RECONSTRUCTION OF THE VOYAGER SATURN ENCOUNTER ORBITS IN THE ICRF SYSTEM

Robert A. Jacobson†

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

The Voyager 1 and Voyager 2 spacecraft visited the Saturnian system in November 1980 and August 1981, respectively. Campbell *et al.*[1] discussed the determination of the spacecraft orbits, and Campbell and Anderson[2] used data from the encounters to improve knowledge of the Saturnian gravity field. In anticipation of the Cassini tour, we have re-examined the results from the Voyager mission. We obtain Voyager trajectories in the International Celestial Reference Frame, and we revise the gravity field taking advantage of improvements made in modelling and data processing since the previous work. We also incorporate a full dynamical model for the Saturnian satellites into the analysis for the first time.

INTRODUCTION

The Saturnian system was visited by the Voyager 1 and Voyager 2 spacecraft in November 1980 and August 1981, respectively. Campbell *et al.*[1] provided a detailed discussion of the determination of the orbits of both spacecraft. Using tracking data acquired during the Voyager encounters, Campbell and Anderson[2] subsequently improved the knowledge of the Saturnian gravity field. The Voyager imaging data also aided in the determination of the orbits of the Saturnian satellites[3,4,5]. As a part of the preparation for the Cassini tour of the Saturnian system, beginning in July 2004, we re-examined the results from the Voyager mission. The objectives of our analysis were:

- to repeat the gravity field investigation taking advantage of improvements made in modelling and data processing since the original analysis.
- 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 obtain Voyager trajectories in the International Celestial Reference Frame (ICRF) which will facilitate combined Voyager and Cassini data analyses; the original Voyager analysis was in the B1950 system and Cassini uses the ICRF.

†Member of the Technical Staff, Jet Propulsion Laboratory, Associate Fellow AIAA.

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 acquired with vidicon system). For Voyager 2 they used a 55 day data arc from 1 August 1981 to 24 September 1981. The data types 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.

In their gravity work Campbell and Anderson used a combination of the Voyager data and coherent Doppler obtained from the earlier Pioneer 11 Saturn encounter[6]. Besides the gravity parameters, they obtained reconstructed trajectories for all three spacecraft. In this case the reconstructions were 'simultaneous' in the sense that estimates of the common parameters such as those of the gravity field were determined from the combined data set. The Voyager 2 data also included 6 hours of noncoherent one-way Doppler just after the Tethys flyby. A single set satellite ephemerides, produced with the analytical theories, covered the three encounters[3]. The data spans, however, were limited to the periods from 10 days before to 5 days after each Saturn closest approach. Consequently, the trajectories applied only the close encounter time frame.

Our analysis relies on 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. To enhance our gravity parameter solutions, we include the Voyager 2 noncoherent one-way Doppler and the Pioneer 11 Doppler used by Campbell and Anderson. We cover the encounters with a single set satellite ephemerides obtained from a dynamically complete numerical integration of the satellite orbits. We have also extended the ephemerides to include the Lagrangian satellites Helene, Telesto, and Calypso. Observations of these satellites provide valuable information on the masses of Tethys and Dione[4].

ANALYSIS

Data

We relied on three basic types of data in the analysis: spacecraft radiometric tracking, spacecraft optical navigation observations, and satellite astrometry. The Pioneer Doppler and Voyager Doppler and range tracking data are essentially identical to that used in the earlier analyses. The only differences, as noted in the previous section, were the in lengths of the Voyager data arcs. A complete description of the spacecraft data appears in the references. We calibrated the tracking data for the effects of the Earth's troposphere and ionosphere and the interplanetary plasma (the Pioneer Doppler was calibrated only for the troposphere). The Voyager imaging data were originally referenced to star catalogs in B1950 system; we modified them, replacing the reference star locations with ICRF positions from the Tycho 2 star catalog.

The satellite astrometry is derived from telescopic observations made at several astronomical observatories over the time period 1966 to 2003. It includes both satellite to satellite relative positions, satellite to planet relative positions, and absolute satellite positions. References for the pre-1990 observations of the major satellites may be found in Strugnell and Taylor[7]. The post-1990 observation set contains relative positions measured photographically[8–11], relative positions measured with CCDs[12–19], and ICRF positions measured with CCDs[20–25]. Photographic relative positions of the Lagrangian satellites may be found in Ref. 26-36, and CCD relative positions appear in Ref. 17,18,37,38. Augmenting the data from Earthbased observatories are satellite to satellite relative positions of the major and Lagrangian satellites obtained with the Hubble Space Telescope[39,40].

Dynamical Model

Our dynamical model contains both gravitational and non-gravitational forces; the former affect the motion of the spacecraft, planet, and satellites whereas the latter affect only the spacecraft.

Sources of the gravitational forces are the Sun, the solar system planets, and the Saturnian satellites. JPL planetary ephemeris DE405[41] provides the positions and masses of the Sun and planets. The satellite positions are from ephemerides based on high precision numerical integration and are significantly more accurate than those from the analyical theories[3] used previously. The increased accuracy not only improves the dynamical modelling of the spacecraft trajectories but also enhances the contribution of the optical navigation data to the determination of the Voyager trajectories. Moreover, the integrated ephemerides, unlike the analytical theories, are sensitive to the values of the gravity parameters; the sensitivity aids in the determination of those parameters.

The gravity field of the planet is represented by the standard spherical harmonic expansion of its gravitational potential. We use the same degree and order harmonic coefficients as did Campbell and Anderson. The orientation of the pole of Saturn (needed for the gravity field model) cannot be accurately determined from spacecraft and satellite data. Campbell and Anderson adopted the pole direction found by Simpson *et al.*[42] using Voyager occultation data. We replaced that pole with the revised one from French *et al.*[43] and have included the pole precession rate of Nicholson *et al.*[44].

Solar radiation pressure effects on the spacecraft are modelled with the formulation of Georgevic[45]. The values of the parameters in the models were determined during the Earth-Jupiter cruise period of each spacecraft. We retained those values.

The Voyager spacecraft are three-axis stabilized. Attitude is changed and maintained by groups of thrusters which are unbalanced, i.e., they do not fire in pairs separated from the center of mass on opposite moment arms. Consequently, there is a net translational velocity imparted to the spacecraft each time a thruster is fired. In addition, due to a design flaw, the exhaust plumes from the pitch thrusters strike the spacecraft adding to the translational velocity when they are fired. We included impulses along the spacecraft axes at the times of a number of the larger attitude changes to account for the translations. The remaining attitude control pulses were modelled as the sum of constant and stochastic accelerations along the spacecraft axes. This model also absorbed the effects of non-isotropic thermal radiation from the RTGs (Pu^{238} radioactive thermal generators which provide electrical power) and solar pressure mis-modelling. The non-gravitational accelerations were a major source of Voyager navigation error; Ref. 46 contains an excellent discussion of them. During the time frame of our analysis each Voyager spacecraft made two trajectory correction maneuvers (TCM). We modelled them with the finite burn (rocket equation) model.

The Pioneer spacecraft is spin stabilized(5 rpm). To maintain the high-gain antenna pointing toward the Earth the spin axis had to be re-oriented (precessed) periodically. Two precession maneuvers occurred within our data arc, and we modelled them as velocity impulses along the spacecraft axes. Pioneer is also subject to non-gravitational accelerations due to gas leaks in the attitude control system, thermal radiation from the RTGs, and mis-modelling of the solar pressure acceleration. We accounted for these effects with a constant acceleration along the spin axis; the spacecraft's rotation causes the effects of accelerations normal to the spin axis average out.

