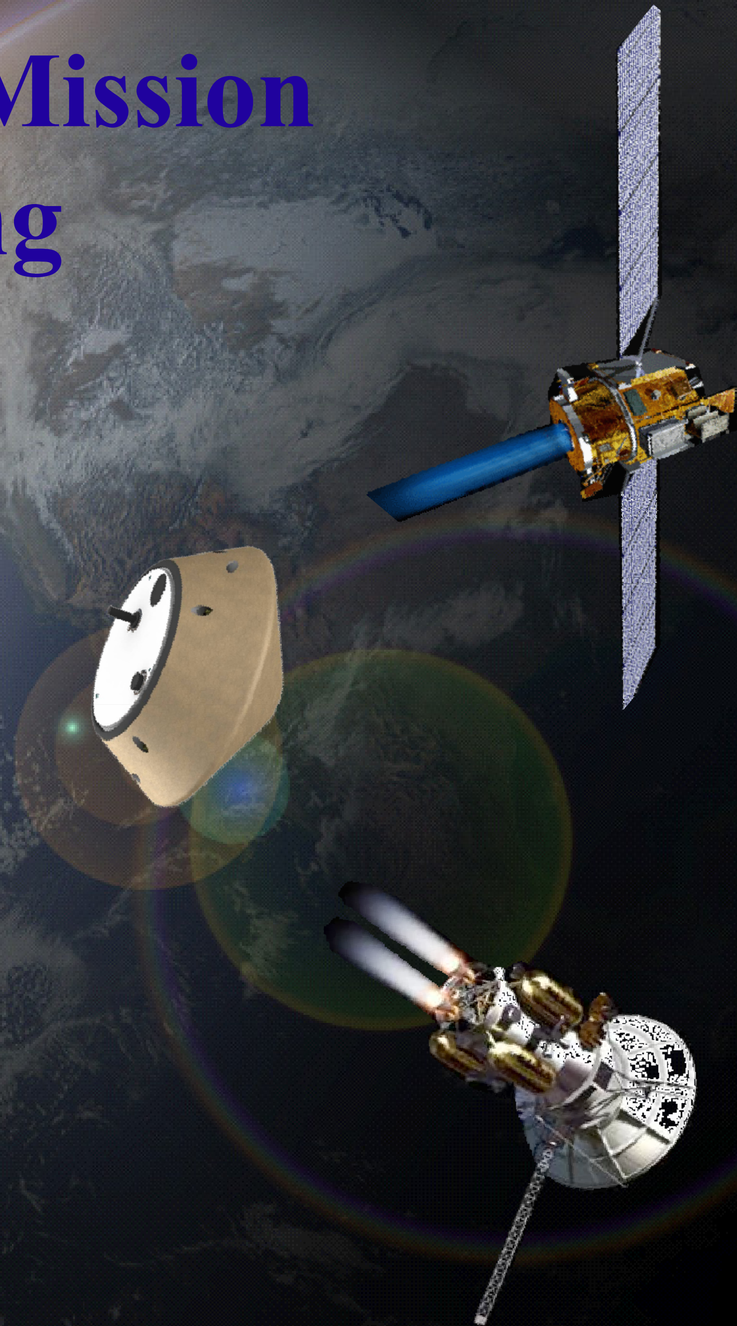
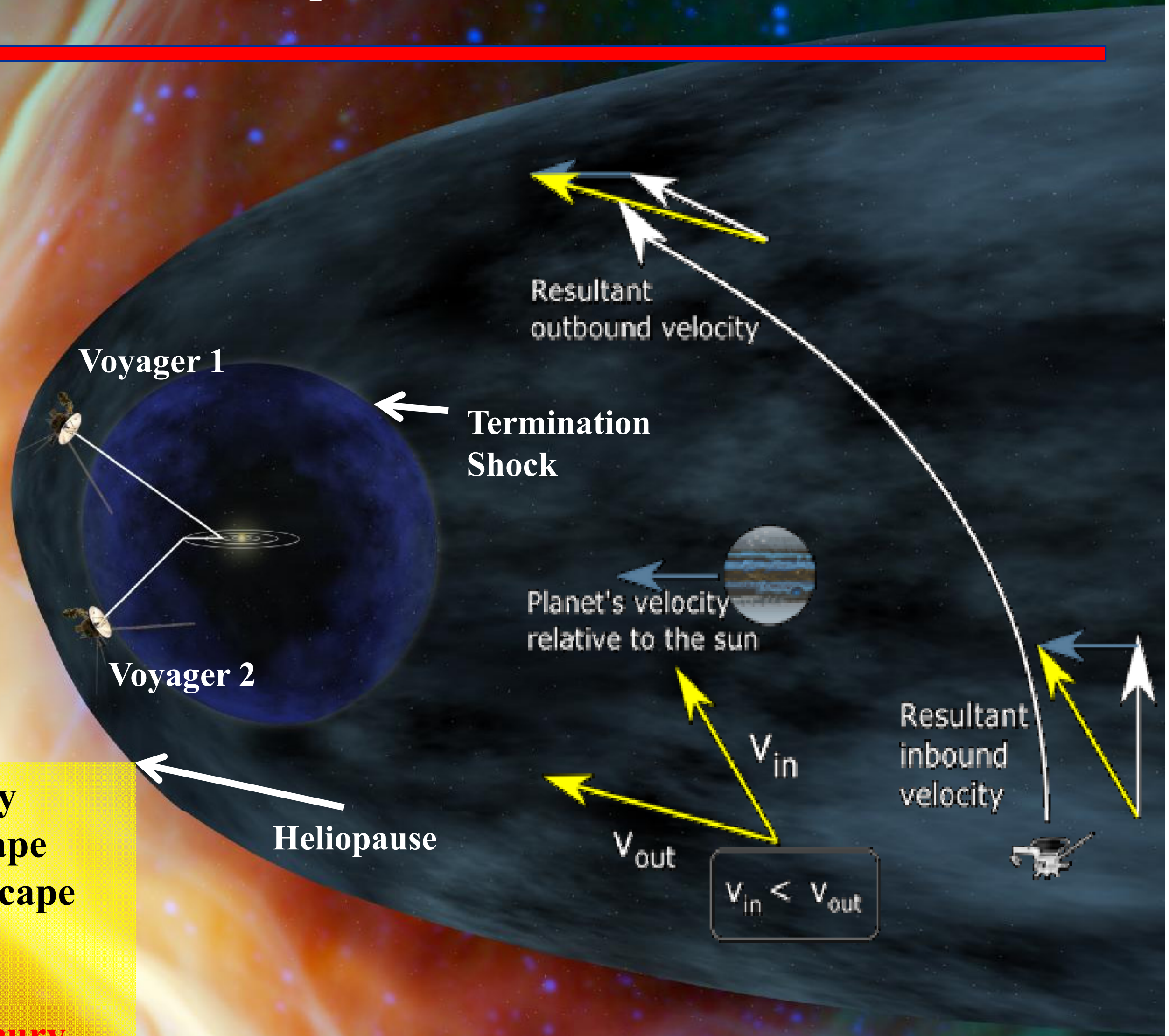
Astrodynamics and Mission Design Tools Enabling Science



