Jet Propulsion Laboratory
California Institute of Technology

Memorandum
IOM 392R-16-003
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Subject: Planetary ephemeris DE435

1. Introduction

The planetary ephemeris DE435 was created in January 2016 for the Cassini project and is primarily an incremental improvement for the orbit of Saturn. DE435 is based on most of the same observations used for the planetary ephemeris DE430 (Folkner et al. 2014). For DE435 the Cassini spacecraft orbit estimates were updated with additional data through end of 2015. The difference in the orbit of Saturn for DE435 is relatively small, with less than 1.5 km change in position with respect to Earth over the time period 1950 to 2050.

2. Saturn position data from Cassini

Radio range and Doppler measurements of Cassini by the NASA Deep Space Network (DSN) from the time of entry into orbit about Saturn in 2004 have been used to estimate the spacecraft trajectory. The range measurements of the spacecraft with respect to Earth have signatures from both the position of Saturn with respect to Earth and for spacecraft maneuvers, especially maneuvers performed while not being tracked by the DSN. In order to separate the signatures of maneuvers from the Saturn ephemeris, spacecraft trajectory segments were estimated using only Doppler data, and the range data reduced to give estimates of the distance between Earth and Saturn. This is the same procedure used earlier for DE430, and described in more detail in Hees et al. (2014). For DE435 range data taken since the DE430 fit were included, and the spacecraft orbits estimated with only Doppler tracking data were updated. The residuals to these range estimates after being fit for DE435 are shown in Figure 1. These are similar to figure 35 from the DE430 fit. The range residual noise, or scatter, is somewhat smaller than for DE430, primarily from changes in the spacecraft orbit estimation process.

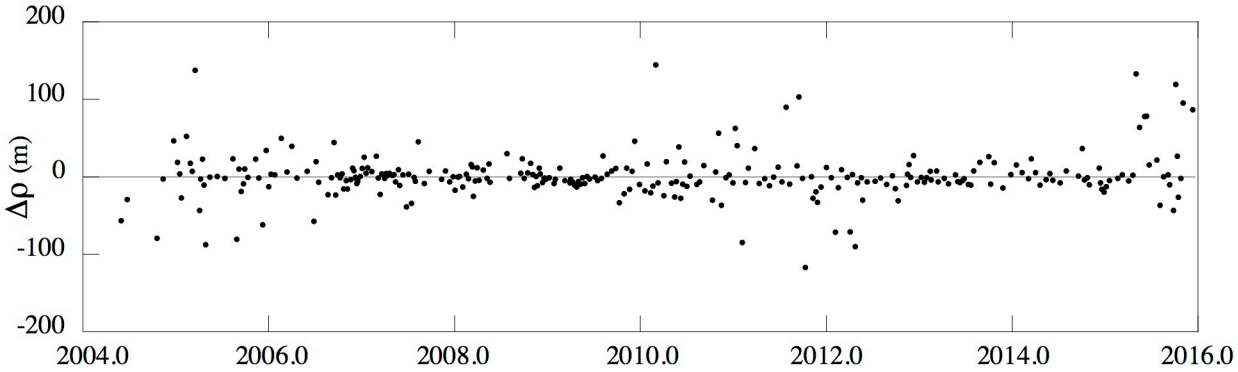

Figure 1: Residuals of distance of the Saturn system barycenter from Earth on DE435 from Cassini spacecraft range measurements and orbits estimated from Doppler data.

The angular position of Saturn, right ascension and declination, relative to extra-galactic radio sources, have been measured using the Very Long Baseline Array (VLBA). The original measured used for DE430 (Jones et al. 2011) have been reprocessed using improved source positions and uncertainties from updated radio source catalogs (Jacobs and Kroger, 2015) and targeted source survey (D. L. Jones, private communication). Figures 2 and 3 show the residuals of measurements used for the DE435 estimation.

