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Fuel Consumption Estimation via Bookkeeping Method for Geostationary Satellites: Case Study and Application

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Abstract – *This work focuses on the Satellite Propulsion Subsystem (UPS), a critical aspect of satellite technology that can be supported by various propulsion types: electrical, chemical, cold gas, and nuclear propulsion. For communication satellites, chemical propulsion emerges as the most suitable option due to its simplicity and lower energy requirements. The chemical propulsion subsystem comprises oxidizer and fuel tanks, gas pressuring tanks utilizing helium. Wherein, Thrusters are employed for diverse tasks, encompassing tank sinking, orbital maneuvers (correction), attitude control, and deorbiting. These processes induce propellant consumption from orbit transfer to the deorbiting operation. The satellite's mission life hinges on propellant quantity, emphasizing the need to maintain sufficient reserves for deorbiting at satellite's end of life. Thus, accurately estimating propellant mass becomes a crucial task. This work delves into propellant mass estimation methods, specifically Bookkeeping (BKP). Moreover, we introduce and test a developed tool based on the Bookkeeping method. This tool proves instrumental in estimating the remaining propellant, offering a valuable resource for satellite mission planning and longevity.*

***Keywords**: GEO Satellite, propellant estimation, propulsion Subsystem, Book-kepping, thrusters.*

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I. Introduction

In the intricate realm of space exploration, the propulsion system stands as a pivotal element orchestrating the dynamic maneuvers and controlled movements essential for a spacecraft's mission. Before delving into the nuanced intricacies of our propellant estimation method, it is imperative to provide a concise overview of the propulsion system's integral role throughout the spacecraft's operational lifecycle.

The geostationary satellite propulsion subsystem, working in tandem with other spacecraft subsystems, plays a multifaceted role encompassing attitude control, orbit maneuvers, and mission-critical transitions. From the initial launch vehicle separation to the sustained operational phase of the spacecraft, this pressure-fed system, equipped with a single apogee engine and two functionally redundant thrusters' branches, shoulders the responsibility of ensuring precise control and maneuverability [1]. Key functions of this propulsion subsystem include generating thrust for transfer orbit firings to achieve geostationary orbit, providing impulse for spacecraft attitude and orbit control during geostationary orbit operations, and delivering minimum impulse bits for momentum wheel unloading in normal mode operation [2-5]. Moreover, it plays a crucial role in performing Delta-V and controlling attitude during station-keeping maneuvers, ensuring control capability during spin down, and facilitating end-of-life de-orbiting capability [6-8]. Additionally, the propulsion subsystem is instrumental in executing sun acquisition and earth acquisition maneuvers, further highlighting its comprehensive role in the spacecraft's operational repertoire [9].

As we delve into a more comprehensive exploration of our propellant estimation method, this introduction sets the stage by elucidating the integral functions performed by the geostationary satellite propulsion subsystem, emphasizing its critical contributions to the success of spacecraft missions. In the context of the liquid propellant/gas pressurant system examined in this paper, two operational modes are viable: blowdown and pressure-regulated.

In the blowdown mode, the propellant tank undergoes pressurization by the gas pressurant. As the mission progresses, the propellant tank pressure naturally decreases as propellant is expelled ("blown out") from the tank during thruster activation. In the pressure-regulated mode, a constant pressure is sustained in the propellant tank by introducing additional pressurant gas while the thrusters are firing. The pressure-regulated mode offers an advantage in maintaining a steady propellant flow rate, a critical requirement for bipropellant-type engines. This consistency ensures the constant mixture ratio necessary for achieving optimal thruster performance throughout the mission [10]. In satellite operational planning, a key parameter of utmost importance is the knowledge of the remaining propellant onboard each spacecraft. The quantity of propellant serves as a critical factor influencing the remaining operational life of commercial telecommunication satellites and is a major consideration in decisions related to replacement and relocation strategies. For telecommunication spacecraft, it is especially crucial to have precise information about the anticipated date when the inboard propellant will be exhausted to facilitate effective mission management [11]**.** Presently, three common methods are employed to assess the remaining propellant for a spacecraft in flight: BK, PVT, and thermal gauging methods. Methods such as BK or PVT demonstrate high accuracy at the initial stages of a spacecraft mission. This accuracy is attributed either to the absence of accumulated errors, as seen in the BK method, or to the heightened sensitivity of helium (He) pressure to volume changes at the mission's outset, as observed in the PVT method. Conversely, gauging methods like thermal, which may exhibit lower accuracy at the mission's outset, tend to become highly accurate towards the end of the spacecraft's mission life [12-14].

