Propellant Endurance Prognosis for GEO Operations

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For satellites in Geostationary Earth Orbit (GEO) the available propellant mass leads to a limited yet predictable operational life span. Already in an early phase during routine operations the question arises whether the remaining propellant is sufficient to fulfill the expected operational lifetime. Especially towards the end of operational life the remaining propellant mass is the driving factor for deciding when to re-orbit the satellite to the graveyard orbit. Therefore, at any time during mission operations, a statement about the expected durability of the remaining propellant mass is desired. A simple extrapolation of retrospective propellant mass data is insufficient since the mass consumption is affected. Three impacts that severely influence the propellant consumption are identified. The major impact on the satellite is the sequential consumption of the propellant mass seen over the whole satellite lifetime. With diminishing satellite mass the amount of propellant needed to create a specific velocity increment, is decreasing. As an effect of the sequential propellant mass reduction the propellant pressures drop over the long term, which represents the second major impact. Therefore, an increasing amount of propellant is needed to create a specific velocity increment. The perturbations on the orbit due to the moon and the sun constitute the third impact on the satellite. As a consequence of these perturbations the propulsive requirements to keep the satellite in its operational box and the corresponding annual propellant consumption are inconstant. This paper presents a method of analyzing the retrospective propellant mass data taking into account the described impacts and their effects. The result of the method, which is called Propellant Endurance Prognosis (PEP), is a graph of the propellant mass drawn over the whole expected satellite lifetime. Finally, data from the PEP are compared with in-flight data from a GEO mission operated at the German Space Operations Center (GSOC).

Nomenclature

m	=	Mass
Δm	=	Mass difference between two masses, used for mass consumption in this paper
$\dot{m}$	=	Mass flow
p	=	Pressures
Δv	=	Velocity increment, also called delta-V
Isp	=	Specific impulse
η	=	Efficiency of specific impulse
t	=	Time
g_0	=	Gravitational acceleration at Earth's surface (~9.81 m/s²)
F	=	Thrust

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I. Introduction

For satellites in Geostationary Earth Orbit (GEO), one of the major factors restricting the lifetime of a satellite mission is the propellant. It is a balancing act between maximizing the lifetime with the amount of remaining propellant and conserving enough for finally reaching the graveyard orbit. In every phase during routine satellite operations it is very important to permanently evaluate the propellant mass on-board. Even with an accurate accounting of the propellant mass it is difficult to make a statement about the endurance of the remaining fuel and oxidizer. The main reason is that several factors have an influence on the prospective propellant usage. Consequently, a simple extrapolation of propellant mass data is insufficient. This is particularly unsatisfactory for determining whether the remaining propellant is enough to fulfill the expected satellite lifetime. Especially after unplanned thruster activities such as collision avoidance maneuvers or safemodes it is important to know about the endurance of the propellant.

In this paper, the authors describe a concept for analyzing the remaining propellant for further usage and for estimating the remaining lifetime of GEO satellites in their operational box. The concept is called Propellant Endurance Prognosis (PEP) and is not intended to replace conventional mass determination methods. It rather offers a possibility for interpreting the propellant mass data for prospective mass consumption.

For this paper, data from 1.2 years mission time was gathered from two almost identical satellites, based on the Spacebus 3000B2 platform with a bipropellant propulsion system. Both of them are operated at the German Space Operations Center (GSOC). In order not to transgress confidentiality, real in-flight data are only used for demonstrating nonconfidential information (e.g. Fig. 1). Confidential data are therefore modified in a realistic fashion in order to describe and illustrate the PEP in this paper.

II. Mass Consumption Behavior

The PEP is applied for creating a prognosis concerning the further usage of the remaining propellant mass which reflects the real consumption behavior of a satellite as accurately as possible. Therefore, it is necessary to identify the regular thruster activities with their corresponding mass consumption. The identification is done with data gathered during routine operations (in-flight data) from the GEO mission mentioned in section I and its results are presented in Fig. 1. It illustrates the breakdown of the mass consumption for the different thruster activities. One major statement is that Station Keeping Maneuvers (SKM) cause the main proportion of the total mass consumption. As explained in further detail in section III.A.1, the SKM occur in two different directions: as East/West SKM (EWM) and North/South SKM (NSM). Due to the design of the satellites that delivered data for this paper, the NSM are divided into two different delta-V types (cf. III.A): high delta-V and low delta-V (Fig. 1). Both NSM types account for 96% of the total consumption and consequently shape the PEP. Nevertheless, minor proportions, such as EWM (3%) as well as the attitude keeping activities (1%) are considered in the PEP. The percentage distribution of the mass consumption reflects the priority in which the mass consumptions are considered in the PEP. Unforeseen thruster activities such as collision avoidance maneuvers or safemodes are not included in the graphic. The influence of those events cannot be predicted since their occurrence and the corresponding mass consumption are different for every satellite.

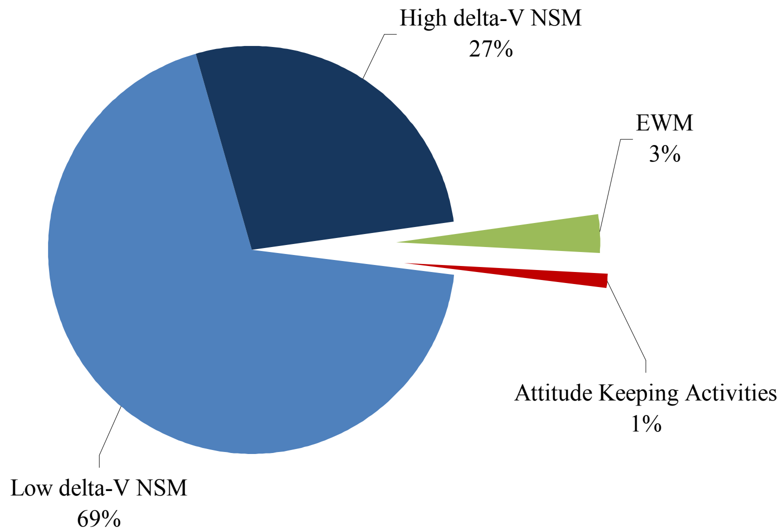

Figure 1. Percentage distribution of the mass consumption with respect to the different thruster activities.

