Determination of the Performance-Optimum SSF Inclination for SSP Support Missions

Mark C. Allman
Rockwell Space Operations Co.
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1 Introduction

The purpose of this study is to identify Space Shuttle Program (SSP) ascent yaw steering performance savings by placing Space Station Freedom (SSF) in an orbit with an inclination slightly greater than 28.45 degrees. The overall objective is to identify methods and procedures which enhance SSF payload-to-orbit capability and increase payload flexibility.

2 Background

Launch opportunities arise when the rendezvous phasing window for the target (SSF) overlaps the range safety launch window of the chase vehicle (orbiter). The rendezvous phasing window is a launch timespan where rendezvous can be achieved on a certain flight day and within flight rules for proper approach and docking. SSP SSF assembly missions are currently baselined to rendezvous on the third flight day. This constraint reduces the number of launch opportunities, and therefore increases the importance of maximizing the launch window length as restricted by range safety and ascent performance constraints.

The optimal time of launch is when the target inertial orbital plane intersects the launch site latitude. This is referred to as the "in-plane" time. Launching at any other time and targeting the same orbital plane requires steering to that plane which costs performance (propellant). For rendezvous missions to the initial SSF baseline inclination of 28.45 degrees, the in-plane launch time occurs near the end of the window which is constrained by range safety (Figure 1, 28.45 degree curve). Examination of this curve shows that to launch when the range safety window opens incurs a performance cost on the order of 1300 lbs. Therefore to utilize the full range safety window, targeting the initial SSF baseline inclination, requires 1300 lbs of ascent performance margin.

3 Mechanics of Varying Inclination

The orbital inclination which minimizes performance requirements at the in-plane time is the same as the latitude of the launch site. This results in a launch azimuth of 90 degrees (due east) which maximizes the contribution from the Earth's rotational velocity to the vehicle's velocity. For rendezvous missions to an orbit at this inclination, the target plane will intersect the launch site latitude once (Figure 2, middle illustration). This intersection time is the optimum time of launch and any other launch time will require yaw steering to reach the target plane. The performance penalty relative to the in-plane launch time, measured as the extra propellent required to reach the target orbit, resembles a parabola (Figure 1, 28.45 degree curve).

For target orbits with inclinations lower than the latitude of the launch site there are no launch site-target plane intersections. Therefore a launch at any time will require performance to steer to the target orbit, with the minimum performance penalty occurring when the target orbit's northern-most point passes closest to the launch site (Figure 2, top illustration). The performance curve as a function of launch time is similar to the due-east case, but the minimum performance penalty is higher and the slope of the curve is larger (Figure 3).

Targeting to an orbit with an inclination greater than the latitude of the launch site results in two in-plane launch opportunities (Figure 2, bottom illustration). The launch azimuth of the first opportunity is north of due-east while the azimuth for the second opportunity is south. These opportunities, while optimum for the target inclination, will require additional propellent relative to the due-east case. The launch azimuth is no longer due-east and is therefore unable to take full advantage of the Earth's rotation rate. The performance curve as a function of launch time becomes somewhat W-shaped (Figure 4). The two minimums in the curve result from the two in-plane opportunities. The center rise-then-fall in performance cost corresponds to the launch times between the in-plane opportunities. An important point to notice from Figure 4 is that the launch window length, constrained only by performance, would be considerably wider than the due-east window for the same performance penalty.

4 Determining the Range Safety Launch Window Length

Space Shuttle Direct Insertion (DI) launches are constrained by range safety requirements for disposal of the External Tank (ET). Currently the ET disposal footprint cannot lie within 25 nm crossrange and within 200 nm uprange or downrange of a land mass. For DI missions the limiting land masses are Palmyra Island at window open and Hawaii at window close, with both limits being in crossrange distance. Also, the trajectories are constrained by Gilbert Island at the uprange limit and the west coast of North America at the downrange limit.

Figure 5 illustrates a typical ET disposal footprint for SSP SSF missions (DI to 160 nm apogee, 28.45 degree inclination). The footprints represent the range safety limiting cases which determine window open time, close time and window length (55 minutes for this example). Varying the orbital inclination changes the angle at which these footprints pass between Palmyra and Hawaii and therefore changes the window length slightly. For example, the window is reduced 2 minutes for a 28.80 inclination.