The objective of this paper is to spotlight the bookkeeping method as a primary approach for estimating the remaining propellant in Geostationary Earth Orbit (GEO) satellites operating in the blowdown mode. The paper emphasizes the significance of this method in accurately calculating and managing the propellant levels throughout the mission life cycle, particularly in the context of GEO satellites utilizing the blowdown operational mode.

II. Satellite propulsion subsystem

A GEO (Geostationary Earth Orbit) satellite platform, as shown in Figure 1, refers to satellites positioned in geostationary orbit, approximately 35,786 kilometers above the eqator. These satellites appear stationary relative to a fixed point on Earth, making them ideal for continuous communication, weather monitoring, and broadcasting. Their fixed position enables stable coverage over a large area, facilitating applications like television broadcasting, internet services, and long-distance communication. GEO satellites are also utilized for weather observation, navigation, surveillance, and limited Earth observation. Despite advantages, they have limitations like higher latency and limited coverage at high latitudes, and different orbits may be preferred for specific applications.

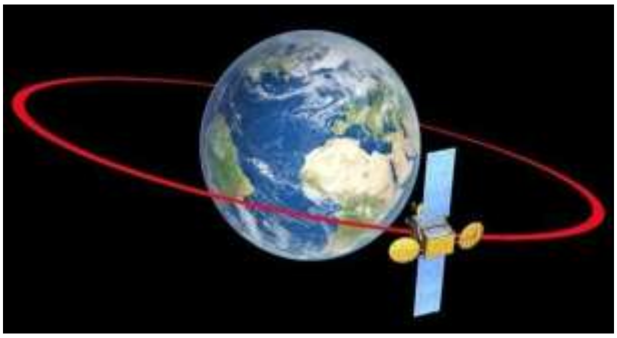

Figure 1. GEO satellite platform

The most GEO satellite platform is equipped with a Chemical Propulsion System using bipropellant MMH-NTO for its propulsion systems, is a regulated bipropellant propulsion system for transfer orbit from GTO to GEO and blowdown mode during its life in GEO orbit. As example, Figure 2 represents the unified propulsion subsystem for a geostationary satellite.

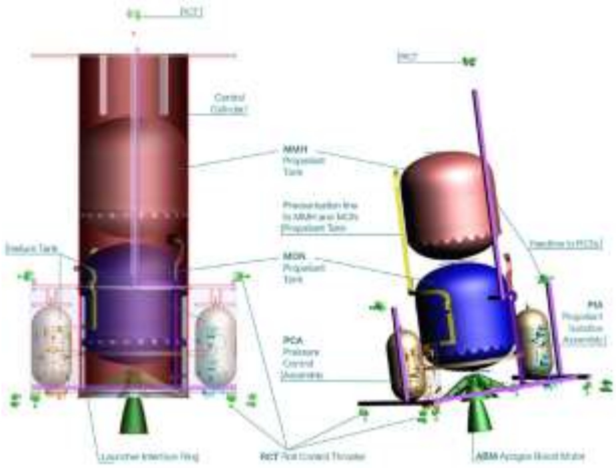

Figure 2. Unified propulsion subsystem

As Illustrated in the schematic diagram in Figure 3 [15], the UPS Generaly comprises two Gas Tanks (GT), which, following pressure reduction facilitated by a redundant dual-stage Pressure Regulator, pressurize the propellants (MMH and MON-3) stored in two identical surface tension Propellant Management Device (PMD) Liquid Tanks [16, 17]. These liquid tanks supply eight dual-seat Reaction Control Thrusters in two redundant branches (A and B), along with the Liquid Apogee Engine (LAE). Other components of the UPS are Normally Closed Pyrovalves, Normally Open Pyrovalves, Gas Filter, Liquid Filters, Pressure Transducers, Fill and Drain/Vent valves and Latching valves.

