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SPACE LAUNCH SYSTEM

08/21/2018

Closed Loop Guidance Trade Study for Space Launch System Block-1B Vehicle

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2018 Astrodynamics Specialist Conference

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- Motivation & Pre-Trade Investigations
- Trade Study Goals
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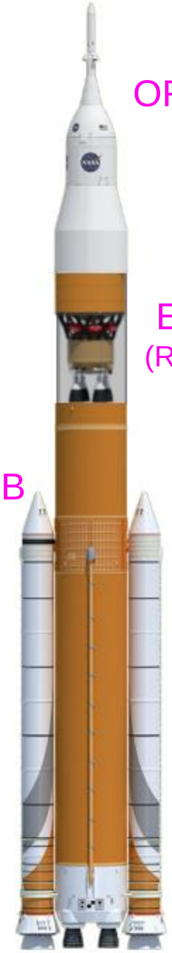
Background

SLS BLOCK-1
70 tons to LEO

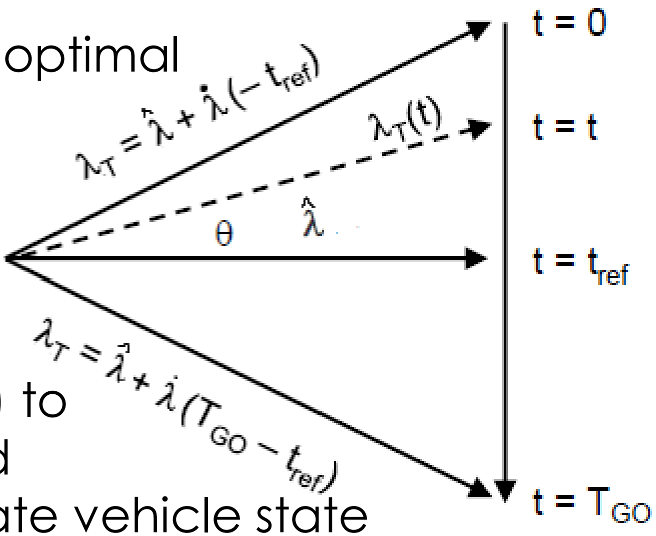
- **NASA Marshall Space Flight Center (MSFC) is currently building the Space Launch system (SLS) Block-1 launch vehicle for the Exploration Mission 1 (EM-1) test flight**
  - Block-1 ascent profile is similar to Space Shuttle
    - Allows for use of a modified version of Shuttle's Powered Explicit Guidance (PEG), a Closed Loop Guidance (CLG) algorithm
  - Contains two Solid Rocket Boosters (SRBs), a single core stage powered by four RS-25 engines, and the Interim Cryogenic Propulsion Stage (ICPS)
  - MSFC is only responsible for ascent portion of Guidance Navigation & Control (GN&C) design, requiring insertion of payload into 22X975 Nmi orbit
- **Meanwhile, design of the next evolution of SLS Block-1B is underway for future missions**
  - Characteristics of Block-1B are inherited from Block-1 but with a new upper stage: Exploration Upper Stage (EUS) powered by 4 RL-10 engines
  - Extends MSFC's GN&C responsibility to ascent and in-space trajectories.
  - More than doubles burn durations compared to Block-1 ascents



SLS BLOCK-1B
105 tons to LEO

Algorithm Backgrounds

- **PEG**
  - Semi-analytical predictor-corrector algorithm
  - Uses Linear Tangent Guidance (LTG) result from optimal control minimum time problem
    - $\boldsymbol{\lambda_T} = \hat{\boldsymbol{\lambda}} + (T - t_{ref})\dot{\boldsymbol{\lambda}}$
    - $\hat{\boldsymbol{\lambda}}$ *and* $\dot{\boldsymbol{\lambda}}$ are orthogonal co-states ; $\boldsymbol{\lambda_T}$ is direction of optimal thrust at time, T
    - t_{ref} is the reference time
  - Iterates and uses velocity to gain by thrust (vgo) to analytically solves for initial co-state vectors and reference time which are then used to propagate vehicle state
  - Correction to vgo is based on difference between desired and actually velocity at burn cutoff