Presented to SBAG
John Dankanich
July 11, 2012

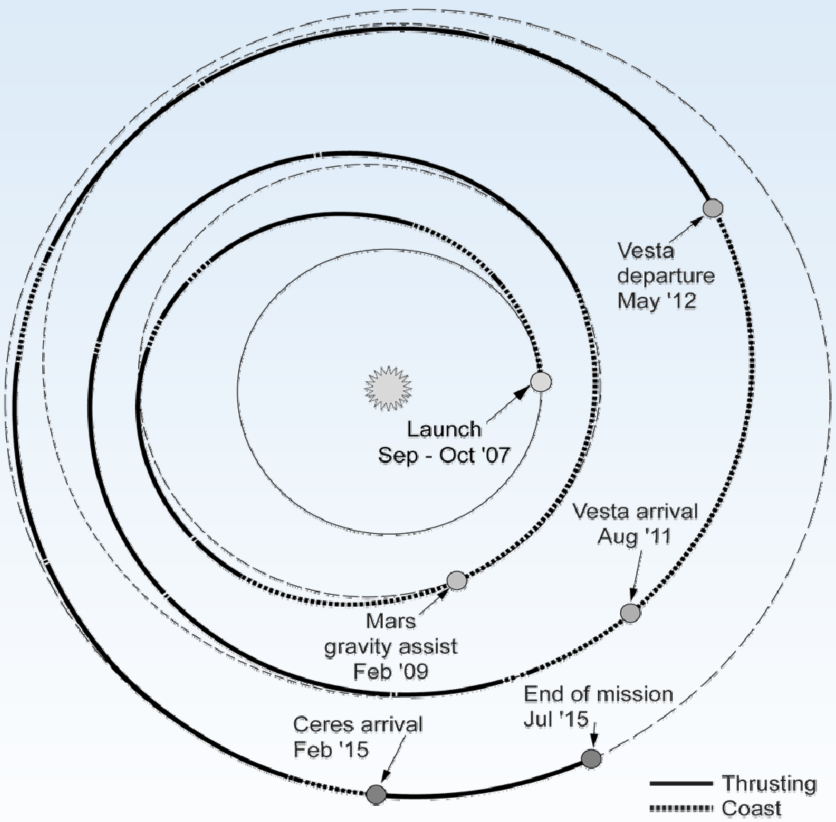
The Gravity Assist

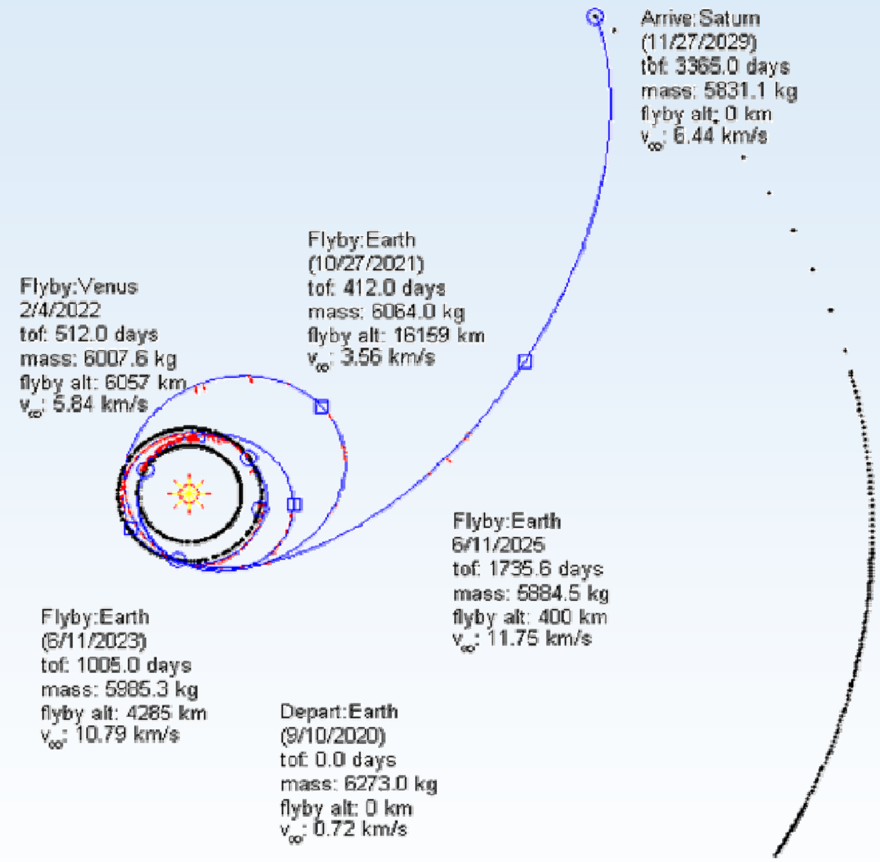


Mariner 10 VGA to Mercury
Voyager 1 JSGA to Solar Escape
Voyager 2 JSUNGA to Solar Escape
Galileo VEEGA to Jupiter
Cassini VVVEJ to Saturn
Messenger EVVMMM to Mercury

The gravity assist opened the solar system.

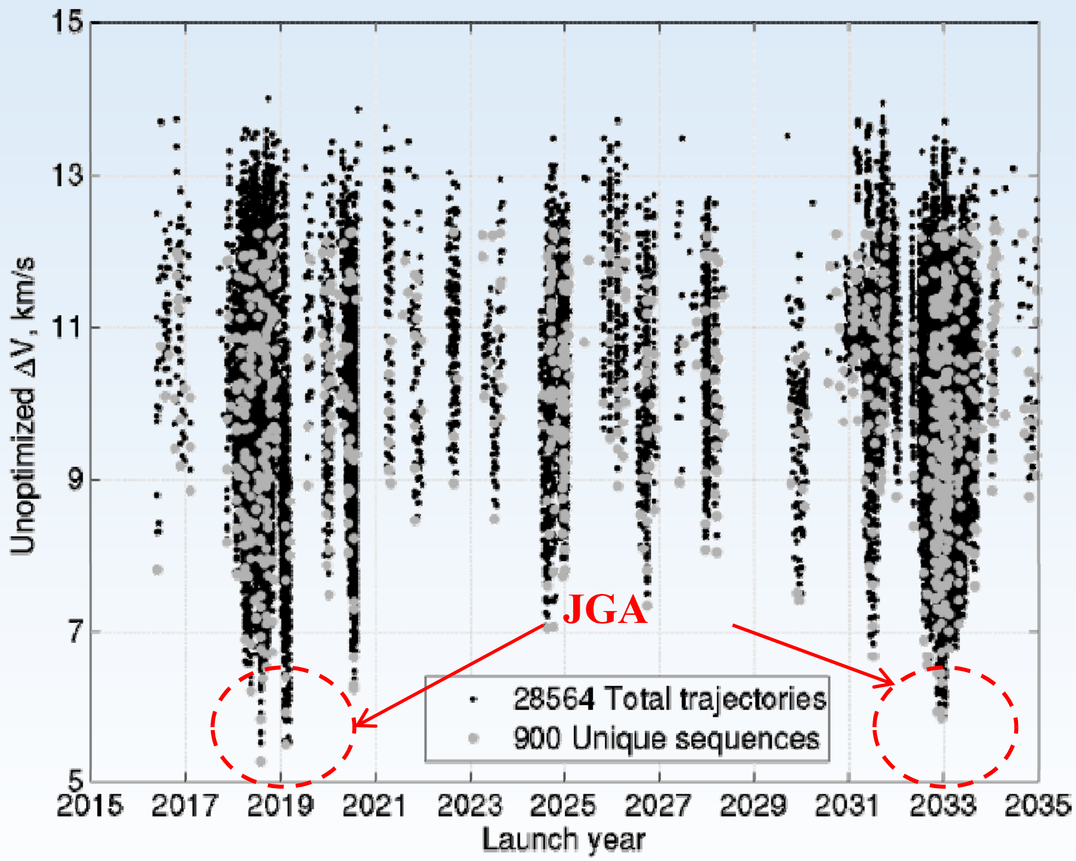
Low-thrust Mission Design





Low-thrust trajectory capabilities enabled Dawn and the TSSM w/o Aerocapture.