III. Data sources

Data as input for the algorithm of the PEP are needed from several sources. Even though the data alone might be standard for regular GEO satellite operations, the merging of the data is the most important component of the PEP.

The following data sources and their outputs, which are the inputs for the PEP, are explained in the following sections in further detail.

A. SKM Simulation from Flight Dynamics

The main focus of the SKM simulation is to achieve a correct prediction of the total delta-V necessary for maintaining the orbit during the expected satellite lifetime. The SKM simulation is generated at the beginning of the satellite mission in order to optimize the SKM strategy (cf. III.A.2) and takes into account all known perturbations, statistical maneuver execution errors and cross-coupling effects due to the installation of the thrusters[1]. The satellite model used for the simulation mainly considers the average satellite mass and the satellite projection area towards the sun. Primarily, the simulation is independent of the satellite mass which only plays a role for the consideration of the secondary effect of the solar radiation pressure. It does not include effects such as the drop of propellant pressure and the sequential decrease of the satellite mass. The software for the simulation uses an optimal velocity increment per SKM to fulfill the annual delta-V. Due to the design of the satellite that delivered data for this paper, a fixed delta-V for NSM and a variable delta-V for EWM are used. During routine satellite operation activities the simulated annual delta-V from the SKM simulation is compared to the real performed annual delta-V in retrospect, in order to check the consistency of the simulation. Up to now the SKM simulation shows good accordance with the real performance of the satellites.

Input for the PEP:

- Annual delta-V and total delta-V
- Number of annual SKM cycles
- SKM cycle period and time intervals in-between EWM and NSM

1. *Orbit Perturbations and their Effects on the Orbit*

Every kind of perturbation has a different effect on the orbit. While the solar radiation pressure changes the eccentricity of the orbit, the asymmetry of the earth causes a longitude drift of the spacecraft. Due to their gravitational pull, the sun and moon leads to a drift in the inclination of the orbit.

SKM in two different directions are necessary to compensate all those effects: the EWM to maintain eccentricity and longitude[2] and the NSM to maintain the inclination[2]. The annual velocity increment needed for the EWM depends mainly on the longitude of the spacecraft, which determines the tangential acceleration that has to be compensated. The maximum delta-V for EWM is merely around 2 m/s per year[2]. For NSM the annual velocity increment is independent of the satellite position but varies over the time with a period of about 18.6 years, due to the rotation of the moon's ascending node[2]. The resulting annual velocity increment is approximately varying between a minimum of 40 m/s and a maximum of 51 m/s per year[2]. The oscillation of the annual delta-V for NSM has an important consequence for the PEP which is explained in further detail in section IV.C. Figure 2 illustrates a plot of the oscillating annual delta-V for NSM and the total accumulated delta-V plotted over the whole mission time. The curve of the annual delta-V has its shape due to the chosen SKM strategy. The dashed line in Fig. 2 is the linear interpolation of the accumulated delta-V. It illustrates the oscillation of the accumulated delta-V due to the inconstant annual delta-V.

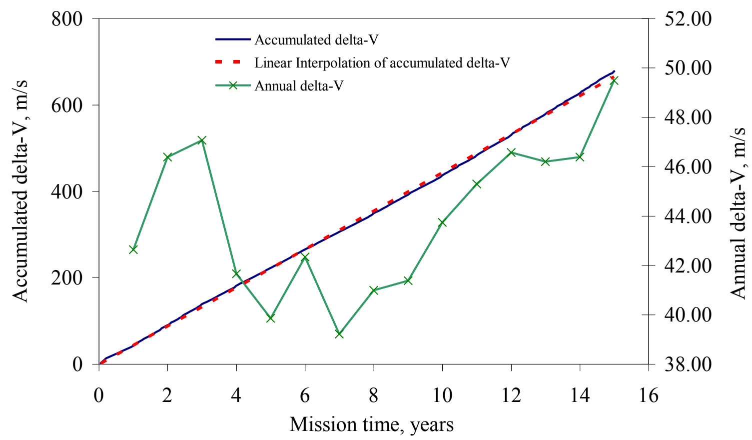

Figure 2. Accumulated delta-V compared with the annual delta-V. The variation of the accumulated delta-V is visible in comparison to the linear interpolation of the accumulated delta-V.

2. *SKM Strategy*

How often SKM are necessary and how many SKM are used for compensating the perturbations, depends mainly on the SKM strategy: a set of NSM and EWM, is defined as a SKM cycle, which occurs in regular time periods (SKM cycle period). In every cycle the time interval between each EWM and each NSM is constant. A strategy with one or two EWM and one single NSM per cycle with a period of 7 or 14 days is common. The longitude drift rate and the eccentricity cannot be controlled independently from each other with just one EWM for each SKM cycle. This is only possible with two or more EWM. However, it is always possible to control the inclination with one single NSM per cycle.

Both satellites that delivered data for this paper have a relatively small ratio of the satellite mass and the projection area towards the sun. Hence, the effects of the perturbations on the orbit's eccentricity are only small. The SKM simulation shows the feasibility of implementing one EWM and one NSM for each cycle over a period of 21 days. The main intention of this strategy is the control of the longitude, whereas the eccentricity is controlled parasitically. This means that the eccentricity is controlled only by shifting the execution time of the EWM within certain limits, whereas the delta-V is determined by the longitude control requirement. Even though this strategy equals 17.4 cycles per year, just integer cycles can be performed per year. This equals for every first and second year 17 cycles and for every third year 18 cycles.

The SKM strategy is important for the PEP since it delivers the framework for the PEP algorithm (cf. IV.C). The strategy consists of the number of NSM and EWM, the number of cycles and their SKM cycle period.

