Monte for Orbit Determination

By Jonathon SMITH, Theodore DRAIN, Shyam BHASKARAN, Tomas MARTIN-MUR

[1)] *California Institute of Technology / Jet Propulsion Laboratory, Pasadena, California*

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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 all 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. The base language also evolved over this time to take advance of new hardware platforms, moving through Fortran IV, Fortran V, Fortran 77 and Fortran 95.

By the late 1990s, 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 underpinning 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 swith 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 OD		Shadow OD
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. 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. 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.

To help simplify this deployment process, the Monte developers have created a special interface, known simply as the "UI System", that implements the *lock-update-run* operations workflow developed at JPL (Fig. 1).

2.1. Lock-Update-Run

Monte's UI System is designed to support the lock-update-run style of navigation operations which has been in use for several decades at JPL. In this system, a flight project develops a general input *lockfile* that contains all the astrodynamic mod-

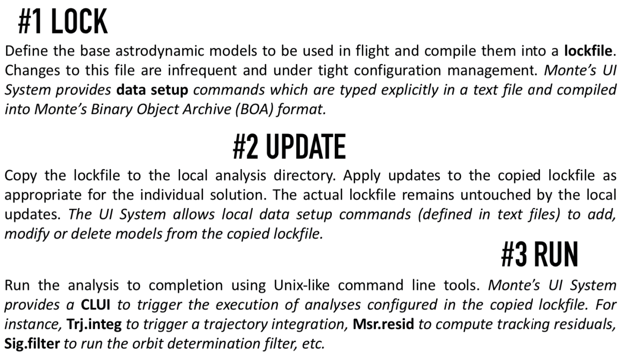

Fig. 1. The *lock-update-run* style of navigation operations supported by Monte's UI System.

els 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 explicit permission to do so. The lockfile is made available in a public folder on a shared navigation file system, and used as a starting point when running specific navigation solutions in local working areas.

The general procedure for creating a navigation solution is to first copy the lockfile to a local working directory, and then update it with any specific model changes needed to run the 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 to the local copy of the lockfile, and don't impact 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.

Polar motion frame accounts for the motion of the instantaneous axis of the rotation of the Earth with respect to the Earth-fixed frame.

Sidereal frame accounts for the change in the Earth's orientation as it rotates in inertial space.

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.

Precession frame accounts for the change in orientation of the Earth's rotational axis as seen in the space-fixed frame.

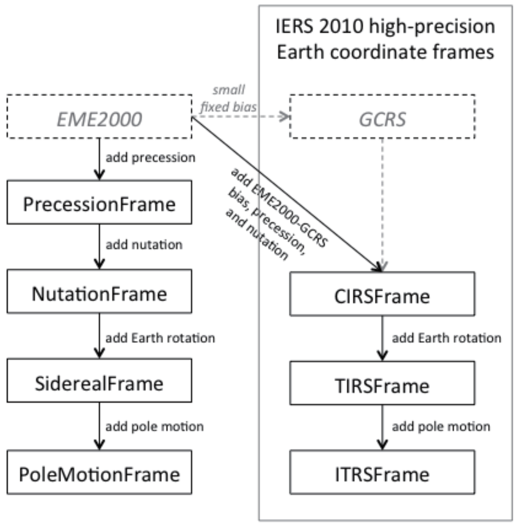

Fig. 2. Relationship between Moyer and IERS high-precision Earth frames.

When transforming from Earth-fixed to inertial, the order of rotation is pole motion, sidereal, nutation, and finally precession. Reversing this order yields a transformation from inertial to the Earth-fixed frame. Monte contains both the Moyer[2] and IERS[8] formulations (Fig. 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, 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.

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 residu-

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

File Type	Description
EOP	Earth Orientation Parameter File
EOP2[9]	IERS EOP File (Trk2-21)
DSN Media[10]	Ionosphere & Troposphere (Trk2-23)
TDM Media[12,13,14]	TDM Media Calibrations
DSN Tracking[11]	Tracking data (Trk2-34)
TDM Tracking[12,13,14]	Tracking Data Message File
UTDF Tracking[15]	UTDF tracking data file
GN Tracking	Ground Network UTDF files
GPS Tracking[16]	JPL FLINNR data files
JPL PSF[17]	Picture Sequence File (optical)
JPL ITDF[18]	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[2,19]	SC-to-SC Doppler observable
Instant Range[20]	SC-to-SC range observable
Instant Range Rate[20]	SC-to-SC range rate observable
Instant Range Accel[20]	SC-to-SC range accel observable
Phase GPS	GPS phase observable
Pseudo Range GPS	GPS range observable

als 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), *weighted* (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 "prefit" 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-