Broad Search Capabilities

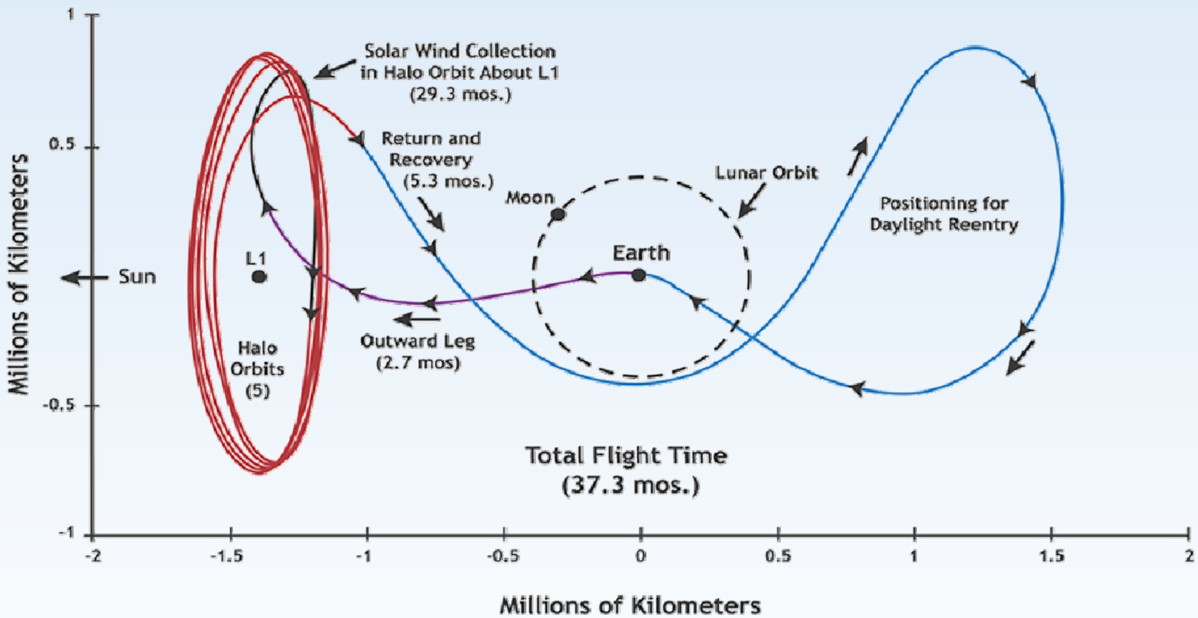


Automated process to find all possible gravity assist options

Landau, D., Lam, T., and Strange, N., "Broad Search and Optimization of Solar Electric Propulsion Trajectories to Uranus and Neptune," AAS 09-428

Lissajous and N-body research

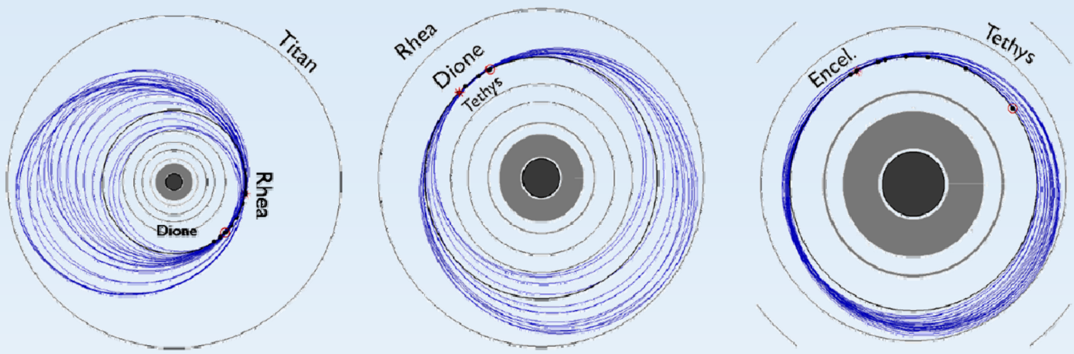
Genesis - The Genesis mission designers found a trajectory with essentially zero deterministic ΔV. This reduced the spacecraft complexity and requirements for a Discovery class sample return mission.

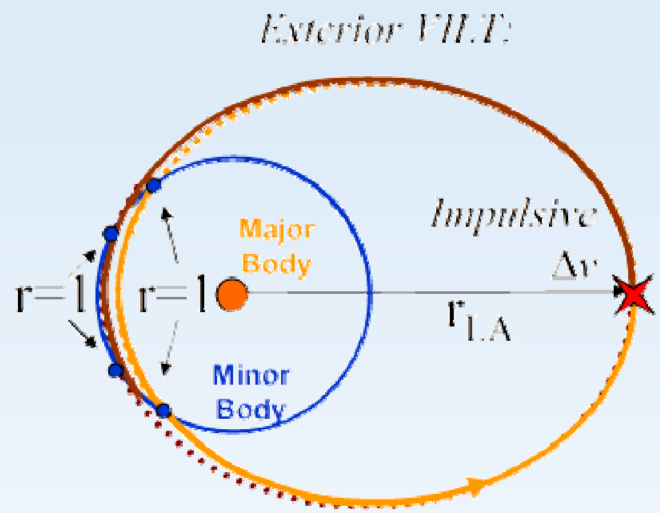


GRAIL – Using low-energy transfers to get to the Moon enabled the GRAIL mission to use a production bus augmented by off-the-shelf tanks. This reduced spacecraft development contributing to the Discovery Mission low risk rating.

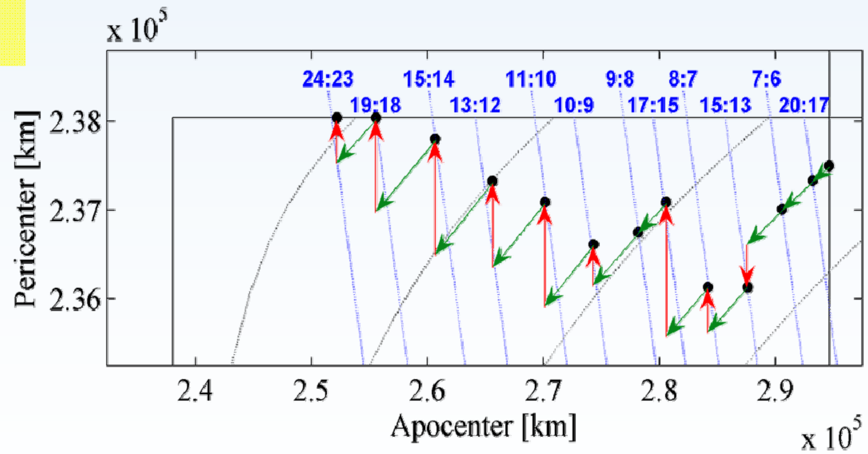
N-body Research has enabled low risk mission concepts.

V_∞ Leveraging





Direct Insertion	**= 3,933 m/s**
Original Flyby Sequence	**= 734 m/s**
Tisserand graph / VILT tours	**= 445 m/s**



Potentially enables two flagship mission with a single spacecraft.

Campagnola, S., Strange, N. K., and Russell, R. P., "A Fast Tour Design Method Using Non-Tangent V_∞ Leveraging Transfers." AAS 10-164

Missions Saved by Modern Astrodynamics

HITEN: Japan's first lunar mission experienced a failure stranding the vehicle in a highly elliptical Earth orbit. Ed Belbruno used the weak stability boundary theory to place HITEN into lunar orbit.

Galileo: After the challenger accident, a direct launch to Jupiter was not available. The use of gravity assists prevented the mission cancellation and enabled the tour.

Cassini/Huygens Mission Redesign: A design flaw in the Huygens receivers made the nominal Huygens mission completely impossible. Mission designers found a new trajectory that allowed full communication for Huygens and preserved the Cassini tour saving hundreds of work years of planning.

Hayabusa**:** Multiple failures of multiple systems, but a revised low-thrust trajectory enabled the sample return.*

AEHF: The apogee engine failed to place the spacecraft in the desired orbit. A series of mono-prop and several months of low-thrust maneuvers will eventually place the spacecraft into an operational orbit.*

* EP Saved the mission

Advanced trajectories and tools have saved numerous missions.

A Missing Community Capability

Only a few years ago, the trajectory design community had several key challenges:

- Trajectory tools were kept in-house
    - Limited public documentation
    - Required significant tool specific expertise
    - Results could not be independently validated
- Tools were very cumbersome and limited

The ISPT Program was asked by PSD to invest in a common set of trajectory design tools that would be **fully documented, more user friendly, robust for convergence, provide consistent results, and be available to the community.**

The ISPT Program sponsored the LTTT Suite.

