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Thermal Propellant Gauging - Enhancing Spacecraft Propellant Management for the EDRS-C Satellite

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Abstract

During a geostationary satellite mission, one of the most crucial factors is the knowledge of the remaining propellant in the satellite's tanks to ensure its maximum lifespan. Continuous station-keeping maneuvers (SKMs) are necessary to stay within their designated control box. Using principles of heat transfer and thermal dynamics, the Thermal Propellant Gauging Technique (TPGT) describes an alternative technical approach to measure the remaining propellant in comparison to the more conventional bookkeeping method. By applying controlled heat to a propellant tank using existing heater lines, monitoring and recording the resulting temperature changes with precise sensors, TPGT is not only almost independent of mechanical components but also a non-intrusive method ensuring that there is no contamination or disruption of the propellant. These properties make TPGT highly advantageous for a mission in space. Different thermal responses of fluids and gases constitute the fundamental physical concepts of TPGT. When heating the components of the tank, the rate of temperature change varies depending on the thermal properties of these materials. The remaining liquid propellant has a higher thermal mass and conductivity than the ullage gas and therefore reacts differently to the heating process. Thermal gradients and temperature evolution are analyzed over time and the results are compared with thermal models of the tank. Considering the material properties and geometry of the tank, as well as the thermodynamic behavior of the propellant, the remaining amount of fuel can be determined. With decreasing propellant masses towards the end of the life of a satellite, TPGT demonstrates superior precision compared to the conventional bookkeeping method to keep track of used propellant. To put a theoretical method into context with real-life missions, the European Data Relay System (EDRS) serves as an illustrative case study. EDRS, alternatively known as SpaceDataHighway, is a network of geostationary satellites designed to provide fast real-time data transmission from Earth observation satellites in low Earth orbit to ground stations. The SpaceDataHighway is a public–private partnership between the European Space Agency (ESA) and Airbus, with the laser terminals developed by Tesat-Spacecom and the German Space Administration Deutsches Zentrum für Luft- und Raumfahrt (DLR). Airbus, which owns and operates the system, provides commercial services for the SpaceDataHighway, while the execution of EDRS flight operations are conducted by DLR's German Space Operations Center (GSOC) in Oberpfaffenhofen. Consequently, to prolong the lifespan of the EDRS mission and to ensure the continuous and reliable data relay, the TPGT method is used in combination with other proven techniques to manage the remaining propellant. This paper first gives an overview of the Thermal Propellant Gauging Technique within a physical context, followed by an implementation of the method using the EDRS-C mission as an example. In addition, it explores the different techniques for tracking the remaining propellant employed by the mission and compares the results between different phases of the mission. Concluding, the paper discusses potential approaches for automating this process as the satellite approaches the end of its operational life, positioning TPGT as the primary source of managing the remaining propellant.

Keywords: SpaceDataHighway, European Data Relay System (EDRS-C), propellant estimation

Acronyms/Abbreviations

DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
EDRS	European Data Relay System
EDRS-C	second node of the EDRS system
EoL	End of Life
ESA	European Space Agency
FDIR	Failure Detection, Isolation and Recovery
FDS	Flight Dynamic System
FOP	Flight Operation Procedure
GOP	Ground Operation Procedure

GSOC	German Space Operations Center
LEO	Low-Earth Orbit
LEOP	Launch and Early Orbit Phase
LMS	Link Management System
MMH	Monomethyl Hydrazine
MON	Mixed Oxides of Nitrogen
OOL	Out Of Limit
ProToS	Procedure Tool Suite
PVT	Pressure-Volume-Temperature
S/C	Spacecraft
SKM	Station-Keeping-Manuever
TM	Telemetry
TPGT	Thermal Propellant Gauging Technique
ViPER	Versatile Propellant Estimation Routine

1. Introduction

The efficient operation of geostationary satellites is of essential importance for modern telecommunications, navigation and Earth observation. Positioned in orbits approximately 36,000 kilometers above the equator, one of the many geostationary satellite-(constellations) in orbit, is EDRS, also known as the SpaceDataHighway. The SpaceDataHighway is a public–private partnership between the ESA and Airbus, with laser terminals developed by Tesat-Spacecom and the DLR German Space Administration. Airbus, which owns and operates the system, provides commercial services for the SpaceDataHighway, while the execution of EDRS flight operations are conducted by DLR's GSOC in Oberpfaffenhofen. The main goal of the SpaceDataHighway is to provide near-real-time communication services between LEO satellites and ground stations, hence its naming. The EDRS-C satellite, launched in 2019, is the second node of this system, designed to expand the coverage and capacity of the EDRS network. EDRS-C plays a vital role in supporting a wide range of applications, including Earth observation, navigation, and telecommunications. By enabling rapid and reliable transmission of data between low-earth orbit (LEO) satellites and ground stations, EDRS-C can aid the propagation of critical information, such as weather forecasts, natural disaster monitoring, and emergency response services.