5 Evaluating Different Inclinations

The inclinations evaluated in the conceptual stage of this study were 28.05, 28.80, 28.85, 29.45 and the initial SSF baseline of 28.45 degrees. A 3 degrees of freedom (DOF) simulation program (SORT IV) was used to generate the trajectory data for the conceptual stage of the study. Subsequent detailed analyses and verification using 6-DOF simulation software (SVDS) were conducted with trajectory I-loads and inertial orbital plane (IY) targets produced for 28.79, 28.80, 28.81 and 28.45 degrees.

The Single Axis Roll (SAR) pitch and yaw values, along with throttle-up times, were optimized for each inclination at the in-plane and window open times, with the exception of 29.45--the in-plane time didn't fall in the range safety window. The trajectories were optimized at these times since they produce (approximately) mean optimum SAR pitch & yaw and throttle-up times for the launch window. The optimum SAR pitch & yaw and throttle-up times were then fixed and the launch times varied across the range safety window to evaluate performance requirements. For the conceptual phase of the project, which used 3-DOF SORT-IV software, the target ascending node was actually changed since SORT assumes the targets are Earth-fixed and not inertial. Additionally, optimum SAR pitch & yaw and throttle-up times at points across the window were also computed and used to obtain a theoretical best-performance curve. Figure 6 illustrates this for the 28.80 inclination case.

The inclination which minimizes the performance penalty across the entire range safety window is the inclination where the performance penalties at launch window open and close are the same. Analysis of the 28.85 inclination results using 3-DOF simulation indicated that a 28.80 trajectory optimized at the launch window open time (see Figure 1) would equalize the performance penalties. Subsequent evaluation of 28.80, employing a fixed SAR yaw angle of 86 degrees, yielded a difference in performance penalties at window open and close of about 6 lbs.

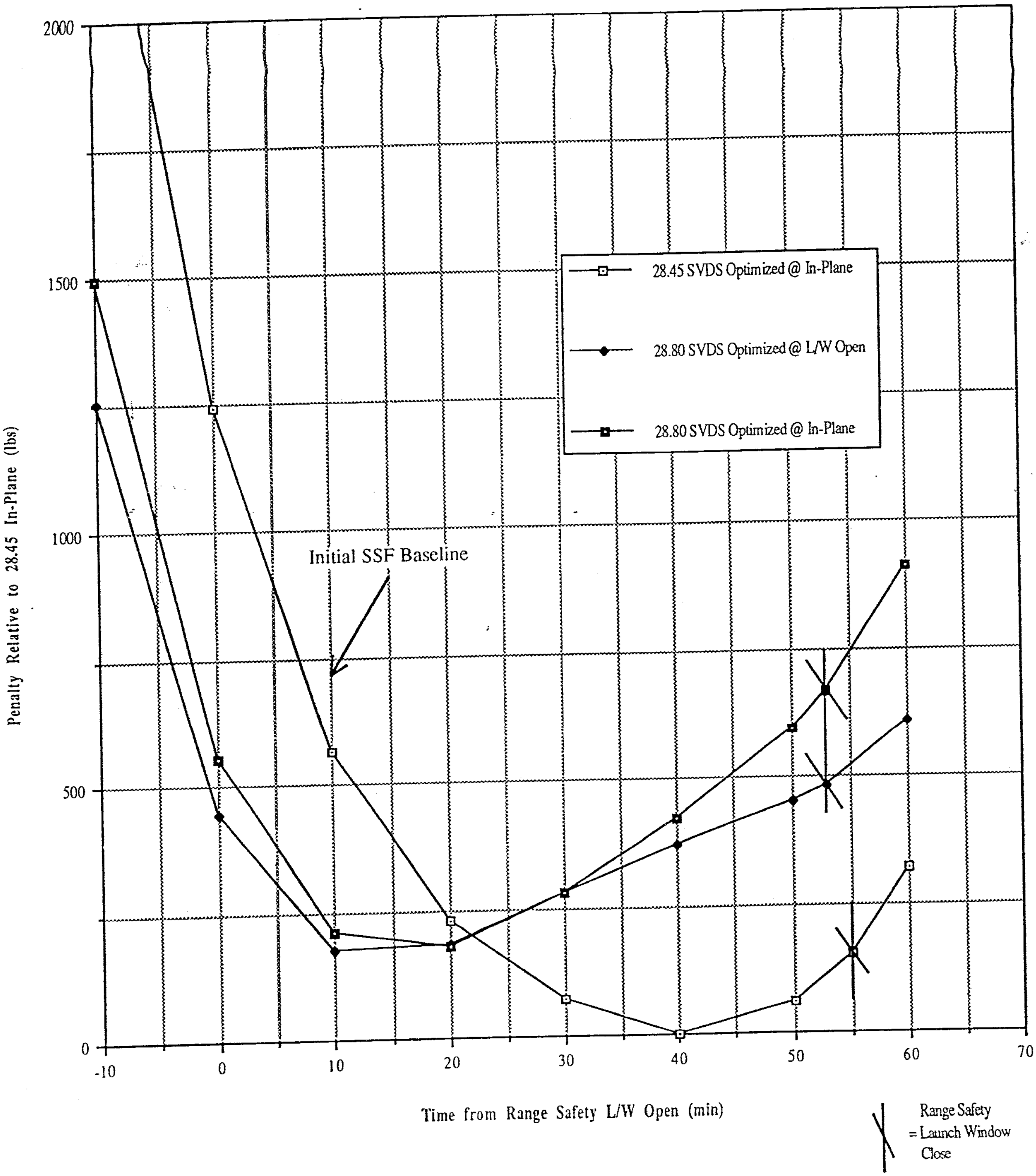
The conceptual results obtained using 3-DOF simulation (Figure 6) furnished both a proof-of-concept and an approximate optimum inclination. Subsequent 6-DOF detailed analyses (Figure 1) have both verified the performance savings proof-of-concept and provided accurate trajectory data for determination of the optimum inclination. Comparison of the 3-DOF and 6-DOF simulation results (Figure 7) shows that the relative performance curves obtained by the two simulators agree to within 50 lbs.

