Aerobraking the ExoMars TGO: The JPL Navigation Experience

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Abstract

In October 2016, ESA's Trace Gas Orbiter entered into orbit around Mars. The transfer from its initial 24-hour elliptical orbit into the final 2-hour science orbit was helped by means of 952 aerobraking passes between March 2017 and February 2018. For this first aerobraking operation by European Space Operations Centre (ESOC), a dedicated partnership was organized between ESOC and NASA's Jet Propulsion Laboratory (JPL) to allow for JPL navigation team's support during the TGO aerobraking operations. The Mission Design and Navigation section at JPL supported the mission by providing consulting in aerobraking navigation operations and independent orbit determination solutions during TGO's aerobraking. This paper discusses the JPL Navigation team's experience, challenges faced, and lessons learned during TGO's aerobraking at Mars. Topics include the collaboration between the two navigation teams, configuration of orbit determination for aero drag passes, arrangement of automated orbit determination, and reporting processes.

Keywords: ExoMars, TGO, Aerobraking, Navigation

I. Introduction

ExoMars TGO mission

ESA's Trace Gas Orbiter (TGO) is the first mission of the ESA-Roscosmos ExoMars cooperation program. TGO's final operational orbit is a quasi-circular two-hour period orbit to maximize the coverage for science purposes while providing frequent and regular contacts with Mars landers [1]. Launched in March 2016, TGO carried the Schiaparelli Entry, descent, and landing Demonstrator Module (EDM) to Mars. In addition to the delivery of the EDM, the objective of TGO is to search for signs of life from Mars orbit; a detailed analysis of atmospheric trace gases such as methane is conducted, and the Mars surface is studied to identify possible trace gas sources stemming from biological processes that are still active. Equipped with a UHF Electra radio that ensures a bi-directional link between TGO and landers and rovers on Mars' surface, TGO will provide data relaying services for existing and future NASA missions to Mars' surface, as well as for the upcoming ExoMars 2020 mission.

ExoMars TGO was launched from Baikonur by a Russian Proton launcher on March 14, 2016. Carrying the Schiaparelli EDM, TGO arrived at Mars after a 7-month long type-II interplanetary transfer, a trajectory that was assisted by two large Deep Space Maneuvers. Three days after releasing the Schiaparelli lander, TGO successfully performed the Mars Orbit Insertion maneuver on October 19, 2016, and entered into a 4-sol, near-equatorial, highly elliptical orbit. A series of chemical maneuvers changed this orbit into a 1-sol, 74-degree inclination orbit in early 2017. The TGO spacecraft without the Schiaparelli lander is depicted in Fig. 1.

Fig. 1: TGO spacecraft without EDM (copyright: ESA/ATG media lab)

TGO's aerobraking

From March 2017 to February 2018, TGO used aerobraking to gradually reduce the orbit period from ~24 hours to ~2 hours [2],[3]. The aerobraking technique utilizes the drag of the planet's upper atmosphere to decrease the spacecraft velocity in order to reach a lower-energy orbit. TGO's year-long aerobraking consisted of several different phases:

- Walk-in phase: Starting March 15, 2017, a total of seven pericenter lowering maneuvers gradually decreased the pericenter altitude. The walk-in phase was declared completed on May 1 with TGO reaching aerobraking altitude, where the atmospheric drag is effective in reducing the orbit energy.
- The 1st aerobraking phase: Aerobraking operations started immediately after the last walk-in maneuver being completed. The flight team carefully monitored the atmospheric drag and adjusted the subsequent periapsis altitude by maneuvers. The pericenter height was adjusted to be shallow enough to not endanger the spacecraft structure, and deep enough to effectively reduce the orbit energy. During this phase, the orbit period was reduced from ~22 hours to ~14 hours.
- Solar conjunction: Aerobraking operations were paused while TGO passed through the solar conjunction period (June 25 – August 30, 2017). The periapsis altitude was raised by a maneuver to stop aerobraking operations, and lowered again by maneuvers to resume aerobraking. During this hiatus, the flight team took the opportunity to perform tasks that would be disruptive to aerobraking operations, such as flight software updates.
- The 2nd aerobraking phase: Aerobraking operations resumed after the end of solar conjunction with a pericenter lowering maneuver on August 30. After long, careful trade studies, the original plan was slightly adjusted to end aerobraking operations when the apocenter altitude was reduced to 1000 km. During this phase, the orbit period was reduced from ~14 hours to ~2 hours. Operations during the last period of this phase, where the orbit period drops as low as 2 hours, is called the "end-game" and posed many technical difficulties to the flight team.

- Walk-out: TGO walked out from the aerobraking phase by a series of maneuvers to raise the periapsis beginning February 20, 2018.

Upon completion of aerobraking, the TGO's orbit was adjusted by a series of chemical maneuvers to reach the final science orbit. The 360 x 413 km frozen orbit, with eccentricity and argument of periapsis being approximately constant, was in 373:30 resonance with Mars' rotational period. In April 2018, TGO began its science operation and readied itself for communication relay for existing and future NASA/ESA landers and rovers. TGO's aerobraking phases and progression of orbit period and periapsis altitude are shown in Fig. 2.

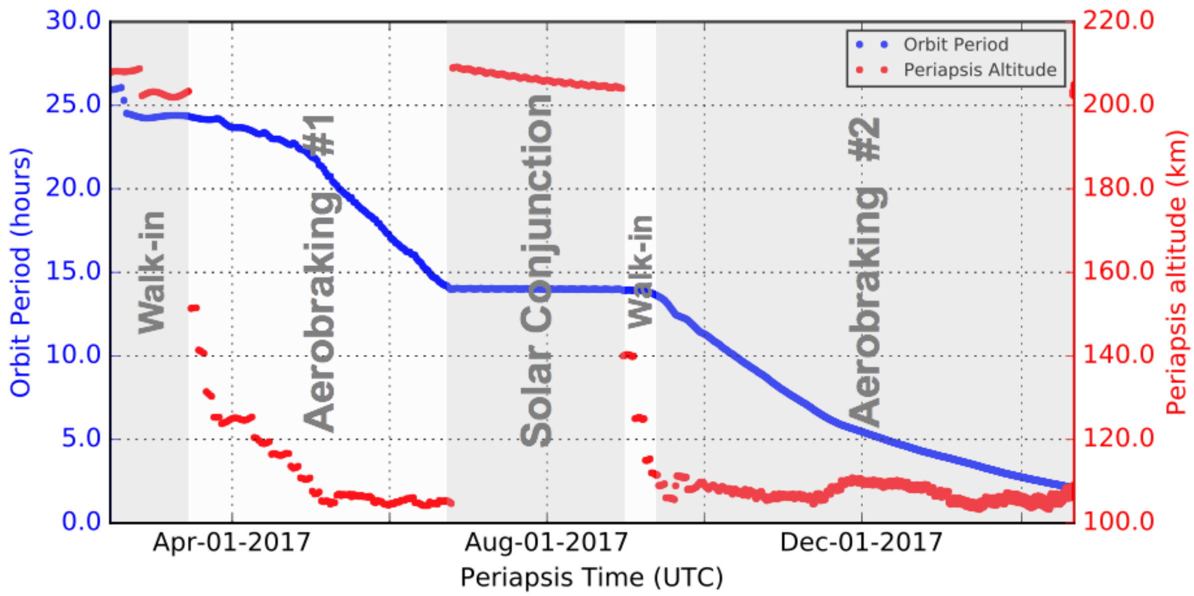

Fig. 2: TGO's orbit progression during aerobraking

History of JPL/ESOC navigation collaboration

The collaboration between JPL Navigation (JPL-Nav) and ESOC's Flight Dynamics (ESOC-FD) team began during ESA's first deep space mission Giotto to comet Halley in 1985 [4]. Cooperative efforts between NASA and the European Space Agency (ESA) in support of Giotto's flight to Halley's Comet included prelaunch checks of ESOC's navigation software and delivery of validated DSN radiometric tracking data during the mission.