Method of Solution

We determined the orbits of the spacecraft, the planet, and the satellites by adjusting parameters in the dynamical model to obtain a weighted least-squares fit to the observational data. The fundamental adjustable parameters were:

- epoch position and velocity of each spacecraft and satellite
- elements of the Saturn orbit
- GM's of the Saturnian system and the satellites
- gravitational harmonics of Saturn
- thrust magnitude and direction for large spacecraft maneuvers
- impulsive velocity changes for small spacecraft maneuvers
- non-gravitational accelerations

In order to obtain an adequate fit to the observations we also had to adjust the following parameters in the observation model:

- one-way Doppler biases and drift rates
- station dependent range biases
- spacecraft camera pointing angles

Unlike all previous analyses we did not need to account for errors in the locations of the Earth tracking stations because they are well known in the ICRF system. For the same reason we ignored possible errors in the ephemeris of the Earth.

We processed the observations with a batch-sequential, square-root information filter, treating the stochastic non-gravitational accelerations as colored noise with a 1 day correlation time and the range biases and camera pointing angles as white noise. The accelerations were batched at 1 day intervals, the range biases were batched by tracking pass, and the pointing angles were batched by picture. As did Campbell and Anderson, we included a priori information on Saturn's zonal harmonics from the ringlet constraint devised by Nicholson and Porco[47]. A priori information on the Saturn orbit, based on the data used in the development of DE405, was provided by E. M. Standish[48].

With multiple data types data weights balance the information provided by each type as well as represent the accuracy of the type. Assigning the weights is as much an art as a science. Our selections were guided by knowledge of the potential accuracy of the type coupled with an examination of the data residuals.

We set separate Doppler weights for each DSN pass to correspond to an accuracy of 2.5 times the root-mean-square (rms) of the residuals for that pass. However, no two-way Doppler was weighted tighter than 1.0 mm sec^{-1}, and no one-way or three-way Doppler was weighted tighter than 2.0 mm sec^{-1}. The accuracies represented by the range weights were 400 m for Voyager 1 and 200 m for Voyager 2 (the interplanetary plasma had a higher effect on Voyager 1). The range was deweighted from its actual accuracy of a few tens of meters because fitting it is sensitive to the non-gravitational accelerations. The stochastic range biases account for range calibration errors and further deweight the range data. The biases had 10 m a priori uncertainties.

The accuracy assumed for most of the imaging data was 0.5 pixels for the stars and major satellites and 1.0 pixels for the Lagrangian satellites (their locations were not measured as carefully as were the locations of the major satellites). Near the encounter the weights for the major satellites were decreased to represent a larger uncertainty of 1.0 pixel. The change accounted for the increased difficulty in finding the image centers as their size grew with decreasing spacecraft range. Moreover, the close encounter images were overexposed further complicating the centerfinding. The post-encounter Voyager 2 images, taken with the wide angle camera, were deweighted (7.0 pixel uncertainty) because of centerfinding problems introduced by their high phase angles.

The satellite astrometric data were grouped according to data type, observatory, and the observing period in which they were acquired. The accuracy of each group was taken to be equal to the rms of residuals of the group.

RESULTS

Our estimated gravity field parameter values and those obtained by Campbell and Anderson appear in Table 1. We are in close agreement on the GMs of the system, Rhea, and Titan, and the J_2 of Saturn and, except for the Dione and Iapetus GMs, agree within the uncertainties on the other parameters. Our analysis included a massive Hyperion based on an assumed density of 1.1 gm/cm^3 but omitted the effects of the masses of the Lagrangian satellites (their GMs are estimated to be less than 0.002 km^3sec^{-2}). We ignored the Saturnian C_{22} and S_{22}; Campbell and Anderson's determination of those two parameters was marginal at best suggesting that they have little effect on the spacecraft trajectories.

Our GMs of the inner four satellites are determined primarily from the Earthbased observations and the satellite dynamics. The Lagrangian satellite data are the primary source of the information on the Tethys and Dione GMs; the earlier values were found by Kozai[49] based on observations of Mimas and Enceladus and the Mimas-Tethys and Enceladus-Dione orbit resonances. Those resonances coupled with observations of Tethys and Dione (and the Lagrangian satellites) also lead to the GMs of Mimas and Enceladus. We match Kozai's GMs surprisingly well considering our differing observation sets and orbital motion model (he used an approximate analytical theory).

Our Iapetus GM is about 25% larger than Campbell and Anderson's result and is somewhat less certain. However, it is close to the values they found from the Pioneer data only (136 km^3sec^{-2}) and the Voyager 1 data only (131 km^3sec^{-2}). Their final result was apparently dominated by the contribution of the Voyager 2 data; we did not find that domination.

We estimated corrections to the Saturn ephemeris of the order of 800 km in the in-orbit direction and 250 km in the radial and out-of-plane directions. The in-orbit correction is slightly larger than the 700 km 1-σ uncertainty associated with DE405; it should be noted that no Voyager Saturn data were used in the development of DE405.

Our corrected satellite ephemerides differ from those described in Ref. 5 by less than 150 km. A thorough discussion of the satellite orbit determination will appear in a future paper.

Table 2 provides the distances and times of the Pioneer and Voyager spacecraft close approaches to Jupiter and its satellites. The values are in good agreement with those given by Campbell and Anderson. Differences are mainly due to differences in the satellite ephemerides.

Table 1

GRAVITY PARAMETERS

Parameter†	Campbell and Anderson	Reconstruction
GM_{system}	37940630. ±200.	37940672. ±100.
GM_{Mimas}	2.50± 0.06‡	2.56± 0.04
$GM_{\text{Enceladus}}$	4.9 ± 2.4‡	5.77± 1.19
GM_{Tethys}	45. ± 10.	41.21± 0.04
GM_{Dione}	70.2 ± 2.2‡	73.13± 0.02
GM_{Rhea}	154. ± 4.	154.59± 3.87
GM_{Titan}	8978.2 ± 1.	8978.03± 0.92
GM_{Hyperion}		0.72± 0.35‡
GM_{Iapetus}	106. ± 10.	131.72± 15.00
J_2 (× 10^6)	16298. ±10.	16294.6± 6.0
J_4 (× 10^6)	−915. ±40.	−919.8±26.1
J_6 (× 10^6)	103. ±50.	99.7±27.6
J_8 (× 10^6)	−10.‡	−10.‡
C_{22} (× 10^6)	0.7± 1.	
S_{22} (× 10^6)	−0.2± 1.	
α_p	40.580±0.016‡	40.5955±0.0036‡
δ_p	83.540±0.002‡	83.5381±0.0002‡
$\dot{\alpha}_p$		−0.04229‡
$\dot{\delta}_p$		−0.00444‡

†units: GM(km^3sec^{-2}), α_p, δ_p(deg), $\dot{\alpha}_p, \dot{\delta}_p$(deg century^{-1})
‡not estimated