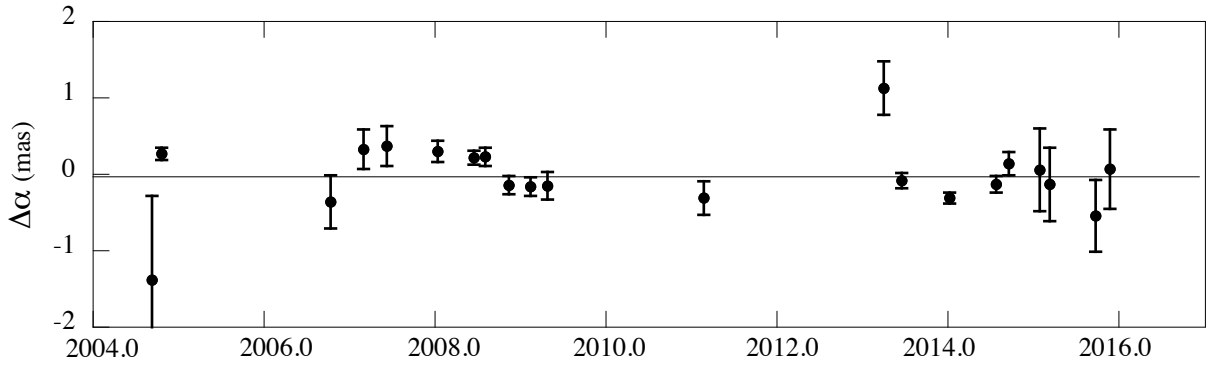

Figure 2: Residuals of VLBA right ascension measurements Saturn used for DE435.

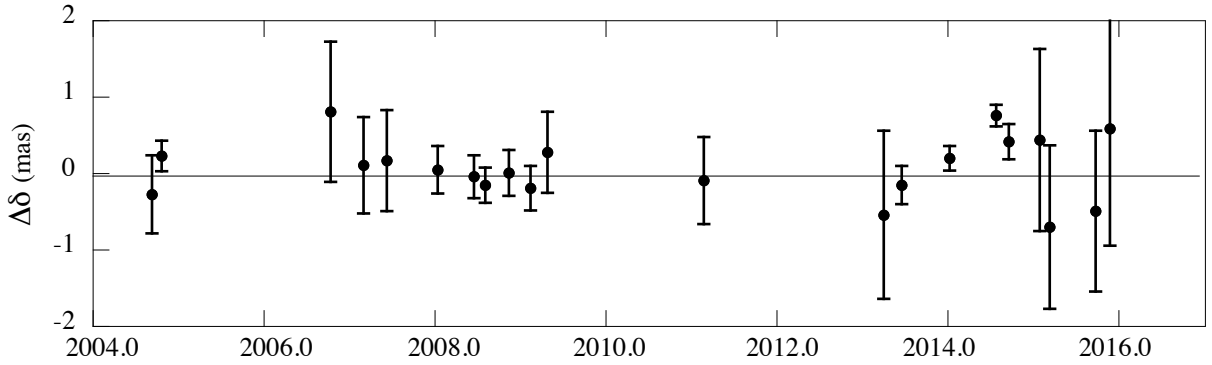

Figure 3: Residuals of VLBA right ascension measurements Saturn used for DE435.

3. Change in Saturn orbit

The difference in the estimated position of Saturn with respect to Earth from DE435 and the earlier DE430 is shown in Figures 4, 5, and 6. Note that a difference in right ascension or declination of 0.1 mas (1 mas = 0.001 arcsecond ≈ 5 nanoradian) corresponds to an offset of position of ~1.5 km. The estimated uncertainty in the orientation of the orbit of the Earth is ~0.25 mas (Folkner and Border, 2015). The difference in the orbit of Saturn in DE435 from DE430 is smaller than the Earth orbit uncertainty because most the Cassini data from 2004 to 2012 were used for both. The accuracy of Saturn relative to Earth has improved slightly, but the overall uncertainty with respect the current realization of the International Celestial Reference Frame (Ma et al. 2009) has not significantly improved.

