ASTROMETRY OF CASSINI WITH THE VLBA TO IMPROVE THE SATURN EPHEMERIS

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ABSTRACT

Planetary ephemerides have been developed and improved over centuries. They are a fundamental tool for understanding solar system dynamics, and essential for planetary and small body mass determinations, occultation predictions, high-precision tests of general relativity, pulsar timing, and interplanetary spacecraft navigation. This paper presents recent results from a continuing program of high-precision astrometric very long baseline interferometry (VLBI) observations of the Cassini spacecraft orbiting Saturn, using the Very Long Baseline Array (VLBA). We have previously shown that VLBA measurements can be combined with spacecraft orbit determinations from Doppler and range tracking and VLBI links to the inertial extragalactic reference frame to provide the most accurate barycentric positions currently available for Saturn. Here we report an additional five years of VLBA observations along with improved phase reference source positions, resulting in an improvement in residuals with respect to the Jet Propulsion Laboratory’s dynamical ephemeris.

Key words: astrometry – planets and satellites: individual (Saturn) – techniques: interferometric

1. INTRODUCTION

For the past decade, observations of Cassini have been carried out by the Jet Propulsion Laboratory (JPL) and the National Radio Astronomy Observatory (NRAO) with the Very Long Baseline Array (VLBA) (Jones et al. 2011, 2012). These observations are planned to continue until the end of the Cassini mission in 2017. We will then have high accuracy measurements over the largest possible fraction of Saturn’s orbital period. The error in determining the plane of Saturn’s orbit (latitude) decreases rapidly as the total time span of observations increases, and a longer total time span for the astrometric observation allows the ephemeris improvements to be extended much further into the future. Accurate ephemerides are one of the basic tools of astronomy, whose accuracy requires regular observational support to maintain and improve. As an example, NANOGrav and other pulsar timing arrays (e.g., Perridon, et al. 2013) will directly benefit from future ephemeris improvements.

The orbits of the inner planets are accurately tied together with current data, but the outer planets are not as well tied to the inner planets or each other. The Cassini mission provides our first opportunity to incorporate high-accuracy data from a spacecraft orbiting an outer planet for an extended period of time. Our goal is to improve the accuracy of barycenter position measurements of Saturn in the inertial international celestial reference frame (ICRF2, Fey et al. 2004, 2009; Ma et al. 2009) through phase-referenced very long baseline interferometry (VLBI) observations of Cassini at 8.4 GHz combined with orbit determinations from Doppler and range tracking. (See Asmar & Armstrong 2005 for a summary of spacecraft Doppler tracking.) The Cassini orbit can be determined to about 2 km at apoapse and 0.1 km at periapse relative to the center of mass of Saturn. The exact accuracy of Cassini orbit solutions varies from orbit to orbit, as the orbital period changes and shorter orbits provide fewer Doppler measurements per orbit segment. Previous work has demonstrated a reduction in ephemeris residuals for Saturn of a factor of three by combining observations made with the VLBA and Cassini spacecraft orbit solutions from Deep Space Network (DSN) tracking.

The stability of the ICRF2 (rotational accuracy) is approximately 0.01 milliarcsec (mas; 1 mas = 5 nrad), although individual sources may have position errors of 0.05–0.15 mas or more (Fey et al. 2004, 2009; Ma et al. 2009; Porcas 2009) due to changes in source morphology. The high resolution imaging capability of the VLBA allows us to detect source changes. Prior phase-referenced VLBI astrometry results (e.g., Lestrade et al. 1999) suggest that a precision of 0.1 mas with respect to nearby ICRF2 sources can be achieved for Cassini. Thus, the combined error of our absolute Cassini positions with respect to the ICRF2 is expected to be about 0.2 mas, similar to VLBI spacecraft tracking errors calculated by Lanyi et al. (2007), Border et al. (2008), and Curkendall & Border (2013).

2. NEW OBSERVATIONS

We have observed Cassini with the VLBA during 12 epochs between 2008 and 2014 under experiment codes BJ061, BJ067, BJ079, and BJ082. Results from the first eight epochs were reported in Jones et al. (2011). Table 1 lists the observing epochs up to early 2014, including the VLBA antennas used during each epoch. The VLBA consists of ten 25 m diameter radio antennas located in the northern hemisphere from the US Virgin Islands to Hawaii. It has demonstrated a uniquely good astrometric precision of <0.01 mas (10 μas) in particularly favorable circumstances (e.g., Fomalont & Kopeikin 2003).