Table 2

CLOSE APPROACH DISTANCES AND TIMES

Object	Pioneer 11		Voyager 1		Voyager 2	
	R (km)	T_{CA}	R (km)	T_{CA}	R (km)	T_{CA}
Saturn	80930	E^a	184141	E^b	161126	E^c
Mimas	104210	E- $0^h.1$	88406	E+ $2^h.0$	309758	E- $0^h.8$
Enceladus	222311	E+ $2^h.0$	201934	E+ $2^h.1$	87020	E+ $0^h.4$
Tethys	329398	E+ $1^h.9$	415532	E- $1^h.5$	93018	E+ $2^h.8$
Dione	291292	E- $0^h.5$	161499	E+ $3^h.9$	502289	E- $2^h.3$
Rhea	345723	E+ $6^h.0$	73985	E+ $6^h.6$	645320	E+ $3^h.1$
Titan	362910	E+$25^h.5$	6498	E-$18^h.1$	666096	E-$17^h.8$
Hyperion	665977	E-$82^h.5$	870823	E+$17^h.0$	472737	E-$26^h.0$
Iapetus	1033186	E-$76^h.5$	2476562	E+$43^h.5$	908483	E-$74^h.0$

[a] 1 Sep. 1979 16:30:34 GMT, [b]12 Nov. 1980 23:45:43 GMT
[c]26 Aug. 1981 03:24:05 GMT

Tables 3 and 4 constrast the navigation results found by the previous analysis and our reconstruction. The tables contain the standard B-plane coordinates, the error ellipse semi-major (SMAA) and semi-minor (SMIA) axes and orientation angle (θ) measured from the T axis, and the time of closest approach (TCA) and the error in that time. The agreement between the results is quite good considering differing reference frames, models, and estimation procedures. The most striking differences are our larger error ellipse semi-major axis and smaller arrival time uncertainty for Voyager 2. We speculate that the differences are caused by Campbell *et al.* 's use of the non-dynamic satellite ephemerides versus our use of the integrated ephemerides for Voyager 2.

The estimated velocity changes imparted by the spacecraft maneuvers appear in Table 5. Except for the TCMs all changes are referred to the spacecraft coordinate axes. For Pioneer 11 the Z axis is along the spin axis which was maintained within 3 degrees of the Earth direction; the other two axes were normal to Z and to each other. For the Voyagers the Z axis is the axis of symmetry of the spacecraft bus and the X and Y axes are the pitch and yaw axes, respectively. The centerline of the high gain antenna is aligned with the Z axis and was normally pointed toward the Earth. For the TCMs, modelled as finite burns, the table contains the ICRF coordinates of the velocity change accumulated during the maneuver.

Table 3

VOYAGER 1 NAVIGATION PERFORMANCE - TITAN B-PLANE

Source	B·R (km)	B·T (km)	SMAA (km)	SMIA (km)	θ (deg)	TCA (H:M:S)	σ_{TCA} (sec)
Campbell *et al.*	1875	6250	2.	1.	67.7	5:41:14	0.03
This work	1879	6252	1.3	0.2	110.1	5:41:14	0.04

Table 4

VOYAGER 2 NAVIGATION PERFORMANCE - JUPITER B-PLANE

Source	B·R (km)	B·T (km)	SMAA (km)	SMIA (km)	θ (deg)	TCA (H:M:S)	σ_{TCA} (sec)
Campbell *et al.*	-17797	364021	1.5	1.4	48.2	3:24:57	0.1
This work	-17802	364024	13.4	1.1	87.6	3:24:57	0.01

The values of the constant non-gravitational accelerations are given in Table 6. The Pioneer acceleration is less than the level found by Null. The Voyager constant accelerations are consistent with those found during Voyager mission operations. Figures 1 and 2 show the Voyager stochastic accelerations along the Z axis; the accelerations along the other axes are an order of magnitude smaller. The stochastic accelerations are near the expected levels of 5×10^{-12} km sec^{-2}; the root-mean-square values are less than 3×10^{-12} km sec^{-2}.

Figures 3—10 show the spacecraft data residuals and give an idea of the data spans, noise levels, and quality of the data fit. The residuals confirm that our fit to the data is as good if not slightly better than the fits done for the earlier navigation and gravity analyses.

Some of the variation in the noise in the Doppler data is the result of differing sample times. All of the close encounter data had 1 min sample times. At the start of the arc the Voyager 1 data was compressed to a 1 hour sample time; the Voyager 2 data used 20 min samples. Near the encounter times the compression varied between 5 min and 20 min for both spacecraft. Solar conjunction is responsible for the Voyager 1 data gap in late September. Solar plasma effects related to the conjunction caused the high data noise in early September and October. In general both the Voyager 1 range and Doppler are noisier than that of Voyager 2; probably reflecting higher activity in the interplanetary plasma during the Voyager 1 encounter period.

In the optical residual figures the symbols (somewhat difficult to see), indicate which satellite was being imaged: Mimas(M), Enceladus(E), Tethys(t), Dione(D), Rhea(R), Titan(T), Hyperion(H), Iapetus(I), Helene(h), Telesto(+), Calypso(C). The residuals are well within the observational uncertainties. The degradation of fit to the close encounter images and post-encounter Voyager 2 images, attributed to centerfinding errors, can clearly be seen.

CONCLUDING REMARKS

In this paper we have reported a new reconstruction of the Voyager Saturn encounter trajectories. The reconstruction was done as part of an investigation of the Saturnian system gravity field and the orbits of the Saturnian satellites. The new trajectories are needed in order to properly process the Voyager tracking and optical navigation data for that investigation. Because of improvements in our models and data processing procedures and our use of the modern ICRF reference frame, we believe the new trajectories to be the most accurate descriptions produced thus far for the spacecraft motion through the Saturnian system.

Table 5

MANEUVERS (mm sec^{-1})

Time(TDB)		$\Delta\dot{X}$	$\Delta\dot{Y}$	$\Delta\dot{Z}$	Event
			Pioneer 11		
28-Aug-1979	13:37:09	-0.031	0.030	2.622	precession
28-Aug-1979	17:47:22	-0.035	0.031	1.347	precession
			Voyager 1		
19-Aug-1980	11:45:00	-1.826	-1.670	-3.009	Ant. & Sun sensor cal.
23-Aug 1980	09:00:00	-1.742	-1.399	-3.705	Cruise science maneuver
10-Oct-1980	19:09:51	-1360.092	1183.900	-274.575	TCM8
07-Nov-1980	03:39:58	-550.847	1229.873	-640.546	TCM9
13-Nov-1980	05:30:00	85.474	-130.685	-3.876	Science turns
13-Nov-1980	07:30:00	-56.798	109.931	-2.383	Science turns
13-Nov-1980	21:30:00	0.533	-3.247	-0.863	Science turns
			Voyager 2		
19-Jul-1981	11:16:25	-469.649	882.511	648.463	TCM8
01-Aug-1981	00:00:00	-32.493	129.775	-5.097	Vertical system scan
13-Aug-1981	08:00:00	16.595	-3.544	-1.218	Roll to Procyon
15-Aug-1981	09:30:00	-14.098	27.154	-0.660	Roll to Canopus
18-Aug-1981	21:26:16	-230.733	1205.871	-534.300	TCM9
24-Aug-1981	07:50:00	-45.395	80.021	-0.821	Roll to Miaplacidus
25-Aug-1981	12:40:00	-31.074	-10.945	3.606	Science turns
26-Aug-1981	02:39:11	-2.299	-0.946	4.739	Science turns
26-Aug-1981	02:47:31	-2.147	-0.880	4.712	Science turns
26-Aug-1981	03:08:47	-16.523	-6.713	4.669	Science turns
26-Aug-1981	03:26:06	-14.960	-6.070	4.683	Science turns
26-Aug-1981	05:25:39	-1.346	-0.569	7.691	Science turns
26-Aug-1981	05:41:53	-1.288	-0.543	-1.243	Science turns
26-Aug-1981	07:38:00	-0.214	-0.034	1.315	Science turns
26-Aug-1981	08:09:10	34.063	23.412	1.947	Roll to Vega
04-Sep-1981	01:46:00	-0.505	-2.052	-0.781	Roll to Canopus
05-Sep-1981	03:10:00	0.269	0.964	-1.329	Roll to Miaplacidus
09-Sep-1981	22:30:00	0.606	0.469	-3.519	Scale factor test

