Monte for Orbit Determination

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Monte is the Jet Propulsion Laboratory's (JPL) signature astrodynamic computing platform. Its main interface is a collection of Python-language libraries that can be used either for one-off analyses or to build high-quality software applications. Perhaps nowhere is Monte's versatility and excellence better demonstrated than in its use for operational orbit determination (OD). Over the period from 2007 to 2016, Monte was the prime OD solution for fourteen JPL flight projects, and secondary for seven non-JPL projects. These missions span the range of Solar System destinations and operational protocols, yet each were successfully serviced by Monte's flexible OD library.

This paper reviews the missions on which Monte has been used for OD, with an eye toward pointing out the different ways it has been deployed to solve unique problems. It also gives an outline of the main elements of the orbit determination library and how they work together to navigate flight missions.

Key Words: Astrodynamics, Orbit Determination, Software, Python

1. Background

The first software programs created by NASA's Jet Propulsion Laboratory (JPL) to navigate spacecraft were written on punch-cards and processed through an IBM 7090 mainframe.[1] Since that time, advances in JPL's astrodynamic capabilities have been intimately tied to computing technology. As more storage and faster processing became available, engineers rushed to create software to take advantage of this extra power by crafting increasingly detailed and sophisticated models of spacecraft and Solar System phenomena.

Starting in 1964, a group of engineers, led by Ted Moyer, began developing the astrodynamic algorithms and software that would eventually become the Double Precision Trajectory and Orbit Determination Program, or DPTRAJ/ODP.[2][3] Over its forty-plus years of active life, JPL engineers used the DPTRAJ/ODP to navigate the "Golden Age" of deep space exploration. This included the later Mariner and Pioneer missions, Viking, Voyager, Magellan, Galileo, Cassini and more. Also over this time, its base language moved through Fortran IV, Fortran V, Fortran 77 and Fortran 95 as the computational appetites of navigators grew ever larger.

By 1998 it was clear that the aging DPTRAJ/ODP needed to be updated once again. Rather than initiate another refactor, JPL's navigation section commissioned a new effort that would depart from its predecessor in two important ways. First, the new software would be an object-oriented library, written in C++ and exposed to the user as a Python-language library. Second, it would be a general-purpose astrodynamic computing platform, not a dedicated navigation program like the DPTRAJ/ODP. The goal was to create a single library that could be used for astrodynamic research, space mission design, planetary science, etc., in addition to deep space navigation. This new project was affectionately named Monte (Python).

Throughout the first half of the 2000s, Monte was carefully constructed by reshaping the algorithms under-pinning the DPTRAJ/ODP into a rigorously tested and well documented object-oriented software package.[4] In 2007, Monte had its first operational assignment navigating NASA's Phoenix lander to a successful encounter with Mars. Since 2012, Monte has powered all flight navigation services at JPL, including the Cassini Extended Mission, Mars Science Laboratory, MAVEN, GRAIL, Dawn, Mars Reconnaissance Orbiter, Juno, and more (Table 1).

Table 1. Flight missions using Monte for orbit determination, 2007-2016.

PRIME ORBIT DETERMINATION		SHADOW ORBIT DETERMINATION
Phoenix	Chandra	Rosetta
Juno	Spitzer	Hayabusa
Cassini	Kepler	Hayabusa 2
GRAIL	MAVEN	Chandrayaan
EPOXI	MRO	Planet-C
MSL	SMAP	MOM
Dawn	Odyssey	New Horizons Pluto

2. Flight Operations

Monte was built to be a general purpose astrodynamic computing platform, not a dedicated navigation program. It supplies the models and computational algorithms needed for trajectory design and optimization, mission analysis, orbit determination and flight path control, but doesn't force the end-user into any specific workflow or interface. As a result, before Monte can be used on a flight mission, it must be *deployed* for that mission. This entails using Monte in cooperation with other applications and libraries to assemble a custom navigation framework.

The process of deploying Monte for a flight mission can be quite involved. The effort to build a navigation system for the Cassini Extended Mission took over two years, and required the use of many other Python libraries in addition to Monte. The resulting navigation framework can not be properly characterized as Monte itself. Rather, it is a custom application built using the Monte library to perform navigation for that specific mission.