6 Conclusion

Placing SSF in a 28.80 degree inclination orbit and optimizing the trajectory at the range safety window open time will reduce the required SSP ascent performance margin for SSF support missions. Potential yaw steering performance savings per mission relative to the initial SSF baseline are approximately 800 lbs (58%) and reduce the range safety window by only 2 minutes (3.6%). As can be seen from Figure 1, constricting the launch window approximately 14 minutes (25.5%) and targeting the initial SSF baseline inclination of 28.45 degrees will also reduce the performance margin by 800 lbs. However, as stated earlier, performance margin reductions must also maximize the range safety window length. Therefore this study concludes that the optimum performance and launch window length will be achieved by placing SSF at an orbital inclination of 28.80 degrees.

The Johnson Space Center (JSC) Mission Operations Directorate (MOD) and the Space Shuttle Program Office (SSPO) have accepted these results and recommended the SSF baseline inclination be changed to 28.80 degrees. Review by the Space Station Freedom Program Office (SSFPO) and NASA Level 2 management is in progress.

Figure 1
Performance Penalty Across the Range Safety Launch Window
Optimization at Window Open and In-Plane Times



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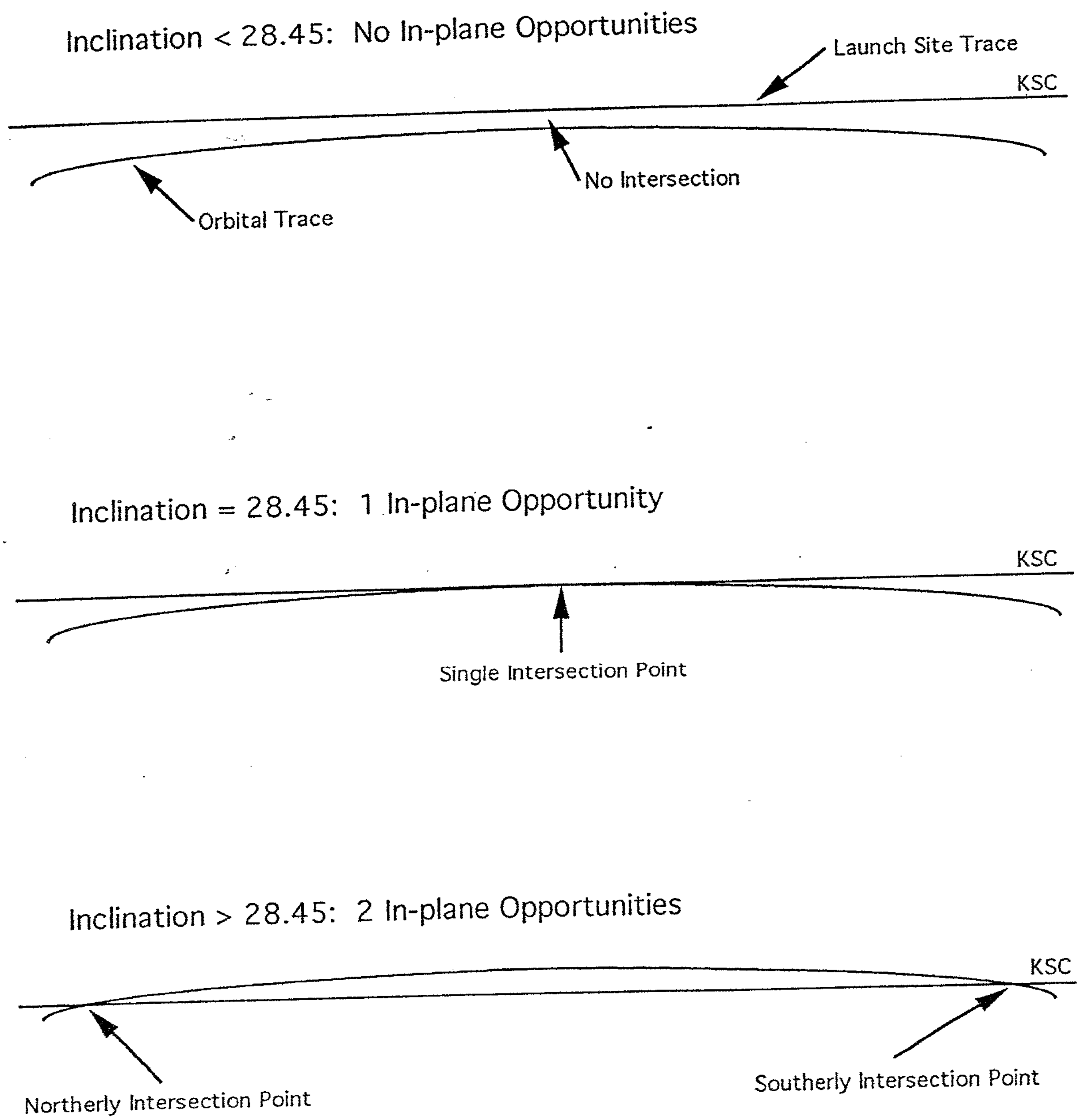

Figure 2

In-Plane Launch Opportunities as a Function of Inclination

Figure 3
Performance Penalty Across the Launch Window
28.05 Degree Inclination SORT Results

