Low Thrust Trajectory Team – Technical Interchange Meeting
Arcadia, California 4-5 August 2004
Presenting To: Day 2

Gerald L. Condon -NASA/Johnson Space Center

Abstract

Status of Low Thrust Work at JSC

High performance low thrust (solar electric, nuclear electric, variable specific impulse magnetoplasma rocket) propulsion offers a significant benefit to NASA missions beyond low Earth orbit. As NASA (e.g., Prometheus Project) endeavors to develop these propulsion systems and associated power supplies, it becomes necessary to develop a refined trajectory design capability that will allow engineers to develop future robotic and human mission designs that take advantage of this new technology. This ongoing work addresses development of a trajectory design and optimization tool for assessing low thrust (and other types) trajectories. This work targets to advance the state of the art, enable future NASA missions, enable science drivers, and enhance education. This presentation provides a summary of the low thrust-related JSC activities under the ISP program and specifically, provides a look at a new release of a multi-gravity, multi-spacecraft trajectory optimization tool (Copernicus) along with analysis performed using this tool over the past year.

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Background

In 2002, AFMD created and hosted a Low Thrust Trajectory Team (LTTT) Technical Interchange Meeting (TIM) near JSC. The purpose of this meeting was to provide information exchange among NASA centers, as well as academia and industry, concerning the state-of-the-art in low thrust trajectory and mission design. An outgrowth of this meeting was the involvement of JSC in the In-Space Propulsion (ISP) program. ISP has been dispensed by Code S through the Marshall Space Flight Center (MSFC) for the past two years. JSC personnel in the Aeroscience and Flight Mechanics Division (AFMD) have maintained continuous funded involvement in this program via low thrust trajectory design and optimization capability development, tool building and analysis support. The LTTT TIM evolved into an annual forum for technical exchange and demonstration of new capabilities among NASA centers, academia, and industry. This year, the 3rd annual LTTT TIM is hosted by JPL in Arcadia, California.

DRAFT

Low Thrust Trajectory Team Status
JSC

Presented to the Low Thrust Technical Interchange Meeting
Arcadia, California
August 4-5, 2004,
by

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Introduction

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Advanced Multi-Body/Multi-Spacecraft Trajectory Optimization System (Copernicus)

- **Part of a multi-center trajectory analysis capability development**
- **Work being conducted at JSC with University of Texas at Austin**
- **JSC point of contact – Jerry Condon**
- **UT point of contact – Cesar Ocampo**

Purpose

- **Develop Copernicus software as a part of the NASA Low Thrust Trajectory Team "toolbox"**
- **Enhance NASA mission design capability**

Motivation for "Low Thrust" Analysis Development

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- Developing refined capability to effectively perform expected future mission design work
  - Once ISS is operational, the agency will be looking forward to the next adventure
  - The system described will contribute to allowing NASA to be a key player in this future work
- Provides potential to "discover" new and possibly enabling solutions to current and future problems as well as new methodologies for solving these problems
- NASA leadership role in future human and human-enabling robotic missions
  - Poise NASA to support potential Nuclear Space Initiative (NSI) work

"The bottom line is that we have reached a crossroads here. We have reached the limits of what we can do (with conventional propulsion and power)," said Ed Weiler, chief of NASA's space science division. "We are doing space exploration the way we did it 40 years ago. It's time to move forward."

Applicability of Work

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Provides for advanced mission design and assessment including tools, models, and simulation

Advance state of the art

- Unifies the approach to solving a wide range of missions
- Facilitates and simplifies the analysis process for complex missions
- Comprehensive system (covers wide range of problems)

Enable future NASA missions

- Will provide optimal solutions to wide variety of existing and new classes of NASA missions

Enable science drivers

- Allows trajectory designers to show scientists the feasibility of science missions

  Low-thrust Europa mission, comet/asteroid sample return, Mars sample return,
  Formation flying – Terrestrial Planet Finder, astronomical observatories, etc.)

Enhance education

- Student instruction, student preparation, public relations

JSC Status of “Low Thrust” Trajectory Analysis and Tool Development Activities

Background

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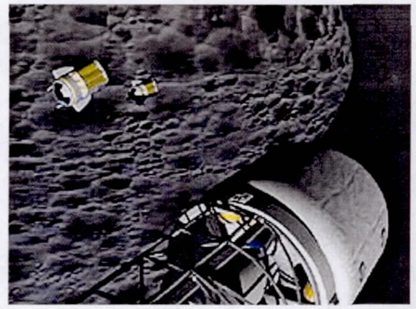
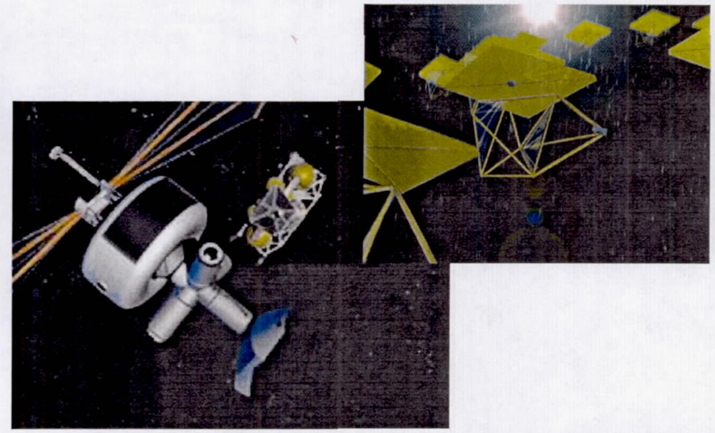
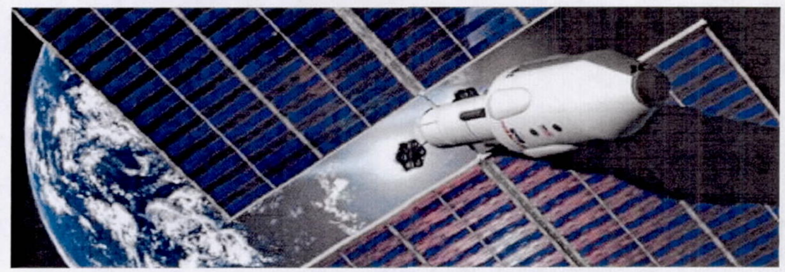
- Future missions* will involve:
  - multiple spacecraft
  - multiple destinations
  - multiple gravity fields
  - multiple (hybrid) propulsion





- Future mission design will require:
  - Complex trajectory design and optimization
  - Fast, high precision results
  - Large multi-dimensional trade spaces
  - Analysis of both mission design and mission operations
  - Assessment of Guidance/Navigation requirements



- Current capability
  - Solves only ‘pieces’ of the overall problem; integrated solutions are limited

Currently, no general, robust, efficient, and practical trajectory optimization system exists at JSC for efficient and accurate solutions

*Recent NASA recent initiative - electric propulsion

Objective

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- Develop a comprehensive **trajectory design and optimization system**
  - Develop and enhance the necessary methods, algorithms, and strategies

- Validate system to support proposed future missions*:
  - Analysis, Research, Verification, Design, Operations

- Baseline the prototype system for comparison against other design and optimization systems

- Standardize and unify the methodologies used to design classes of trajectories needed to address the problems posed by future crewed and robotic missions

- Begin training mission planners and navigators

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* Insure that the system is capable of addressing the design, analysis, and optimization of nuclear electric low thrust propulsion systems (a NASA initiative)

Anticipated Results

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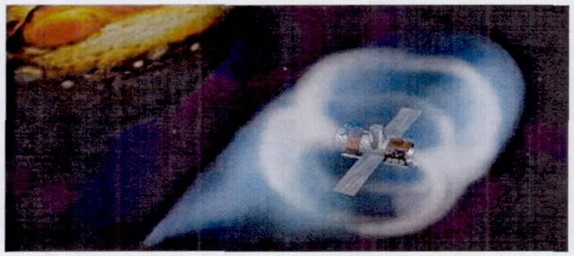
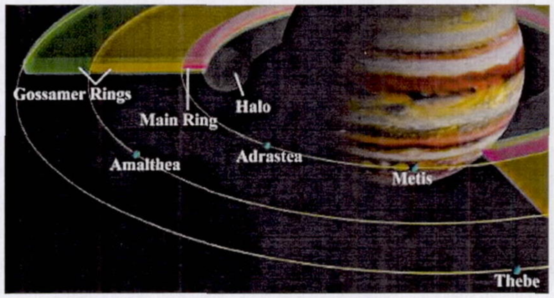
- A **system** that can effectively provide high precision solutions to complex trajectory and mission design problems in a timely manner
  - Can be used by researchers, mission designers, and students.