#1 LOCK

Define the base astrodynamic models to be used in flight and compile them into a **lockfile**. Changes to this file are infrequent and under tight configuration management. *Monte's UI System provides* **data setup** *commands which are typed explicitly in a text file and compiled into Monte's Binary Object Archive (BOA) format.*

#2 UPDATE

Copy the lockfile to the local analysis directory. Apply updates to the copied lockfile as appropriate for the individual solution. The actual lockfile remains untouched by the local updates. *The UI System allows local data setup commands (defined in text files) to add, modify or delete models from the copied lockfile.*

#3 RUN

Run the analysis to completion using Unix-like command line tools. *Monte's UI System provides a* **CLUI** *to trigger the execution of analyses configured in the copied lockfile. For instance,* **Trj.integ** *to trigger a trajectory integration,* **Msr.resid** *to compute tracking residuals,* **Sig.filter** *to run the orbit determination filter, etc.*

Fig. 1. The *lock-update-run* style of navigation operations supported by Monte's UI System.

2.1. Lock-Update-Run

The Monte developers have created a special interface for Monte, simply called the "UI System", that supports the *lock-update-run* style of navigation operations which was developed at JPL and has been in use for several decades. In this system, a flight project develops a general input "lockfile" that contains all the astrodynamic models and general software constructs to be used for navigation. This file is "locked down" in that, once created, it is rarely updated, and only by someone with permission to do so. Individual navigation solutions are created in local working directories. First, the lockfile is copied to the local directory, and updated with any specific model changes needed to run the local analysis. These updates may include modifying the initial state of the spacecraft, changing the harmonic values in a gravity field, adjusting the spacecraft shape model, burn error models, etc. The important thing is that these changes are made locally, and don't impact other other directories which reference the lockfile. Once all local updates have been applied, the orbit determination solution is run using a series of Unix-like command line tools. These tools usually drive the solution in incremental steps, allowing the analyst to examine and adjust the solution at the break points.

Monte has an extensive suite of core astrodynamic systems including time, trajectory, and coordinate frame modeling,[5] numerical integration,[6] parameter and partial derivative computation,[7] and more. On top of these, Monte has built a series of components that move a user through the two main steps of the orbit determination process: measurement processing and parameter estimation.

2.2. High-Precision Earth Station Locations

Accurate knowledge of Earth tracking station locations is required for spacecraft navigation and measurement computation. High-precision Earth station locations in turn depend on the implementation of high-precision time frames, high precision Earth coordinate frames, and accurate modeling of the corrections that need to be applied to the station locations due to local geological, hydrological, and atmospheric processes.

Monte supports the high-precision TAI and UT1 time frames, and high precision station clock offsets. The former are necessary for rotating from an inertial coordinate frame into a high-precision Earth fixed frame. This rotation happens in four steps, which are modeled by four sequential frames in the Monte system. Each frame accounts for geological and spatial shifts of the Earth relative to the earth-fixed and space-fixed frames.

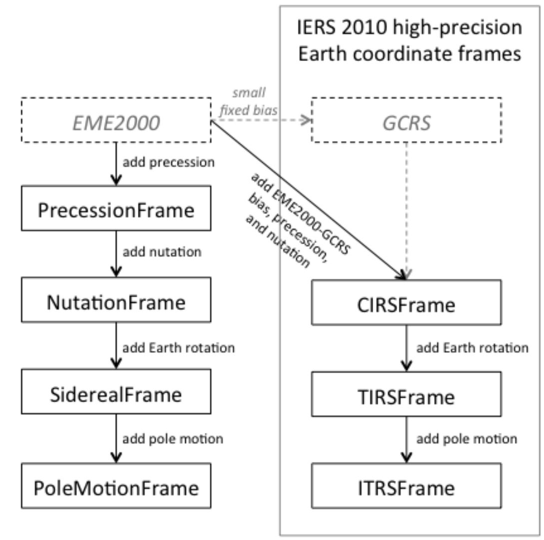

Fig. 2. Relationship between Moyer and IERS high-precision Earth frames.

> **Polar motion frame** accounts for the motion of the instantaneous axis of the rotation of the Earth with respect to the Earth-fixed frame (a.k.a. Earth-fixed frame or Earth-Body-True-Equator frame).
> **Sidereal frame** accounts for the change in the Earth's orientation as it rotates in inertial space (a.k.a. Earth-UT1-True-Equator).
> **Nutation frame** accounts for the short-period oscillations in the motion of the rotational axis of the Earth as seen in the space-fixed frame (a.k.a. Earth-Space-True-Equator frame).
> **Precession frame** accounts for the change in orientation of the Earth's rotational axis as seen in the space-fixed frame (a.k.a. Earth-Space-Mean-Equator frame).

