Total Fuel Management at EOL

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End–of-Life operations require careful long-term planning in order to meet conflicting requirements. On the one hand, the satellite operator wants to increase mission life, which requires maximum use of propellant. On the other hand, the operator has to make sure that the remaining propellant is enough to de-orbit a satellite in accordance with the internationally-established recommendation of 300 kilometers above geosynchronous orbit.

This paper discusses the strategy and planning for the extension of EOL operations for an LM3000 satellite that was de-orbited in summer 2007. The plan consisted of three phases. The first phase included monitoring of fuel level using a Propellant Gauging System (PGS) which has a high accuracy of propellant estimation at EOL and provides confidence that the satellite has a fuel load sufficient for de-orbiting. Propellant gauging tests were conducted regularly over a span of 3 years in order to pinpoint the exact time for de-orbiting. In the second phase, Active Propellant Management (APM) was employed to suppress daily fuel migration and to reduce the risk of accidental tank depletion at the end of the satellite mission life. The APM procedure was employed in order to fully utilize the remaining propellant. Thanks to the measures undertaken, the satellite life was extended for several years while being confident that the satellite still had enough fuel for de-orbiting. De-orbiting of the satellite constituted the third phase. It included several steps: E/W thruster calibration during orbit raising to 50 km; two pairs of orbit raising maneuvers to reach an altitude of 300 km; depletion maneuver to deplete the remaining fuel and execution of satellite shut-down procedure

Thanks to these activities, the satellite life was extended for several years and successfully de-orbited in accordance with international EOL requirements.

I. Introduction

Satellite End-of-Life(EOL) operations require careful long-term planning in order to meet conflicting requirements. On one the hand, a satellite operator wants to increase satellite mission life, which requires maximum use of propellant. On the other hand, the operator has to make sure that the remaining propellant is enough to de-orbit a satellite in accordance with the internationally-established recommendation of 300 kilometers above geosynchronous orbit.

Maximization of satellite life leads to increased revenue to the operator and to containing costs at the same time. Maximization does require some additional activity, which has its own cost. In this case, the benefits outweigh the costs.

The EOL planning should begin several years prior to de-orbiting. This paper demonstrates with the example of a LM (RCA heritage) 3000 satellite that careful, long-term planning of de-orbiting is required in order to maximize

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the life of a satellite and successfully de-orbit it while meeting all international recommendations for safe de-orbiting.

II. End-of-Life Satellite Management

The LM (RCA heritage) Series 3000 Spacecraft was launched in 1995 with a mission life designed for 7 years. EOL was expected in September 2002. As the result of successful satellite EOL management, its mission life was significantly extended, for nearly 5 years. The satellite was de-orbited in July 2007.

Mission life extension operations commenced four years before the planned de-orbit execution, as shown in Figure 1. Satellite mission life was extended by 72%. EOL satellite management was implemented in three phases:

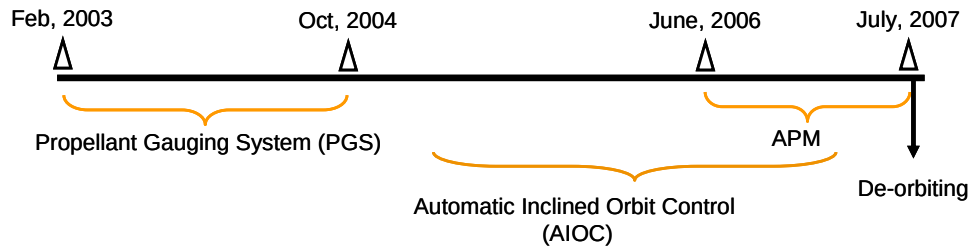

Figure 1 EOL planed activities

- Phase I
  a. Propellant Gauging System (PGS) for precision fuel measurement
- Phase II
  a. Automatic Inclined Orbit Control (AIOC) achieved with ground software modification
  b. Active Propellant Management (APM) to protect tanks from accidental depletion
- Phase III
  a. De-orbit Maneuver planning
  b. De-orbit Maneuver execution

A. Propellant Gauging

Three methods are typically employed in the industry to estimate the propellant remaining in orbit. These are bookkeeping, Pressure-Volume-Temperature (PVT), and thermal Propellant Gauging System (PGS). Basics of the modern PGS method can be found elsewhere1,2. The current state of the art for the PGS method is superior in numerous ways to the published initial work.