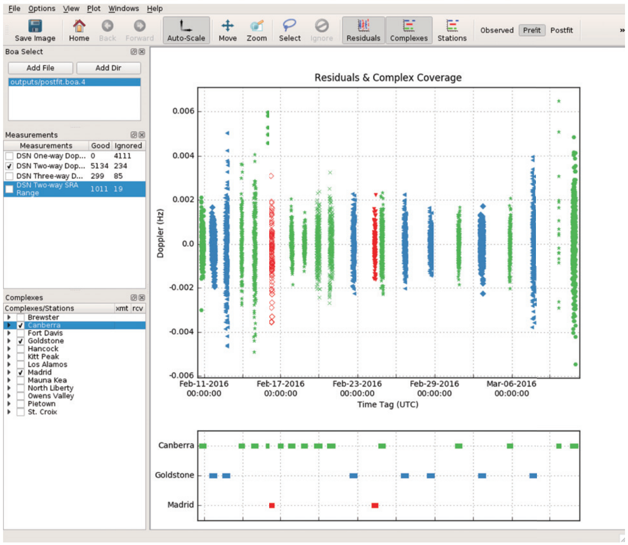

Fig. 3. Monte's Residual Viewing and Editing Tool.

root information (SRI) filter.[21] 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[22] (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[23] of filter solutions.

In addition to generating filter solutions, Monte can also map solution uncertainty forward and backward in time. State variables 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 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, velocity change (ΔV) magnitude, ΔV components (x,y,z) and duty cycle to be estimated.

3. Pre-Flight Analysis

Monte also support pre-flight navigation design efforts through its *Measurement Simulation Toolbox* (MsrSim). MsrSim provides 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 complexes).

Once a nominal schedule has been created, MsrSim will synthesize simulated tracking data which can be processed through

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, Mars-GRAM 2001 / 2005 / 2010, Venus-GRAM 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.

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 ephemerides 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.

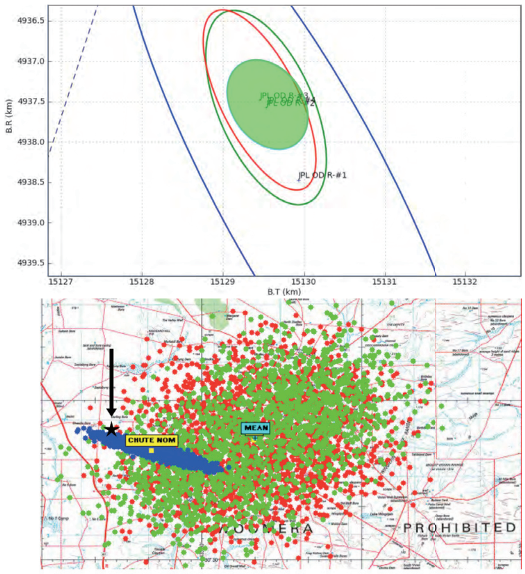

Fig. 5. Final Hayabusa JPL OD delivery (top) mapped to Earth's surface (bottom).

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** reentered 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. Figure 5 shows the final OD solution delivered by JPL prior to Hayabusa's reentry. On the top, the solution is represented in Earth's B-Plane (shaded ellipse in center), and

ORBITER CONFIGURATION

Navigate closed orbit around a center planetary or satellite body.

FOUNDATION

Atmosphere model and high-precision gravity field for center body ■ High-precision Earth station locations and associated models ■ 2-Way Doppler and range ■ Spacecraft shape model for SRP and atmospheric drag ■ Impulsive and finite burn maneuvers

SPECIALIZATIONS

- Data-driven predictive atmosphere model (used on **SMAP**)
- Interpolated atmosphere model e.g. Mars-GRAM (used on **MAVEN**)
- Automation of OD processing (used on **MRO**)

Fig. 6. Monte Orbiter configuration.

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.[24)]

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 Fig. 6, for navigation. To satisfy trajectory prediction requirements, the SMAP OD team uses the semi-empirical Drag Temperature Model (DTM) for Earth atmospheric density calculations.[25)] 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.[26)] 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.[27)]

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, 2 hour 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 far 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 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 them on a configurable chart which can be overlaid with expected execution values (Fig. 7).[28)]

4.2. To the Inner Planets

The **Mars Science Laboratory (MSL)** was launched in November 2011 on a nine month interplanetary trip to Mars.

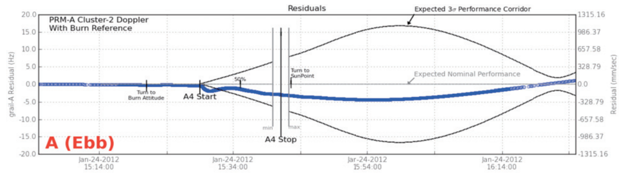

Fig. 7. GRAIL RTRV display with burn start, stop and 3-Sigma corridor overlays.

CRUISE CONFIGURATION

Navigate interplanetary space, possibly with gravity-assist encounters.

FOUNDATION

B-Plane targeting ■ Gravity fields for encounter bodies ■ Point masses and ephemerides of significant third-body influences ■ Earth Station locations ■ DDOR ■ 2-Way Doppler and range ■ SRP modelling ■ Impulsive and finite maneuvers

SPECIALIZATIONS

- EDL interface and mapping to direct descent body (used on **Hayabusa** & **MSL**)
- Rapid switch to Orbiter Configuration (used on **MAVEN**)
- OpNav on approach (used on **New Horizons Pluto**)
- 3-Way Doppler and range (used on **New Horizons Pluto**)

Fig. 8. Monte Cruise configuration.