When transforming from the Earth-fixed to inertial, the order of rotation is pole motion, sidereal, nutation, and finally precession. Reversing this order would yield a transformation from inertial to the Earth-fixed frame. Monte contains both the Moyer[2] and IERS[8] formulations (Figure 2 shows the relationship between the two).

The location of a tracking station on the Earth's surface is altered by a number of things, including deformations of the Earth due to tectonic motions, solid Earth tides, and ocean effects, as well as alterations of the Earth's surface due to local geological, hydrological, and atmospheric processes. A station correction is an offset applied to the position of a station, which accounts for one or more of these effects. Monte currently models offsets from five different sources.

- Center of Mass Offset
- Benchmark Offset
- Plate Motion Correction
- Pole Tide Correction
- Solid Tide Correction

All of these systems are necessary for the first step of the orbit determination process, measurement processing.

Table 2. Monte can natively read many file types associated with measurement processing.

File Type	Description
EOP	Earth Orientation Parameter File
EOP2[11]	IERS EOP File (Trk2-21)
DSN Media	Ionosphere & Troposphere (Trk2-23)
TDM Media[14,15,16]	TDM Media Calibrations
DSN Tracking	Tracking data (Trk2-34)
TDM Tracking[14,15,16]	Tracking Data Message File
UTDF Tracking	UTDF tracking data file
GN Tracking	Ground Network UTDF files
GPS Tracking[12]	JPL FLINNR data files
JPL PSF[13]	Picture Sequence File (optical)
JPL ITDF[17]	In-situ tracking (SC to SC)

Table 3. Monte supported measurement types.

Type	Description
Doppler[2]	1/2/3 way Doppler observables
Range (DSN)[2]	1/2/3 way range-unit observables
Range (phase)	2/3 way DSN phase observables
Range (mag)	1/2/3 way unit-length observables
Angle (DSN)	Az/El & X85/Y85 observables
Wide/narrow VLBI	DDOR observables
Accelerometer	SC acceleration observable
Torque	SC torque observable
Altimeter	SC-to-body altitude observable
Optical	Body center/landmark observables
Two-leg Doppler[2,10]	SC-to-SC Doppler observable
Instant Range[9]	SC-to-SC range observable
Instant Range Rate[9]	SC-to-SC range rate observable
Instant Range Accel[9]	SC-to-SC range accel observable
Phase GPS	GPS phase observable
Pseudo Range GPS	GPS range observable

2.3. Measurement Processing

Monte has dedicated systems to support the complex series of steps necessary to process spacecraft tracking data. It has a series of utilities that read common measurement and calibration file formats, and converts their data into Monte native types. Table 2 lists the file formats currently supported by Monte.

Once data has been read into the system, Monte provides the infrastructure needed to compute observables and residuals from the observed measurements. Table 3 lists the supported measurement types, which include tracking station to spacecraft observables, spacecraft to encounter body observables, spacecraft to spacecraft observables, and more.

Monte provides a *data editing language* which allows adjustments to be made to the computed measurements and observables. Individual or groups of measurements can be *ignored* (allow user to view points but don't include them in filter solution), *deleted* (remove data entirely), *weighed* (assign filter weights), *adjusted* (apply manual offset to points), and *calibrated* (using media calibration data).

The tracking data residuals generated through measurement processing can be passed into Monte's filtering system to iteratively generate orbit determination solutions. Monte provides several utilities for viewing and editing measurement residuals as they are being processed by the filter (Fig. 3). Corrupted points can be interactively removed from the data set, and "pre-

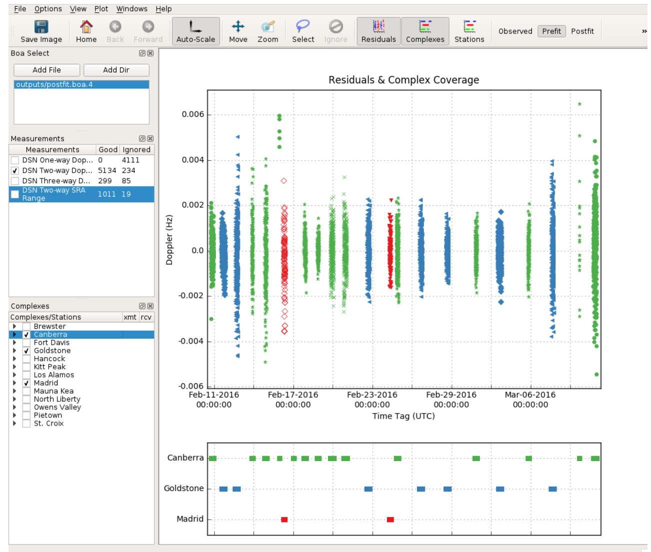

Fig. 3. Monte's Residual Viewing and Editing Tool.

fit" residuals (before the filter is run) can be compared to "postfit" residuals (after the filter is run) to gauge solution convergence.

