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CASSINI POWER DURING THE 20 YEAR MISSION AND UNTIL THE FINAL PLUNGE INTO SATURN

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The NASA-ESA Cassini mission ended on September 15, 2017, after almost 20 years of operations. Electrical power telemetry data is presented for the entire mission from launch and End Of Mission (EOM). The Cassini spacecraft was powered by three Radioisotope Thermoelectric Generators (RTGs) connected in parallel. These three RTGs generated 882.1 W at the beginning of the mission. At EOM, the power level was 600.3 W. The electrical output of Cassini's power subsystem decayed consistently, as predicted, during the entire mission between October 1997 and September 2017. Further, no heating of the RTGs was reported in telemetry during the last minutes of the mission, nor was there any variance apparent in the final output of the three RTGs that is attributable to the final plunge into Saturn.

I. INTRODUCTION

This paper presents the power output telemetry data for the entire mission. It then discusses the last hours and minutes of power telemetry data during the final plunge of the Grand Finale, with a focus on the last 20 minutes of the mission when Cassini entered Saturn's atmosphere through spacecraft destruction. Finally, an overview of Cassini's trajectory during the Grand Finale phase, and the spacecraft state, with an emphasis on the RTGs, will be presented.

II. CASSINI POWER OVER TIME

Cassini launched on 15 October 1997 and the mission ended on 15 September 2017 with a final plunge into Saturn's atmosphere. Fig. 1 shows the entire power history telemetered by the spacecraft, including the very last datapoint sent just before the end of the mission. The overall RTG power decay shows an exponential behavior going from 882.1 W on the first day of the mission to 600.3 W on the last day. This corresponds to a power decay of 32% over the 20-year mission. Fig. 1 demarks four distinct mission phases just above the X-axis: (a) the Venus-Earth gravity assist, (b) the cruise to Saturn, (c) orbiting Saturn, and (d) the Grand Finale. The power data associated with the first three phases were described in an