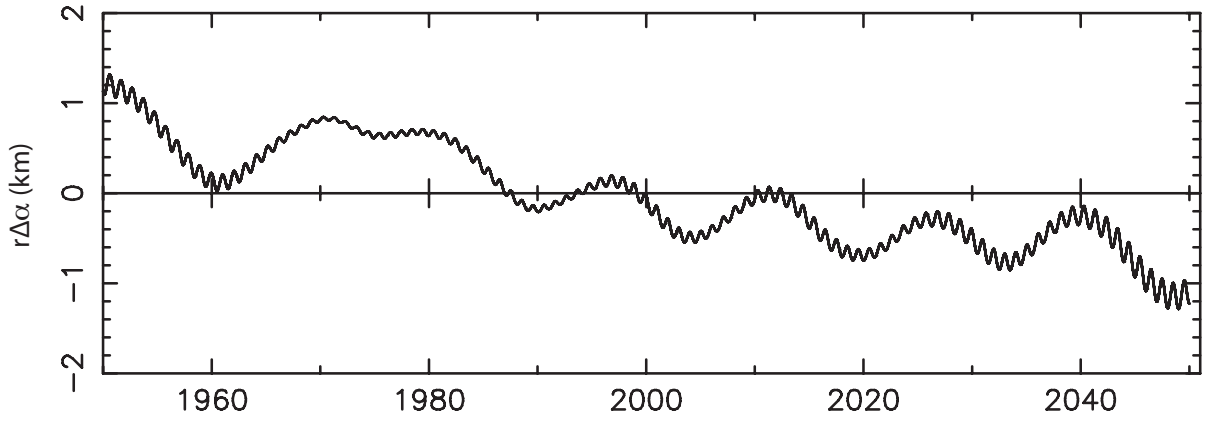

Figure 4. Difference in position of Saturn relative to Earth in direction of increasing right ascension from DE435 compared with DE430.

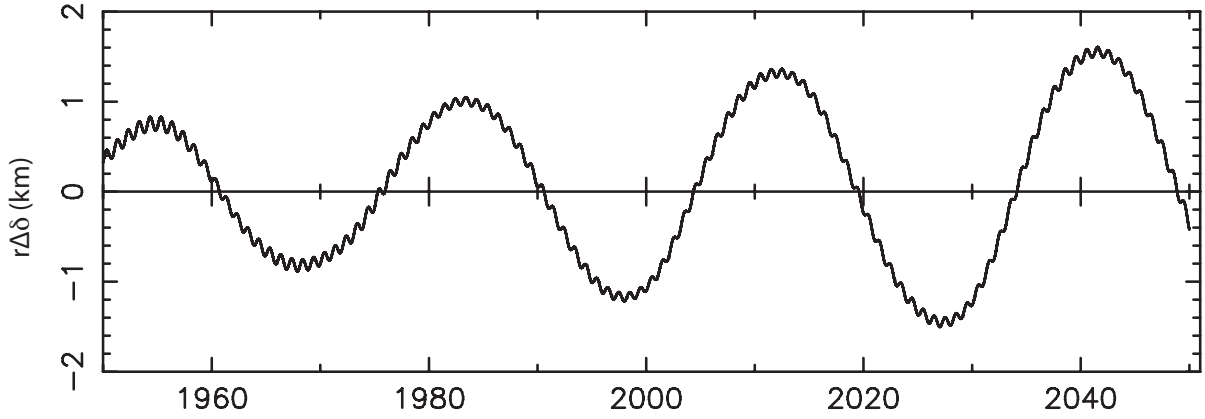

Figure 5. Difference in position of Saturn relative to Earth in direction of increasing declination from DE435 compared with DE430.