2.4. Filters

Monte's filtering package is responsible for processing measurement residuals and using them to compute uncertainties and updates to model parameters. The current package includes both a UD-factorized batch Kalman filter and a square-root information (SRI) filter.[18] Both support the estimation of dynamic (time-varying), bias (time-invariant) and stochastic (piecewise-continous) parameters. Additionally, the uncertainty of bias parameters may be considered in the filter solution without being estimated (*consider paramters*).

Both formulations support current state (all parameters are referenced to the new batch epoch) and pseudo-epoch state[20] (dynamic and bias parameters are referenced to the initial filter reference epoch; only the stochastic parameters are updated at each batch change) run modes. Monte also supports stochastic smoothing[19] of filter solutions.

In addition to generating a filter solution, Monte can also map solution uncertainty forward and backward in time. State variable can be mapped in any combination of supported coordinate types (Cartesian, spherical, cylindrical, and conic) and in any supported frame.

2.5. Parameter Estimation

Most of Monte's astrodynamic models support parameter estimation via the filtering package. Figure 4 lists out the Monte models which support estimation. Note that for any given model, there may be multiple parameters which can be estimated. For instance, the Finite Burn model allows the burn start time, duration, delta-V magnitude, delta-V components (x,y,z) and duty cycle to be estimated.

3. Pre-Flight Analysis

In the previous section, we looked at the systems Monte provides to support flight orbit determination. However, Monte also provides support for pre-flight navigation design efforts.

Monte's *Measurement Simulation Toolbox* (MsrSim) pro-

CELESTIAL MODELS Gm, Relativistic gamma & beta, Cap/disk/ring/point mascons, Constant inertia, Gas giant tide, Gravitational tide, Lense-Thirring, Planetary rings, Solar plasma density, Spherical harmonics & periodic corrections

EPHEMERIS MODELS Fixed offset trajectory, GPS broadcast ephemeris, Earth station trajectory, Equinoctial ephemeris, Hermite interpolation trajectory, Initial integration state, Offset trajectory group, Optimization control point, Planetary / small body ephemeris, Position & velocity state

FRAME MODELS IAU body-fixed pole & prime meridian, IERS2010 ITRS Frame & UT1 model, Mars angles, Nutation & precession, Offset frame, Pole motion, Polynomial frame & direction, UT1 time frame

ATMOSPHERE MODELS Atmospheric drag, Exponential atmospheric density, Multiple atmospheric density, MarsGram 2001 / 2005 / 2010, VenusGram 2005

BURN MODELS Burn group, Finite maneuvers, Impulsive maneuvers, Isp thrust, Isp-pressure thrust, Named thrust, Polynomial thrust, Small maneuvers

SPACECRAFT MODELS Mass, Accelerometer bias, Albedo pressure, Colatitude table shape, Cylindrical shape, Exponential accelerations, Flat plate shape, Parabolic dish shape, Polynomial state function, Polynomial torque, Solar pressure, Spacecraft bus shape, Spherical shape

MEASUREMENT MODELS Ionosphere media delay, Troposphere media delay, Measurement bias, Optical Navigation Camera, Optical Navigation Picture, Optical Phase Bias, Quasar set, Star catalog, Polynomial clock offset, Polynomial frequency history

MATH MODELS Fixed direction, Generic user defined polynomial, Harmonic table shape, Monomial, Named direction, Polynomial with trigonometric functions, Polynomial with exponential functions, Table-interpolated acceleration manager, Periodic accelerations, Polynomial accelerations

Fig. 4. Monte models which support parameter estimation.

vides an end-to-end solution for pre-flight covariance analysis. Its *scheduler* allows an analyst to calculate tracking station-to-spacecraft view periods, which serve as the starting point for drafting a tracking schedule. This base schedule can be refined using a combination of constraints (e.g. only track when the spacecraft is above 15 degrees elevation from the viewing station) and *rules* (e.g. select three radiometric tracking passes per week from a series of tracking complexs).