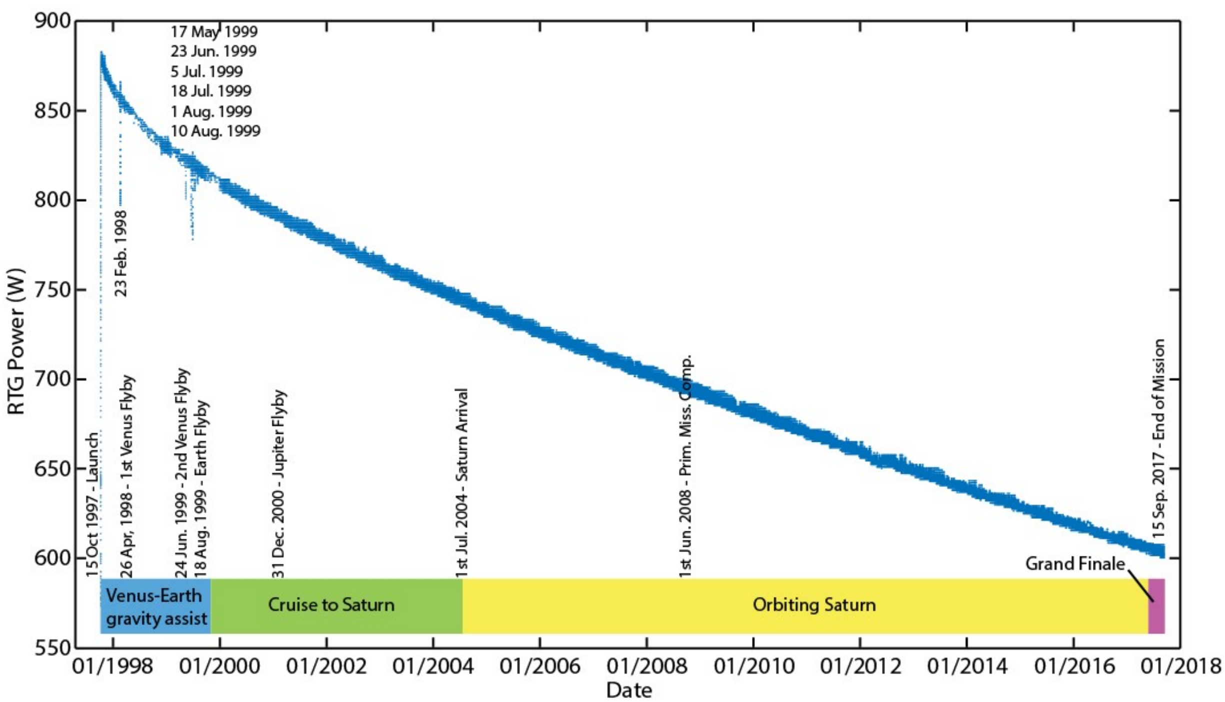

Fig. 1. Cassini recorded power output telemetry data over the entire mission between launch and EOM. The data is divided into four mission phases: The Venus-Earth gravity assist, the cruise to Saturn, orbiting Saturn and the Grand Finale.

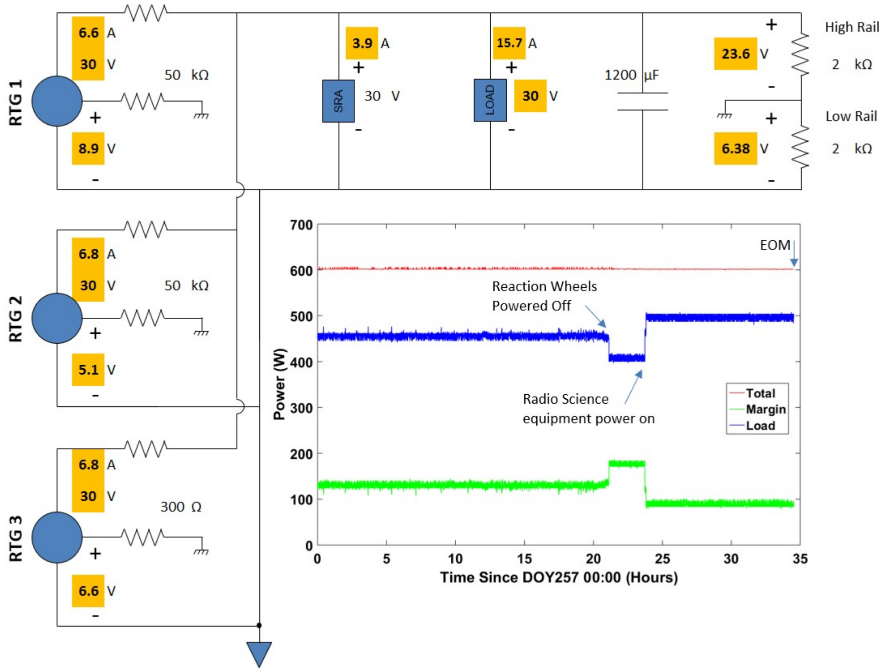

Fig. 2. Cassini functional bloc diagram. The plot shows the total, margin, and load power during the last hours of Cassini starting from SCET 2017-257T00:00.

earlier paper[1]. The Grand Finale started on 26 April 2017, when Cassini dove in between Saturn's rings and the planet's upper atmosphere for the very first time. During a five-month period, Cassini passed 22 times through that gap until the final plunge. During that period, the electrical output of Cassini's power system decayed consistently, without any major deviation from power predictions. At the time of the development of Cassini, the choice of using RTGs as a power source was essential. A Cassini-type solar-powered Saturn mission would have required a solar array of about 600 square meters[1]. Solar cell technology has improved by a factor of two since the development of Cassini, however even this amount of area (i.e., 300 m^2) is challenging. Therefore, even given these advances in solar cell / array technology, a Cassini-type mission with a similar science instrument payload would most likely still require a RTG power system solution.

