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Satellite Rescue - Luck or Skillful Application of Technology

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There are a lot of stories about spacecraft rescue. The majority of them describe efforts by engineers or operators in qualitative terms without looking at the technology which facilitates the spacecraft rescue. This paper discusses real cases and different technologies involved in satellite rescue. One of the cases is a satellite which started to experience bubbles in fuel lines while fuel load estimation indicated enough fuel remaining to sustain s/c for several years. Using a special technique of tank balancing, the satellite was saved and its mission life was extended. Other cases illustrate how application of an innovative and accurate method of propellant estimation rescues spacecrafts including a US government satellite in danger of de-orbiting and a recent NASA mission. These and other cases described in the paper will show a significant role of the "thinking out of box" in spacecraft rescue.

I. Introduction

According to the data, there are more than 3000 satellites are now in flight. Even with high fidelity satellite manufacturing and high quality control , there are a myriad of factors which can lead to spacecraft malfunctions or unexpected behaviors; in these situations the spacecraft requires rescue. On other hand, a dead satellite occupies an orbital slot and should be removed/rescued. The history of space exploration and utilization is filled with examples of situations when spacecraft should be rescued. The factors which create such situations could be s/c or subsystem design flaws; misunderstanding how the subsystems work; poor quality control; faulty mechanisms or unit; human error, etc.

One of the recent examples is the launch of the military AEHF-1 (Advanced Extremely High Frequency) satellite which had to be rescued due to clogged a propellant line leading to the main engine. Apparently, even for a $ 2 billion satellite, quality control was not the best. Anik E1 and E2 present other cases of satellites which had to be rescued due to problems with temperature control design.

A lot money is spent to rescue a satellite so the question arises- is this worth the effort?. The answer is obvious for AEHF satellite but it is not clear cut for other cases. We are going to discuss it later in this paper.

II. Study Cases

Let us look at several cases of satellite rescue. Regardless of the nature of the problem, the solution is usually nonconventional and requires out-of-the-box thinking.

A. AEHF

The Military AEHF-1 (Advanced Extremely High Frequency) satellite was the first of four satellites built by Lockheed Martin. An AEHF satellite is a sophisticated system and will eventually replace Milstar communication network. The launch was on Aug. 2010. As usual, the satellite was launched into an elliptical orbit and was then supposed to go circular orbit using bi-prop LAE (liquid apogee motor). The LAE failed after several seconds of firing. The second attempt

Figure 1 AEHF (artist's conception [1])

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failed as well. The fuel line blockage was attributed to a piece of cloth that had been placed to protect the line from contamination but was never removed[2].

The satellite has two smaller engines - mono-prop REA (reaction engine assemblies) and HCT (Hall Current Thruster) designed for station keeping, not for orbit raising. The decision was made to use these small engines (0.05 pounds of HCT thrust) to use for orbit raising. It was an excursion into uncharted territory. Such prolonged use (10-12 hours of HCT firing per day) is rare. HCTs are using Xenon as a propellant and require electric power Due to HCT's electrical need the solar arrays have been deployed unusually earlier in a flight. This could be bad for solar arrays because they could be damaged by high energy particles situated in the Van Allen Belts. shigh energy particles . Finally, the satellite reached the orbital slot on Oct.2011, 14 months after the launch.

The takeaways of this story are:

- poor quality control by Lockheed Martin which was fined by $15 mln[2] and was the main reason for need of rescue operation
- out-of-box thinking and unusual use of propulsion led to successful rescue of the spacecraft.

Apparently, the successful use of ion thrusters for orbit raising led to the decision by two commercial satellite operators, ABS (Hong Kong) and Satmex (Mexico), to order a Boeing 702SP which has only an electric propulsion system. Of cause, it will require much longer time for orbit raising (about 7-8 months) than usual, but the satellite is much lighter (1600 kg of chemical propellant vs. 300 kg of Xenon) and can be launched in combination with other satellites.

B. Stardust spacecraft

The Stardust spacecraft was launched on February, 1999. During its seven-year prime mission, the Stardust performed several tasks including the main task of collecting dust particles from the comet Wild 2 (January 2004) and successfully returned those particles to Earth in January 2006. The spacecraft was healthy at the end of the primary mission so it was decided to extend the mission (Stardust NExT) to fling by the comet 9P/Tempel 1 in 2011 to follow up on the previous Deep Impact investigation in 2005. One of the major tasks of the mission was to get images of the crater resulting from the 2005 Deep Impact mission. The success of the mission relies on many factors including having enough fuel for attitude control with thrusters.