Once a nominal schedule has been created, MsrSim will then synthesize simulated tracking data which can be processed through the filtering system to estimate the mission uncertainty profile. This data can be treated the same as real measurements, in that it can be viewed, edited and adjusted using the same operational tools described in Section **2.3.**.

An additional highlight of Monte's pre-flight navigation analysis suite is that it integrates seamlessly with Monte's trajectory design and maneuver analysis tools. Data can be passed natively between these systems to allow the mission design and navigation teams to iterate on designs. For instance, mission designers can create a reference trajectory using Monte's Cosmic trajectory optimization tool. This trajectory can then be passed directly to the navigators for OD covariance analysis. The resulting mission uncertainty profile can be handed off to the flight path control team to perform statistical maneuver analysis. All of this is done within the Monte system, without the need to write intermediate interface files.

4. Recipes from Flight Experience

Whenever Monte is deployed for flight, there are a set of base models so useful that they are included for most every mission. These include point mass gravity and ephemeredes for the Sun and planets, high-precision Earth station locations and associated models (plate motion, gravity tides), solar radiation and spacecraft shape model, and impulsive and finite burn models. Beyond these base models, experience from flight has identified four configurations for deploying Monte for orbit determination. These are the **orbiter**, **cruise**, **irregular body**, and **tour configurations**, and they will be described in the coming sections.

No two missions are alike, so these configurations are really just starting points on which missions specialize further for actual operations. In the following sections, we look at deployment recipes for Monte in the context of actual missions where it has been used for navigation. In the process we will highlight what is unique about the individual deployments and how Monte was configured to successfully meet those challenges.

4.1. In the Earth-Moon System

On June 13, 2010, the **Hayabusa spacecraft** re-entered Earth's atmosphere after spending seven years in interplanetary space, and the JAXA spacecraft didn't come empty handed. Although the main spacecraft was due to burn up in the atmosphere above Australia, a protected capsule was released prior to reentry containing samples from asteroid Itokawa. The goal was to land the capsule in the Woomera Prohibited Area in South Australia, safely away from any urban centers. During the Earth return, a team at JPL used Monte to provide orbit determination solutions to the flight path control team at JAXA. Navigators targeted an entry keyhole in Earth's B-Plane, and after every solution update, the Entry, Descent and Landing (EDL) team would map the achieved B-Plane encounter (and uncertainty) to the ground.

Monte's scriptability was a key asset during this process. It allowed multiple orbit determination variations to be run for any given solution. These were autonomously processed and turned into Entry State Files (ESFs) which were used by the EDL team to map the solution from the B-Plane to its footprint on the ground. Fig. 5 shows the final OD solution delivered by JPL prior to Hayabusa's re-ntry. On the top, the solution is represented in Earth's B-Plane (shaded ellipse in center), and on the bottom is the mapping of that solution to the ground. The overlapping red and green dots show the ballistic mapping of the B-Plane dispersions (red and green represent different atmospheric models), whereas the tighter collection of blue dots on the left side of the figure show the anticipated landing zone of the parachute-equipped capsule. The actual recovery location of the capsule, indicated by the black star, was about 22 km from the nominal landing location.

The **Soil Moisture Active and Passive (SMAP)** mission has used Monte for orbit determination since launch in early 2015. SMAP is in a 685 km near-circular polar orbit, and uses Monte's *orbiter configuration*, summarized in Figure 6, for navigation.

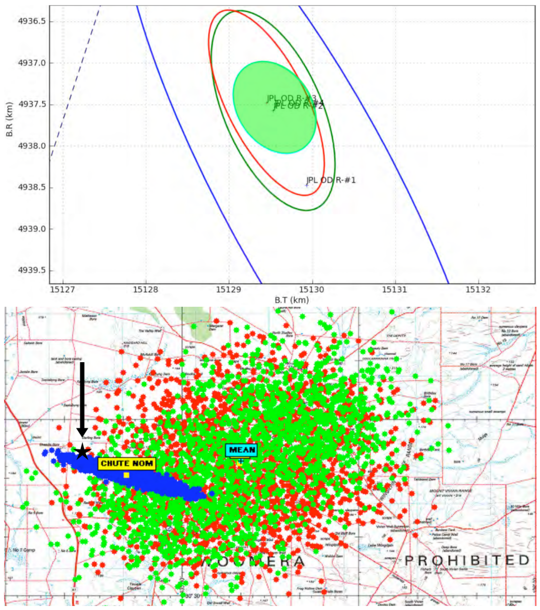

Fig. 5. Final Hayabusa JPL OD delivery (top) mapped to Earth's surface (bottom).

