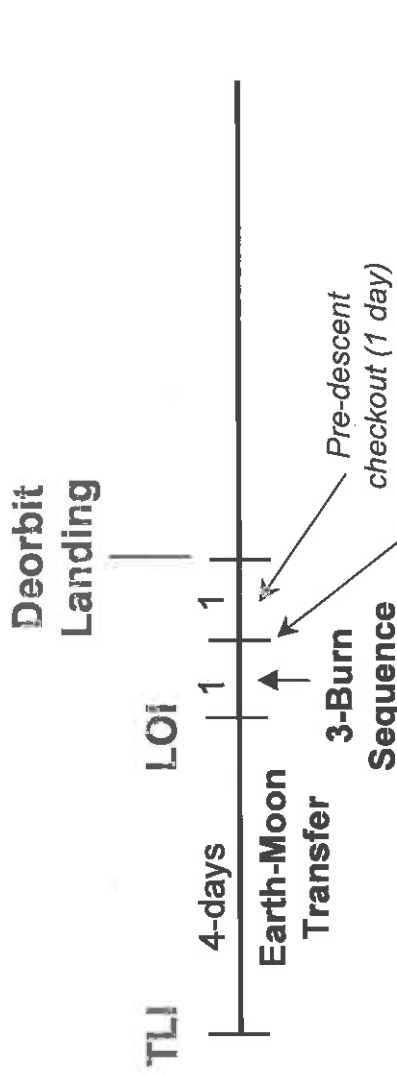
TLI \leq 3150 m/s, LOI ΔV minimized

Increment of extended lunar loiter = 12 hours



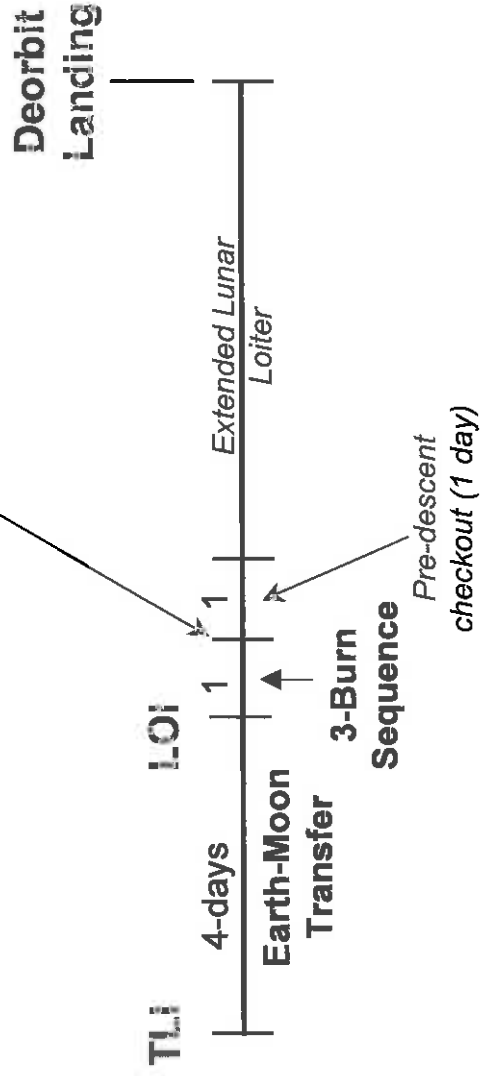
Mission Sequence

3-Burn Sequence Nominal



Arrival Epoch
12/25/34

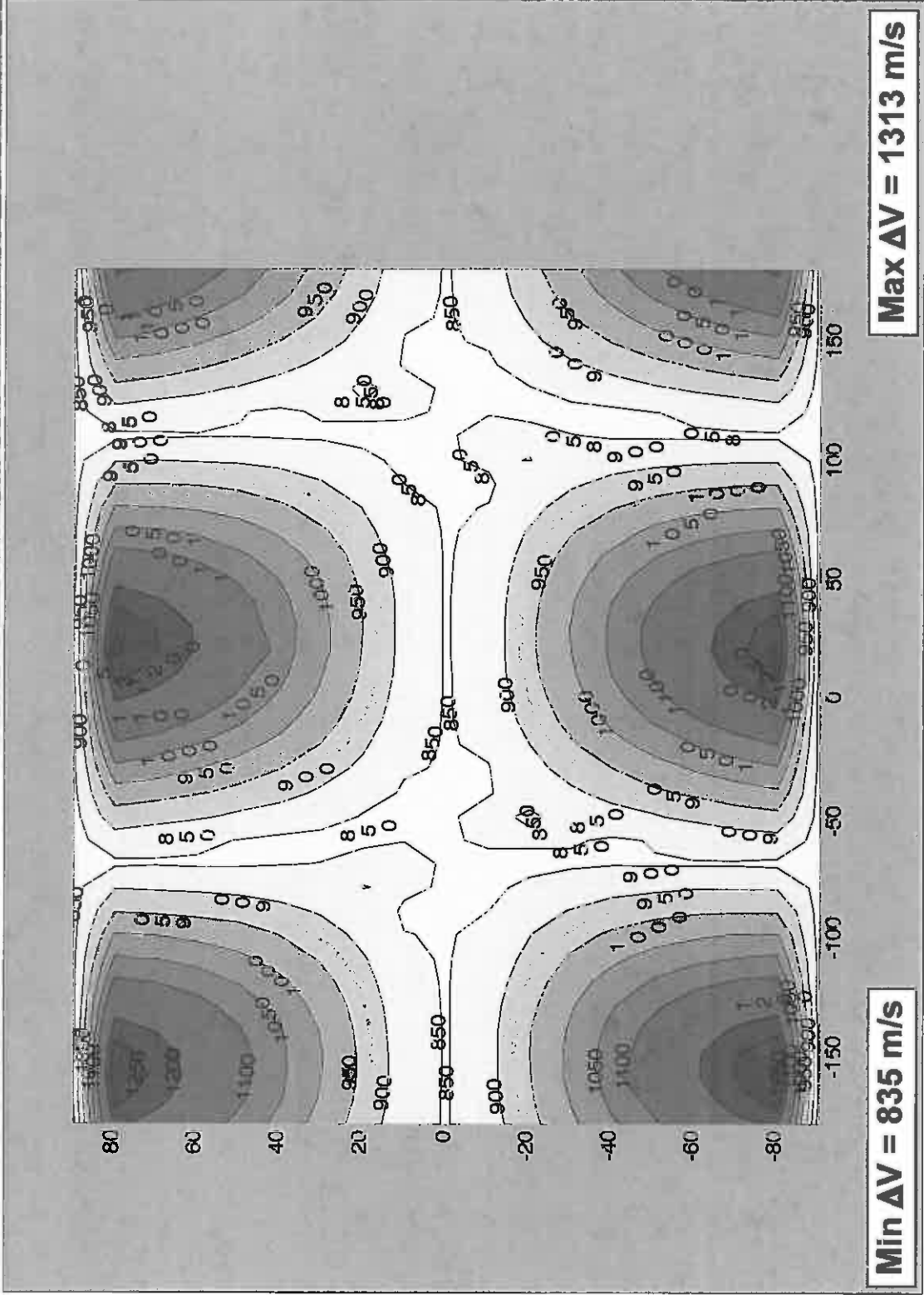
3-Burn Sequence Extended Lunar Loiter





Nominal Mission – LOI Delta-V

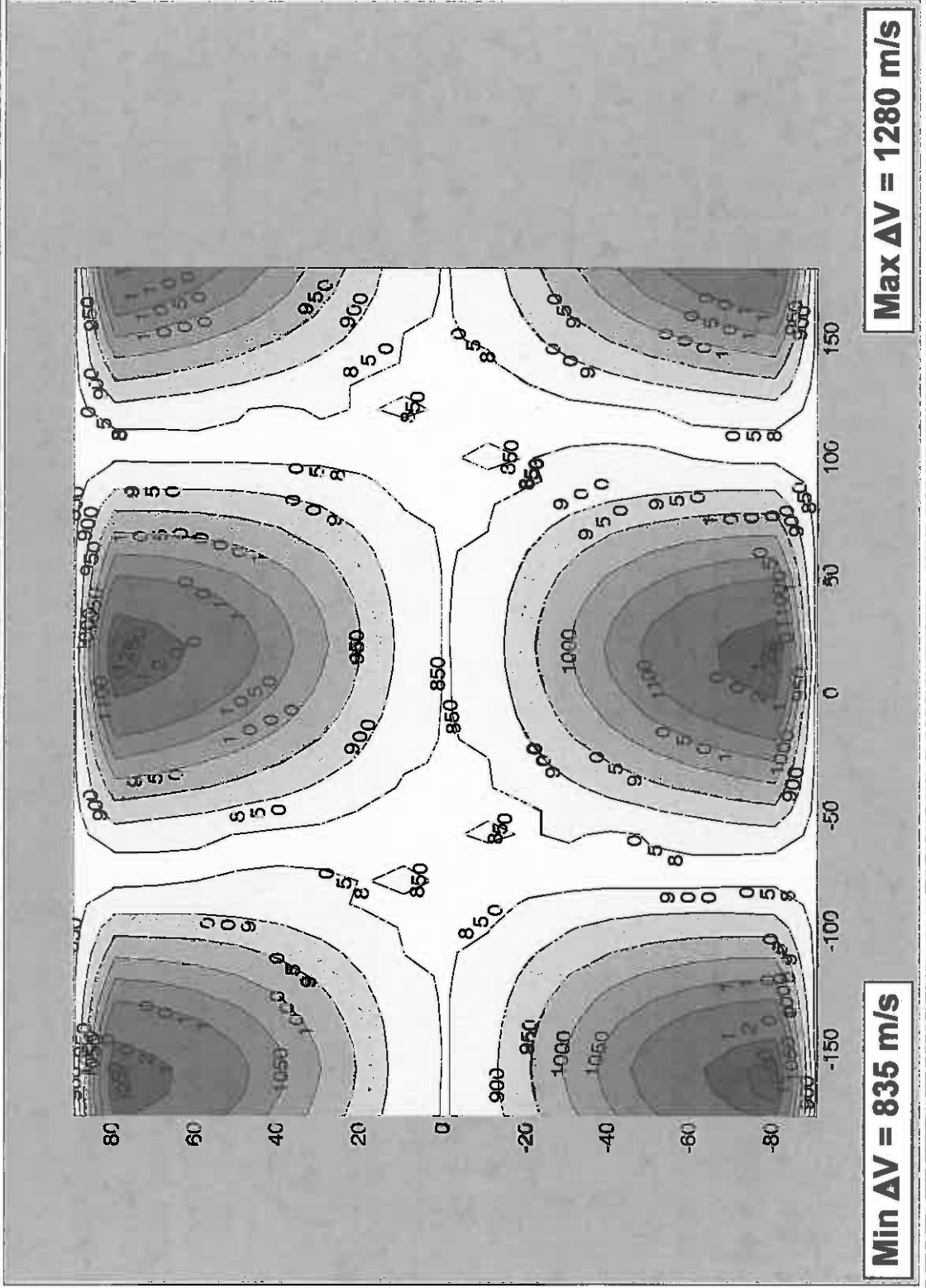
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-0 days





Nominal Mission – LOI Delta-V

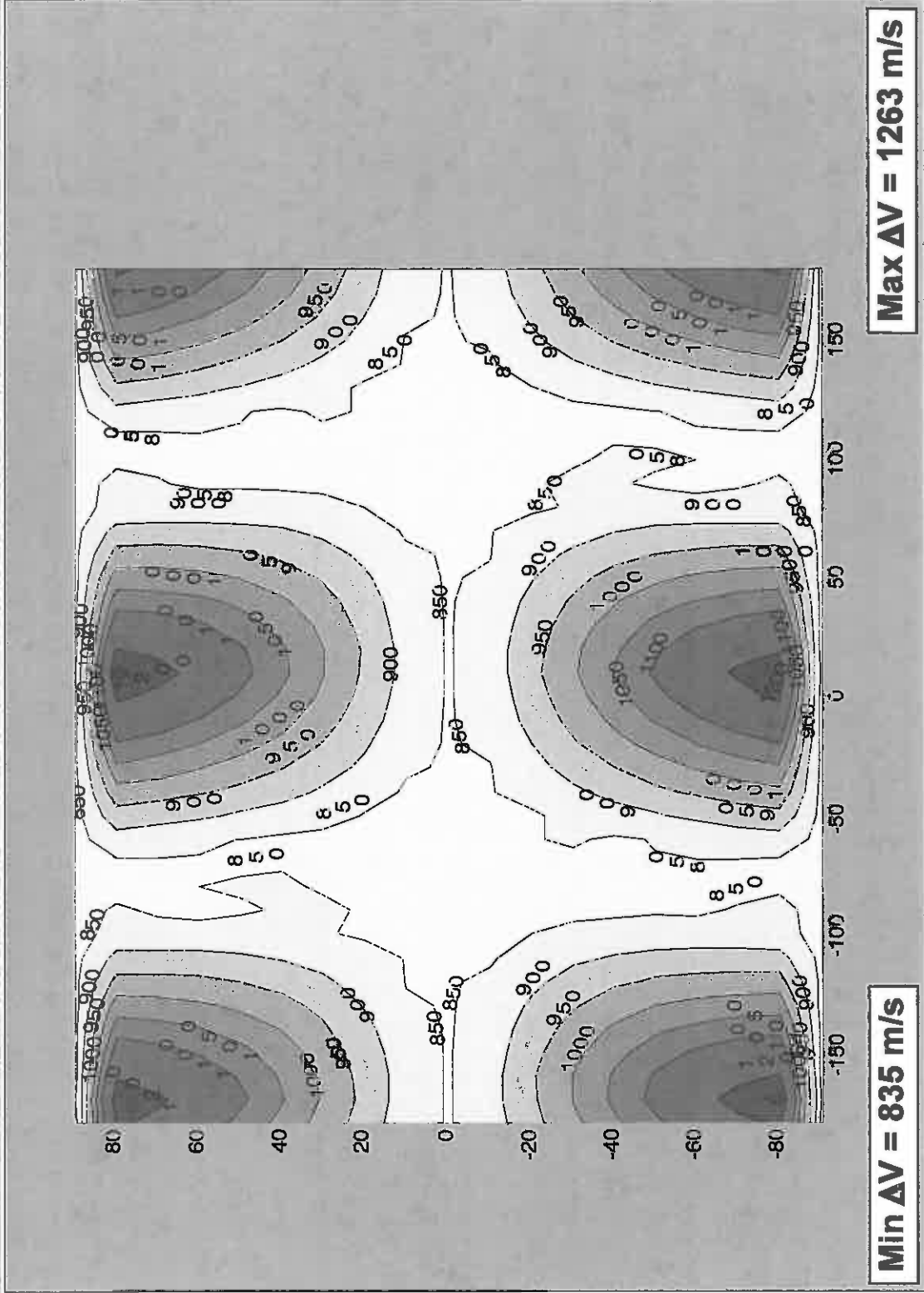
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-0.5 days





Nominal Mission – LOI Delta-V

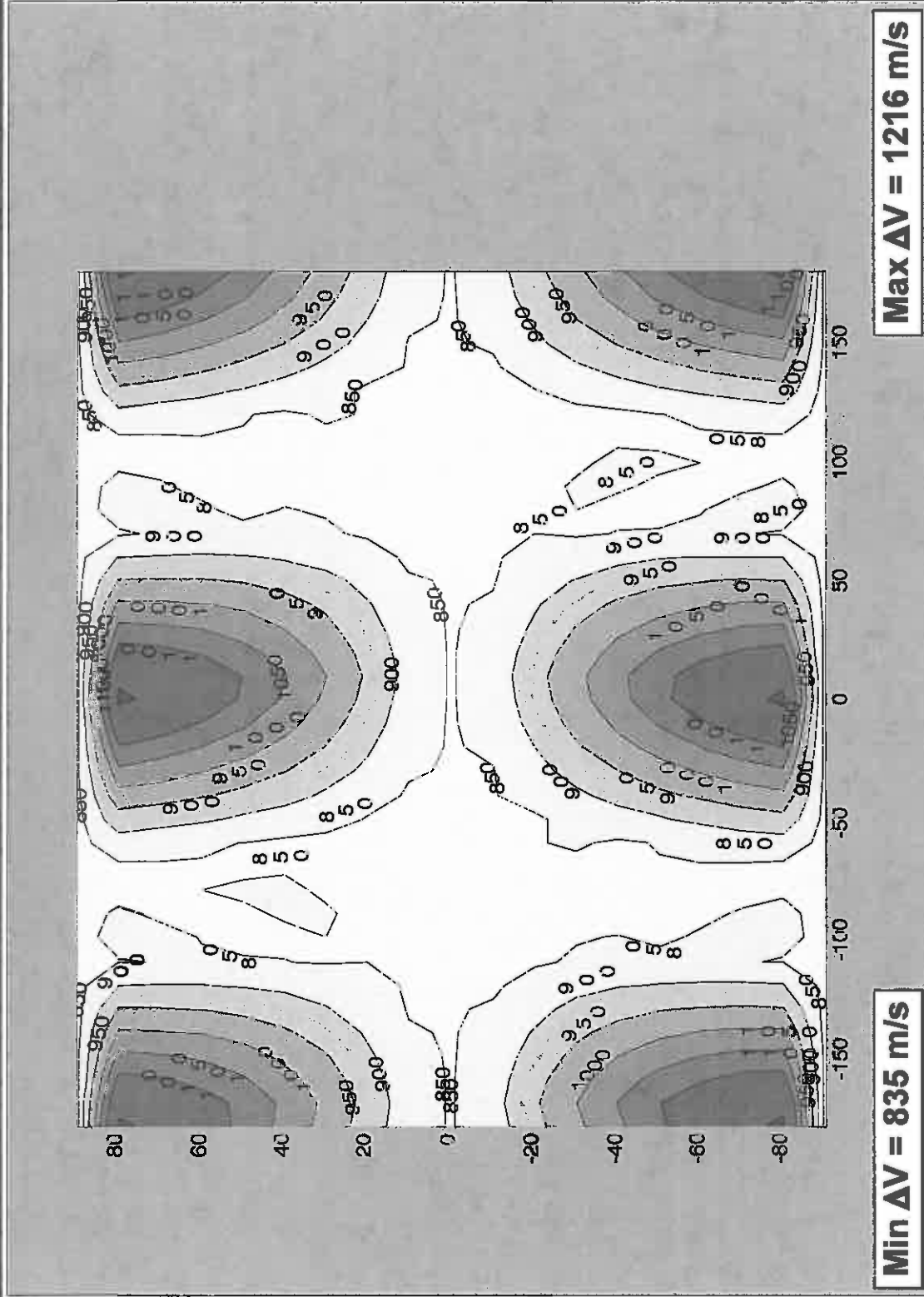
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-1.0 days





Nominal Mission - LOI Delta-V

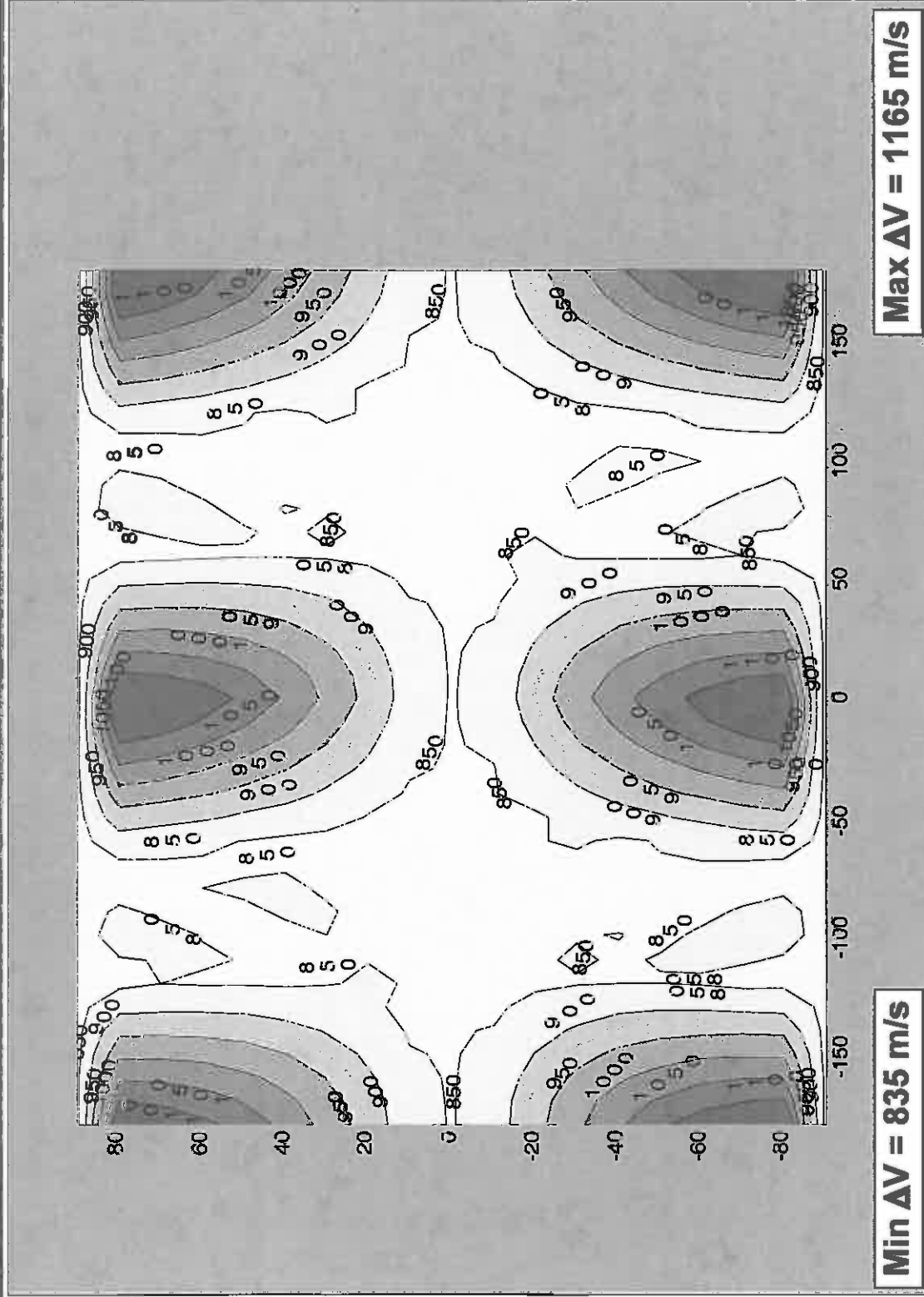
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-1.5 days





Nominal Mission – LOI Delta-V

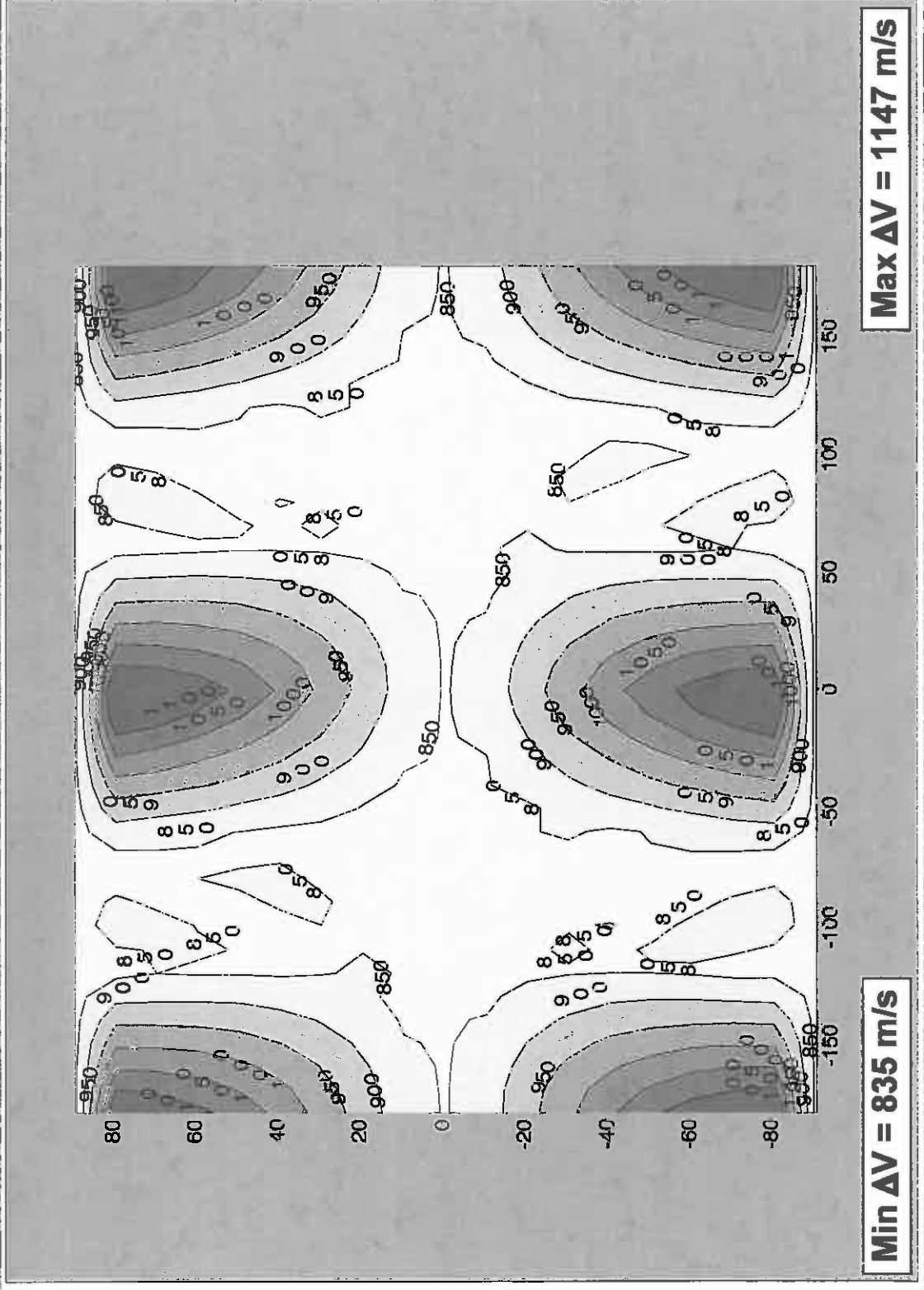
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-2.0 days