Table 6

NON-GRAVITATIONAL ACCELERATIONS
(km $sec^{-2} \times 10^{-12}$)

Axis	Pioneer 11	Voyager 1	Voyager 2
X		-3.583	-1.241
Y		6.360	1.594
Z	-3.840	-5.348	-4.039

ACKNOWLEDGEMENT

We would like to thank Bill Owen for converting the Voyager optical data to the ICRF system. Thanks to George Null, Jim Campbell, Steve Synnott, and Ed Riedel for their informative discussions. The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. Campbell, J. K., Jacobson, R. A., Riedel, J. E., Synnott, S. P., and Taylor, A. H. (1982) 'Voyager I and Voyager II Saturn Encounter Orbit Determination', AIAA Paper No. 82-0419, presented at the AIAA 20th Aerospace Sciences Meeting, Orlando, Flordia.
2. Campbell, J. K. and Anderson, J. D. (1989) 'Gravity Field of the Saturnian System from Pioneer and Voyager Tracking Data', *The Astronomical Journal*, **97**, pp. 1485-1495.
3. Jacobson, R. A., Campbell, J. K., and Synnott, S. P. (1982) 'Satellite Ephemerides for Voyager Saturn Encounter', AIAA Paper No. 82-1472, presented at the AIAA/AAS Astrodynamics Converence, San Diego, California.
4. Jacobson, R. A. (1995) 'The Orbits of the Minor Saturnian Satellites' *Bulletin of the American Astronomical Society*, **27**, No.3, 1202-1203.
5. Jacobson, R. A. (1996) 'The Orbits of the Saturnian Satellites from Earthbased and Voyager Observations, *Bulletin of the American Astronomical Society*, **28**, No.3, 1185.
6. Null, G. W., Lau, E. L., Biller, E. D., and Anderson, J. D. (1981) 'Saturn Gravity Results Obtained from Pioneer 11 Tracking Data and Earth-based Saturn Satellite Data', *The Astronomical Journal*, **86**, pp. 456-468.
7. Strugnell, P. R., and Taylor, D. B. (1990) 'A catalogue of ground-based observations of the eight major satellites of Saturn, 1874-1989', *Astronomy and Astrophysics Supplement Series*, **83**, 289.
8. Standish, E. M. (1996) 'Astrographic Positions of the Satellites of Jupiter, Saturn, and Uranus', JPL Internal Document IOM 312.1-96-020, Jet Propulsion Laboratory, Pasadena, Ca.
9. Veiga, C. H. and Vieira Martins, R. (1999) 'Photographic positions for the first eight satellites of Saturn', *Astronomy and Astrophysics Supplement Series*, **139**, 305.
10. Whipple, A. L. (1993) 'McDonald observations in 1992 and 1993', personal communication.

11. Whipple, A. L. (1995) 'McDonald observations in 1994', personal communication.
12. Harper, D., Murray, C. D., Beurle, K., Williams, I. P., Jones, D. H. P., Taylor, D. B., and Greaves, S. C. (1997) 'CCD astrometry of Saturn's satellites 1990-1994', *Astronomy and Astrophysics Supplement Series*, **121**, 65.
13. Harper, D., Beurle, K., Williams, I. P., Murray, C. D., Taylor, D. B., Fitzsimmons, A., and Cartwright I. M. (1999) 'CCD astrometry of Saturn's satellites in 1995 and 1997', *Astronomy and Astrophysics Supplement Series*, **136**, 257.
14. Peng, Q. Y., Vienne, A., and Shen, K. X. (2002) 'Positional measuring procedure and CCD observations for Saturnian satellites', *Astronomy and Astrophysics*, **383**, 296.
15. Nicholson, P. D. (1992) 'Palomar observations in 1990', personal communication.
16. Nicholson, P. D. (1994) 'Palomar observations in 1993', personal communication.
17. Rohde, J. R. and Pascu, D. (1993) 'Astrometric Observations of Helene (SXII), Telesto(SXIII), and Calypso (SXIV)', *Bulletin of the American Astronomical Society*, **25**, 1235.
18. Rohde, J. R. and Pascu, D. (1994) 'CCD astrometry of Helene (SXII), Telesto(SXIII), and Calypso (SXIV): 1993 observations', *Bulletin of the American Astronomical Society*, **26**, 1024.
19. Vienne, A., Thuillot, W., Veiga, C. H., Arlot, J.-E., and Vieira Martins, R. (2001) 'Saturnian satellite observations made in Brazil during the 1995 opposition with an astrometric analysis', *Astronomy and Astrophysics*, **380**, 727.
20. Owen, W. M. (2002) 'Table Mountain observations', personal communication.
21. Qiao, R. C., Shen, K. X., Liu, J. R., and Harper, D. (1999) '1994-1996 CCD astrometric observations of Saturn's satellites and comparison with theories', *Astronomy and Astrophysics Supplement Series*, **137**, 1.
22. Rapaport, M., Teixeira, R., Le Campion, J. F., Ducourant, C., Camargo, J. I. B., and Benevides-Soares, P. (2002) 'Astrometry of Pluto and Saturn with the CCD meridian instruments of Bordeaux and Valinhos', *Astronomy and Astrophysics*, **383**, 1054.
23. Stone, R. C. and Harris, F. H. (2000) 'CCD positions determined in the international celestial reference frame for the outer planets and many of their satellites in 1995-1999', *Astronomical Journal*, **119**, 1985.
24. Stone, R. C. (2000) 'CCD positions for the outer planets and many of their satellites. IV. FASTT observations taken in 1999-2000', *Astronomical Journal*, **120**, 2124.
25. Stone, R. C. (2001) 'Positions for the outer planets and many of their satellites. V. FASTT observations taken in 2000-2001', *Astronomical Journal*, **122**, 2723.
26. Lamy, P. and Mauron, N. (1980) IAU Circ. No. 3491
27. Laques, P. and Lecacheux, J. (1980) IAU Circ. No. 3483
28. Leliévre (1980) IAU Circ. No. 3545
29. Retisema, H. J. (1980) IAU Circ. No. 3466
30. Veillet, C. (1980) IAU Circ. No. 3470
31. Larson, S. M. and Fountain, J. W. (1981) IAU Circ. No. 3602
32. Pascu, D. and Seidelmann, P. K. (1981) IAU Circ. No. 3619
33. Reitsema, H. J. (1981) 'The libration of the Saturnian satellite Dione B', *Icarus*, **48**, 23.
34. Seidelmann, P. K., Harrington, R. S., Pascu, D., Baum, W. A., Currie, D. G., Westphal, J. A., and Danielson, G. E. (1981) 'Saturn Satellite Observations and Orbits from the 1980 Ring Plane Crossing', *Icarus*, **47**, 282.
35. Oberti, P., Veillet, C. and Catullo, V. (1989) 'Lagrangian satellites of Tethys and Dione. I. Reduction of observations', *Astronomy and Astrophysics Supplement Series*, **80**, 289.

