GPS Satellite CW Tones Measured with Prelude

Mike Davis
March 2006

Summary Part 1: GPS Satellite CW Tones: Observation of PRN24 on November 15, 2005

Measurement of the CW tones in the first nulls of the Global Positioning Satellite spread spectrum signal from PRN24 revealed two unexpected results. The amplitude of the signal varies in a systematic way, rising and falling on a time scale of about 20 minutes. Amplitudes in the upper frequency null are approximately out of phase with those in the lower null. Further observations are needed to determine if the amplitude variation is intrinsic to the satellite or may be caused by multi-path arrival at the ATA feed. In addition, the Doppler shift disagrees with that predicted from the ATA ephemeris program by~ 0.2%. The velocity discrepancy does not appear to be related to refraction, as it does not track secant (zenith angle). Further refinement of the ATA ephemeris, in particular, the radial distance calculation (for which no high accuracy is claimed) may resolve this.

Summary Part 2: Comparison with Published GPS Satellite Coordinates

Radial velocity residuals for satellite NP24 measured on November 15, 2005, reported in my earlier memo, are shown in Figure 1 (small squares). The present ATA Ephemeris routine was not designed to provide extremely accurate Doppler shift corrections, so this memo recalculates the expected velocities using the NGS Geodetic Toolkit with data from the GPS 'Final' ephemeris. This ephemeris, accurate to about 5 cm, is available online with a delay of about two weeks. The resulting disagreement of about 0.2 m/s (~1 Hz) shown in Figure 1 (large squares) is much less, ~0.02 %, but is still highly systematic.

GPS Satellite CW Tones: Observation of PRN24 on November 15, 2005

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SUMMARY

Measurement of the CW tones in the first nulls of the Global Positioning Satellite spread spectrum signal from PRN24 revealed two unexpected results. The amplitude of the signal varies in a systematic way, rising and falling on a time scale of about 20 minutes. Amplitudes in the upper frequency null are approximately out of phase with those in the lower null. Further observations are needed to determine if the amplitude variation is intrinsic to the satellite or may be caused by multi-path arrival at the ATA feed. In addition, the Doppler shift disagrees with that predicted from the ATA ephemeris program by~ 0.2%. The velocity discrepancy does not appear to be related to refraction, as it does not track secant (zenith angle). Further refinement of the ATA ephemeris, in particular, the radial distance calculation (for which no high accuracy is claimed) may resolve this.