Each individual Reaction Control Thruster (RCT) will be securely mounted on a dedicated assembly, which includes a support bracket complete with essential adjusting devices. This assembly ensures the precise positioning and flexibility needed for optimal performance and maneuverability of each RCT during the satellite's operations in space.

The Liquid Apogee Engine (LAE) will be provided with a specialized mounting bracket specifically designed to interface seamlessly with both the spacecraft (S/C) structure and the heat shield. This ensures secure attachment and optimal integration of the engine within the overall spacecraft system, guaranteeing reliable performance during critical mission phases, including apogee maneuvers and orbital adjustments.

According to the block diagram shown in Figure 1, the propulsion subsystem can be divided in six main functional parts:

- The Helium supply.
- The Pressure regulation.
- The Propellant storage.
- The Propellant Distribution.
- The Thrusters and Engine.
- The electronics.

Typical mission operation for the propulsion subsystem are:

- Venting: the AOCS thrusters are opened to vent residual gas from the system downstream.
- Priming: to allow propellants to fill the fuel and oxidizer lines to the LAE and AOCS thrusters.
- Pressurization: initiating helium gas flow to pressurize the propellant tanks.
- LAE Firing. The LAE is fired in the pressure regulated mode. Before LAE firing, AOCS thrusters would be work a few seconds for propellant sinking in tanks.
- Beginning of Life. Following the last LAE firing, the LAE is isolated by closing the isolation pyro valves upstream of the engine. The AOCS thrusters are then operated in blowdown mode for the rest of the mission lifetime. And the pressuring part is also isolated by closing the isolation pyro valves upstream of the propellant tanks.