The next collaboration between the ESOC-FD team and JPL-Nav team did not take place until ESA's first Mars mission; Mars Express [5]. The joint effort began several years before its launch in June 2003, and ended with the successful Mars Orbit Insertion in December 2003. The tasks included another navigation software cross-verification, implementation of Delta Differential One-way Ranging (DDOR) data processing, and routine exchange and comparison of orbit determination solutions during the cruise. After completion of the successful joint operations, both navigation teams agreed to continue communication via monthly teleconferences and yearly face-to-face meetings.

Another mission that benefitted from elaborate joint efforts by the two navigation teams was ESA's Rosetta mission. Similar to the Mars Express mission, Rosetta carried instruments built and supported by scientists in the USA. Planning for the navigation collaboration had begun well before its eventual launch in March 2004, and the operational collaboration did not begin until Rosetta woke up from its long deep space hibernation in January 2014. From the approach phase to the Phillae landing in November 2014, the two navigation teams joined forces for another collaboration. Navigation software cross-verification tests were focused on optical navigation with a landmark database [6]. Exchange of routine Orbit Determination (OD) solutions, that the JPL-Nav team called "shadow navigation", were provided by JPL-Nav team during this period [7]. Rosetta concluded its mission by landing on the comet in June 2015. In order to maximize the probability of a successful landing of the Rosetta spacecraft, ESOC-FD invited the JPL-Nav team to provide independent orbit determination solutions during the final two months of the mission [8].

In addition to providing navigational support for the above listed missions, the collaboration between the two teams continued in various forms. Beginning with New Norcia in 2002, ESA has built a total of three deep-space antennas under the ESA Tracking (ESTRACK) network to date. Since the geographic locations of these antennae complement those of NASA's DSN network, sharing deep space antenna services between ESA and NASA has become a common practice, particularly during critical mission events such as launch and Mars orbit insertion. The JPL-Nav and ESOC-FD teams were deeply involved in these events.

Another notable collaboration between the two teams involves participating in a collision avoidance process between all Mars orbiters. Routine monitoring of possible close approaches between multiple Mars orbiters had begun as Mars Express entered into Mars orbit in 2003. This collision avoidance interface became especially significant during TGO's aerobraking phase as the frequency of TGO's orbit crossing with other orbiters increased during that time.

TGO was the first full aerobraking operation by ESOC. JPL's Mission Design and Navigation section provided cross-support to the ESOC-FD team during planning and the operational phase of aerobraking. Discussion regarding collaboration efforts between the two teams, JPL-Nav team's roles and challenges, JPL-Nav's OD modeling, and lessons learned during TGO's aerobraking at Mars will be carried out in subsequent sections.

II. JPL-Nav's roles and contributions in TGO aerobraking

The JPL Mission Design and Navigation section has extensive experience in aerobraking operations, particularly with Mars orbiters. The 1993 Magellan mission to Venus was the first JPL mission to use aerobraking. Since then, the aerobraking technique has been repeatedly used throughout JPL's Mars orbiter missions. From 1997 to 1999, Mars Global Surveyor first used the technique at the planet to reduce the orbital period from 45 hours to 2 hours [9]. The Mars Odyssey spacecraft completed aerobraking in 2002 and reduced the orbital period from 18.5 hours to 2 hours [10]. During the 11-week aerobraking phase, the cumulative drag force provided the equivalent of a 1.08 km/s ΔV. Finally, the Mars Reconnaissance Orbiter performed aerobraking from March to August of 2006 to reduce the orbital period from 35.5 hours to 1.9 hours and saved 1.2 km/s of ΔV [11].

Request for JPL navigation support during TGO aerobraking was made by ESOC-FD in September 2016. The requested support during TGO aerobraking can be broken into three parts: consultancy in aerobraking navigation operations; a review of strategy for walk-in and end-game phase in the area of Guidance, Navigation and Control; and shadow navigation of TGO with regular exchange of orbit determination and prediction solutions. Collaboration efforts between JPL-Nav and ESOC-FD during TGO aerobraking can be categorized into the following:

Technical Interchange Meeting (TIM)

One of the key lessons learned from previous collaborations are the benefit of face-to-face meetings between the two teams. These in-person meetings benefitted the participating navigation engineers' understanding of each other when meetings between two teams were later conducted in a voice-only teleconferencing format. A total of four meetings were arranged to exchange information, discuss and review plans, and for collaborative problem solving.

- TIM 1, November 2016 at JPL

  The first meeting was to reach an agreement regarding and prepare for aerobraking support details. JPL-Nav also reviewed ESOC's aerobraking strategy, with a focus on walk-in phase operations.

- TIM 2, February 2017 at ESOC

  The second meeting was held at the same time as ESOC's operational readiness review. Discussion of ESOC's institutional review board responses, review of the revised walk-in phase operation plan, and refinement of the data-exchange interfaces were key topics.

- TIM 3: August 2017 at JPL

  This meeting was held concurrently with the hiatus from aerobraking during the solar conjunction period. The main discussion topic was to prepare for end-game operations. JPL-Nav reviewed ESOC's end-game operational plan and also provided answers to ESOC-FD's questions, based on previous aerobraking experiences, regarding end-game operations.

- TIM 4: January 2018 at ESOC:

  The final face-to-face meeting was held after the second aerobraking phase had already begun. Final discussion of end-game support plans and an exchange of findings from TGO's aerobraking were key discussion topics. All operations up to this point were smooth so the meeting was shorter than originally planned.

Software cross-verification test

Extensive software cross-verification test campaigns had been an integral part of the two teams' past collaborations. From Giotto to Rosetta, each test campaign added specially focused cases. TGO's software tests were focused on implementing atmospheric modes (exponential, Mars Climate Database (MCD), Mars Global Reference Atmospheric Model (Mars-GRAM)). Test cases were structured so that orbit propagation exchanges started from a simple point mass solution and expanded to include Mars gravity field, solar radiation pressure, and finally the atmospheric drag and thrust pulses.

Independent OD solution exchanges

Two separate OD solution exchange campaigns took place during TGO aerobraking. Both teams delivered their own independent OD solutions using the same set of tracking data. The first campaign occurred during the walk-in phase (March 14 - April 28, 2017) with deliveries taking place one to three times per week. The exchange schedule was organized in line with the

Periapsis Lowering Maneuver design cycles. The JPL-Nav team used this campaign to gain confidence in the OD configuration, data exchange interface, and modeling.