THE OBSERVATIONS

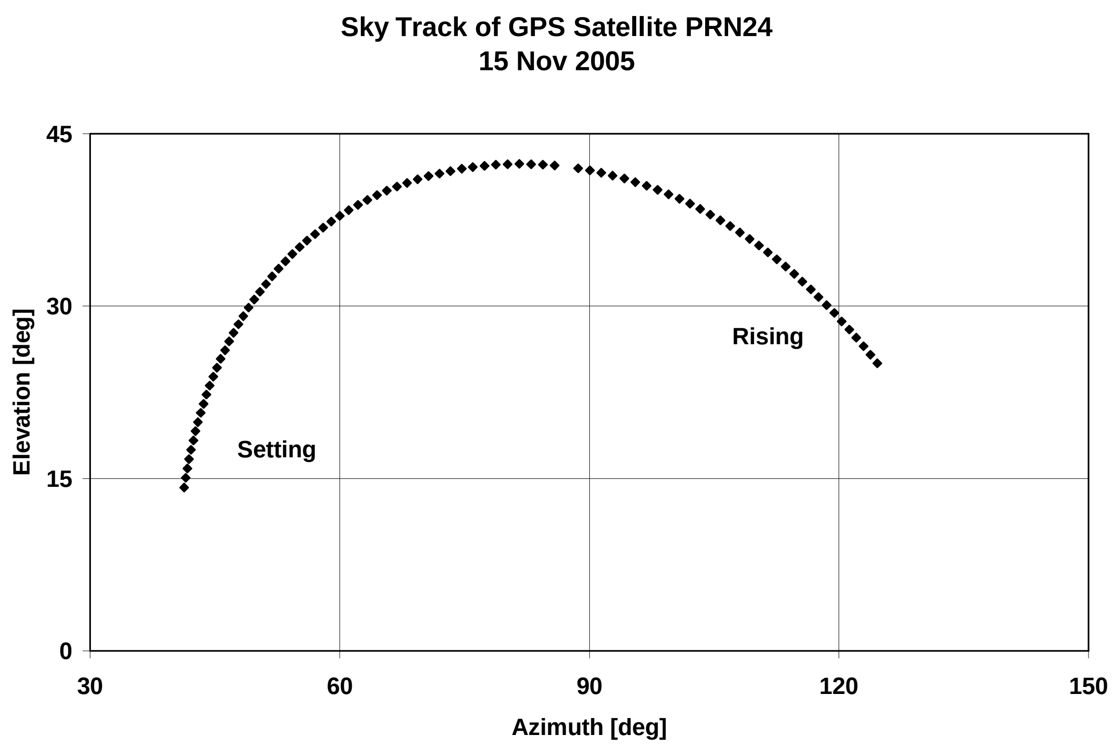

Figure 1. The 87 points represent the positions of independent estimates of the amplitude and radial velocity of Global Positioning Satellite PRN24. The points are spaced 134 seconds apart; one bad point has been removed. Data are missing at the start of the track due to a late start. The telescope stopped tracking at 18 degrees elevation, but the signal continued to be detectable in the main beam and sidelobes for some time beyond that.

Jack Welch suggested that we observe GPS satellites, to familiarize ourselves with observing methods and the quality of information obtainable. Jane Jordan and Tom Kilsdonk set up the Prelude system to track and measure the very faint CW tones generated at 1575.42 $\pm$ 1.023 MHz as a byproduct of very slight asymmetry in the 1.023 MHz spread spectrum modulation. I set up one of the PTA dishes to track the predicted satellite orbit with Rick Forster's assistance. We had done this on a short track on November 4; the purpose of these observations was to obtain a full track from rise to set, to verify and further characterize a velocity disagreement we saw on Nov. 4th.

The CW tones, though 60 to 80 dB below the integrated power in the spread spectrum, are easily detectable as monochromatic but drifting signals in the Prelude detector. The detector provides both signal strength (signal to noise ratio) and frequency for each observation.

SIGNAL STRENGTH

The signal to noise ratio for each observation is shown in Figure 2, separately for the signals at 1576.443 MHz (HIGH) and 1574.397 MHz (LOW). Neither the time variation nor the difference in HIGH and LOW signal strength is understood. There is some indication from the last five points that the variation may be caused by telescope motion. Tracking stopped at 23:10 UT; the last five data points were taken with the antenna fixed at 18^o.