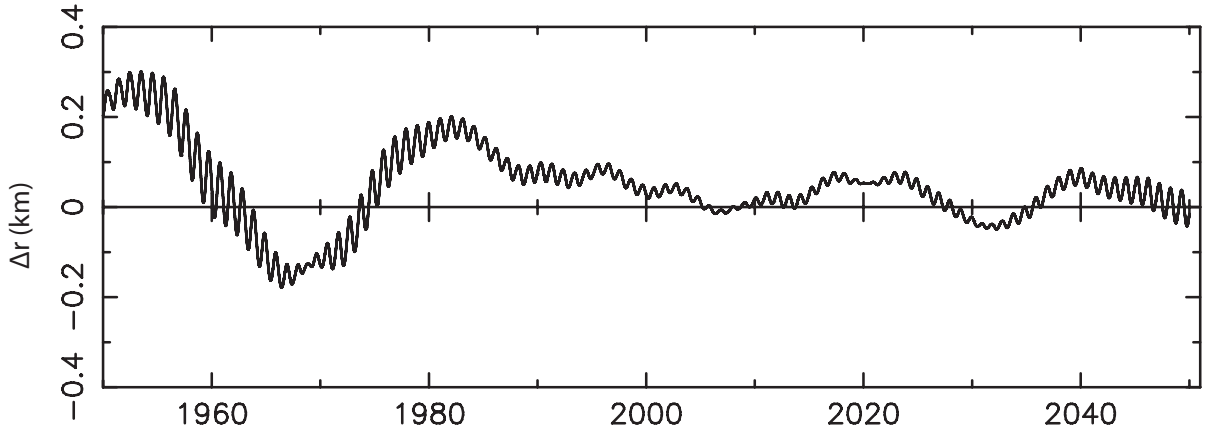

Figure 6. Difference in distance of Saturn to Earth from DE435 compared with DE430.

4. Revision of VLBA measurements

Following the integration of DE435, one more VLBA measurement was processed (D. L. Jones, private communication) and further radio source position updates became available (Gordon et al. 2016). The updated residuals are shown in Figures 7 and 8. The measurement uncertainties have significantly improved. Previously many of the estimated uncertainties were limited by uncertainty in the radio source positions dominated the Saturn position uncertainty. With the updated radio source position catalogs, the uncertainties are now mainly due to uncertainty in the position of the spacecraft with respect to Saturn. The declination residuals and uncertainties appear consistent. The right ascension residuals and uncertainties show hints of systematic errors not yet taken into account. Overall the residuals of the reprocessed measurements are near zero mean with no clear orbital signature.

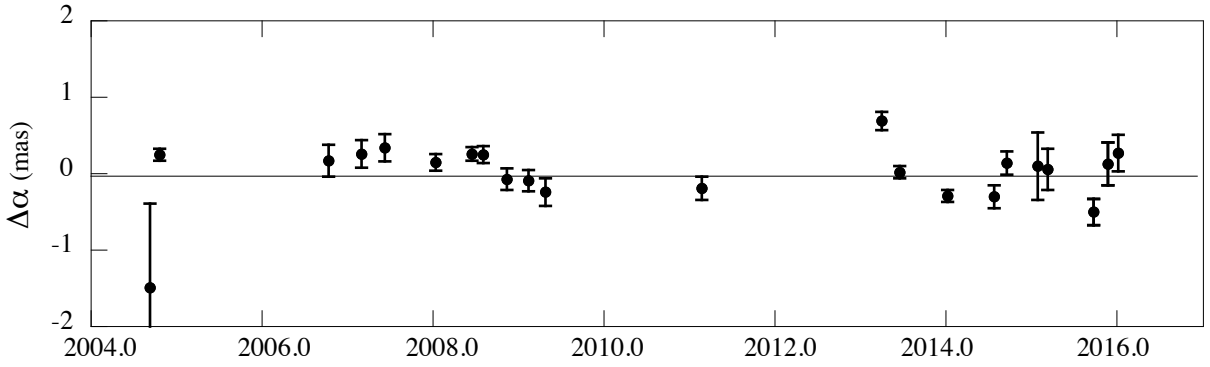

Figure 7: Residuals of VLBA right ascension measurements Saturn updated after creation of DE435.