36. Veiga, C. H. and Vieira Martins, R. (2000) 'Astrometric photographic observations of Helene', *Astronomy and Astrophysics Supplement Series*, **143**, 405.
37. Martinka, S. and Pascu, D. (1998) data held at the U. S. Naval Observatory, personal communication
38. Veiga, C. H., Vieira Martins, R., Vienne, A., Thuillot, W., and Arlot, J.-E. (2003) 'CCD astrometric observations of Saturnian satellites', *Astronomy and Astrophysics*, to appear.
39. French, R. G. (2001) 'HST observations', personal communication.
40. McGhee, C. A., Nicholson, P. D., French, R. G., and Hall, K. J. (2001) 'HST observations of Saturnian satellites during the 1995 ring plane crossings', *Icarus*, **152**, 282.
41. Standish, E. M. (1998) 'JPL Planetary and Lunar Ephemerides,DE405/LE405', JPL Internal Document IOM 312.F-98-048, Jet Propulsion Laboratory, Pasadena, Ca.(available electronically at http://ssd.jpl.nasa.gov/iau-comm4)
42. Simpson, R. A., Tyler, G. L., and Holberg, J. B. (1983) 'Saturn's Pole: Geometric Correction based on Voyager UVS and Radio Occultations', *The Astronomical Journal*, **88**, pp. 1531-1536.
43. French, R. G., Nicholson, P. D., Cooke, M. L., Elliot, J. L., Matthews, K., Perkovic, O., Tollestrup, E., Harvey, P., Chanover, N. J., Clark, M. A., Dunham, E. W., Forrest, W., Harrington, J., Pipher, J., Brahic, A., Grenier, I., Roques, F., and Arndt, M. (1993) 'Geometry of the Saturn System from the 3 July 1989 Occultation of 28 Sgr and Voyager Observations', *Icarus*, **103**, pp. 163-214.
44. Nicholson, P. D., French, R. G., and Bosh, A. S. (1999) 'Ring plane crossings and Saturn's pole precession', *Bulletin of the American Astronomical Society*, **31**, pp. 1140.
45. Georgevic, R. M. (1971) 'Mathematical Model of the Solar Radiation Force and Torques Acting on the Components of a Spacecraft', JPL TM 33-494, Jet Propulsion Laboratory, Pasadena, Ca.
46. Campbell, J. K., Synnott, S. P., Riedel, J. E., Mandell, S., Morabito, L. A., and Rinker, G. C. (1980) 'Voyager 1 and Voyager 2 Jupiter Encounter Orbit Determination', AIAA Paper No. 80-0241 presented at the AIAA 18th Aerospace Sciences Meeting, Pasadena, California.
47. Nicholson, P. D., and Porco, C. C. (1988) 'A New Constraint on Saturn's Zonal Gravity Harmonics from Voyager Observations of an Eccentric Ringlet', *Journal of Geophysical Research*, **93**, pp. 10209.
48. Standish, E. M. (2002) 'A covariance for Saturn', personal communication.
49. Kozai, Y. (1957) 'On the Astronomical Constants of the Saturnian Satellites Systen', *Annals of the Tokyo Astronomical Observatory Second Series*, **5**, pp. 73.