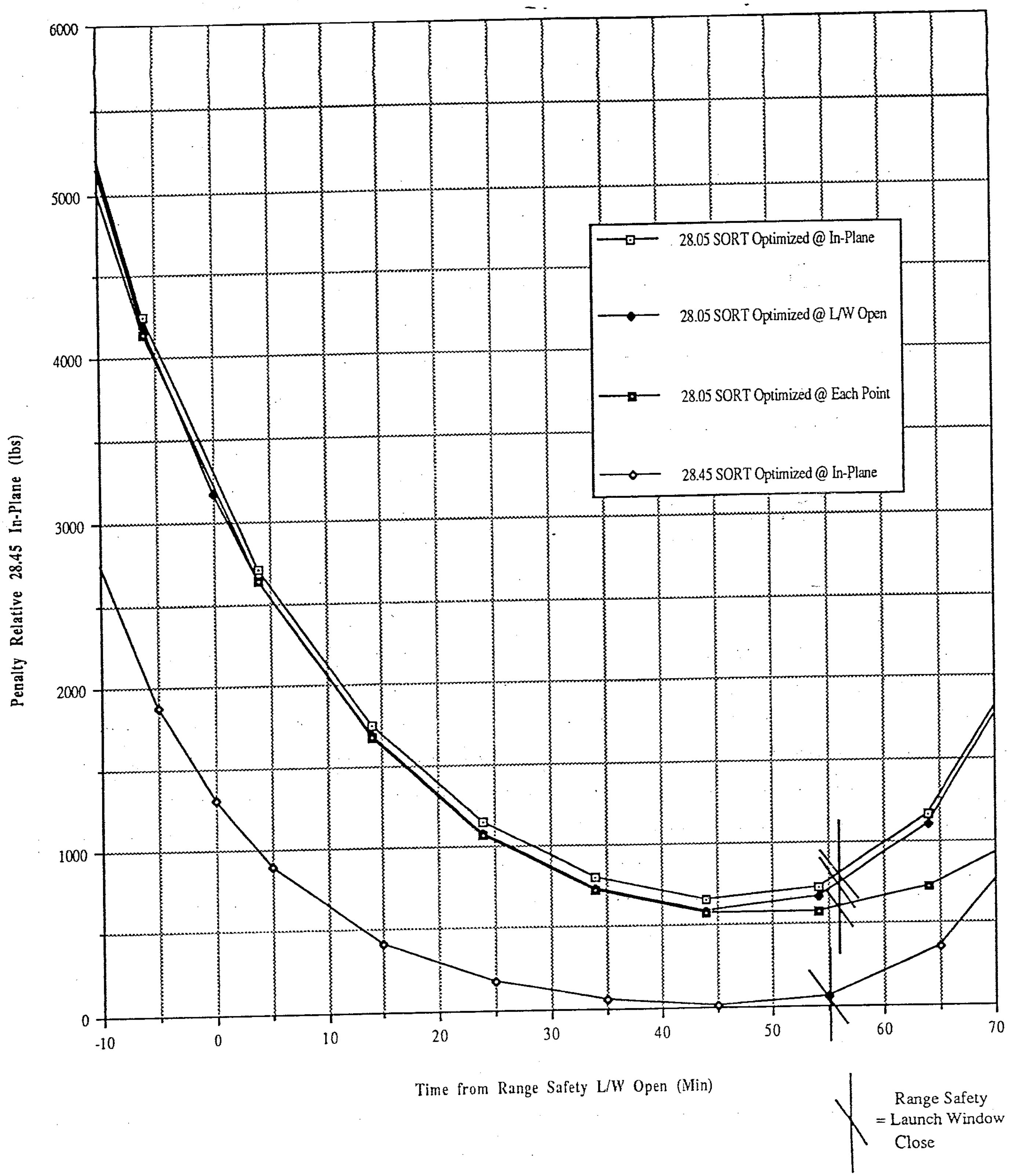

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Figure 4
Characteristic Performance Penalty Curves
Inclination 28.45 Degrees and *Inclination > 28.45 Degrees*