B. Data Record as output from Mass Determination

During mission operations any consumption of the propellant mass due to thruster activities is logged into a data record. In this paper the term "mass log" is used for this data record. It is possible to create such a mass log with the three common mass determination methods:

- Bookkeeping method[5,7,8]
- Ideal gas method (PVT)[5,7,8]
- Thermal propellant gauging technique (TPGT)[7,8]

The different mass determination methods are not described in this paper and are just listed for the sake of completeness. Due to the experience with the application of the bookkeeping at GSOC, the parameters stated in Table 1 have been identified as input and output of the bookkeeping method. Consequently, these parameters have to be logged in the mass log. The availability of these data allows further analysis to review the consumption behavior per thruster activity. The real performed delta-V (Δv_{SKM}) determined by the use of angle and ranging tracking data are attributed to the corresponding entries in the mass log. This attribution of parameters allows the computation of the effective and the ideal *Isp*. Also the efficiency (η) of the *Isp* (cf. IV.B and Eq. (8)), which depends on the SKM direction[5] and the delta-V type[5], can be calculated from the ideal and real *Isp*. The propellant masses stated in the mass log constitute the retrospective data part of the propellant mass curve of the PEP (cf. IV).

Table 1. Overview of parameters in mass log.

Parameter	Description
$m_{s/c}$	Satellite mass
m_{ox}, m_{fu} , m_{total}	Propellant masses
Δm_{ox}, Δm_{fu} , Δm_{total}	Mass consumptions of propellant
p_{ox}, p_{fu} ,$p_{Average}$	Propellant pressures (from telemetry)
t_0 and $\Delta t_{Duration}$	Sample time and duration

Input for the PEP:

- Latest satellite and propellant mass (cf. IV.A)
- Mass consumption due to attitude control, which is linearly extrapolated (cf. IV.A)
- Effectiveness of the *Isp* if not supplied by the manufacturer (cf. IV.B)
- The function pressure over time $\left(p = f\left(t\right)\right)$ if information is not available from the manufacturer (cf. IV.B)

C. Propulsion System Specific Data from Manufacturer

Driven by requirements of the satellite customer the expected lifetime is defined as one of the major factors influencing the satellite design. Directly influenced by that is the design of the propulsion system and the amount of fueled propellant. The propellant usage simulated by the manufacturer is stated in a propellant budget[6]. It proves the sufficiency of the fueled propellant to keep the satellite on its dedicated orbit. Other important information used as input for the PEP is the amount of the nonusable propellant[6]. Due to the design of the propulsion system, this proportion of propellant resides[6] in the tanks, pipes and auxiliary equipment after the contemplated end of life (EOL). This number of propellant is also considered for the lifetime estimation by the PEP. The manufacturer can provide an analysis of the pressure and the *Isp* regarding time. Since the information about pressure and *Isp* is not available for the mission at GSOC, an alternative for the PEP is explained in section IV.B.

Input for the PEP:

- Expected satellite lifetime
- Residual propellant mass
- Pressure and *Isp* pattern regarding time or thruster specific parameters and pressure box
- (Propellant budget, not necessary but useful as reference for comparison)

IV. Approach of the PEP

The PEP is a method to simulate prospective mass consumption data in order to make a statement about the remaining satellite lifetime. For the simulation of a realistic mass consumption behavior with the help of the PEP, the major impacts influencing the propellant consumption over the whole expected satellite lifetime have to be identified. The three identified influences and their induced impacts on the PEP algorithm are illustrated in Fig. 3. The impacts and their effects are explained in the following sections in further detail.

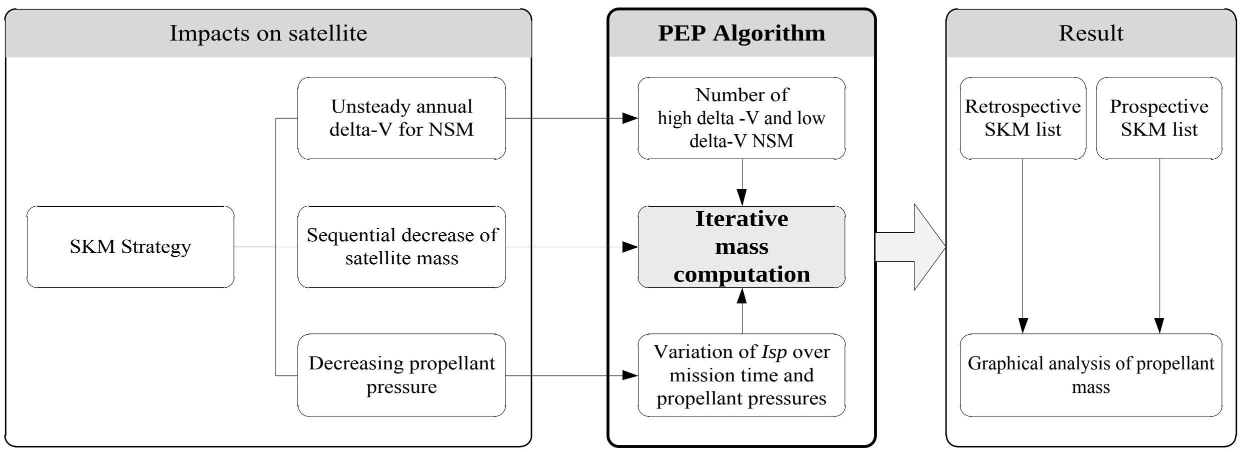

Figure 3. Processes related to the PEP split into three main groups. Each impact on the satellite leads to a specific computational algorithm. The prospective SKM lists, together with the retrospective SKM list from the mass log, allow a graphical analysis of the propellant mass.

As illustrated in Fig. 3, the sequential mass reduction leads to an iterative mass computation. The major framework for the iteration process stems from the SKM strategy which states the number of SKM per year, the SKM cycle period and the annual delta-V and total delta-V. The variations of the annual velocity increment leads to the number of low and high delta-V SKM per year. One effect of the diminishing propellant mass is that the propellant pressures drop. In the PEP algorithm this effect is considered with a variable *Isp* that depends on the pressure and consequently on the mission time. Since every iteration step equals one SKM, the *Isp* is computed accordingly for every SKM (cf. IV.B). This is only possible due to the fact that the SKM are scheduled. The PEP algorithm leads to a list of SKM which allows a graphical analysis. The retrospective SKM data are not part of the PEP algorithm itself and derive from data in the mass log. The PEP algorithm basically delivers the prospective data as stated in Table 2.