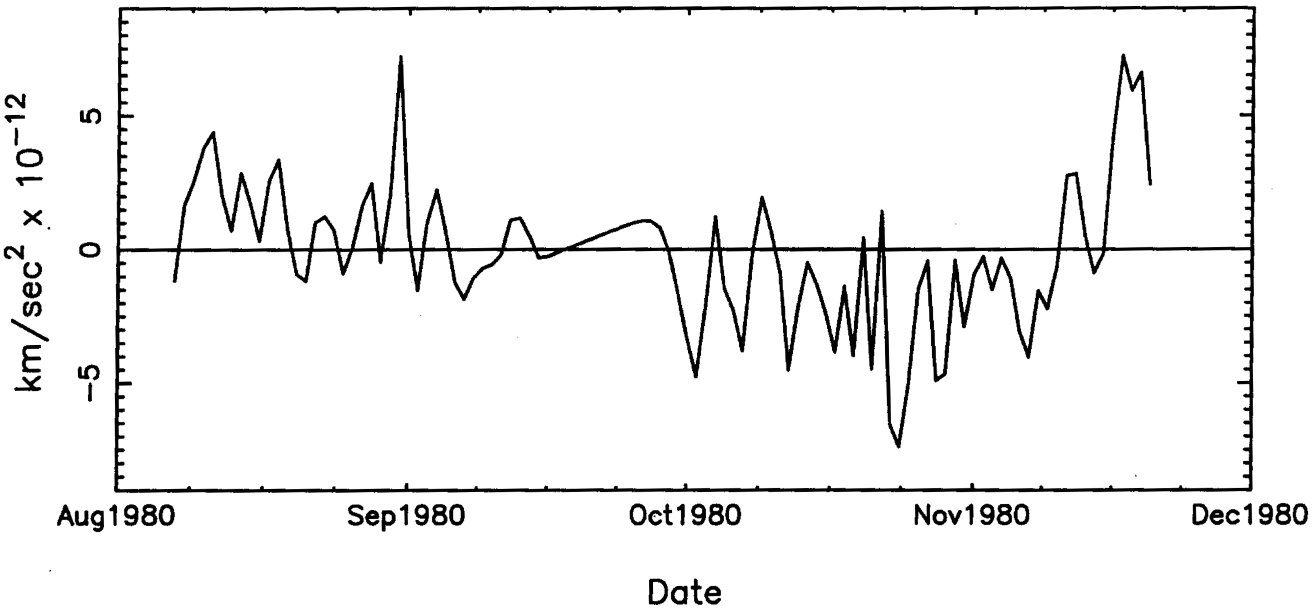

Figure 1: Voyager 1 Z Stochastic Acceleration

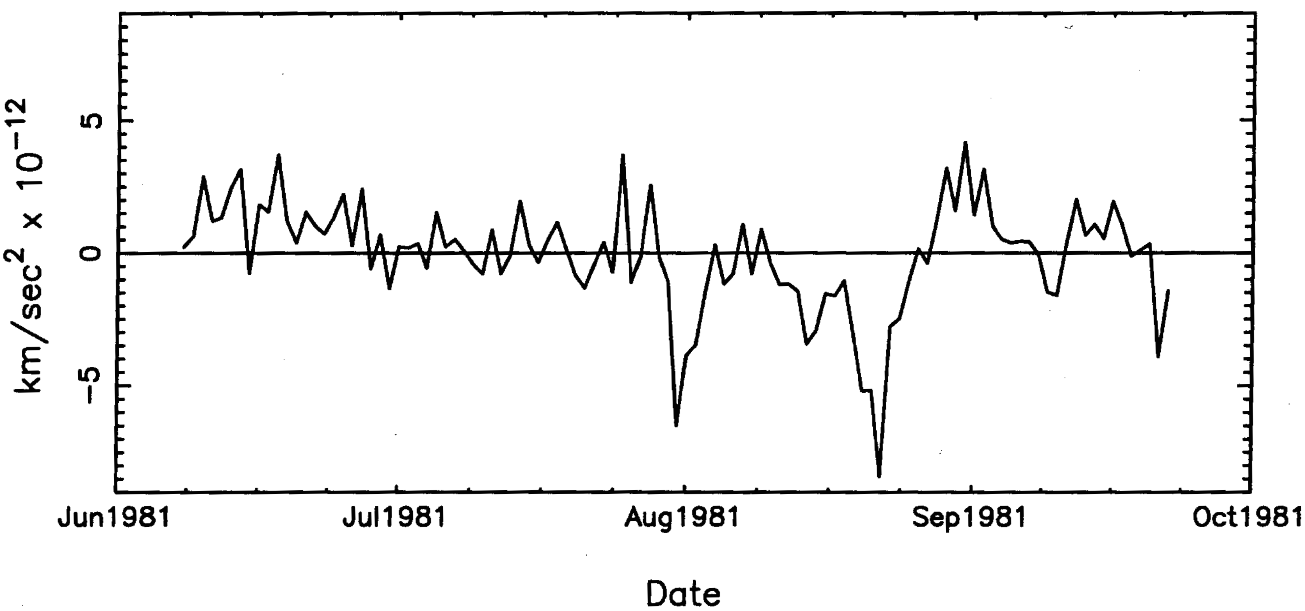

Figure 2: Voyager 2 Z Stochastic Acceleration

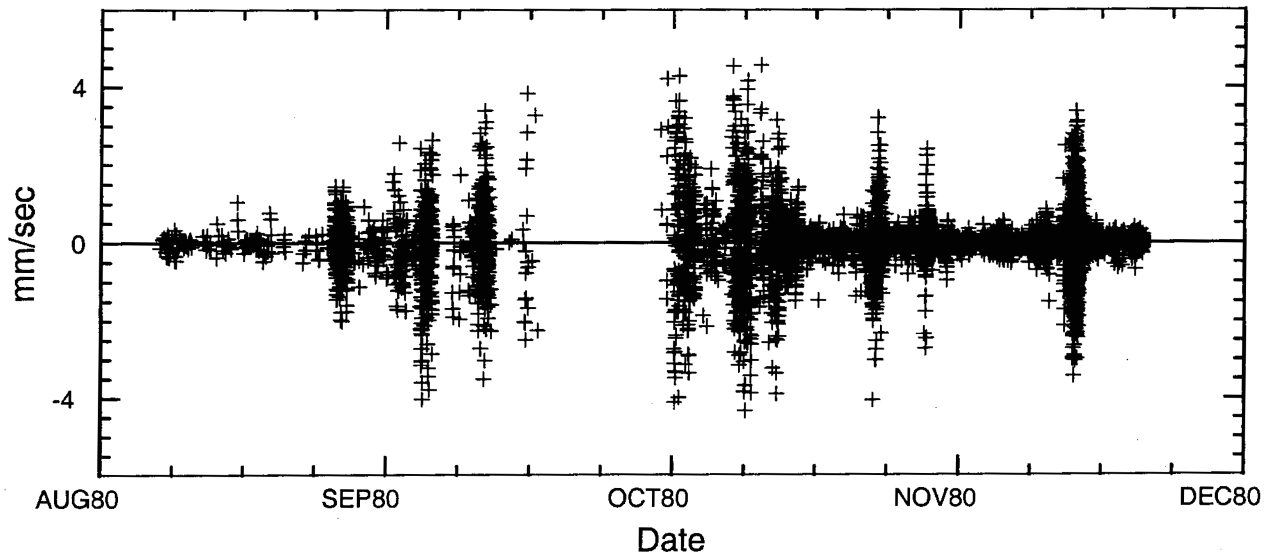

Figure 3: Voyager 1 Doppler Residuals

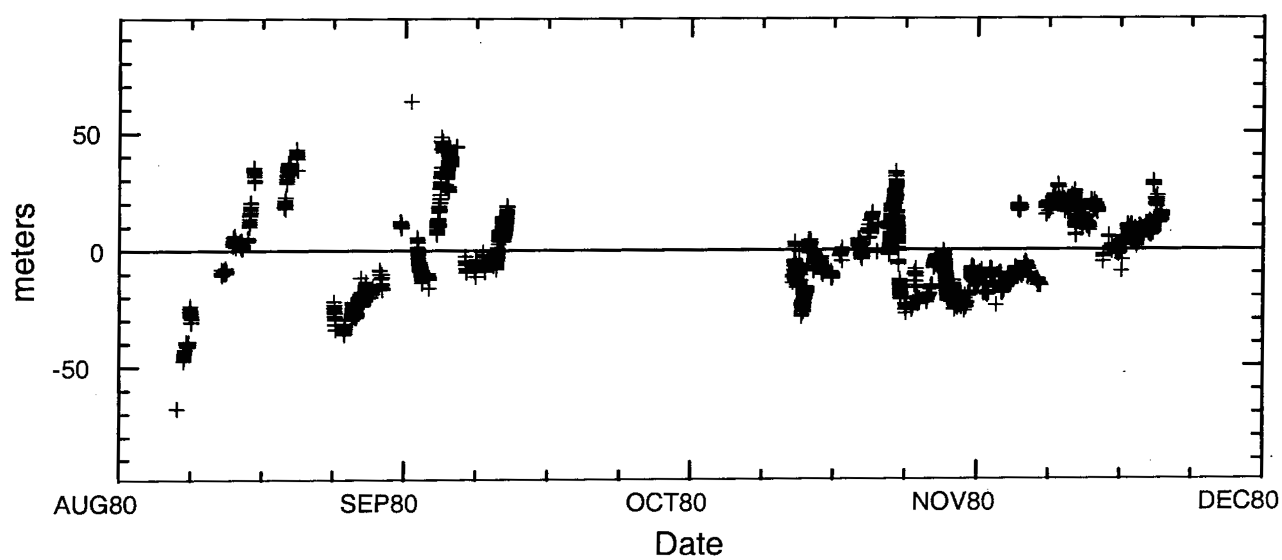

Figure 4: Voyager 1 Range Residuals

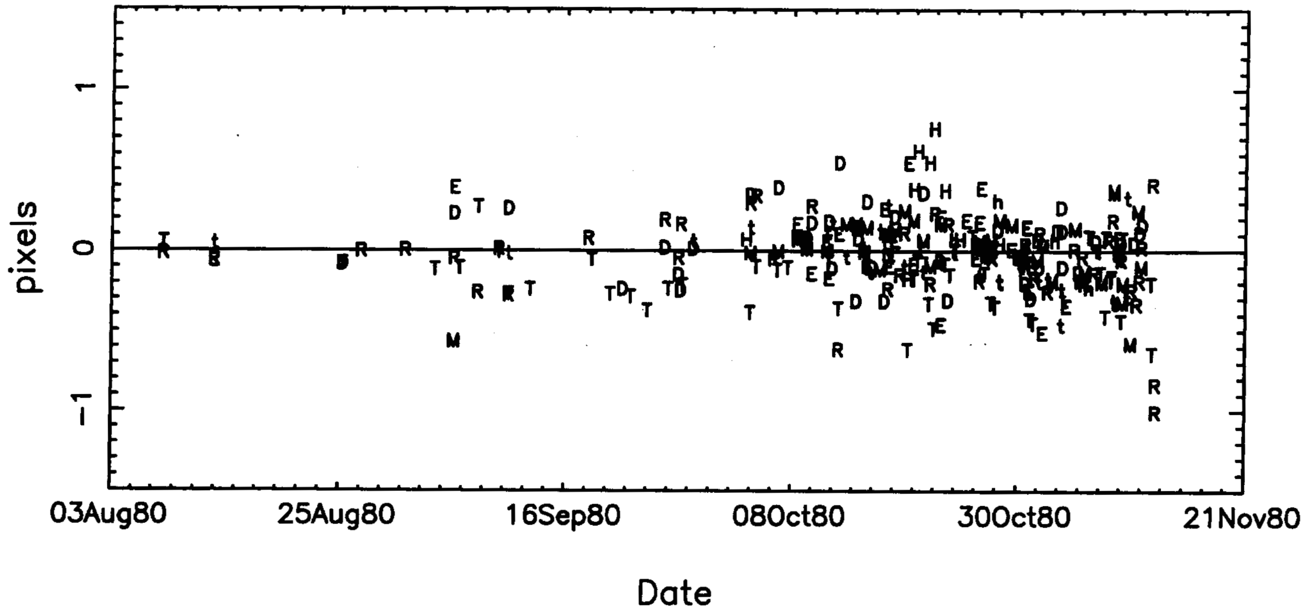

Figure 5: Voyager 1 Pixel Residuals