A key factor, determining the longevity and effectiveness of the satellites, is their onboard propellant supply. The propellant is essential for maintaining the satellite's orbital position by executing SKMs, compensating for gravitational perturbations or radiation pressure of the sun and executing and therefore ensuring that the satellite remains within its designated control box. Lastly, at the end of its life-cycle, the satellite has to be maneuvered to the graveyard orbit - the disposal orbit all geostationary satellites are moved to after the end of their mission. For those de-orbiting maneuvers, enough propellant has to be left over. Consequently, a technique is required to quantify the remaining propellant. The most common approach involves tracking the consumption of propellant over time through bookkeeping, which is based on the propulsion system's performance characteristics and the specific impulses achieved during thruster firings. However, this method has some inaccuracies due to various factors, such as variations in thruster efficiency, changes in operational conditions, and unforeseen events like propellant leaks or tank pressurization anomalies, especially towards End of Life (EoL) of the satellite. Therefore, new methods have been tested, exploring innovative techniques to improve propellant management and address these challenges. Among these, TPGT has emerged as a promising approach. TPGT leverages the principles of thermodynamics to estimate the quantity of propellant within the satellite's tanks. By applying controlled heat to the tank and measuring the resulting temperature changes, this method offers a non-intrusive measure of propellant levels.

The integration of TPGT on the EDRS-C satellite represents a step forward in the development of advanced propellant management systems. Using the unique capabilities of TPGT, the EDRS-C mission aims to demonstrate the effectiveness of this innovative technology, in combination with the well-established bookkeeping, improving the accuracy and reliability of propellant level measurements, especially towards EoL. To ensure accuracy during this time, multiple TPGT tests will be performed during the lifetime of the mission, validating the underlying thermal model. The first test of TPGT was already conducted during the Launch and Early Orbit Phase (LEOP) in November 2019, while the first execution during the routine phase took place in June 2023. Going forward, the interval between the executions will decrease, until at EoL an execution of TPGT is foreseen for every week, alternating between both propellant tanks of EDRS-C, the monomethyl hydrazine (MMH) and mixed oxides of nitrogen (MON).

This paper first gives an overview of TPGT within a physical context in Sec. 2, followed by an implementation of the method using the EDRS-C mission as an example (Sec. 3). In addition, it explores the different techniques for tracking the remaining propellant employed by the mission and compares the results between different phases of the mission (Sec.4). Concluding, the paper discusses potential approaches for automating this process as the satellite approaches the end of its operational life, positioning TPGT as the primary source of managing the remaining propellant in Sec. 5.

2. The Thermal Propellant Gauging Technique

Operating on heat transfer principles, TPGT utilizes the fact that liquid propellant and ullage gas in a spacecraft tank possess distinct thermal properties due to variations in thermal conductivity, specific heat capacity, and density. When heat is introduced to the tank, either through environmental conditions or controlled heating, it propagates at different rates depending on whether it is interacting with liquid or gas. The ability to measure and analyze these differences is the basis of TPGT and allows for an accurate calculation of the proportion of liquid and gas within the tank.

The equation of heat conduction connects the rate of temperature change with thermal diffusivity which depends on the thermal conductivity, density, and heat capacity of the material. Because of their higher density and specific heat capacity, liquid propellants absorb and distribute heat more efficiently than gases, resulting in a slower and more uniform temperature rise in regions of the tank containing liquid in contrast to regions filled with gas. This difference in thermal response is critical for distinguishing between the liquid and gaseous phases within the tank. When a known amount of heat is applied to the tank's external surface, typically via onboard heaters, the heat propagates inward, and temperature sensors strategically placed around the tank track how the temperature changes over time. The heat flux through the tank wall is proportional to the temperature gradient, according to Fourier's law [1].