To illustrate both lists, the propellant masses from retrospective and prospective SKM are drawn versus the mission time (Fig. 4). This graph allows the interpretation of the endurance of the remaining propellant at any time during the running mission. In Fig. 4, three boundary masses are plotted parallel to the time axis. The lowest of these parallel lines is based on the propellant

Table 2. Example of prospective SKM list.

Date	Maneuver Type	DV	S/C Mass	Propellant	Isp	Consumption
---	---	m/s	kg	kg	s	kg
12/04/2020	NSM - low delta-V	2.10	1198.27	217.13	265.64	0.97
12/06/2020	EWM	0.09	1198.23	217.08	250.03	0.04
12/25/2020	NSM - high delta-V	3.90	1196.44	215.29	265.62	1.79
12/27/2020	EWM	0.09	1196.40	215.25	250.01	0.04
01/22/2021	NSM - high delta-V	3.90	1194.61	213.46	265.60	1.79
01/24/2021	EWM	0.09	1194.56	213.41	250.00	0.04
12/02/2021	NSM - low delta-V	2.10	1193.60	212.45	265.59	0.96

that remains due to the design of the propulsion system. When the curve of the propellant mass crosses the residual mass line, the EOL is reached and the satellite should already be in the graveyard orbit. The propellant mass necessary to re-orbit to the graveyard orbit either stems from the manufacturer or can be calculated if the delta-V, necessary for re-orbiting, is known. The line, corresponding to the re-orbit mass consumption, is also plotted in Fig. 4 parallel to the time axis. Wherever the propellant mass line crosses the re-orbit line the satellite should begin the re-orbiting process. For some missions a station repositioning might be not scheduled but expected. In this case the corresponding mass consumption can also be drawn parallel to the time axis. As soon as the station repositioning is performed the PEP should be updated with the most current data from the mass determination.

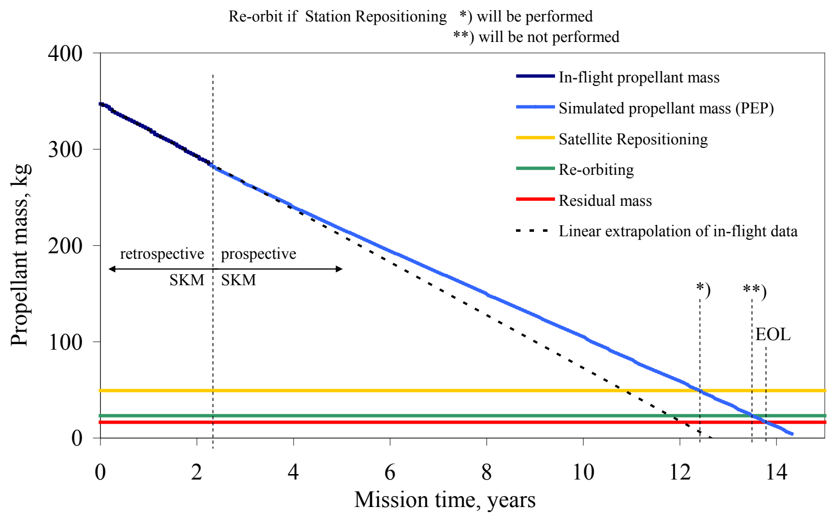

Figure 4. Graphical analysis as output of the PEP. It shows the curve of remaining propellant mass and its mass boundaries.

A. Iterative Computation Algorithm due to the Decrease of the Satellite Mass

The reduction of the satellite mass over time infers that the energy necessary for producing a specific velocity increment decreases. Consequently, the mass consumption corresponding to the velocity increment decreases with elapsing mission time. This effect is reproduced in the PEP as an iterative computation algorithm in order to simulate the sequential use of propellant. The number of iteration steps in the algorithm complies with the number of SKM that still have to be performed until EOL. The expected satellite lifetime together with the number of already performed SKM leads to the number of pending SKM.

Figure 5 illustrates the iterative process with a decision ("All pending SKM computed?") and two backward loops ("Next SKM"). Every iteration step represents a SKM and is supposed to take place at a specified date. The initial date is taken from the last SKM entry in the mass log. Every consecutive iteration step is computed according to the SKM strategy and is attributed to the corresponding iteration step. The date of a SKM is used for computing the effective *Isp* (cf. IV.B). The algorithm of the iterative mass computation illustrated in Fig. 5 is mainly based on the known ideal rocket equation by Tsiolkovsky[4,5] as stated in Eq.(1):

$$\Delta m_{SKM} = m_{s/c,inbound} \cdot \left[1 - exp\left(\Delta v_{SKM} / \left(g_0 \cdot Isp_{eff} \right) \right) \right] \tag{1}$$

To be able to compute the mass consumption (Δm_{SKM}) per iteration step, the initial inbound satellite mass ($\Delta m_{s/c,inbound}$) ,the delta-V (Δv_{SKM}) and the effective *Isp* (Isp_{eff}) of the initial SKM is needed (Fig. 5). The satellite mass and the SKM direction are taken from the last SKM entry in the mass log. The initial inbound satellite mass equals the mass from the mass log. According to the SKM strategy the initial SKM direction is the one that consecutively follows the last performed SKM. Hence, the PEP starts with the last known situation of the satellite. Similar to the GEO satellite mission at GSOC, the delta-V for each iteration step is constant and depends on the SKM-direction and delta-V type. The only difference between real mission and PEP is that the PEP uses for EWM a constant delta-V. Its impact on the validity of the PEP is considered to be minor due to the small proportion in the consumption behavior (Fig. 1). The effective *Isp* depends on the SKM type and the average propellant pressures that appear at the date the SKM (cf. IV.B). Beside the mass consumption of the SKM, the consumption due to attitude keeping activities are also considered in Eq. (2):

$$\Delta m_{att,dis} = \Delta m_{att,perf} \cdot \left(\Delta t_{lifetime} / \Delta t_{perf} - 1 \right) \cdot \left(1/n_{SKM} \right) = const. \tag{2}$$