The second OD solution exchange campaign occurred during the aerobraking end-game (January 3 - February 20, 2017). Daily OD solutions from both teams were exchanged and the teams compared the solutions during the weekly teleconference. Up to this point, all OD solution exchanges were made using the same set of tracking data. Consistency between the two independent orbit solutions might have provided confidence to ESOC-FD team, but did not provide any practical benefit for the aerobraking operations. During the end-game, when orbit periods were 2 to 3 hours short, orbit solutions had to be updated for every new periapsis pass, and comparisons of the previous day's solutions did not add significant value to the ESOC-FD team. The JPL-Nav team decided to move the data cut off to the ESOC-FD's early morning local time, intending to fill in the ESOC-FD staffing gap at nights. The JPL-Nav team provided early warnings of any anomalies that might have occurred during ESOC-FD's night time, and JPL-Nav's solution could then be used as a priori information for ESOC-FD's OD process in the morning.

In addition to manually creating daily OD solutions, the JPL-Nav team built a process to provide regular automated OD solutions. This automated process computed key parameters of the aero drag passes and a summary OD report to the ESOC-FD team after each 4 orbits. Details of this "quicklook" OD will be further described in section V.

Mars atmospheric weather forecast

JPL's previous aerobraking missions have proven the scientific consultancy on atmospheric state throughout aerobraking to be invaluable to the operations team. The Atmospheric Advisory Group (AAG) has provided Mars weather forecasts, including information on dust storms and turbulent regions of the atmosphere, such as the polar vortex, to the aerobraking mission operations teams. The AAG uses observations made from Earth, Mars orbiters, the science payload of the aerobraking orbiter itself, and from the accelerometer readings from in situ measurements during the drag pass. The AAG's weather forecasts played a significant role during the daily maneuver decision processes for JPL's aerobraking missions. The AAG's Mars weather forecasts reports for JPL's MAVEN mission were routinely shared with the ESOC TGO team.

Collision Avoidance (COLA) among Mars orbiters

Both JPL-Nav and ESOC-FD have been continuously running collision avoidance analysis for all orbiters at Mars. All Mars orbiters (NASA's MRO, Odyssey, MAVEN, ISRO's MOM, ESA's TGO, and MEX) exchange orbit predictions via JPL's dedicated file exchange server. When the predicted close approach distance violates predefined criteria, participating missions are notified and possible mitigation plans are discussed. This COLA process was particularly important during the aerobraking phase, when long-term orbit predictions were significantly more uncertain than that of missions that had already reached final science operation orbits. Since the aerobraking mission had more frequent opportunities of maneuvers that required rapid decision making, TGO often used the upcoming maneuver to avoid collision events.

III. JPL-Nav team's challenges

Preparations and operational support for TGO's aerobraking posed several challenges to the JPL-Nav team. The first obstacle was the extremely limited time given to prepare for the mission. All previous collaborations and joint operations between JPL-Nav and ESOC-FD usually began during the development phase of the mission. Collaboration had never been initiated during the operational phase of the mission until TGO. From the original request memo written in November 2016 to the first OD solution exchange in March 2017, JPL-Nav had less than 5 months to learn and prepare for the mission support. Lessons learned and established procedures and interfaces from previous collaboration were essential for the JPL-Nav team to be ready in the short preparation time given.

Assembling an operations team with a short lead time and limited budget was not a simple task. The Inner Planet Navigation group in JPL's Mission Design and Navigation section supports multiple missions, including three Mars missions (Odyssey, MRO, and MAVEN) and thus provided a pool of navigation analysts who were already familiar with navigation topics specific to Mars orbiters and aerobraking operations. Borrowing software tools and templates from MAVEN and customizing them for TGO saved extra resources that would have spent for creation, installation, and a validation of new set of software tools. In addition, the section provided technical consulting and peer reviews on ESOC-FD's aerobraking operations plan. Multi-mission support by those with shared expertise, as well as technical peer reviews by subject matter experts in the JPL Mission Design and Navigation section made effective support by the JPL-Nav team during TGO aerobraking possible, despite short preparation time and a limited budget.

In aerobraking operations, particularly during the end-game stage with a short orbit period, timely updates on information regarding S/C configuration and state changes are essential for orbit determination. In addition, information from the ground station during the tracking pass is equally important for tracking data editing prior to OD process. The JPL-Nav team did not have any connections to ESTRACK station operators, nor had they had any direct interface with TGO's telemetry. Although all information from the telemetry was delivered in formatted data files, as described in section IV, any changes after the daily delivery were unknown to the JPL-Nav team. ESOC-FD sent a summary of key events or anomalies at the end of its daily shift, but no updates were made during ESOC-FD's night shifts. This limitation created additional difficulty to JPL-Nav's OD process, particularly when developing logic for autonomous OD solutions as described in section V.

IV. Data and solution exchange interface

Orbit determination of a Mars orbiter requires a large number of inputs: tracking and calibration data from the ground antenna, physical modeling of the spacecraft, physical constants and ephemerides of Mars, and constantly updated spacecraft activity reports from telemetry. Setting up the interfaces for these inputs, as well as the procedures for modeling updates require a significant amount of the navigation team's resources. The difficulty of this process is amplified if the spacecraft is built and operated by a foreign agency. From the long history of collaborations, Interface Control Document (ICD) for generic navigational data exchange had already been established between JPL-Nav and ESOC-FD. This ICD significantly benefitted both navigation teams in preparing for the OD solution exchanges. Adjustments were made to the generic ICD in the areas particular to TGO, distinctly in aerodrag pass information exchanges.

Each agency has its own established internal data formats and processes and rarely shares the same data format with other space agencies. Data exchange with foreign agencies must require a detailed agreement on data format. The *Consultative Committee for Space Data Systems* (*CCSDS*) provides recommendations for common data types, including tracking data and trajectory information. Both teams attempted to use CCSDS-recommended formats as much as possible. If no CCSDS guideline were available, data formats were documented in the ICD. All data exchanges between the two navigation teams had been made via JPL's dedicated navigation data exchange server. By the 2nd aerobraking phase, most of the project's data exchanges were automated by Unix cron jobs in order to reduce the extra delay added by human process initiation.

Spacecraft physical data

ESOC-FD provided a database file that contained all physical parameters relevant to navigation, including spacecraft geometrical data, optical properties of surfaces, ballistic coefficients, position and alignment of the spacecraft appendages, spacecraft dry mass, and transponder delay.

Spacecraft dynamic data

ESOC-FD provided reconstructed data from telemetry in the following formats:

- Event Log: A text file that contained Guidance Navigation Control (GNC) mode transitions, in chronological order, as reconstructed from telemetry.
- Thruster pulse file: A text file that contained chronologically ordered records with the accumulated ΔV vector as executed by the on-board thrusters. The file contained all thruster actuations from the beginning of aerobraking up to the latest available telemetry.
- Accelerometer data file: A text file that contained chronologically ordered records with the accumulated ΔV vector as measured by the accelerometers. The file contained all accelerometer measurements during the aerobraking passes from the beginning of aerobraking up to the latest available telemetry.