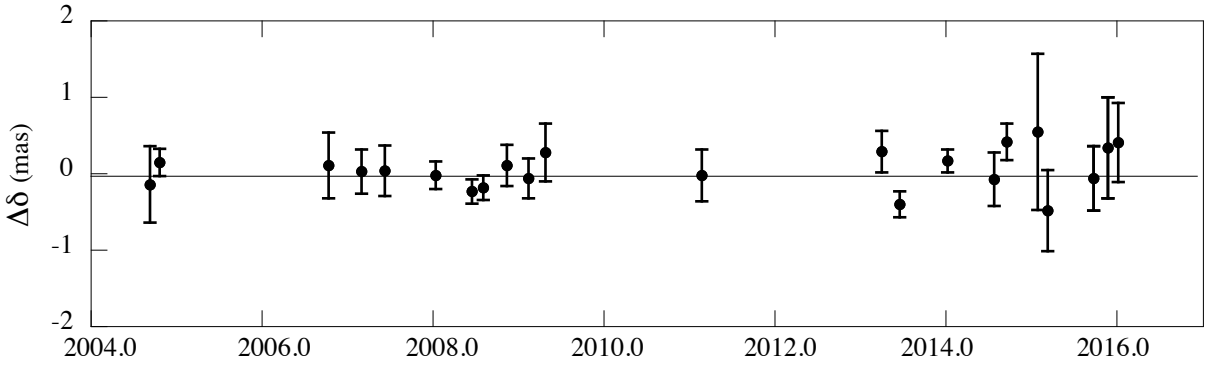

Figure 8: Residuals of VLBA right ascension measurements Saturn updated after creation of DE435.

4. Orbit of Jupiter

DE434 was primarily intended to update the ephemeris of Jupiter for the Juno mission (Park et al., 2015a). DE435 uses the same observation set for Jupiter as DE434 did, but the relative weights of the different data types were changed slightly, after examination of the residuals following the delivery of DE434. The resulting change in the position of Jupiter is shown in Figures 9, 10, and 11. The difference is less than the estimated uncertainty (Park et al., 2015b).

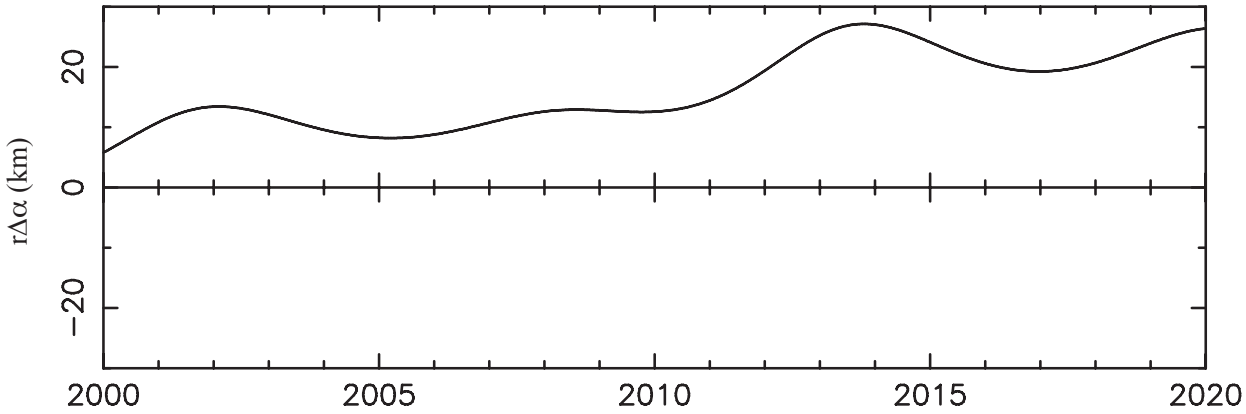

Figure 9. Difference in position of Jupiter with respect to the Sun in direction of increasing right ascension from DE435 compared with DE434.