- A standard methodology to solve trajectory problems for requirements associated with complex force fields, multiple vehicles, and multiple propulsion systems.



- Actual baseline solutions and methods to problems involving interesting targets
  - Mars, the Outer Planets and their moons, planetary Rings, the near Earth/Moon environment, and libration points missions between any number of celestial bodies.

- Prototype system application:
  - Impulsive, high and how thrust finite burn trajectories for central body orbit transfers, Earth-Moon transfers, Sun-Earth-Moon Libration point trajectories, interplanetary trajectories

JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Previous Accomplishments

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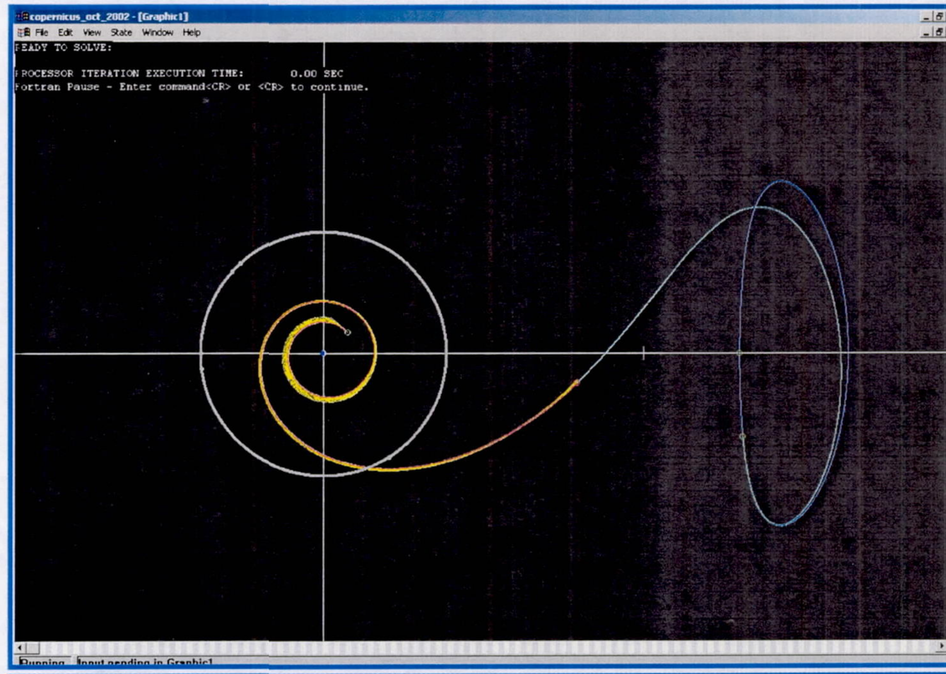
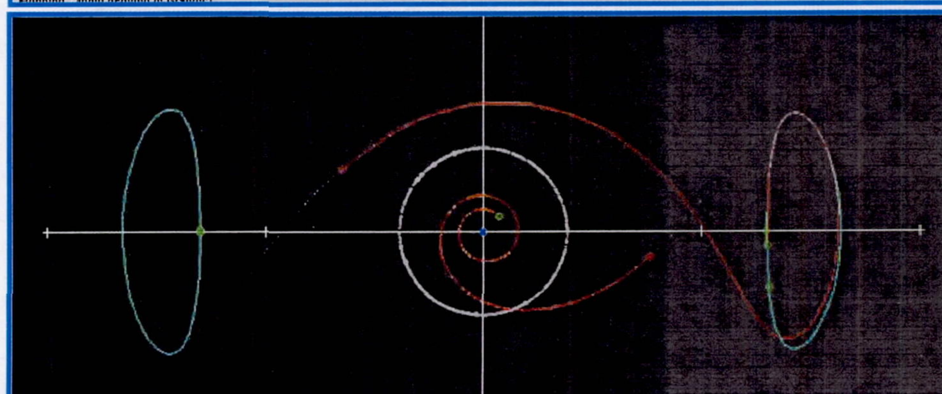
- Developed prototype system
  - Designed/implemented solution methods and architecture
  - Defined/implemented required algorithms
    - Numerical integrators, nonlinear equation system solvers, and nonlinear constrained optimization routines
- Generated nominal solutions for various mission classes
  - Libration points (any system), lunar, inner/outer planets, asteroid/comet rendezvous, planetary cyclers
- Documentation of system methodology and results (papers, articles)





Ongoing Work

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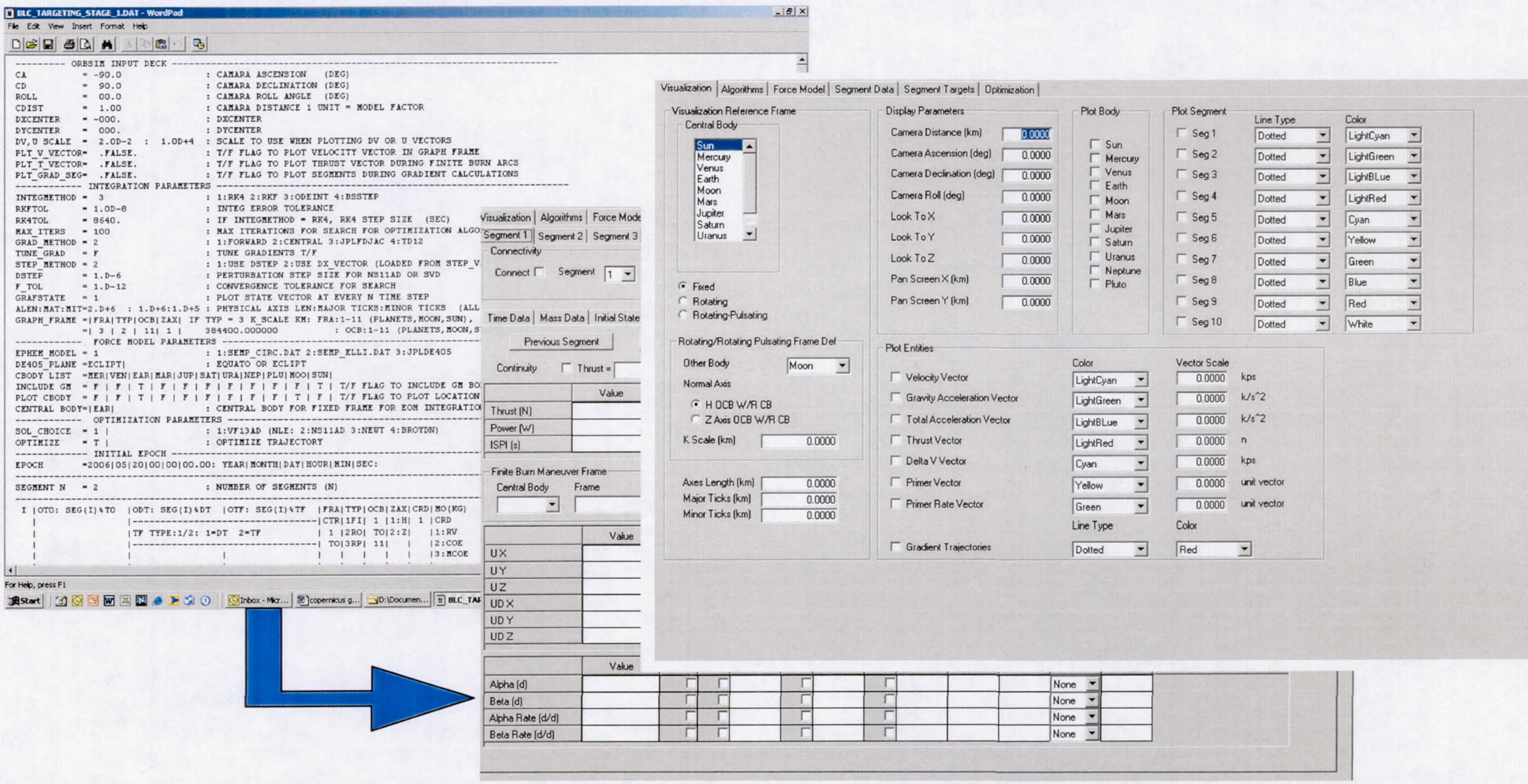
Transition Copernicus from text-based input to Graphical User Interface