According to the consumption behavior illustrated in Fig. 1, the mass consumption due to attitude keeping has merely a small effect on the satellite lifetime. Therefore a linear extrapolation Eq. (2) from data stated in the mass log over the whole expected satellite lifetime is assumed to be sufficient for the consideration of the attitude keeping in the PEP. The extrapolation is based on the sum of all mass consumption due to attitude keeping activities ($\Delta m_{att,perf}$) that occurred since the begin of life (BOL). Both, the mass consumption and the corresponding mission elapsed time (Δt_{perf}) are stated in the mass log. Beside these two parameters, the expected lifetime ($\Delta t_{lifetime}$) and the number of remaining SKM (n_{SKM}) are also needed as input for Eq. (2). The result is the mass consumption from attitude keeping distributed over the number of remaining SKM ($\Delta m_{att,dis}$). In reality, the main attitude keeping activities, for instance wheel unloads, occur in-between the SKM and their mass consumption alternate due to diverse influences. For the PEP these mass consumptions in-between the SKM are constant over the whole lifetime and equal the average mass consumption due to attitude keeping activities. For each iteration step one SKM (Δm_{SKM}) and one average attitude keeping activity ($\Delta m_{att,dis}$) occurs. Therefore the corresponding mass consumption is subtracted from the inbound satellite mass ($m_{s/c,inbound}$):

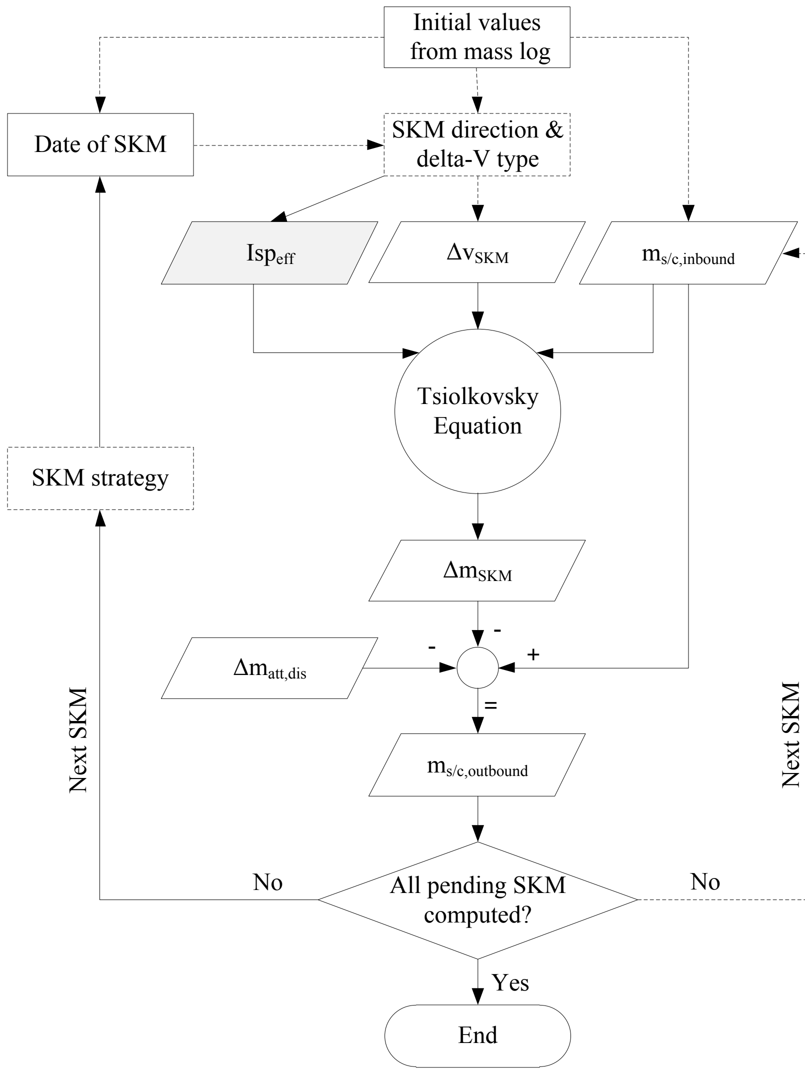

Figure 5. Process flow of the iterative mass computation as centerpiece of the PEP. The time dependent effective *Isp* is not illustrated and is separately explained in IV.B.

$$m_{s/c,outbound} = m_{s/c,inbound} - \Delta m_{SKM} - \Delta m_{att,dis} \quad (3)$$

The result of Eq. (3) is the outbound mass ($m_{s/c,\ outbound}$) of the computation step. Due to the iterative computation algorithm, the outbound satellite mass equals the inbound satellite mass for the next iteration step. As soon as all pending SKM are computed, the list of all prospective SKM is available (Table 2).

B. Consideration of the Propellant Pressures Drop and the *Isp*

For the iterative mass computation, the effective *Isp* is the only pressure dependent input parameter in Eq. (1). Figure 6 illustrates the process of retrieving the *Isp* from the average propellant pressures that in turn are depending on the date of the SKM. Each iteration step equals one SKM with a corresponding date why the indirect time dependency of the *Isp* is the goal of this section. Since the manufacturer does not always supplies the necessary corresponding data an alternative must be found. This alternative is described in the following paragraphs in further detail.

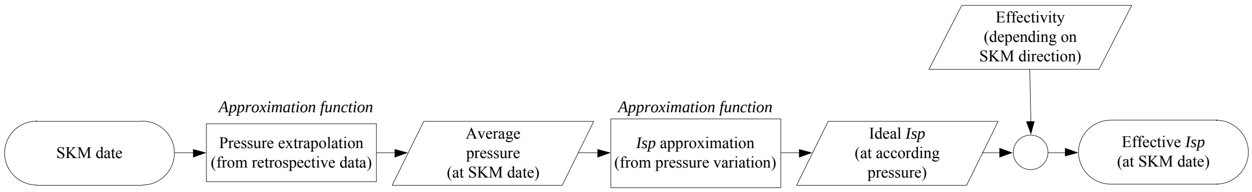

Figure 6. Process of transforming a maneuver time into the effective *Isp*. The ideal *Isp* is calculated with the time dependency of the propellant pressures and the pressure dependency of the ideal *Isp*.

