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Astrographic observations of Phoebe from Voyager 2

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Abstract. This article provides the reduced astrographic observations of the ninth Saturnian satellite, Phoebe, derived from star-satellite imaging data acquired by the Voyager 2 spacecraft. The data set contains 8 pairs of spacecraft-centered right ascension and declination observations and includes all of the observations used in Voyager encounter operations. The conversion process from imaging to astrographic observations was identical to that used for the Neptunian satellites (Jacobson 1991) and Uranian satellites (Jacobson 1992). The effect of using the astrographic rather than imaging form in ephemeris improvement is evaluated.

Key words: Astrometry – Planets and satellites: general – Planets and satellites:individual: Saturn – Planets and satellites:individual: Phoebe – Solar system: general

1. Introduction

Optical observations of planetary satellites made from spacecraft provide high quality accurate data for determining the satellite orbits. Processing this data in its original form, however, requires the use of complex software, e.g., JPL's Optical Navigation Program (Owen 1988), to generate the computed observables, residuals, and associated partial derivatives. This requirement makes it difficult for most researchers to incorporate the original spacecraft based observations into the study of satellite orbits and the development of satellite ephemerides. Consequently, for spacecraft based data to be readily usable, it should be in an alternate but equivalent form.

Duxbury and Callahan (1988,1989) converted the Viking and Mariner imaging data for the Martian satellites into an equivalent astrometric form and published it together with the associated spacecraft information needed to process it. Similar conversions were carried out by Kolyuka et al. (1991) for the observations of the Martian satellites acquired by the Phobos spacecraft, by Jacobson (1991, Paper I) for the observations of the major Neptunian satellites acquired by the Voyager 2 spacecraft, and by Jacobson (1992, Paper II) for the observations of the major Uranian satellites acquired by the Voyager 2 spacecraft. This article continues the conversion of the Voyager 2 imaging data focusing on Phoebe, the ninth satellite of Saturn.

The next section describes the imaging data and gives an overview of the procedure for their conversion. Subsequent sections discuss the observation modeling for orbit improvement, present the astrographic data and their errors, and examine the differences in satellite orbit determination induced by the use of the astrographic rather than the original form of the data.

2. Imaging data and its conversion

The imaging data relevant to satellite orbit analysis are those acquired for the purpose of spacecraft navigation. They are pictures made with the Voyager narrow-angle camera of satellites against a star background. The satellite and star images in the picture provide information on both the satellite orbits and the inertial pointing direction of the camera. The camera, a Vidicon imaging instrument, is described in detail in Smith et al. (1977); the images, their error sources, their processing, and their use in navigation are discussed by Synnott et al. (1986) and Riedel et al. (1990).

Voyager 2 acquired a total of 8 pictures of Phoebe during the period from 17 June 1981 to 15 August 1981. Spacecraft-satellite ranges varied from 15 to 57 million km giving observation accuracies of 50 to 150 km.

The specific observables within the pictures are the two dimensional measures of satellite and star image locations. Each picture is actually a two dimensional charge distribution on a photoconductive surface produced by exposure to incoming light from the viewed objects. The surface is divided into an array of picture elements (pixels) which are scanned and sampled by an electron beam. The locations of images are specified by cartesian coordinates in a system which has its horizontal axis aligned with the scanning direction and its vertical axis normal to the scanning direction. The abscissa and ordinate of the image are

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known as its pixel and line coordinates. The "pixel" coordinate is also known as "sample" in some communities.

Papers I and II discuss in detail the conversion from pixel and line to inertial angles. Briefly, the procedure is as follows: first, the pixel and line coordinates are related to the focal plane coordinates through a matrix which describes the physical layout (1 1 the pixels within the focal plane; next, the focal plane coordinates are related to the components of the unit pointing vector in the camera body reference frame through a gnomonic projection involving the camera focal length; finally, the pointing vector is rotated from camera body to inertial coordinates giving the unit vector in the direction of the viewed object, $\hat{\mathbf{T}}'$. Because the effects of stellar aberration are included in the imaging data processing, $\hat{\mathbf{T}}'$ is actually the *apparent* position of the object as seen from the spacecraft. When processing observations, the actual rather than apparent position of the object is preferred. For that reason, we remove the stellar aberration effects from the observations. The relationship between unit vectors in the actual and apparent position directions (see Paper 1) is