To improve consistency across the agency of low-thrust trajectory optimization.

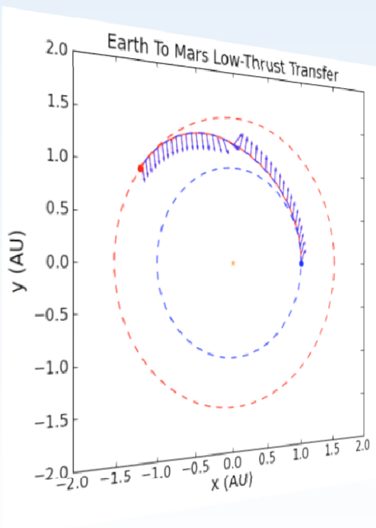
To create (provide) a set of more "user-friendly" low-thrust trajectory tools.

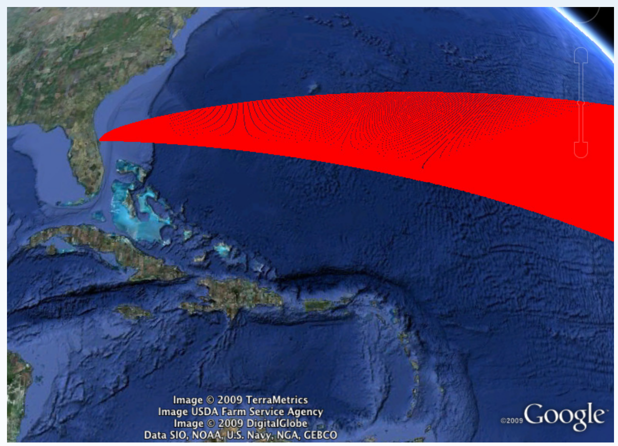
- Reduce time to converge solutions, reduce guessing
- Reduce level of tool expertise required to validate missions
- Validate tools against one another

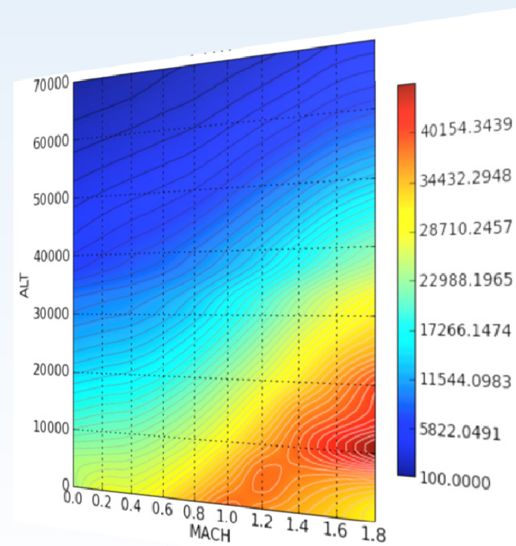
Transfer advanced astrodynamics techniques from research to rapid design teams and the science mission planning community

OTIS 4

- Key Capabilities
  - Size vehicle subsystems simultaneously with trajectory
  - Optimize trajectories with atmospheric and/or exoatmospheric components
  - Define custom equations of motion to optimize non-aerospace vehicle dynamic systems
- Recognition
  - 2008 NASA Software of the Year
  - 2009 R&D 100 Award Winner

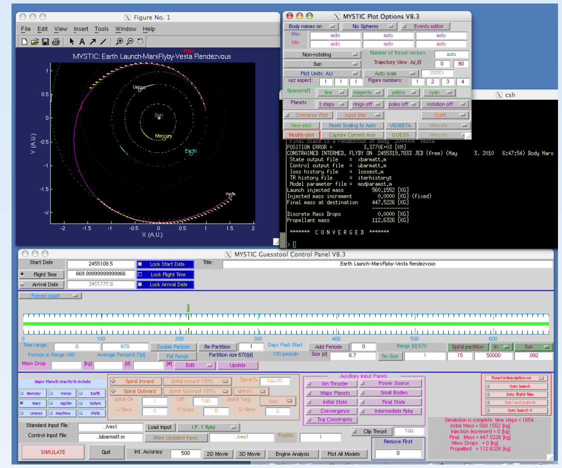




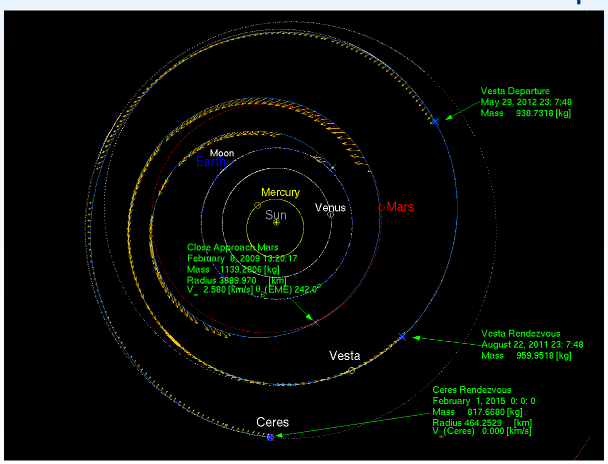


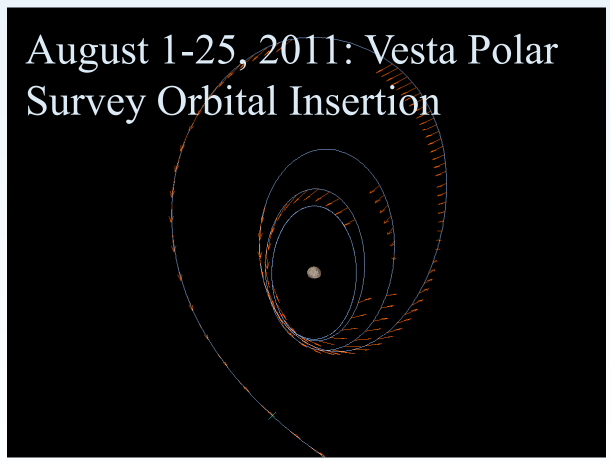
- Availability
  - Open source through http://technology.grc.nasa.gov/, export controlled, SNOPT
  - Training held via WebEx, contact Rob Ralck, rfalck@nasa.gov

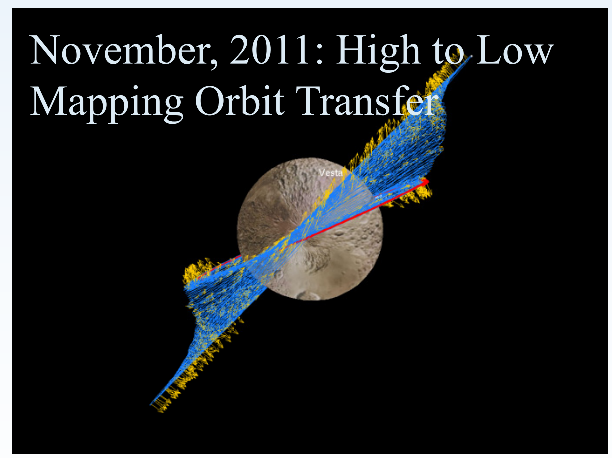
Mystic



- Key Capabilities
  - Computes optimal trajectories using SDC algorithm
  - Rapid high fidelity propagation and suboptimal design with Q-law
  - More than 100 analysis tool kits
  - Monte-Carlo with Optimization in the loop
  - High fidelity animation
- Recognition
  - Dawn flight operations
  - Extended Cassini Operations