- **Optimal Guidance (OPGUID)**
  - Semi-analytic predictor algorithm
  - Satisfies all the necessary conditions of optimality, including the Euler-Lagrange equations
  - Iterates on initial co-state vectors and burn time
  - Correction to the co-state and burn time based on achieved state using Newton-Raphson correction method

PEG uses LTG and OPGUID satisfies all the necessary conditions of optimality, including the Euler-Lagrange equations

Motivation and Pre-Trade Investigations

- **Block-1B ascent trajectories proved challenging for Block-1 version of PEG**
  - EUS's low thrust- to-weight and higher-energy target orbits significantly increased ascent profile (to ~17-to-20 minutes)
  - Longer duration = burn arcs 35^0-to-50^0 (Block-1B) versus 15^0 (Block-1)
  - Engine failures stressed flat earth assumption used in PEG Linear-Tangent steering law leading to either convergence issues or seriously degraded performance

- **OPGUID, a CLG algorithm used on previous projects at MSFC, was able to run the Block-1B ascent and in-space trajectories**
  - Has been used for Constellation program, official Block 1 ICPS in-space insight trajectories, and advanced GN&C project

- **Since the Block 1B ascent trajectories have proven challenging, it was prudent to trade PEG (Enhanced Shuttle PEG) against OPGUID to ensure the choice for the guidance system meets the future needs of the evolved SLS vehicle**
  - As a result of earlier Block-1B analysis, SLS guidance team further enhanced Block-1 version of PEG to accommodate long burn profile and stressing engine-out cases. For further information, see "Powered Explicit Guidance Modifications & Enhancements for Space Launch System Block-1 and Block-1B Vehicle"