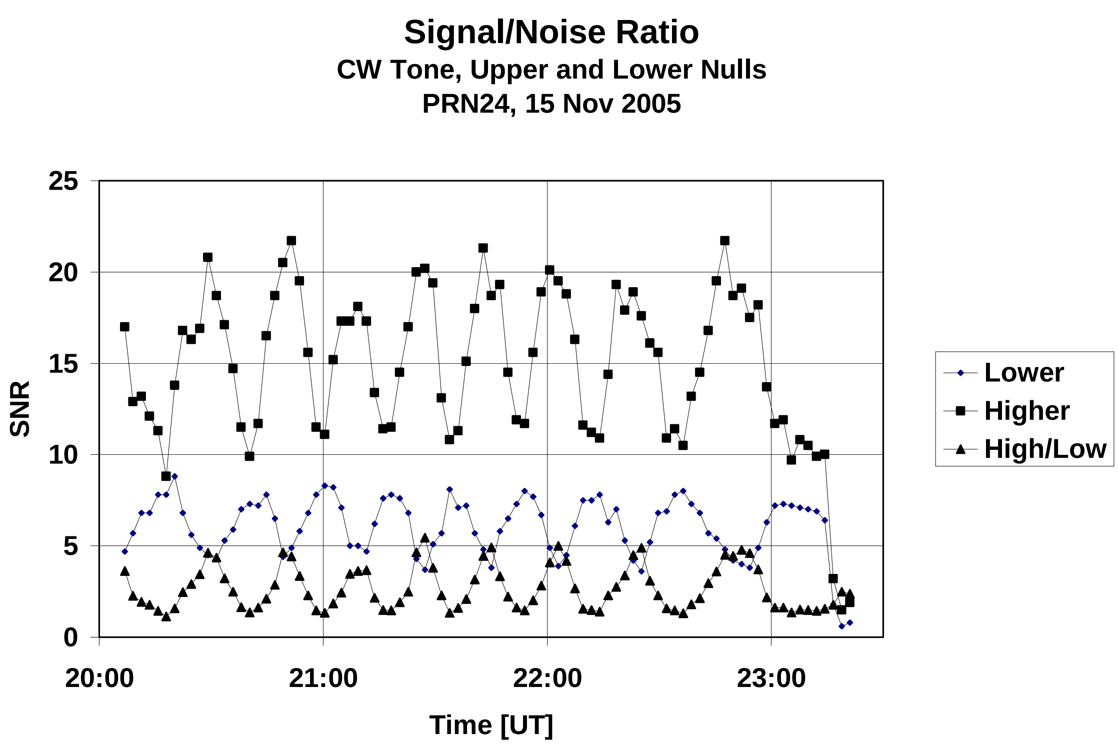

Figure 2. Signal to Noise ratio (SNR). There is an approximately sinusoidal variation by a factor of ~two with a period of about 20 minutes. The signal strength in the two nulls is ~anti-correlated, as shown in the bottom plot of the HIGH/LOW ratio.

DOPPLER VELOCITY

Figure 3 shows the apparently excellent agreement between the observed and predicted radial velocities. Figure 4 shows that, on closer inspection, the observed velocity is about 0.2% larger than the predicted ephemeris values. Figure 5 shows the discrepancy plotted against secant (zenith angle), to test a suggestion that the extraction of the radial component was computed at the apparent (refracted, therefore higher elevation) position rather than the true position. It is apparent that the variation changes much more slowly than expected at high zenith angle, so this cannot explain the velocity difference. Figure 6 is the same as Figure 4, but with the fitted slope removed. This reduces the error by an order of magnitude, but there are still systematic variations, well-fit by a third order polynomial, of order 1 Hz, or 20 cm/s.