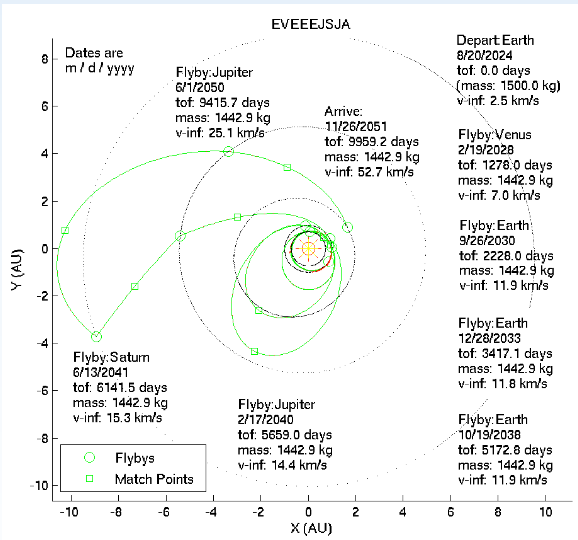


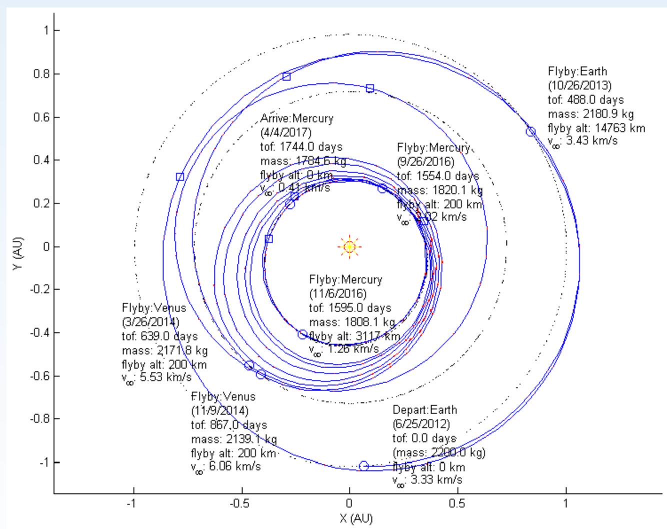


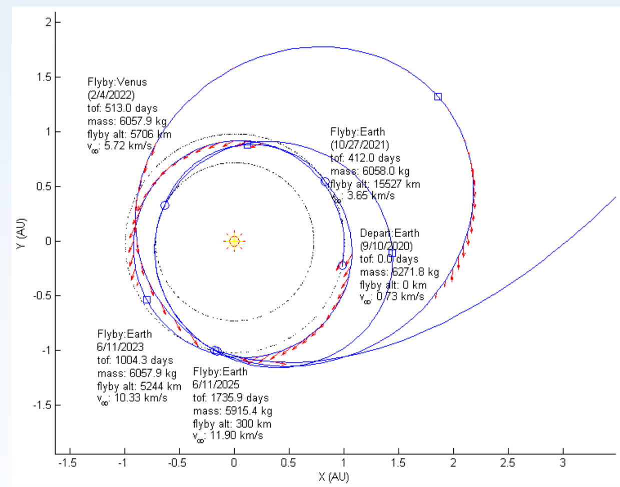
- Availability
  - Currently only available only to NASA and NASA contractors
  - Distributed by JPL: https://download.jpl.nasa.gov/

MALTO

- Key Capabilities
  - User friendly GUI (MATLAB)
  - Rapid convergence of complex trajectories, multiple gravity assists
  - Medium fidelity tool for preliminary mission design and parametric trades
- Highlight
  - Used by JPL for multiple GTOC victories



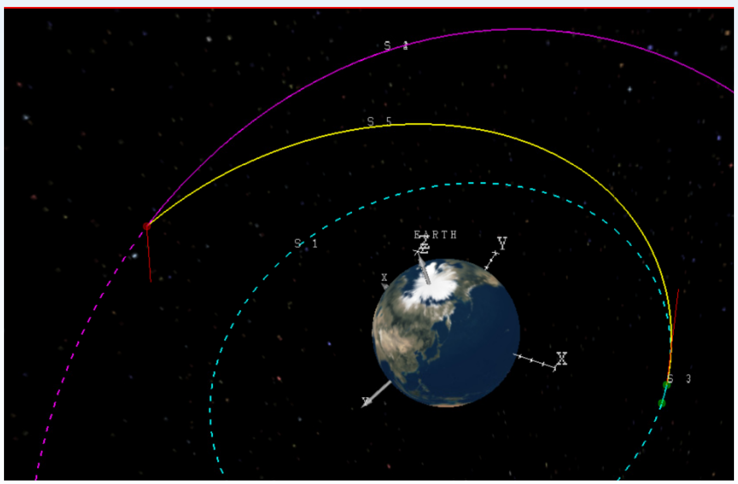


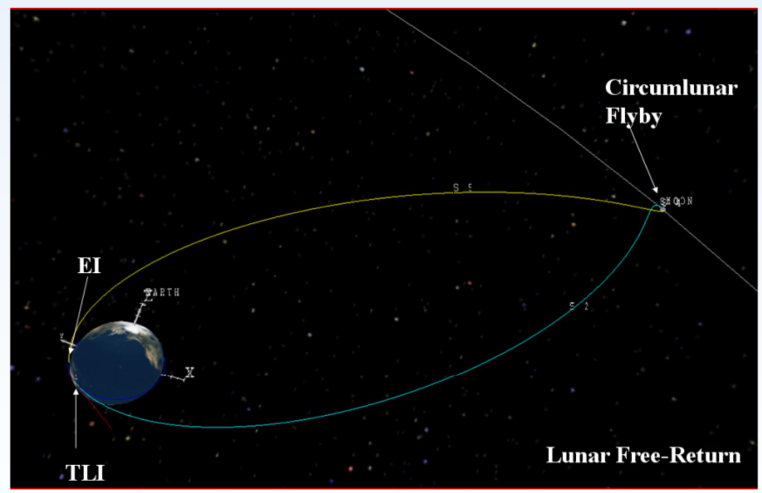


- Availability
  - Free to NASA contractors, CS, and academia through JPL: https://download.jpl.nasa.gov/
  - Commercial licenses through Caltech Office of Tech. Transfer: http://www.ott.caltech.edu/
  - Training available, MALTO in use throughout NASA and industry

Copernicus

- Key Capabilities
  - Generalized Optimization Program
  - High Fidelity n-body analysis
  - Both Low-thrust and High-thrust high fidelity results
- Recognition
  - Baseline Analysis Tool of the Exploration Program
  - Runner-up for NASA Software of the Year





- Availability
  - Currently available to NASA and NASA contractors, Academia and NASA/Industry
  - Training available, Copernicus in use throughout NASA and industry

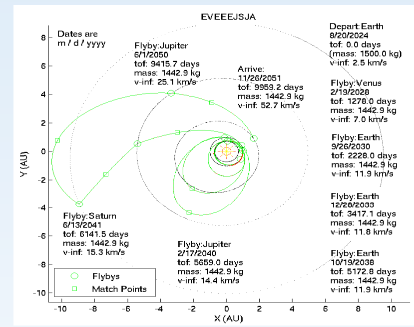
Copernicus Upgrade

- Several new capabilities under development relative to Small Bodies
  - Small Body Gravity Models: Allows insertion and science orbit mission design
    - Single and dual axis spin
    - Ellipsoid harmonics (evolving to polyhedral)
  - Path Constraints
    - Ex) Surface illumination
  - Science Phase Optimization
    - Proximity Operations
    - Instrument swath
      - Minimum time for >99% coverage, etc.
      - 2D and 3D science mapping

Mission Design Training / Systems Analysis

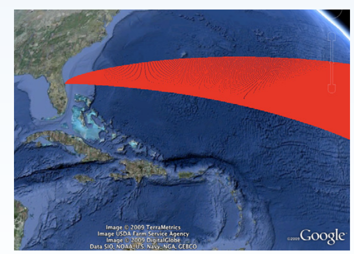
In order to infuse new technologies, the users must be able to assess the payoff.