$$\hat{\mathbf{T}} = \left[\left(\hat{\mathbf{T}}' \cdot \boldsymbol{V}\right) + \sqrt{1 - (\boldsymbol{V}\cdot\boldsymbol{V}) + \left(\hat{\mathbf{T}}' \cdot \boldsymbol{V}\right)^2}\right]\hat{\mathbf{T}}' - \boldsymbol{V} \quad (1)$$

where $\boldsymbol{V}$ is the spacecraft velocity relative to the Solar System barycenter in units of the speed of light. The components of $\hat{\mathbf{T}}$ define the inertial angles α and δ,

$$\alpha = \arctan \hat{T}_2/\hat{T}_1 , \quad (2)$$

$$\delta = \arcsin \hat{T}_3 . \quad (3)$$

Uncertainty in the inertial angles is the result of the uncertainty in the original pixel and line coordinates and additional uncertainty introduced by the transformation from pixels and lines to the angles. The sources of the pixel and line coordinate uncertainty are the measurement errors and the error in finding the center of the viewed objects. The uncertainty in the transformation to the angles is strongly affected by uncertainty in the star positions and weakly affected by uncertainty in the spacecraft and viewed satellite positions. Paper I provides more details on the computation of the uncertainty in the angles.

3. Observation modeling

In order to process the observations of a satellite, its position as seen from the spacecraft is computed at the observation time from the expression

$$\mathbf{T} = [\boldsymbol{s}(t - \tau) + \boldsymbol{b}(t - \tau)] - [\boldsymbol{r}(t) + \boldsymbol{b}(t)] . \quad (4)$$

In the above t is the observation time (ET), $\boldsymbol{s}$ is the satellite position relative to the planetary system barycenter, $\boldsymbol{r}$ is the spacecraft position relative to the planetary system barycenter, $\boldsymbol{b}$ is the planetary system position relative to the Solar System barycenter, and τ is the light travel time from the satellite to the spacecraft. Since $\tau = |\mathbf{T}|/c$ (where c is the speed of light), its determination is an iterative process; the iteration procedure is described by Moyer (1971). The need for the planet positions in Eq.(4) may be eliminated by adopting the modified spacecraft position

$$\boldsymbol{r}'(t,\tau) = \boldsymbol{r}(t) + [\boldsymbol{b}(t) - \boldsymbol{b}(t - \tau)] . \quad (5)$$

Introducing the above expression into Eq.(4) reduces it to

$$\mathbf{T} = \boldsymbol{s}(t - \tau) - \boldsymbol{r}'(t,\tau) . \quad (6)$$

Equations (2) and (3), together with Eq.(6), can be used as observation equations for the improvement of the satellite orbits by relating the vector $\boldsymbol{s}$ to model parameters.

Papers I and II describe a model which could be used to account for spacecraft position errors. This model employs a hyperbolic conic approximation for the trajectory relative to the planet and assumes that errors in the orientation of the asymptote of the hyperbola are the largest remaining, which affect the observations. The asymptote is defined in terms of its right ascension and declination, α_a and δ_a. Each paper gives the appropriate a priori uncertainties for these angles.

In the case of the Voyager 2 Saturn encounter, the characterization of the trajectory errors remains an open question. The Phoebe orbit determination from the full set of Earthbased observations and original Voyager imaging observations (Jacobson 1996, Paper III) assumed an error free trajectory. Pending a future reconstruction of the Voyager 2 trajectory, we recommend that spacecraft position errors be neglected when processing the observations.

4. Astrographic observations

Table 1 contains the Voyager 2 astrographic observations. The entries in the table are:

- the Voyager Picture Identification (PICNO),
- the observation time (time of the center of the exposure) in Julian Ephemeris Date (Date),
- the Voyager centered, astrographic right ascension of the satellite in the FK5/J2000 system with units of degrees (α),
- the Voyager centered, astrographic declination of the satellite in the FK5/J2000 system with units of degrees (δ),
- the uncertainty associated with the observed right ascension with units of degrees ($\sigma_\alpha \cos\delta$),
- the uncertainty associated with the observed declination with units of degrees (σ_δ).