To fine-tune the measurements, a thermal resistance model of the tank is created, accounting for contributions from both the liquid and gas phases. The total thermal resistance of the system is the sum of the resistances of the liquid and gas phases. Because the liquid is less resistant to heat flow, a tank with more remaining propellant will have a lower overall thermal resistance than a tank nearing depletion. The liquid fraction within the tank can be accurately determined by numerically solving the transient heat conduction equation and comparing observed temperature data to precomputed thermal models. To ensure reliable measurements, TPGT must be calibrated accurately and temperature sensors placed precisely. To avoid systematic errors, it is necessary to account for heat losses to surrounding spacecraft structures, variations in external heating from the space environment, and the thermal properties of the tank materials. These effects are mitigated by creating spacecraft-specific thermal models that incorporate detailed knowledge of the tank's geometry and predicted heat flow characteristics [2].

In contrast to other propellant gauging techniques such as Pressure-Volume-Temperature (PVT) analysis [3], which relies on monitoring the pressure of the ullage gas to estimate the remaining propellant, TPGT does not depend on pressure measurements and is therefore unaffected by variations in gas compressibility or pressure fluctuations due to temperature changes. PVT methods are typically more accurate in the early phases of a mission when the tank is mostly full and gas volume is minimal, leading to measurable pressure changes with fuel consumption. However, as the propellant level drops and the gas volume increases, the pressure variations become smaller and harder to detect, making PVT less effective in later stages of the mission. In contrast, TPGT becomes more reliable as propellant levels decrease because the temperature differences between liquid and gas become more pronounced, improving the sensitivity of the measurement.

Because TPGT is a passive and non-intrusive technique, it does not interfere with the majority of normal spacecraft operations, nor does it require additional hardware inside the propellant tank. Instead, it utilizes the already implemented heater lines and temperature sensors to heat the tanks and measure the resulting temperature changes, making it an ideal solution for long-duration missions where traditional methods lose accuracy over time. The physics underlying TPGT ensure that the technique is scalable across different spacecraft designs, provided that appropriate thermal models are developed to match the specific tank geometry and material properties. With carefully calibrated models and well-placed temperature sensors, TPGT provides a robust and reliable means of estimating remaining propellant, particularly in the later stages of a spacecraft's operational life when there is only a small amount of liquid fuel left, leading to a uniform distribution of the introduced heat [4]. This approach has been tested on various spacecrafts (S/Cs) [5, 6] and is also implemented on EDRS-C.

3. Implementation on EDRS-C

Although TPGT is used mainly towards the end of life of a satellite, additional TPGTs are performed on EDRS-C throughout its lifetime to validate the underlying model. Specific remaining propellant masses were chosen, with decreasing intervals, leading to more occurrences of TPGT toward the EoL phase; see also Tab. 1. Additionally, the first TPGT was performed directly after the LEOP in November 2019.

The execution of TPGT on EDRS-C must be carefully planned to ensure accurate measurements while maintaining spacecraft operational constraints. Since the method relies on controlled heating to determine the remaining propellant mass, it is critical to prevent disturbances that could alter the thermal response of the tank, such as thruster firings. The 10N attitude control thrusters introduce dynamic and thermal disturbances, which would affect the data of the measurements. Therefore, thruster activity is strictly prohibited during the TPGT heating process, which means that the execution of TPGT has to be planned around the nominal station-keeping cycle and the corresponding angular momentum management.

Mass MON	Mass MMH	Estimated Date
200 kg	330 kg	06 / 2023
160 kg	265 kg	04 / 2026
122 kg	201 kg	11 / 2028
84 kg	139 kg	01 / 2032
68 kg	113 kg	08 / 2033
53 kg	88 kg	02 / 2035
37 kg	61 kg	09 / 2036
30 kg	49 kg	05 / 2037
21 kg	35 kg	03 / 2038
17 kg	29 kg	08 / 2038
14 kg	23 kg	12 / 2038

Table 1. Planned TPGTs before EoL to validate the model. The frequency of executions increases as the mission advances, resulting in shorter intervals between each TPGT run.

In EDRS-C, nominal SKMs are conducted every second week, on Tuesdays and Thursdays. To prevent interference, TPGT heating must be scheduled in between two consecutive east-west SKMs, ensuring that no intermediate north-south firings occur. Another operational constraint is that TPGT cannot be performed during an eclipse phase. For a geostationary satellite these take place for around 6 weeks surrounding the spring and fall equinox. The absence of solar heating affects the spacecraft's overall thermal equilibrium, making temperature stabilization more difficult and additionally reducing the available power for the heaters.