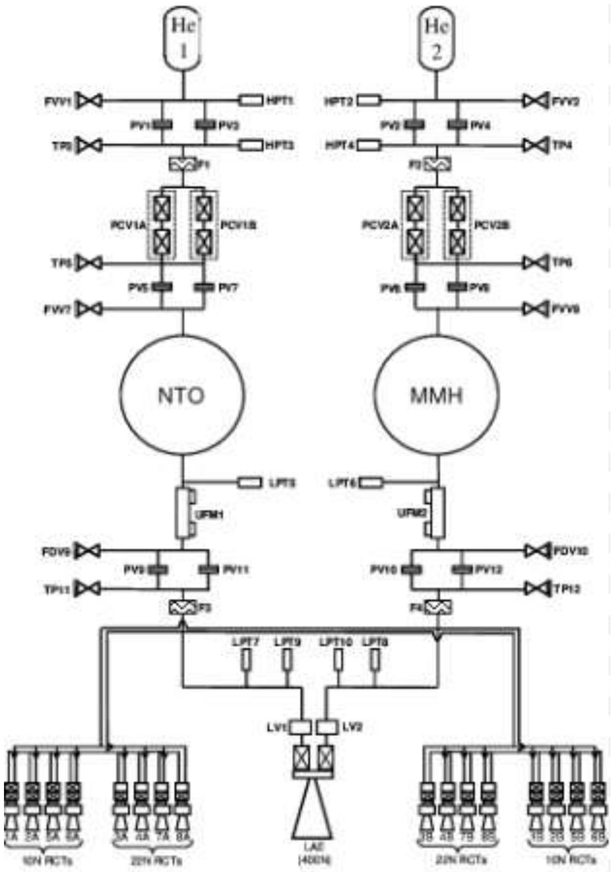

Figure 3. Propulsion subsystem scheme

III. Bookkeeping method

The book-keeping method, also called " dead reckoning methos"or "thrust usage accounting" rely directly on the thruster flow rate prediction also on factors like thrust, specific impulse, and propellant flow rate for each operation to calculate the propellant's usage [11]**.** This estimation method is effective in determining propellant consumption by meticulously accounting for both the Liquid Apogee Engine (LAE) and thruster firings. The approach involves the computation of the mass consumed by each thruster. However, the method used is different during the apogee engine firing and the station keeping. The accounting method necessitates thorough records of every propulsion system operation to accurately gauge the propellant utilized within a satellite. For employ this method effectively, maintaining a comprehensive record of all propulsion system activities, both routine and irregular, throughout the mission is essential [16, 17]. These records serve as the groundwork for assessing propellant consumption during orbital adjustments involving the propulsion system. The consumed quantity is subsequently subtracted from the initially calculated fuel volume to determine the remaining fuel. Nevertheless, due to the cumulative nature of summing up fuel consumption over the mission's duration, inaccuracies in the calculation of fuel usage may accrue over time. The prediction of fuel consumption during particular maneuvers requires the integration of variables such as thrust, specific impulse, and a synthesis of remotely sensed data, in conjunction with an analytical model representing fuel consumption. The book-keeping method, while effective, does have limitations. It doesn't allow for the determination of propellant load for individual tanks in a multibank configuration when tanks are interconnected. In several satellite configurations, the propulsion system comprises multiple connected propellant tanks, typically organized as pairs [18]. The bookkeeping method provides the total propellant quantity in a pair but cannot forecast how the propellant is distributed between the tanks.

This section presents the mathematical argument for the thrust and specific impulse curves method of computing the propellant consumed from a tank during specifc time interval

$$F = C_0 + C_1 * P - C_2 * P^2 [\frac{T}{T_{ref}}]^{C_3 + C_4 * P} \quad (1)$$

$$I_{sp} = d_0 + d_1 * P - d_2 * P^2 [\frac{T}{T_{ref}}]^{d_3 + d_4 * P} \quad (2)$$

F: Thrust.

T_{ref} : inlet propellant temperature at which the data were taken

$I_{sp:}$ Specific impulse.

P : Propellant tank pressure.

T : Initial propellant temperature

$C_{0,}$ C_1 , C_2, C_3 ,C_4 : Thrust polynomial coefficient.

-d_0, d_1, d_2, d_3, d_4 : I_{sp} polynomial coefficient.

If T and T_{ref} are equal, then thrust and I_{SP} are function of tank pressure

Given thrust and I_{sp} the propellant flow rate is easily determined

$$\dot{\omega} = \frac{F}{I_{sp}} \quad (3)$$

Where $\dot{\omega}$ is the propellant flow rate.

The propellant mass escarping the tank can be determined by the following formula:

$$\dot{m} = \int_{t_0}^{t_1} \dot{\omega}\ dt \quad (4)$$

-dt: time period

The propellant mass can be also expressed by as follow:

$$\dot{m} = \int_{t_0}^{t_1} \frac{\int_{P_0}^{P_1} \frac{\int_{T_0}^{T_1} \dot{\omega}\ dT}{T_1 - T_0}}{P_1 - P_0}\ dt \quad (5)$$

$P_{0:}$ Tank pressure at t0.

P_1: Tank pressure at t1.

T_0: Temperature at t0.

T_1: Temperature at t1.

The density of oxidizer and fuel are:

$$\rho_{fuel} = 876 - 0.17 \times T_{fuel} \quad (6)$$

$$\rho_{oxidizer} = 1632 - 0.56 \times T_{oxidizer} \quad (7)$$

The mixture ration is

$$mixture\ ratio = \frac{m_{Oxidizer}}{m_{fuel}} \quad (8)$$

IV. Developed tool for bookkeeping method

Based on the aforementioned methods Book-keeping, an applications tools have been developed to calculate the remaining propellant in tanks during in its geostationary orbit considering the bipropellant propulsion system (Hydrazine and Nitrogen tetroxide) equipped with: pressuring tanks and two propellant tanks one for fuel the other for oxidizer, thrusters and feeding systems equipped with valves ressure transducer, filters and pipes. The propulsion subsystem is working during the life time in blowdown mode. This application has its own input parameters for the book-keeping.