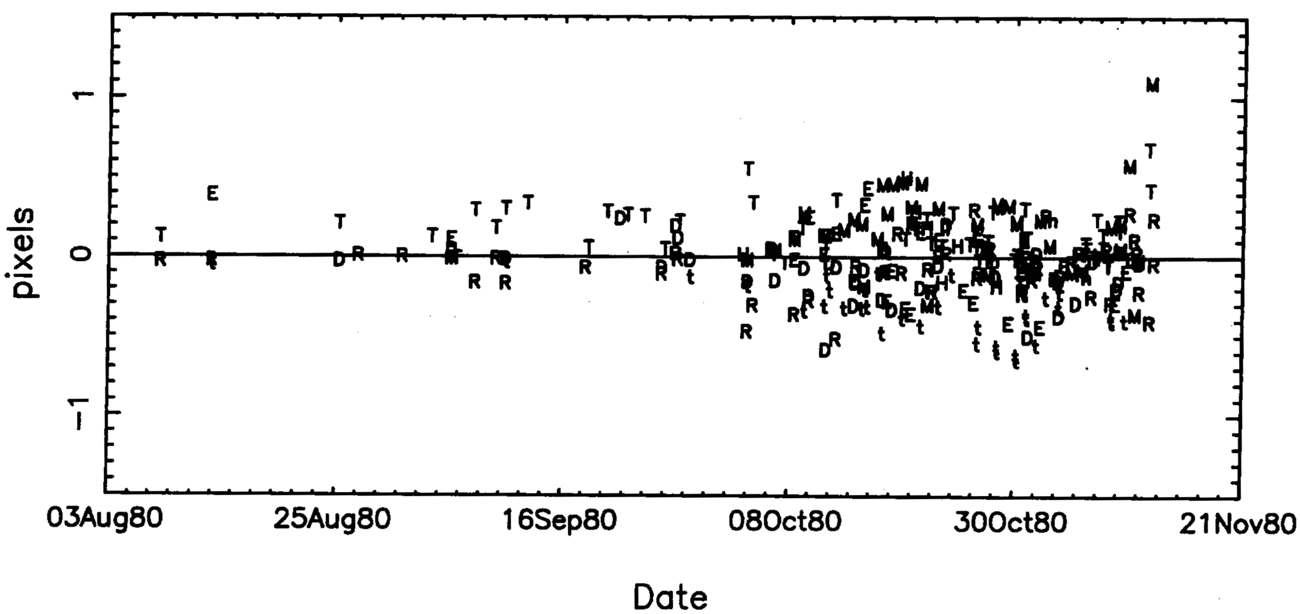

Figure 6: Voyager 1 Line Residuals

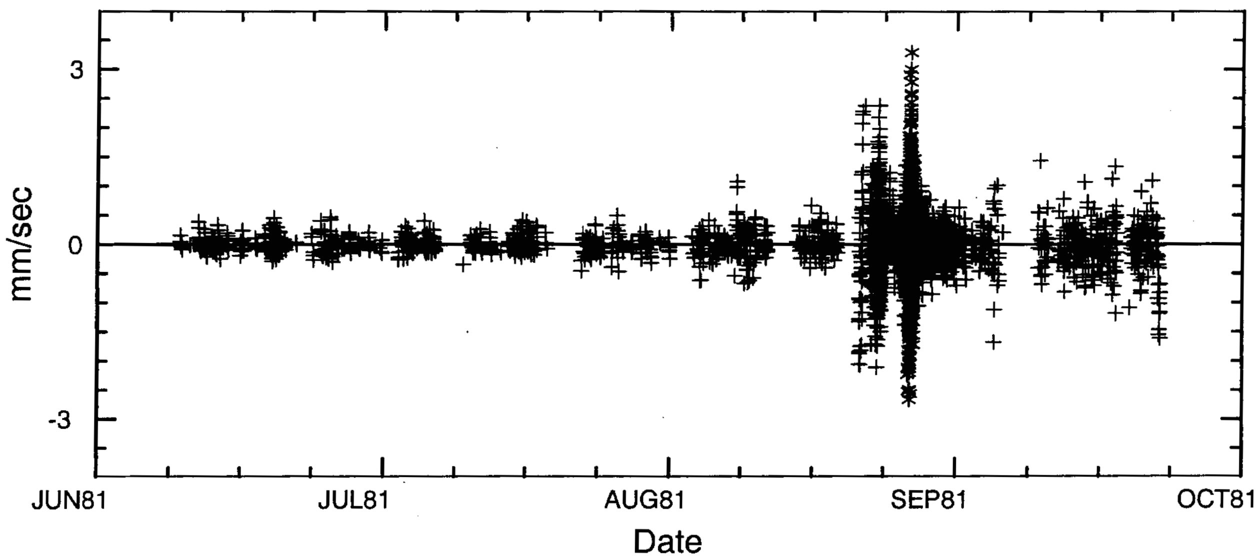

Figure 7: Voyager 2 Doppler Residuals

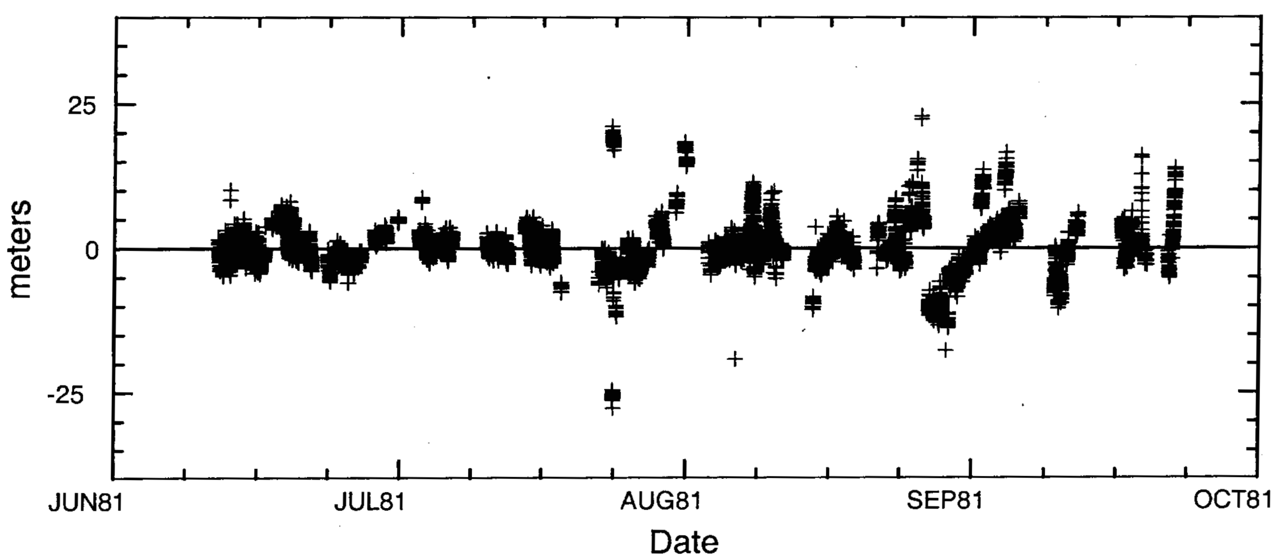

Figure 8: Voyager 2 Range Residuals

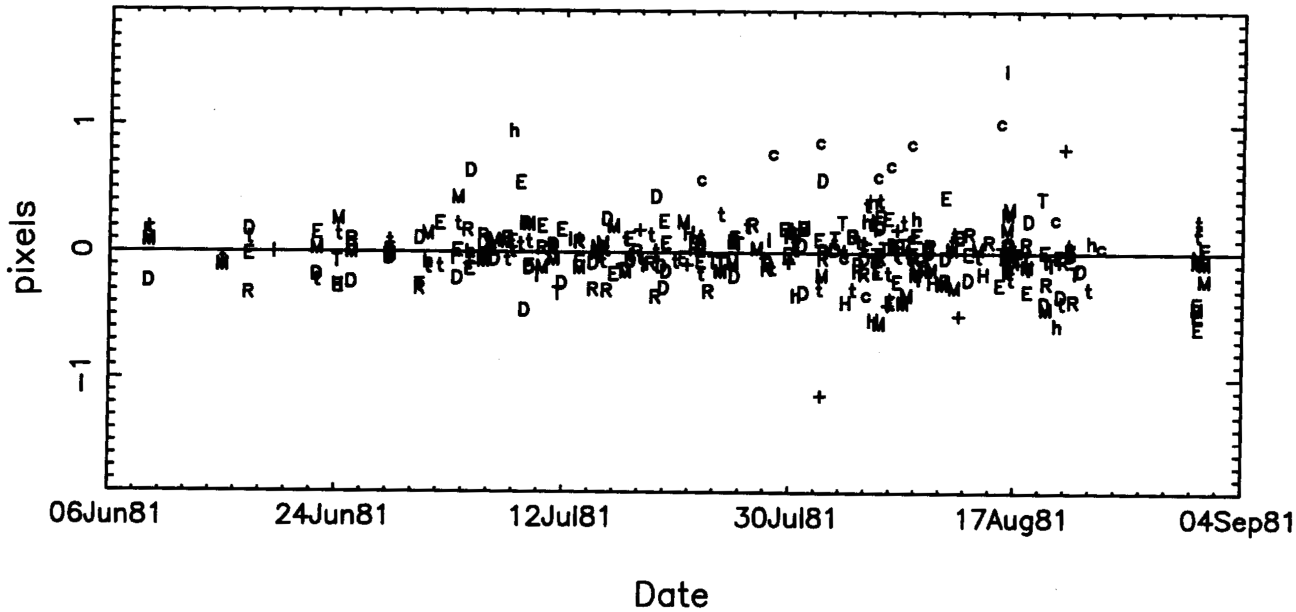

Figure 9: Voyager 2 Pixel Residuals

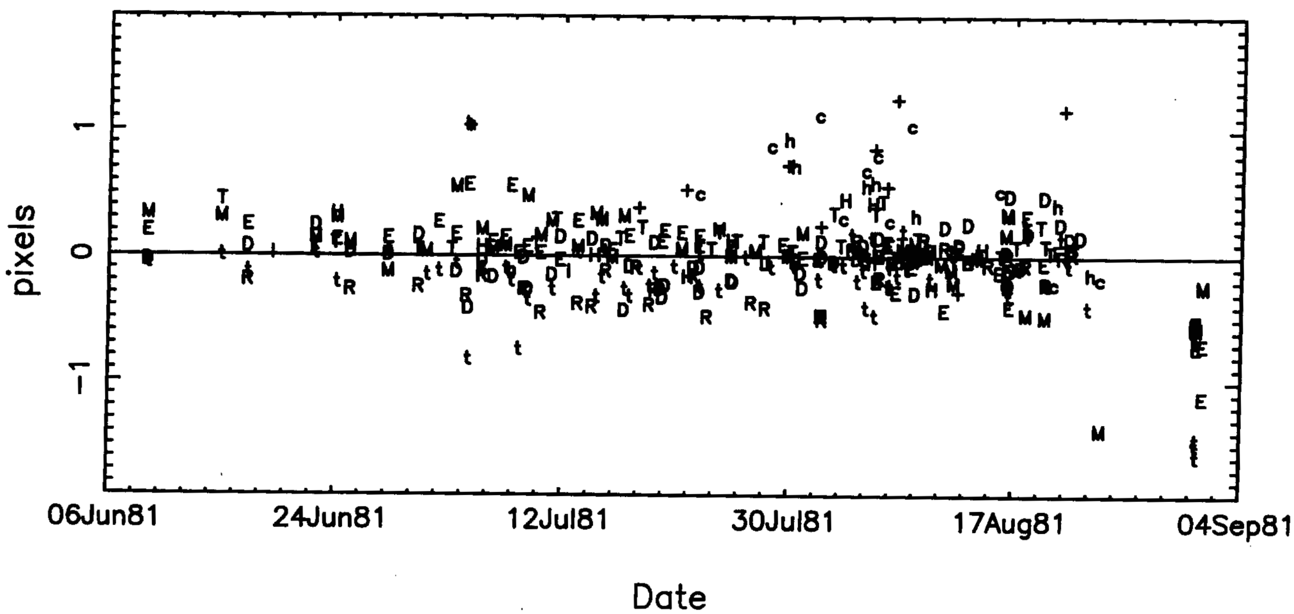

Figure 10: Voyager 2 Line Residuals

Conclusions

- ***ICRF now extended to K and Q-bands at sub mas accuracy !***

24 and 43 GHz observations: 3 sessions
108 sources
~ 250 μas formal precision
systematics at 500 μas level or less

Source parameters not yet well separated with only 3 days data - more data needed.

- ***Future Plans***

More K and Q-band data on the way.

Planning for simultaneous 8.4 / 32 GHz (X/Ka) data