To be able to perform the TPGT, a minimum temperature difference of 12 K between the start of the measurement and the end of the heating process has to be reached. Additionally, the time period for not only the heating process but also the cool-down has to be considered. Shortening the cooling time can affect the accuracy of delta-V predictions for the next SKM, leading to a different performance of the thrusters compared to the model used by the flight dynamic system (FDS). Therefore, enough time must be allowed to complete the thermal stabilization before the next SKM. In accordance with these limitations, TPGT can be effectively executed on EDRS-C with precise and accurate propellant estimates without compromising the stability of the spacecraft or maneuver planning and hence providing uninterrupted operation of the SpaceDataHighway.

The operational execution follows a structured approach, incorporating a ground operation procedure (GOP) addressing all ground-related activities, and flight operation procedures (FOPs) specific to each tank. A detailed timetable integrates TPGT into routine operations, see Fig. 1. On the ground, adjustments to operational limits must be made, including monitoring and controlling angular momentum build-up due to the absence of thruster firings. This gets even more important if TPGT is performed during the months of May - July, as the seasonal effect of momentum build-up is strongest during this time period. Additionally, ground limits regarding the temperatures need to be adapted in order to prevent so-called "out of limits" (OOLs) triggering. These measures help maintain the spacecraft's stability while ensuring that thermal measurements remain undisturbed.

At the spacecraft level, specific configurations must be considered, particularly the adaptation of the Failure Detection, Isolation and Recovery (FDIR) limits for the heater lines and the respective set points, which determine when the heaters are activated. In EDRS-C, each tank is subdivided in the three sections, the upper dome, middle dome, and lower dome. Each of these sections possess their own heater lines with associated set points and limits.

Timetable	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
CW	Configuration for Measurement Phase MON	N/S maneuver		2x E/W maneuver Start Measuring Phase MON (ViPER)		Validity Check and Configuration for Heating Phase MON (can be time-tagged)	
CW+1				Stop Heating Phase and Validity Check MON	Configuration back to normal MON as soon as possible		
CW+2	Configuration for Measurement Phase MMH	N/S maneuver		2x E/W maneuver Start Measuring Phase MMH (ViPER)		Validity Check and Configuration for Heating Phase MMH (can be time-tagged)	
CW+3				Stop Heating Phase and Validity Check MMH	Configuration back to normal MMH as soon as possible		
CW+4		N/S maneuver		2x E/W maneuver			

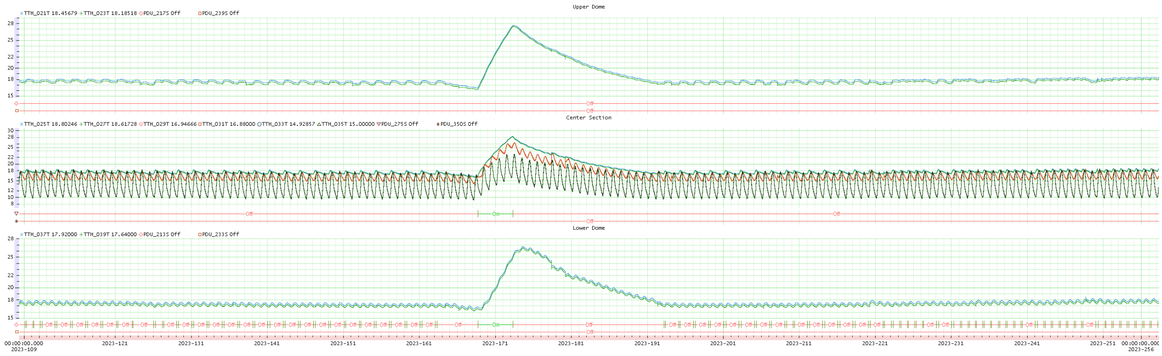
Fig. 1. Timetable of the TPGT on EDRS-C before EoL. Both tanks are measured within a time span of two maneuver cycles. In yellow are all activities related to the MON tank and in blue all activities related to the MMH tank. Maneuvers are marked in grey.