Table 2 provides the ancillary information needed to process the astrographic data. It contains:

- the Voyager Picture Identification (PICNO),
- the light travel time from the satellite to the spacecraft in units of seconds (τ),

Table 1. Astrographic data of Phoebe

PICNO	Date (JED)	α (deg)	δ (deg)	$\sigma_\alpha \cos\delta$	σ_δ
41901B+37	2444772.50883454	203.23256	-7.79820	0.00026	0.00026
42182B+27	2444781.86994565	205.30355	-8.74984	0.00026	[illegible]
42351B+55	2444787.51878928	206.79624	-9.42060	0.00026	[illegible]
42800B+50	2444802.48267817	212.10627	11.70900	0.00026	[illegible]
43300B+39	2444819.14334484	222.79324	15.83743	0.00026	0.00026
43461B+08	2444824.49278928	228.63002	17.80772	0.00026	0.00026
43491B+27	2444825.50334484	229.96594	18.22879	0.00026	0.00026
43696B+50	2444832.34944484	241.98215	21.49774	0.00026	0.00026

the modified Saturnbarycentric position of the spacecraft $\mathbf{r}'(t, \tau)$ at the observation time in FK5/J2000 coordinates with units of km (x', y', z'),
the right ascension and declination of the unit vector along the approach trajectory asymptote in the FK5/J2000 system with units of degrees (α_a, δ_a).

The camera pointing angles used in the generation of the astrographic observations were those obtained as a byproduct of the analysis described in Paper III. These angles were originally referenced to a star catalog in the FK4/B1950 system from which the E terms of aberration had been removed (Klemola et al. 1979). For the work in Paper III, the star positions were rotated to FK5/J2000 system following the IAU Commission 20 conversion procedure (Standish et al. 1992). The spacecraft positions are [illegible] the best available Voyager 2 trajectory, the trajectory used in the Paper III analysis; the same trajectory provided the velocities for the stellar aberration correction.

The uncertainties in Table 1 represent the pixel and line uncertainties used in the Voyager imaging data processing [illegible] astrographic form. The imaging data had an uncertainty of 0.5 pixel. Uncertainty due to the camera pointing was ignored (see the discussion in the next section).

5. Evaluation of the astrographic observations

To evaluate the effect of processing the astrographic data rather than the imaging, the Phoebe orbit fit to the former was compared to that described in Paper III. The astrographic data fit simply repeated the fit described in Paper III, but substituted the astrographic data for the imaging data. The camera pointing was the same in both fits, and both included the Earthbased observations in addition to the Voyager data. The imaging data fit estimated the camera pointing angles, as a consequence, accounted for pointing uncertainty. Two different determinations of the orbit were made with the astrographic data: one in which the data weights included the effect of the pointing uncertainty and another in which they did not. Of these orbits, the one found with weights where the pointing [illegible] certainty was neglected agreed best with the Paper III orbit. For this reason the recommended uncertainties in Table 1 exclude the effect of pointing.

Figures 1-3 compare the orbits obtained from the astrographic and imaging data fits. They show the in-orbit, radial distance, and [illegible] of plane differences over the period from January 1900 to January 2000. Because the two fits are identical except for the form of the Voyager observations, the orbit differences represent a direct measure of the errors introduced by the use of the astrographic rather than the imaging data. The RMS differences between the two orbits over the time period 1900 [illegible] 2000 are 1.7 km in the in-orbit direction, 0.2 km in the radial direction, and 2.3 km in the out-of-plane direction. Overall differences are much less than the accuracy of the most accurate imaging data and well below the actual uncertainty in the orbits from Paper III.