The PGS method has distinct advantages over the bookkeeping and PVT methods, particularly near EOL. Bookkeeping accuracy drops due to the accumulation of error with time. The decline of PVT accuracy is the result of decreased pressure sensitivity to Helium volume changes when the amount of propellant in the tank is small. However, the accuracy of the PGS method increases with decreasing propellant mass. Fig. 2 shows the general trend for the uncertainty of a propellant-remaining estimation for the bookkeeping and PGS methods with time. This shows that bookkeeping has better accuracy than PGS at the beginning of a satellite life. The accuracies of both methods become comparable in the middle of life. The PGS method typically becomes superior to bookkeeping between mid-life and end-of-life.

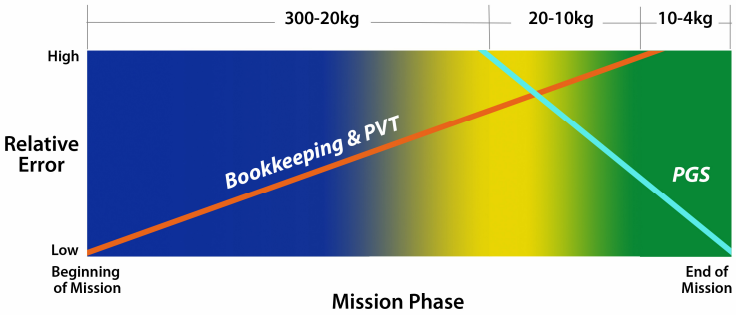

Figure 2. Error of different propellant gauging methods

Another important difference between the PGS and bookkeeping methods is found in applications to multi-tank propulsion systems in which the valves between the tanks are normally open. PGS is capable of determining the fuel load in each tank while the bookkeeping method can determine only the total fuel load of a satellite with a

multi-tank propulsion system. Any imbalance in fuel distribution between the tanks would be hidden from the user in the bookkeeping method, and can thus lead to unexpected tank depletion and early decommissioning of the satellite.

The thermal PGS is based on the concept of measuring the thermal capacity of a tank containing liquid propellant and pressurant gas by measuring the spatially-varying time-dependent thermal response of the propellant tank to heating and comparing the observed temperature rise to simulation results. During a PGS test, the tank heaters apply a known amount of energy to the propellant tank and the resulting temperature increase with time is recorded. This on-orbit data is then compared to the computed temperature response of a tank thermal model versus time for different propellant loads (see Fig. 3). The propellant load is calculated by a least-squares interpolation between these propellant calibration curves. The tank thermal model includes the propellant management device (PMD) vanes and sponges, spatial capillary-dominated propellant positioning in the tank, the tank wall materials, heaters, thermistors, multi-layer insulation (MLI), and the satellite thermal environment in which the tanks exist. Developing a model of sufficient fidelity is the key to success. Improvements over previously published work include superior volumetric meshing, improved spatial resolution in the thermal model, increased accuracy in modeling the spacecraft thermal environment, and multiple-tank capability.

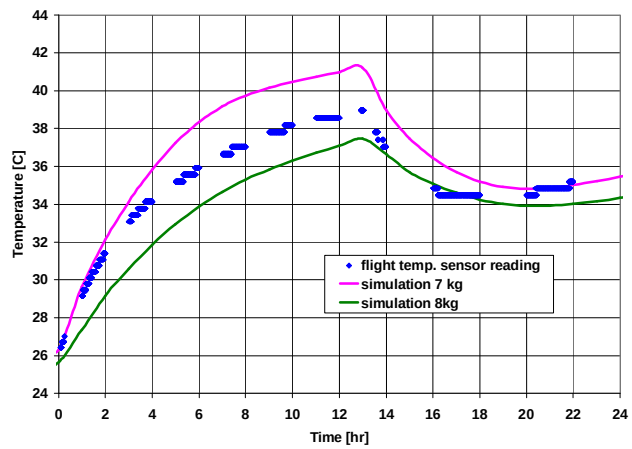

Figure 3 Comparison flight and simulation data *(typical)*

The temperature distribution on the tank surface is non-uniform because of non-uniform heater power distribution, uneven propellant distribution inside the tank, etc. Non-uniformity of heater power distribution stems from the fact that heater strips cover only a fraction of the tank surface. Propellant position in the tank during microgravity is controlled by a vane-type PMD[3]. At times near EOL in the satellite, the propellant is located in the sump and in the corners formed by PMD vanes and the tank wall. A significant portion of the internal tank wall is dry and not in contact with propellant. All these factors lead to significant temperature gradients on the tank wall. Therefore, the temperatures measured by the temperature sensors on the outer side of the tank wall depend on the sensor locations. The temperature distribution on the tank surface must be determined accurately to compare the test data with calculated temperatures successfully.