Nominal Mission - LOI Delta-V

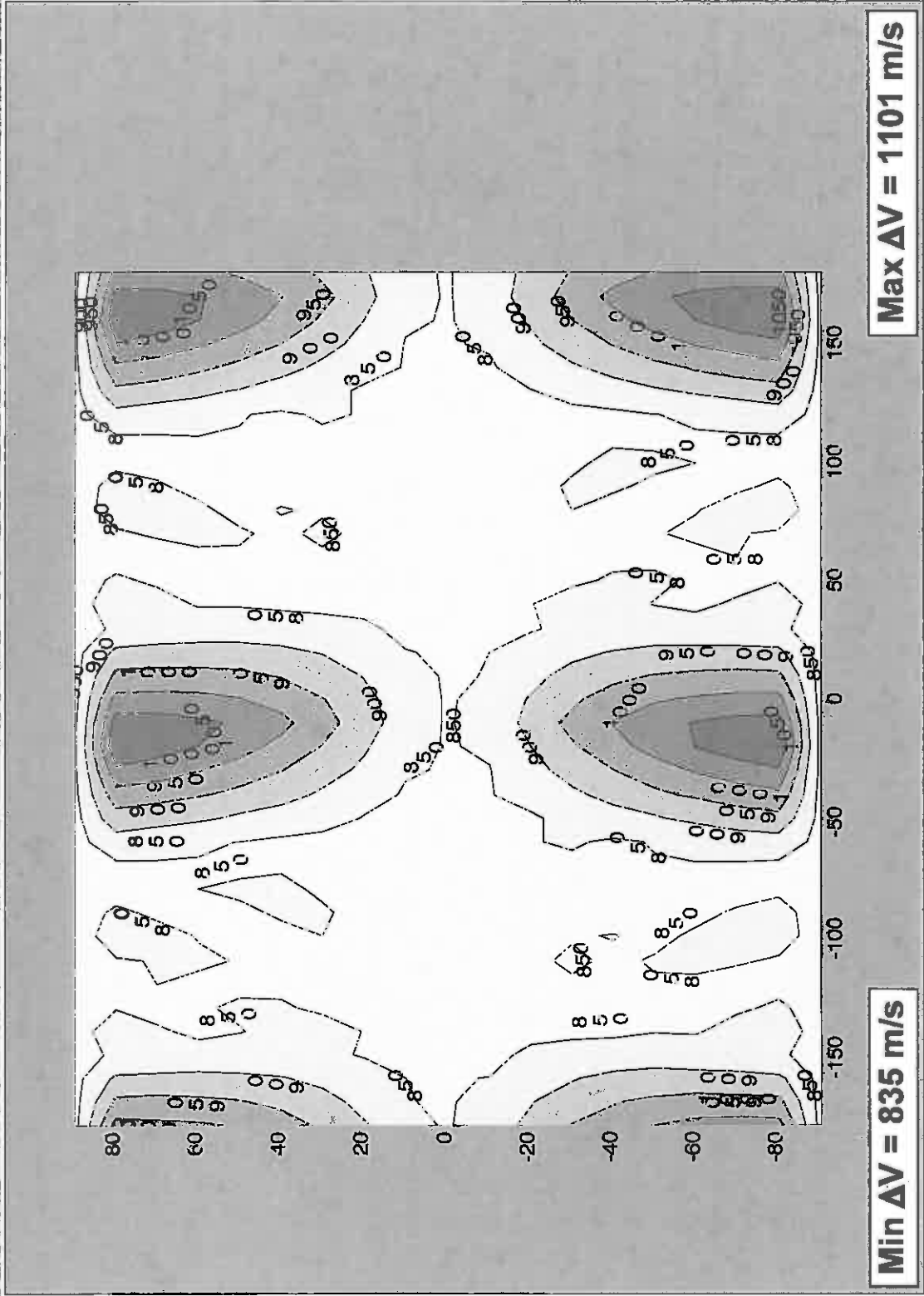
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-2.5 days





Nominal Mission - LOI Delta-V

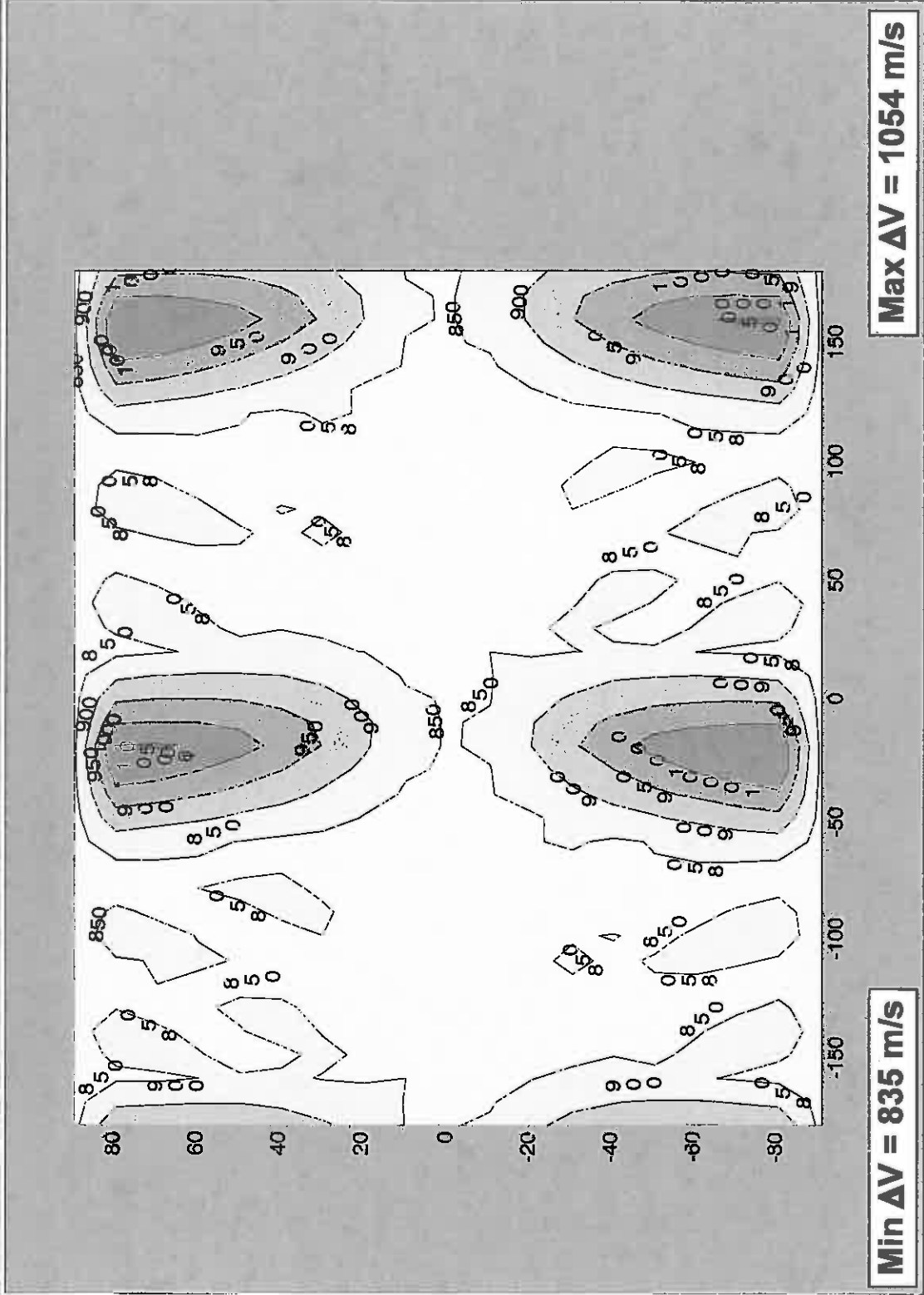
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-3.0 days





Nominal Mission – LOI Delta-V

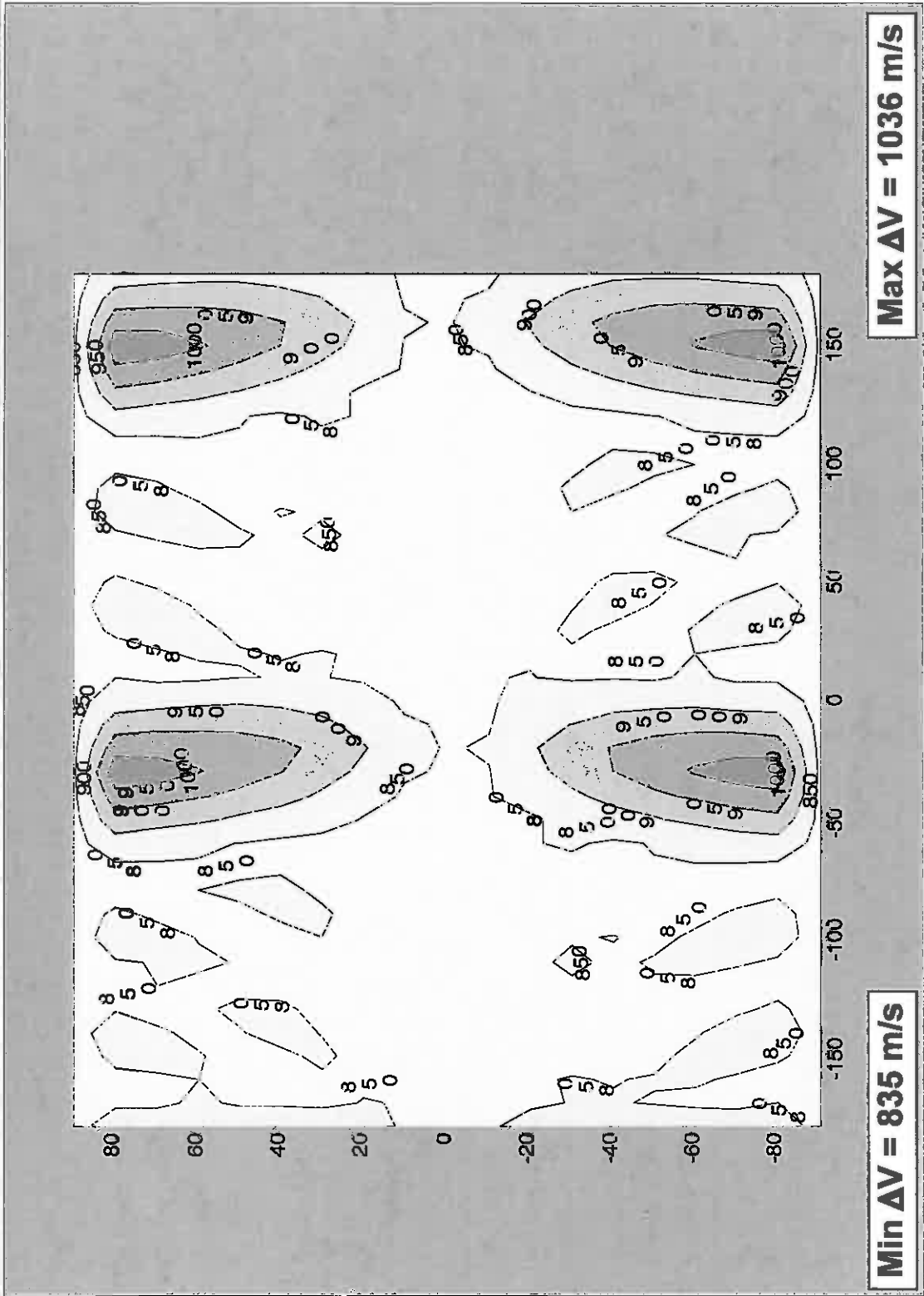
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-3.5 days





Nominal Mission - LOI Delta-V

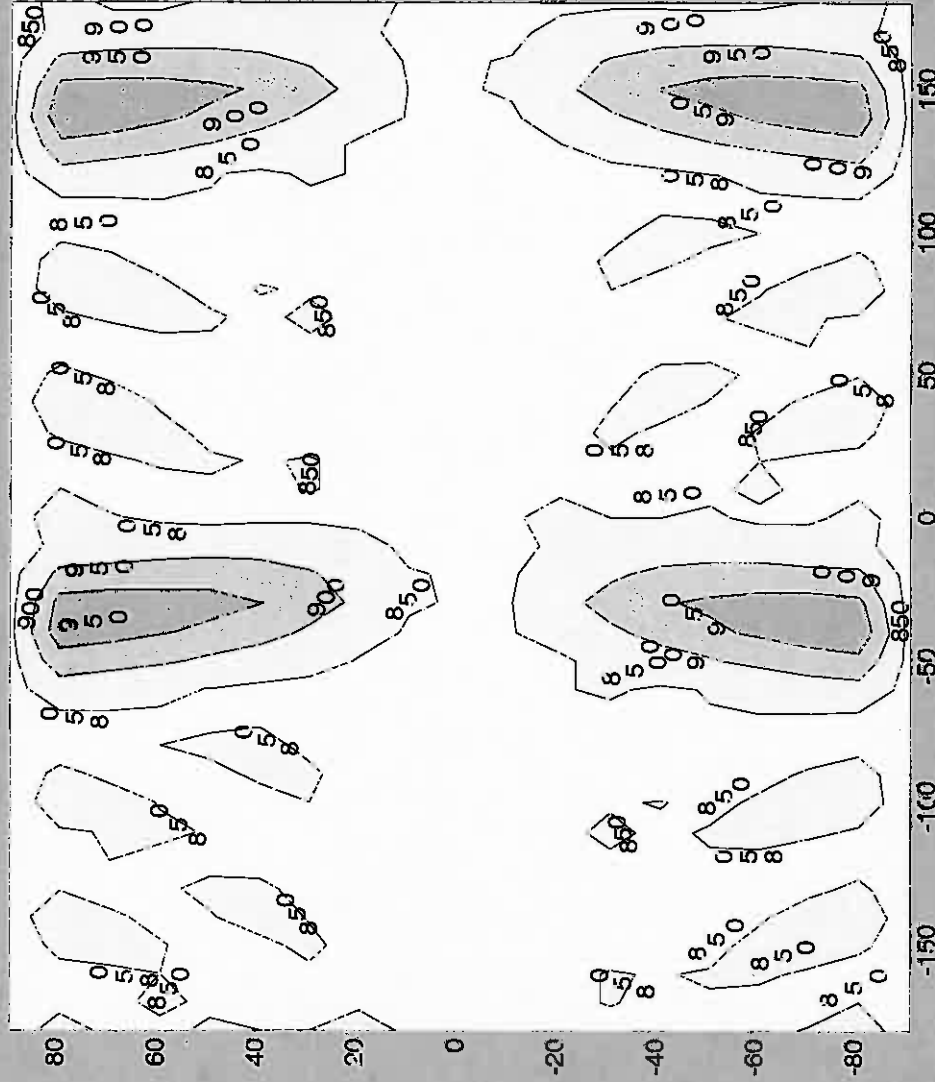
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-4.0 days





Nominal Mission - LOI Delta-V

Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-4.5 days



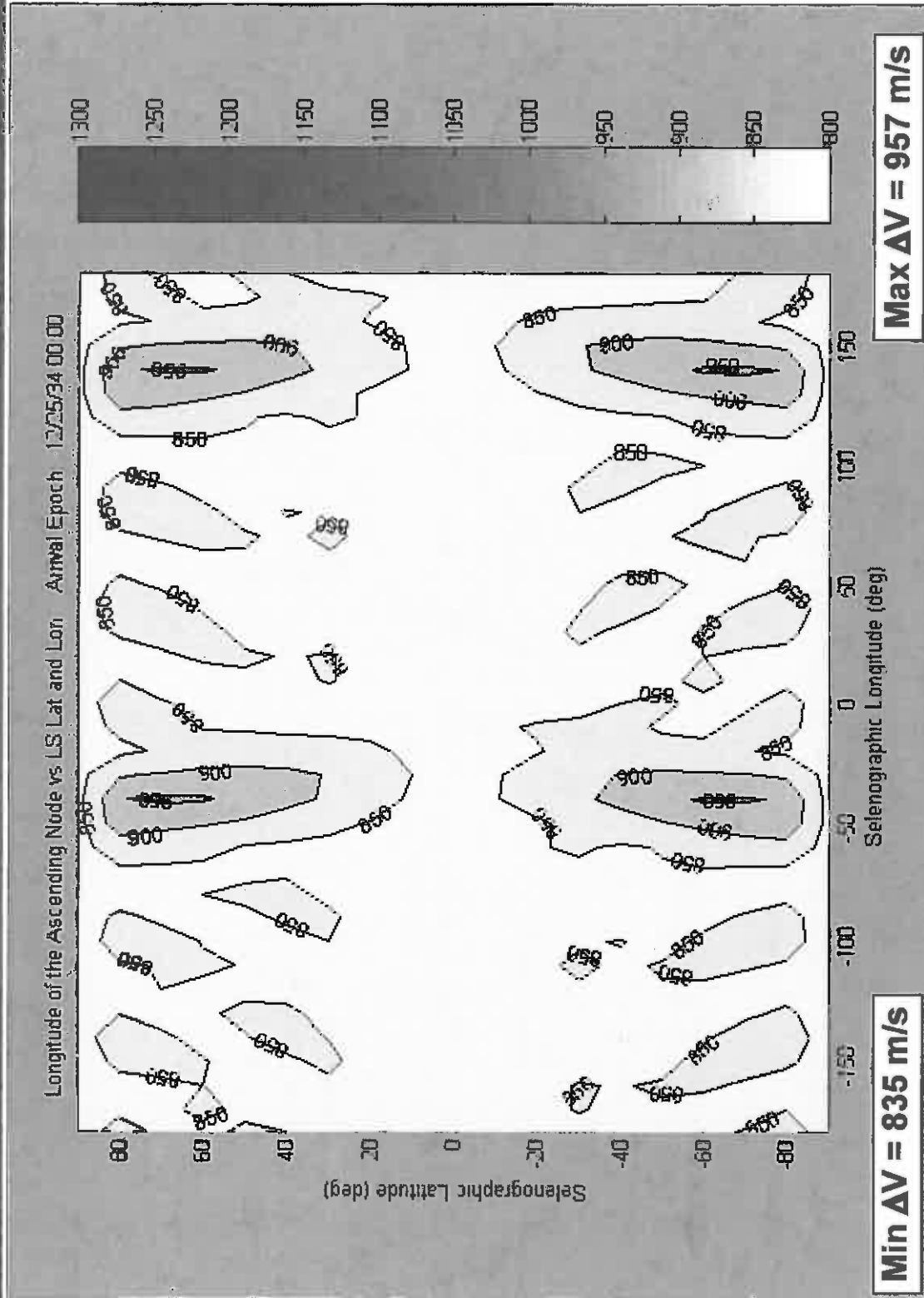
Min $\Delta V = 835$ m/s

Max $\Delta V = 990$ m/s



Nominal Mission - LOI Delta-V

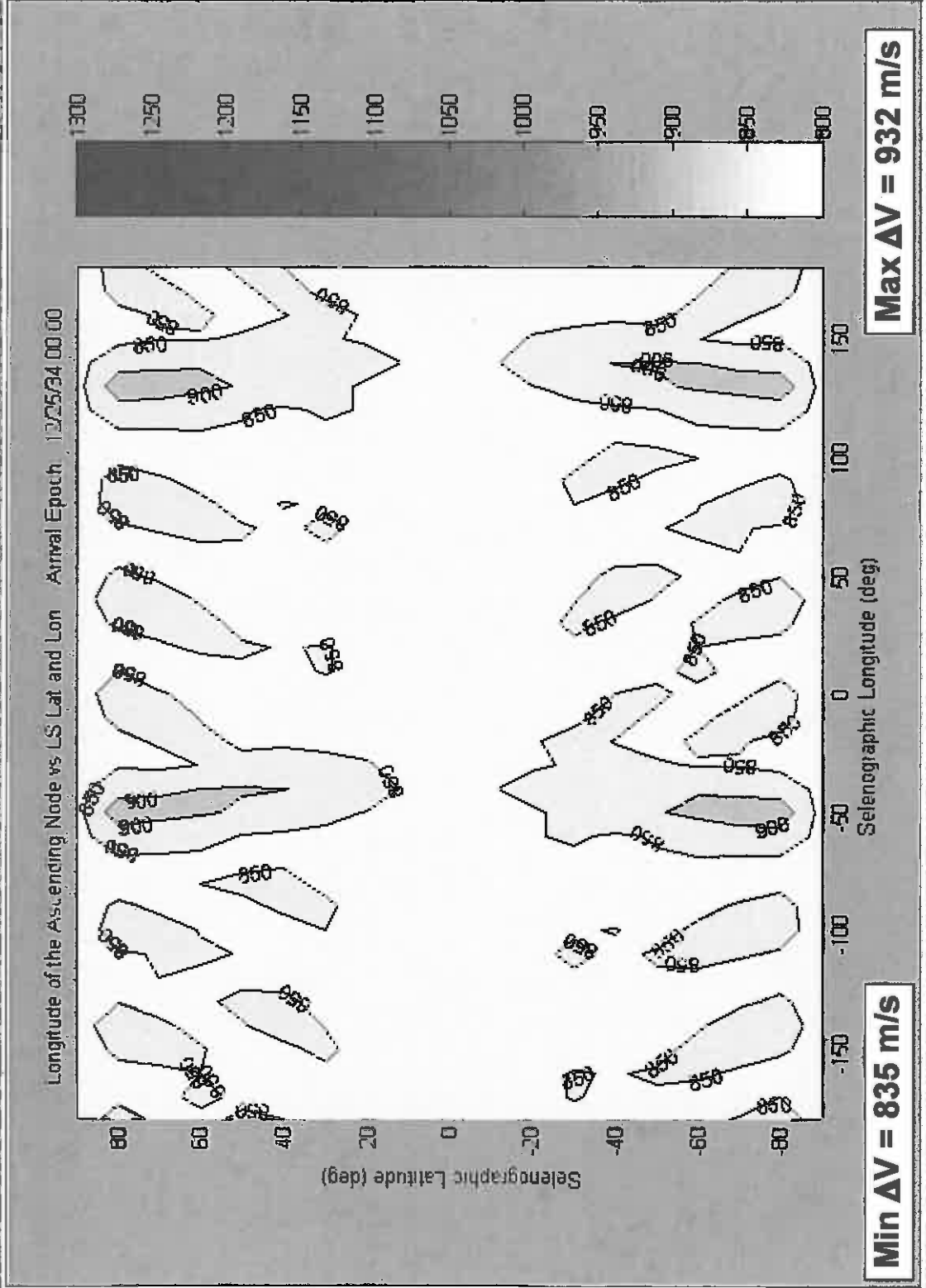
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-5.0 days





Nominal Mission - LOI Delta-V

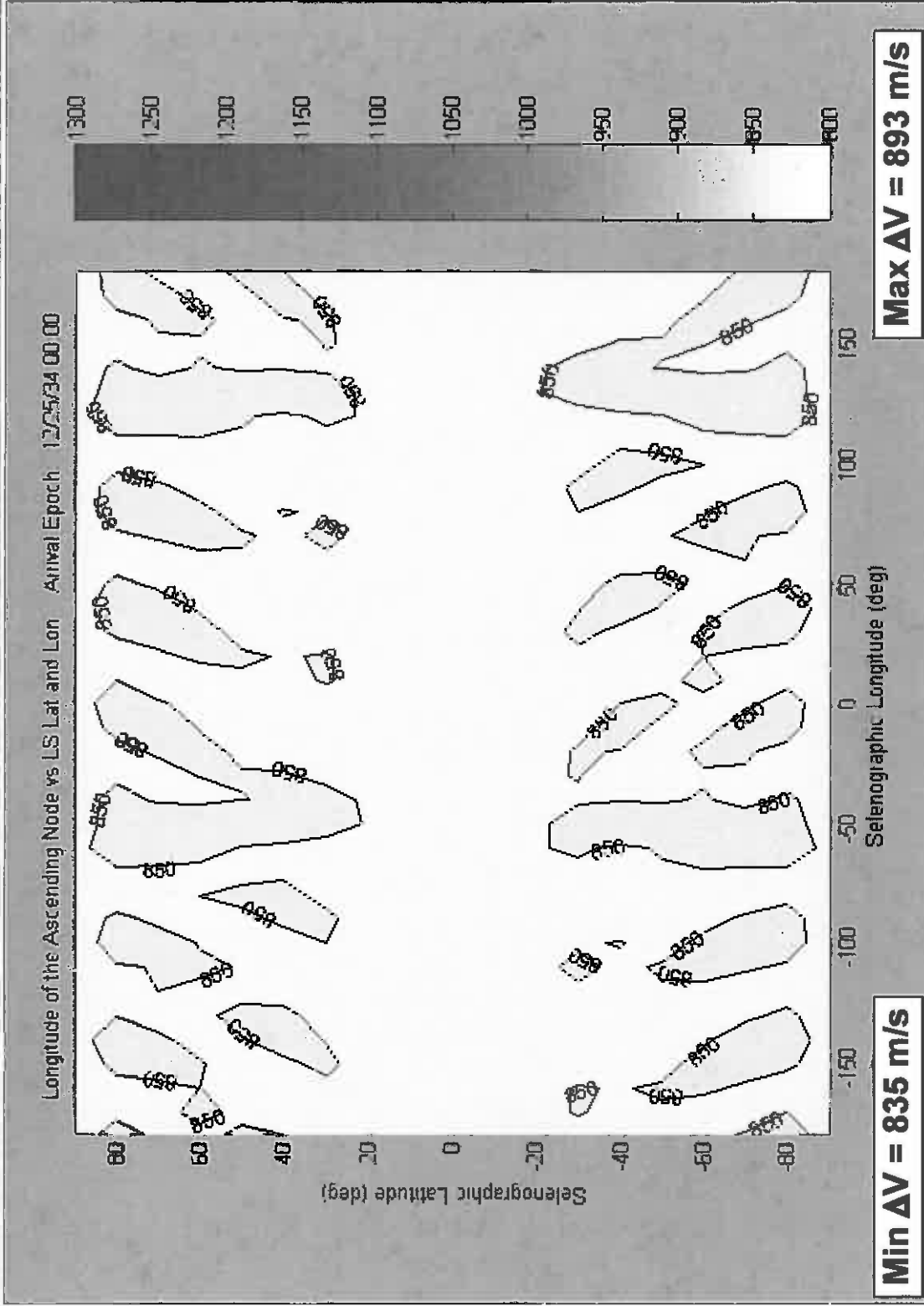
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-5.5 days