III. FINAL POWER SUBSYSTEM STATUS

The Cassini Power and Pyrotechnic Subsystem (PPS) relied on three RTGs connected in parallel, and very limited energy storage[2]. The power bus was regulated at 30V with a linear-sequential shunt regulator and contained about 1200 μF for bus stability. The Cassini functional block diagram is depicted in Fig. 2, where average voltage, current, and resistance values are shown during the last hours of the mission. Because the three RTGs were connected in parallel, the current generated by each RTG was additive and the RTGs operated at the same voltage. The graph shown in Fig. 2 plots the total power output and the Load and Margin values during the last 35 hours of the mission. The Load was the actual power consumption of the spacecraft and the excess in power, or Margin, was discarded through thermal radiation via the Shunt Regulator Assembly (SRA). The drop in Load 14 hours before the end of the mission corresponds to when the reaction wheels were powered off. The increase in Load 10 hours before the end of the mission corresponds to Radio Science equipment powering on.

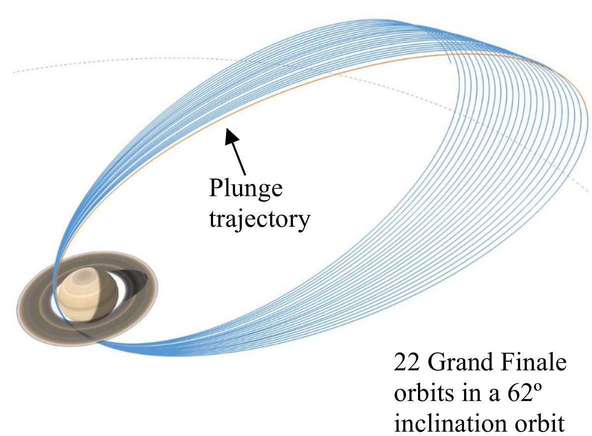

Fig. 3. Depiction of the 22 Grand Finale orbits of the Cassini spacecraft at Saturn, ending with the final plunge.

IV. CASSINI END OF MISSION

Nine years before the End Of Mission, planning began for the last phase of the Cassini mission at Saturn. Several potential scenarios were studied. Putting the spacecraft into a long-term, stable Saturn orbit was one option. Another was to use a Titan gravity-assist to leave Saturn orbit entirely. But the most scientifically rich possibility required plunging into the gap beteween Saturn's rings and atmosphere in a final "blaze of glory." The reason this idea was of great interest was because it involved "jumping over" the rings with a trajectory that would fly, once a week for 22 weeks, through the ring plane inside the rings and just above Saturn's cloud tops (Fig. 3). A 3,000 km-wide "clear zone" was predicted just above Saturn's atmosphere and inside the inner edge of Saturn's rings. Cassini had never flown through that gap and might encounter dust dense enough to disable the spacecraft during these 22 ring plane crossings. It turned out that there was even less dust than predicted; in fact, it took special planning to sample any dust at all in most of the ring plane crossings. From a spacecraft safety standpoint, this was great news. From a science standpoint, it likely limited their "signal" for dust analysis. Only during the last of these remarkable high-inclination orbits would a final nudge from Saturn's moon Titan put Cassini on a flight path that would plunge it directly into Saturn. This ending allowed in-situ sampling of Saturn's atmosphere for several precious minutes until the aerodynamic torque overwhelmed Cassini's thrusters

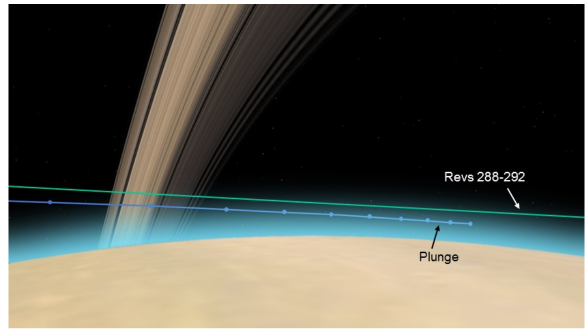

Fig. 4. The final five periapses of the Cassini mission at Saturn. The final plunge occurred on the very next orbit, ending an very successful mission.