The challenges in using the thermal PGS include the development of a thermal model of a single fuel tank that adequately simulates the propellant tank response to heating. Such a model was developed for the tanks in this satellite. The major features of the model include three-dimensional fuel distribution in the tank in microgravity, the effect of the tank environment on the tank thermal response, details of the tank design such as tank material properties, heater and temperature sensor locations, etc.

Depending on how much detailed information about the tank is available and used in the model development, the thermal tank model can range from a high-fidelity model to the lower-fidelity baseline model previously published[1,2]. The high-fidelity model typically consists of 40,000 nodes or more. It provides detailed propellant and temperature distributions in the tank including the transient temperature profile on the tank outer surface where temperature sensors are located.

The thermal PGS system has been successfully applied to more than 15 different satellites which include satellites of different manufactures, namely, LM A2100, Ax2100, LM (RCA heritage) series 3000, 5000, 7000, LM (GE Astrospace heritage), DSCS III, SS/Loral FS1300, Boeing SS 601, and Astrium/EDS EuroStar 2000. More than 40 propellant estimations have been conducted using the PGS method.

The PGS method is flight proven. Five satellites have been super-synced. In all cases, the difference between predicted and actual propellant loads was about 1–2 months worth of propellant consumption.

Propellant gauging operations were conducted 6 times on the LM 3000 satellite in question from Feb. 2003 through Oct. 2004. The first PGS operation was to calibrate the tank and satellite models. The following 5 PGS operation were used for propellant estimation. The PGS operations were conducted 3-4 month apart in order to follow the propellant consumption. The PGS operation procedure changed with time, as fuel load decreased, to

reduce the uncertainty in the estimate. The last PGS operation reduced fuel movement between tanks during the operation in order to improve the accuracy. The fuel load of each tank was determined individually.

The accuracy of the fuel estimate was proved during de-orbiting. Comparison of the last PGS estimate with the actual fuel consumed at de-orbit showed a difference of only 1 months-worth of fuel.

B. Automatic Inclined Orbit Control

The primary need for fuel consumption for an in-orbit geostationary communications satellite is the execution of north/south station-keeping maneuvers to maintain orbit inclination. To save valuable fuel on board the LM 3000 spacecraft, execution of North/South station-keeping maneuvers was terminated approximately two years before satellite end of life. Without North/South maneuvers, the orbit inclination will grow at an approximate rate of 0.96 deg./year.

Allowing orbit inclination to grow creates two major problems for geosynchronous communications satellites. First, the satellite will no longer appear stationary in the sky, but will instead appear to move North/South in a diurnal cycle requiring the ground stations to track the motion. Second, the antenna pattern on the ground will vary diurnally due to the orbital motion. This second problem can be corrected by adjusting the spacecraft attitude.

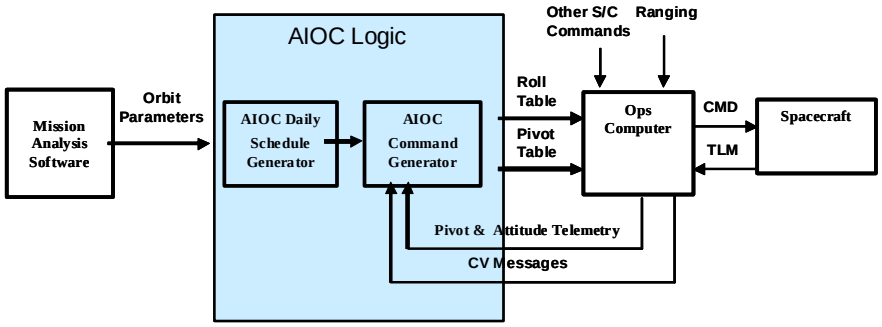

Figure 4 AIOC block diagram

The LM series 3000 satellite is an older bus design and has limited onboard flight software for inclined orbit control. A ground system software solution was developed to compensate for both of the two problems created by not performing N/S station-keeping maneuvers. This ground software is called Automatic Inclined Orbit Control (AIOC). The AIOC software requires generating the daily IOC commanding schedule, transmitting the commands to the spacecraft, retransmitting commands with proper data values if for some reason commands are not successfully received, and managing command conflicts. The block diagram of the AIOC is shown in Figure 4.