Nominal Mission – LOI Delta-V

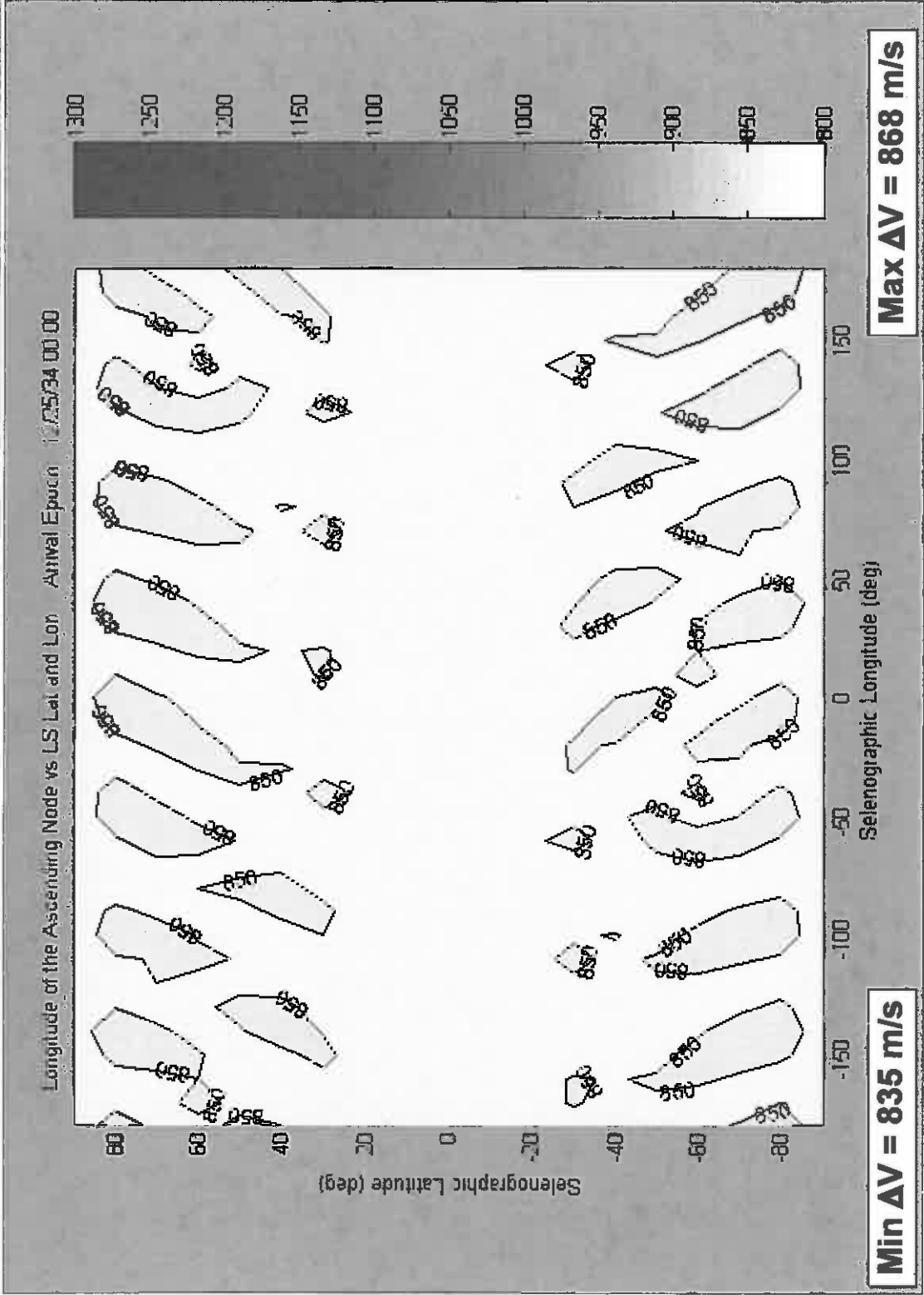
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-6.0 days





Nominal Mission - LOI Delta-V

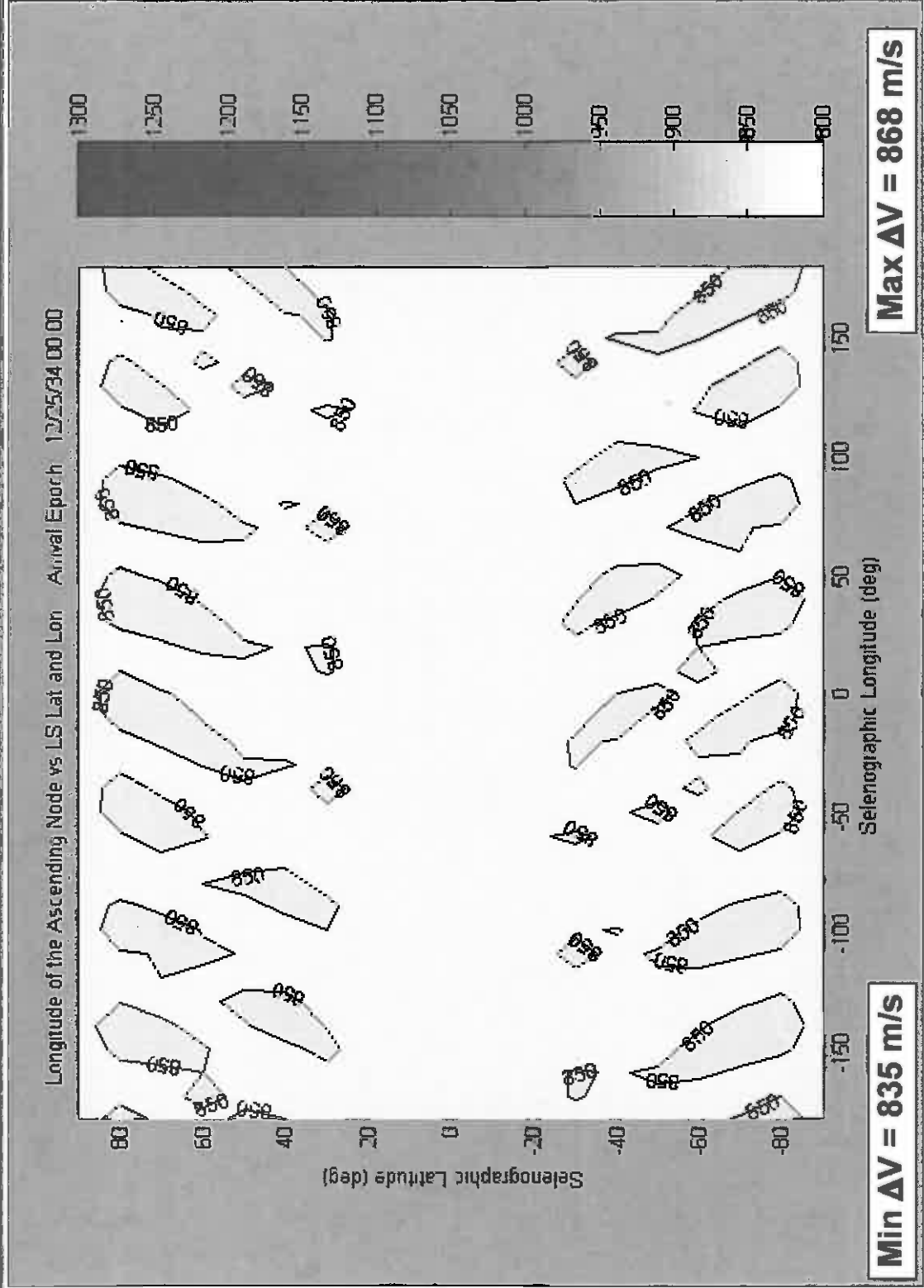
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-6.5 days





Nominal Mission - LOI Delta-V

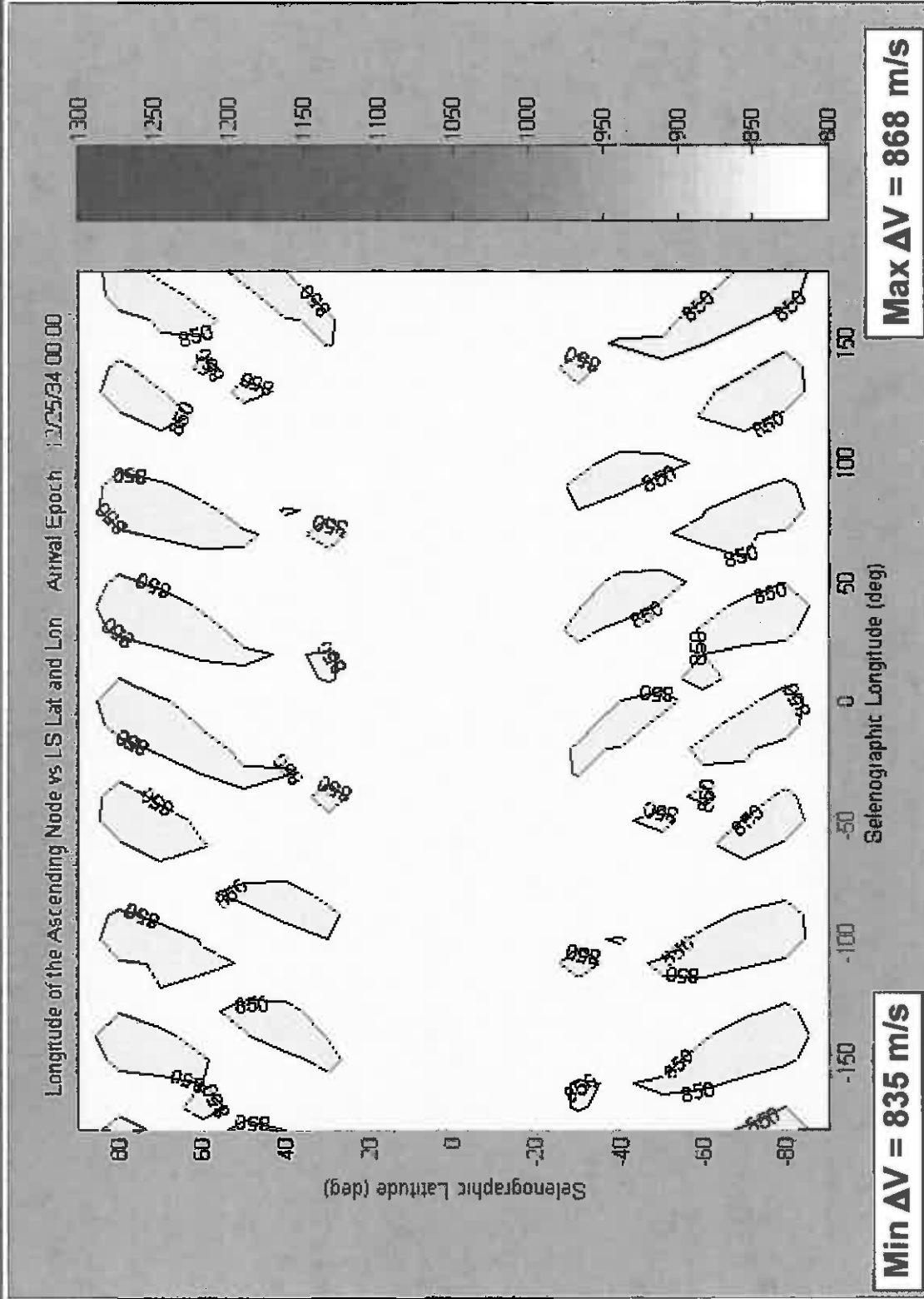
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-7.0 days





Nominal Mission - LOI Delta-V

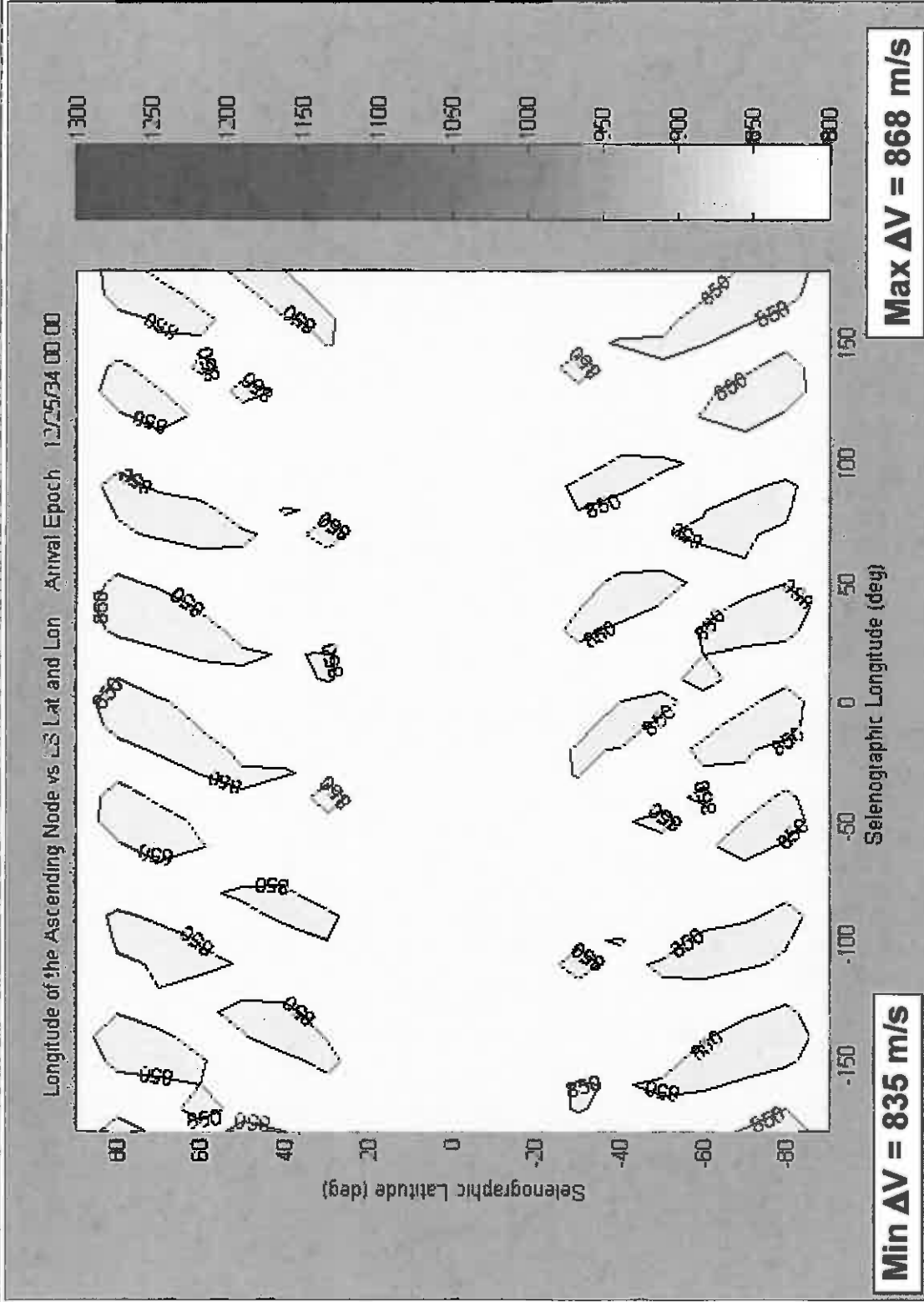
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-7.5 days





Nominal Mission – LOI Delta-V

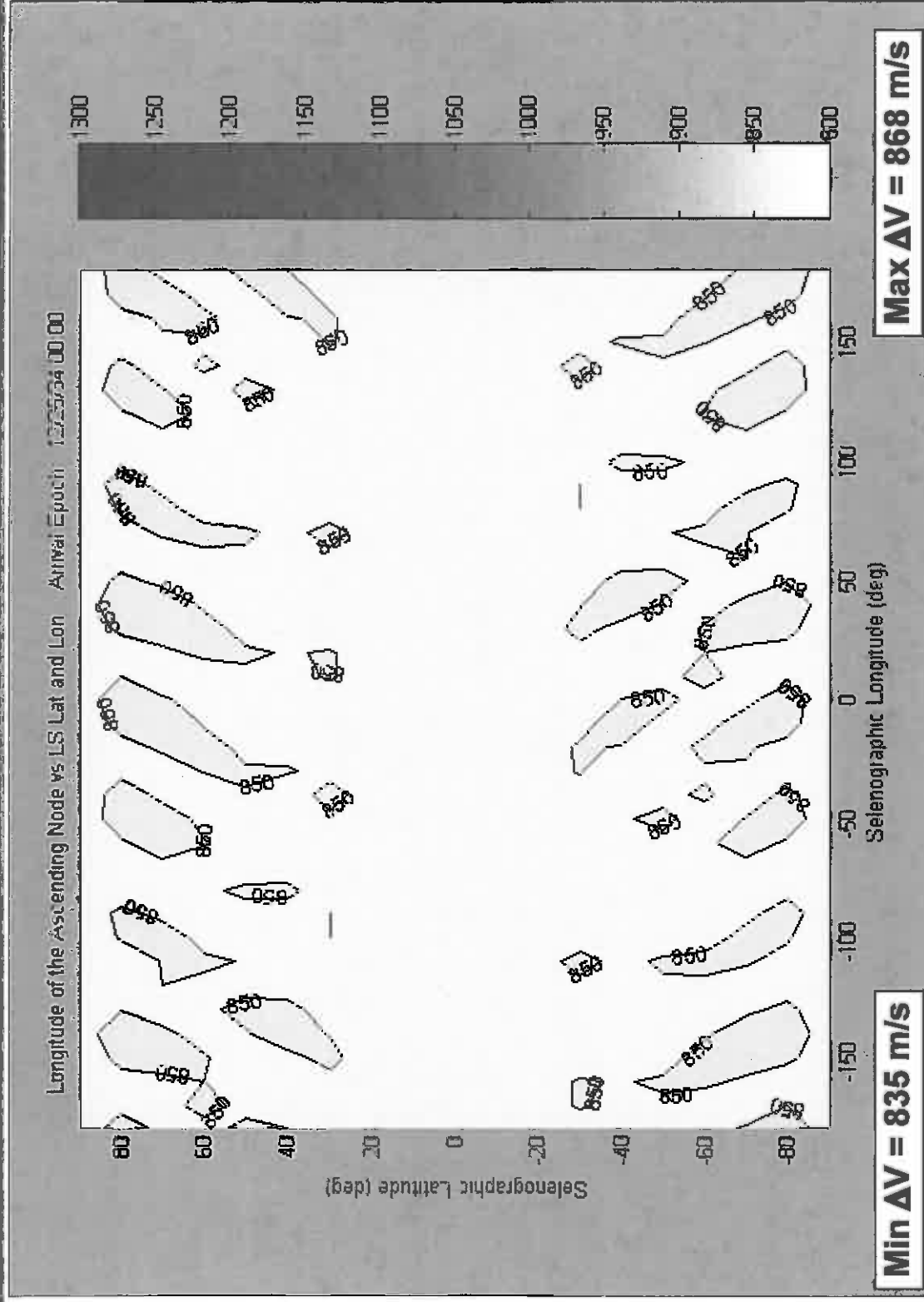
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-8.0 days





Nominal Mission – LOI Delta-V

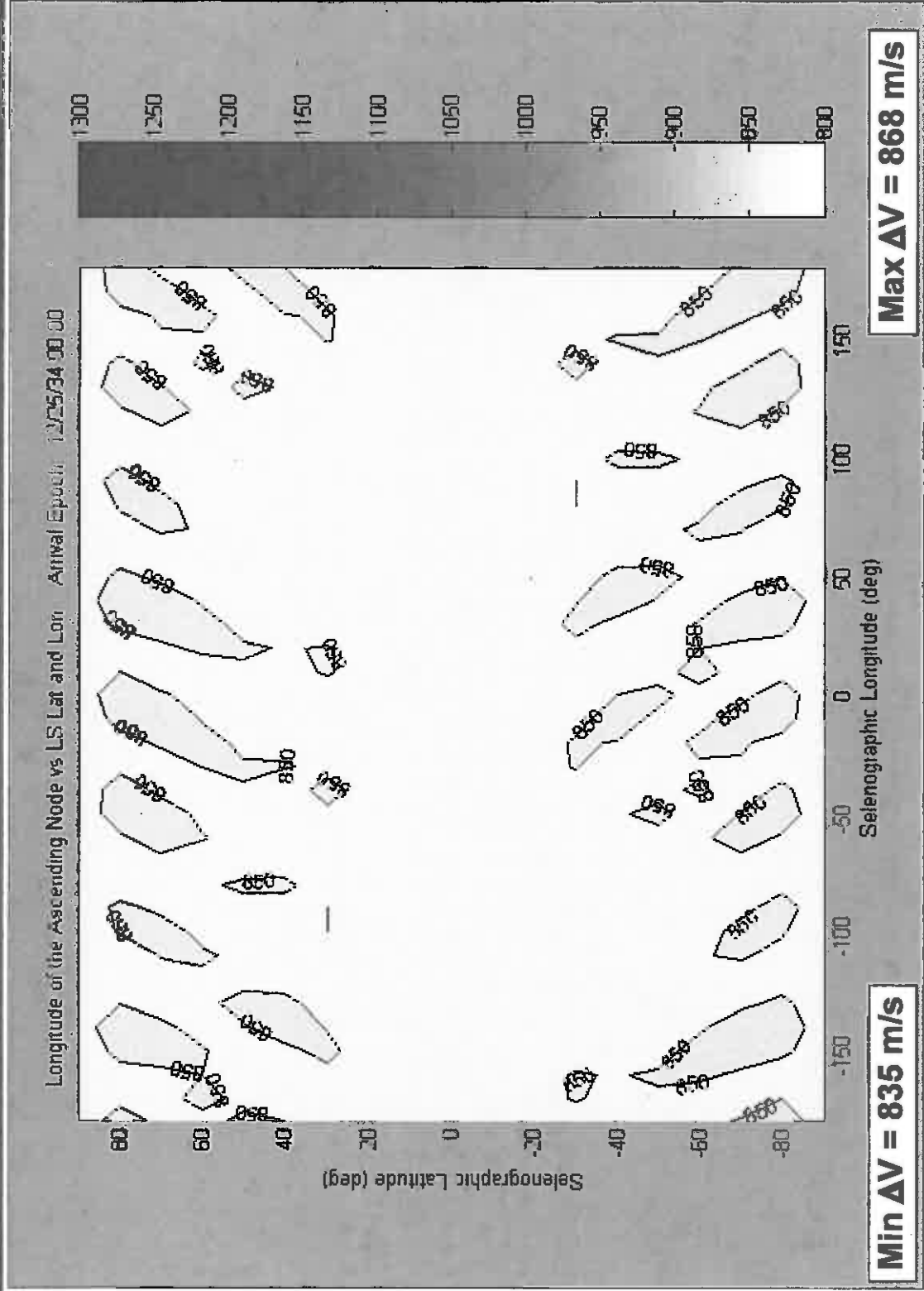
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-8.5 days





Nominal Mission – LOI Delta-V

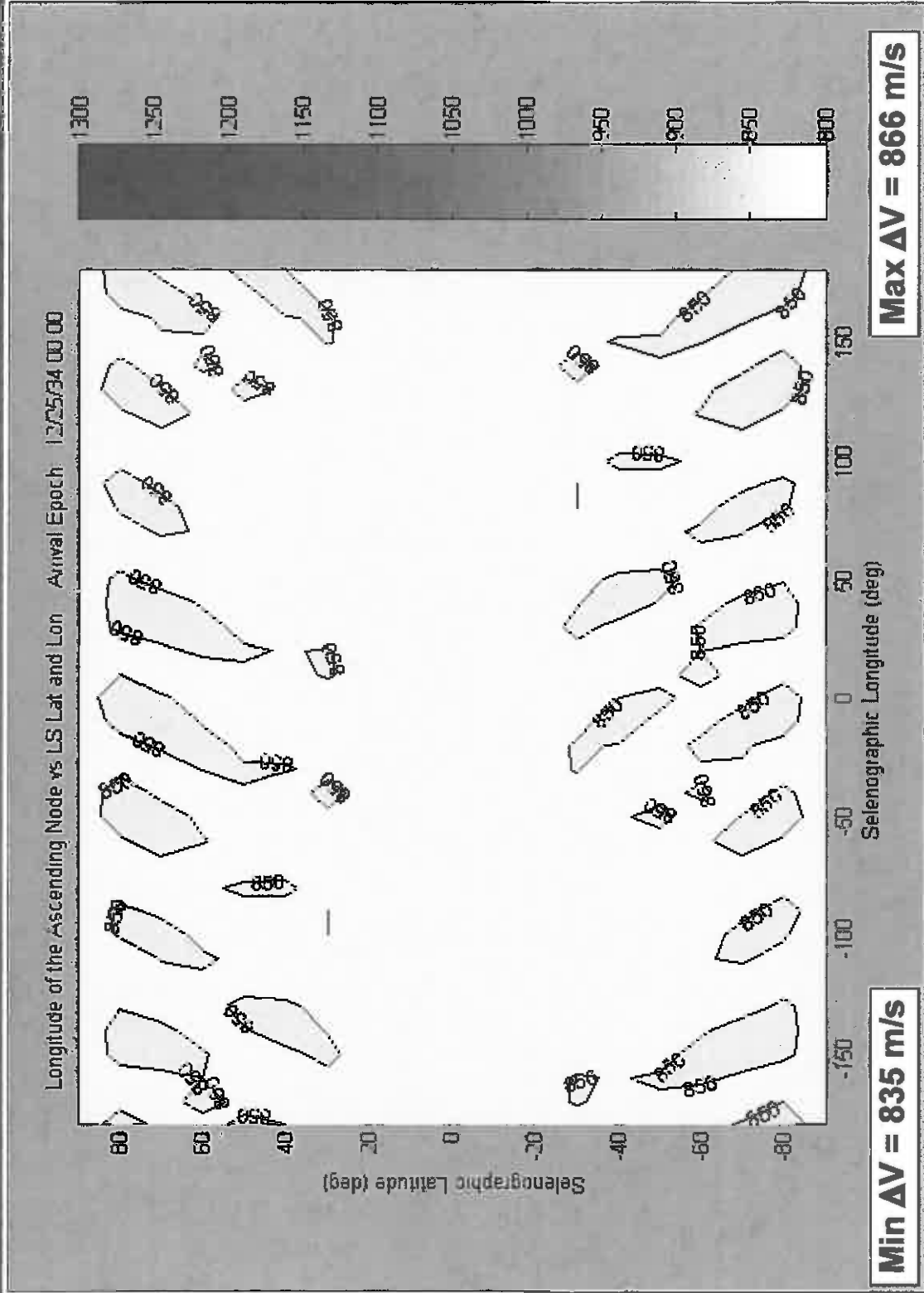
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-9.0 days