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 back 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 to 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 ΔV 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 periapsis altitude of 150 km (2-10 mm/s nominal vs. 300 mm/s deep dip). This poses a challenge to navigation, requiring a high accuracy model of the Martian atmosphere and attitude drag profile of the spacecraft. The MAVEN OD team uses the Mars-GRAM 2005 density model,[30)] made available natively in Monte, which they modify with an estimated multiplicative scale factor per orbit to accommodate the observed drag ΔV seen in Doppler measurements (Fig. 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 downtrack range after 25 days in the nominal science orbit.[31)]

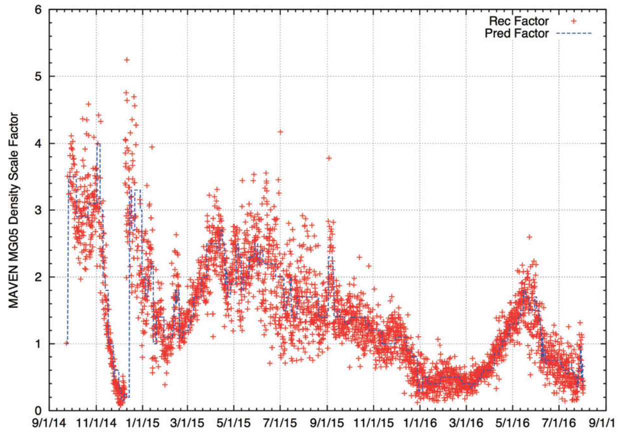

Fig. 9. MAVEN OD estimated scale factor on Mars-GRAM 2005 model for nominal and deep dip drag passes.

IRREGULAR BODY CONFIGURATION

Navigate near an irregularly shaped body such as an asteroid or comet.

FOUNDATION

Harmonic, polyhedral, or mascon gravity field ■ OpNav observables ■ Estimation of body ephemeris, pole and rotation ■ Gm and ephemerides for third-body influences ■ Earth Station locations ■ DDOR ■ 2-Way Doppler and range ■ SRP modelling ■ Impulsive and finite maneuvers

SPECIALIZATIONS

- Landmark processing (used on **Dawn**)
- Comet outgassing model for ephemeris estimation (used on **EPOXI**)
- Moving atmosphere to model comet coma (used on **Rosetta**)
- 6-DOF integration of body ephemeris (used on **Rosetta**)

Fig. 10. Monte Irregular Body configuration.

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 spacecraft navigators to refine and update their knowledge of the body's position on approach. The **EPOXI spacecraft** took a campaign of optical navigation (OpNav) images as it approached 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.[32)]

The irregular shape of many small bodies makes proximity operations particularly difficult. Often, navigators need to iteratively characterize the small body's gravity field by placing the spacecraft on 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 Fig. 10. Monte provides several models to calculate and estimate the gravity field of a small body.

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.

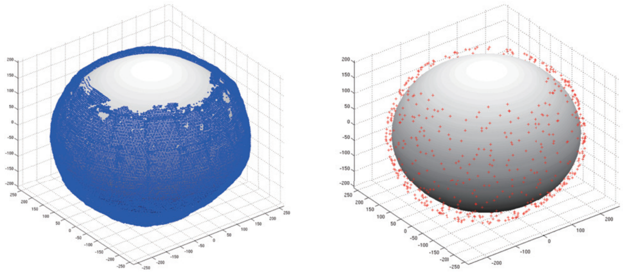

Fig. 11. Vesta landmarks processed by Dawn navigation, full database (left) and random down sample (right).

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.[33)] 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 to estimate landmark locations, shown on the right side of the figure. In general, a random downselect of 10-25% of the total landmarks were used in OD processing.

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 Centre (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.[34)] Monte's scriptability was extensively excercised 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 Saturn's largest moon Titan which it encounters regularly. Less frequently it flies by icy satellites like Enceladus and Dione. In 2012, Monte was deployed in the *tour configuration*, summarized in Fig. 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 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

TOUR CONFIGURATION

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

FOUNDATION

Point masses and ephemerides for satellite system ■ Gravity fields for flyby bodies ■ Encounter-to-encounter OD arc segmentation ■ B-Plane targeting ■ Earth Station locations ■ 2-Way Doppler and range ■ SRP modelling ■ Impulsive and finite maneuvers

SPECIALIZATIONS

■ Satellite atmosphere modelling (used on **Cassini**)
■ Estimation and integration of satellite system ephemerides (used on **Cassini**)
■ Ring mass modeling and estimation (used on **Cassini**)

Fig. 12. Monte Tour configuration.

the altitude of periapsis to between the innermost ring and the top of Saturn's atmosphere. In order to accurately model flight in this region, the Monte team 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 ΔV 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 is high quality users. 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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