Maneuver plan

After completion of a Flight Dynamics commanding cycle, ESOC-FD would deliver the maneuver planning and the orbit predictions for the commanding period in the following files:

- The predicted trajectory, including future maneuvers, in CCSDS Orbit Ephemeris Message (OEM) format
- "Res" file containing the future maneuver plan
- Maneuver Summary file
- Popup maneuver file containing historical and future emergency popup maneuvers
- Heat flux maneuver file containing historical and future flux reduction maneuvers

The flux reduction maneuver and popup maneuvers are types of autonomous periapsis raising maneuvers and are described in detail by Castellini [2].

Tracking data and calibration data

During the aerobraking phase, TGO was supported by both ESTRACK and DSN stations. Tracking data coming from ESTRACK stations were delivered to the ESOC-FD team and subsequently delivered to JPL-Nav team. Tracking data from DSN stations was available to both ESOC-FD and JPL-Nav via JPL's dedicated navigation data exchange server. During past collaborations, tracking data was exchanged in the original format provided by the ground stations. ESTRACK's deep space antennas used Intermediate Frequency MODEM (IFMS), and DSN's tracking data were in TRK-2-18 or TRK-2-34 format. For the TGO aerobraking collaboration, both teams agreed to use CCSDS standard Tracking Data Message (TDM) as the designated tracking data exchange format when possible. DSN's tracking data delivery had been set up to use TDM format throughout the aerobraking. DSN's media calibration data, both ionospheric and tropospheric corrections, were provided in DSN standard CSP format.

From ESTRACK stations, the meteorological data, the tracking data, and the corresponding calibrations were provided in IFMS format. Up until superior solar conjunction, calibrations for range measurements were also provided in a separate text file. In addition, CSP files were delivered that contained the total tropospheric delay, which were consistent with the IFMS meteorological data. After solar conjunction, the delivery of the IFMS data has been automated and the delivery of the range calibration and CSP tropospheric calibration file has been stopped. During the second part of aerobraking the IFMS receivers in the ESTRACK stations Malargüe and Cebreros were replaced by new tracking receivers called Telemetry Telecommand and Control Processor (TTCP). Both IFMS and TTCP data were converted from ESOC-FD to CCSDS compliant TDM prior to the delivery to JPL-Nav. After switching to TDM, these deliveries were used as the prime tracking data interface, while IFMS and TTCP files were provided as backup only.

Orbit determination solution

Solutions from orbit determination, using tracking data up to the pre-defined data cut off time, were exchanged as a set of files. The list of files ESOC-FD sent to JPL-Nav are the following:

- Reconstructed orbital trajectory in OEM format
- Summary of the OD solution in text format
- Post-fit Doppler residuals in text format
- A text file containing prediction parameters needed for the propagation of the orbit into the future
- A text file containing the atmospheric model and its parameters needed for orbit propagation
- Aeropass history file, which contained the history of all the drag passes since the beginning of aerobraking. For every pericenter pass, this file included pericenter time, altitude, sub-spacecraft latitude and longitude, atmospheric scale factor, scale height, maximum density value and time, maximum dynamic pressure value and time, maximum heat flux value and time, and heat load

In exchange, the JPL-Nav team sent to ESOC-FD the following files;

- Reconstructed orbital trajectory in OEM format
- Summary of OD solutions in text format
- Post-fit Doppler residuals in text format

- Prediction parameters for orbit propagation
- OD report, in PDF format, which contained comparison plots of all estimated parameters between JPL-Nav and ESOC-FD solutions. This report was particularly useful during teleconferences, when comparing OD solutions.

JPL-Nav's OD Modeling

The trajectory model for TGO included gravitational forces, atmospheric drag, solar pressure, impulsive wheel offloading burns (WOLs), orbit trim maneuvers, and thruster firings, as well as multiple impulses around periapsis to capture density profile variations not represented by the atmosphere model. These forces were implemented and estimated in the Monte [12] software, and integrated using the DIVA propagator, which uses a variable step size based on the computed forces at each previous time step. The ESOC-FD team used the same kinds of models, though the implementation details differed in some areas.

The gravitational force due to Mars was modeled using the MRO 110C gravity field, a 110x110 set of spherical harmonic terms, which is NASA's most up-to-date operational definition. This model also includes periodic J_3 corrections and gravitational tides due to the sun, Phobos, and Deimos. Additional gravity terms included are the Earth, Moon, Sun, Mercury, Venus, and the barycenters of the Jupiter, Saturn, Uranus, Neptune, and Pluto systems, as well as the moons of Mars: Phobos and Deimos. The DE432s and Mar097 ephemerides were used in the computation of these gravity terms. ESOC-FD used the simpler MGS85F2 gravity field without the corrections used by JPL-Nav.

A variety of thruster impulses occurred during flight. Wheel Offloading (WOL) maneuvers were used to desaturate the reaction wheels, and velocity-aligned maneuvers at apoapsis were used to vary the periapsis altitude based on observed atmospheric trends. Information about the occurrence of these were provided by ESOC-FD as input files that could be read into the JPL-Nav OD definition. Because WOL burns were nominally balanced, the telemetry-derived vectors were not considered credible, and were thus modeled with zero nominal ΔV and a spherical covariance of 0.3 mm/sec. The apoapsis maneuvers were included at the telemetry-derived epoch with the nominal commanded ΔV, and were estimated in the filter with a 4% 1σ proportional uncertainty as well as a 10-minute timing uncertainty, due to variations in the on-board estimated periapsis time. Additionally, more angular momentum would accumulate during a drag pass than the reaction wheels could store, so unbalanced thruster firings occurred after each drag pass to maintain the spacecraft orientation. These were recorded in telemetry and delivered regularly to JPL-Nav, and were included in the model. Because they were unbalanced and the drag estimates allowed sufficient fitting of other parameters, these ACS firings were not included in the set of filtered parameters, though the option to do so was available to the analyst if necessary. The ESOC-FD team used a similar approach.

To account for solar pressure, the spacecraft shape was modeled as a simple sphere, with an area and reflectivity set to match ESOC-FD models, based on the physical spacecraft, with a pre-defined constant solar flux value. A single scale factor on this force was estimated per arc, by both JPL-Nav and ESOC-FD.

JPL-Nav estimated drag forces by applying the Mars-GRAM 2010 density model with a multiplicative density scale factor (DSF), with drag computed based on the spacecraft velocity and a constant area sphere with assumed drag coefficient, based on data provided by ESOC-FD. The Mars-GRAM 2010 model was selected based on engineering experience, with the details in section 4.4. A scale factor was estimated for each reconstructed orbit, to account for atmospheric variability, and then the average DSF was computed to define a prediction model. This scale factor approach has been used by past JPL aerobraking missions, and has typically seen orbit-to-orbit variations of ±100%, with an expected error in the average of ±30%. Initially, ESOC-FD used a different approach applying the measured accelerations from the onboard accelerometer as a force model, and postprocessing the data against ESA's MCD to get a predicted scale factor. Challenges in the use of MCD and concerns about a dependency on telemetry availability led ESOC-FD to adopt the scale factor approach, referenced to simple exponential model of the atmosphere.