During the process of TPGT the heaters of the lower and middle dome of the respective tanks are permanently activated. To ensure this setting, the temperature set points are set to 49°C and 50°C as the lower and upper value, respectively. Since the FDIR limit for nominal operation outside of TPGT is only 28°C, it need to be adjusted accordingly. The chosen value is 55°C for all three sections per tank. These modifications ensure that the generated heat is recognized as a controlled operation and not mistakenly flagged as an anomaly.

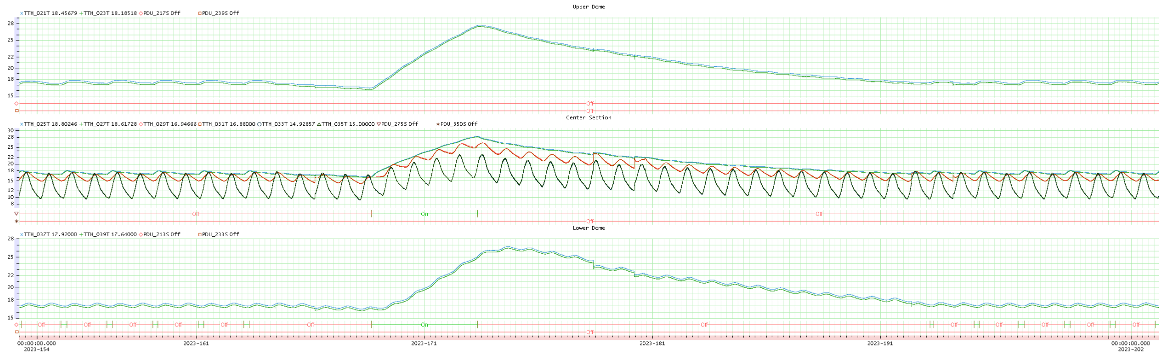
To evaluate the results, the underlying model developed by the satellite manufacturer OHB was implemented into the Propulsion Tool of EDRS-C, the Versatile Propellant Estimation Routine (ViPER) [7]. Multiple sets of simulation data are imported to ensure an always fitting model. To assess the precision of both bookkeeping and TPGT, error calculations are performed. For TPGT, both the result and the error are typically calculated using two sets of simulation data to match the telemetry (TM) collected from the S/C. Therefore, differences in the upper and lower boundary can occur. In contrast, bookkeeping errors arise from the accumulation of small uncertainties in propellant consumption estimates over time, which can lead to significant deviations from the true propellant mass towards EoL. As the mission progresses, the error associated with bookkeeping will increase due to the compounding effect of these small uncertainties. In contrast, TPGT errors remain relatively constant or even get smaller, as each measurement provides an independent estimate of the propellant mass and TPGT gets more precise towards EoL.

4. Results of First Executions of TPGT

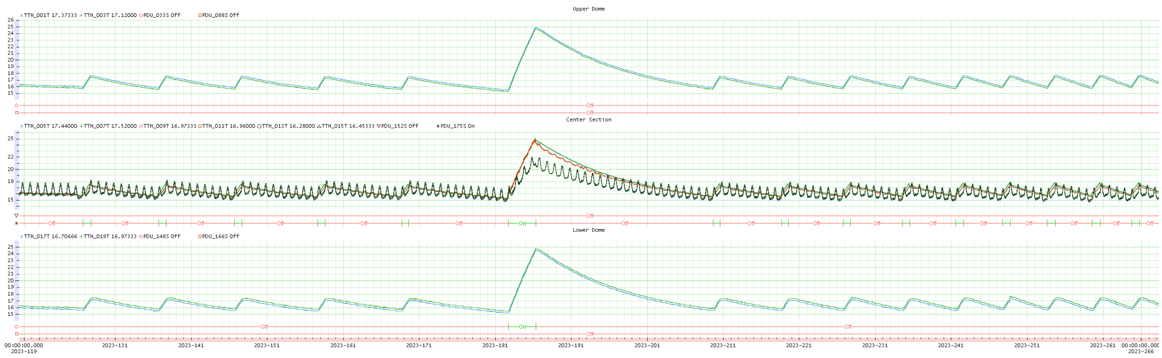
In October 2019 and June 2023 the first of several TPGTs before EoL were executed in order to validate the underlying thermal model (see also Tab. 1). Since the tanks are still much more filled compared to the EoL phase, it was agreed to only heat the tanks to a difference of 8 K (instead of 12 K, see Sec. 3). This step ensured the execution of all maneuvers as originally planned, while still giving enough data to validate the thermal model of the satellite. This was especially crucial for the second execution in 2023, because deviating from the long-term maneuver plan can interrupt the service of the SpaceDataHighway, as maneuver times are communicated to the customers long in advance, so they themselves can plan accordingly.