and caused the spacecraft to tumble and turn away from Earth-point. The Grand Finale orbits were an unprecedented opportunity to obtain new science. By flying so close to Saturn, Cassini was able to map its magnetic field and gravity in great detail. By flying between the planet and the rings, Cassini was able to separate the gravitational effects of the rings from Saturn itself. This allowed Cassini scientists to establish the aggregate mass of the rings (which was a key clue to learning how old the rings are). Cassini directly sampled the composition of Saturn's atmosphere, just as it had done at Titan and the plumes at Enceladus. Spectacular Earth and Sun occultations of the rings made the proximal orbits of great interest. Cassini began each proximal flyby

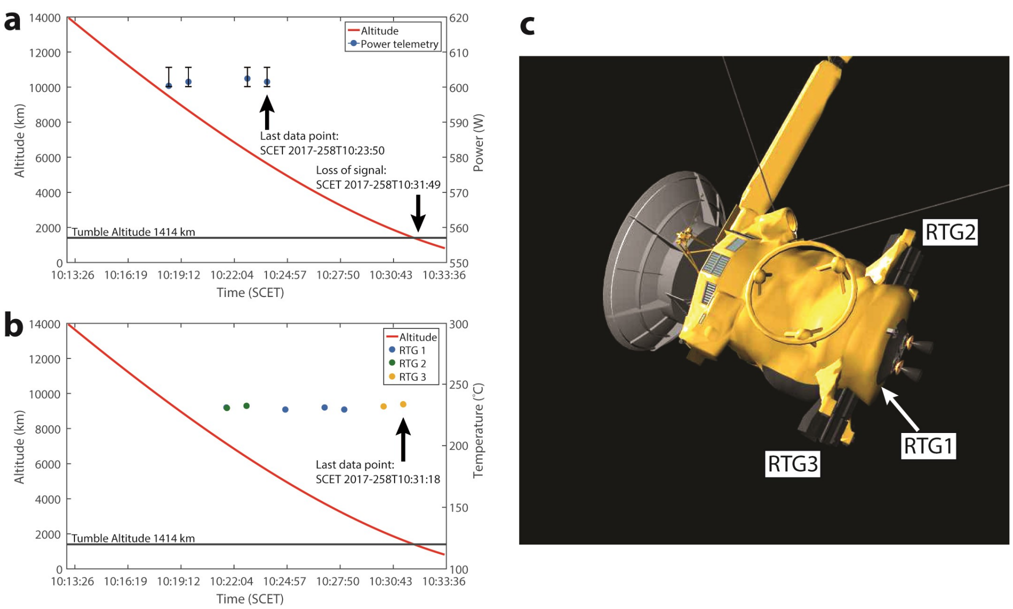

Fig. 5. (a) Cassini final altitude values and actual power telemetry for the last twenty minutes of the mission on September 15th 2017. The last power telemetry value was recorded at SCET 2017-258T10:23:50, eight minutes before final loss of signal. (b) Cassini final altitude values and actual case temperature telemetry values for RTG1, RTG2 and RTG3. The last temperature telemetry value was recorded for RTG3 at SCET 2017-258T10:31:18, just a few second before final loss of signal. (c) Cassini pointing towards Earth and sending final measurements in real time during the final plunge. The velocity vector is pointing towards the reader. This is the perspective of Cassini with respect to the "wind".

