Reconstruction of the Voyager Saturn Encounter Orbits in the ICRF System

by

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The Saturnian system was visited by the Voyager 1 and Voyager 2 spacecraft in November 1980 and August 1981, respectively. Campbell *et al.* 1982 provides a detailed discussion of the determination of the orbits of both spacecraft. Data acquired during the Saturn encounters was subsequently used to improve knowledge of the Saturnian gravity field (Campbell and Anderson 1989) and the orbits of the Saturnian satellites (Jacobson *et al.* 1982, Jacobson 1996). In anticipation of the Cassini tour of the Saturnian system, beginning in July 2004, we have decided to re-examine the results from the Voyager mission.

The objectives of the new analysis are:

- to obtain Voyager trajectories in the International Celestial Reference Frame (ICRF) which will facilitate any future combined Voyager and Cassini data analysis; the original Voyager analysis was in the B1950 system and Cassini uses the ICRF.
- to utilize all of the Voyager imaging data in the development of the Saturnian satellite ephemerides; the archival Voyager reconstructed trajectories do not span the entire data interval.
- to repeat the gravity field investigation taking advantage of improvements made in modelling and data processing since the original analysis.

Campbell *et al.* performed separate reconstructions for each spacecraft. In the Voyager 1 case they used a 42 day data arc from 11 October 1980 to 22 November 1980. The data included noncoherent one-way Doppler, coherent two-way and three-way Doppler, range, and imaging (pictures of the satellites against a stellar background). The data processing estimated the spacecraft state, planet and satellite ephemeris parameters, gravity field parameters, spacecraft maneuvers, non-gravitational accelerations (treated as both bias and stochastic parameters), Earth-tracking station locations, one-way Doppler bias and drift parameters, and camera pointing (treated as stochastic). For Voyager 2 they used a 55 day data arc from 1 August 1981 to 24 September 1981. The data types and processing procedures were identical to those of Voyager 1 with the exception that no one-way or three-way Doppler was used. The Saturnian satellite ephemerides during the Voyager 1 encounter, where a high accuracy Titan orbit was needed, were produced with numerical integration; during the Voyager 2 encounter they were based on less accurate analytical theories.

Our reconstructions use data arcs of 105 days (7 August 1980 to 20 November 1980) for Voyager 1 and 106 days (8 June 1981 to 22 September 1981) for Voyager 2. The arcs begin at the time of the earliest useable imaging data; they terminate slightly earlier than those of Campbell *et al.* because we elected to stop at the end of the availability of the calibrations for the effects of interplanetary plasma. In addition to the longer arcs, we added to the Voyager 2 data set the noncoherent one-way Doppler that was used in the gravity field work of Campbell and Anderson. Our data processing procedure is essentially the same as that of Campbell *et al.*. However, we are performing a simultaneous reconstruction for the two spacecraft; this means estimates of the common parameters such as those of the gravity field are determined from the combined data set. Moreover, we do not estimate the the

tracking station locations, because they are well known in the ICRF system. Our more modern software also permits a more sophisticated treatment of the stochastic parameters and allows us to include tracking pass dependent biases in the range data.

Because the second of our objectives is to use the Voyager data to improve the satellite orbits, we are covering both encounters with one set of numerically integrated satellite ephemerides. In the data processing the epoch states of the integration are determined from the Voyager data together with Earth-based astrometric observations spanning the period from 1971 to 2002. Both the spacecraft and Earth-based observation sets are considerably larger than those previously used (Jacobson 1996).

Our third objective, a new investigation of the gravity field, is met as a byproduct of the reconstruction because we obtain a single estimate for the common gravity parameters. Campbell and Anderson determined the masses of the Saturnian system, Tethys, Rhea, Titan, and Iapetus, and the harmonic coefficients of Saturn's gravity field. They unable to obtain an accurate estimate of Saturn's rotational pole and instead adopted the direction found by Simpson *et al.* 1983 using occultation data. Our analysis does not estimate the mass of Tethys but instead fixes it at the value determined by Jacobson 1995 from the effects of Tethys on its Lagrangian satellites Telesto and Calypso. We also adopt the revised Saturn pole direction from French *et al.* 1993.

The paper provides a detailed discussion of reconstruction of the Voyager Saturn encounter trajectories and a preliminary analysis of the Saturnian gravity field. We compare our results to those previously reported.

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