Nominal Mission - LOI Delta-V

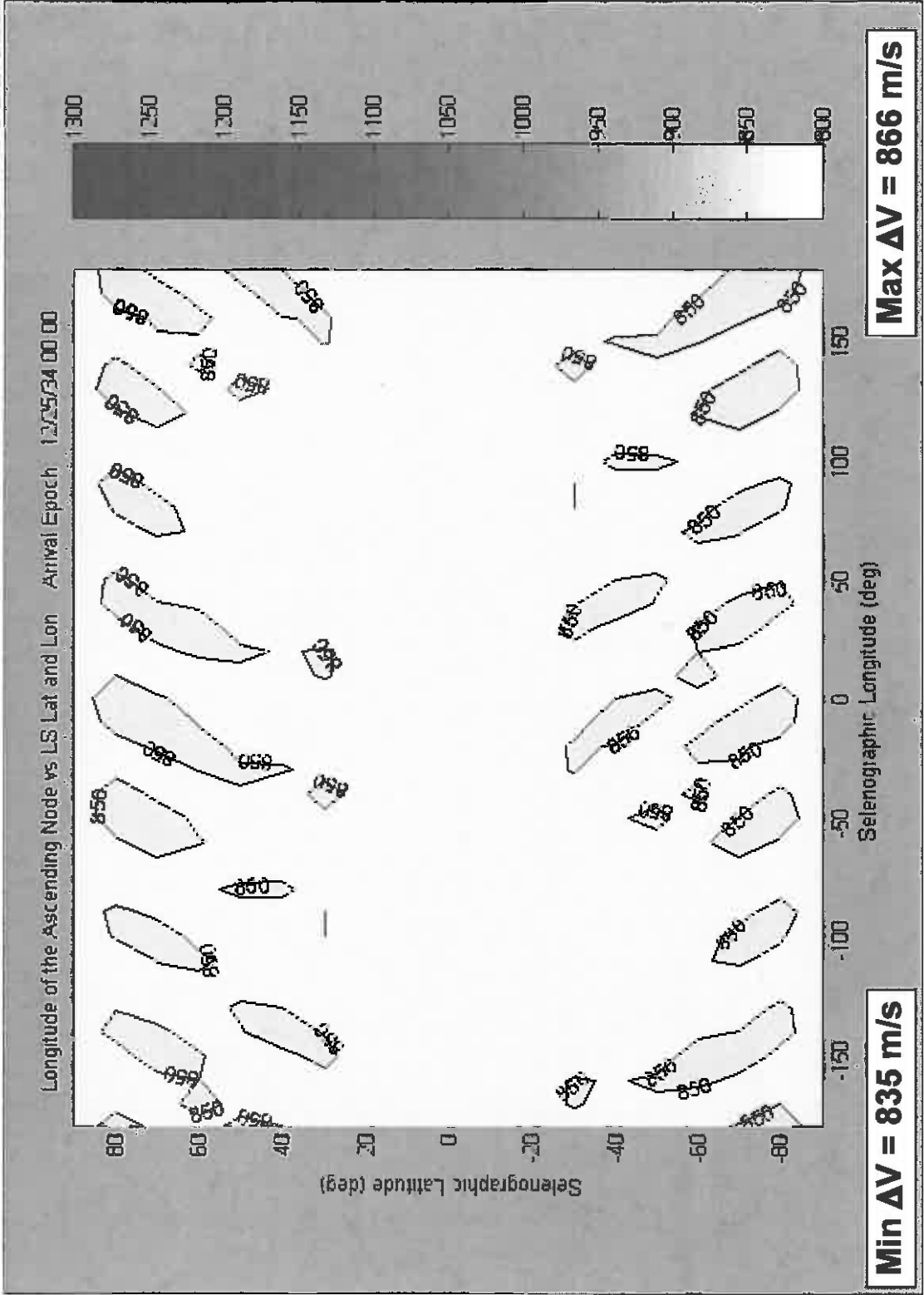
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-9.5 days





Nominal Mission - LOI Delta-V

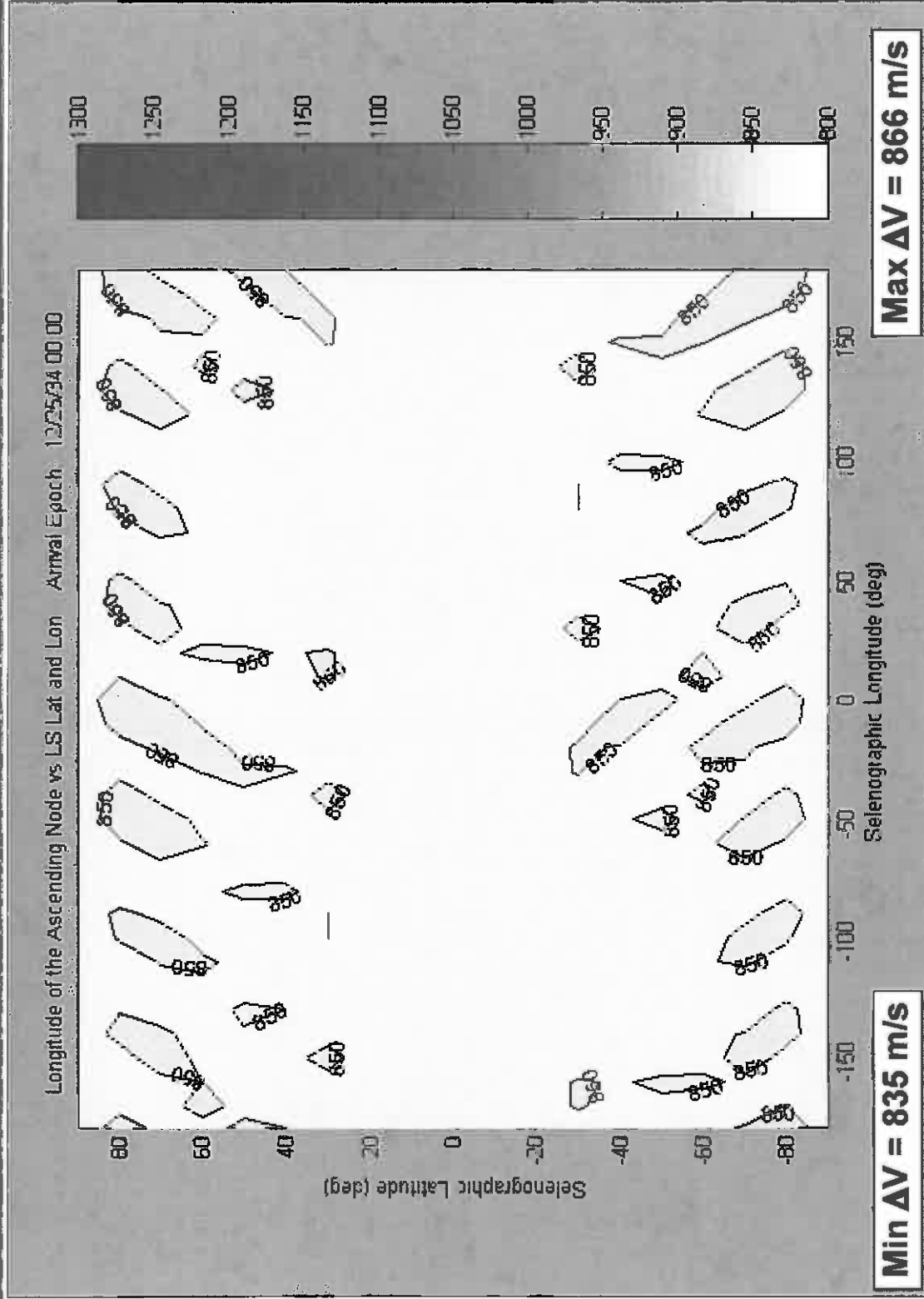
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-10.0 days





Nominal Mission - LOI Delta-V

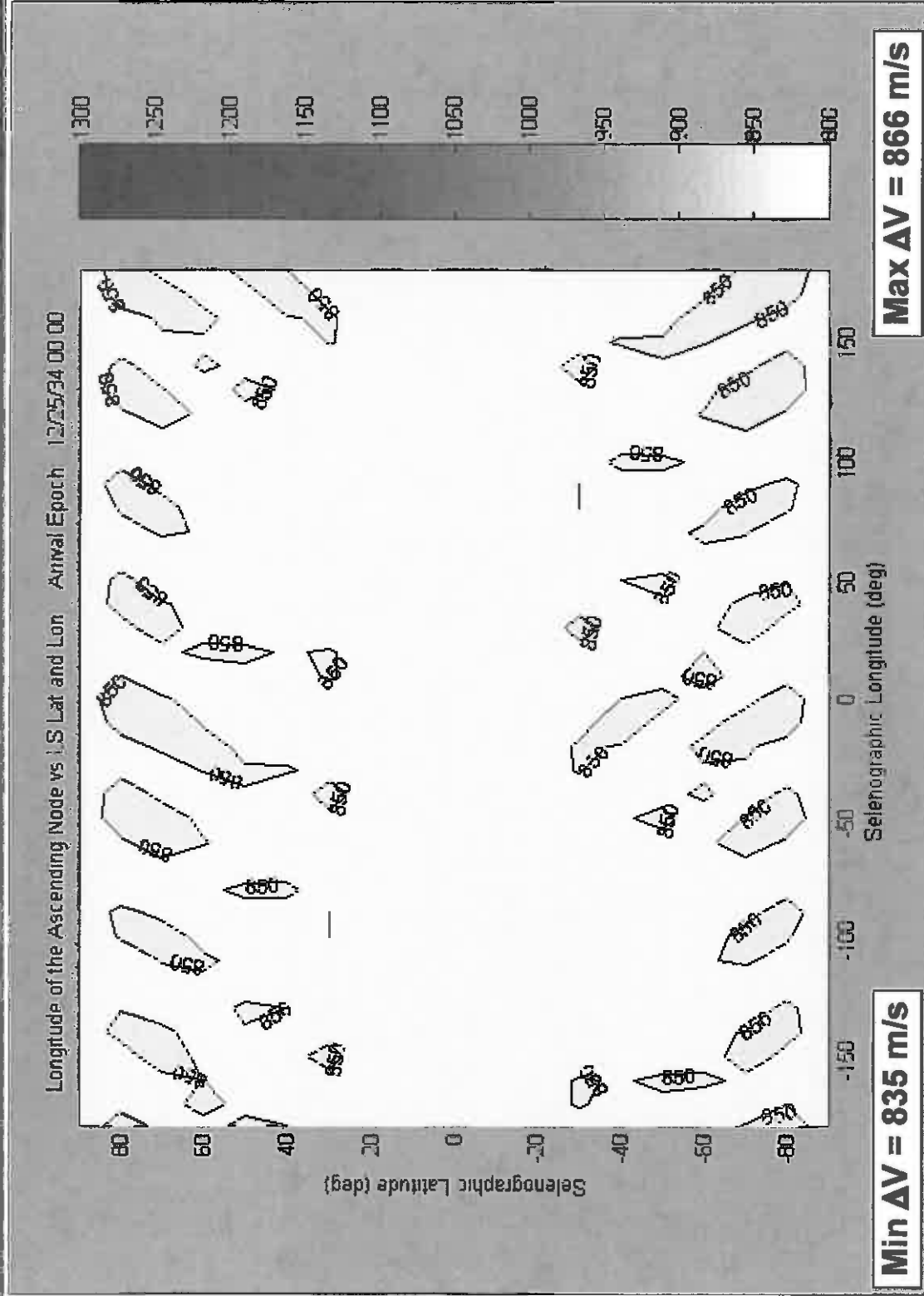
Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-10.5 days





Nominal Mission - LOI Delta-V

Arrival Epoch: 12/25/2034 Extended Loiter Time = 0-11.0 days





Lunar Loiter - Comments



- Loitering in low lunar orbit can reduce the LOI ΔV cost for a range of lunar landing site latitudes and longitudes
- Many of the lunar surface sites can be accessed for nearly a coplanar LOI injection ΔV cost if the loiter were extended to 14 days
- To guarantee complete global coverage for a 7-day surface stay and with a near coplanar LOI injection ΔV cost, the loiter time would have to be extended to about 21 days (worst case)



Results

Nominal Mission (with delayed epoch arrival) LOI ΔV

Nominal LOI Completion Epoch - December 25, 2034

Nominal lunar loiter prior to landing - 1 day

TLI \leq 3150 m/s, LOI ΔV minimized

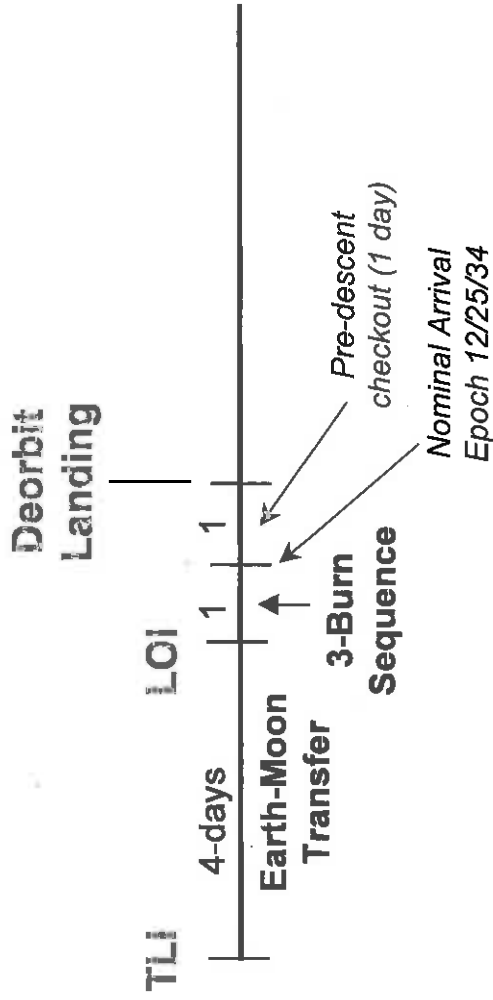
Increment of epoch delay = 12 hours

Moon at minimum inclination ($\sim 18.3^\circ$)