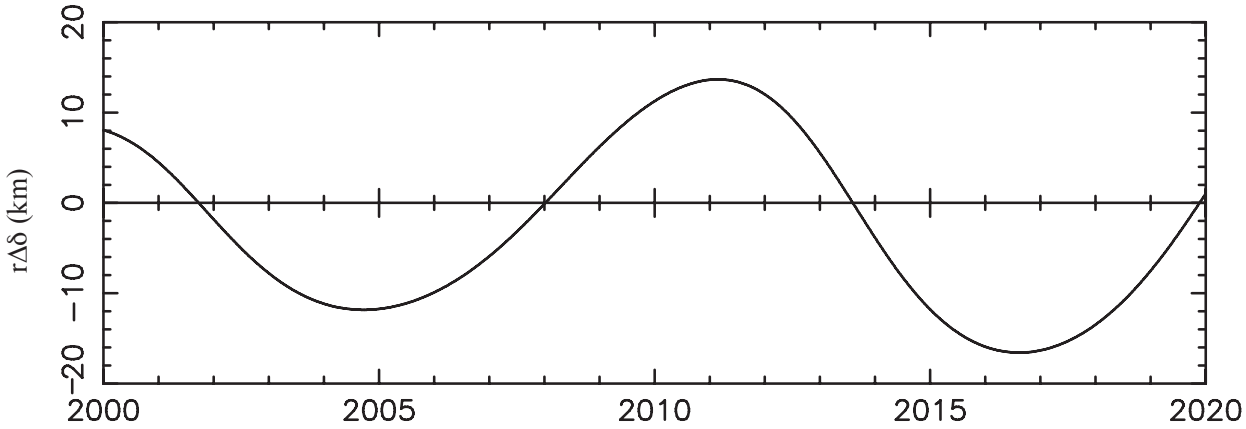

Figure 10. Difference in position of Jupiter with respect to the Sun in direction of increasing declination from DE435 compared with DE434.

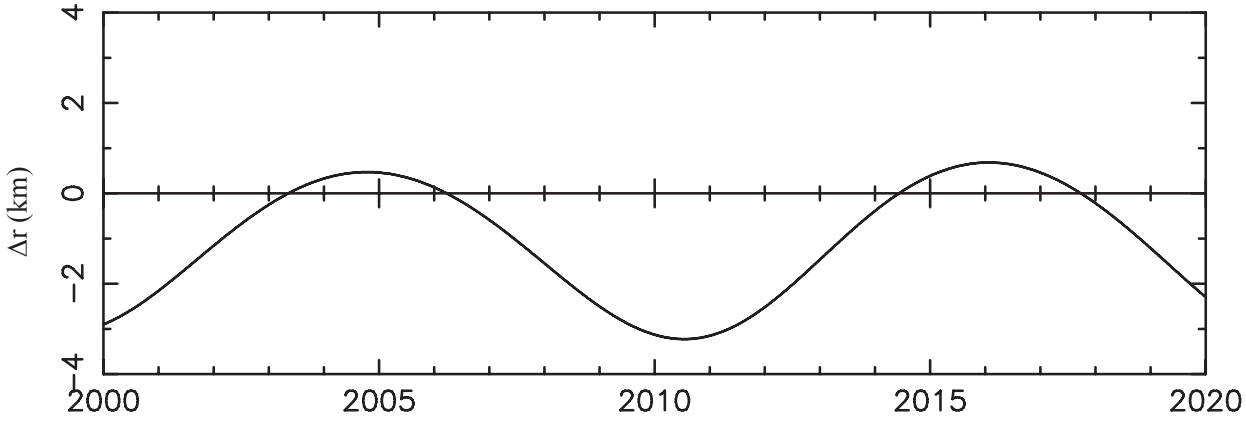

Figure 11. Difference in distance of Jupiter with respect to the Sun from DE435 compared with DE434.

Acknowledgements

Dayton Jones performed and pre-processed the VLBA Measurements. Chris Jacobs provided pre-prelease information on the VLBA calibrator catalog update.

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