We used standard phase-referencing techniques (Counselman et al. 1972; Shapiro et al. 1979; Lestrade et al. 1990; Guirado et al. 1997, 2001; Fomalont 2006) with rapidly
alternating scans between Cassini and angularly nearby reference sources (see Table 2). Each of our observing epochs was four hours long, including both the alternating short scans on Cassini and phase reference sources and a period of about 40 minutes during which we observed multiple strong sources spread over the sky to allow better fitting for the tropospheric delay at each site (Lestrade 2004; Mioduszewski & Kogan 2004; Fomalont & Kogan 2005). We used an instrument configuration that provided either four separate frequency bands in both right and left hand circular polarizations (RCP and LCP), or eight frequency bands in RCP only. In both cases we spaced the multiple receiving bands non-uniformly across a wide frequency range of several hundred MHz centered near 8.4 GHz to allow accurate group delay measurements. During our most recent three epochs we were able to benefit from an upgrade in the VLBA data recording rate to 2 Gb s$^{-1}$ from 512 Mb s$^{-1}$. This effectively doubled the array sensitivity and allowed us to utilize weaker but angularly closer reference sources to improve the cancelation of tropospheric delay errors. All data were processed by the DiFX software correlator (Deller et al. 2007, 2011) at NRAO in Socorro, NM.

Data from each epoch were used to produce a phase-referenced image of the spacecraft signal without self-calibration, using the Astronomical Image Processing System (AIPS)$^6$ for data editing, calibration, fringe fitting, and image formation and deconvolution. The position of the signal peak was measured and the image shifted to the nominal phase center. This position shift, plus any residual position error measured from the post-shift baseline phases, was combined with the VLBI geometric model to produce total phase delay data. The difference in the total delays between the spacecraft and reference source is the observable used by JPL navigation and ephemeris software.

The analysis of data from a phase-referenced VLBI experiment involves the removal of multiple sources of error (e.g., Lanyi et al. 2005). The following subsections describe the more important of these corrections.

\section*{2.1. Experiment Scheduling}

Because the apparent motion of Saturn on the sky reverses direction twice every year, it is possible with careful scheduling to use the same phase reference source during multiple epochs. This reduces the number of separate phase reference sources that need to be tied to the ICRF. It was not always possible to find a suitable phase reference source within $2^\circ$ of Cassini because we were constrained to observe during times when Cassini had its high gain antenna pointing toward earth and was transmitting. We used schedules of Cassini tracking passes at the DSN Goldstone complex in California to determine when a signal would be present. There is also a tradeoff between the angular distance to a particular reference source and its nominal flux density. The increased VLBA data rate will help in this regard, allowing useful data to be obtained from reference sources with flux densities well below 100 mJy (our previous flux density cutoff). In addition to the systematic error cancelation advantages of using angularly closer reference sources, there is evidence that weaker radio sources have morphologies that are more dominated by single compact components (Deller & Middelberg 2014).

\section*{2.2. A Priori Calibration}

The geometric model used during correlation (Romney 1999) provided the initial delays. However, the a priori spacecraft position and proper motions available before each epoch were not sufficiently accurate for correlation, so reconstructed orbit files from JPL were used after each epoch to improve the geometric model. The model takes into account the difference in general relativity corrections for signals

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propagating different distances through gravitational fields in the solar system (only part of the solar system gravitational field applies to signals from Cassini).

Initial amplitude calibration was based on continuously recorded system temperatures and previously determined gain curves for each VLBA antenna. Corrections were applied for the two-bit signal quantization used at the VLBA antennas, and phase corrections were applied to account for changing parallactic angles and for up-to-date earth orientation parameters (UT1 and polar motion). Fixed delay offsets in the electronics were corrected by fringe fitting a strong calibration source and using the resulting delay corrections to align phases within each frequency band. The data were examined manually to verify that a priori calibration had been applied correctly.

2.3. Ionosphere Delay Calibration

The frequency differences between our frequency bands were not large enough to accurately calculate dispersive ionosphere delays. Instead, these delays were calculated from Global Ionosphere Maps (GIMs) determined from a large network of GPS receivers at two-hour intervals (Mannucci et al. 1998). For each antenna location the zenith total electron content values from the global maps were linearly interpolated between maps on either side of a particular observing scan. In addition, a weighted longitude correction was introduced to account for the expected movement of ionospheric features with the Sun during the period between GIM epochs.