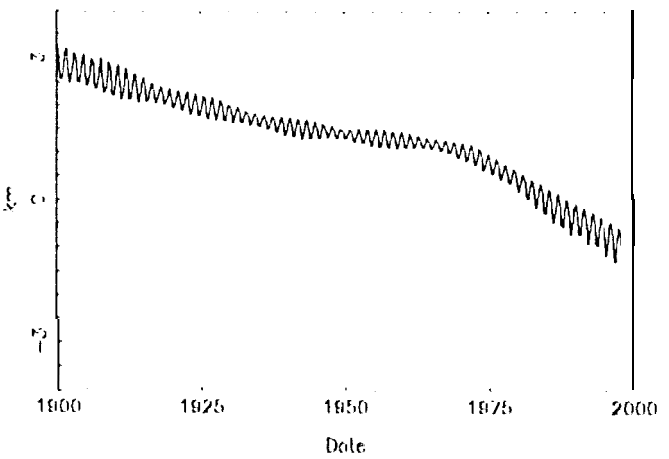

Fig. 1. In-orbit difference: astrographic minus imaging

Table 2. Ancillary astrographic data for Phoebe

PICNO	τ (sec)	x' (km)	y' (km)	z' (km)	α_p (deg)	δ_p (deg)
41901B+37	191.456	63212736.7	19186851.2	4917903.3	278.06	64.12
42182B+27	167.105	54904219.2	16711065.1	4293684.9	278.09	64.04
42351B+55	152.730	49888983.2	15216249.1	3916749.3	278.10	64.01
42800B+50	115.854	36591810.2	11251581.6	2917321.2	278.15	63.87
43300B+39	77.283	21739084.8	6822820.3	1799033.7	277.96	64.36
43461B+08	65.783	16946480.2	5393289.7	1437905.0	277.96	64.35
43491B+27	63.688	16038780.6	5122490.1	1369484.5	277.96	64.35
43696B+50	50.472	9856617.7	3277257.0	9[13(177,4	277.96	64.35

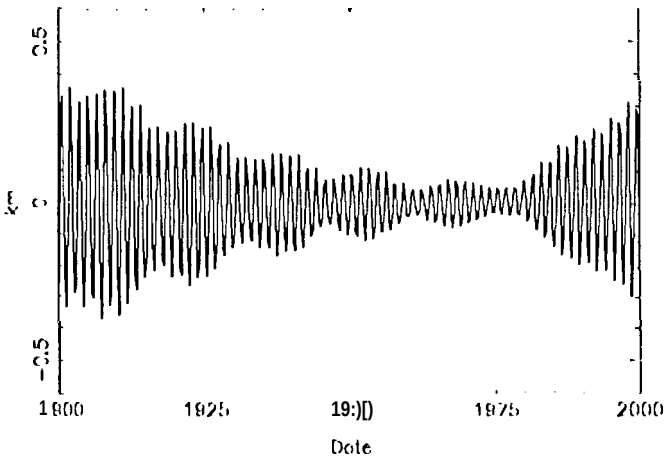

Fig. 2. Radial distance difference: astrographic minus imaging.

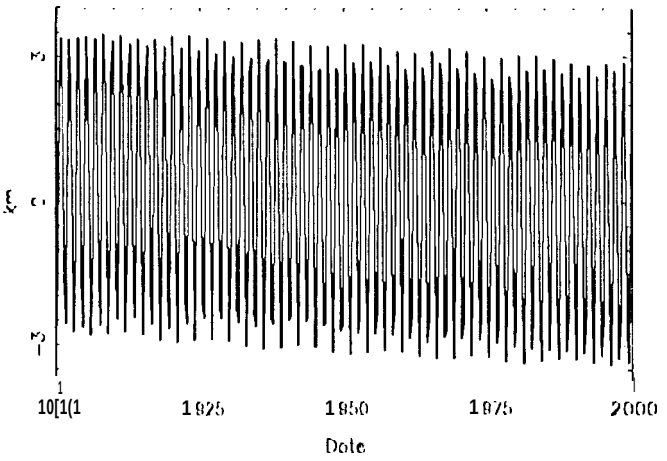

Fig. 3. 0111 of plane difference: astrographic minus imaging

6. Concluding remarks

The Voyager 2 encounter with Saturn provided a number of very accurate observations of Phoebe. The observations, in their original form, permitted the determination of the precise orbit for Phoebe needed by the Voyager project. Later the same observations contributed 1(I a redetermination of Phoebe's orbit which incorporated post Voyager Earthbased observations. This article has presented the observations converted to a more convenient, but equivalent, astrographic form. The effect of errors introduced by the conversion process was examined and found 1(I be negligible.

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