– Provides: faster orientation of new users, improved (faster) analysis, easier modification,



Ongoing ISP Development Activities

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- Development of production tool
  - GUI development/updating
  - Investigation of Open GL techniques
  - System integration (GUI/Copernicus)
  - System refinement/testing/validation
    - Beta testing

- Enhance speed and capability through integration of analytical and numerical based optimization methods

- Provide added capability
  - Targeting to natural satellites of any inner/outer planet (Titan)
    - Employ SPICE ephemeris
  - Station-keeping and orbit maintenance (EM L1, SE L1/L2)*
  - Guidance along arbitrary powered and ballistic arcs
  - Close proximity relative motion

- Generate benchmark and baseline mission templates
  - Goal: templates for 100+ mission classes

*EM = Earth Moon L1 libration point; SE L1/L2 = Sun-Earth L1 or L2 libration point

Planned Future ISP Development Activities

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- Overall system testing and validation
- System training of personnel
- Benchmark against other systems or tools
- Identification of any system drawbacks
- Development of improved solutions methods if necessary

- Multi-Year Deliverables
  - Year 0 - Copernicus prototype multi-body/multi-spacecraft trajectory optimization software (Completed)
  - **Year 1 - Copernicus beta version with working GUI**
  - Year 2 - Copernicus operational version (Ver. 1)
  - Interim report and associated research articles for each year
  - Copyright or patent registration if applicable

Funding

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- Total FY2003 - $280k - received
  - Start date – April 2003
  - Current spending $ 57k August 15, 2003
  - Projected spending $223k May 1, 2004

- Contractor Workforce
  - University of Texas Professor (Dr. C. Ocampo)
    - Full Time for 2 mos.
  - Research scientist (Dr. J. Senent)
    - Full time
  - Two graduate students
    - Full time – 1 year each

- Resources
  - Equipment – laptops, computer supplies, reference texts
  - Software - libraries, GUI tools, license updates

Other Funding (Received or Projected) with Potential Benefit to Copernicus Development

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Funded

- A NASA-Goddard GSRP to study optimization of complex multi-body flybys (e.g., cyclers)
- A NASA-Goddard Grant to examine specific mission applications with COPERNICUS (e.g., Titan mission)
- A NASA-JSC grant to examine Earth-Saturn/Titan integrated Design/Optimization/Navigation
- NDSEG fellowship to study human crew-based mission studies for Earth-Mars roundtrip missions using variable specific impulse engines such as VASIMR
- NASA/JPL GSRP study of autonomous Mars orbit rendezvous for sample return missions

Projected

- NASA/JSC GSRP proposal for low thrust station-keeping for libration point orbits

*

External Activities

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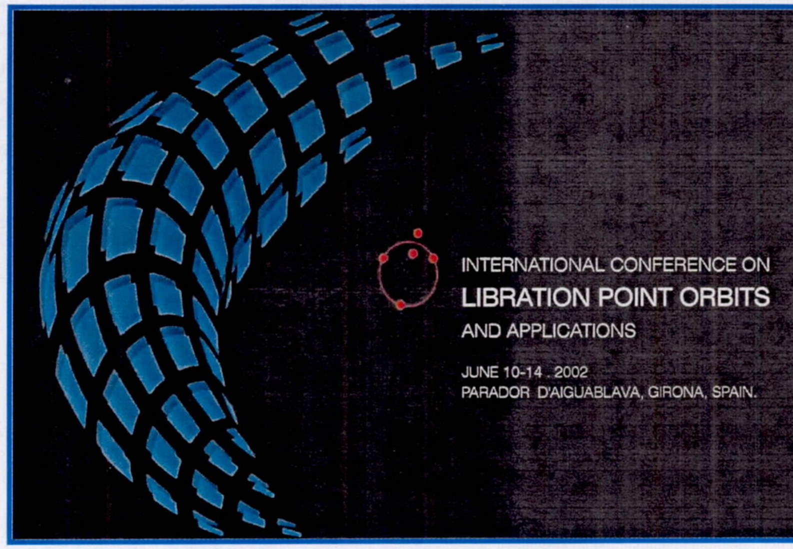
- System presented at:
  - NASA MPSET Meeting (NASA JSC Nov 2001)
  - The International Conference on Libration Points and Missions (Girona, Spain June 2002)
  - NASA Sponsored Low Thrust Technical Interchange Meeting (LPI Houston, June 2002)
  - Numerous meetings at JSC



- System used to support:
  - NASA JSC VASIMR Workshop (Oct 2002)
  - NASA Official Peer Review of the VASIMR Project (Nov 2002)
  - Exploration Office working meeting

- System currently being used as an instructional tool at UT-Austin
  - 3 courses taught by the university PI
  - Training both undergraduate and graduate students

External Activities (continued)

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Related Article/Reports

- **Transfers to and Station-keeping for Unstable Periodic Orbits with Low Thrust Propulsion** Proceedings for the AAS/AIAA Astrodynamics Specialist Conference, Big Sky Montana August 2003
- **Optimization of Roundtrip, Time-Constrained Finite Burn Trajectories via an Indirect Method,** Proceedings for the AAS/AIAA Astrodynamics Specialist Conference, Big Sky Montana August 2003
- **Combined Long Duration Finite Burns and Gravity Assist Interplanetary Trajectories using an Indirect Method with Analytical Gradients,** Proceedings for the AAS/AIAA Astrodynamics Specialist Conference, Big Sky Montana August 2003
- **A Geometric Analysis of Half and Full Revolution Return Trajectories Via Planetary Flybys**, Proceedings for the AAS/AIAA Astrodynamics Specialist Conference, Big Sky Montana August 2003
- **A Systematic Method for Constructing Earth-Mars Cyclers using Direct Return Trajectories**, Proceedings of the AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico, Feb 2003 (accepted to the Journal of Guidance, Control, and Dynamics)
- **Finite Burn Maneuver Modeling and Optimization for a Generalized Trajectory Design and Optimization System**, Proceedings of the New Trends in Astrodynamics – An International Conference, Jan 20-22 2003, Washington D.C. and to appear in the Annals of the New York Academy of Sciences
- **An Architecture for a Generalized Trajectory Design and Optimization System**, Proceedings for the International Conference and Libration Point Missions and Applications, Girona, Spain June 2002

External Activities (concluded)

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Related Article/Reports Under Preparation

- A Systematic Method for Constructing Realistic Powered/Unpowered Earth-Mars Cyclers
- Automation of Ballistic Lunar Capture Trajectories
- Optimal Low Thrust Trajectories to the Natural Satellites of the Outer Planets

Real Time Interactive Visualization

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- Examples only illustrate the real time advanced visualization capability planned for Copernicus
  - Simulations shown are not necessarily related to Copernicus
- Real time 3-D graphics engine planned for COPERNICUS
- Simulation Data in these examples are computed in real time; these are not movies or previously generated data
- Satellite Simulation
- Circular Restricted Three Body Problem Simulation in Fixed Coordinates (Earth/Moon sizes are exaggerated)
- Circular Restricted Three Body Problem Simulation in Fixed Coordinates (Earth/Moon sizes are exaggerated – speed is increased with longer trail)
- Four Celestial Body Simulation
- Rotation of Body Relative to Coordinate Frame
- Simple Attitude Simulation
- Copernicus currently has real time iteration display; however, window is not interactive as shown in the examples.