Trade PEG against OPGUID to ensure proper choice of Guidance Algorithm

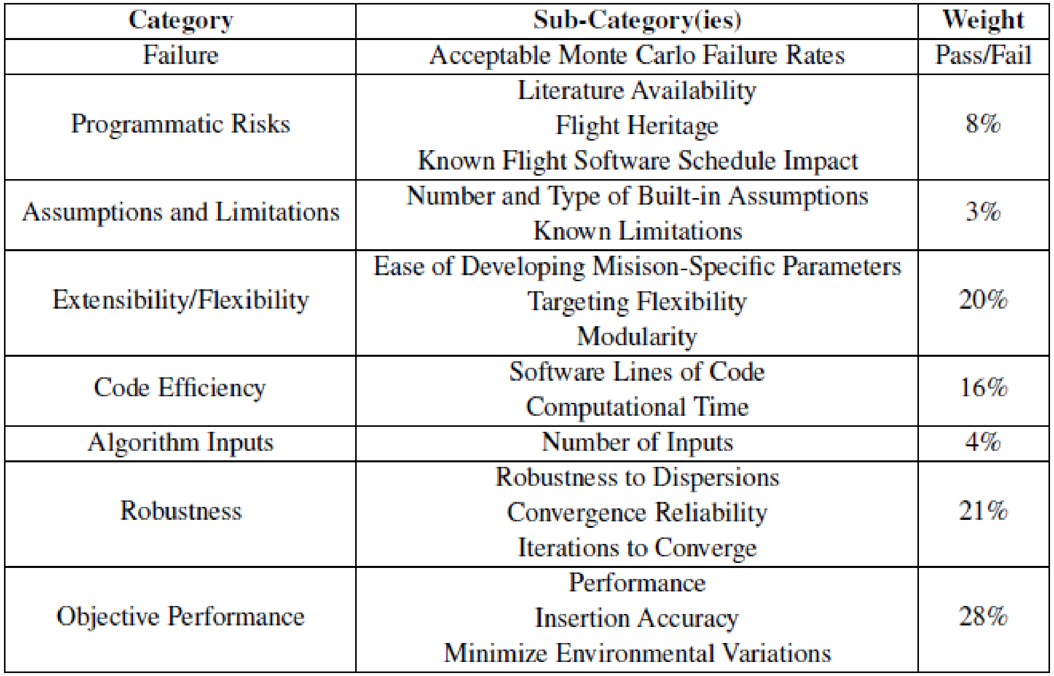
Trade Study Goals

- **Desired to have CLG algorithm that can perform multiple burns**
  - Block-1B class missions include ARB, TLI, Earth Departure Burn (EDB) and RCS Disposal
- **Needs to be able to handle long burn arcs on the order of 1000 seconds (17 minutes)**
  - Long mission duration cause larger burn arcs (35 degrees) and fundamental assumption needs to be insensitive to this
- **Works well with multiple stages that have drastically different acceleration levels and thrust-to-weight**
- **Includes targeting flexibility**
  - Able to take on new missions with a well understood path forward to implement new targeting schemes
- **Correct level of accuracy for models**
  - For example: thrust and gravity
- **Balance computational complexity and robustness**
  - For example: modularity, runtime, and software lines of code
- **Identification of algorithm assumptions and limitations**
- **Minimization of programmatic risks such as Flight Software (FSW) Readiness schedule and cost impacts**
- **Accommodates single engine failure (RS-25 or RL-10).**
  - Able to successfully meet objective under Monte Carlo (MC) 3-sigma stressing cases

Team's desire to select proper algorithm led to identification of Trade Study Goals

Categories, Weights & Scoring

- **Review Team was established to conduct trade study**
- **Based on trade study goals, Review Team came up with general categories and assigned subjective weighting**
  - For example, Objective Performance was deemed most desirable. Next to it, Robustness and Extensibility/Flexibility category being next two important categories.
  - Failure Category was straight forward Pass/Fail.



Category	Sub-Category(ies)	Weight
Failure	Acceptable Monte Carlo Failure Rates	Pass/Fail
Programmatic Risks	Literature Availability Flight Heritage Known Flight Software Schedule Impact	8%
Assumptions and Limitations	Number and Type of Built-in Assumptions Known Limitations	3%
Extensibility/Flexibility	Ease of Developing Misison-Specific Parameters Targeting Flexibility Modularity	20%
Code Efficiency	Software Lines of Code Computational Time	16%
Algorithm Inputs	Number of Inputs	4%
Robustness	Robustness to Dispersions Convergence Reliability Iterations to Converge	21%
Objective Performance	Performance Insertion Accuracy Minimize Environmental Variations	28%

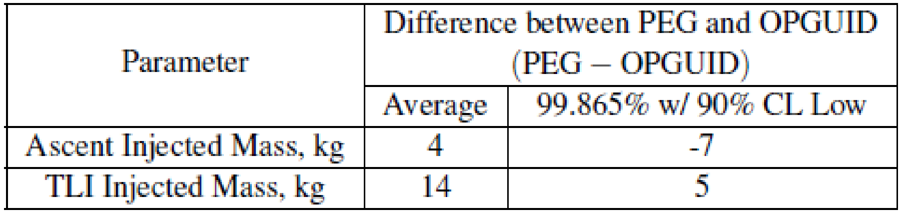
- **Scoring for each sub-category was subjective based on inputs from Guidance team's experience and Review Team.**
  - Qualitative scoring: Literature availability, Flight Heritage/TRL, FSW schedule impact, Number of built in assumption and limitations, Targeting Flexibility and Modularity
  - Quantitative scoring: Engine Failure, Ease of mission specific I-Loads, Software Lines of Code (SLOC), computational time, number of inputs, Robustness to dispersions, Convergence reliability and iteration to converge.

Based on Trade Goals, Review Team defined categories, assigned subjective weighting with qualitative and quantitative scoring