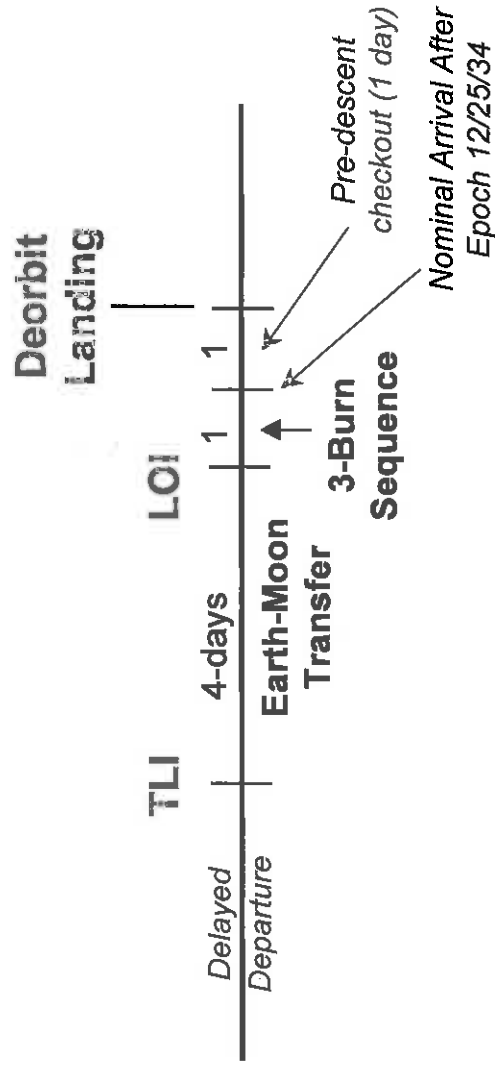


Mission Sequence

3-Burn Sequence Nominal



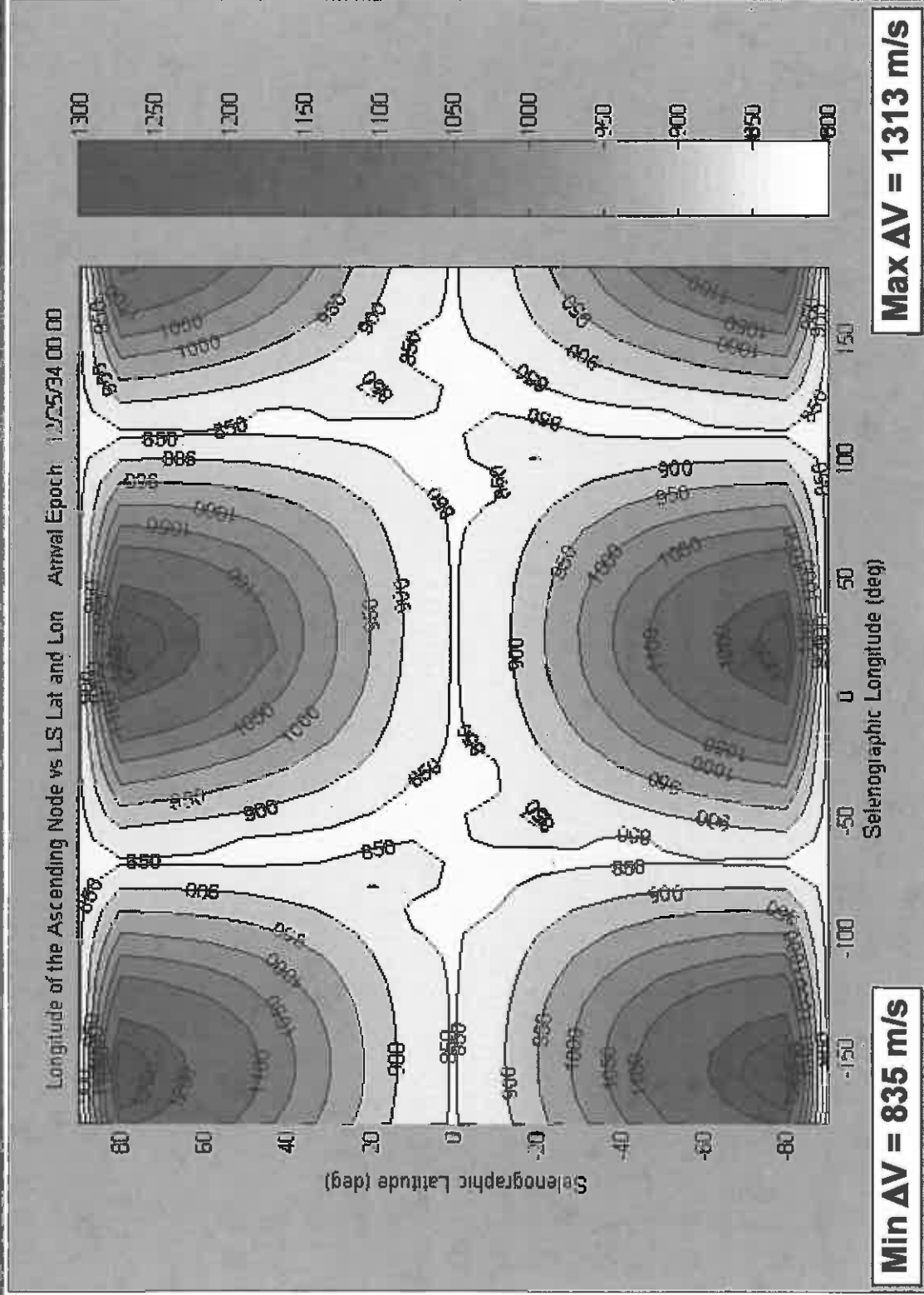
3-Burn Sequence Delayed Epoch Arrival





Nominal Mission – LOI Delta-V

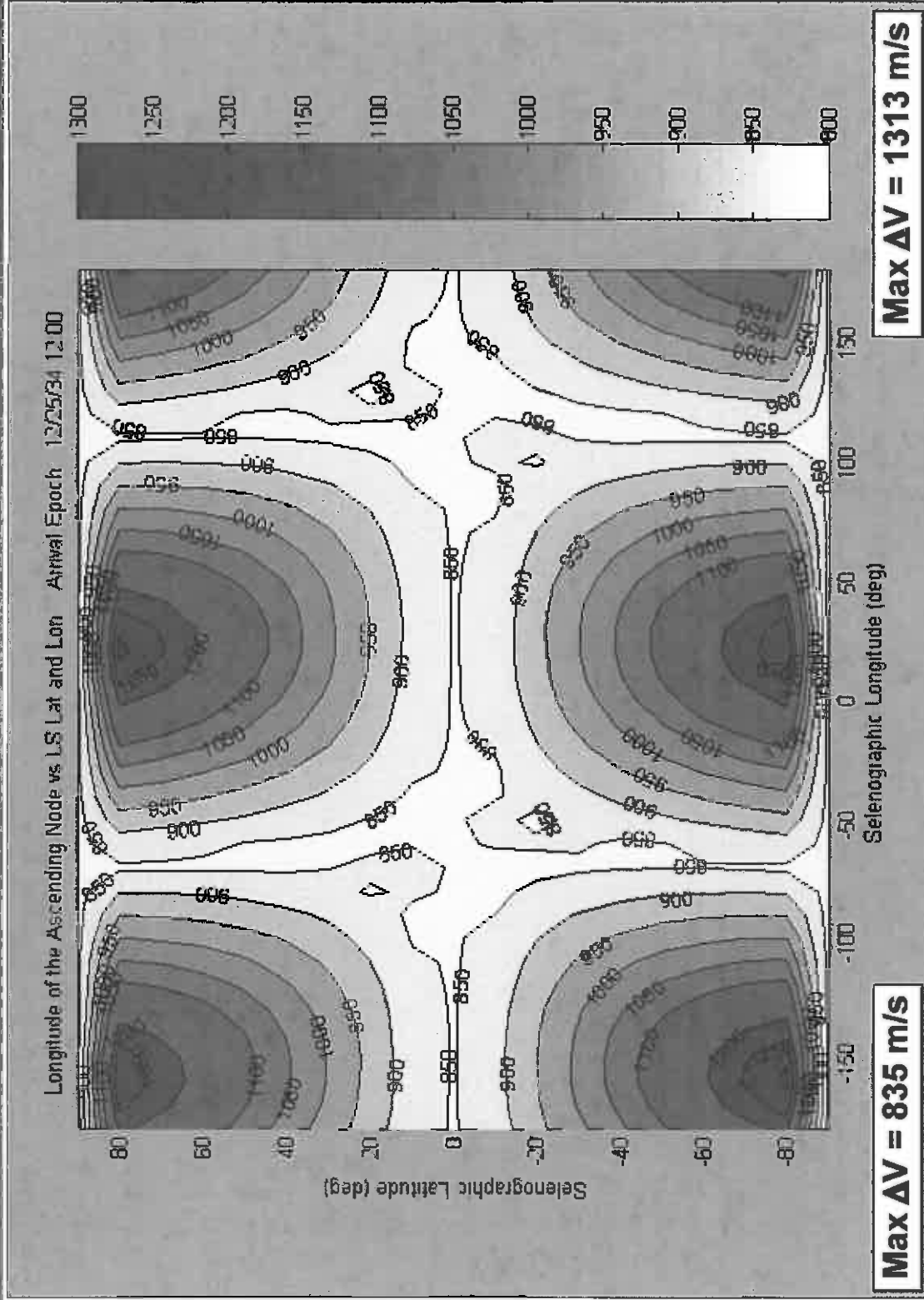
Arrival Epoch: 12/25/2034 00:00





Nominal Mission - LOI Delta-V

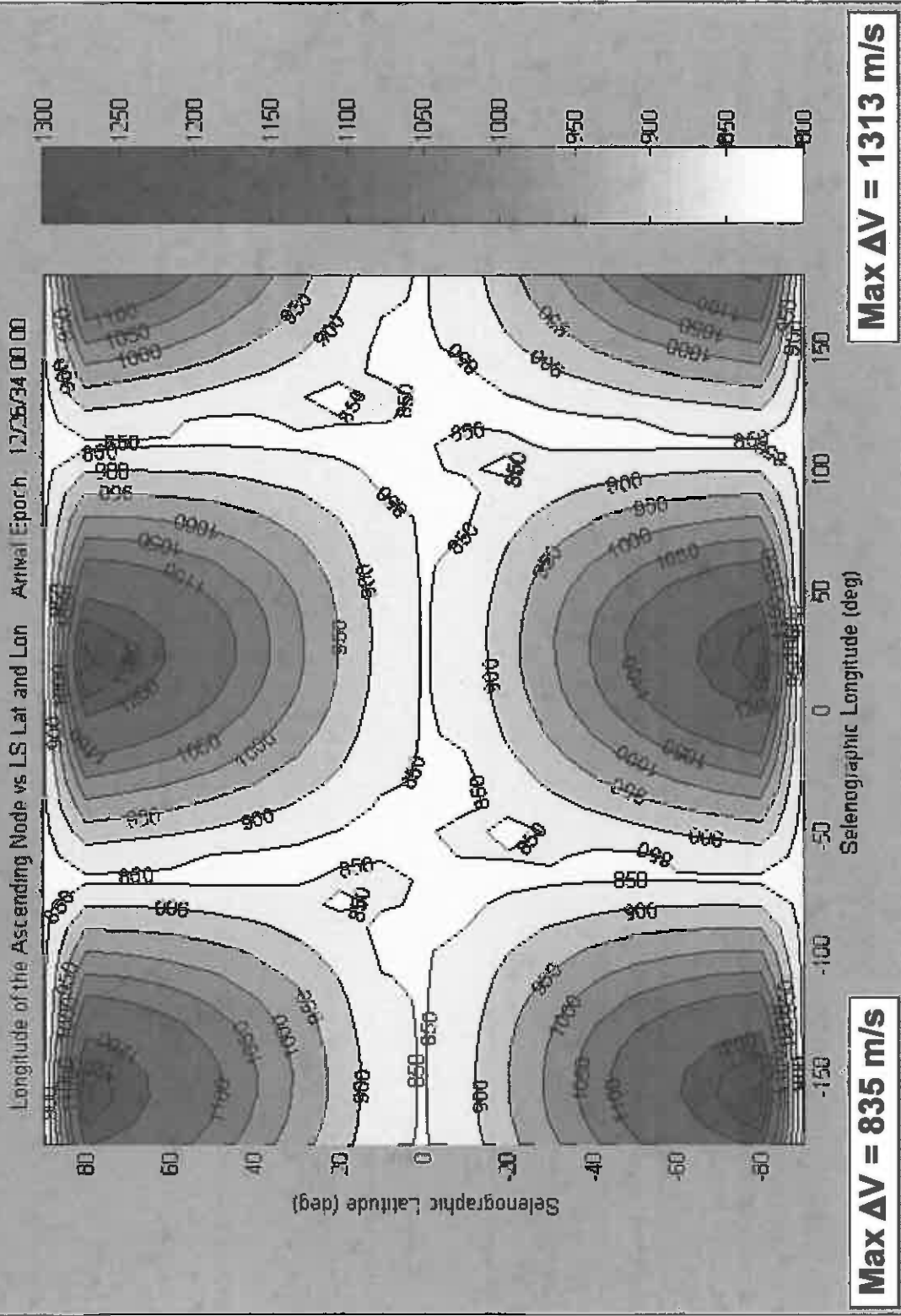
Arrival Epoch: 12/25/2034 12:00





Nominal Mission – LOI Delta-V

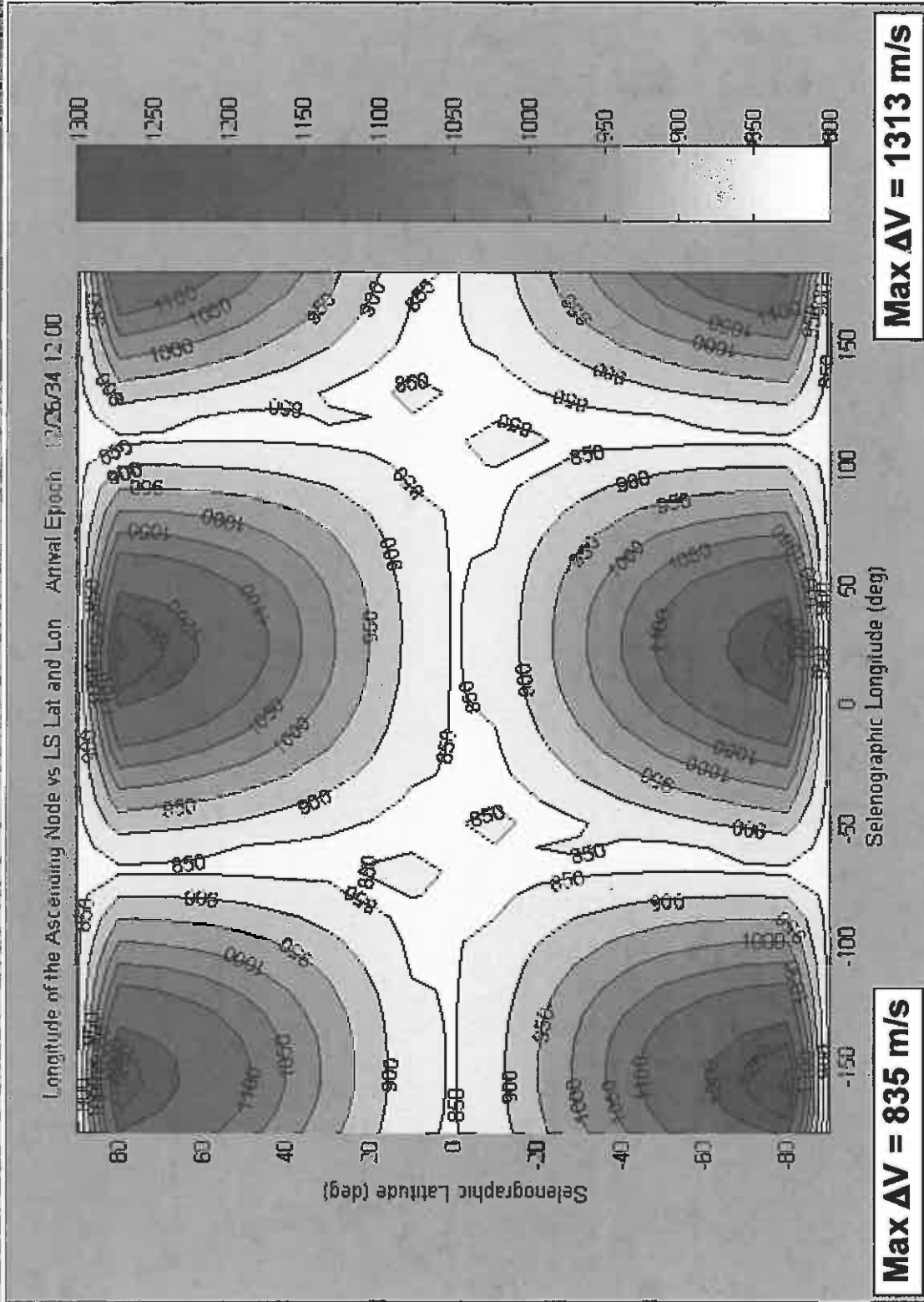
Arrival Epoch: 12/26/2034 00:00





Nominal Mission – LOI Delta-V

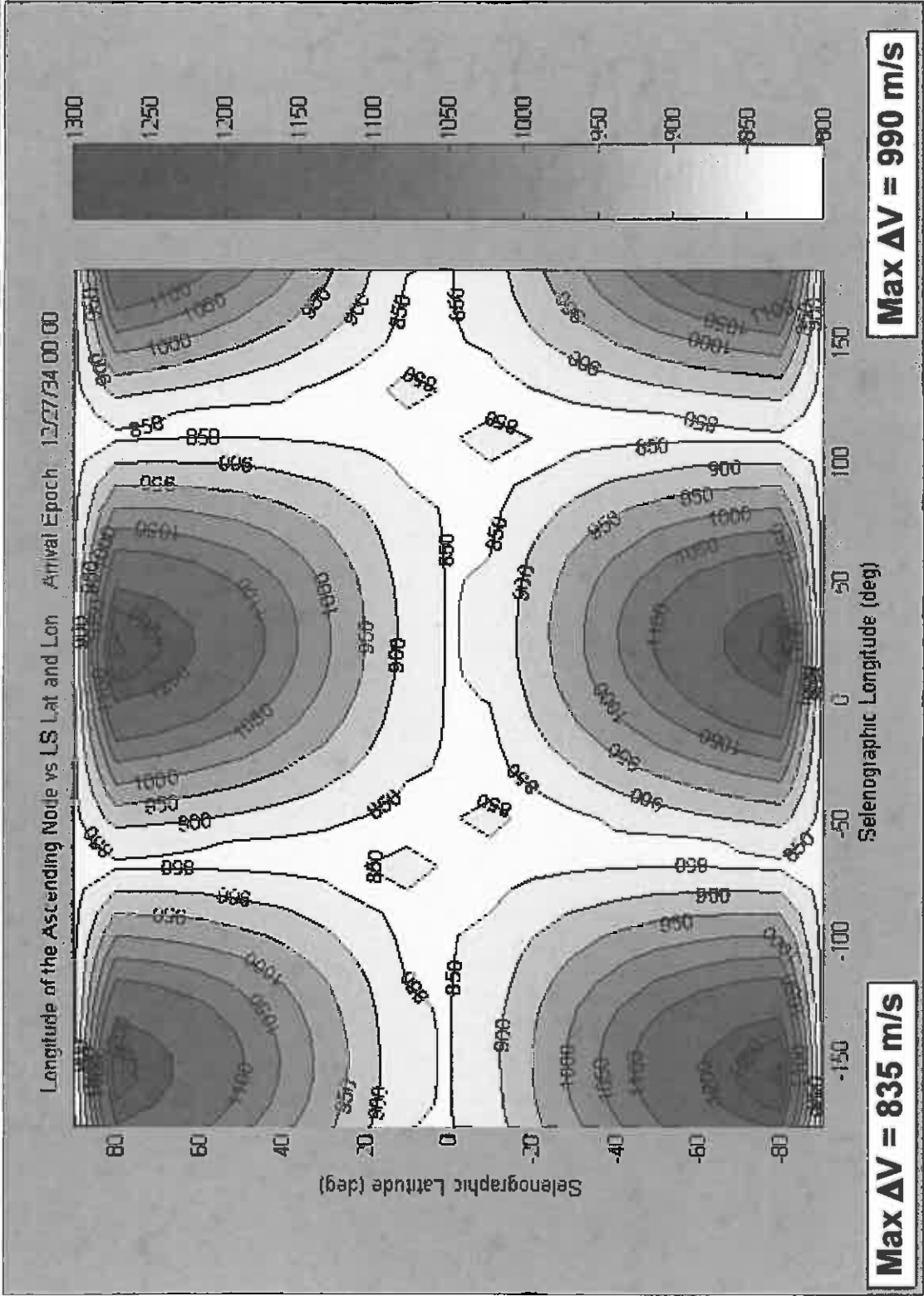
Arrival Epoch: 12/26/2034 12:00





Nominal Mission - LOI Delta-V

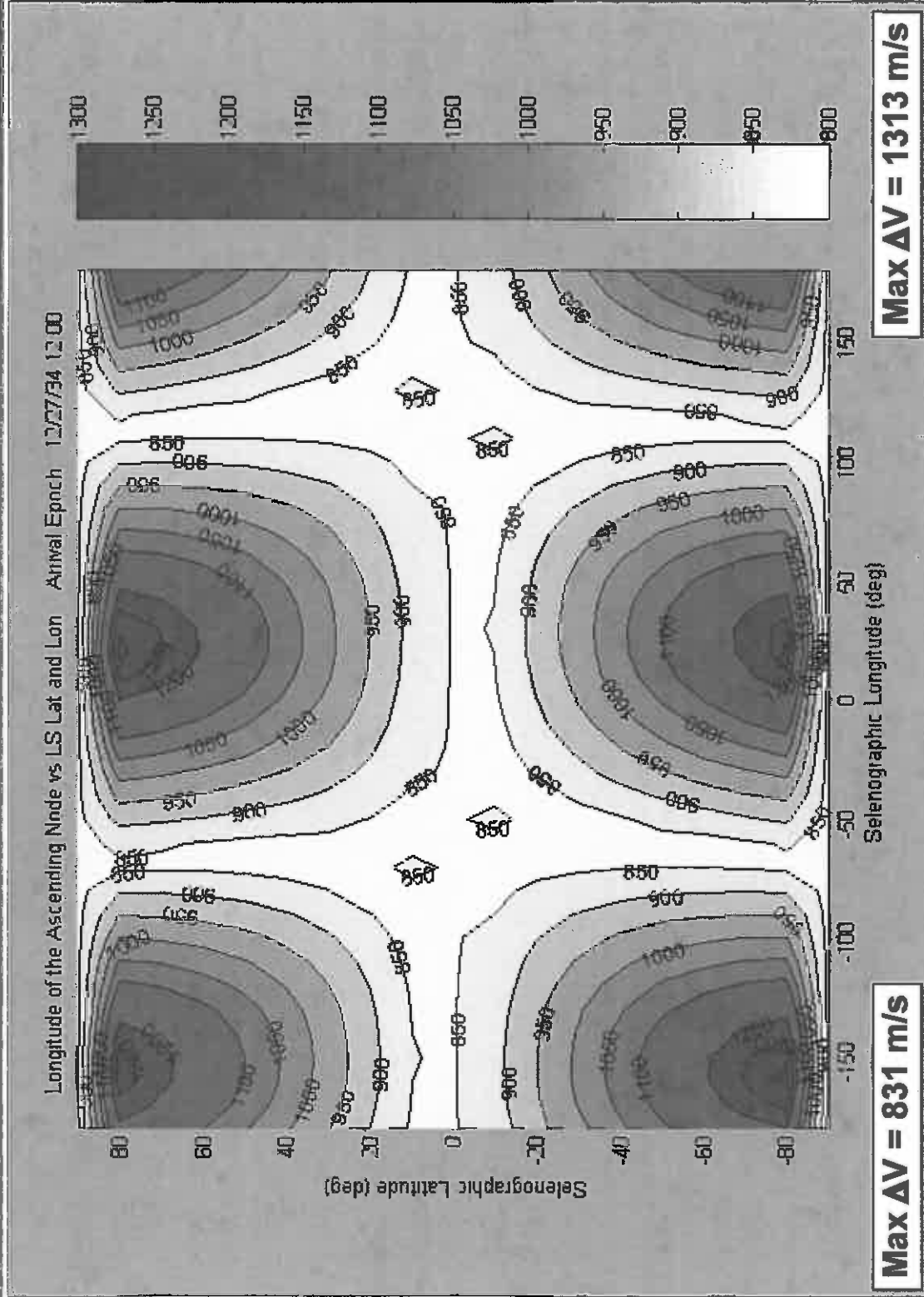
Arrival Epoch: 12/27/2034 00:00





Nominal Mission - LOI Delta-V

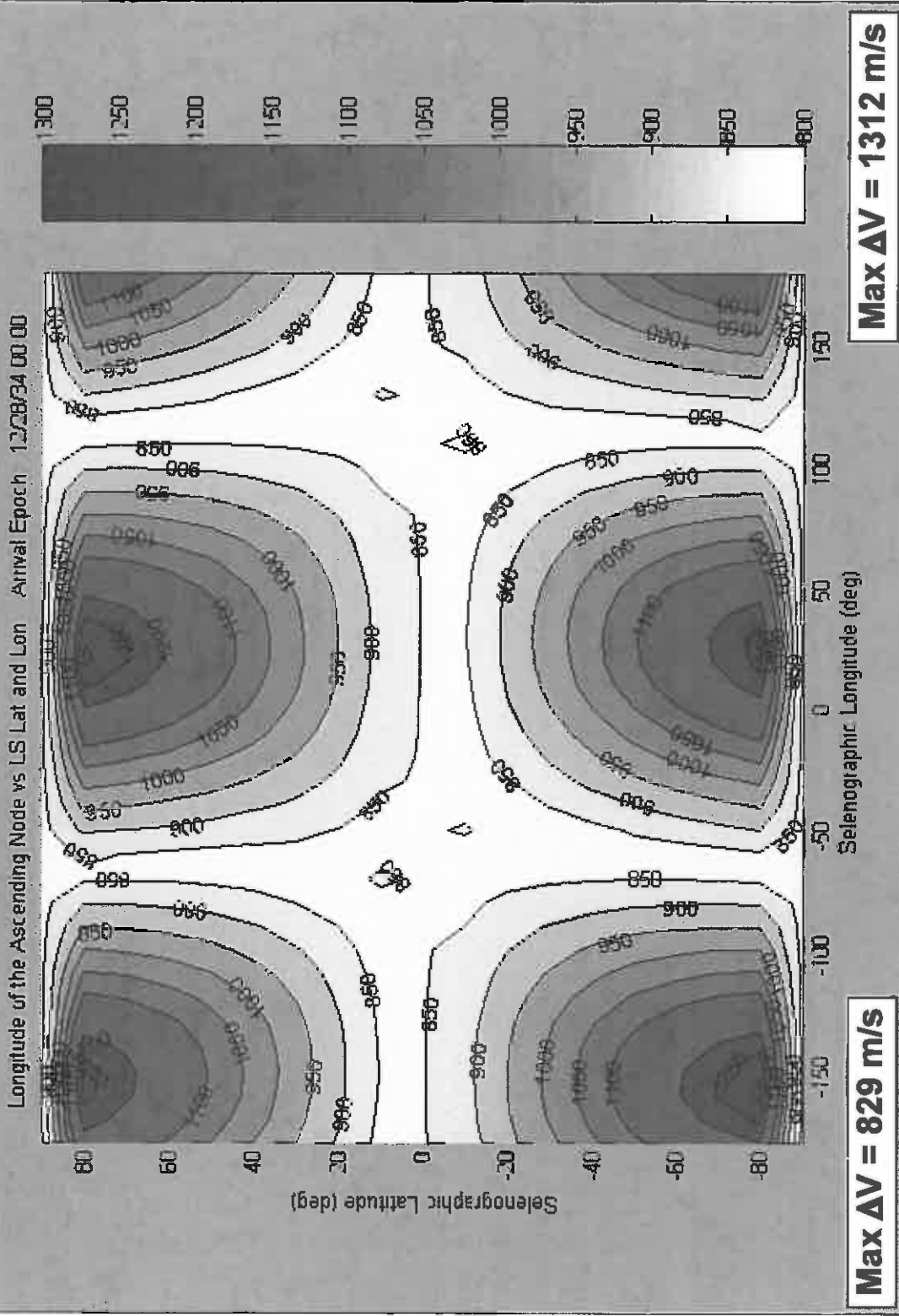
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Nominal Mission - LOI Delta-V