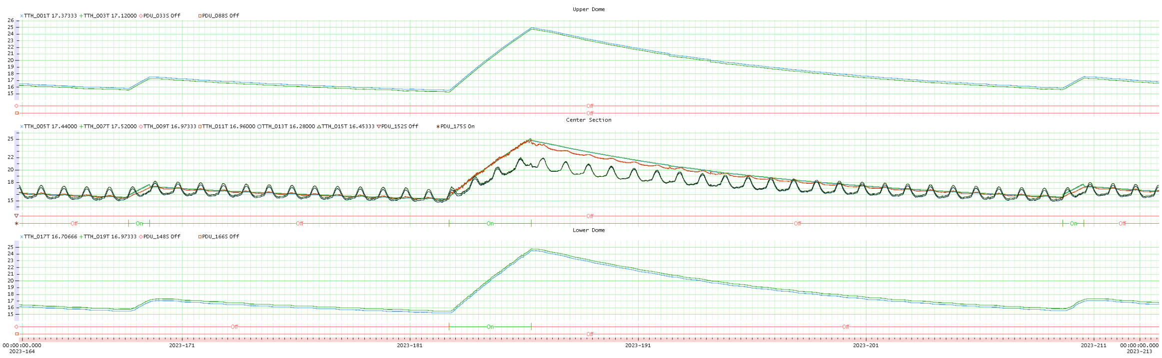
(a) MON: Approximately 150 days, the TPGT phase can clearly be seen in the temperature curves of all domes.



(b) MON close-up: Approximately 50 days, note the long cool-down period.



(c) MMH: Approximately 150 days, the TPGT phase can clearly be seen in the temperature curves of all domes.



(d) MMH close-up: Approximately 50 days, note the long cool-down period.

Fig. 2. Temperature curves of the upper, middle and lower dome of the MON and MMH tanks. The normal temperature fluctuations can be seen in every plot, however, the temperature increase due to thermal gauging is clearly visible.

As specified in the GOP (Sec. 3), preparations were made by starting with the MON tank on both instances. To minimize the impact of daily temperature fluctuations, the heaters were first turned off to stabilize the temperature curve. This action not only achieved the desired stability but also had a cooling effect, making it easier to reach the necessary temperature difference of 8 K during the subsequent heating process. During the stabilization phase, thruster firing is allowed, therefore, this phase of the TPGT can already start during a maneuver week. As soon as the maneuvers were flown (see also the timetable in Fig. 1), the first measuring phase could begin. After 48 hours of data collection, the heating process was started by adjusting the temperature set points of the respective heater lines, switching them on permanently. After approximately 4.5 days, the target temperature difference of 8 K was reached and the cooling period could begin in order to prepare the S/C for the upcoming N/S maneuver. During this time frame, the process has already begun again for the second tank (MMH) with the stabilizing phase. The heating curves of both tanks of the execution from 2023 can be found in Fig. 2.

Date	Bookkeeping	TPGT
10 / 2019	415.40 ± 7.59 kg	$413.71^{+48.03}_{-47.37}$ kg
06 / 2023	327.88 ± 8.51 kg	$313.36^{+37.36}_{-36.73}$ kg

Table 2. Results of the TPGT: MON

Date	Bookkeeping	TPGT
10 / 2019	252.70 ± 5.20 kg	$253.45^{+26.98}_{-26.84}$ kg
06 / 2023	199.39 ± 5.67 kg	$193.37^{+23.32}_{-22.88}$ kg