Trade Study Results

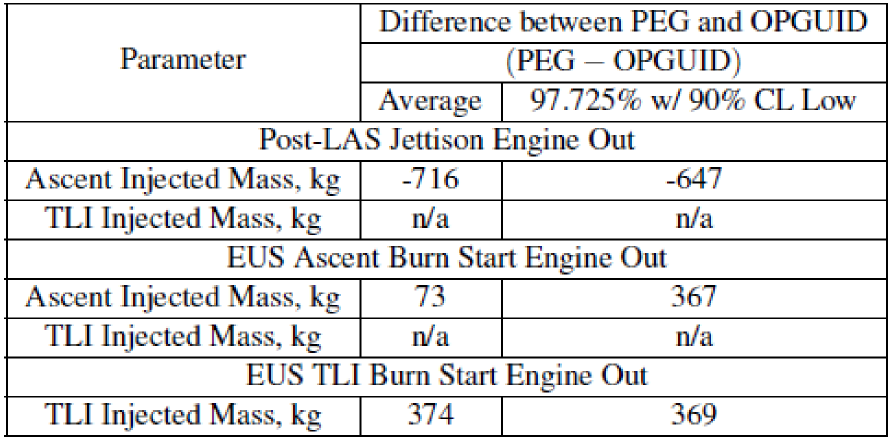
- **More than half of the categories resulted in a tie**
  - Failure
    - Both OPGUID and PEG performed all SLS mission trade study MCs with no failures
  - Extensibility/Flexibility
    - it was fairly easy to develop and tune mission specific inputs for each algorithm
    - Both algorithms demonstrated flexibility in adapting new set of target routines
  - Robustness
    - Both algorithm showed robustness to dispersions when observing their performance, vehicle rates, attitudes and convergence behavior during flight and at the end of each burn
  - Algorithm Inputs
    - Similar number of inputs required for both of these algorithms
  - Objective Performance
    - Difference in mass-to-orbit were within 200 lbm for nominal mission.
    - Apogee/Perigee and plane errors were within desired range

Mass to orbit differences between PEG and OPGUID was insignificant for nominal mission



Parameter	Difference between PEG and OPGUID (PEG – OPGUID)	
	Average	99.865% w/ 90% CL Low
Ascent Injected Mass, kg	4	-7
TLI Injected Mass, kg	14	5

In an engine failure situation, mass to orbit difference depend on time of the failure



Parameter	Difference between PEG and OPGUID (PEG – OPGUID)	
	Average	97.725% w/ 90% CL Low
Post-LAS Jettison Engine Out		
Ascent Injected Mass, kg	-716	-647
TLI Injected Mass, kg	n/a	n/a
EUS Ascent Burn Start Engine Out		
Ascent Injected Mass, kg	73	367
TLI Injected Mass, kg	n/a	n/a
EUS TLI Burn Start Engine Out		
TLI Injected Mass, kg	374	369

PEG & OPGUID were mostly tie with similar performance

Trade Study Results

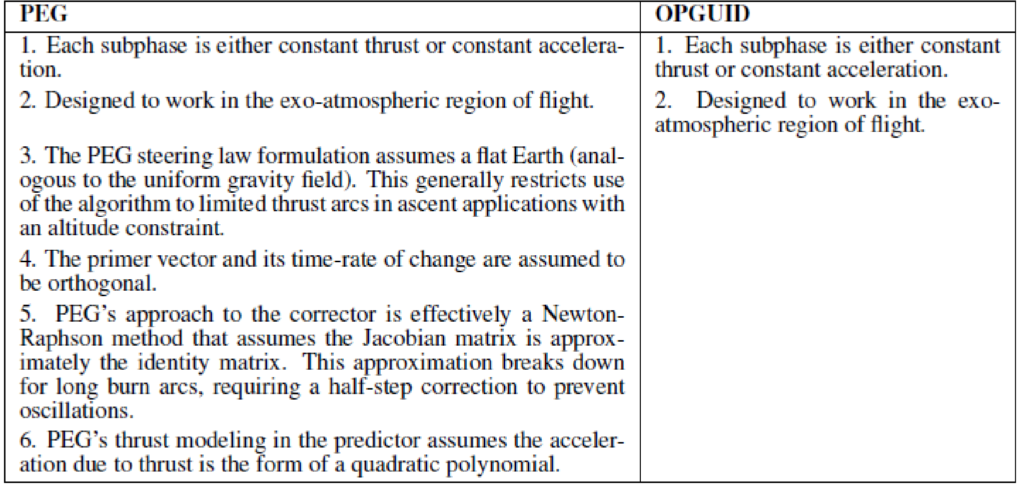
- **PEG was the winner in Programmatic Risks and Code Efficiency Categories. Received +5.6 points**
  - 47% shuttle heritage
  - 26% code needed to be brought under FSW coding standards as compare to 99% for OPGUID
  - SLOC count for PEG was 2488 where as OPGUID was at 4131
- **OPGUID was the winner in Assumption/Limitation category Received +3.2 points**
  - PEG had 3x number of assumption and 5x number of limitations as OPGUID

Final Score:

PEG: 51.7%

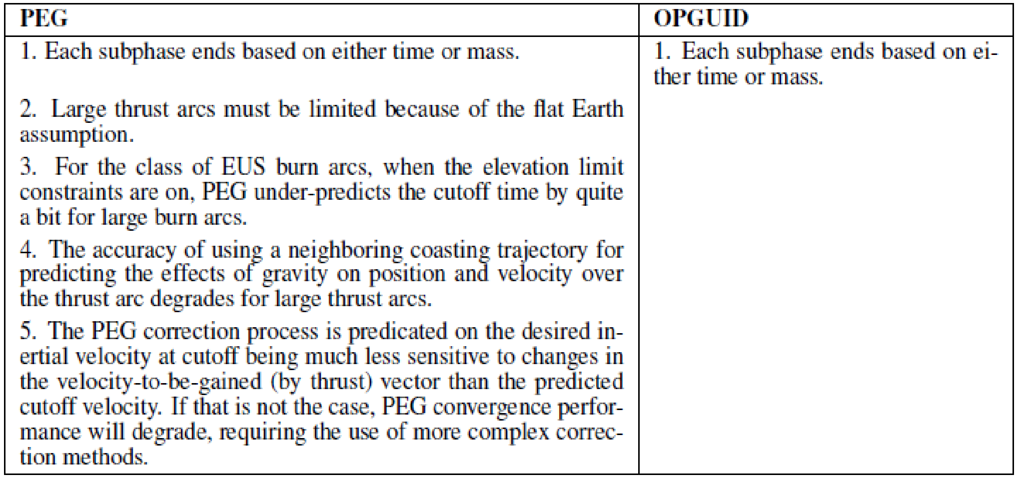
OPGUID: 48.3%

Algorithm Assumptions



PEG	OPGUID
1. Each subphase is either constant thrust or constant acceleration. 2. Designed to work in the exo-atmospheric region of flight. 3. The PEG steering law formulation assumes a flat Earth (analogous to the uniform gravity field). This generally restricts use of the algorithm to limited thrust arcs in ascent applications with an altitude constraint. 4. The primer vector and its time-rate of change are assumed to be orthogonal. 5. PEG's approach to the corrector is effectively a Newton-Raphson method that assumes the Jacobian matrix is approximately the identity matrix. This approximation breaks down for long burn arcs, requiring a half-step correction to prevent oscillations. 6. PEG's thrust modeling in the predictor assumes the acceleration due to thrust is the form of a quadratic polynomial.	1. Each subphase is either constant thrust or constant acceleration. 2. Designed to work in the exo-atmospheric region of flight.

Algorithm Limitations



PEG	OPGUID
1. Each subphase ends based on either time or mass. 2. Large thrust arcs must be limited because of the flat Earth assumption. 3. For the class of EUS burn arcs, when the elevation limit constraints are on, PEG under-predicts the cutoff time by quite a bit for large burn arcs. 4. The accuracy of using a neighboring coasting trajectory for predicting the effects of gravity on position and velocity over the thrust arc degrades for large thrust arcs. 5. The PEG correction process is predicated on the desired inertial velocity at cutoff being much less sensitive to changes in the velocity-to-be-gained (by thrust) vector than the predicted cutoff velocity. If that is not the case, PEG convergence performance will degrade, requiring the use of more complex correction methods.	1. Each subphase ends based on either time or mass.

Conclusion

- **Team Recommendation to select PEG as a baseline for Block-1B**
- **Trade Study result showed that PEG is less complicated and will require less work for FSW readiness and maintenance**
  - OPGUID's use of full Euler-Lagrange equations increase the complexity compare to PEG's pseudo-analytic formulation
  - SLOC count and percentage of FSW ready SLOC is significantly low for PEG
  - PEG is 47% shuttle heritage
- **Implication of PEG's limitation are well understood**
  - Shuttle's elevation limit needed to get around Flat Earth assumption only ends up under predicting cutoff time, but no performance issues as compared to PEG
  - Identity Jacobin assumption during PEG's correction can be multiplied by scalar to handle long burn cases
- **Trade study showed that OPGUID is a viable algorithm though lacking maturity from perspective of FSW development**
  - Continuous improvement will be made to OPGUID as it will be used to compare PEG's performance through Block-1B analysis

- **Finally, the trade study experience provided significant insight into the behavior of OPGUID and PEG. As a result, number of improvement were incorporated into the PEG base code, increasing its robustness and reliability**

Thank you!