1. Time Dependency of the Propellant Pressures

The drop of oxidizer (*ox*) and fuel tank pressures ($p_{ox,}$ p_{fuel}) originate from the decrease of the propellant mass. Since the conditions in the thrusters' combustion chambers are affected by the pressure drop, the use of the propellant becomes less effective with elapsing mission time. Short term variations of the pressures can be balanced by the tank heaters. However, in the long term, the pressure drop is tangible and therefore has an effect on the usage of the propellant. Consequently, the propellant pressures vary from BOL to EOL.

To ease the consideration of the pressure drop in the PEP, merely the average of the oxidizer and fuel pressure is considered. The pressure box defines the area in which the oxidizer and fuel pressures may reside in order to keep the propulsion system operational. Therefore differences between oxidizer and fuel pressure are within certain limits. Hence, the time dependent propellant pressures can be approximated with only one function for the average pressures of oxidizer and fuel. The pressure data for the extrapolation are gathered either from telemetry data or effectively from the mass log. Constraints such as the minimum propellant pressure for the extrapolation are defined by the nature of the pressure box.

The available pressures from the telemetry are described with an exponential approximation function which is then extrapolated according to the minimum pressure from the pressure box. The approximation curve and the real values from the mass log are illustrated in Fig. 7. This function is adapted with increasing availability of sample sources.

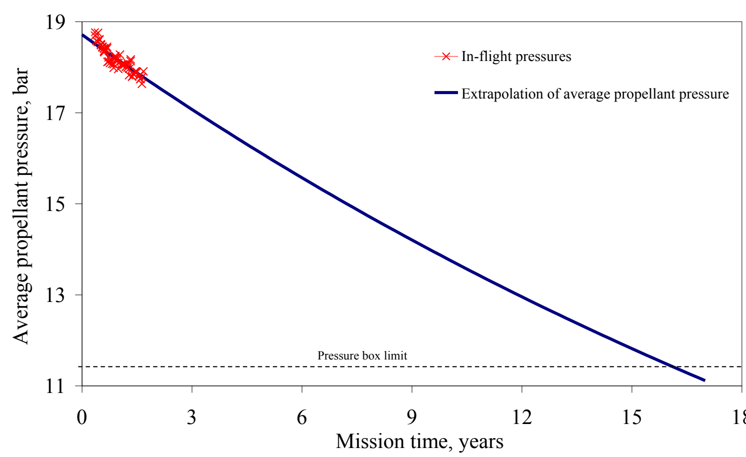

Figure 7. Exponential extrapolation of propellant pressures based on in-flight data.

2. Pressure Dependency of the Isp

To find the pressure dependency of the *Isp,* specific propulsion system data such as thruster specific coefficients (c_i, d_i, e_i)[5] are necessary. The pressure dependency of the oxidizer and fuel mass flow ($\dot{m}_{ox,ssf}$,$\dot{m}_{fuel,ssf}$) for steady state firing (*ssf*) is based on a polynomial approximation[5] with the thruster specific coefficients as constants (Eq. (4)-(5)). Consequently, the steady state thrust ($F_{0,ssf}$) can be computed with the thruster specific coefficients and the propellant mass flows (Eq. (6)):

$$\dot{m}_{ox,ssf} = f\left(c_i , p_{ox}, p_{fuel}\right) \tag{4}$$

$$\dot{m}_{fuel,ssf} = f\left(d_i , p_{ox}, p_{fuel}\right) \tag{5}$$

$$F_{0,ssf} = f\left(e_i , \dot{m}_{ox,ssf} , \dot{m}_{fuel,ssf}\right) \tag{6}$$

With the calculated steady state mass flow and the corresponding thrust from Eq. (4)-(6), the ideal *Isp* (Isp_{ideal}) can be calculated with Eq. (7):

$$Isp_{ideal} = F_{0,SSF} \Big/ \left[\left(\dot{m}_{ox,ssf} + \dot{m}_{fuel,ssf} \right) g_0 \right] \tag{7}$$

Reality shows that the oxidizer and fuel pressures are alternating which can be reflected with Eq. (7) that indirectly depends on the propellant pressures. In order to find a function $Isp_{ideal} = f(p_{propellant})$ at first a variation of the pressures has to be done. The oxidizer pressures are varied in 0.1 bar steps from the minimum to the maximum pressure possible in the pressure box. For the variation, the fuel pressure is varied ± 1 bar from the oxidizer pressure. The result is a set of curves that constitute the different oxidizer and fuel pressure combinations (Fig. 8). A second degree polynomial approximation of the set of curves is used to find one single function for the pressure dependency of the *Isp*. The ideal *Isp* delivered by Eq. (7) does not contain the loss of efficiency due to pulse mode firing which itself depends on the SKM direction and delta-V type. The effective *Isp* is deduced with the efficiency (η) from the ideal *Isp* and is calculated according to the following equation:

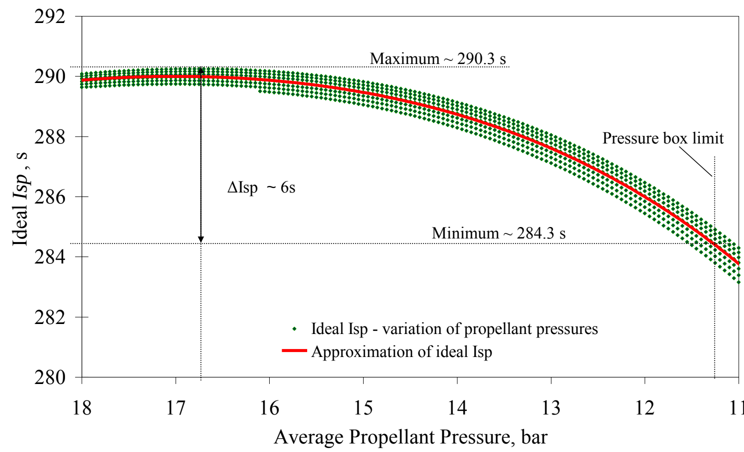

Figure 8. Polynomial approximation curve of ideal *Isp*. Derived by calculating the *Isp* with varying propellant pressures as input.

$$Isp_{eff} = \eta \cdot Isp_{ideal} \tag{8}$$

Since the different pulse firing modes are not supposed to change over the time, the efficiency should as well remain constant. The efficiency is either given by manufacturer specifications, or it is manually calculated from the data stated in the mass log. In summary it can be stated that for each iteration step, the effective *Isp* depends on the SKM date, and the efficiency in turn depends on to the SKM direction and velocity type.