2.4. Troposphere Delay Calibration

Troposphere delay calibration has been especially important for the more recent observing epochs, as Saturn has been moving south in decl. for the past several years. For a northern hemisphere VLBI array that means that observations must be made at lower elevation angles where troposphere effects are enhanced. During each epoch a sample of approximately 15 strong compact sources covering a wide range of elevation angles at each VLBA antenna were observed in a rapid sequence. By fitting a linear phase slope to the frequency channels we obtained multi-band delays for each source. The Chao (1974) troposphere delay mapping function was then fit to the multi-band delays to determine the zenith troposphere delay, clock offset, and clock rate for each antenna (see Sovers et al. 1998; Mioduszewski & Kogan 2004). When the troposphere delay was properly calculated and removed, the phases were aligned between all frequency bands for each source. We have not used multiple calibration sources bracketing the position of Cassini to further improve the troposphere delay corrections, as demonstrated by Fomalont & Kogan (2005), because we wished to keep the beam switching cycle time as short as possible. Future observations will explore the trade between these observing approaches.

2.5. Bandpass Calibration

The bandpass amplitude and phase response, and any remaining antenna-based residual delays, were corrected by observing a strong calibration source during each epoch. This is important for our measurements because the spacecraft signal occupies only a small fraction of the bandwidth containing the reference source signal. Uncalibrated bandpass phase variations would produce a systematic phase offset between the two signals. After all calibration steps up to this point were applied to the data they were then averaged over single scans and the phases examined for each source and baseline to verify that they were constant within and between frequency bands.

2.6. Phase-referencing

We used a point source model for phase self-calibration of the visibilities for the phase reference calibration sources. The phase corrections from self-calibration were then applied to the Cassini visibilities, removing most of the remaining common errors. The Cassini data were not self-calibrated. Images were made of both the phase reference source and Cassini. The reference source map was examined to check that the point source model had been an adequate approximation. The peak of the Cassini image was usually visibly offset from the image phase center. Figure 1 shows a typical phase-referenced image of Cassini.

A two-dimensional quadratic fit was used to measure the position of the Cassini peak, and an appropriate phase slope was applied to the Cassini visibilities to shift the peak to the phase center of the image. The Cassini baseline phases were examined after the position shift to verify that they were (nearly) flat. The position shift applied to the Cassini image is the offset in the a priori Cassini position with respect to the a priori position of the phase reference source and the geometric model used. Consequently, the uncertainty in the ICRF position of Cassini at any epoch can be no better than the uncertainty in the ICRF2 position of the associated reference source, even though the relative position offset between Cassini and the reference source may have a much smaller uncertainty. Thus, the accuracy of our phase reference source ICRF2 positions is an important issue. Continuing observations...
of ICRF2 catalog source positions are constantly improving the accuracies of these positions (e.g., Fey et al. 2009; Ma et al. 2009). We also use source positions obtained by the DSN (Border 2009; Jacobs 2013), and by GSFC and Petrov (2012). Ideally we would focus on reference sources that display persistent interstellar scintillation, as these appear to have a more compact structure and higher astrometric positional stability (Schaap et al. 2013). However, the relatively small number of potential phase reference sources precludes using this additional selection filter.

Table 3 shows the positions used for our primary phase reference sources. Most of these positions are from the ICRF2 or DSN source catalogs, depending on which appeared to have the best accuracy for each source. Note that some of the sources in Table 3 have slightly different positions and smaller errors compared to the positions used by Jones et al. (2011). Note also that despite the continuing improvements in positional accuracy, 4 of the 10 sources in Table 3 still have errors (slightly) greater than 0.2 mas in decl. All errors are less than 0.2 mas in R.A. The source J1217-0029 does not appear in Table 2 because it was used during epoch BJ067B, which occurred during a period when Cassini was not transmitting to Earth. It is included in Table 3 for completeness.

ICRF and DSN source positions are based on group delay measurements, while our Cassini astrometry is based on phase delay measurements. Source positions measured with group delays are less affected by variations in opacity along the inner regions of radio jets. Consequently there can be time-variable offsets between group delay and phase delay measurements of the position of the radio centroid of a given reference source. Investigation by Porcas (2009) has found that the offsets between group and phase delay positions are normally less than 0.2 mas at 8.4 GHz. This is similar to the errors expected from imperfect troposphere delay calibration and individual ICRF2 source position errors, so this effect does not dominate our experimental error budget.

### 2.7. Total Delays

Total delays for use with JPL navigation and ephemeris software were calculated from AIPS data tables containing the correlator geometric model, the measured residual delays (Cassini image position shift), and any additional small delay corrections from the post-shift Cassini baseline phases. Calculation of the total delays and the creation of output data files in the format needed by JPL was done with a program software were calculated from AIPS data tables containing the correlator geometric model, the measured residual delays (Cassini image position shift), and any additional small delay corrections from the post-shift Cassini baseline phases. Calculation of the total delays and the creation of output data files in the format needed by JPL was done with a program written by E. Fomalont.