of Saturn by gliding down from Saturn's northern hemisphere as it skimmed above the rings themselves. Each approach was on the sunlit side of Saturn (near Noon local Saturn time). Cassini passed inside the inner D ring in the 3,000 km gap just above Saturn's cloud tops. Cassini reached its periapsis just three minutes after the descending ring plane crossing and roughly 5° below Saturn's equator. The Earth and Sun were occulted by the rings for about 27 minutes beginning at the moment of ring plane crossing. About 42 minutes after closest approach, Cassini came within 51,000 km of the south pole of Saturn. Orbits 18 through 22 of the Grand Finale (known as Revs 288 through 292 of Saturn) skimmed well into Saturn's atmosphere as depicted in Fig. 4. To avoid tumbling, the spacecraft reaction control system (RCS) was placed in thruster control about an hour before periapsis in each of these orbits. RCS control provides about 10 times more control authority than the reaction wheel control system. On the very last orbit, the 23rd in this remarkable Grand Finale, Cassini skimmed even closer to Saturn's atmosphere. So close in fact that the flight path angle and atmospheric drag guaranteed that the spacecraft would thermally and structurally break apart, ending the mission in spectacular fashion. Science and engineering data were successfully transmitted back to Earth right up to the very last second when the atmosphere overwhelmed Cassini's ability to stay Earth-pointed. At 3.5 hours prior to loss of signal, Cassini transitioned to transmitting data in real time. The high gain antenna (HGA) made an angle of 114 degrees with respect to the velocity vector during the plunge. The HGA stayed Earth-pointed with an angle less than 0.5 mrad during the plunge until Cassini began to tumble. It is estimated that telemetry was lost when the HGA moved about 4 mrad away from the Earth-line as the tumbling started. The carriers hung on 10-15 seconds longer as they can still be received out to several degrees away from the Earth-line. The Spacecraft started to tumble at an altitude of 1,414 km. Altitude was defined as the distance between the Spacecraft and the 1 bar surface in the planet's atmosphere. The attitude control thrusters were firing at 100 percent of capacity in order to keep the spacecraft's antenna pointed at Earth. During those last seconds, the spacecraft was travelling at a velocity of about 123,000 km/h and was able to sample Saturn's atmosphere from about 300 kilometers deeper into Saturn than on any of its previous orbits. On September 15, at SCET (Spacecraft Event Time) 2017-258T10:31:49, at an altitude of 1,402 km, an atmospheric density of 1.3e-10 kg/m^3 and a velocity of 31.0 km/second, Cassini permanently lost contact with Earth. Soon after, Cassini burned up and disintegrated. This represented the successful End of Mission[3]. Fig. 5a shows the altitude of Cassini during the last 20 minutes of the mission. The altitude showed a deceleration of the Spacecraft as it was entering Saturn's atmosphere. There was no altitude telemetry data but the prediction was close to the true altitude. During that 20-minute period, the last four power telemetry data points were recorded and are shown in Figure 5a. These are also the four data points from Figure 1. The last case temperature telemetry data are presented for RTG1, RTG2 and RTG3 in Figure 5b. Fig. 5c shows Cassini pointing towards Earth as it was transmitting the final data in real time and the trajectory is orthogonal to the image and flying towards the reader. Therfore, the atmosphere was impinging upon RTG2 and RTG3 as it descended into the atmosphere. Neither power values nor RTGs case temperature varied from their trend prior to the final plunge. As Cassini was entering Saturn's atmosphere, heating of the RTG cases and decrease in power output could have been observed. However, signal was lost before any appreciable heating of the RTG cases or power output decrease had occurred.

V. CONCLUSIONS

Cassini delivered incredible science about Titan, Enceladus, and Saturn and its rings throughout its amazing mission lifetime. Cassini delivered science that will re-write the science textbooks about these bodies in our solar system and provide us with endless clues and conclusions about our solar system dynamics, past and present. Like so many components of the Cassini spacecraft, the RTGs functioned right up to the very last second of science and instrument telemetry data. It was a fitting end to a remarkable space mission using RTG technology.

ACKNOWLEDGMENTS

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