One challenge was that each orbit incurred ΔV between 0.5 and 1.5 m/sec, so that fits over multiple orbits built up minutes of downtrack timing error, which is outside the regime of straightforward linear convergence. Larger numbers of shorter arcs were inconvenient, particularly because the JPL-Nav team preferred to match the ESOC-FD arcs, and were impossible in cases where a missed tracking pass required longer arcs. Instead a "step fit" process was used, to automatically perform what an OD analyst would manually do in this situation. It fit through the first periapsis, updated the a priori DSF for that orbit, and then proceeded to the next orbit, keeping each subsequent fit within a reasonable linear regime. By taking a straightforward but tedious task and making it automatic, the team was able to more easily handle these challenging orbit solutions. This technique has been passed to the MAVEN aerobraking team to support that process in February of 2019.

In addition to the down-track ΔV incurred during a drag pass, there are additional terms to consider as well. The spacecraft shape can lead to significant lift (radial) forces, as well as sideslip (cross-track) forces. Additional cross-track forces can occur due to high altitude winds, which can be hundreds of meters per second, a significant fraction of the spacecraft velocity. Additionally, longitudinal gradients in the density mean that the peak density does not necessarily occur at periapsis where the baseline model would predict, moving by up to a minute before or after periapsis, effectively changing the applied epoch of the drag ΔV impulse. With short arcs, these effects can be ignored, using increased differences in an arc's initial state from the previous arc as term to absorb these errors. This was the approach taken by previous JPL missions. Instead, a technique developed for MAVEN deep dips was applied. First, a nominally 0 m/sec impulse at periapsis was included, with the filter estimating a cross-track and radial term with a 1σ uncertainty of 10% of the downtrack ΔV. To handle gradients, two impulses were placed 5 minutes before and after periapsis, with an a priori covariance that was perfectly negatively correlated, so that the filter would always apply equal and opposite downtrack components to each burn, yielding a total net ΔV of zero, and which therefore had the effect of shifting the effective centroid of all the downtrack ΔV during the drag pass. The magnitude of the diagonal of this covariance was set to a level that corresponds with a 30 second timing shift in the time of peak drag. These impulses proved valuable in all arcs longer than three orbits for MAVEN, and continued to prove useful for TGO. At JPL-Nav's suggestion, ESOC-FD adopted this approach as well.

Accelerometer Data

In addition to radiometric Doppler data, onboard accelerometers provide valuable information about the size and shape of the drag effects. While these data have proven useful in the past for scientific analysis and confirmation of the validity of OD solutions, they have proven difficult to integrate directly into the filter. Early in aerobraking, ESOC-FD integrated the data by using it directly as a force model, rather than using a model atmosphere, as described previously. Unfortunately, this approach showed some fragility when data were not available, particularly for short orbits with less available transmit time. Other efforts to use the data as measurements have been attempted, but showed poor convergence with real-world a priori errors [13], or did not conform with usual processes and thus proved difficult to implement in practice [14]. An alternative approach, developed for MAVEN operations, where limited tracking data made accelerometer data especially valuable, was demonstrated and used for TGO aerobraking.

First, it was necessary to understand why accelerometer data were difficult to integrate into the filter. The drag impulse, and thus the accelerometer signature, lasts a few minutes, while even the shortest orbit, at 1.9 hours, is orders of magnitude longer, and thus the Doppler data vary on a similarly longer time scale. This variance in time scale is the root of these challenges. Typical operations schedules allow a certain amount of timing error to build up between solutions, and this is kept small enough that reasonable linear convergence can occur within those errors. Due to the time scales, the range of linear convergence for high rate accelerometer data is much smaller than the range for Doppler data, so that inclusion of the accelerometer data in OD results in wild variability and poor convergence. Adapting processes to account for the variable time scales would require changes to processes that would introduce significant new sources of risk, limiting interest in this approach. Additionally, the high rate data may contain local features that are not easily parameterized into a simple OD trajectory model.

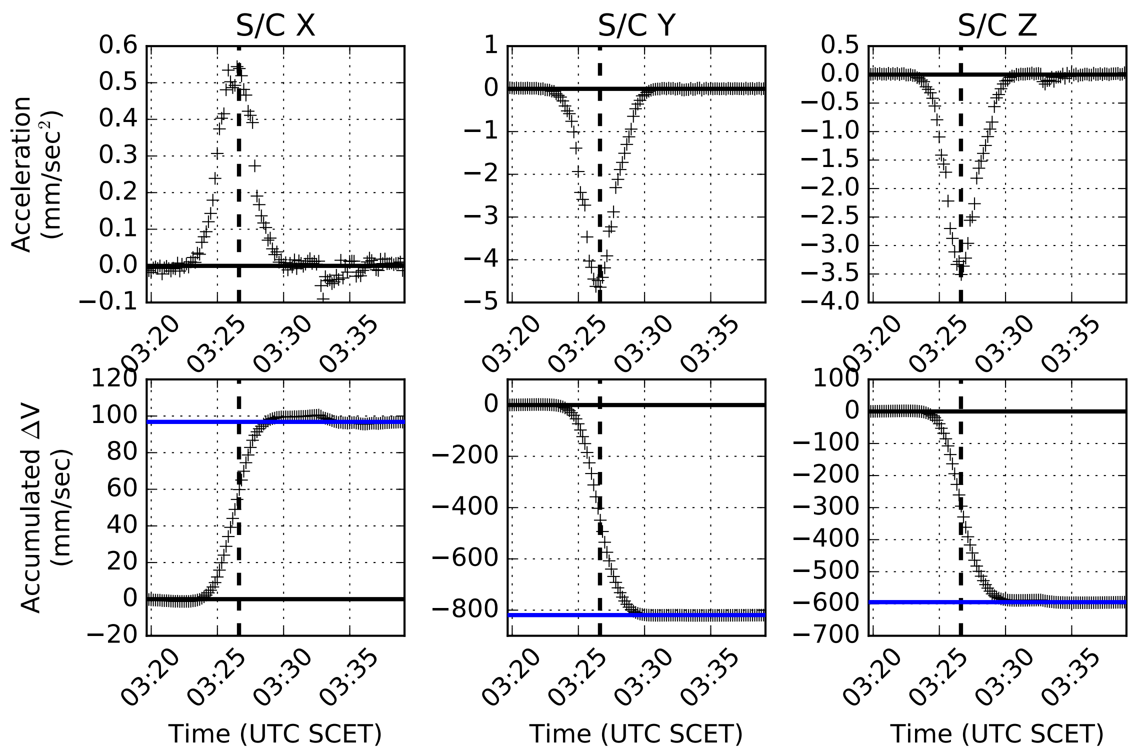

Fig. 3: Example accelerometer data with derived values

Recognizing the problem, and that the OD process is more interested in the overall effect of the drag pass rather than the local details, the preferred approach is to compute the accumulated acceleration over the entire drag pass into a single measurement of the total ΔV for the time period, and use this measurement in the filter [15]. By eliminating the short-term details that are of little value to OD (though of considerable scientific interest), the range of convergence can be extended to integrate well with operations schedules and processes designed around Doppler data. These data can be collected as either a total vector or magnitude value, and the time-weighted average can also be computed, to yield an effective centroid of the drag pass. At the time of TGO aerobraking, experimental versions had been demonstrated for MAVEN, but it had not yet been deployed for operations. Examples of the raw and accumulated values are shown in Fig. 3.

