# Trajectory Dispersion Control for the Cassini Grand Finale Mission

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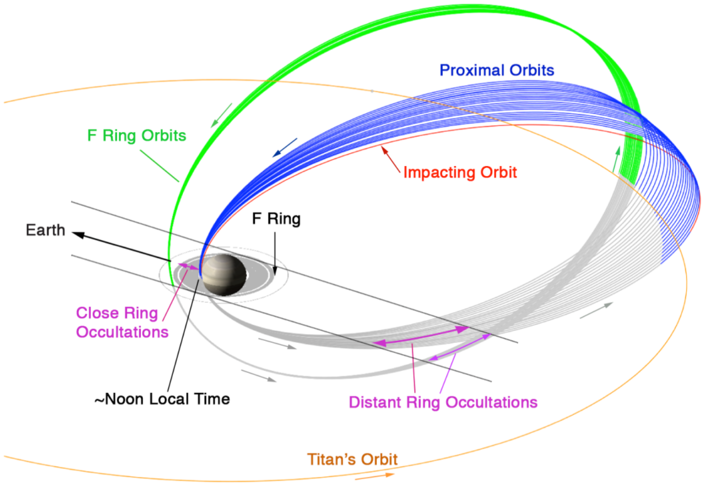
After a decade of exploring and collecting valuable scientific data with unprecedented details of the Saturnian system, the highly successful Cassini mission is slated to enter the last phase of its 20-year interplanetary endeavor – the Grand Finale Mission *(also known as the Proximal Orbits, as depicted in the illustration)*. It will begin with one last targeted, close flyby of Titan in April 2017 that sets up the subsequent 22 highly inclined (~62 degrees), short period (~6.5 days), ballistic orbits each passing through the gap between the inner D-ring and the upper atmosphere of Saturn. The unique geometry of these orbits will afford scientists opportunities, previously unavailable, to further study the intricacies of the Saturnian system. For instance, the last 5 of these 22 orbits will pass through regions where the atmospheric density is ~ $10^{10}$ $cm^{-3}$ (0.1 nbar) to allow for direct sampling of the species in Saturn's thermosphere. After these close flybys, the Cassini spacecraft will dive deeper into Saturn's atmosphere and be permanently captured in September 2017.



To facilitate the planned science observations, trajectory dispersions of the orbits need to be controlled such that the trajectory events of interest can be identified and located with high precision in the science sequencing process. For this reason, statistical maneuvers are required to account for navigation uncertainties including flyby, orbit determination, and maneuver execution errors, which are normally unavoidable in operations. In addition, because of the diverse, tightly packed science observations planned during the Grand Finale mission, many reaction control system (RCS) thruster activities (> 70) are needed to accordingly adjust the orientation of the spacecraft with efficiency. Some of these RCS activities will take place near periapses and have non-trivial uncertainties (~ 70 mm/s per axis) that can contribute significantly to the overall trajectory dispersions. Furthermore, the trajectory perturbations due to aerodynamic forces the spacecraft may experience from its close skimming of Saturn's atmosphere have been shown to be non-negligible. It is the responsibility of the Cassini Navigation Team to analyze and design a control strategy so that the Cassini Grand Finale Mission can be flown with relatively small dispersions to ensure the safety of the spacecraft, comply with the planetary protection program, and accommodate various requests from the science team. These conditions can be summarized as follows:

- Achieve Saturn atmospheric capture at the end of mission ($R < 60{,}848$ km) to avoid possible future collision with and contamination of natural satellites
- Protect spacecraft's health by keeping safe margins from the inner D-ring ($R < 64{,}300$ km)
- Maintain spacecraft's controllability by staying above the tumble altitude ($R > 61{,}750$ km)
- Control the trajectory dispersions (68th percentile RSS deviation) to be under 250 km for the majority of the mission to aid science planning and sequencing
- Minimize the number of maneuvers required and the propellant usage; refrain from placing maneuvers at locations with high science activities (e.g. periapses)

In the Prime, Equinox, and Solstice tours of the last ten years, up to three maneuvers could be used to target every close satellite flybys that served as discrete control points of the trajectory. In the Grand Finale mission, however, the navigation goal of minimizing the overall dispersion for all of the 22 orbits will have to be achieved with no more than a few maneuvers. Because of the mission's unique characteristics, existing statistical analysis tools need to be modified and new ones developed to physically model the many coupling, inter-dependent sources of uncertainties, and to accurately compute the resulting perturbed and controlled trajectories. Our approach can in general be divided into three modules: 1) Orbit Determination (OD) covariance analysis that yields the uncontrolled trajectory dispersions with uncertainty contributions from the last Titan flyby, state knowledge, RCS activities, etc.; 2) Linear statistical maneuver analysis that makes use of OD covariance matrices and performs linear mappings to approximate trajectory dispersions at discrete points and strategize statistical maneuver usage; 3) Direct Monte Carlo Simulation and Trajectory Integration analysis that implements direct Monte Carlo sampling of various error distributions, iteratively computes corrective maneuvers, and incorporates these perturbations and DVs in a fully integrated trajectory; an ensemble of these complete, self-consistent trajectories are generated each with different initial conditions sampled from an OD covariance state matrix. Preliminary results have shown that without control the spatial dispersions can reach thousands of km within days of the last Titan flyby, and that with 3 – 4 strategically located maneuvers having a total DV cost of a few m/s, the dispersions can be kept below the requested 250 km level for the majority of the mission, and that Saturn atmospheric capture is statistically guaranteed. More detailed descriptions of the analyses and the most up-to-date results will be given in the meeting.