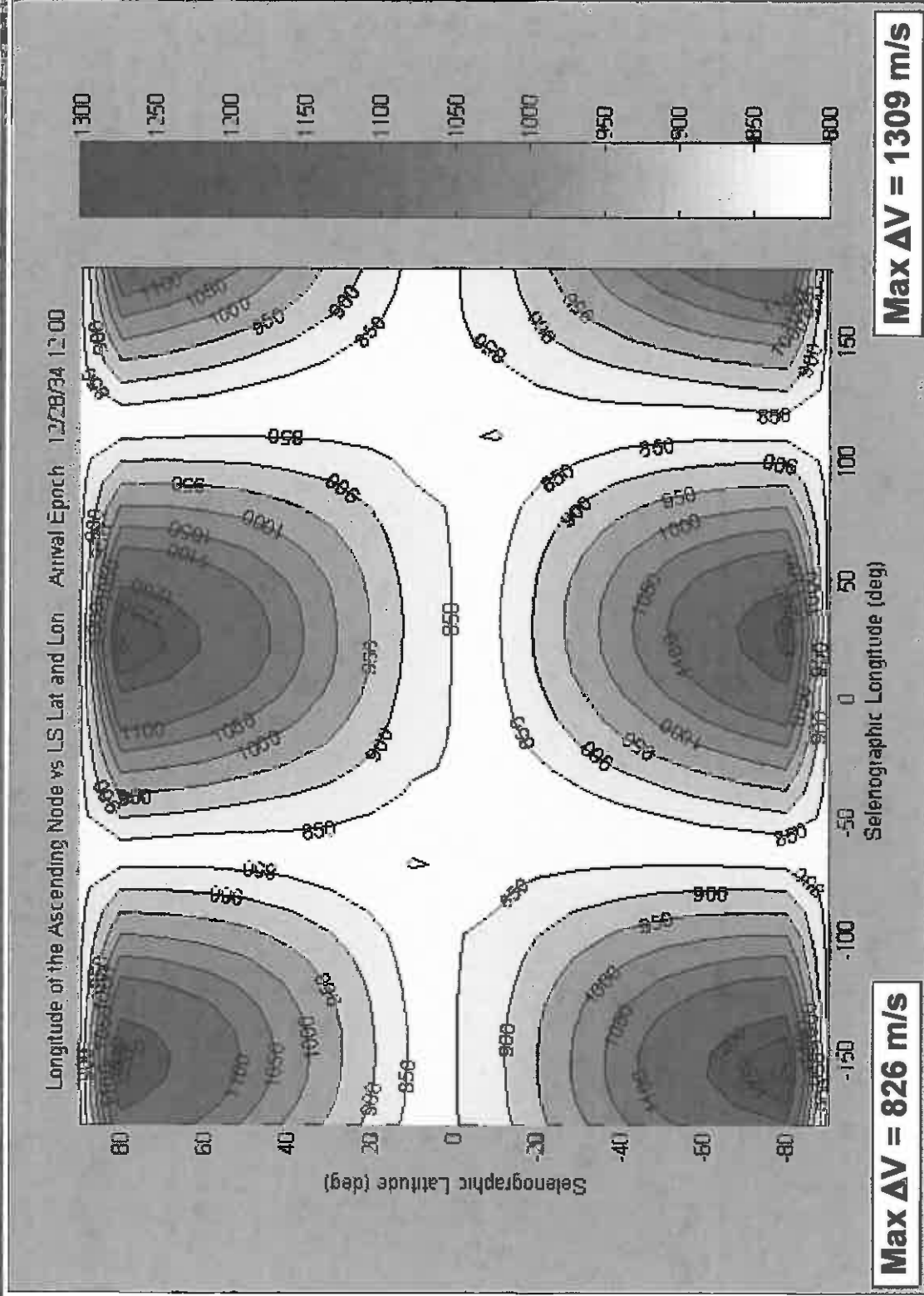
Arrival Epoch: 12/28/2034 00:00





Nominal Mission – LOI Delta-V

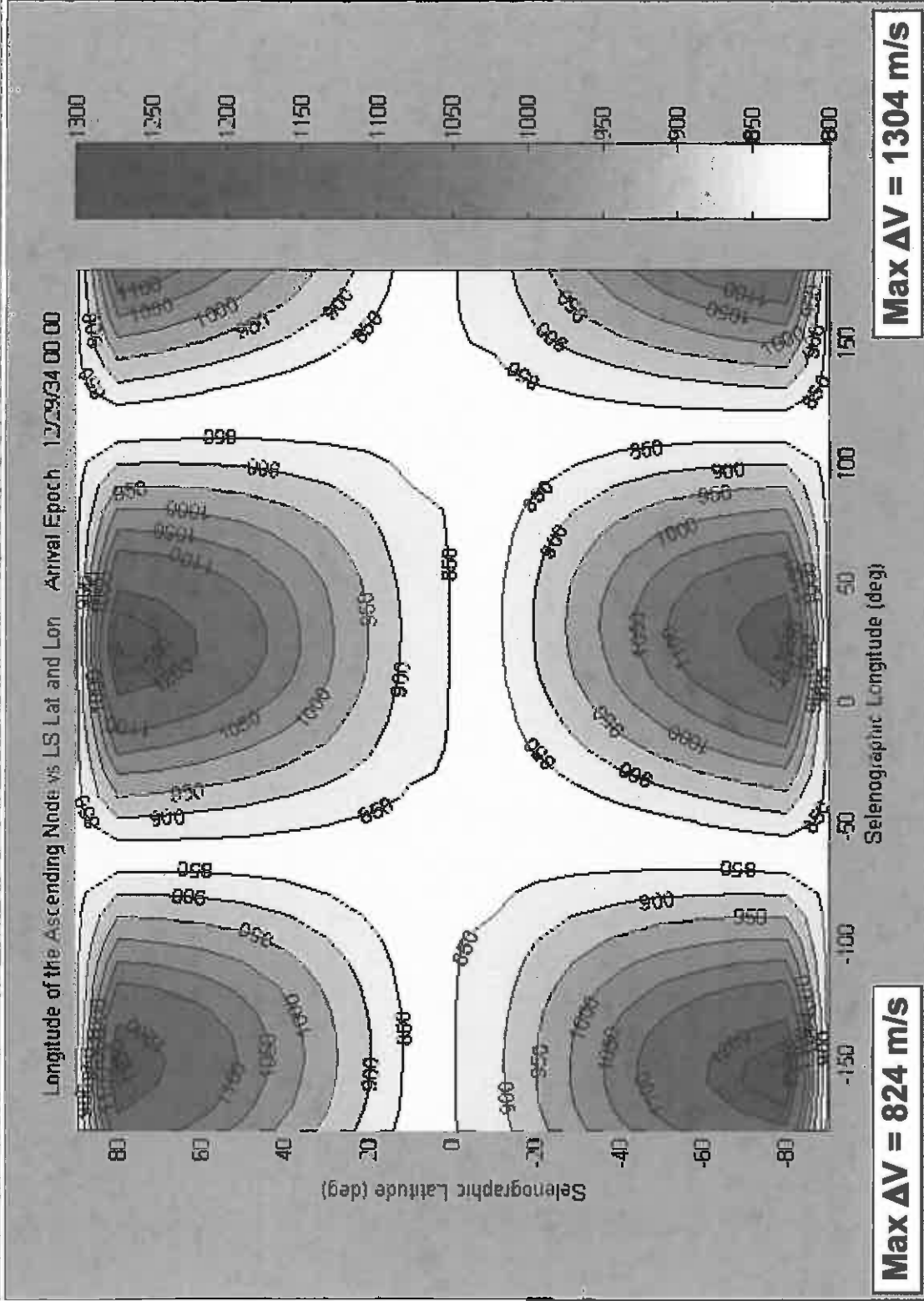
Arrival Epoch: 12/28/2034 12:00





Nominal Mission - LOI Delta-V

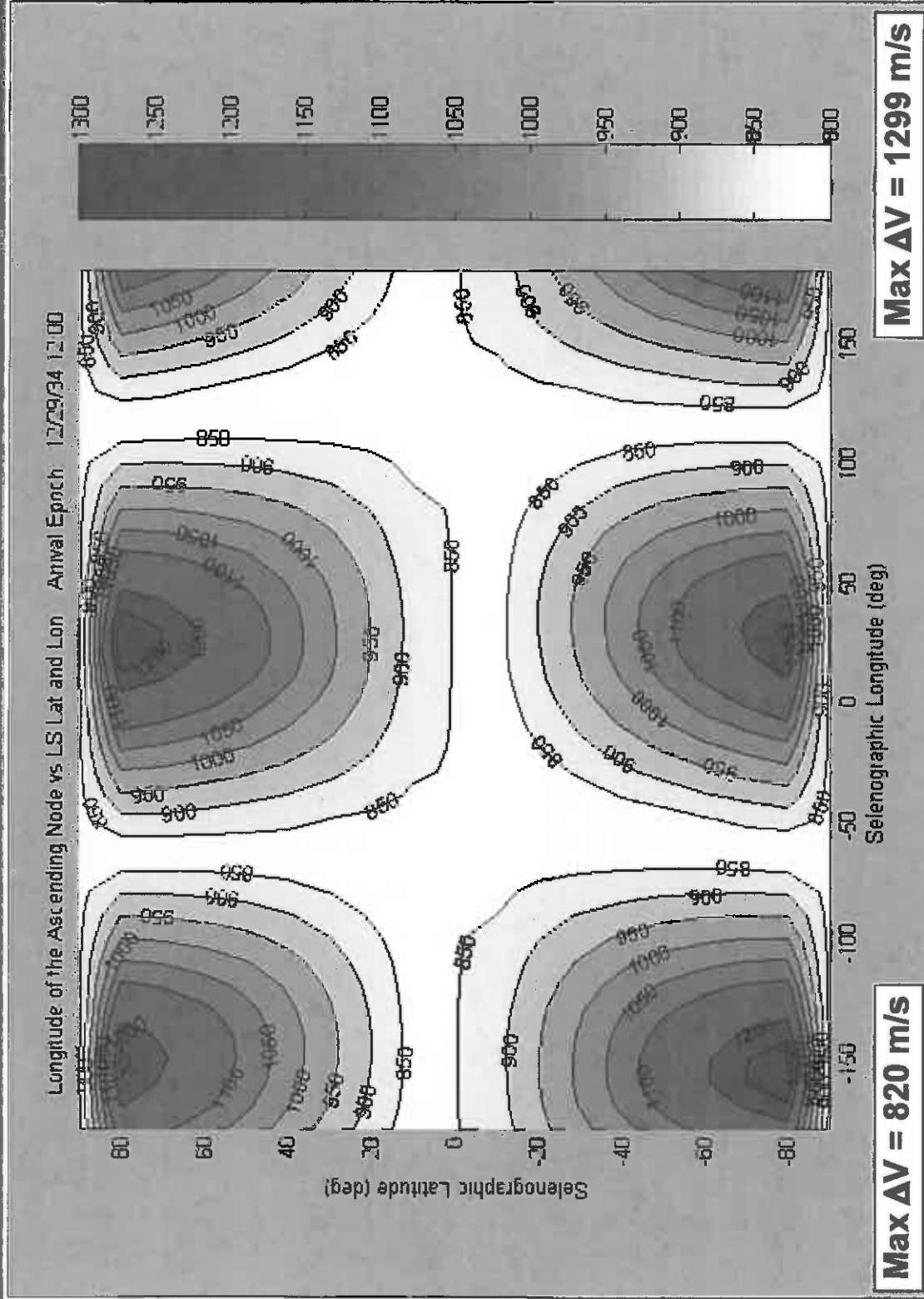
Arrival Epoch: 12/29/2034 00:00





Nominal Mission - LOI Delta-V

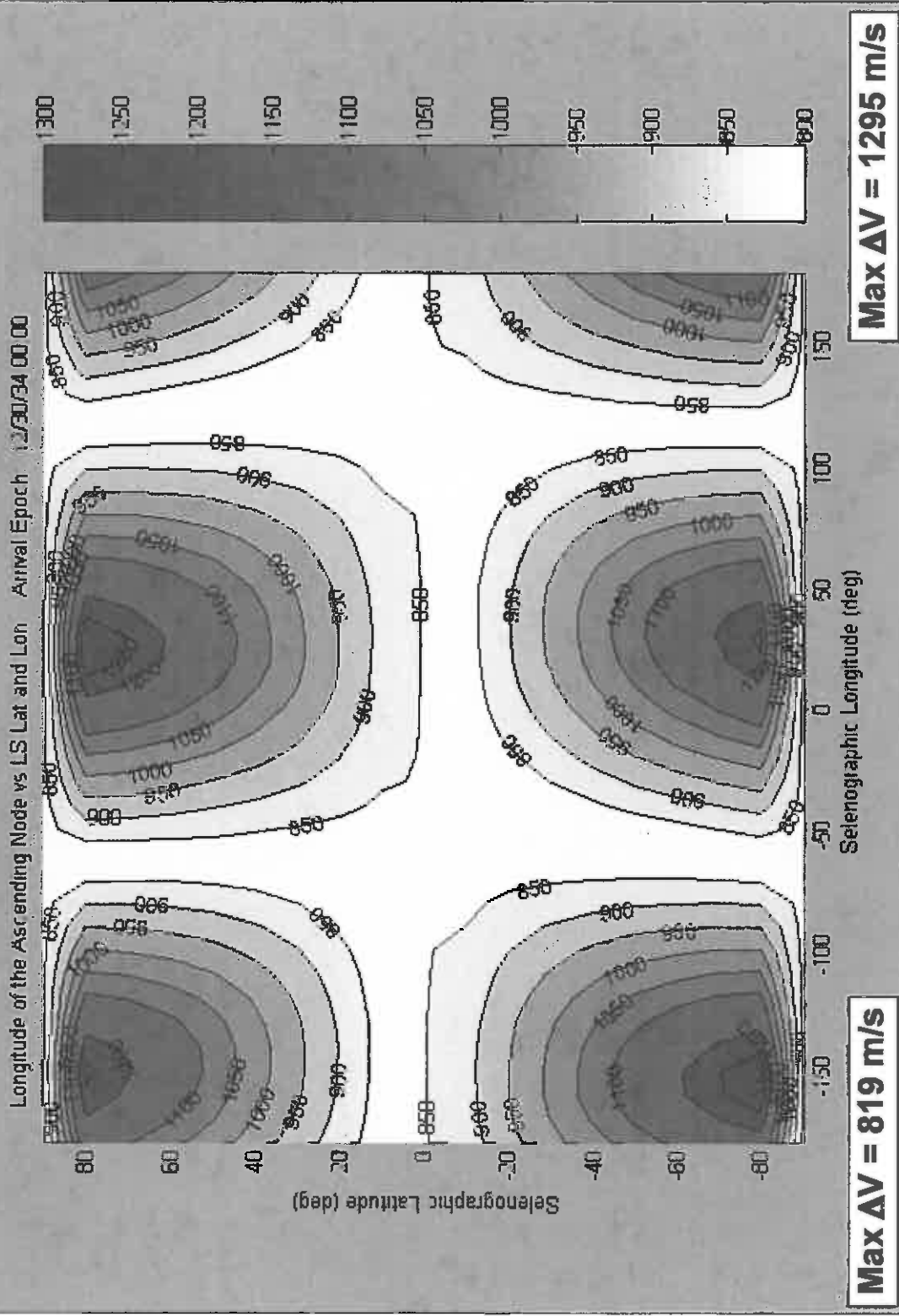
Arrival Epoch: 12/29/2034 12:00





Nominal Mission - LOI Delta-V

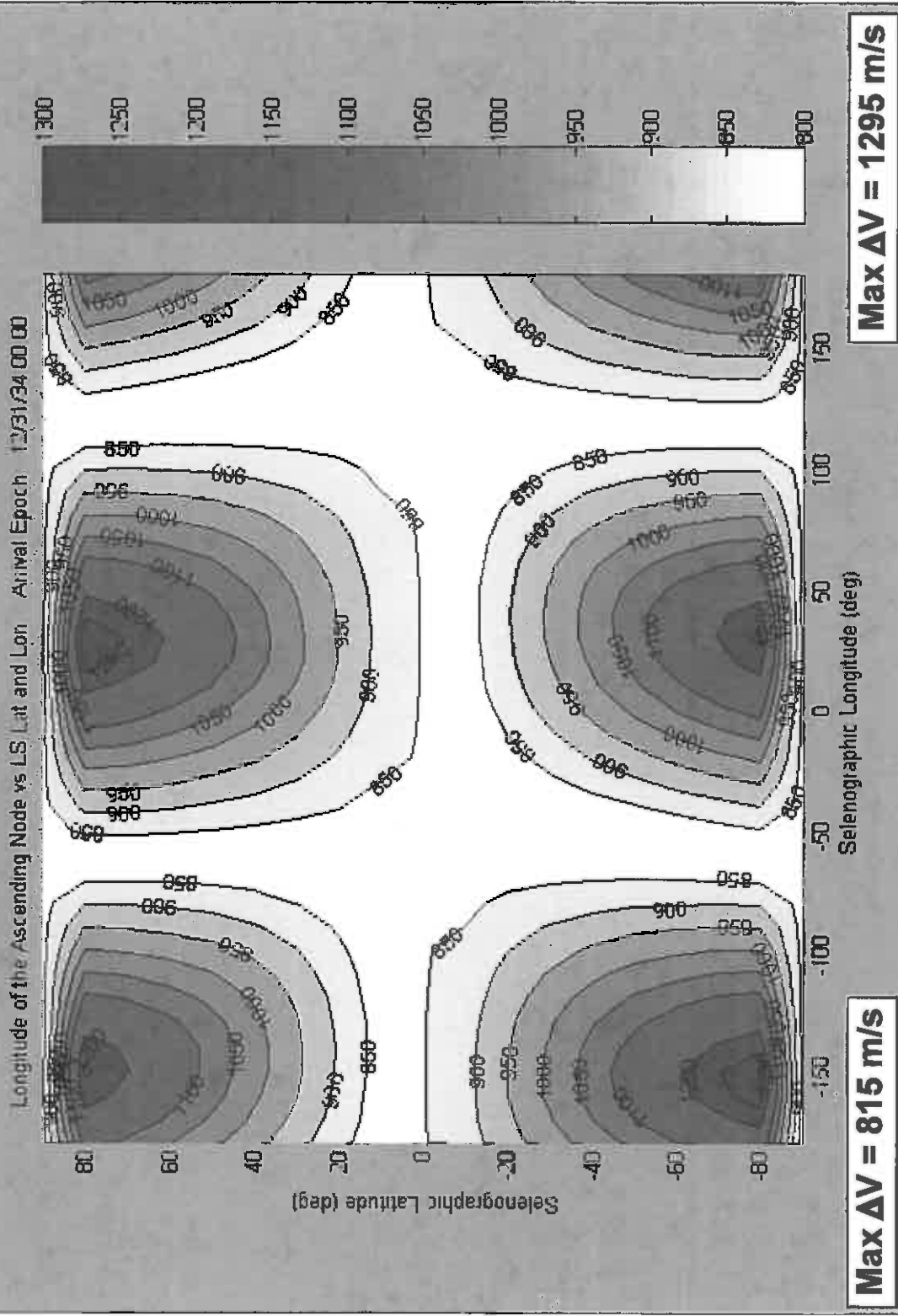
Arrival Epoch: 12/30/2034 00:00





Nominal Mission – LOI Delta-V

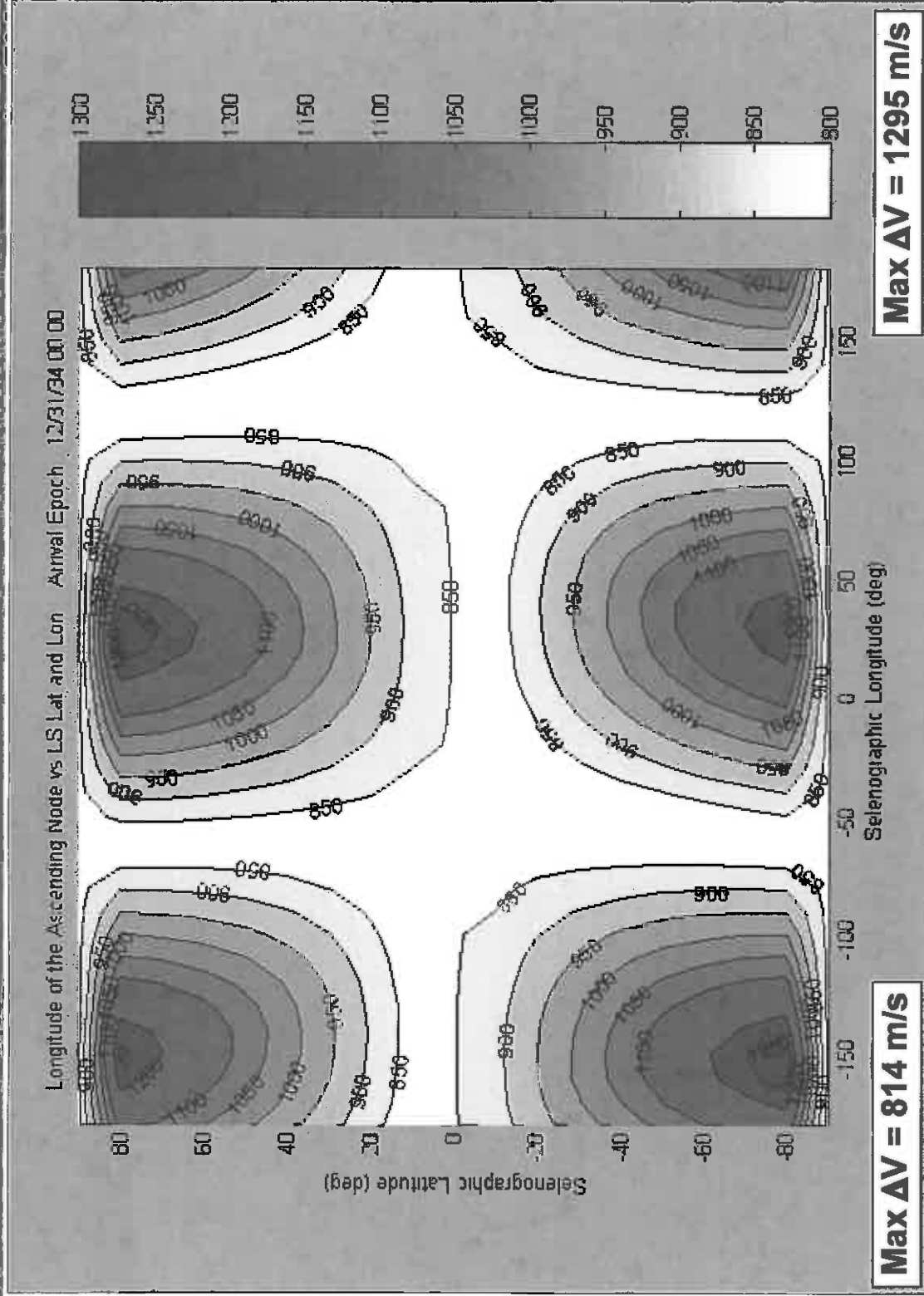
Arrival Epoch: 12/30/2034 12:00





Nominal Mission - LOI Delta-V

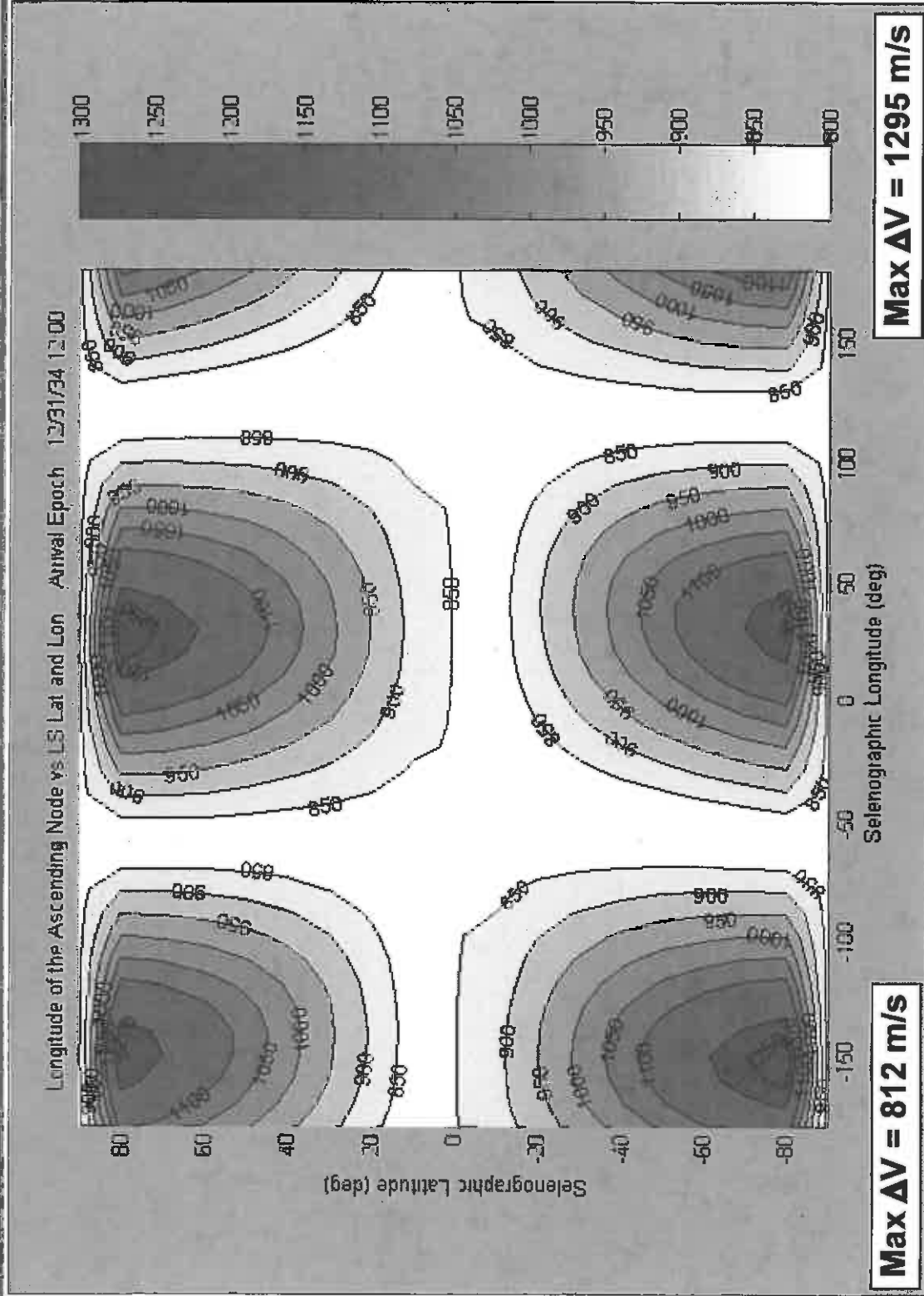
Arrival Epoch: 12/31/2034 00:00





Nominal Mission - LOI Delta-V

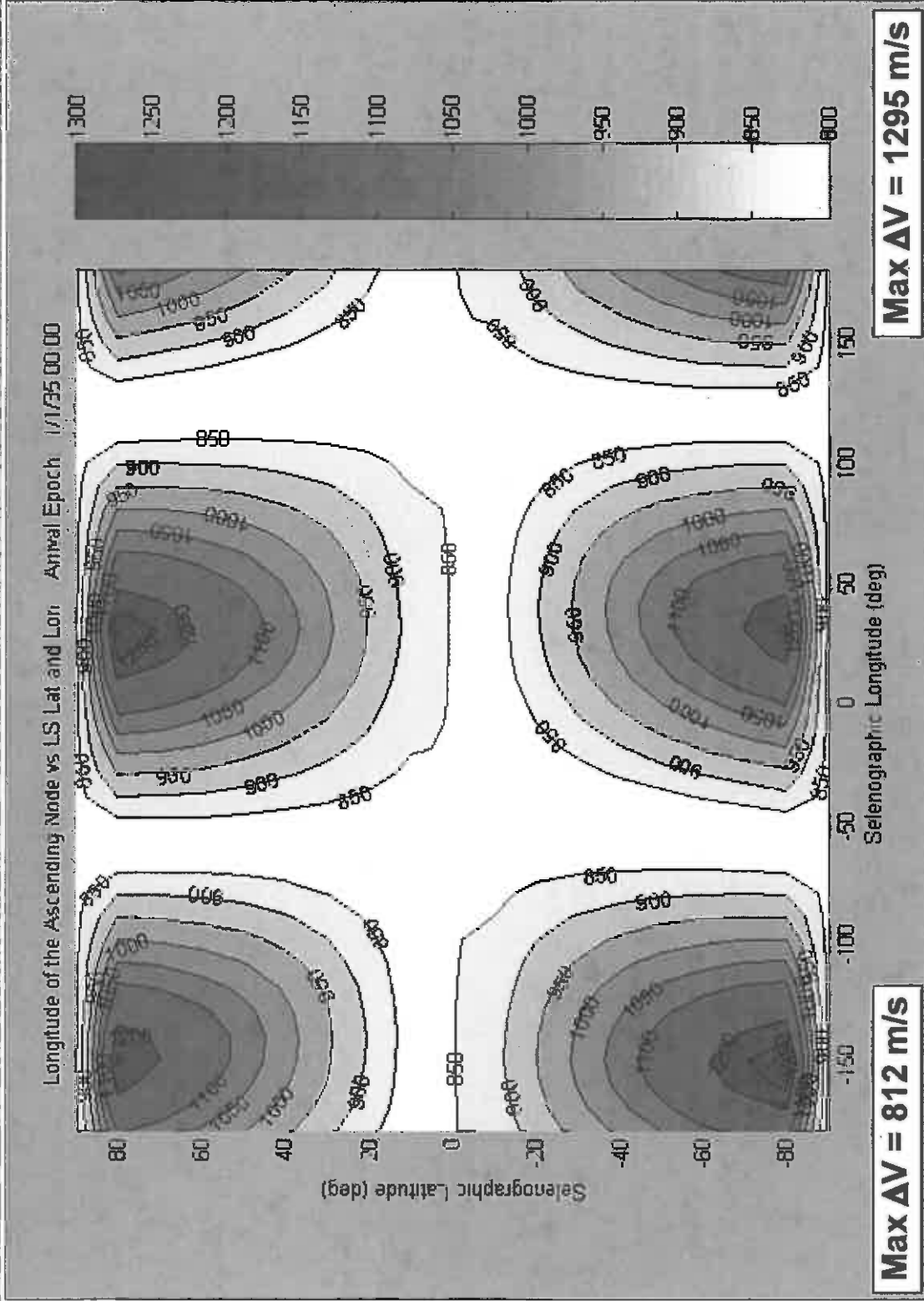
Arrival Epoch: 12/31/2034 12:00





Nominal Mission - LOI Delta-V

Arrival Epoch: 1/1/2035 00:00



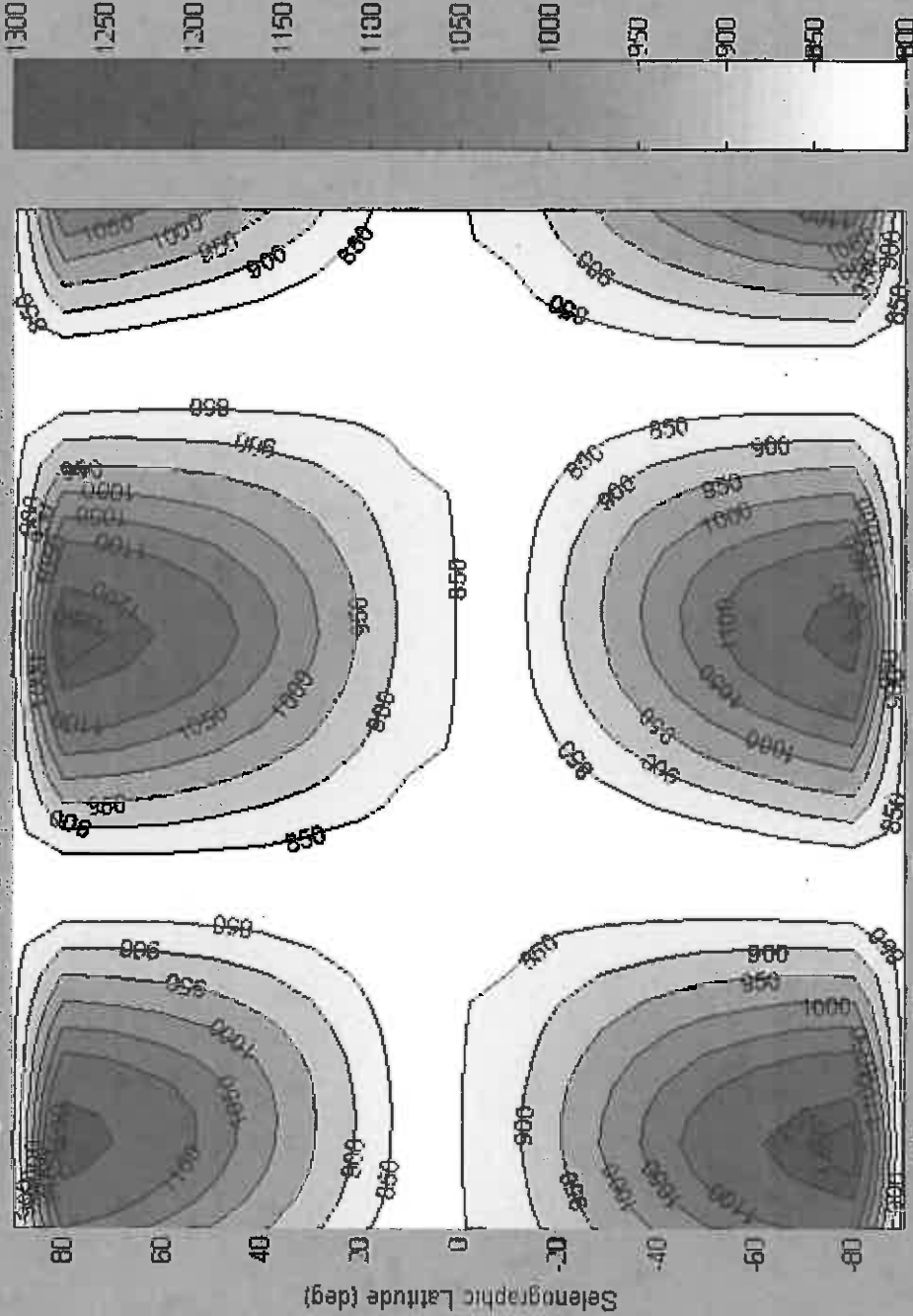


Nominal Mission – LOI Delta-V

Arrival Epoch: 1/1/2035 12:00



Longitude of the Ascending Node vs LS Lat and Lon Arrival Epoch 1/1/35 12:00