To minimize the roll and yaw pointing errors produced by an inclined orbit, the AIOC software algorithms generated both a roll table command and a ground command for the Pivot Assembly (PA) hardware on board the satellite. The PA works in conjunction with a spacecraft momentum wheel which can be tilted on command. By pivoting the momentum wheel, the spacecraft tilts in the North/south direction. The roll pointing error was minimized by using the variable roll offset command. The yaw error was minimized by ground commanding of the PA so that the total spacecraft momentum vector was kept perpendicular to the orbit plane. The implementation of the AIOC required daily PA commanding from the ground station. The ground PA commands were issued automatically by the AIOC software at intervals varying from 3 to 15 minutes depending on the satellite orbit inclination. Commands to update the Roll offset table were performed manually once every two weeks. Other satellite housekeeping commands were interleaved with AIOC commanding. If any IOC commands were missed, the AIOC software switched to catch-up mode, calculated the number of missing command steps, and then automatically transmitted corrective commands.

The AIOC operations were performed successfully for two years allowing the LM 3000 satellite to extend mission life for more than 2 years.

C. Active Propellant Management (APM)

For spacecraft with multi-tank propulsion systems in which the valves between the tanks are normally open, propellant migration between tanks due to temperature differences between the tanks creates some problems. One of them is a small change in the center of gravity of the spacecraft, which can be a problem for imaging spacecraft. Continual propellant migration between tanks may lead to increasing wobbling and reduction in image quality.

Diurnal propellant migration between tanks can also create a problem for tank re-pressurization. Typically, in blow-down propulsion systems, propellant tanks need to be re-pressurized at least once due to the drop in pressure as the pressurant expands. If the tanks are not balanced during re-pressurization, the pressurant gas load can be

different in different tanks which may lead to further load imbalance. Such an imbalance may be a concern for spacecraft operation EOL.

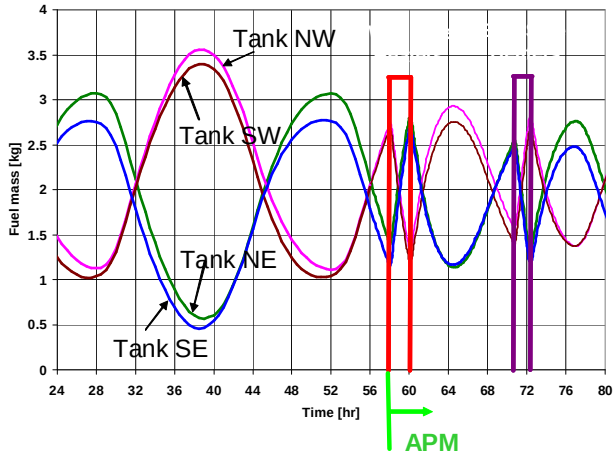

Figure 5 Effect of APM on fuel level in tank

Propellant migration presents an additional challenge for spacecraft operation at EOL. Propellant migration (thermal pumping) can deplete one of the tanks even though the total propellant load is still high and there are no signs of possible depletion. The thermal pumping should be taken into consideration at EOL when the amount of propellant migrating in and out of the tank can be comparable to the propellant load of a single tank.

Typically, propellant tanks have a common point through which tank are connected in multi-tank propulsion systems. In blow-down propulsion systems, which are typical for satellites, propellant tanks are filled with a gas at high pressure, usually helium. When tanks are at different temperatures, propellant is driven by the pressurant gas from warmer tanks to cooler tanks. The temperature difference between propellant tanks stems mainly from the circling of the sun about the satellite. GEO satellites also experience seasonal temperature differences between their north and south sides.

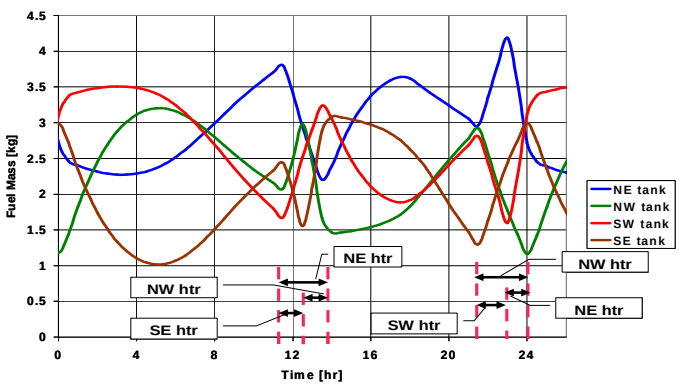

Figure 6 Effect of APM on fuel level in January

Active Propellant Management (APM)[4] minimizes thermal pumping. It also reduces the risk of accidental tank depletion when the propellant load in the tank becomes comparable to the amount of liquid migrating in and out of the tank. Figure 5 shows the effect of the APM on tank load. As one can see, the tank load can be significantly lower than the tank's average load when the tank is warm. For example, according to Fig.5, the minimum tank load can be around 0.5 kg while the average load is about 2 kg. The APM increases the minimum tank load to over 1 kg.