Both JPL-Nav and ESOC-FD implemented a version of this approach, computing the total vector ΔV in the spacecraft body frame, as well as the centroid epoch of that pulse. Within the software, this was implemented as a user-defined measurement, which posed archival problems. Because TGO received Doppler coverage for almost every orbit, the accumulated accelerometer measurements were not used in most cases, because that Doppler data yields more precise information about the drag pass. Late in aerobraking, tracking passes covering 4 periapses were lost due to ground station problems. In addition to the loss of accuracy, as only an average scale factor could be computed across the gap, the fit itself was challenging because of the large errors in the a priori trajectory model that accumulated over the gap that could not be corrected using the “step fit” process. Inclusion of the accumulated accelerometer process made generating a solution with reasonable accuracy straightforward. ESOC-FD implemented this technique as well and used it regularly. This success, particularly over the most difficult portion of the orbit determination, validated the technique. It will also be used for MAVEN aerobraking beginning in February 2019, encouraged by the success for TGO.

Atmospheric Models

A reasonable model of the atmosphere is necessary for modeling and estimating the trajectory of an aerobraking orbiter. The density scale factor approach described previously relies on a representative atmosphere, with some model of well-understood seasonal trends for long-term prediction, and as well as a reasonably accurate scale height, the altitude over which the density changes by a factor of e, which defines the ratio of peak density to drag and the balance between maximum heating rates and heat loads. Since MRO, JPL has used the Mars-GRAM model, an interpolated set of tables from multiple missions’ worth of atmospheric data. The latest version is Mars-GRAM 2010. ESA has developed its own model, the MCD, using a similar approach, and a secondary goal for this collaboration was to understand its use and value for aerobraking. A final fallback option is a simple exponential model with defined reference density, altitude, and scale height.

JPL-Nav implemented an interface with the MCD software, including it in propagations and estimations. While the interface was straightforward, attempts to integrate through a drag pass were extremely slow, often stalling entirely and crashing the propagator. Investigation showed that this was a result of the single precision MCD model interacting badly with the dynamic step size variations of the DIVA propagator. The numerical noise inherent to the single precision computations meant that DIVA was incapable of selecting an appropriate step size, with each step getting smaller and smaller until error conditions were triggered and the integrator crashed. ESOC-FD did not encounter this issue because their integrator varies the step size based solely on the level of the gravity acceleration term. This discovery also helped illuminate a persistent problem for JPL-Nav, where filter convergence using scale factors on Mars-GRAM is sometimes difficult; while Mars-GRAM is implemented using double-precision floating point math, it is still using an external, table-driven interface that leads to small changes in step size and discontinuities that break typical convergence criteria, particularly because partial derivatives of this model must be computed using finite differences.

Even without the ability to directly integrate the MCD model, there was still interest in understanding its behavior in terms of predicted and reconstructed scale factors. Fortunately, this was straightforward to compute via post-processing since the scale factor is well understood as the ratio between the estimated drag ΔV and that which would occur due to the nominal density model, which can be computed without reintegrating the trajectory. Given this, for a sequence of orbits, the nominal density and estimated effective scale factor for Mars-GRAM 2010 (Map Year 0) and MCD are shown in Fig. 4. While the trends in both models are similar, MCD shows a much larger orbit-to-orbit spread than Mars-GRAM, which results in a wider variability of the estimated scale factors referenced to MCD. The variability in MCD is in fact very similar to the variability seen in observed periapsis densities, indicating that MCD includes an effective model of the sources of that variability. Unfortunately, because it is a stochastic process, it does not actually match the details of the observed variability, and is less effective as a reference model than Mars-GRAM 2010, which does not include these terms.

For these reasons, JPL-Nav proceeded through operations using Mars-GRAM 2010, and ESOC-FD used an exponential model, initially with an 8 km scale height, and then reduced to a 6 km scale height after September 2017. While the two teams were using different models, interchanges were simplified by the ΔV-derived definition of scale factor, allowing JPL-Nav to deliver the atmospheric density reconstructs with scale factors relative to multiple models. Each team generated predicted trajectories based on their density model, but due to the short time between deliveries and the fact that reconstruct comparisons were of more interest, this did not prove problematic.