Low Thrust Control Laws

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- In March, 2003, GRC, JSC, JPL, and MSFC participated in a NEP Architecture Mission Study involving a low-thrust human Mars mission
- The purpose of the study was to assess the parametric trades associated with selected Earth departure/arrival and Mars arrival/departure parking orbits
- The mission was originally designed with a rotating artificial gravity transfer vehicle in mind

Low Thrust Control Laws (continued)

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- The initial NEP architecture study was based on full thrust pointing control
- The spinning artificial-G design would only be capable of limited thrust turn rate
- There is a need to assess the effect of limited thrust turn rate on planetary spiral
- JSC/EG is currently examining possible control laws to meet this need
- Eventually, proven control laws could be incorporated into Copernicus to provide a seamless optimized interplanetary mission design incorporating thrust turn rate-limited steering in the departure & target planet vicinities

JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Low Thrust Control Laws (concluded)

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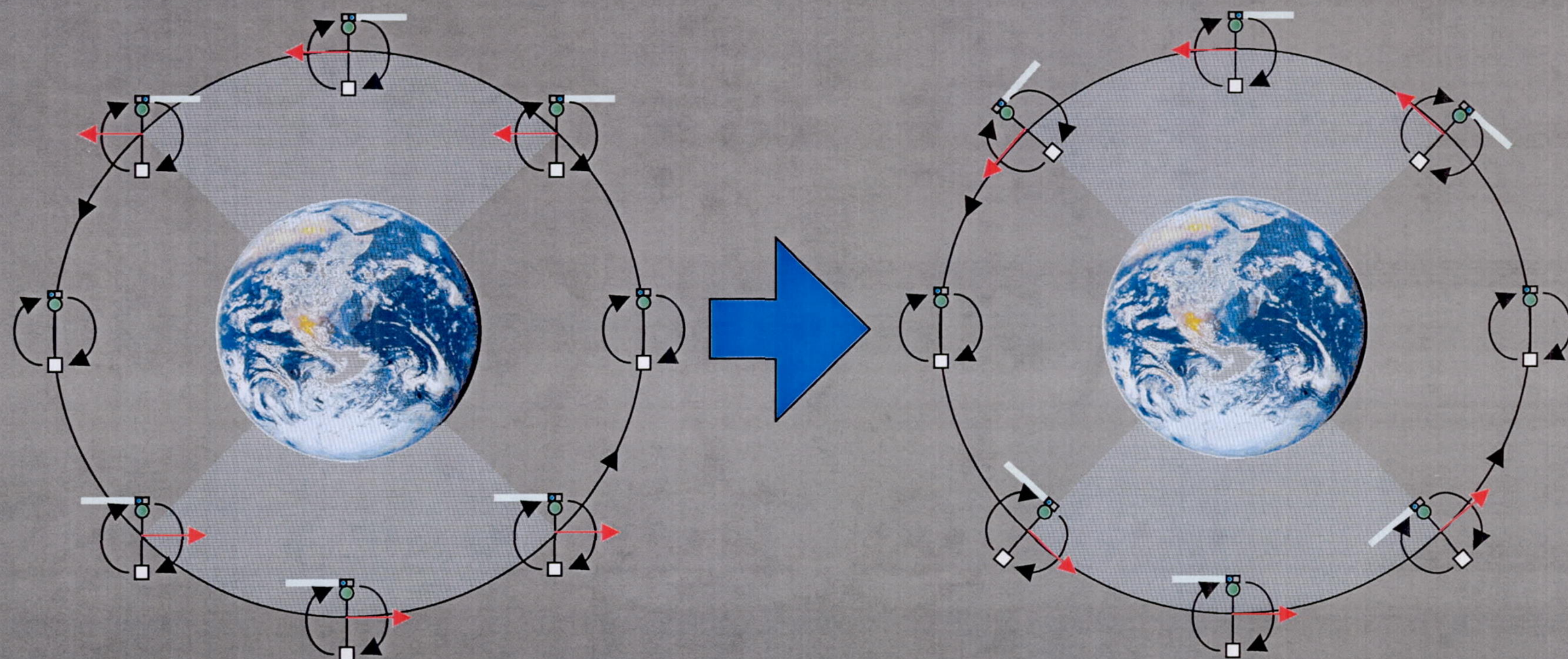

Minimum Thrust Vector Control (Inertial Hold Mode)

Maximum Thrust Vector Control (Gravity Turn)

Note: Rotating design assumes opposing thruster configuration

JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -54.0231

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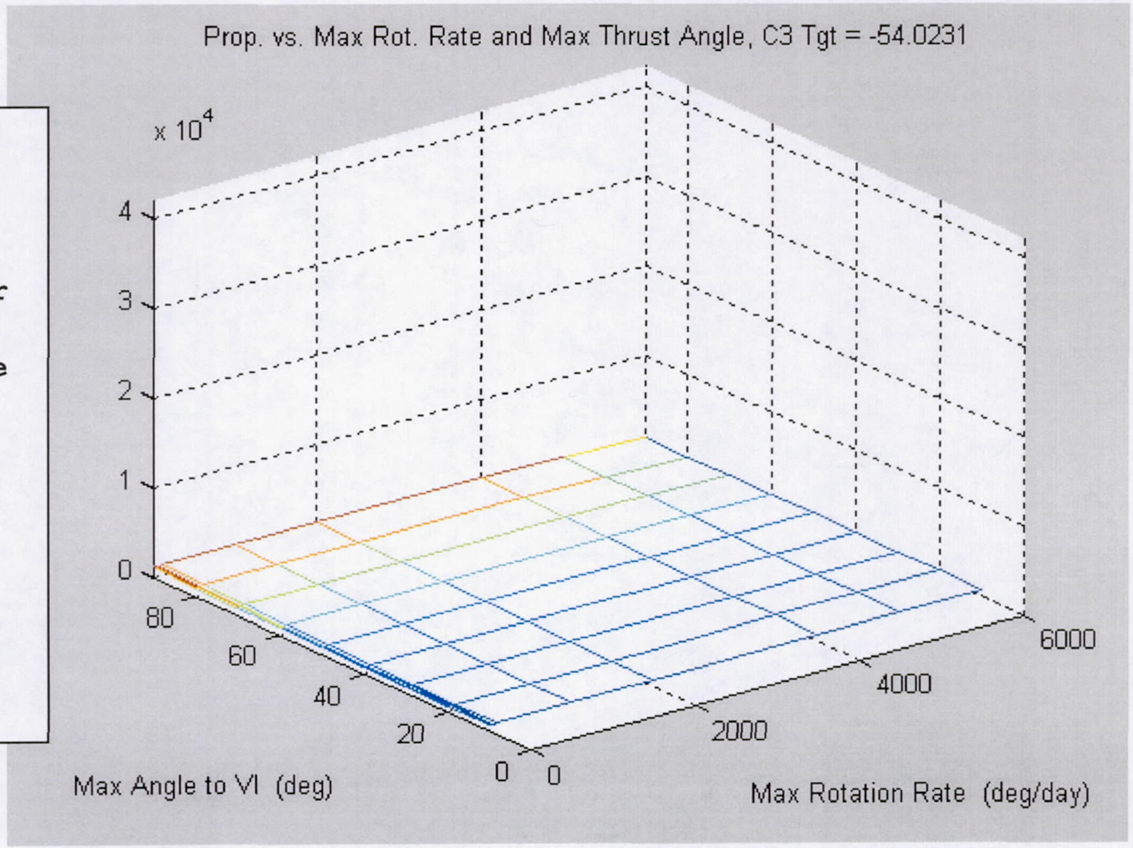
Initial Parking Orbit 700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000



JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -44.8959

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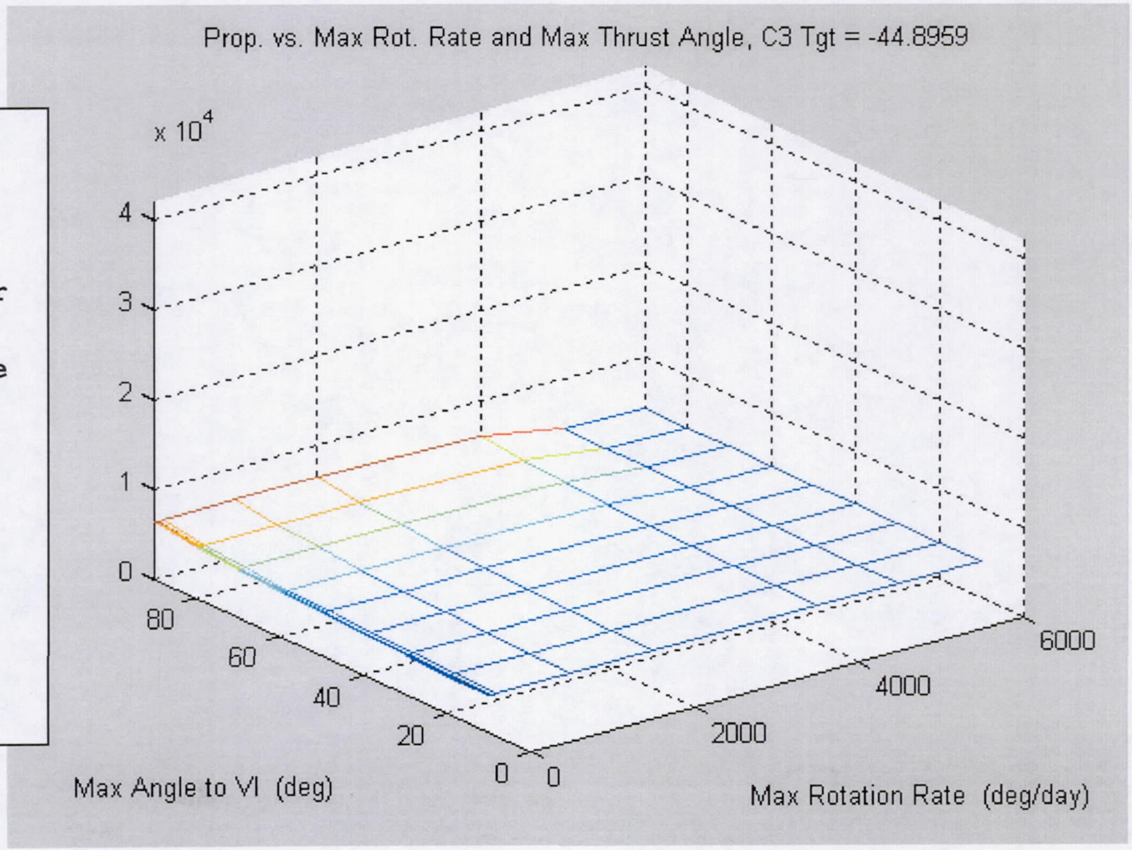
Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000



Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -35.0316

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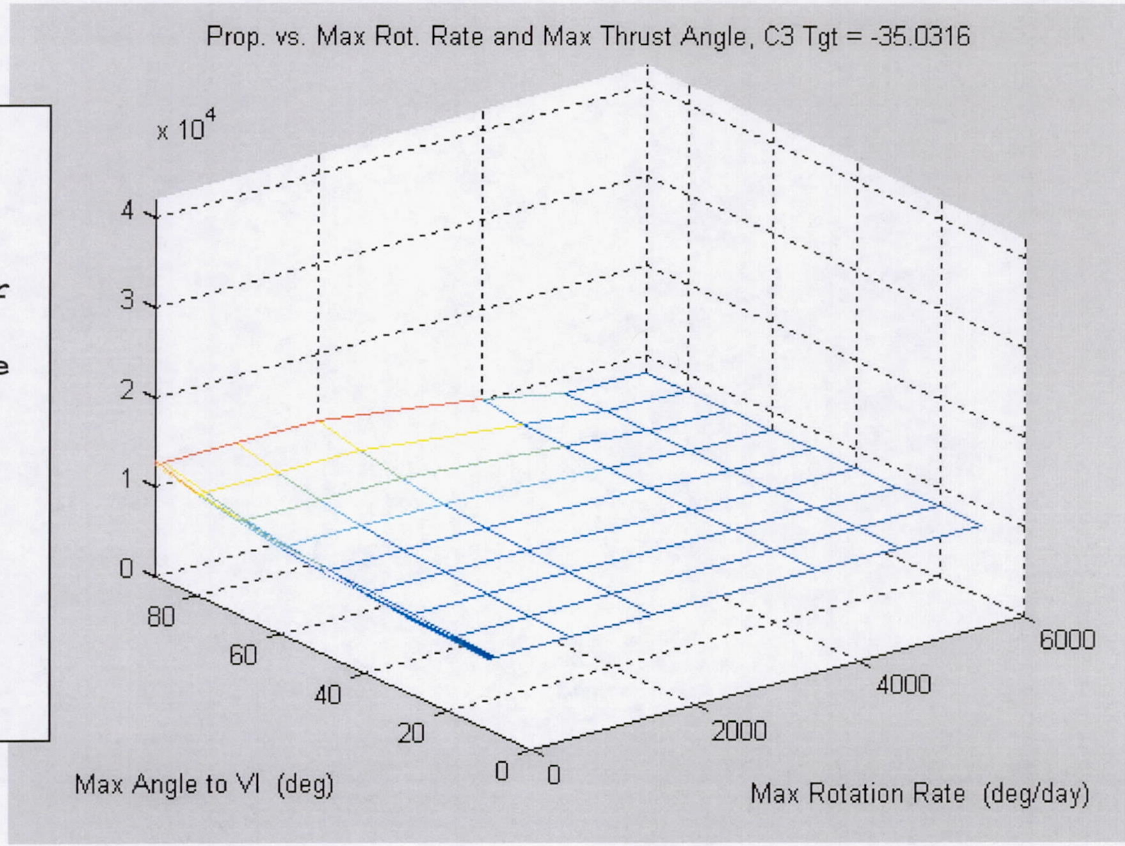
Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000



JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -24.3371

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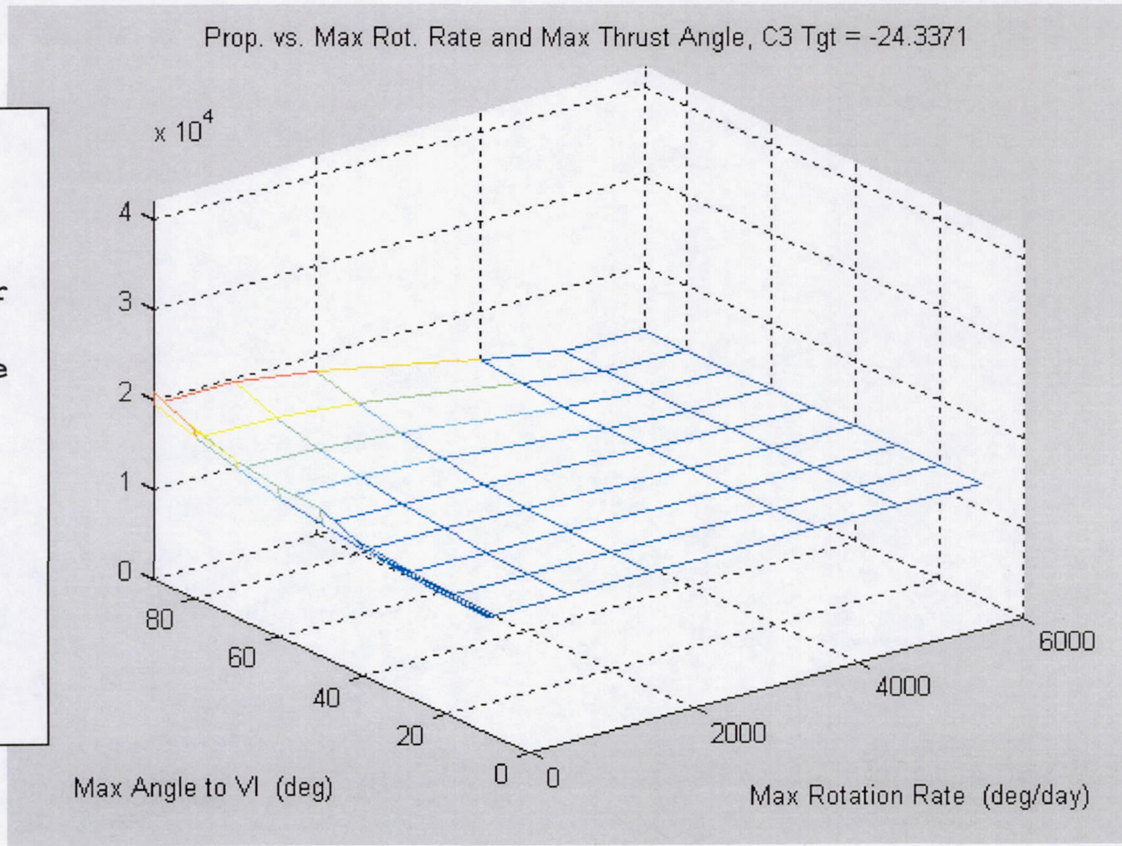
Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000

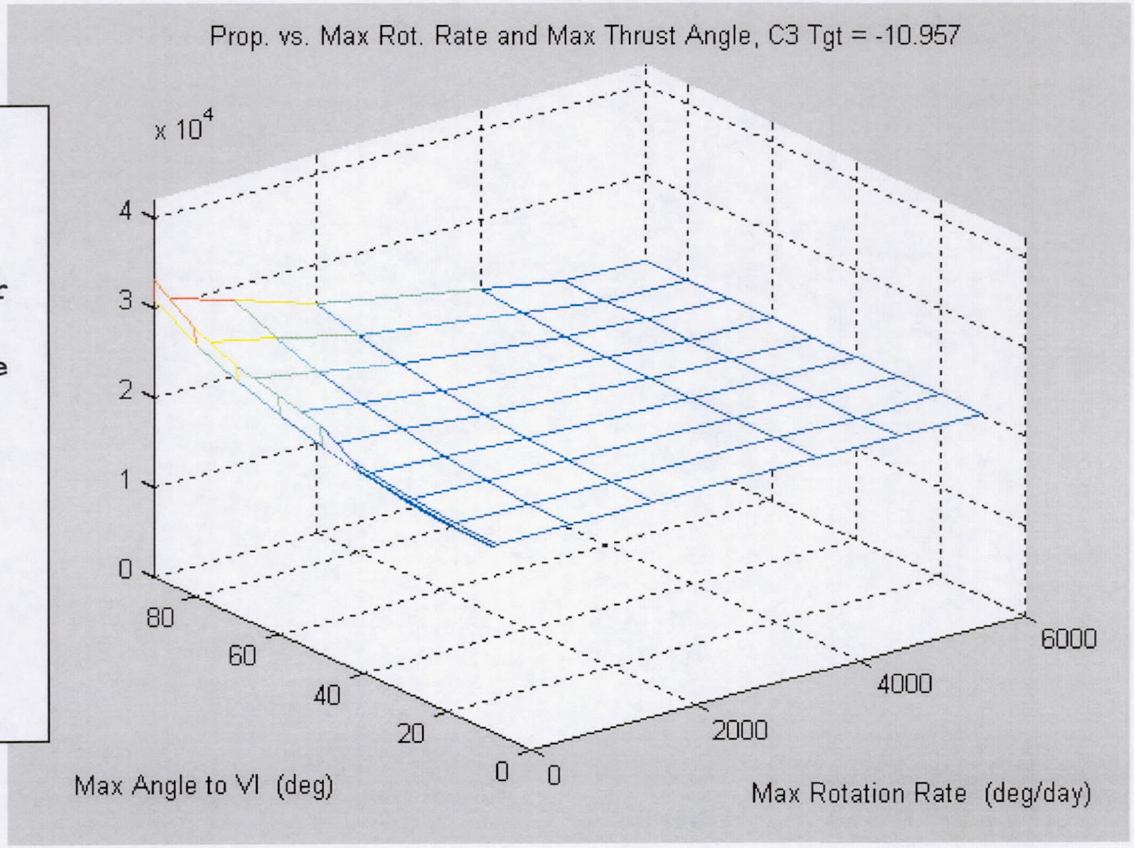


JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -10.9571	Jerry Condon / JSC / EG5

Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000



JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -7.07014	Jerry Condon / JSC / EG5

Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
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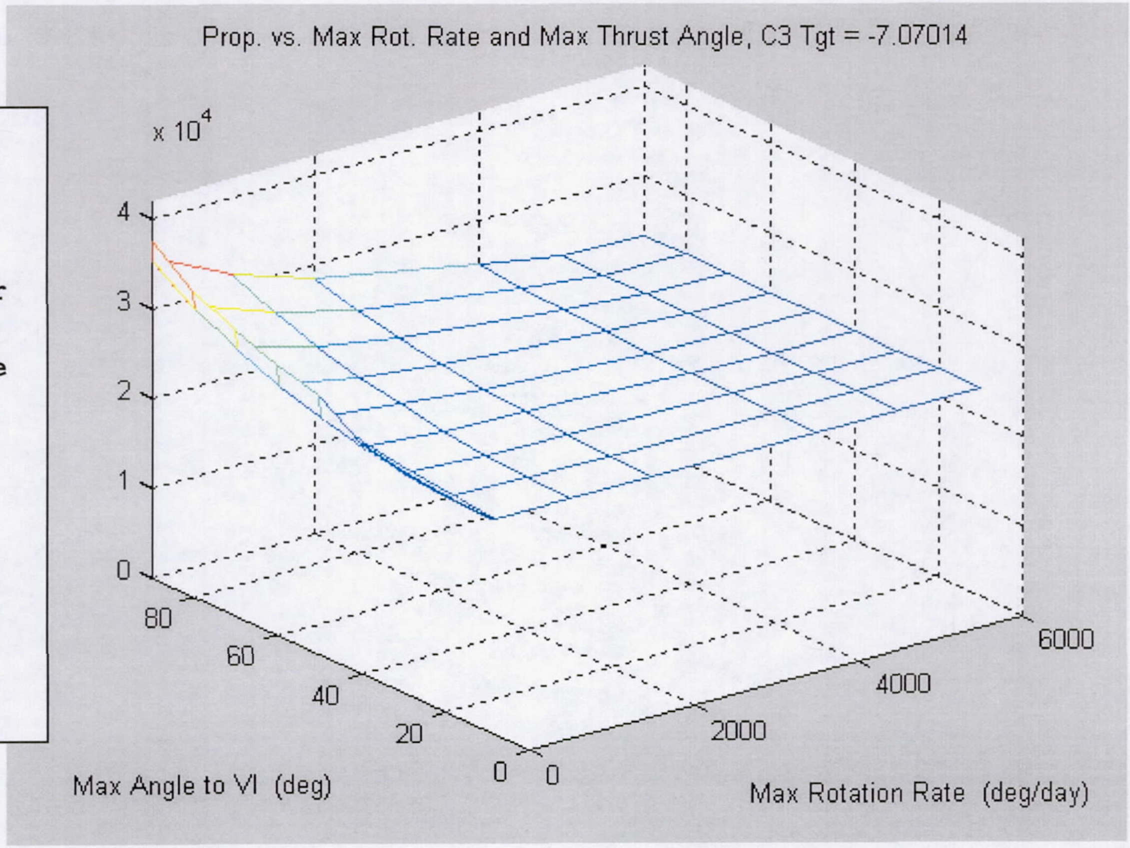

JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -5.2188

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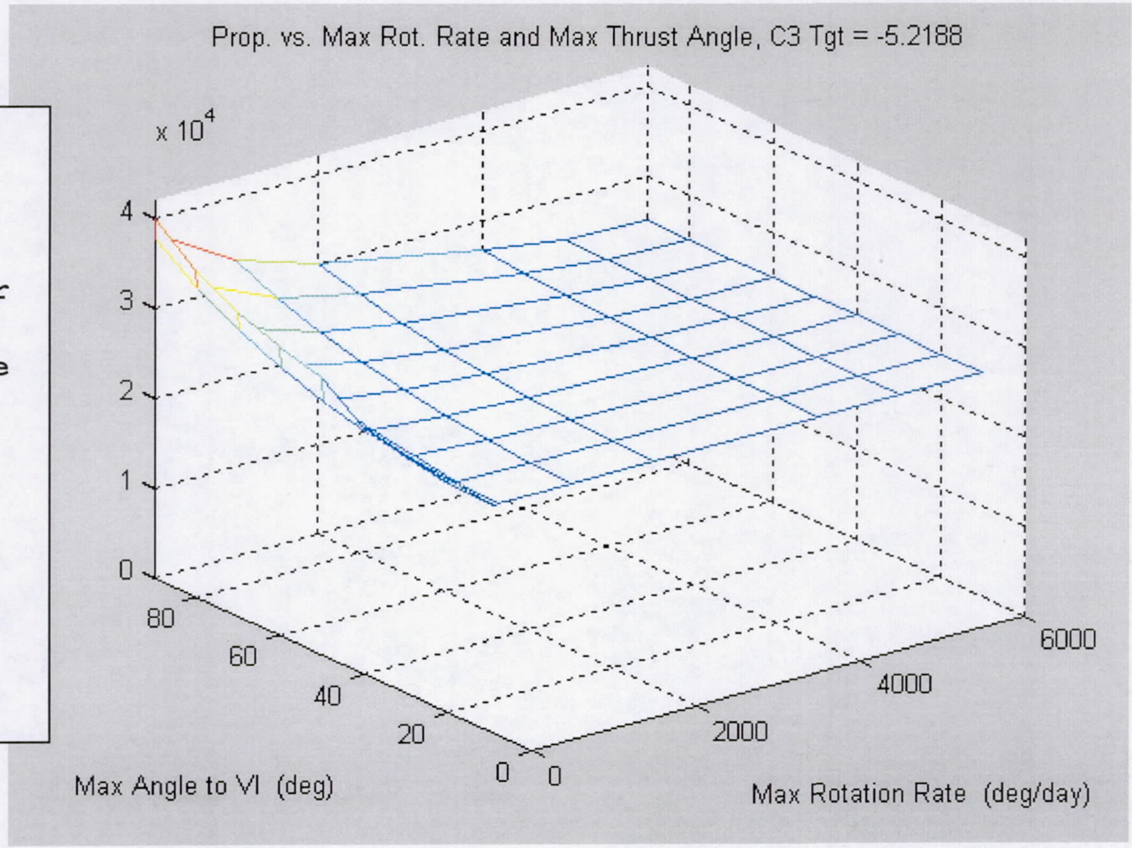
Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
-35.0316	5,000
-24.3371	10,000
-10.9571	30,000
-7.0701	50,000
-5.2188	70,000
-4.1358	90,000



JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

Propellant vs. Max Angle to VI & Max Rotation Rate
Initial Orbit = 700x700 km, Target C3 (km^2/s^2) = -4.1358

Jerry Condon / JSC / EG5

Initial Parking Orbit
700 x 700 km

C3 (km^2/s^2)	Circular Orbit Altitude (km)
-54.0231	1,000
-44.8959	2,500
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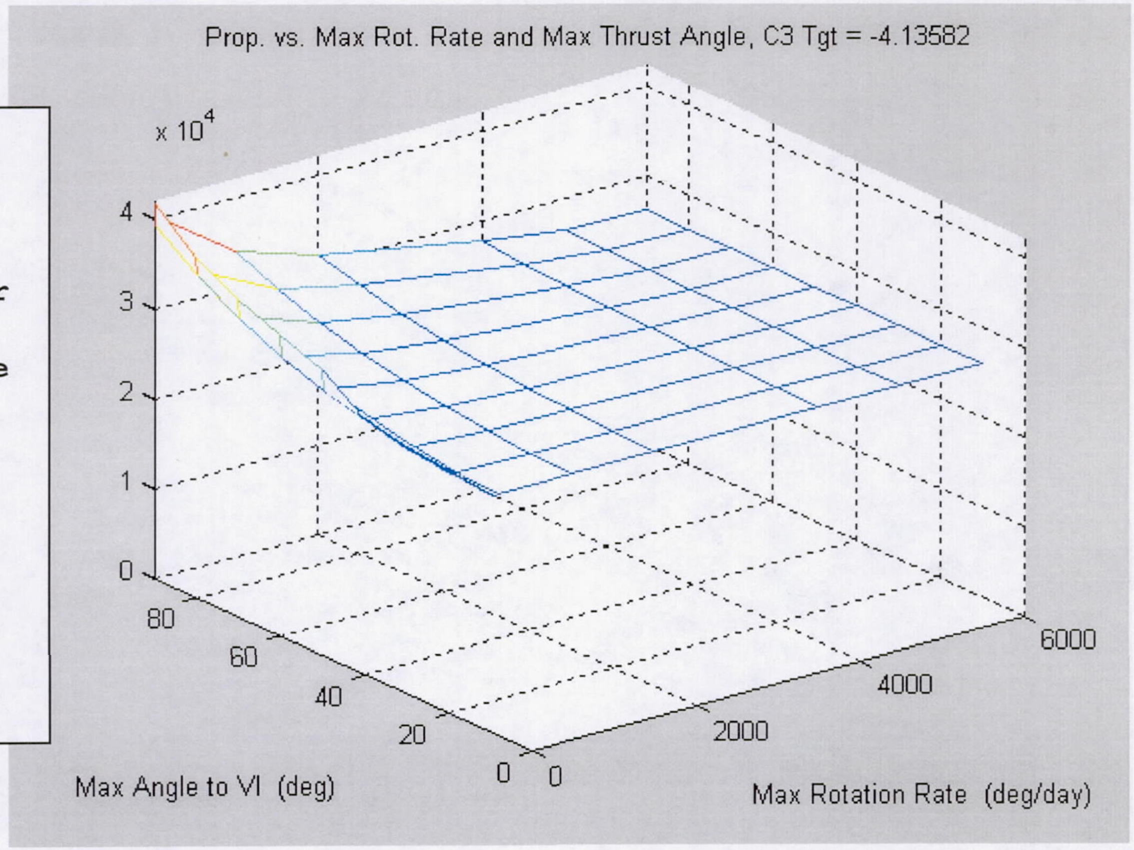