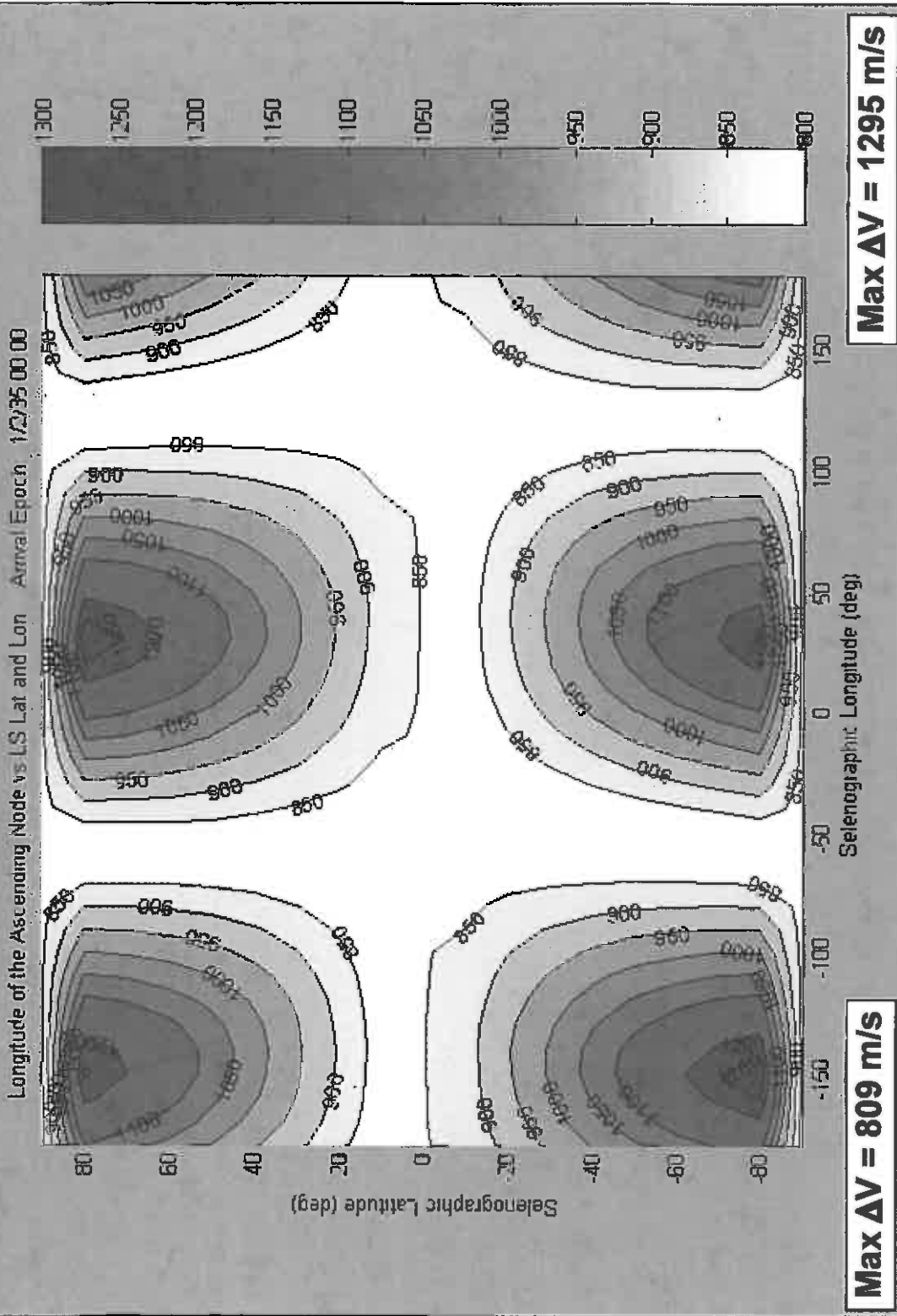
Max ΔV = 810 m/s

Max ΔV = 1295 m/s



Nominal Mission – LOI Delta-V

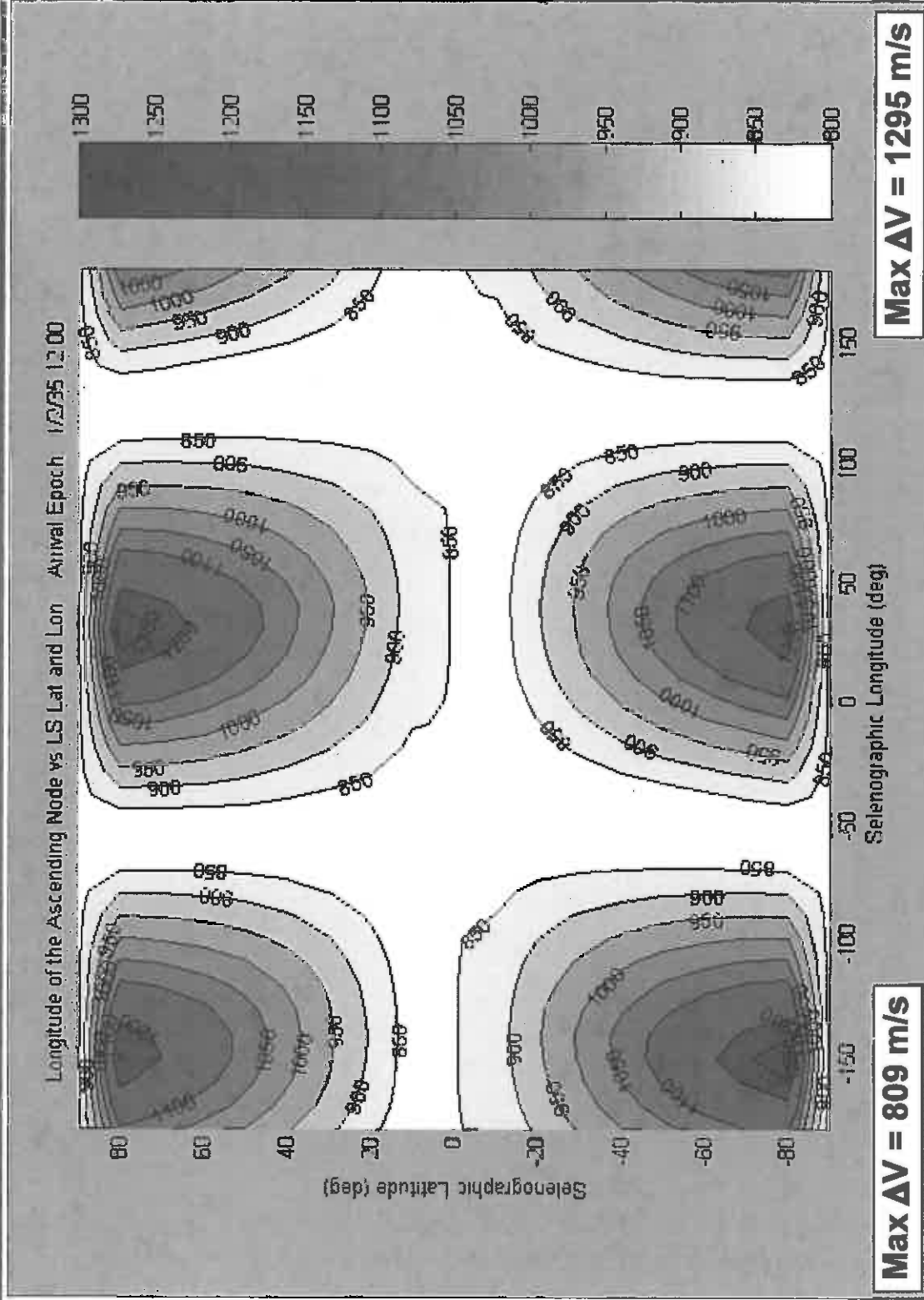
Arrival Epoch: 1/2/2035 00:00





Nominal Mission – LOI Delta-V

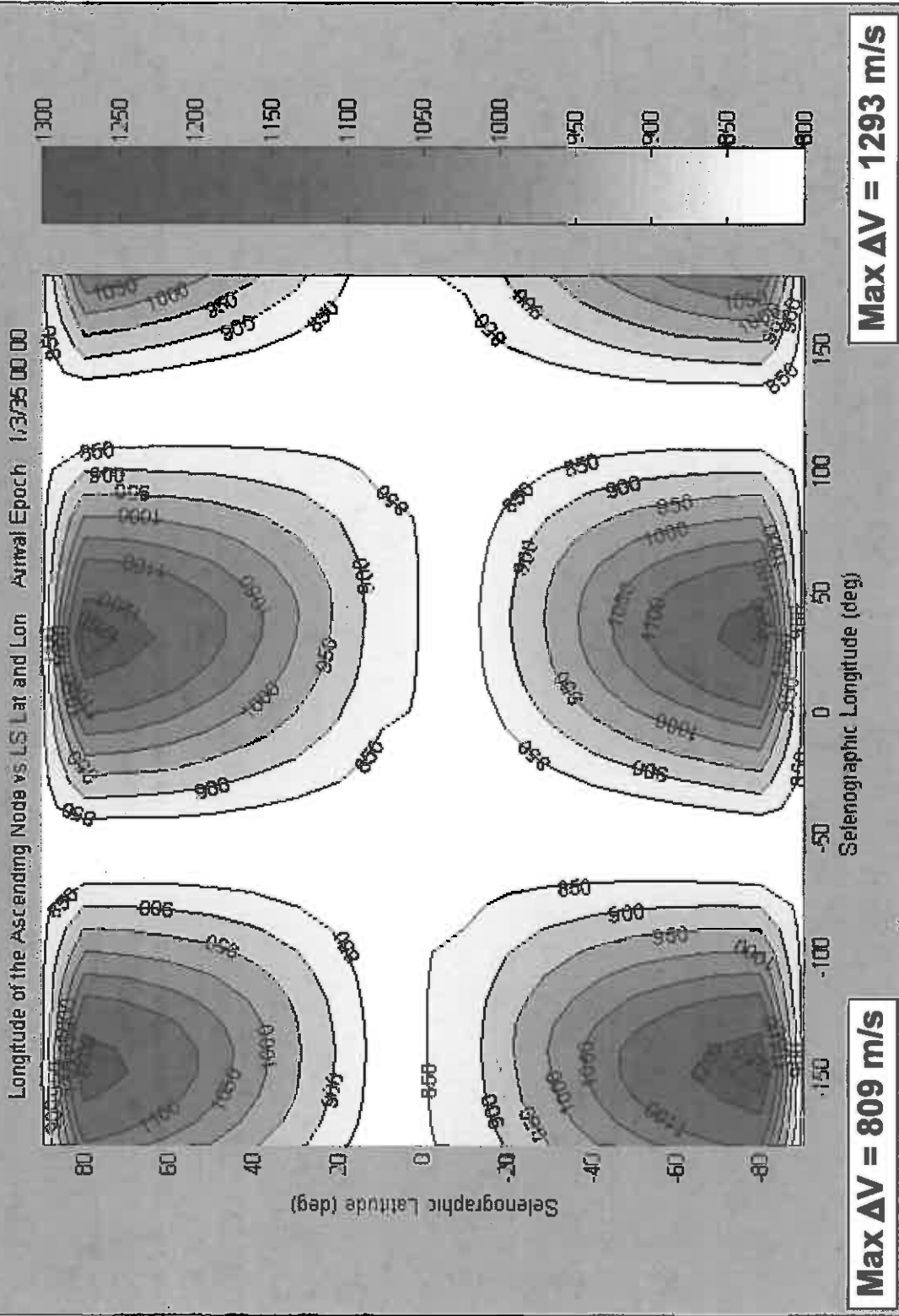
Arrival Epoch: 1/2/2035 12:00





Nominal Mission – LOI Delta-V

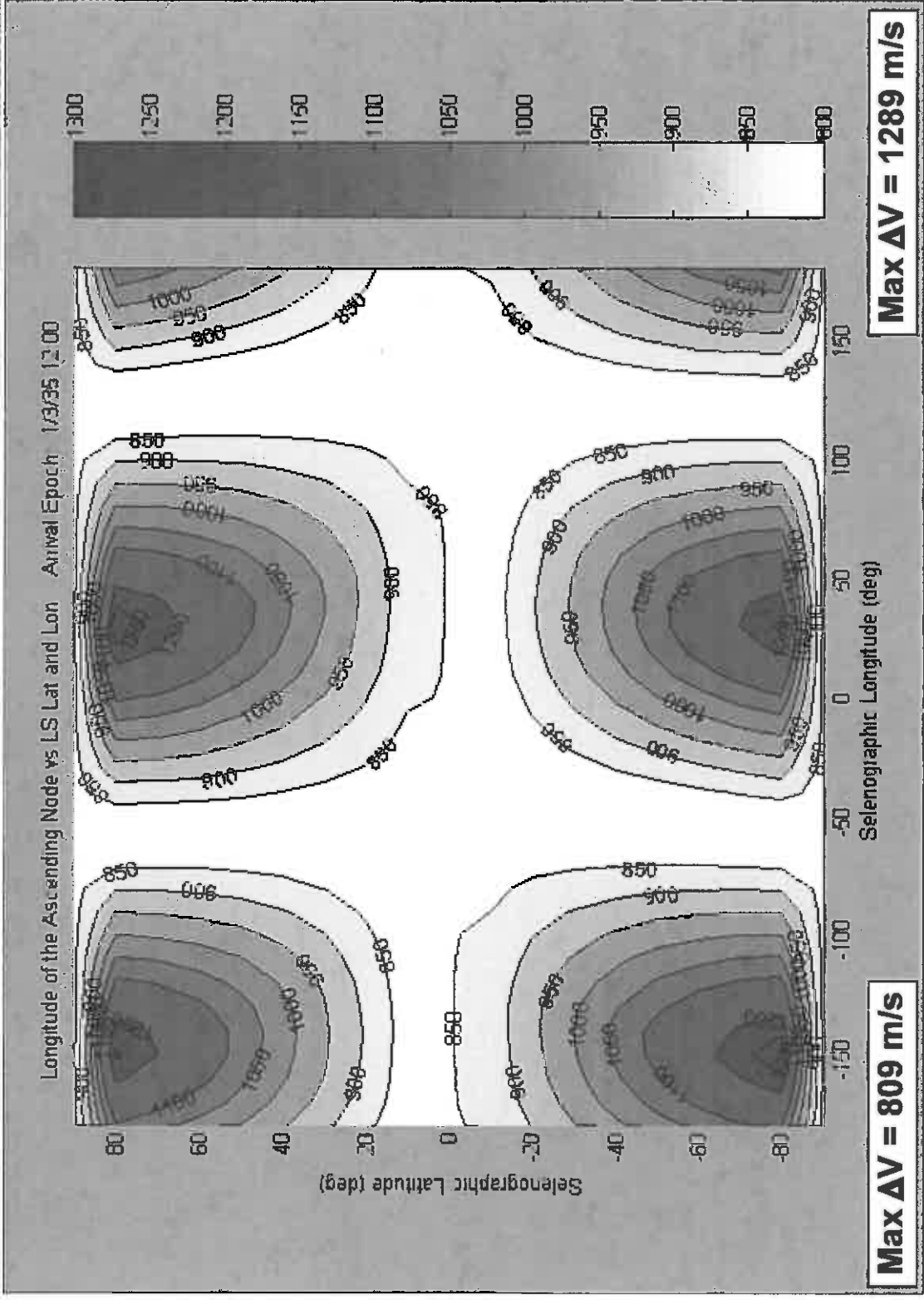
Arrival Epoch: 1/3/2035 00:00





Nominal Mission – LOI Delta-V

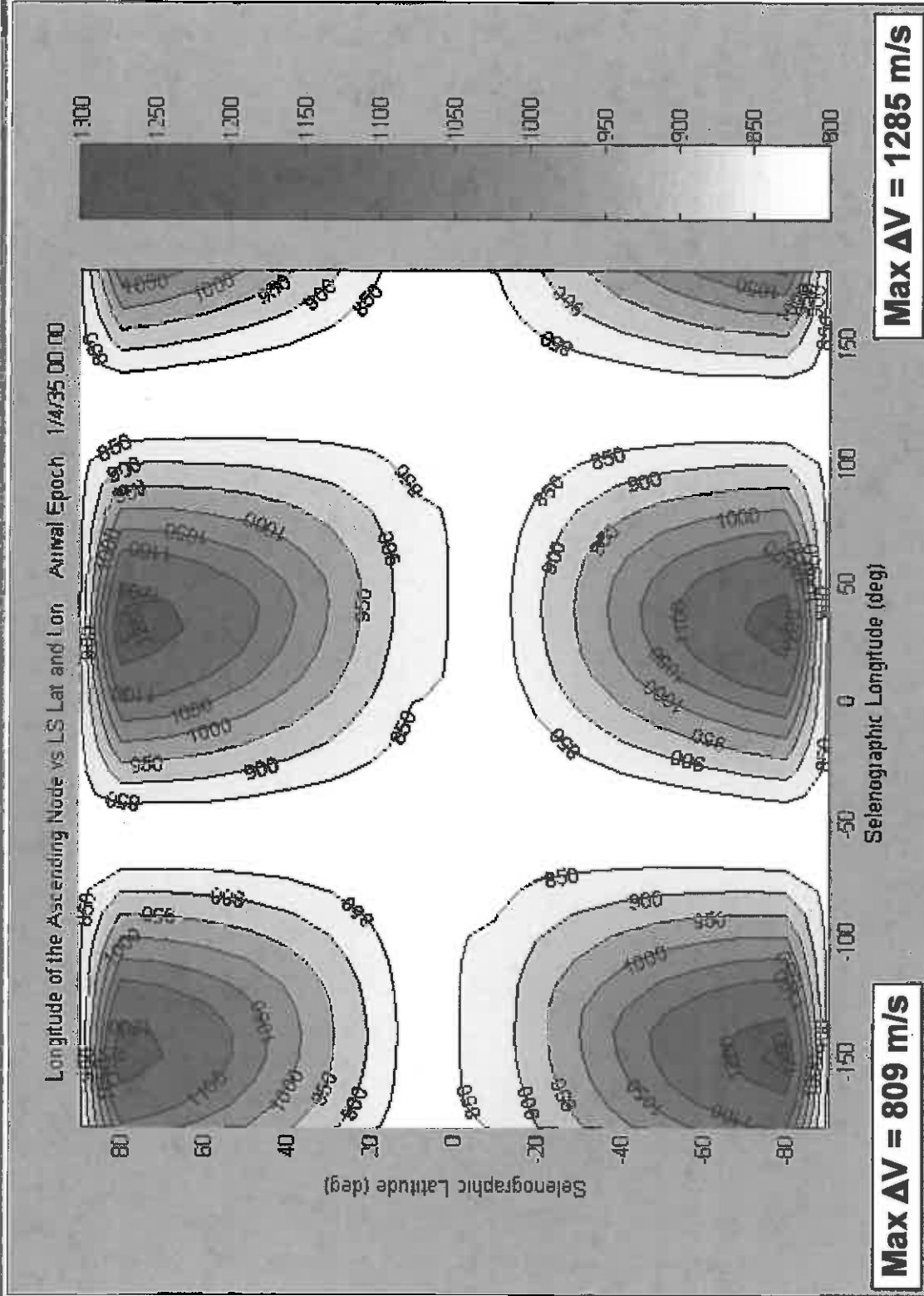
Arrival Epoch: 1/3/2035 12:00





Nominal Mission – LOI Delta-V

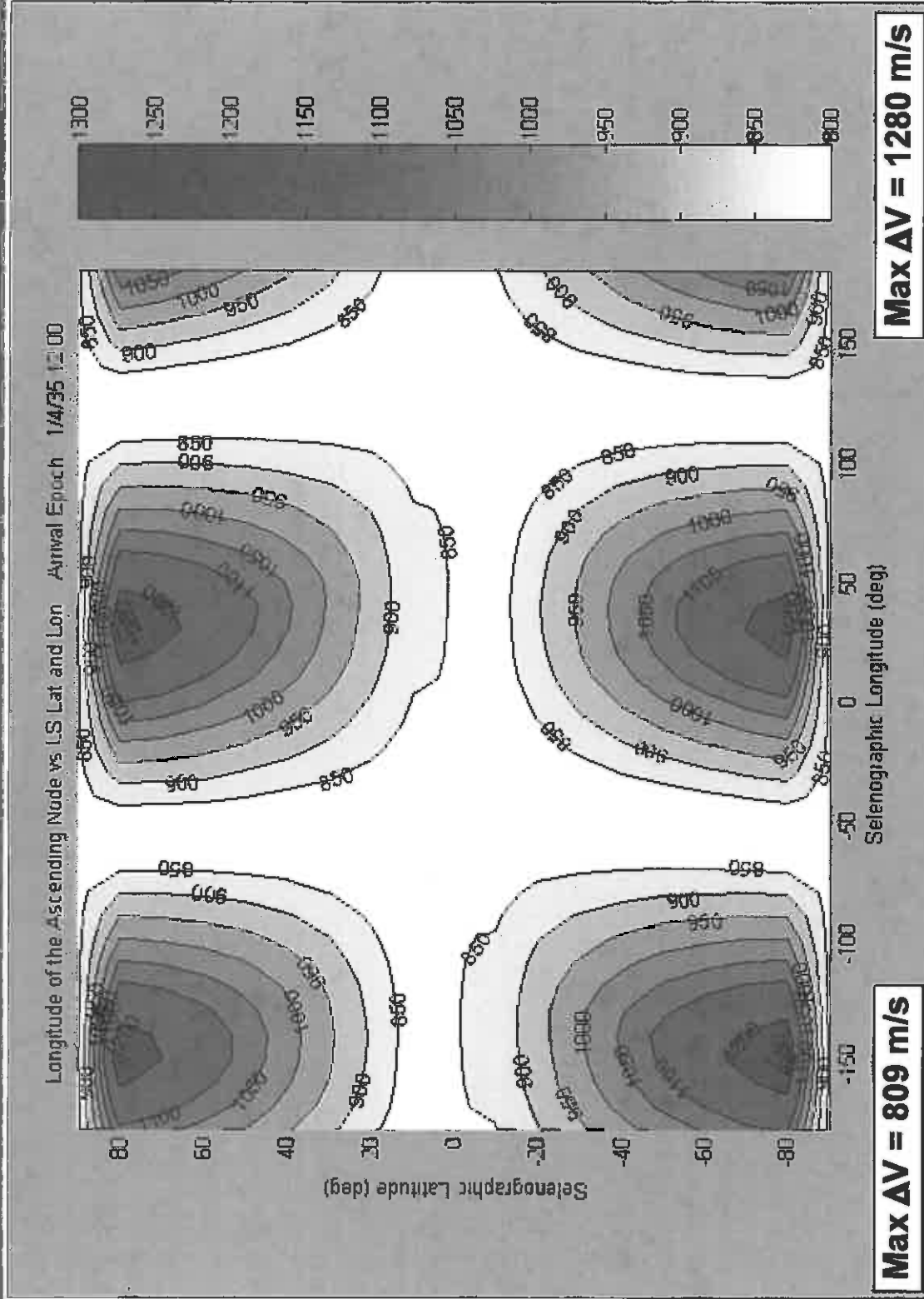
Arrival Epoch: 1/4/2035 00:00





Nominal Mission - LOI Delta-V

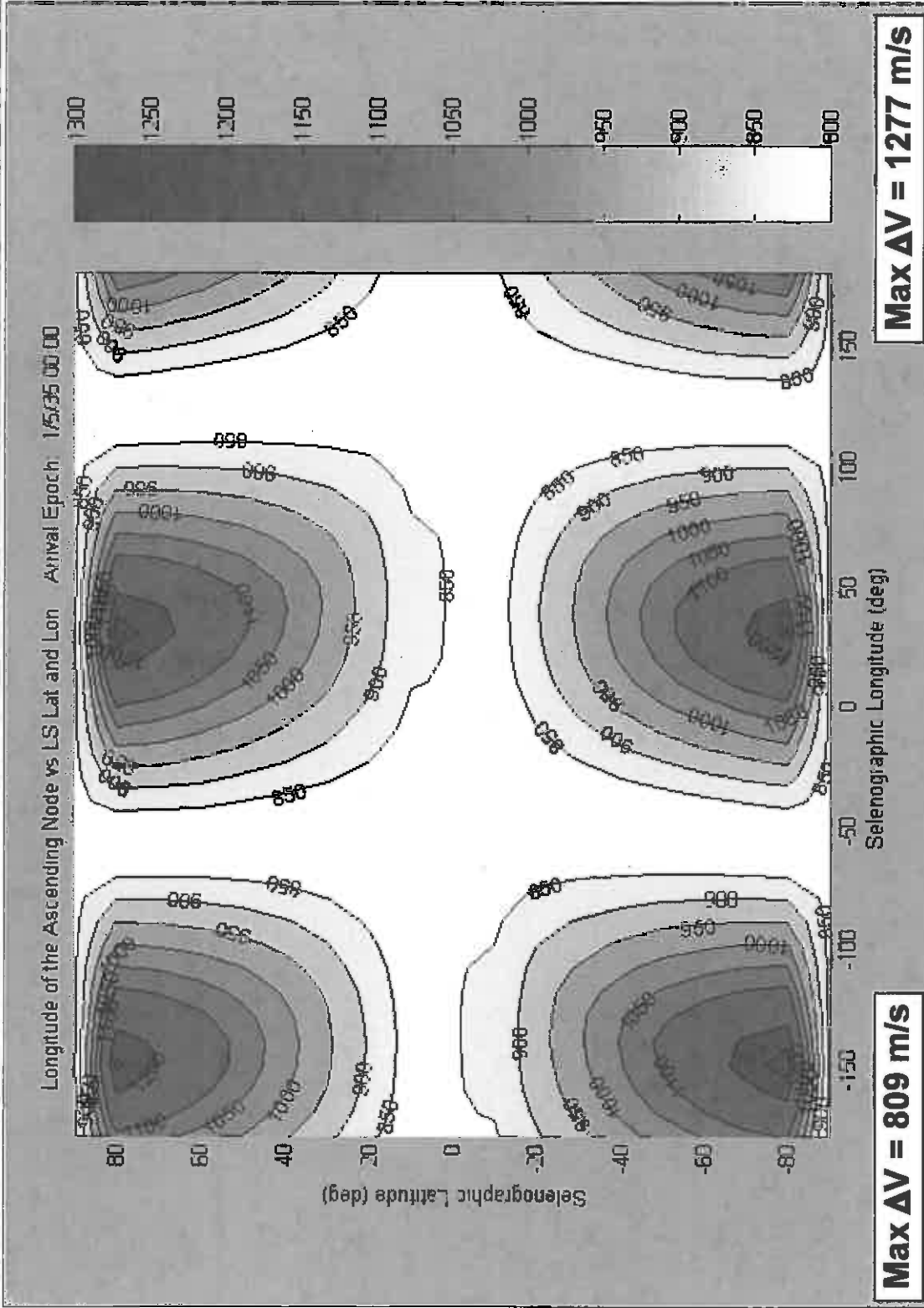
Arrival Epoch: 1/4/2035 12:00





Nominal Mission – LOI Delta-V

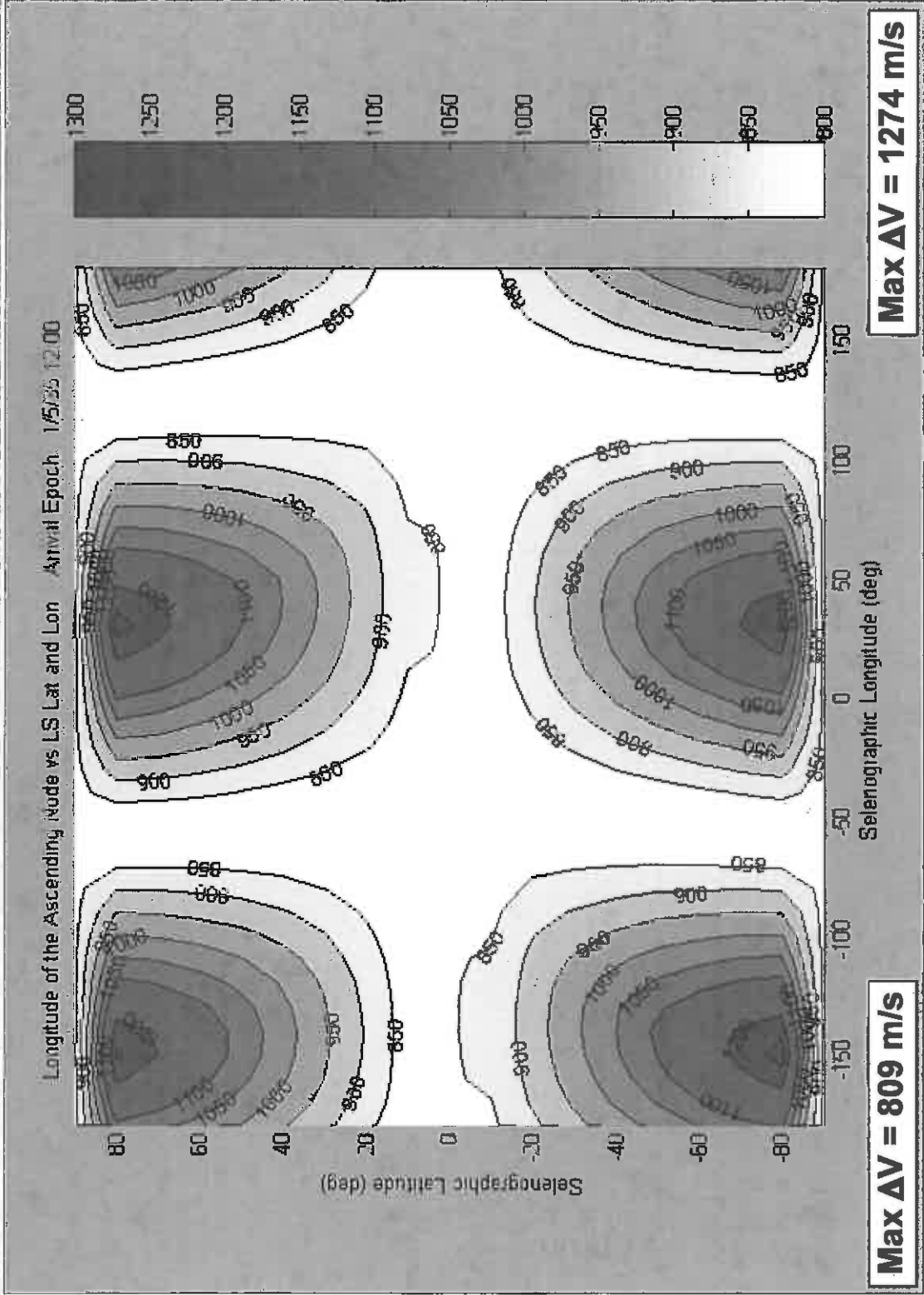
Arrival Epoch: 1/5/2035 00:00





Nominal Mission – LOI Delta-V

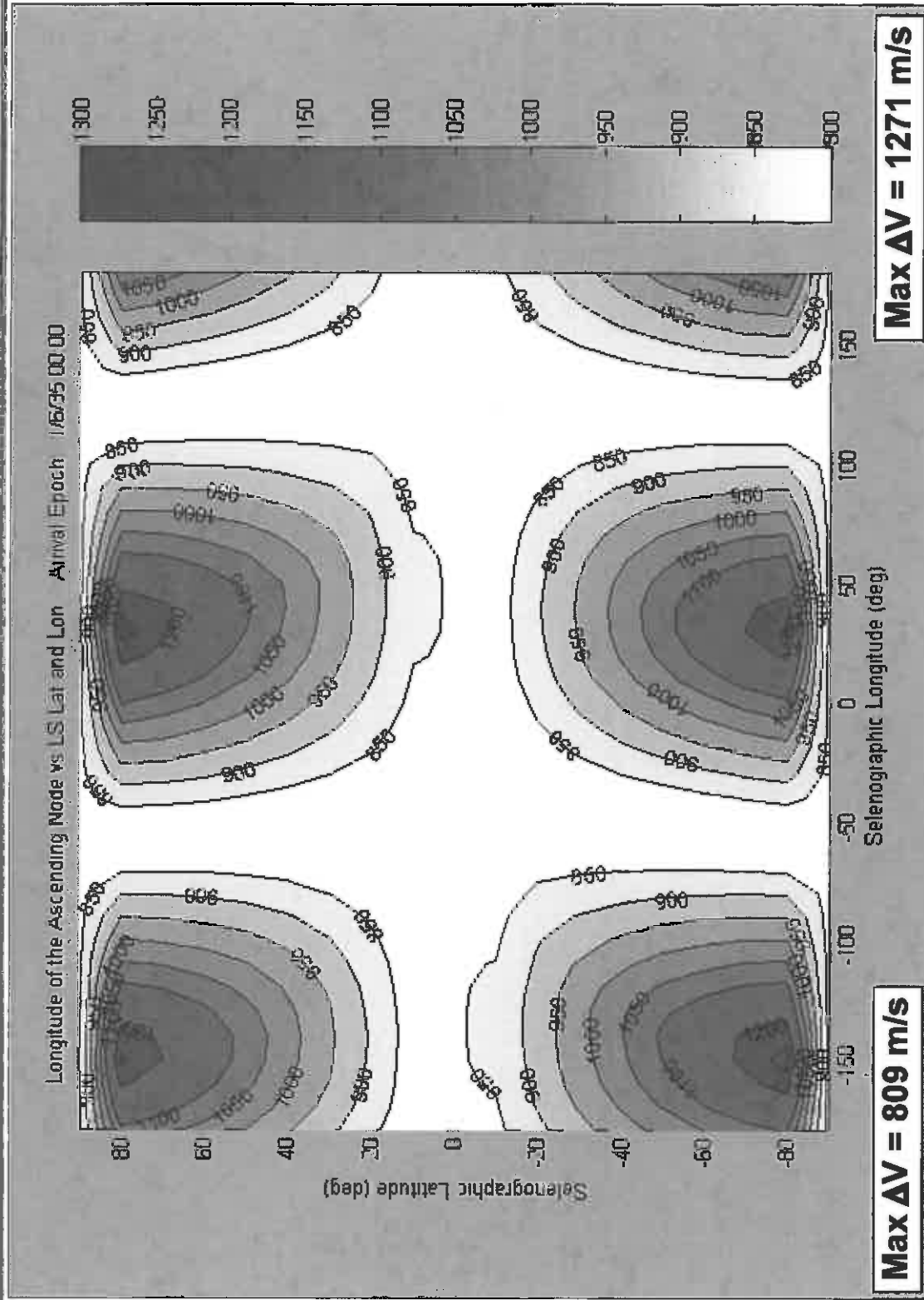
Arrival Epoch: 1/5/2035 12:00





Nominal Mission - LOI Delta-V

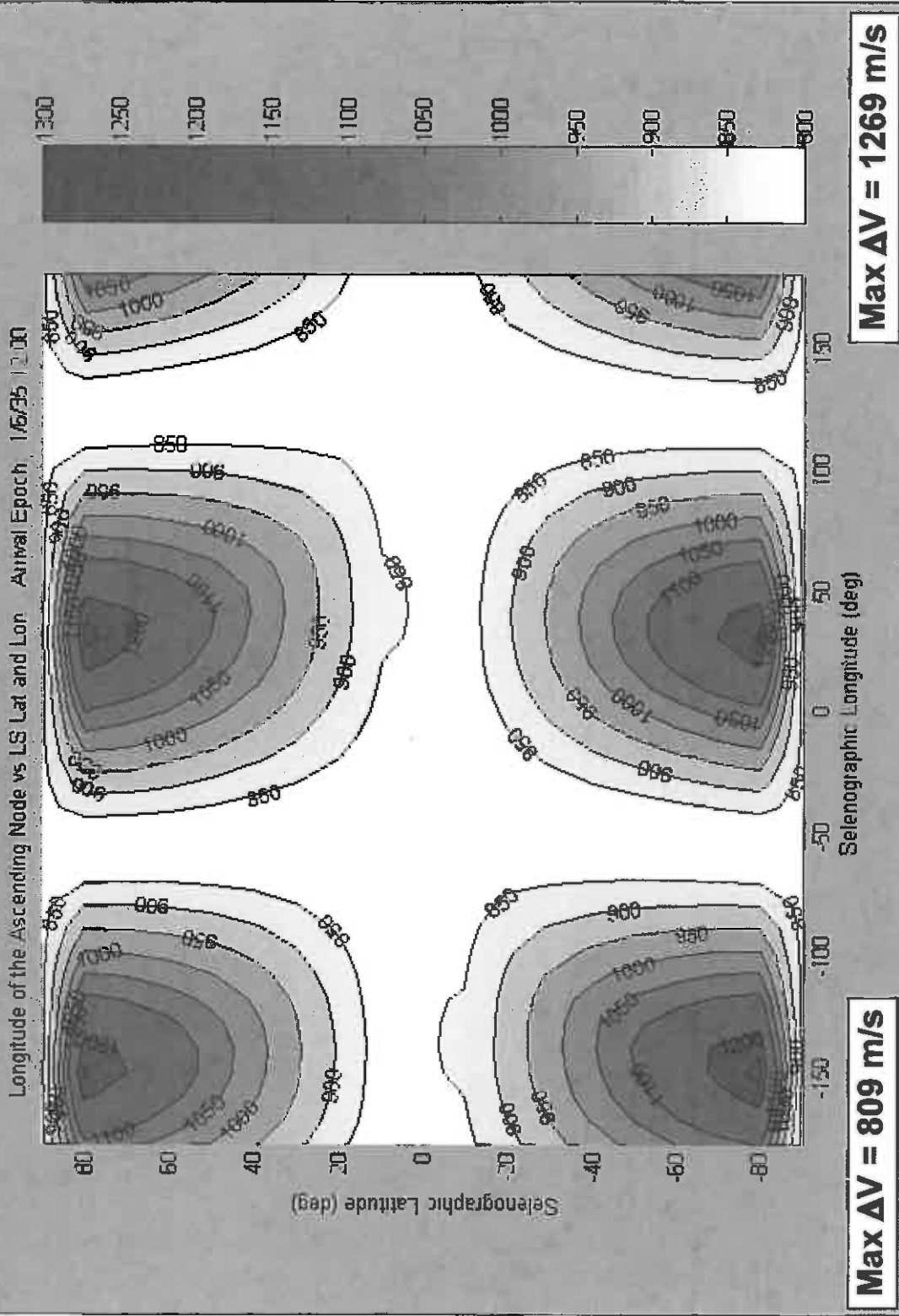
Arrival Epoch: 1/6/2035 00:00





Nominal Mission - LOI Delta-V

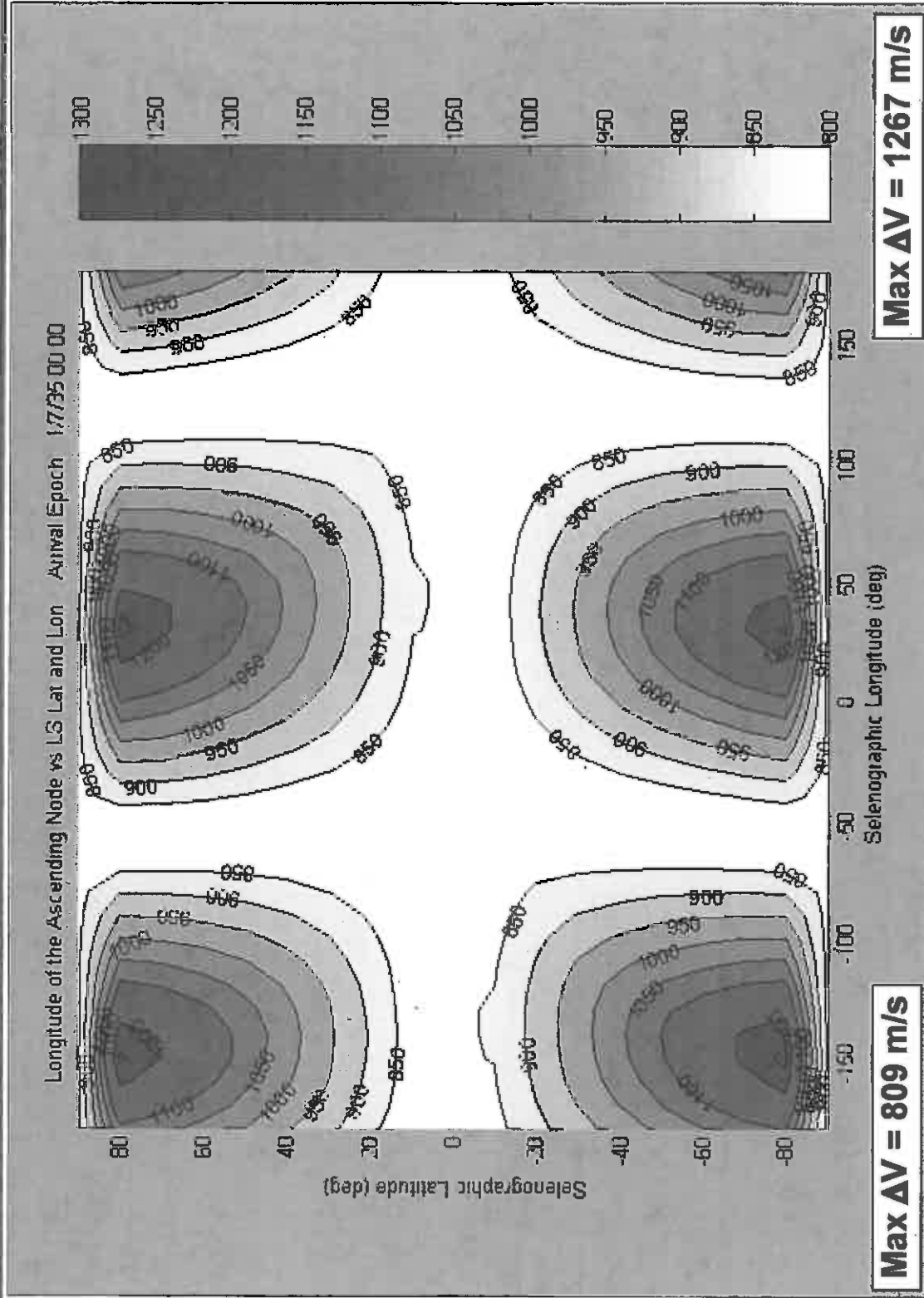