C. Variation of Annual Delta-V for NSM

The magnitude of the delta-V for each NSM must be adapted in order to fulfill the unsteady annual delta-V (cf. III.A.1). The satellites that delivered data for this paper are operated with constant magnitudes for NSM. However, the availability of the two velocity types (high delta-V and low delta-V) still allows complying with the annual delta-V. Hence, the adaption to the annual delta-V happens with the quantity of the two different delta-V types according to Eq. (9). The number of SKM cycles per year ($n_{SKM\ cycles}$) equals the number of NSM per year (n_{NSM}) due to the fact that one NSM per SKM cycle is sufficient to control the inclination. The number of low delta-V NSM ($n_{NSM\ low\ delta\text{-}V}$) and the number of high delta-V NSM ($n_{NSM\ high\ delta\text{-}V}$) may vary but the sum of both must be equal to the number of SKM cycles per year. The annual adaption of high and low delta-V NSM has to be done before the start of the mass computation process. If the high delta-V NSM are scheduled in real satellite operations, their distribution in the PEP over the

Table 3. Annual delta-V, number of high delta-V SKM and cycles per year during mission time.

Mission Year	Annual delta-V, m/s	Annual SKM Cycles	Number of high delta-V SKM
1	42.63	17	2
2	46.38	17	4
3	47.07	18	3
4	41.65	17	1
5	39.86	17	0
6	42.34	18	0
7	39.21	17	0
8	40.99	17	1
9	41.38	18	0
10	43.74	17	2
11	45.29	17	3
12	46.57	18	2
13	46.20	17	4
14	46.38	17	4
15	49.49	18	4

year happens according to schedule. If no schedule is available the high delta-V NSM are equally distributed over the year. Due to the variation of the high delta-V NSM, the corresponding propellant consumption also alternates among the mission years. An example of the adaption of the delta-V types is listed in Table 3.

$$n_{SKM\ cycles} = n_{NSM} = n_{NSM\ low\ delta\text{-}V} + n_{NSM\ high\ delta\text{-}V} \tag{9}$$

The iterative mass computation process can be controlled with two parameters. The first parameter is the delta-V accumulated over all iteration steps. The second parameter is the delta-V accumulated per year which is set to zero as soon as the SKM of the next year is computed. The accumulated annual delta-V can indicate if the numbers of high delta-V and low delta-V NSM were chosen correctly for the PEP. The accumulated total delta-V indicates if the whole iteration process is performed correctly.

V. Comparison of PEP and In-Flight Data

The PEP is in use for both GEO satellites at GSOC to check whether the propellant is still sufficient to fulfill the expected lifetime. After every update of the PEP, the latest results are compared with former results and with the most current data in the mass log. Up to now the comparisons show good consistency. However, small aberrations occur due to a shift of dates of the high delta-V NSM and due to the fact, that these SKM were not strictly scheduled. Furthermore, unforeseen thruster activities occurred in the meanwhile which also leads to smaller discrepancies.

For the PEP and for the in-flight data, the number of high delta-V NSM is in accordance, just their points in time are shifted. As a consequence, the differences between the in-flight and simulated propellant masses show fluctuations (Fig. 9 and Fig. 10). For a comparison real in-flight data were available for a time span of 1.2 years which equals around 21 SKM cycles.

Figure 9 shows the total propellant masses from in-flight data and PEP data plotted over the mission elapsed time. Even though a shift of different high delta-V NSM is apparent, both curves show good consistency. These fluctuations are pointed out in Fig. 10 which illustrates the mass differences between in-flight data from the mass log and simulated SKM from the PEP for eight different start dates with a time interval of 0.17 years (3 SKM cycles) in-between. The mass differences fluctuate around 0 kg, however, more sample data are necessary for a real statement. A long-

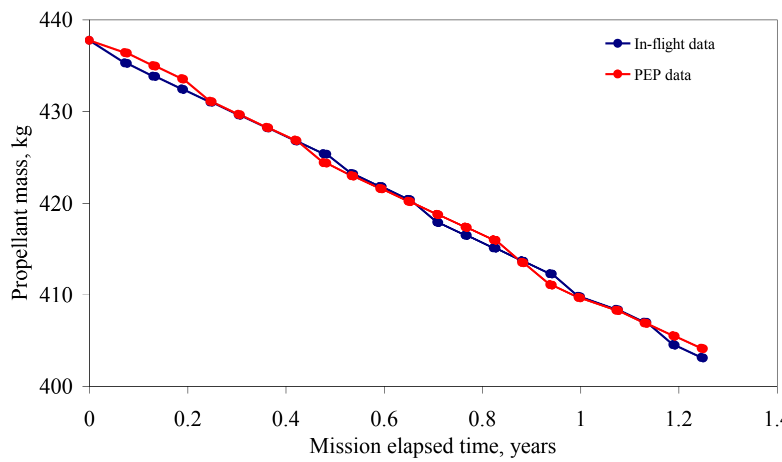

Figure 9. The total propellant masses from the PEP and in-flight data show the consistency of the PEP with small aberrations.