Any questions?

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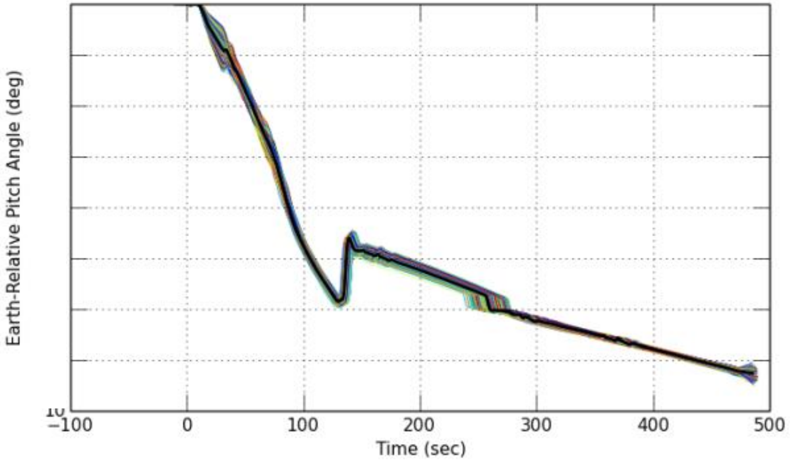
BACKUP

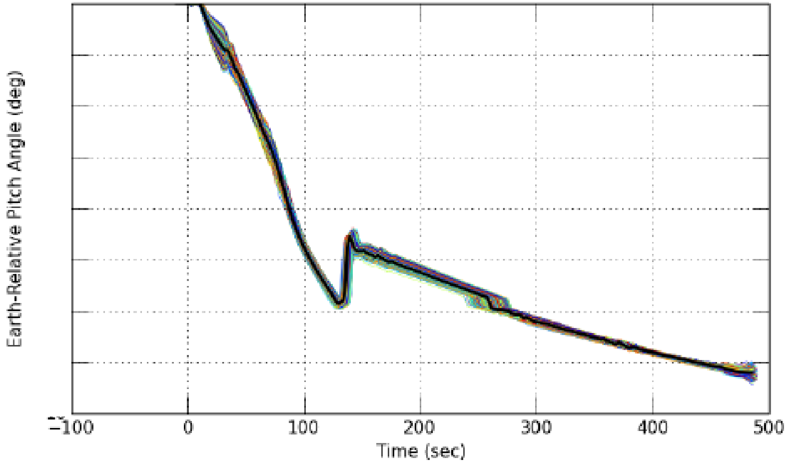
Trade Study Results

- **Attitude time (Pitch) histories were similar for both OPGUID & PEG**

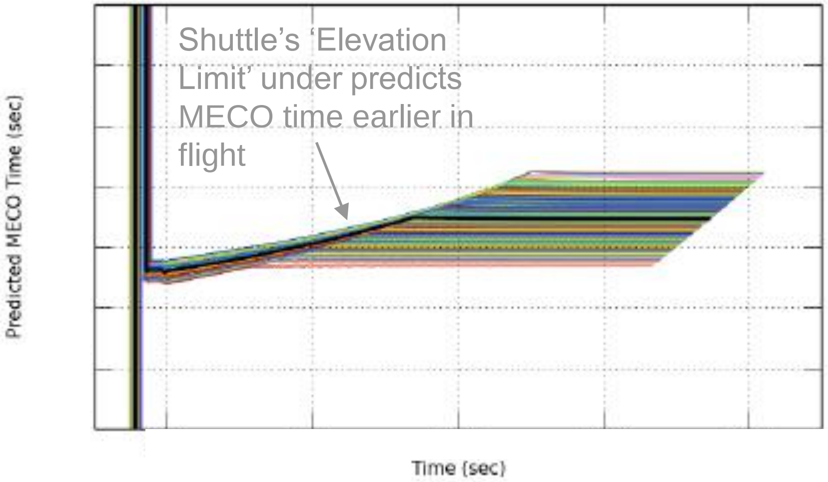
PEG



OPG



- **PEG enhancements were needed to successfully complete single engine failure missions.**



Shuttle's 'Elevation Limit' under predicts MECO time earlier in flight