Arrival Epoch: 1/6/2035 12:00





Nominal Mission - LOI Delta-V

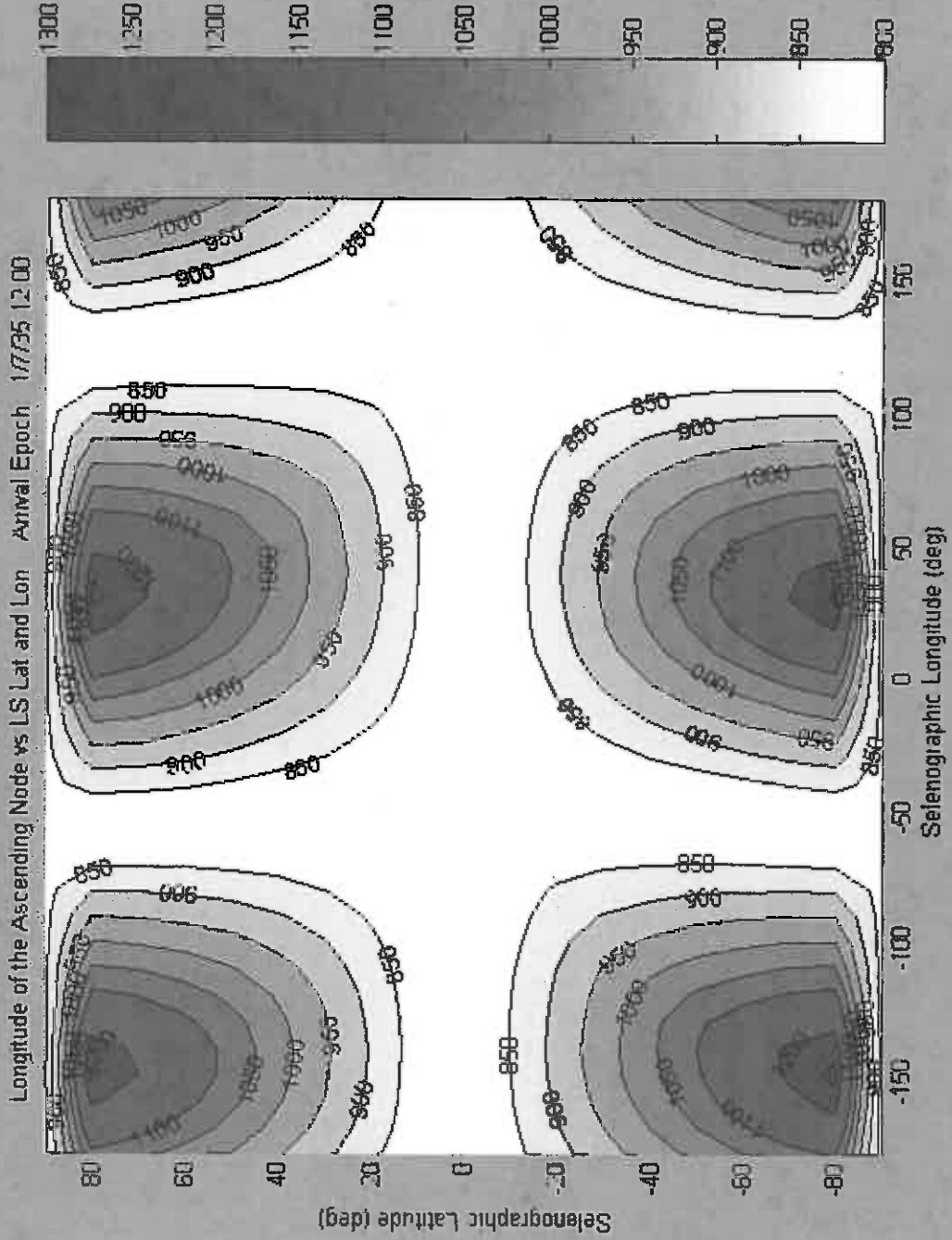
Arrival Epoch: 17/2035 00:00





Nominal Mission - LOI Delta-V

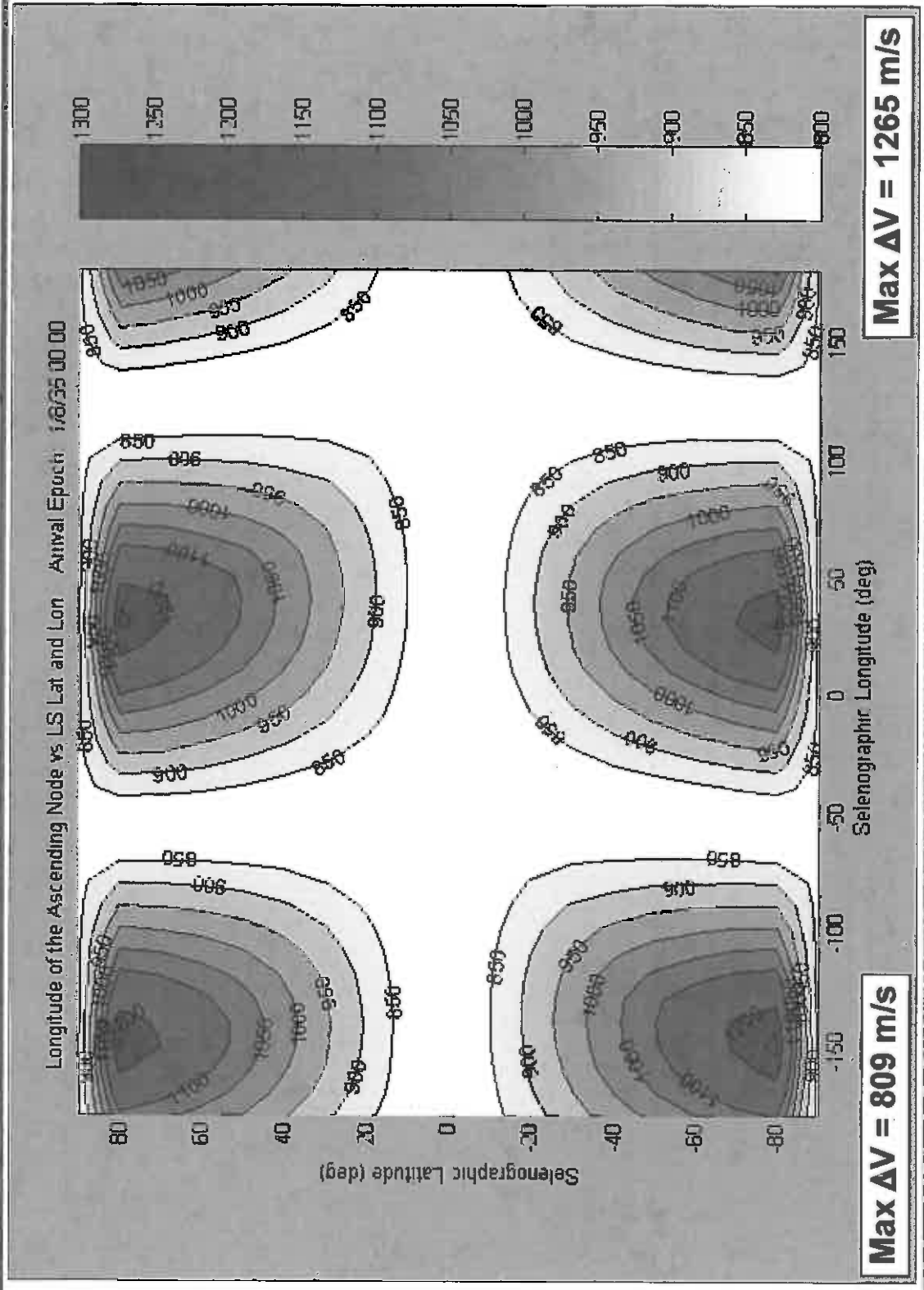
Arrival Epoch: 17/2035 12:00





Nominal Mission - LOI Delta-V

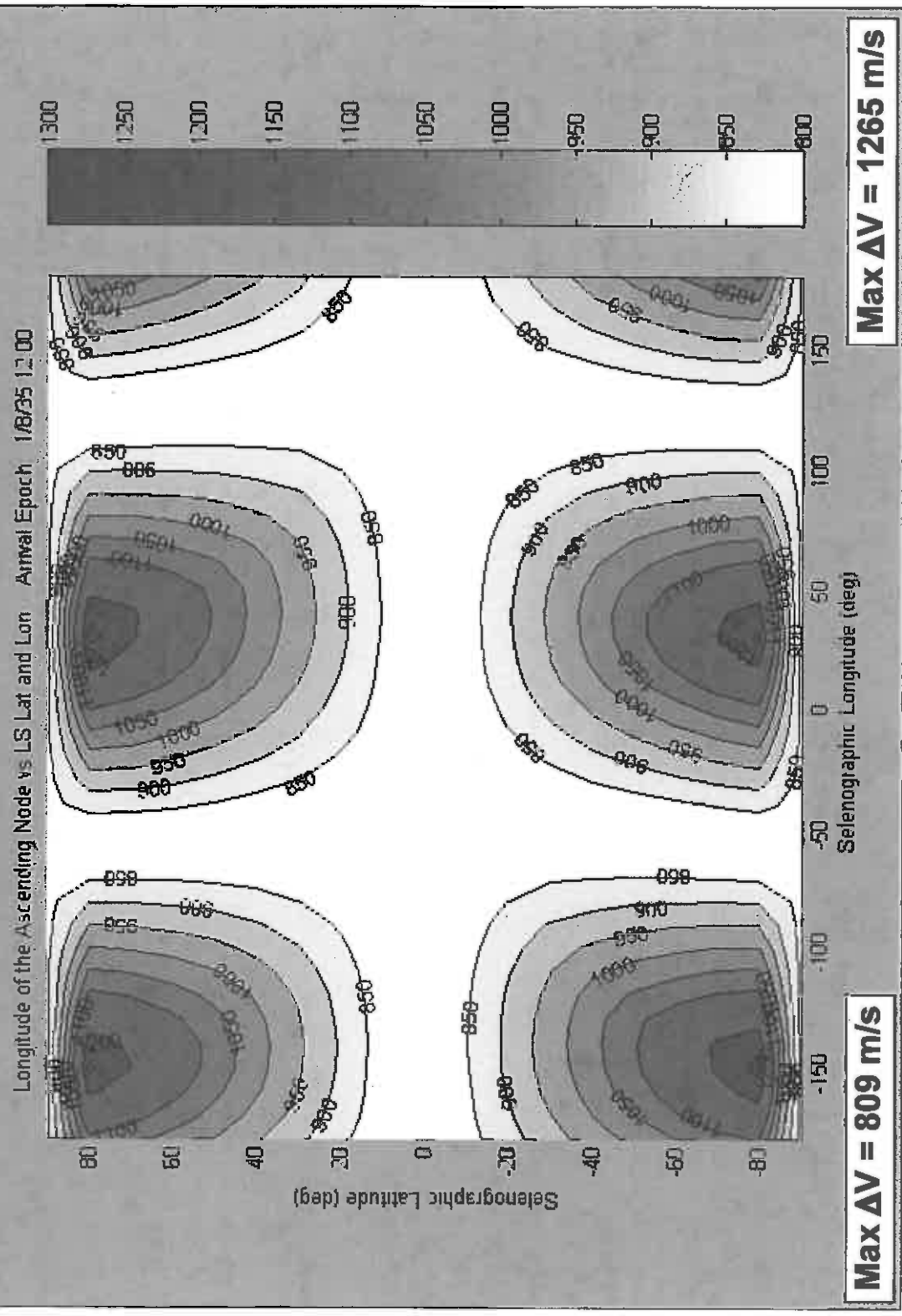
Arrival Epoch: 1/8/2035 00:00





Nominal Mission - LOI Delta-V

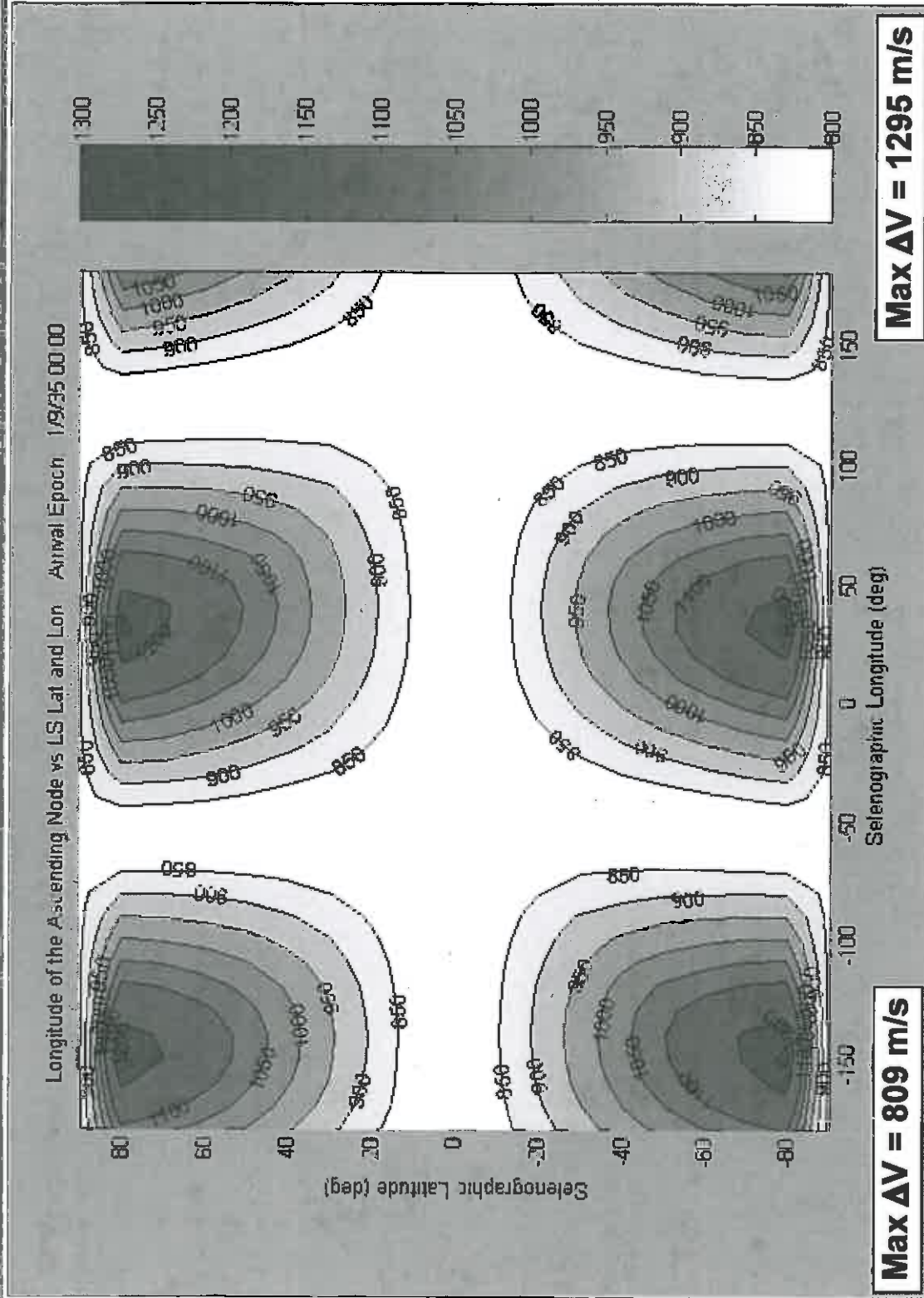
Arrival Epoch: 1/8/2035 12:00





Nominal Mission – LOI Delta-V

Arrival Epoch: 1/9/2035 00:00





Arrival Epoch Variation - Comments



- Some LOI ΔV reduction can be achieved through variation in arrival epoch
 - This could be accomplished by delaying the Earth launch and subsequent TLI (with preferred LEO RAN)
- The LOI ΔV reduction is less for epoch variation than for the case of lunar orbit loiter (for a given delay time)
 - In the case of the epoch variation, the delay time represents time expended prior to launch, before TLI
 - In the case of lunar orbit loiter, the delay time represents the time spent in lunar orbit prior to LSAM landing