- Sponsored development of Mystic, MALTO, Copernicus, and OTIS
  - Need to distribute to the broader community
- MALTO training
- Copernicus training course and videos, website in work
- OTIS training, user group



Mission / system design studies define technology requirements

- Critical to quantify mission benefits before hardware investment
- Mission design for NEXT requirements
- Refocus Study led to NEXT throttle table extension
- Refocus Study led to HiVHAC power range, life requirement
- Decadal study support quantified science benefit for SEP, REP, and AMBR engine technology



"If we want people to buy cars, they need to learn to drive." - Oleson

Demo

(Available after the meeting)

```
shota='Earth',bulsi='1000054',jdl=2009,5,25,coast=t,
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lvcont=0,nsa=17,alfa=0.,0.,3*0.,

na=1,2,

;varyn='pmax',
;minyn=7.25,-0.1,2.5

;varyn='c3d',
;minyn=12.,-0.1,0.

; HiVHAC Baseline Hall
 pmin=0.335, pmax=3.76,
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 ct=4.9665E-03, 42.908E-03, 8.6254E-03, -5.4533E-03, 0.7632E-03,

kt=.15,

p0=9.,

;c3d=  12.16039285
;m0=1182.1,
c3d=10,
;m0=1350.


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varyd='radi','theta','phi','radot','vthe','vphi','ptl',;'dmc3d',
sigx=.25,.05,.05,.25,.05,.05,1.,;0.5,
sigy=.000001,8*.0001,
itmax=999,loops=200,test=1.d-12,10000.,xtrap=
ymin=1.,ymax=100.,copt=t,hminc=2.,hmaxc=4.,hm
varyd='x','y','z',sigy=3*.000001,

; 9 kW Array 1 thruster
; gama=  92.46861578
;f1dot=  1.292453609
;    k1=  .7831071156e-01
;lamda= -3.460030526
;   fff=  2.732597704
; elm0=  1.584002154
;   c3d=  18.08918866
;jdate= -1097.094518
;adate=  149.2918627 $
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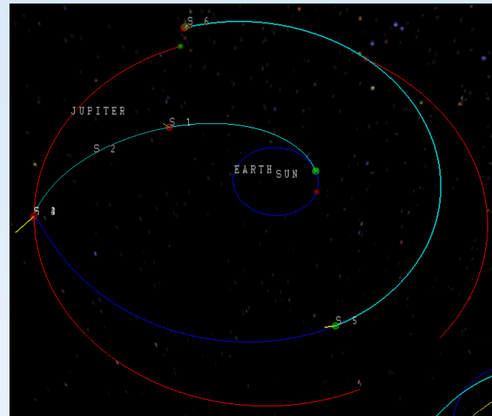
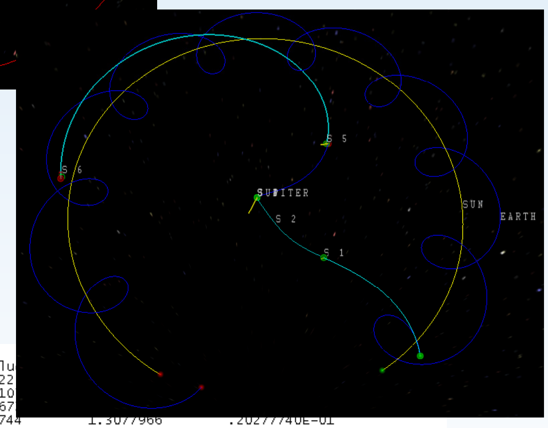


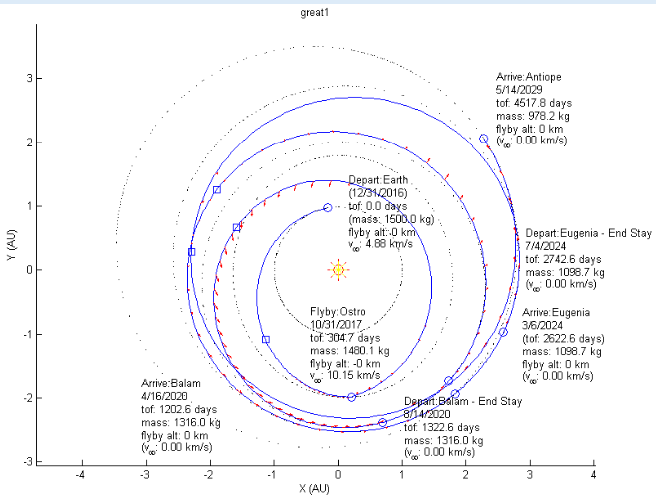


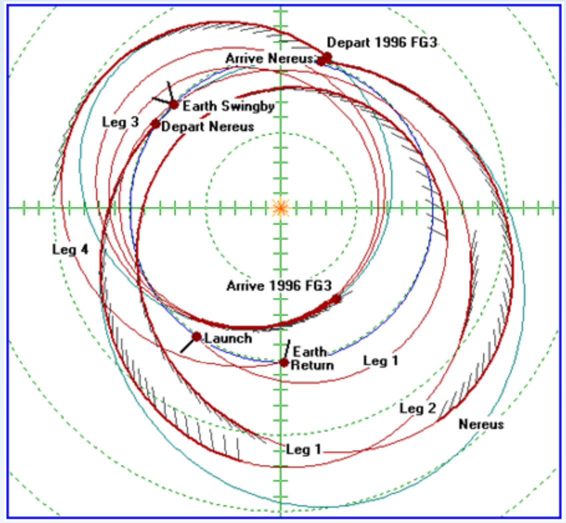

```
                     Independent Variables
            Value          Nominal          Tolerance               Valu
 gama=  89.36765067     92.46861578      .250000              x=  1.377922
f1dot=  .7130741808     1.292453609      .500000E-01          y= -.2382510
   k1= -.7944585338E-02  .7831071156E-01 .500000E-01          z= -.6753367
lamda= -15.93066922    -3.460030526      .250000          radot=  1.3280744     1.3077966     .20277740E-01
  fff=  2.495397705     2.732597704      .500000E-01       vthe=  6.0114509     5.7511733     .26027764
 elm0=  5.363656393     1.584002154      .500000E-01       vphi= -.14913007    -.44743543     .29830536
jdate= -1060.006896    -1097.094518      1.00000            ptl=  .43775861E-01  .0000000     .43775861E-01
adate=  64.77769320     149.2918627      1.00000

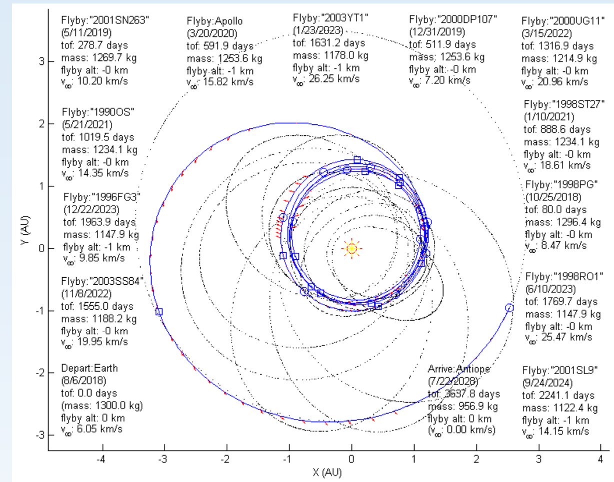
Departure  body              Earth (2,0)                                      Jun 29, 2006  23:50:04   2453916.493
    x  .14151072        y -1.0067435          z  .21193171E-04   xdot  6.1205890     ydot  .85114354      zdot -.29900297E-04
 radi  1.0166405    theta  278.00124        phi  .11944038E-02  radot  .90943506E-02  vthe  6.1794799      vphi -.30089880E-04
  sma  1.0000002      ecc  .16705158E-01    inc  .12265549E-02    lan  174.85368      apf  288.11746      mean  174.86216
   ea  174.94647      tru  175.03010      angmo  6.2823093         hx  .12063499E-04   hy  .13394590E-03    hz  6.2823093