ORBITER CONFIGURATION

Navigate closed orbit around a center planetary or satellite body.

FOUNDATION
■ Atmosphere model and high-precision gravity field for center body ■ Point masses and ephemeredes of significant third-body influences ■ Spacecraft shape model for SRP and atmospheric drag ■ Impulsive maneuvers for attitude control ■ Finite burns for orbit trim maneuvers

SPECIALIZATIONS Data-driven predictive atmosphere model (used on **SMAP**), Interpolated atmosphere model e.g. MarsGram (used on **MAVEN**)

Fig. 6. Monte Orbiter configuration.

To satisfy trajectory prediction requirements, the SMAP OD team uses the semi-empirical Drag Temperature Model (DTM) for Earth atmospheric density calculations.[21)] The model incorporates solar flux and geomagnetic data from, for example, NOAA's Space Weather Prediction Center, to predict near-term future atmospheric densities. The SMAP navigators have constructed a system which autonomously imports this data daily and feeds it into Monte's DTM atmosphere model, which is then used in their 30-day spacecraft trajectory predictions.[30)] Monte also provides an updated DTM model (known as "DTM 2012") which was created by the the Advanced Thermosphere Modelling for Orbit Prediction (ATMOP) project.[22)]

Monte was used to navigate the dual-spacecraft **Gravity Recovery and Interior Laboratory (GRAIL)** mission from launch in fall 2011 through lunar impact in winter of 2012. The science requirements for the mission required keeping the GR-A and GR-B spacecraft in tight formation while collecting science data. The two spacecraft shared the same slightly elliptical, 2hr lunar orbit, with GR-B taking an 85 km down-track offset from GR-A. As better quality gravity field estimates were generated for the Moon, especially those using data collected from the lunar dark side, the fidelity of the gravity field used in Monte for operations was increased from 150x150 to a maximum of 400x400. GRAIL also made extensive use of Monte's

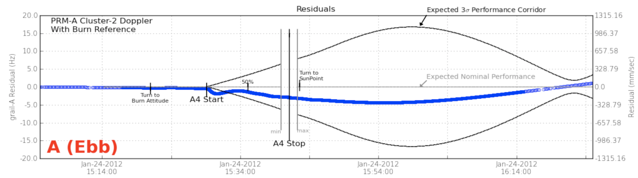

Fig. 7. GRAIL RTRV display with burn start, stop and 3-Sigma corridor overlays.

CRUISE CONFIGURATION

Navigate interplanetary space, possibly with gravity-assist encounters.

FOUNDATION
■ Gravity fields for encounter bodies ■ Point masses and ephemeredes of significant third-body influences ■ SRP modelling ■ Impulsive and finite maneuvers ■ B-Plane targeting

SPECIALIZATIONS EDL interface and mapping to direct descent body (used on **Hayabusa** and **MSL**), rapid switch to Orbiter Configuration (used by **MAVEN**), OpNav on approach (used by **New Horizons Pluto**)

Fig. 8. Monte Cruise configuration.

Real-Time Residual Viewer (RTRV) to monitor and gauge maneuver performance as they were being executed. RTRV can connect directly to a stream of real-time data observables from the DSN, generate residuals based on a trajectory prediction, and display on a configurable chart which can be overlaid with expected execution values (Figure 7).[23)]

4.2. To the Inner Planets

The **Mars Science Laboratory (MSL)** was launched in November 2011 on a nine month interplanetary trip to Mars. Monte was deployed in the *cruise configuration*, described in Fig. 8, for flight orbit determination on MSL. The spacecraft was spin stabilized while en route to Mars, which posed a challenge for measurement processing because its primary antenna was offset from the center of mass. This had the effect of corrupting Doppler observables with a periodic signature due to the angular velocity of the antenna and a frequency bias due to the circular polarization of the signal. Monte was used to model and estimate the motion of the spinning antenna, which allowed the MSL navigators to refer the tracking data to the spacecraft center of mass. These adjustments were calculated using Monte's parameter estimation capability described in Section **2.5.**.[29)]