Hyperlink Slides

JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

NEP Artificial-G Mission Analysis - Results

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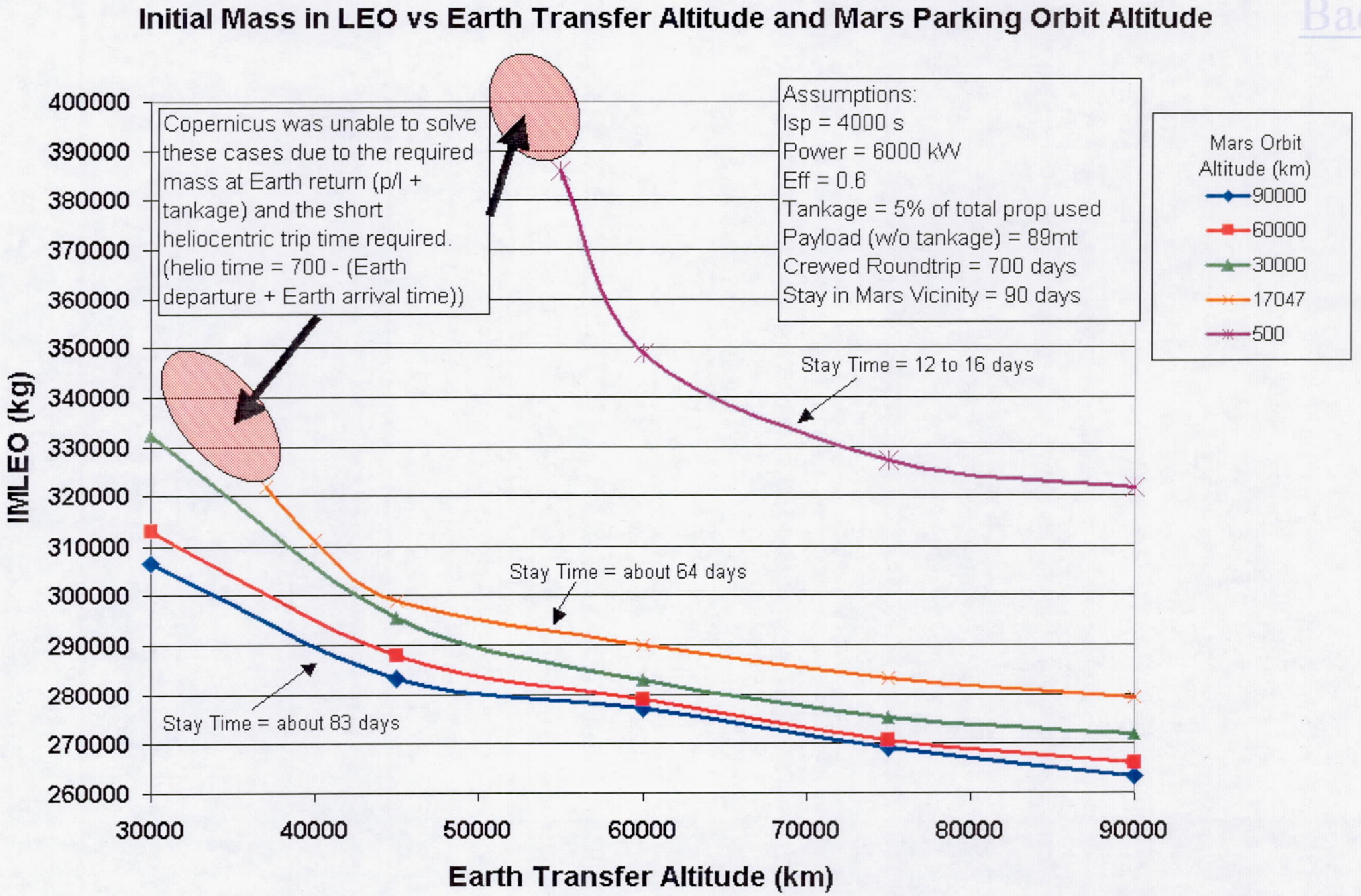
Back



JSC Status of "Low Thrust" Trajectory Analysis and Tool Development Activities

NEP Artificial-G Mars Mission Overview

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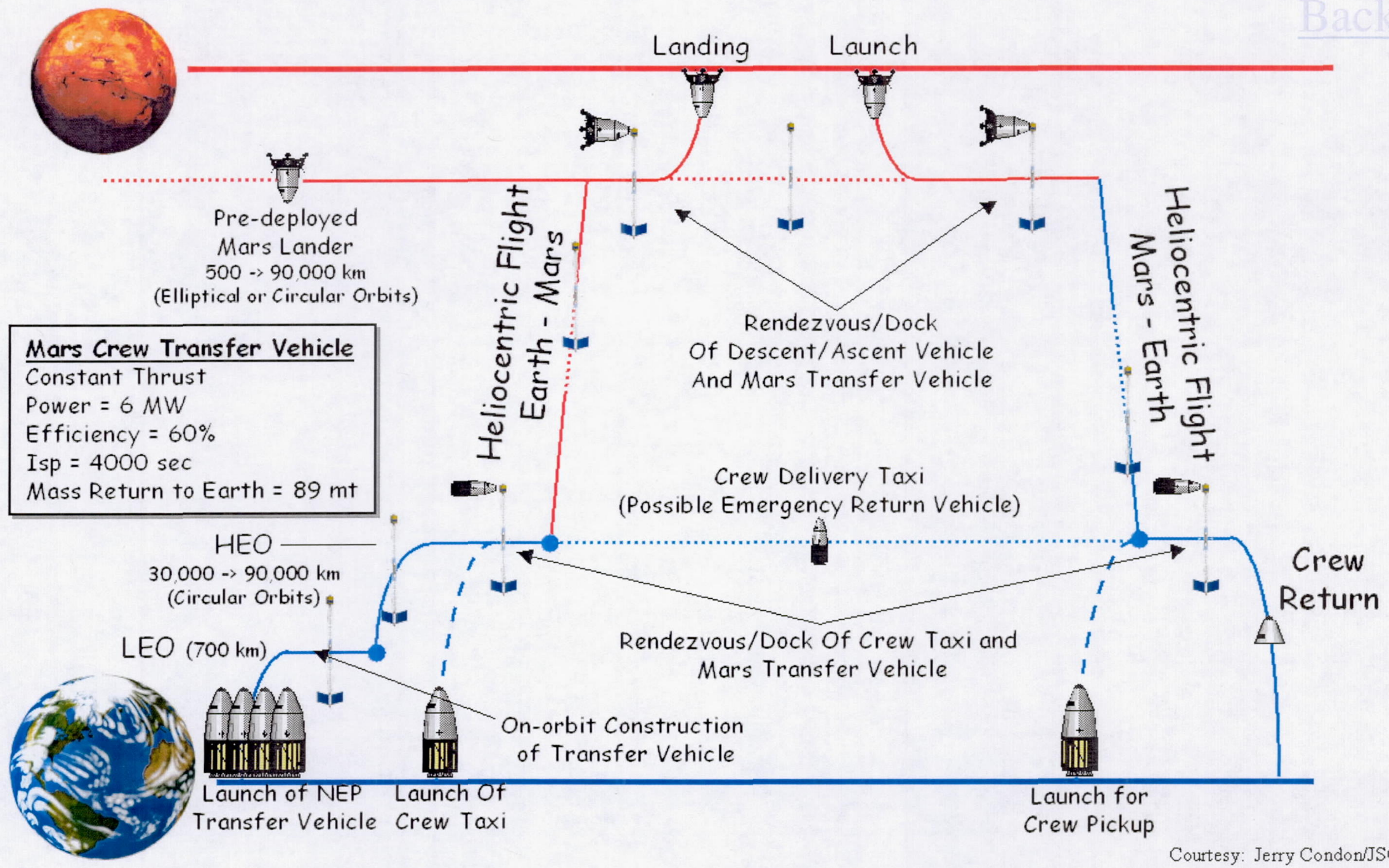
Back



Courtesy: Jerry Condon/JSC