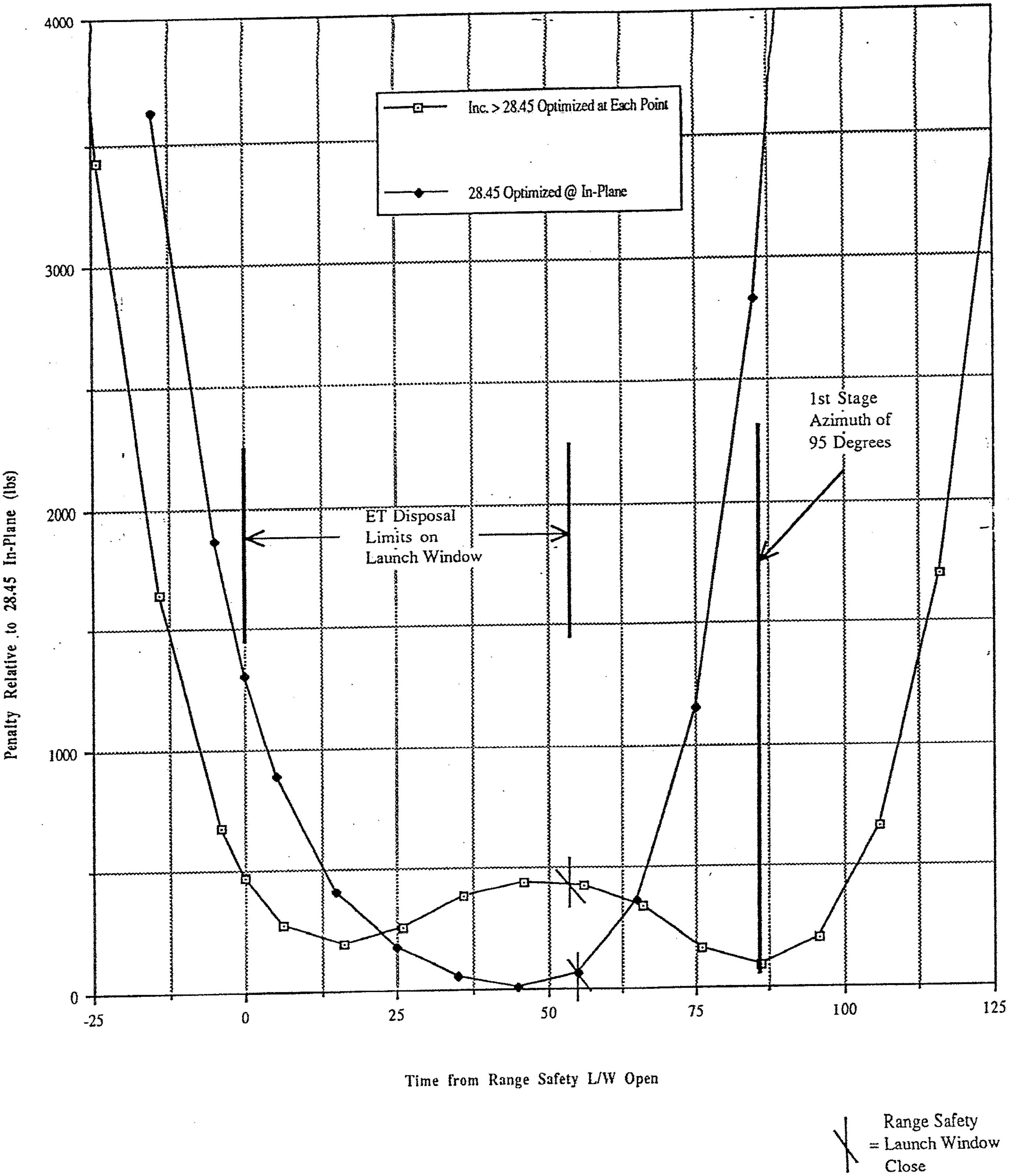


Illustration of the External Tank Disposal
Footprints at Launch Window Open and Close