The **MAVEN mission**, launched in November 2013, followed a similar interplanetary cruise as MSL except that on arrival it went into orbit around Mars. This required developing a second flight navigation framework using the *orbiter configuration* and swapping over to the new configuration after Mars orbit insertion. MAVEN is performing in situ studies of the Mars atmosphere, and science collection requires occasional, week-long "deep dips" which take the spacecraft into higher density regions in the atmosphere. The delta-V produced during these deep-dip drag passes, with an altitude range to-date between 119 to 145 km, is significantly higher than those experienced at MAVEN's nominal periapses altitude of 150 km (2-10mm/s nominal vs. 300 mm/sec deep-dip). This poses a challenge to navigation, requiring a high accuracy model of the Martian atmosphere and attitude drag profile of the spacecraft. MAVEN OD team uses the MarsGRAM 2005 density model,[25)]

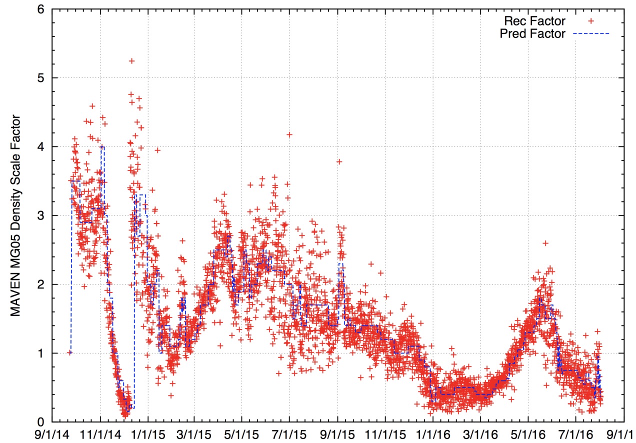

Fig. 9. MAVEN OD estimated scale factor on Mars-GRAM 2005 model for nominal and deep dip drag passes.

IRREGULAR BODY CONFIGURATION

Navigate in proximity to an irregularly shaped body such as an asteroid or comet.

FOUNDATION
■ Polynomial or mascon gravity field ■ Estimation of center body pole and rotation ■ Estimation of center body ephemeris ■ SRP modelling ■ Impulsive and finite maneuvers ■ Body center and landmark OpNav observables

SPECIALIZATIONS Comet outgassing model for ephemeris estimation and a moving atmosphere to model the coma (used by **EPOXI**), 6-DOF integration of body ephemeris (used by **Rosetta**)

Fig. 10. Monte Irregular Body configuration.

made available natively in Monte, which they modify with an estimable multiplicative scale factor per orbit to accommodate the observed drag DV seen in Doppler measurements (Figure 9 shows the estimated scale factor values applied to the Mars-Gram 2005 density values). This setup allows them to predict the location of the MAVEN spacecraft within a 220 sec down-track range after 25 days in the nominal science orbit.[24]

4.3. Around Small Bodies

Navigating small body missions comes with a host of special challenges. Often, the orbit of the body being visited is poorly known. This requires the spacecraft to refine and update its knowledge of the body's position on approach. The **EPOXI spacecraft** used a campaign of optical navigation images as it approach comet Hartley 2 in late 2010. The OpNav observables were processed in Monte and used to estimate the comet ephemeris along with several variations of outgassing models. The improved comet ephemeris was used to redesign trajectory correction maneuvers and re-target to the the nominal flyby conditions.[27]

The irregular shape of many small bodies makes proximity operations particularly difficult. Often, a spacecraft will need to iteratively characterize the small body's gravity field through a succession of tighter orbits. The **Dawn mission** did this through a series of high, medium, and low altitude orbits at Vesta in summer of 2011. Navigators on the Dawn mission deployed Monte in the irregular body configuration, described in Figure 10. Monte provides several models to calculate and estimate the gravity field of a small body.

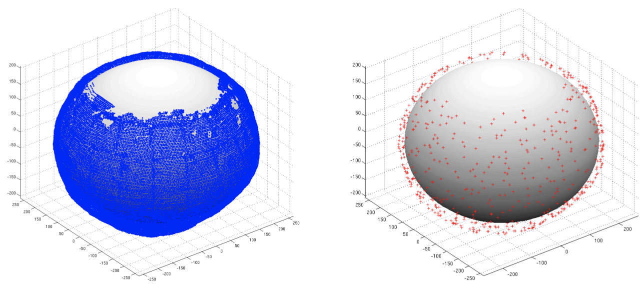

Fig. 11. Vesta landmarks processed by in Dawn navigation, full database (left), random down sample (right).