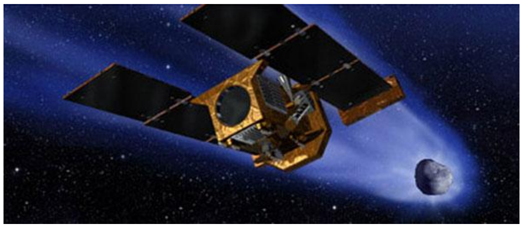

Figure 2 StarDust NExT

Remaining fuel was one of the make or break parameters for a successful mission. Typically, two propellant-tracking Bookkeeping and PVT methods are widely employed in space industry. The book-keeping method is using thruster performance knowledge and on-board thruster usage telemetry to count thruster pulses and estimate propellant consumed. The PVT method is based on Ideal Gas Law.

Both methods were used in a complementary fashion namely, the PVT was used to correct or calibrate the bookkeeping results[3].

The Stardust NExT mission plan required an adjustment of the spacecraft trajectory to intersect with the comet's path. Many factors affected the spacecraft trajectory and, consequently, the fuel consumption. So, the fuel management should take into account a large uncertainty in fuel consumption. The fact that both methods, the book-keeping and PVT, provided close fuel estimates, was assuring in that the spacecraft has enough remaining fuel to accomplish the mission.

As a precautionary measure, a thermal method of fuel estimation, “PGS[4]”, was used in 2008 to verify remaining fuel. Surprisingly enough, the thermal method showed 2kg or 20% less than two other methods. The mission management decided with some reluctance to use lower estimates for mission plan. The mission was accomplished successfully in March 2011.

Decommissioning of the spacecraft has shown that thermal gauging provided the most accurate estimation. As was commented in Ref.3:"... However, had the project not adjusted its mission plan to account for this worst case prediction, the spacecraft would not have had enough fuel to complete its mission, and would not have captured the images the comet...". Essentially, use of fuel estimates provided by the thermal method rescued the StarDust NExT mission.

The takeaways of this story are:

- that two methods of fuel estimation have provided the similar result does not mean that the result is correct
- cautious action facilitated successful completion of the spacecraft mission

C. Satellite with connected propellant tanks

Anik E1and Anik E2 satellites (LM 5000 series, former GE 5000 Series GE Astro) were launched in 1991 with designed lives of 12 years[5]. The propulsion system consists of 4 connected fuel tanks, depicted on Fig.3. The Book-keeping and PVT methods were used to determine fuel remaining. The problem with using the Book-keeping method for propulsion systems with connected tanks lays with the fact that the Book-keeping method can determine the total propellant load ONLY but it can not obtain propellant distribution for each tank.

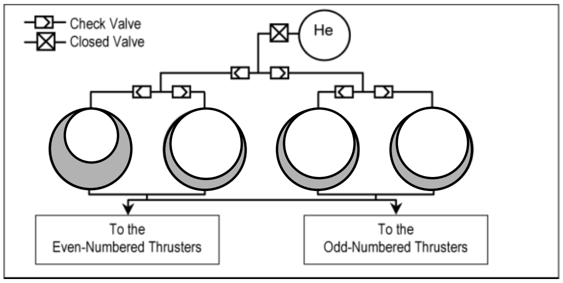

Figure 3 Anik E1 and Anik E2 Propulsion System[5]

Uneven distribution of propellant between connected tanks can be caused by many different factors, but the diurnal change of sun flux onto spacecraft panels is the major factor. The difference in sun flux on different sides of the satellite creates temperature gradients between tanks which causes diurnal propellant migration between tanks. Such movement is supposed to be minimized by a differential heater control which is supposed to lead to even fuel distribution between tanks.

As experience shows, this is not the case for majority satellites with connected propellant tanks. In particular, Anik E1 and Anik E2 satellites had fuel distribution between tanks depicted in Figure 3, namely, one tank contained the majority of the propellant while the other three tanks were almost empty. The book-keeping method will never indicate such a situation which might lead to unexpected satellite de-orbiting even if it has enough propellant according to the book-keeping method.

Telesat (owner of Anik E1 and E2) timely identified the problem using the thermal gauging method and corrected it by applying thermal pumping technique[5,6]. The satellites were saved from premature de-orbiting and provided service for an extra 3.9 years (between both satellites)[5] which led to a significant additional revenue[7].