Table 3. Results of the TPGT: MMH

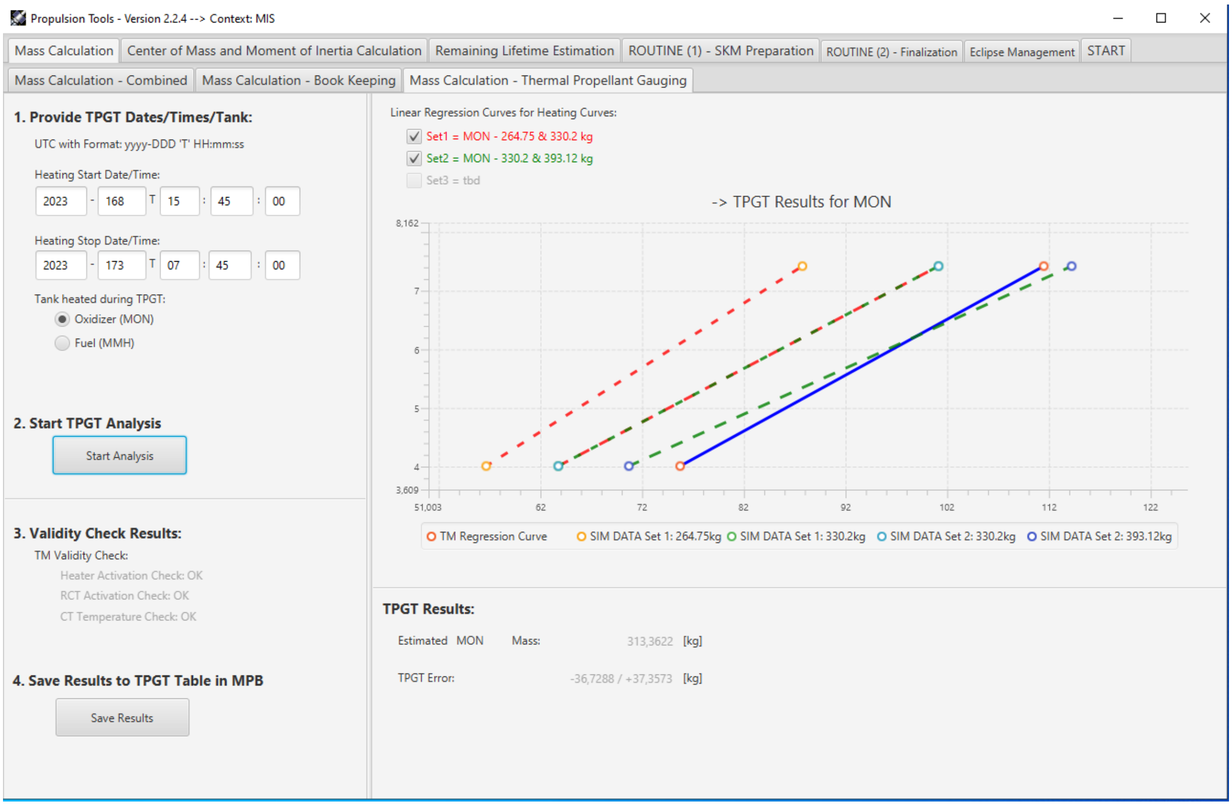
After four weeks of performing TPGT on EDRS-C, the TM was evaluated with ViPER. For both 2019 and 2023, the results showed expected behavior with large arror margins on the TPGT result compared to standard bookkeeping. Results for both executions of TPGT for the MON tank can be found in Tab. 2 and in Tab. 3 for the MMH tank. However, within the error range, both types of fuel consumption showed the same amount of fuel in the respective tanks. In Fig. 3 graphical results of ViPER are shown. While the blue line shows the actual data retrieved from the TM, the other data sets are from simulated thermal models, which are then fitted to the S/C data. The dates in Tab. 1 are derived from the simulation data, which were run for the denoted propellant masses. On the left in Fig. 3 the time frame for the fitting is given, in this case for the execution of June 2023. The different slopes correspond to different masses, a steeper incline pointing to less mass (and therefore a faster heating process) and vice versa.