1. A high order harmonic field can be defined and used for gravity calculations.
2. A shape model for the small body can be specified along with a mass density. Monte's constant density ellipsoid or polyhedral gravity models calculate the appropriate gravitational accelerations.
3. A collection of mass concentrations (mascons) can be defined and layered over a base gravity model (point mass, harmonic, ellipsoid, polyhedral). The mascon gravity model then calculates the mascon perturbations to the underlying field.

Dawn navigators used a high order harmonic field to model Vesta's gravity, which was iteratively updated with each reduction in orbit altitude. Dawn OD also processed landmark observables in Monte to help estimate the pole and rotation rate of Vesta.[26] The left side of Fig. 11 shows the full set of landmarks (approx. 70000 total) processed during the second High Altitude Mapping Orbit (HAMO 2). A random sample (approx. 1%) were extracted and used for OD processing, shown on the right side of the figure.

The **Rosetta mission**, led by the European Space Agency (ESA), did a similar characterization of comet 67P in summer 2014. Proximity operations at 67P were further complicated by the existence of a comet coma. Monte provides the ability to plug-in a "moving" atmosphere model (the motion of atmospheric gas is combined with spacecraft velocity in drag computations) to model coma interactions. Navigators at the European Space Operations Center (ESOC) provided JPL with a coma model for 67P, which was used by JPL in Monte to perform shadow orbit determination solutions in the run up to the Philae landing in late 2014.[28] Monte's scriptability was pushed to the limits by constructing an operations framework that ran in excess of two dozen model variations at the discretion of analysts. These variations provided a daily menu of OD solutions to be reviewed by the navigators.

4.4. Touring the Outer Planets

The Cassini spacecraft has been in a gravity assist tour of the Saturn system since 2004. Its prime pivot is Saturns largest moon Titan which it encounters regularly. Less frequently it will flyby an icy satellites like Enceladus and Dione. In 2012, Monte was deployed in the *tour configuration*, summarized in Figure 12, and replaced the legacy DPTRAJ/ODP as the prime OD software for Cassini.

Many of Saturn's satellites have resonant interactions with each other. When estimating the ephemeris of one of the satellites, it is often necessary to estimate the state of all of them to capture these resonances. An iteration loop was built into

TOUR CONFIGURATION

Navigate a gravity-assist enabled tour of a gas-giant satellite system.

FOUNDATION
■ Planetary and satellite system ephemeris ■ Gravity field for flyby bodies ■ Automated segmentation for OD analysis arcs ■ SRP modelling ■ Impulsive and finite maneuvers ■ B-Plane targeting

SPECIALIZATIONS Simultaneous estimation and integration of satellite system ephemeredes (used by **Cassini**), Ring mass modeling and estimation (used by **Cassini**)

Fig. 12. Monte Tour configuration.

the Cassini navigation system that allowed the ephemerides of the entire Saturn system to be estimated and then reintegrated (along with the spacecraft) as part of the OD solution convergence. Another notable feature of the Saturn system are its iconic rings. The Cassini end of mission plan entails dropping the altitude of periapsis to between the inner most ring and the top of Saturns atmosphere. In order to accurately model flight in this region, Monte has implemented a ring model to represent the gravitational effect of the rings on the spacecraft.

5. Future mission challenges

Monte's first ten years in flight have been critical in shaping it into a first-in-class orbit determination solution. It has flown through a spectrum of solar system destinations and successfully navigated the gamut of mission profiles. However, the next ten years promise to bring new challenges that the software will need to grow into. There are certain key capabilities that are being targeted as priorities by the Monte project.

- Low thrust trajectory design and estimation to accommodate the increasing number of low thrust missions.
- Nonlinear maneuver analysis for more accurate calculation of mission delta-V budget. This includes "OD in the loop" Monte Carlo simulations of the effect of OD uncertainty on maneuver size.
- Efficient uncertainty quantification and optimization under uncertainty. This is important for collision avoidance analysis and next-generation optimization targeting strategies.
- An astrodynamically accurate 3D visualization scripting language. This can be integrated into user-developed applications to provide a detailed window into astrodynamic algorithms. For instance, orbits overlayed with control and break points can be shown changing in real time in response to optimization.

The most important thing a software project can have are high quality customers. Monte has been fortunate enough to serve a world class team of orbit determination analysts in the Mission Design and Navigation Section at JPL. Their innovative use of the software and insightful suggestions have made Monte into a trusted name in space navigation.

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