### 3. RESULTS

The derived J2000 (ICRF2) positions of the Saturn system barycenter from VLBA observations of Cassini, including detailed Cassini orbit reconstructions, are listed in Table 4. This table is the main result of our observations. The orbital solutions for Cassini were produced by integrating the equations of motion as part of a global Saturn ephemeris and gravity field solution (e.g., Antreasian et al. 2008b; Jacobson et al. 2006). These solutions used a large number of recent and historical observations, and include the gravitational effects of solar system objects (including the mutual interactions of Saturnian moons), relativistic perturbations, Saturn oblateness, and non-gravitational effects (spacecraft attitude control, trajectory maneuvers, and solar radiation pressure). Table 4 includes two epochs from VLBA experiment BR103 in 2004, and one epoch from Fomalont et al. (2010) in 2009 February. These experiments were included with the epochs from experiments BJ061, BJ067, BJ079, and BJ082 because they used the same observing technique and instrumentation to determine astrometric positions for Cassini.

Figure 2 shows the post-fit residuals of our Cassini/VLBA-derived Saturn barycentric positions after fitting to a temporary ephemeris. A large part of the improvement since the ephemeris fit shown in Jones et al. (2011) comes from improved positions for our phase calibration sources. The rms of the residuals after fitting is 0.5 mas in R.A. using all data, but only 0.2 mas if the two outliers are removed. One of the outliers is from an epoch prior to Cassini orbit insertion around Saturn when the spacecraft orbit is expected to be less well determined, and the post-fit residual rms in decl. is 0.4 mas. Both rms residual values are consistent with the expected errors. The larger uncertainty in decl. is mainly due to the reduced N-S resolution of the VLBA for low decl. sources. Comparable astrometric results for the European Space Agency’s Venus Express spacecraft have been reported by Duev et al. (2012) using different antennas and software.

The DE430 planetary ephemeris (Folkner et al. 2014) is based on fitting the DE421 ephemeris (Folkner et al. 2009) to our previous Cassini VLBA observations, tracking data from Mars and Venus orbiters (Mars Reconnaissance Orbiter, Mars Express, Mars Odyssey, and Venus Express), and optical observations of the outer planets. The errors are based on independent estimates of the uncertainties in the VLBA positions including uncertainties in the phase reference source positions, and the orbit determination uncertainties in the position of Cassini with respect to the barycenter of Saturn.
Our more recent Saturn position determinations will help constrain the next generation of JPL planetary ephemerides. Figures 3–5 show the formal estimated uncertainty in the R.A., decl., and distance of the Saturn system barycenter from Earth as a function of time. The uncertainty in decl. is determined primarily by the VLBA observations of Cassini described here. The uncertainty in R.A. is determined near the time of the measurements by the VLBA measurements, but increases at later times due to uncertainty in the Saturn semimajor axis, determined primarily by ranging...
measurements to the Cassini spacecraft (Hees et al. 2014). The formal uncertainties shown are typically optimistic since they are based on the assumption that all measurements are uncorrelated. Systematic errors are sometimes common to multiple measurements, such as uncertainty in a quasar location used for multiple VLBA observations, or station delay calibration errors that affect multiple ranging measurements (Konopliv et al. 2011). Actual uncertainties in planetary orbits are typically 2–3 times larger than the formal uncertainties.

4. CONCLUSIONS

The Cassini mission has been extended until 2017. At that time we will have high accuracy measurements covering one-third of Saturn’s orbital period. The error in determining the plane of Saturn’s orbit (latitude) rapidly decreases until the time span of observations exceeds 1/4 of the orbital period, while the error in longitude decreases approximately linearly with increasing time span. Figure 4 shows that the average error in decl. (latitude) does not grow significantly over a century-long time interval. The current error for Cassini positions in the ICRF is estimated to be approximately 0.3–0.4 mas (depending on the specific phase reference source used). Future VLBI observations to maintain and improve the ICRF2 catalog will continue to reduce the position errors of these sources.

The next mission to a gas giant planet is the Juno mission to Jupiter, launched in 2011 August. The Juno spacecraft will orbit Jupiter for at least one earth year beginning in 2016 July. This orbiting mission will provide an opportunity to use the same phase-referenced astrometry techniques with the VLBA, and thereby improve the ephemeris of Jupiter in a similar manner.

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Facilities: VLBA, Cassini.

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