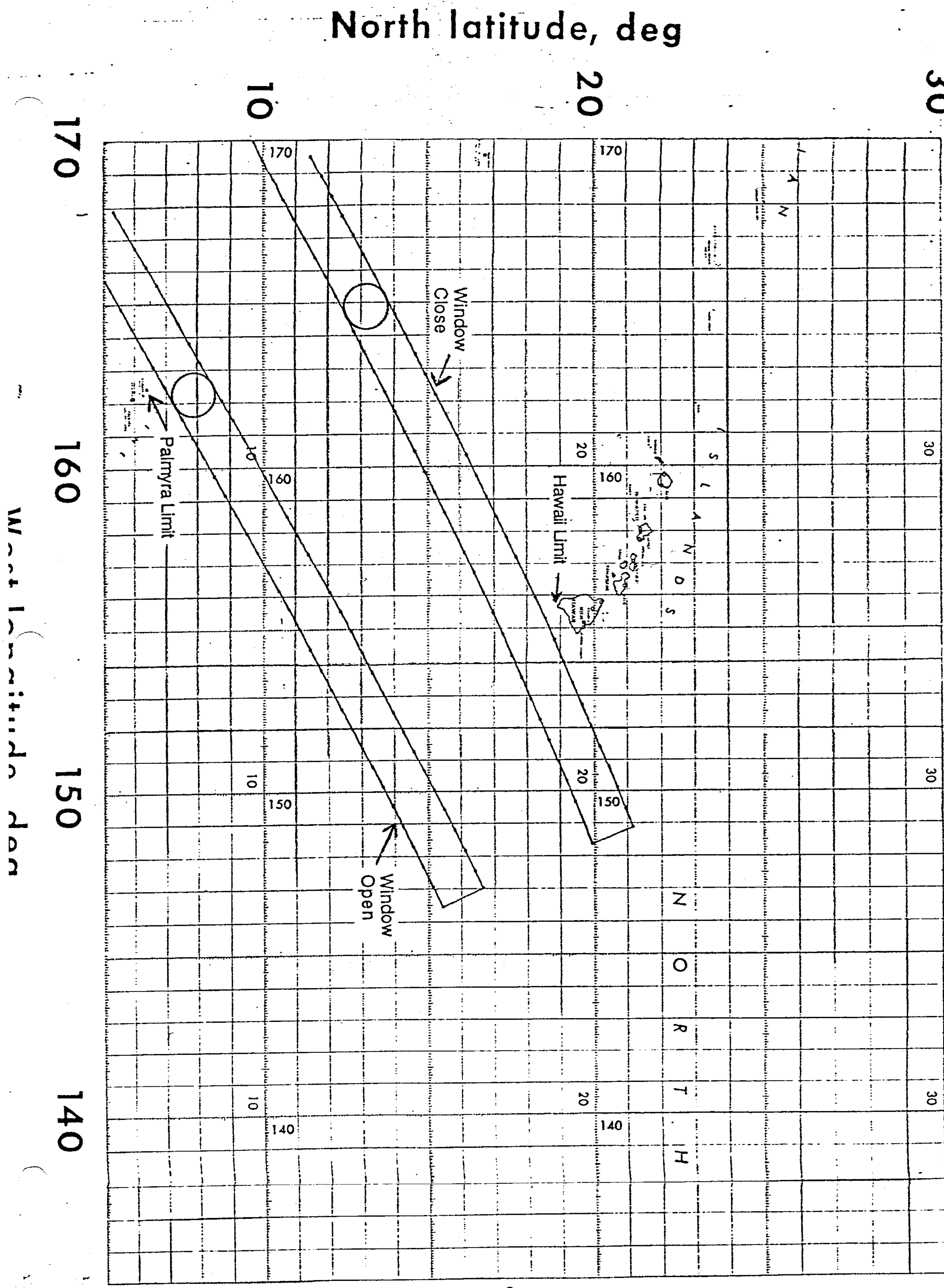


Figure 6
Performance Penalty Across the Launch Window
28.80 Degree Inclination SORT Results