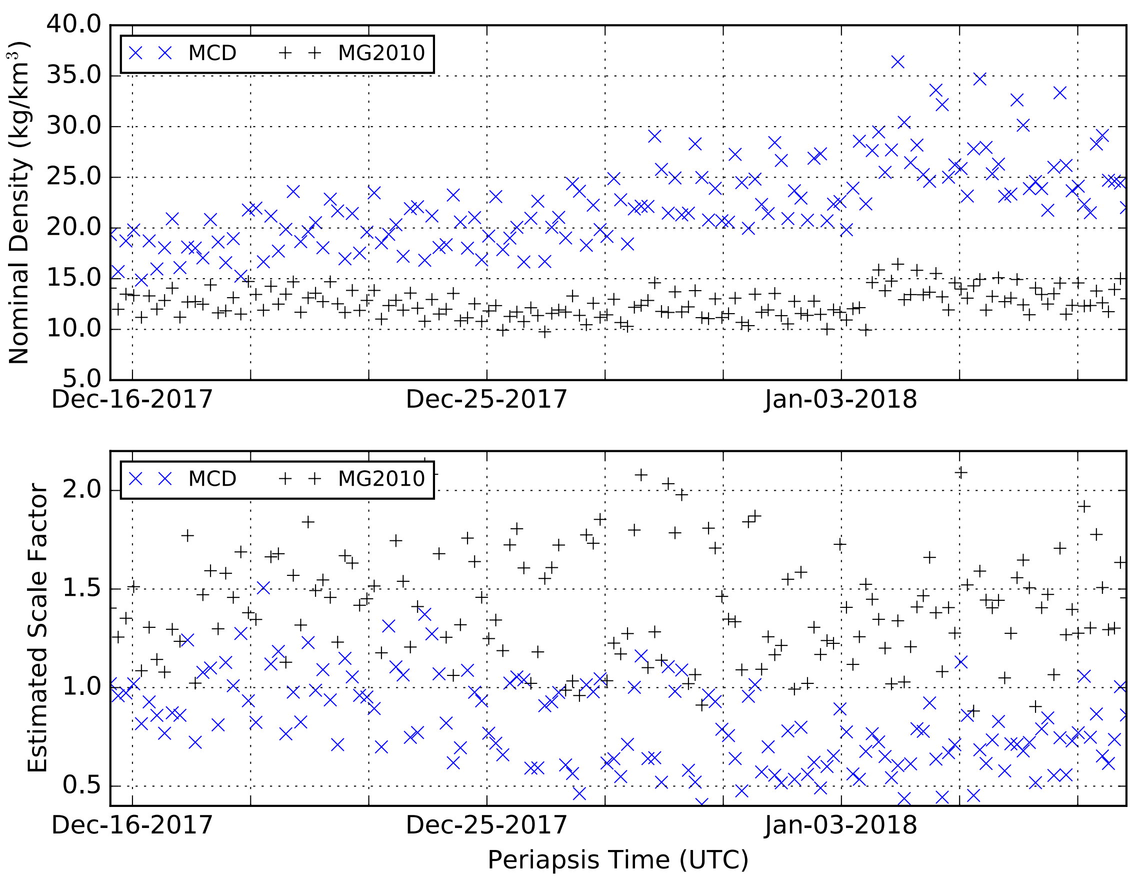

Fig. 4: Comparison of Mars-GRAM and MCD Scale Factors and Nominal Densities

This experience, and the comparison of the models, helped to clarify the role of the reference density model during operations of an aerobraking orbiter. There appear to be three valuable traits for a reference model: valid scale heights, seasonal trending, and stable reference values. Mars-GRAM provides these for JPL-Nav, while MCD did not due to the lack of stable reference values. The exponential model yields stable reference values, but uses an arbitrary scale height and includes no seasonal trending. The exponential model was sufficient for TGO operations, because the rapid OD/upload cycle kept long term trends from becoming important. Because altitudes were kept in a relatively narrow range, a fixed scale height was sufficient, though it did require changing that reference model part-way through aerobraking when the altitude regime changed. For these reasons, the simple exponential is sufficient for traditional high intensity aerobraking, but proves more troubling for a mission like MAVEN with long predictions and more variable altitudes. An alternative for future missions to consider is the Simplified Stewart Model, which includes a Stewart-Culp power law model fit to Mars-GRAM 2000, and can be implemented purely analytically. This model includes reasonable seasonal variations and altitude-based scale heights, and being analytical, is smoother than table-based models like Mars-GRAM and MCD, solving integrator step size challenges.

V. TGO Automated Orbit Determination and Quicklook

Immediate results from orbit determination are particularly valuable for aerobraking missions in assessing the safety of the spacecraft, allowing the team to take swift action if dangerous density trends are emerging. This is why historically aerobraking missions like Odyssey and MRO operated with 24-hour staffing. Given the staffing constraints for TGO, this was not a feasible option. Advances in automated orbit determination techniques make an automated “quicklook” approach the preferred choice.

Heritage

The initial development was derived from quicklook utilities for MAVEN, the most recent mission operating in an aerobraking-like regime. These utilities were themselves derived from tools for MRO and Odyssey. MAVEN orbits with a 4.5 hour period, and gets approximately one 8-hour tracking pass per day, so that a single track usually covers one periapsis, and there are approximately four periapses between tracking passes. Additionally, the target density is relatively shallow compared to true aerobraking missions, so the initial trajectory is usually well within the regime of linear variation with the true orbit. For this reason, the automated OD process was configured to trigger at the end of each tracking pass, as long as there were at least three orbits after the end of the case start, creating a new solution that covered the previous pass and the current one, including the untracked periapses in the middle. This achieved timely solutions, with case definitions similar to those used for manual reconstructions, with full coverage of the periapsis density scale factors. This structure was copied directly to TGO, with a new fit being triggered at the end of each pass, as long as there was a new periapsis in the fit, a new criterion given the long, 24-hour orbits and continuous tracking coverage. Note that for TGO, trigger epochs were set manually based on the known tracking schedule, rather than automated processes based on station allocation files.

Data Processing

Once a new quicklook was triggered and the data span selected, a new working directory was built with the selected start and end times. This was built using the Navigation Operations Versatile Architecture (Nova) toolkit, a navigator-developed set of software that wraps the Monte capabilities. A key insight of this toolkit is that automation and manual operations are made easier when both modes of operation use the same tools, minimizing development effort and blurring the boundaries between the two modes; manual operations would often follow the same steps as the automated process, but with human judgement being applied where most appropriate. For this reason, the automatically-built working areas were identical to those used for manual orbit determination solutions, with a few settings tweaked after creation for more aggressive auto-editing of tracking data. These directories were built in a separate area to keep them distinct from the official manual deliveries and solutions.

The orbit determination process involves computing a least square best fit for a set of measurements linearized about the trajectory, applying the resulting updates to the non-linear propagation, and iterating until convergence. While most of this is easily mechanized, so long as the models capture the actual forces being applied and offsets in the modeled parameters are close enough to the truth for convergence, two steps stand out as requiring human judgement. The first is whether or not the solution is converged; that is, whether or not the updates from the linear filter are small enough to be considered negligible. This was judged by comparing the root mean square of the weighted pre-fit residuals and those of post-fit residuals, and if the difference was less than 1% of the total value, the solution was considered converged. This was sufficient for these purposes, though other criteria to consider might include the changes in the estimable parameters themselves, or whether there is significant signature in the residuals. Often an analyst would iterate once or twice more from this point, but for automated purposes, this looser requirement was preferable since occasionally a solution would diverge or oscillate around a solution, and the looser convergence tolerance was sufficient to estimate accurate density scale factors.

The second task requiring human judgement when completing an OD solution is the editing of the Doppler data. The input measurements often include bad data points that do not inform the correct trajectory. These can include outliers from processing errors or thermal or electric spikes, as well as unmodeled temporary deviations from the model such as antenna motion due to slews or additional delays due to solar activity. Reliable methods of outlier detection have been developed and implemented. The TGO OD toolkit did this by first breaking up the available data into small arcs, split by tracking pass and by orbit. Each of these arcs were then processed using the standard OD filter without iteration. The interquartile range (IQR), the difference of the 75th and 25th percentile values, was computed, and any point more than a configurable value of IQRs away were marked as ignored; this value was set to 3.0 for manual runs, and 2.5 for automated runs. With this set of ignored points, the fit and remove process was repeated, since removing a large outlier could cause smaller ones to become more obvious due to a better fit. Once no new points were removed, the process ended, and the data edits were saved for use in the filter. This method of outlier removal had proven successful for MAVEN and was carried over to TGO.

The input data for TGO had a third source of problematic data, when one-way Doppler data were incorrectly marked as two-way. For the human analyst, these data point series were easy to identify and remove, since they showed large curving signatures that were discontinuous with later data, and not consistent with the patterns typical of correct but poorly fit data. The automated editor did not initially handle these data well, because the bad data were no longer outliers, but series of data with signatures that did not match the models available to the filter. Often these data could cover a significant portion of the entire track, so that the assumption that the 25th to 75th percentile contained mostly "good" values was not necessarily true. This was mitigated by ensuring the autoeditor was aggressive in removing points, and checking that the final RMS residuals were not unreasonably large (greater than 5 Hz), a situation that would cause that specific arc to be removed, but still allow the solution as a whole to proceed. This was understood to possibly remove good and useful data, but removal of good data was considered acceptable as long as an overall solution could still be computed. A second problem was that even if the IQR algorithm converged, there would be still be mis-flagged one-way data that happened to cross zero and would thus be included in the filter, even though further iteration would show them to be invalid, leading to divergence and failed cases. This was mitigated using a technique of "orphan detection", where any set of less than ten measurements separated from other measurements by at least two minutes were considered orphans and removed. Application of this technique was quite successful in correctly removing mis-flagged one-way Doppler data.