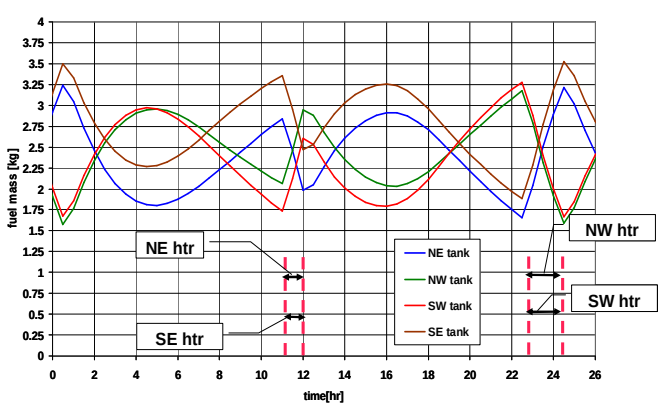

Figure 7 Effect of APM on fuel level in June

Several factors, like tank propellant load, season, etc., relevant to the APM implementation were considered for the APM procedure development. The effect of season on APM operation is shown in Fig. 6 and Fig.7. As one can see, APM procedures are more complex in January than in June due to the sun's effect on the satellite environment. Two heater toggles a day are required in June versus four heater toggles per day in January.

D. De-orbit Maneuvers, Planning and Execution

The successful de-orbit operations in July 2007 of the LM 3000 satellite were a direct consequence of proper planning and accurate measurement of the remaining fuel. Six months prior to the de-

orbit execution, a detailed operations timeline was developed to meet the ITU satellite de-orbit recommendation. Nominal and contingency command procedures were developed and thoroughly validated. Three pairs of orbit-raising maneuvers were planned and executed flawlessly to raise the satellite orbit by 300 km above geosynchronous orbit in July 2007. All three maneuver pairs used the west-facing thrusters in continuous firing mode to provide the delta V. The east facing thrusters were used for attitude control. Orbit determination after the first 2 pairs of orbit-raising maneuvers showed an orbit altitude increase of 188.9 Km versus the planned 170 Km. The durations of last pair of maneuvers were adjusted to keep the final orbit altitude only slightly over 300 Km. Signs of fuel depletion (a drop in tank pressure or a drop in thruster catalyst-bed temperatures) did not materialize after the last orbit-raising maneuver.

Several Fuel Depletion (FD) maneuvers using the north/south (N/S) thrusters were performed to deplete the remaining fuel without changing the satellite's altitude. The first N/S maneuver burn was slightly over one hour. No drop in thruster cat-bed temperatures was observed during the maneuver but a drop in tank pressure of 4 psi was detected, suggesting that helium gas was venting through the thrusters. The second N/S maneuver was aborted by the on-board flight software after 5 minutes because the satellite attitude roll error exceeded its safe limit. Succeeding N/S maneuvers resulted in maneuver aborts due to large roll and/or yaw errors. Controlling the spacecraft attitude was getting difficult with a mixture of helium and hydrazine flowing through the thrusters. The remaining fuel was depleted using east/west (E/W) maneuvers under flight software control. The first three E/W maneuvers were executed without any attitude error. During the third E/W maneuver, the cat-bed temperatures of two thrusters increased at the beginning of the maneuver and then decreased steadily. This condition only occurs when helium flows through the thrusters. One final E/W maneuver was attempted to deplete the remaining fuel above the tank outlets, but the maneuver was aborted right away by the flight software. It was concluded that all fuel had been depleted at this time and final spacecraft shutdown was performed after depletion of battery power.

III. Conclusion

An LM Series 3000 spacecraft mission life was successfully extended by more than 5 years and the de-orbit operation was achieved according to the ITU recommendation of 300 km above geosynchronous orbit. This accomplishment can be directly attributed to long-term planning, team work, commitment, proper execution of the End-of-Life Satellite Total Fuel Management plan, and accurate measurements of the remaining fuel. The PGS method demonstrated its reliability and accuracy. The APM prevented accidental depletion of tanks, and the AIOC provided the means to operate the satellite without inclined orbit control.

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