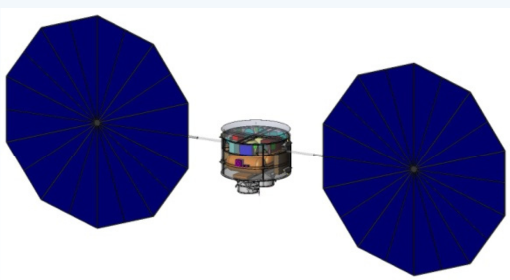
Arrival body          900031 Kopff 22P (2,0,1000054,4000022)                   Jul 28, 2009  18:39:53   2455041.278
    x  1.3110513        y -1.0852975          z -.46809806E-01   xdot  4.6648962     ydot  3.6044092      zdot -.48322129
 radi  1.7026207    theta  320.38180        phi -1.5754198      radot  1.3077966     vthe  5.7511733      vphi -.44743543
  sma  3.4669167      ecc  .54332250        inc  4.7187851        lan  120.91929      apf  162.73717      mean  9.6010074
   ea  20.506096      tru  36.786538      angmo  9.8216561         hx  .69316053       hy  .41516501       hz  9.7883652
 Input                                                      epoch:   May 25, 2009   0:00:00   2454976.500
jdate -1060.0069    adate  64.777693       tend  1124.7846        elx  .95371247      ely  .12290590       elz -.27445703
 eldx -.89891242     eldy  5.9466325       eldz -1.2298566        eli  1.0000000      gama  89.367651     f1dot  .71307418
   k1 -.79445853E-02 lamda -15.930669       fff  2.4953977       elm0  5.3636564       c3d  18.089189       p0  9.0000000
   m0  1046.5000     gam1  1.3207700       gam2 -.10848000       gam3 -.11665000      gam4  .10843000      gam5 -.12790000E-01
  acf  1.0000000    rtilt  .48360924         re  6618.1400         kt  .15000000     scp11  .25000000      pmax  3.7600000
 pmin  .33500000      cm1  .12854000E-05    cm2  .23871000E-05    cm3 -.53560000E-06   cm4  .38500000E-07    cm5  .42000000E-08
  ct1  .49665000E-02  ct2  .42908000E-01    ct3  .86254000E-02    ct4 -.54533000E-02   ct5  .76320000E-03     cf  .90000000
Earth centered departure conditions                                                Equator and Equinox of date
   c3  18.089189      dla -11.656842        rla  13.217785        vhx  4.0550685      vhy  .95243581       vhz -.85934514
  dvi  .0000000       poi  28.500000        pon  35.549351        azi  90.000000      rls  125.54935     disti  104.68115
```

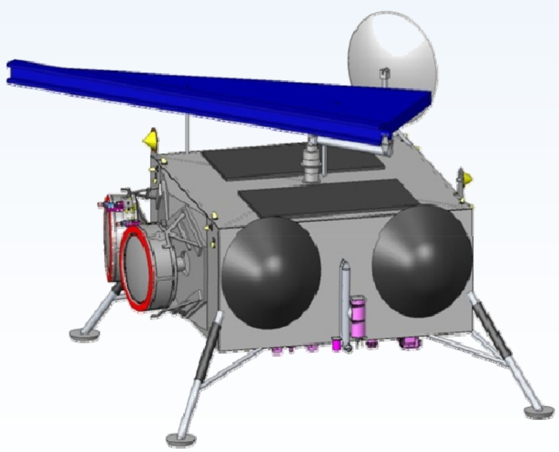
Near-Earth and Mainbelt Asteroids

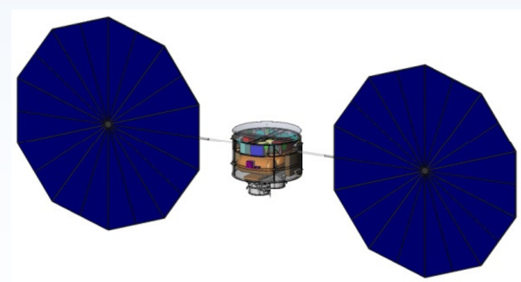






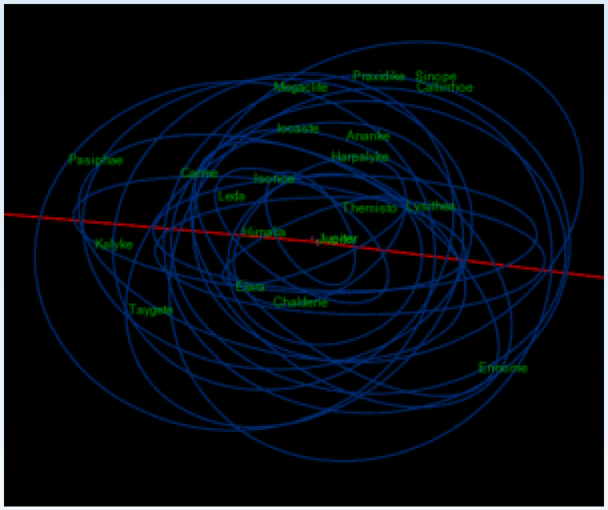


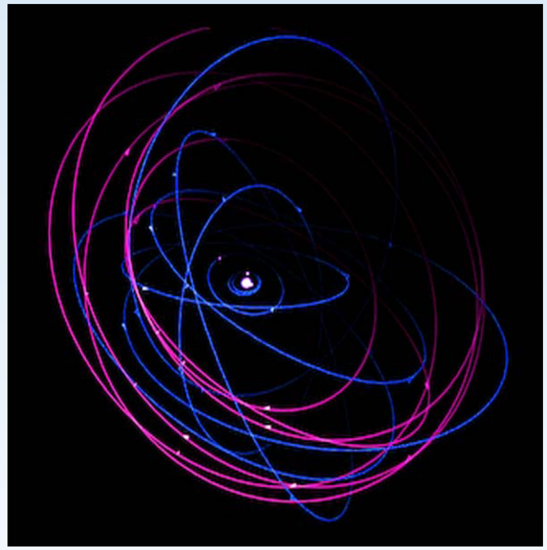


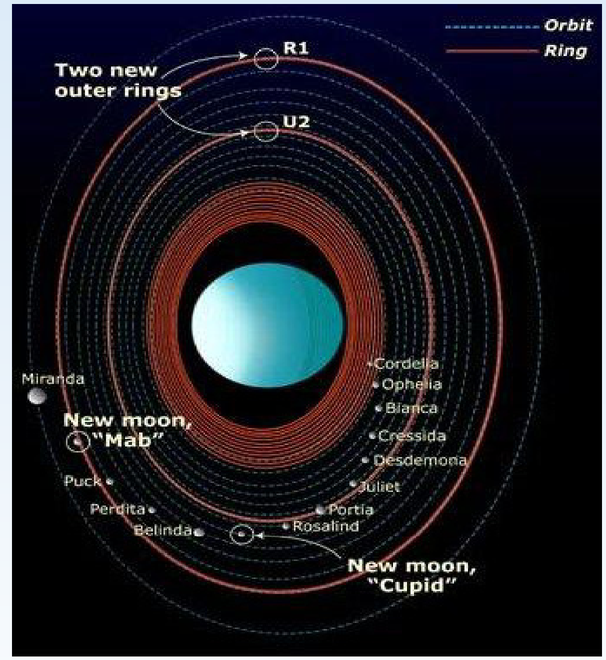


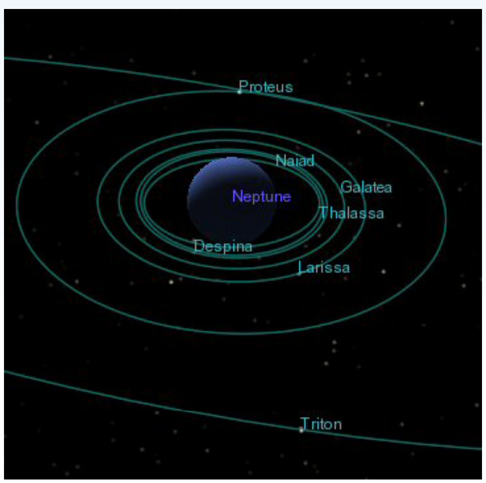
Multi-Rendezvous **Multi-NEA Sample Return** **Mega-Multi Flyby**

Small Body: Outer Planet Moons









Pre-plan small body science on outer planet missions or mission extension for small body science.

Success

The trajectory tools suite was used both by the proposal community and the reviewer community.

Discovery 2010 was the first time that there were no major weaknesses associated with trajectory design!

The NRC and The PS Decadal Survey

The ISPT Tools played a significant role in the Decadal Survey for the NRC.

- Several missions were directed to mission design centers: JPL, GSFC, and APL
- Interplanetary missions leveraged ISPT trajectory tools
- Tools used by ALL design centers

The Planetary Science Decadal Survey recommended continued investment.