5. Conclusion and Outlook

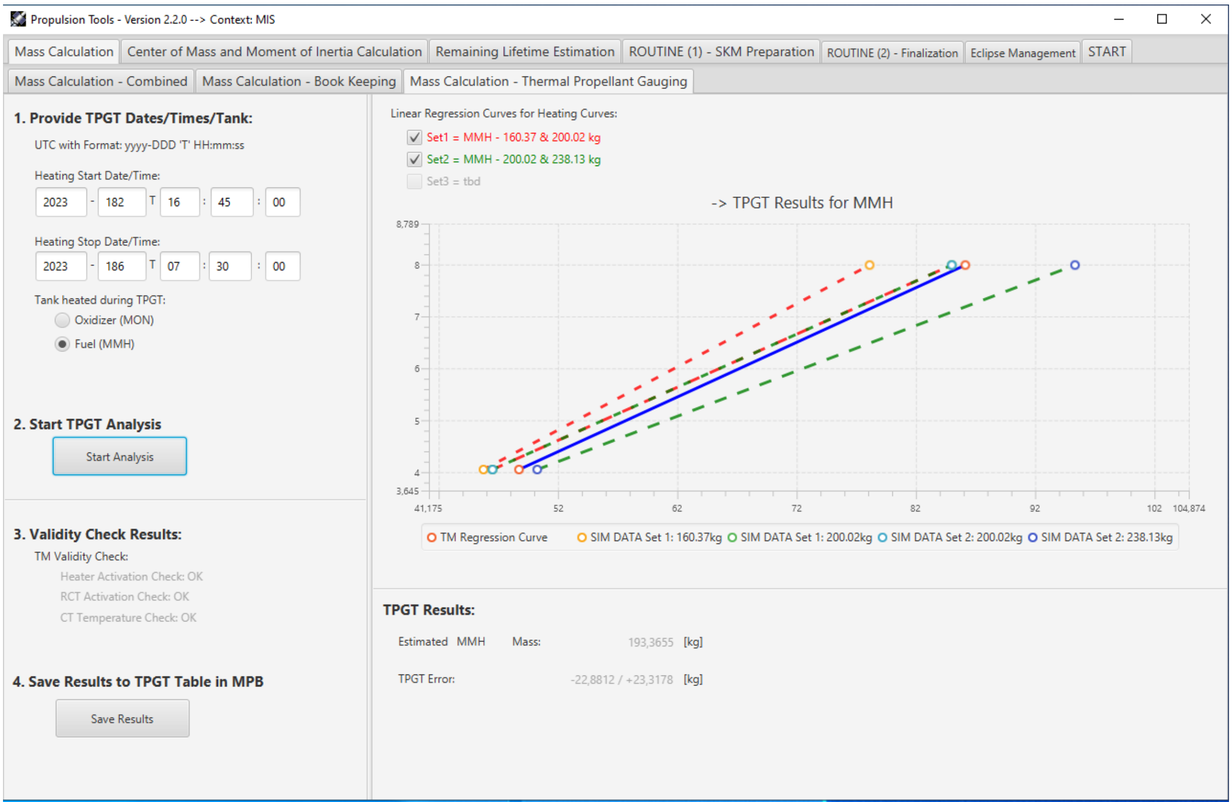
The results from the first two implementations of TPGT on EDRS-C demonstrate its promise for monitoring the remaining propellant more precisely than current monitoring techniques such as bookkeeping or PVT, especially at lower propellant masses. Although current error margins are significantly higher than those achieved with traditional bookkeeping methods, they are decreasing as the fuel mass decreases. In contrast, the error associated with the bookkeeping method will only increase over time due to error propagation. Future TPGT executions over the next few years (see also Tab. 1) will provide valuable insights into the potential of TPGT compared to bookkeeping.

During the EoL phase, the execution of TPGT will become the primary source of propellant estimation for EDRS-C and therefore must be performed at every maneuver cycle to ensure continuous and accurate monitoring of the remaining propellant. As the tanks become increasingly empty, the thermal response to heating changes more rapidly, leading to shorter heating durations compared to earlier mission phases. Therefore the timetable (Fig. 1) will have to be adjusted accordingly. The nearly empty tanks allow for quicker stabilization of temperature gradients, making the process more efficient.

Given the increased frequency of TPGT at EoL, automation becomes a key factor in improving efficiency and reducing operational workload. Automating the execution sequence, including heater activation, data collection, and initial analysis, minimizes the need for extensive manual oversight and ensures that TPGT is conducted consistently within each maneuver cycle outside of the eclipse seasons. Automated adjustments to heater control settings and FDIR thresholds enable real-time adaptation to changing tank conditions, further enhancing the accuracy of propellant estimation. This approach is merely a logical extension of the automation already in place for EDRS-C, with multiple re-occurring tasks already automated. With the obtained knowledge of e.g. flying maneuvers or monitoring every eclipse, the automation of TPGT will be implemented similarly [8–11]. By using the automation machine Procedure Tool Suite (ProToS), which is already in use for many missions at GSOC, including EDRS-C, and the



(a) Results of the MON tank.



(b) Results of the MMH tank.

Fig. 3. Results of the propellant estimation using the TPGT method in June 2023.

EDRS planning tool Link Management System (LMS)[12] to schedule the executions, the automated determination of remaining propellant masses will be enabled, eliminating the need for manual intervention.

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