From operator

-The thruster branch A/B.

-Tank pressures.

From manoeuvers

-The type of maneuver: South-East-West.

-Manoeuvre duration: Start and end date.

From telemetry:

-The actuation duration of all thrusters used in the manoeuvers.

-The number of actuations of all thrusters.

These parameters are Thrusters working time, pressure tank, initial mass flow rate oxidizer and fuel density, thruster’s mixture ratio. The Figure 4 shows interface of developed tools.

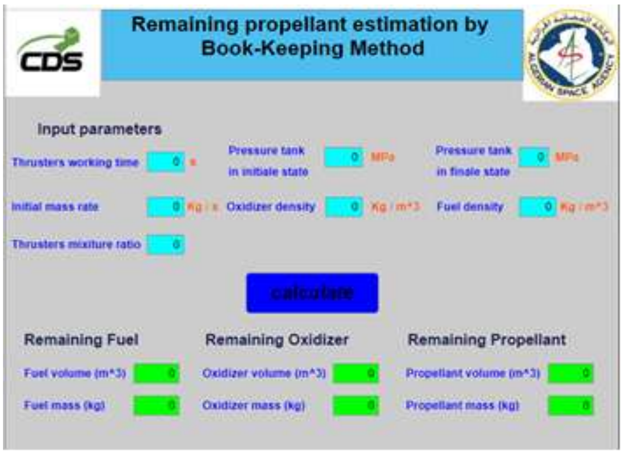

Figure 4. Developed tool for book-keeping method

V. Application example for Book-keeping method

In this dedicated part, we employ the book-keeping method to estimate consumed propellant, utilizing a specialized tool developed in the MATLAB environment. The focus is on calculating remaining propellant, with key input parameters detailed in the table. Oxidizer (MON-1) and fuel (MMH) densities are specified at 875 kg/m³ and 1450 kg/m³, respectively, and the tank volume is set at 1707 liters. The precision of our calculations is ensured through the integration of advanced MATLAB tools, showcasing our commitment to accuracy and innovation in satellite propulsion estimation.

Within Table 1, we strategically aggregate the known input data essential for our estimation endeavors. This organized compilation sets the stage for a systematic and comprehensive analysis. In instances where a maneuver is well-documented, our sophisticated software seamlessly harnesses this wealth of information to effortlessly compute crucial parameters. Among these computations, the software excels at estimating the volume and mass of the fully consumed propellant, offering a glimpse into the intricacies of the maneuver as shown in Table 2.

This streamlined process not only enhances efficiency but also showcases the adaptability of our software in extracting valuable insights from established data, thereby contributing to a more nuanced understanding of propellant dynamics during specific maneuvers.

Table 1. Bookkeeping input parameters

Input parameters	Oxidizer	Fuel
Pressure tank initial (MPa)	1.3922	1.3951
Pressure tank final (MPa)	1.4000	1.4100
Thrusters working time (s)	55.71	55.71
Thrusters mixture ratio	1.68	1.68

Table 2. Bookkeeping output parameters

Output parameters	
Fuel volume	0.0014 m^3
Oxidize volume	.0039 m^3
Propellant volume	0.0054 m^3
Fuel mass	2.074 kg
Oxidizer mass	3.408 kg
Propellant mass	5.558 kg

VI. Conclusion

This study explores the remaining propellant estimation technique known as the bookkeeping method, specifically applying it to communication satellites. The bookkeeping method facilitates the estimation of the remaining propellant, allowing for the determination of both fuel and oxidizer separately. Unlike other methods, it provides a comprehensive assessment of the entire remaining propellant in the initial step. The literature supports the view that the bookkeeping method is most suitable for application during the beginning of the satellite's life phase.

The tool developed in this study can be seamlessly integrated into the suite of tools utilized in the mission processes and data analysis of geostationary satellites. This integration enhances the overall capabilities of tools used in managing and analyzing data for geostationary satellite missions.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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