The story of a dispute between AsiaSat (Hong Kong) and SpaceCom (Israel) over Asiasat 2/Amos 5i satellite exemplifies what might happen when a satellite operator heavy relies on the book-keeping method and does not recognize shortcomings of this method. SpaceCom leased the Asiasat 2 satellite in 2010 to have the satellite as a gap-filler for at least 2 years[8] for $45 M. The AsiaSat 2 was re-named to Amos 5i. However, 6 months later, bubbles in thrusters were discovered during a station-keeping maneuver which indicated low fuel level in tank(s). This indicated that the satellite couldn't perform tasks for which it was leased. The SpaceCom lost customers, revenue and ended-up in arbitration with Asiasat[9].

The takeaways of this story are:

- the book-keeping method is not reliable for satellites with propulsion system with interconnected tanks
- timely recognition of this fact and appropriate measures saved the satellite
- heavy reliance on book-keeping method might cause troubles and satellite loss

D. DSCS satellites

Figure 4 DSCS III satellite

As the backbone of the U.S. military's global satellite communications capabilities, the Defense Satellite Communications System (DSCS) constellation of 14 satellites provides nuclear-hardened, anti-jam, high data rate, long haul communications to users worldwide[9]. Lockheed Martin is a prime contractor for Air Force DSCS constellation.

The DSCS III satellites were designed for a 10 year mission life. However, the method of fuel estimation was not very accurate which led to a proposal for the satellite's de-orbiting. A more accurate method of fuel estimation saved a satellite from de-orbiting and extended mission life by several years for all DSCS satellites. This saved more than $5 M per year. The DSCS Life Extension team was awarded the 2006 Chief of Staff Team Excellence Award[10].

The takeaways of this story is:

- reliance on book-keeping method might cause satellite loss

III. Should or should NOT rescue spacecraft

Satellites rescue requires a lot of resources spent and can be very expensive. The major criteria should be "dollar and sense", namely, it is result of rescue worth of expenditure. Common sense tells us that AEHF rescue was worth the efforts. Recently, a lot of resources were spent on the development of the methods for spacecraft re-fueling in flight. There are two concepts being proposed. One of them is the " fuel depot" idea depicted in Fig.5. According to such an idea, NASA satellites will replenish propellant on way to Mars or during other missions. The major assumption is that the spacecraft is not disable and capable of actively seeking the fuel depot.

Figure 5 Fuel Depot (concept)

The other popular idea is to develop essentially a tanker which will be sent to replenish propellant in the satellite that has run out of propellant. This idea has being widely discussed, in particular, for aging GEO communication satellites. MDA (Canada) is developing Space Infrastructure Services (SIS) vehicle that would be able to provide satellite refueling along with other functions. Intelsat (Luxembourg) interred into agreement with MDA in 2011 to provide re-fueling of Intelsat satellites for $280 million [11]. The agreement ended in 2012 due to lack of government support of the project. Re-fueling of the aging satellite makes sense only if the cost of such an operation is much smaller than the cost of launching new satellite. In fact, all satellite hardware will be about 10-15 years old by the time of the satellite re-fueling. High cost of re-fueling makes such procedure questionable from sense point of view.

Figure 6 Sherpa Space Tugboat

A concept of a space tugboat is getting popularity now. The tugboat could be used to rescue a spacecraft that has been placed in a wrong orbit or stranded in an incorrect orbital location. Another important function of the space tugboat would be cleaning the GEO slots or specific trajectories from dead spacecrafts. According to some sources, number of dead satellites exceeds now is nearing 200.

There are several space tugboats that are under development now, e.g., Sherpa by SpaceFlight (Seattle, WA), SIS by MDA (Canada), etc. Also, DARPA is considering to develop Phoenix system to remove debris from space.

Cleaning space, in particular, GEO slots from dead satellites is very expensive and requires a lot of resources. It is prudent to include either the cost of cleaning into the cost of satellite ownership or it should be included in the cost of an insurance policy. Satellite owners should bear a responsibility for clearing.

IV. Conclusion

This paper shows that the need to rescue a satellite could arise from unfortunate circumstances but usually the problems stem from either quality control or lack of appropriate knowledge. Also, it shows that a heavy reliance on the book-keeping method that estimates remaining propellant can lead to premature satellite loss or mission failure. Use of an accurate propellant estimation combined with the thermal pumping can save satellites from premature de-orbiting and significantly extend spacecraft mission life.

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