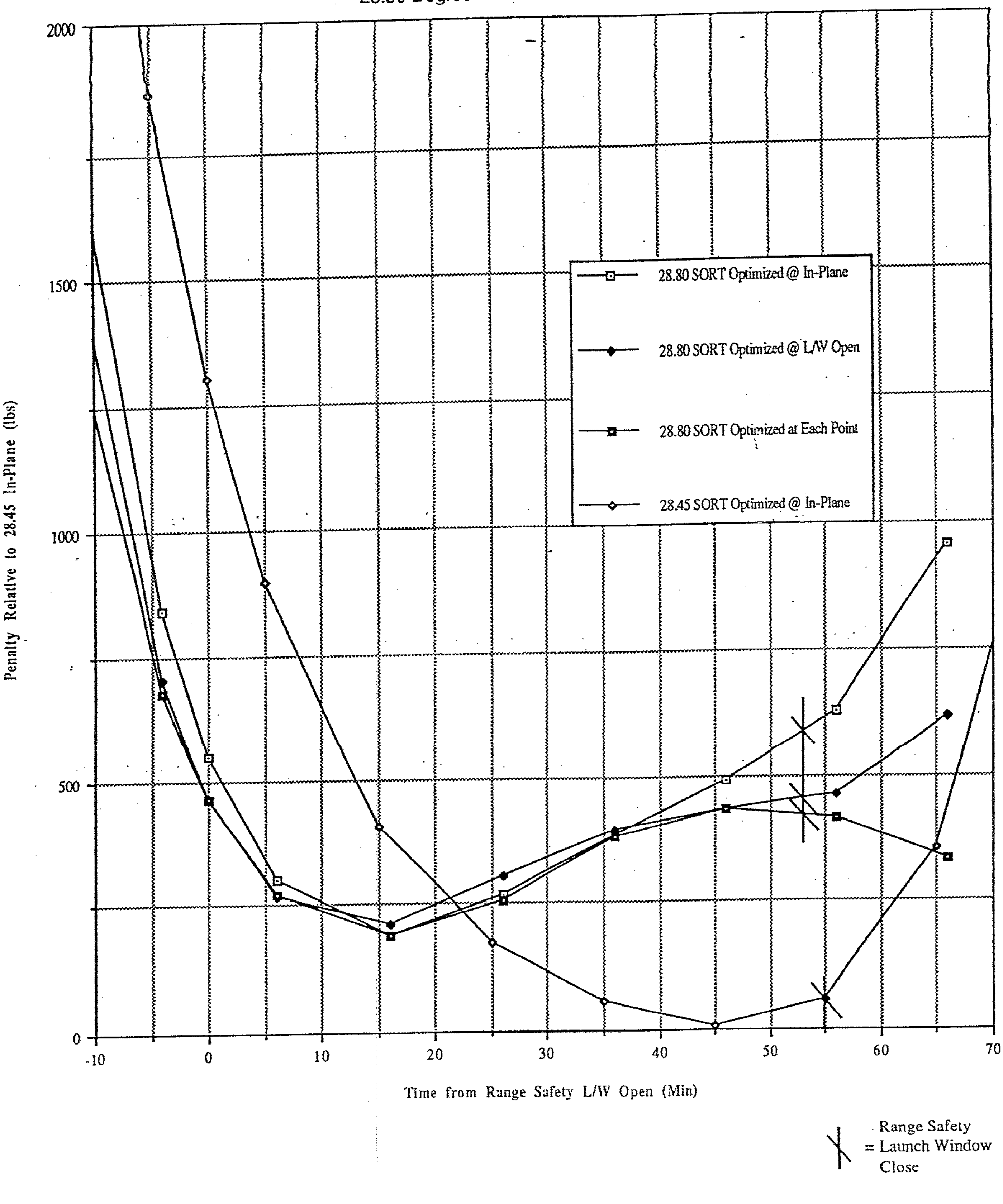
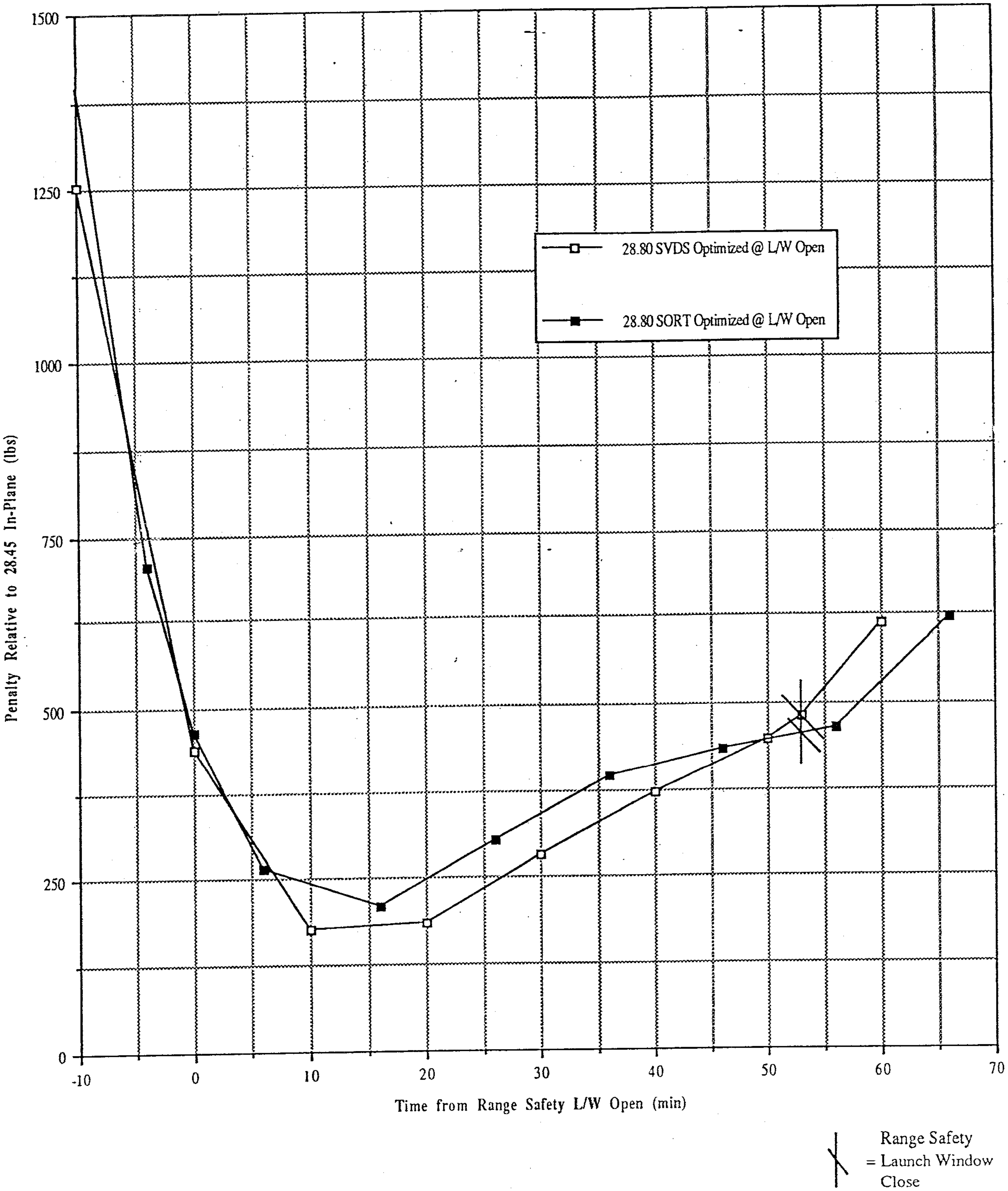


Figure 7
Performance Penalty Across the Launch Window
Comparison of SORT and SVDS Results



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