Updated scheduling algorithm

With both automated data editing and convergence detection implemented, and implemented in such a way to make manual analysis simpler as well, automated solutions proceeded from the start of aerobraking through January of 2018. As the orbital period dropped well below eight hours, in the last months of 2017, the failings of this end-of-pass, once-per-day approach became apparent. First, data were desired more frequently, since it was useful to know of an unexpectedly high periapsis density as soon as possible rather than waiting for the arbitrary start time for an automated run. This was mitigated to some extent by a shortening the minimum case length, but this could not easily be reduced to more often than once every eight hours, which left the process largely redundant with manual solutions performed by ESOC-FD and JPL-Nav teams. Additionally, fitting through ten or more periapses with drag ΔV on the order of 1 m/sec was itself challenging, because the later orbits were usually outside the realm of reasonable linear approximation when compared with the truth, requiring the step fit process described above, which was an additional level of complexity that could not be interrupted and corrected by a human operator in the automated context.

Given these challenges, an alternative was needed. The requirements for this alternative were as follows: the drag ΔV and density for a given periapsis needed to be reconstructed as quickly as possible, the process needed to be robust to where passes ended relative to periapsis times, the procedure needed to be reliably automatable, and the interface needed to run regularly rather than require manual intervention to specify the schedule. A process was developed to meet these goals. It ran every fifteen minutes, taking an existing "current" arc, and extending the data cutoff to the current epoch, adding in any newly available data, and reconverging the filter. After convergence, the a priori initial state and drag scale factors were updated, so that the next run would start in a condition likely to yield easy convergence; this was effectively the same concept as the step fit. Once converged, if the arc was at least twelve hours long, and the last measurement time was at least a quarter-period past the last periapsis, with at least fifty Doppler points after the periapsis, the arc was judged to be "complete", with products generated and delivered to ESOC-FD. After an arc was completed, the same job created a new arc with a one-periapsis overlap that became the new "current" arc that would be continued on the next run. It should be noted that a file system-based "lock" was used to ensure that only a single version of this process was running at a given time.

With data being processed every 15 minutes, a reasonable periapsis estimate, judged as being one with at least twenty Doppler points (with 60 second integration time) after the periapsis, could be obtained nearly as quickly as the data allowed. The trajectory and drag data for the incomplete arc were uploaded to the file interchange server for ESOC-FD access and integration into their solutions on demand. Because the mission did not have 24-hour staffing, an email notification was preferred as well. Unfortunately, an email every two hours over the course of a month could easily become background noise, so a simple system was implemented with the most critical information in the email title itself. If the estimated dynamic pressure, heating rate, and heat load were under the target values of 0.28 pascal, 1120 W/m^2, and 200 kJ/m^2, the email title read "TGO Orbit 785 (GREEN)". If the estimated periapsis values were above those levels, but below the true safety limits of 0.7 pascal, 2800 W/m^2 and 500 kJ/m^2, a "(YELLOW)" flag was included in the title instead. Finally, a "(RED)" flag was used to indicate if any of those safety limits were breached, though this never occurred during operations. With this system, a reasonable level of monitoring could be performed as long as JPL-Nav or ESOC-FD personnel were awake, since these notifications would be readable and clear via smartphone notifications and wearables, without needing to take additional action during off hours. Each email also included residuals and density history plots, to monitor long term trends and the validity of the OD solution as needed. The more complete email notifications that were included in the earlier version of the quicklook process, with tables of drag data, plots, and other forces were generated only when a case was closed, giving a more complete view of the OD quality at a more manageable rate.

Automated Popup Maneuver Watchdog

An additional point of concern was the possibility of a small automated heatflux reduction maneuver (FRM), that increased the altitude by approximately 3 km, or a larger automated popup maneuver (APM), either of which could be triggered autonomously by the flight system. ESOC-FD requested that if JPL-Nav saw one of these while the ESOC-FD team was not working or otherwise unavailable, that they be notified as soon as possible. Initially, the JPL-Nav team proceeded by recognizing that if an unexpected apoapsis maneuver did occur, the quicklook process would not run properly, and that therefore the absence of an expected quicklook notification would be an indication that the JPL-Nav team would need to look to see if a one of these maneuvers had occurred. The problem with this approach was that the absence of an expected notification is far easier to miss than the presence of an unexpected notification. Additionally, a quicklook could be missed for other reasons: lost tracking passes, a misconfiguration or bug in the quicklook process, or temporary losses of email service. Thus, a more robust method was desired.

Initial thinking was to use a passthrough of the latest Doppler data compared to the latest predicted trajectory and look for patterns that would indicate a maneuver at a given time. This idea proved impractical, because the drag uncertainties were large enough to make the signature of a maneuver non-obvious. While this idea may have been a candidate for pattern recognition with machine learning, necessarily based on simulated training data, this approach was not followed due to the ambiguities of these algorithms, particularly when paired with the other sources of "bad" data described previously. Additionally, the application of the machine learning to navigation problems is an area of development that is not ready for operational deployment.

Instead, an approach that relied on the understanding that if a maneuver actually occurred, the initial iteration of a case with a maneuver modeled near the correct epoch would fit significantly better than a case with no maneuver modeled. Every fifteen minutes, an automated process would load the last predicted trajectory, and all tracking data collected since the reconstructed portion ended, and fit that data using the standard filter configuration, saving the postfit measurement residuals. The process then performed the same fit, but injecting a maneuver with the known sizes of the possible maneuvers, delivered by ESOC-FD, at each apoapsis. If the weighted average of the residuals was smaller than the nominal value for any of these cases, and small enough to be considered valid, an email was sent to the JPL-Nav team indicating that a *possible* FRM or APM had occurred.

The selection of the triggering criteria for the email was set rather loosely, because a reasonable false positive rate was acceptable, while a false negative was more problematic. This process ran for the last month of aerobraking, where such a maneuver was most likely to occur. During that time two false positives occurred. The first false alarm was attributable to a logic error, where the autoeditor removed most data in a with-maneuver case, yielding a supposedly "good" but actually trivial solution. This error was corrected to only trigger an email when the amount of data included in the with-maneuver case was not significantly less than the baseline case. The second false alarm, the day before aerobraking completed, was never fully understood, but a manual analysis quickly demonstrated that no unexpected maneuver had occurred. Because no autonomous maneuvers occurred, a true judgement of its effectiveness is impossible, though tests against known maneuvers, with a predicted trajectory that ignored that maneuver were performed, demonstrating the theoretical soundness of the concept.

VI. Conclusion

After a year-long period of aerobraking, TGO successfully entered into the final science orbit in April 2018. Under coordination between ESOC and JPL, collaboration between ESOC-FD and JPL-Nav contributed to the successful completion of this challenging aerobraking operation. JPL-Nav provided consultancy in aerobraking navigation operations, review of the strategy for walk-in and end-game phases in the area of Guidance, Navigation and Control, and shadow navigation for TGO with regular exchange of orbit determination and prediction solutions. In addition to these contributions to TGO's successful aerobraking, JPL-Nav also benefited from this cross-support experience, as it provided operational training and opportunity to re-establish mission design and navigational processes for JPL's next aerobraking mission (MAVEN). Implementation of the Mars Climate Database in JPL's navigation software added additional capability for future Mars missions. Lessons and experiences from past collaborations played an essential role in the successful collaboration between two navigation teams from two space agencies with a short preparation time.

VII. Acknowledgments

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