“The identification of trajectories that enable planetary missions or significantly reduce their cost is an essential and highly cost-effective element in the community’s tool kit.”

“A sustained investment in the development of new trajectories and techniques for both chemical propulsion and low thrust propulsion mission designs would provide a rich set of options for future missions.”

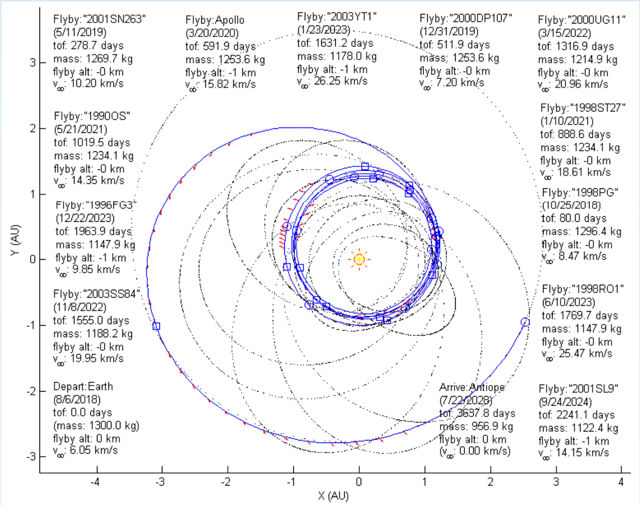
“Research and development in the fields of celestial mechanics, trajectory optimization, and mission design have paid substantial dividends in the recent past, identifying new and higher performance opportunities for planetary missions.”

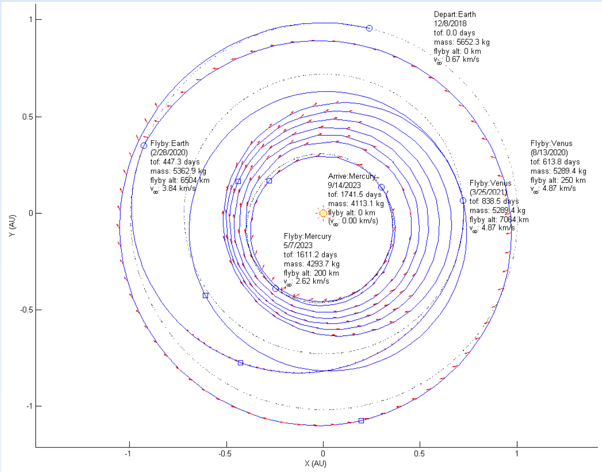
Astrodynamics Research Grants

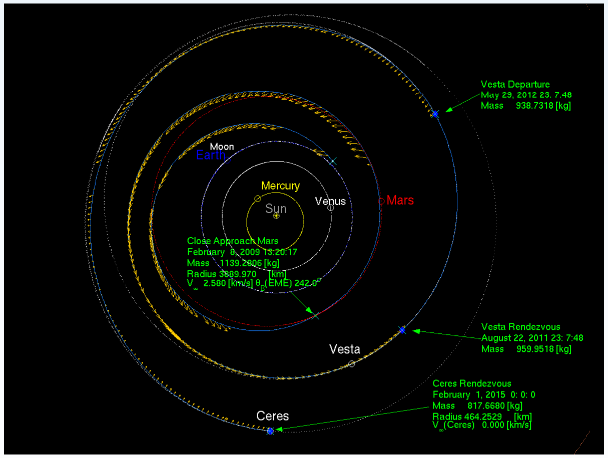
- Directly aligned with decadal survey recommendations
  - Fundamental research had been eliminated
- Astrodynamics Research / Tool Development for PSD Missions
  1) Research or development of an astrodynamics algorithm or methodology for infusion into one of ISPTS existing tools
     - Examples include, but are not limited to: rapid and robust low-thrust geocentric optimization for Copernicus, Lunar Gravity Assist optimization module for Mystic and/or MALTO, Multi-asteroid system gravity model module for Mystic and/or Copernicus, Rapid Uranus Satellite Tour Development Module, Multi-target optimization in MALTO, etc.
  2) Research or development of a new tool to meet the needs of future planetary science missions
     - Examples include, but are not limited to: rapid and robust low-thrust orbit transfer optimization for the n-body Earth-Moon system and escape, V_∞ leveraging tool for rapid assessment of ΔV vs. time for outer planet moon tour development, small body and/or multi-asteroid system orbit insertion and proximity operations rapid design tool, etc..

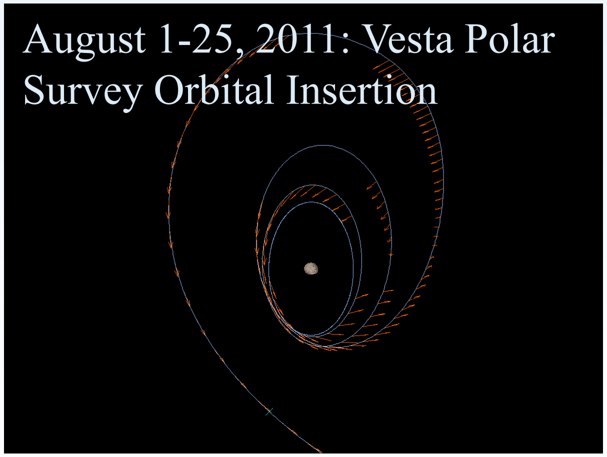
Open solicitation: Proposals due August 20th.

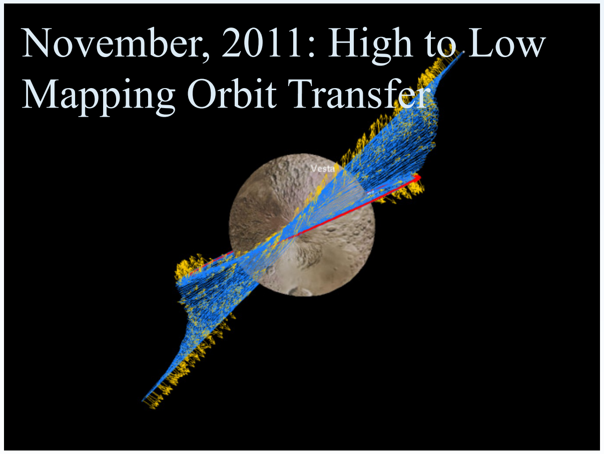
Better Tools = Better Missions











Mission Design Tools have enabled missions and are in use for mission operations today!

- Several tools are available to the mission design / science community
  - SMD mission infusion (Dawn, Cassini, LCROSS)
  - Method to prioritize technology investments with quantitative benefits
- Astrodynamics research and trajectory design has saved multiple high value missions
- Astrodynamics research and trajectory design enables current and future missions
- New astrodynamics techniques are still at the early stage of development
  - We need to continue astrodynamics research within academia
  - We need to advance today's "research" into the rapid design process
- Trajectory analyses and tools are very cost effective investments for the community
  - Investments reduced by x25 over the past 5 years
  - Investments continue to improved capability, offer training
  - Strong support within the Planetary Science Decadal Survey

Higher science return is enabled through astrodynamics research and trajectory design tools.
Suite of tools are continuously upgraded and made available to the community.