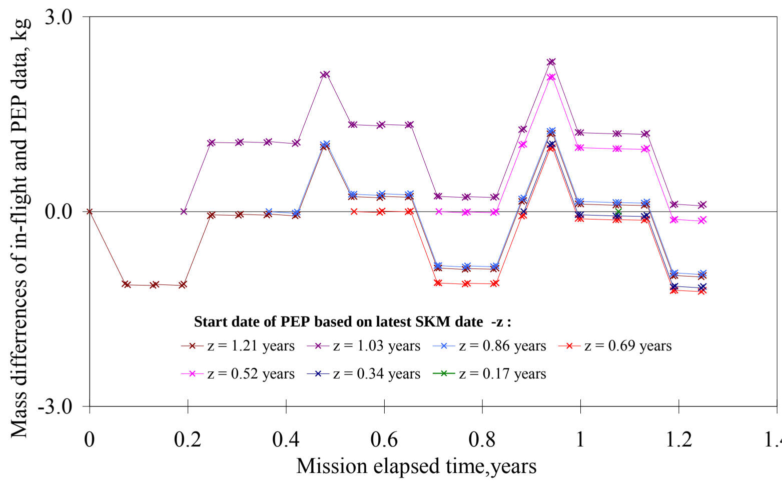

Figure 10. Differences between the propellant masses of PEP and in-flight data. The PEP data is based on seven different start dates.

term drift of the mass differences cannot be identified in Fig. 10. It is assumed that the oscillation of the mass differences vanishes as soon as the high delta-V NSM are scheduled equally for routine operations and the PEP. The space in-between the different curves occurs due to unforeseen thruster activities and the time shift of high delta-V NSM.

Figure 11 shows the propellant masses from all eight PEP drawn over the satellite lifetime of 15 years. All eight curves appear to be identical. However, as pointed out in Fig. 12, which as an enlargement of Fig. 11, the curves do not coincide perfectly. Due to the different starting values all curves have a certain offset to each other with a maximum divergence of 1.2 kg for around 560 iteration steps. A strong influence on the results has the occurrence of unplanned thruster activities and also the time shift of the high delta-V NSM dates.

The development of the propellant mass curves in Fig. 11 and Fig. 4 reflect the previously discussed influences. The iterative mass computation by Tsiolkovsky has the consequence that the curve has an exponential shape that becomes flatter with elapsed life time. This becomes apparent if the propellant mass curve is compared with the linear extrapolation of retrospective propellant mass data from the mass log (Fig. 4). The variation of the annual delta-V for NSM leads to a slight oscillation of the curve within the years. Finally, the slope of the curve is affected by the variable *Isp*.

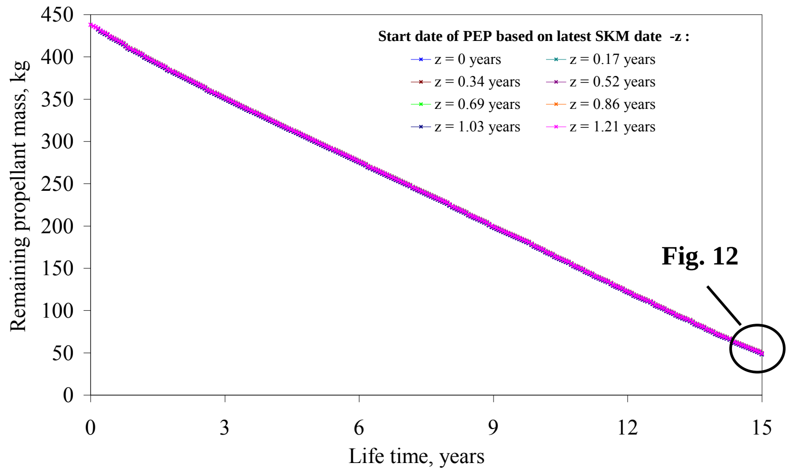

Figure 11. Propellant mass as graphical analysis from PEP data drawn over the lifetime. Eight different start dates were used to create data with the PEP over 560 iteration steps.

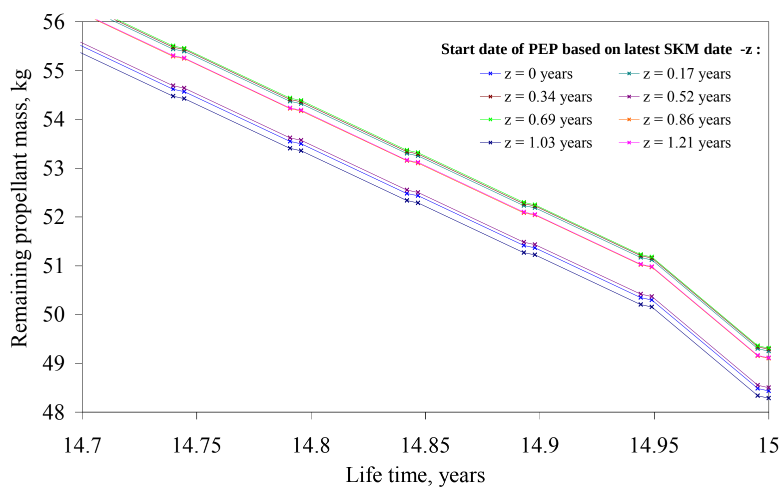

Figure 12. Propellant mass as output of the PEP plotted over the lifetime zoomed in to EOL.

VI. Conclusion

The graphical analysis of the propellant mass and its significance for the evaluation of the satellite lifetime is a useful help during satellite operations. If the in-flight data and the PEP data are consistent the application of the PEP allows the reconstruction of the information given in the manufacturer's propellant budget. Hence, the satellite operator has a better control of the propellant during routine operations. Discrepancies between PEP data and in-flight data indicate errors in the ground system or documentation. Assuming that the PEP algorithm was correctly implemented, errors might occur in the mass computation, SKM simulation, manufacturer's propellant budget or even in the execution of the SKM.

The PEP still has room for improvement, such as including the variation of the ratio of satellite mass and projection area within the mission years. For more accuracy the approximation functions for the ideal *Isp* and for the pressures is updated with increasing availability of in-flight data.

Up to now, for both satellites that delivered sample data for this paper, the comparison of the in-flight data with the PEP data show good results. However, the PEP could not be validated yet, since not enough in-flight data are available. With the elapsing mission time, the quantity of simulated data shrinks whereas the amount of available in-flight data increases. Therefore, the method is updated every six months to assure the actuality of the prognosis. Every update of the PEP implies the comparison of the in-flight data with older PEP data in order to verify its correctness (cf. V). The results are particularly interesting after unforeseen thruster activities. Even though the PEP allows a coarse statement about the satellite lifetime a detailed mass determination is still of high importance to keep control of the satellite mass especially towards EOL.

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