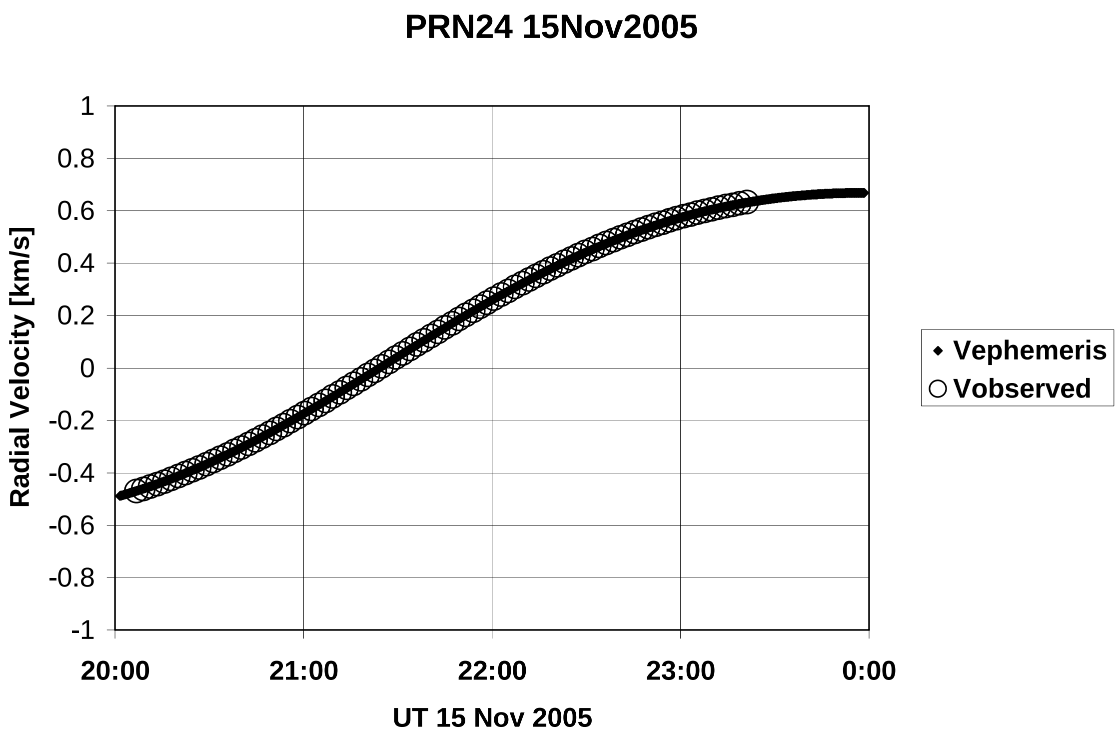

Figure 3. Predicted and observed radial velocities are seen to agree well on the scale of this plot.

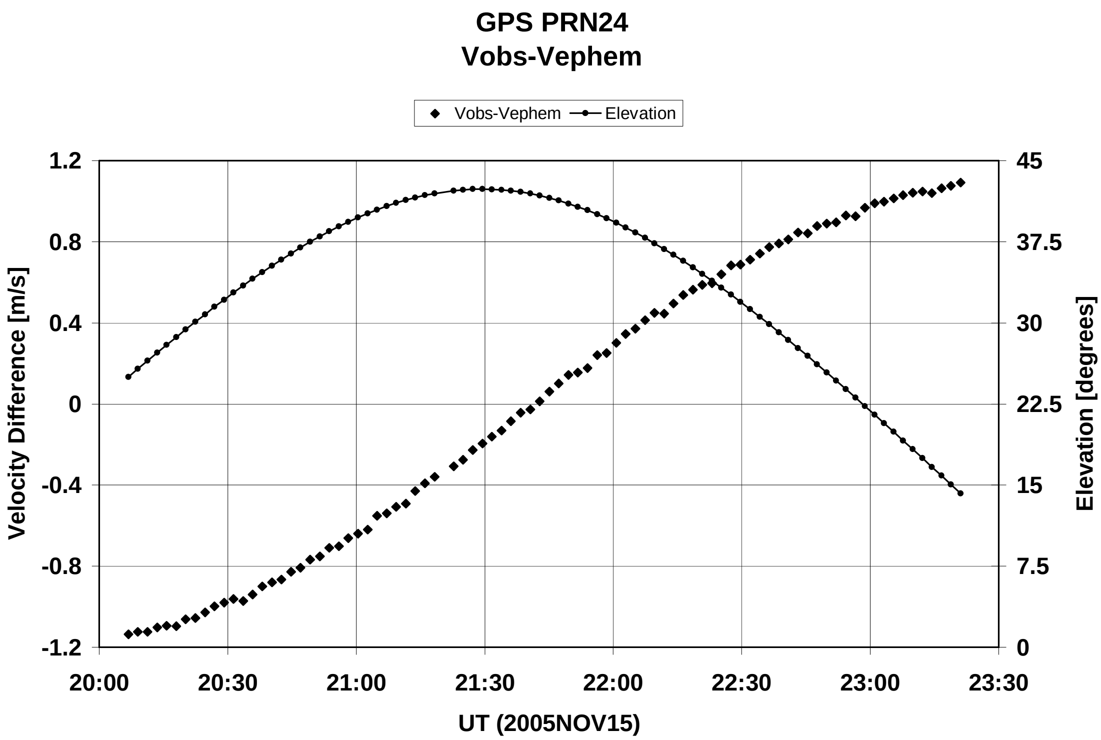

Figure 4. The vertical scale has been greatly expanded, to reveal a difference of about 0.2% between observed and predicted radial velocities.

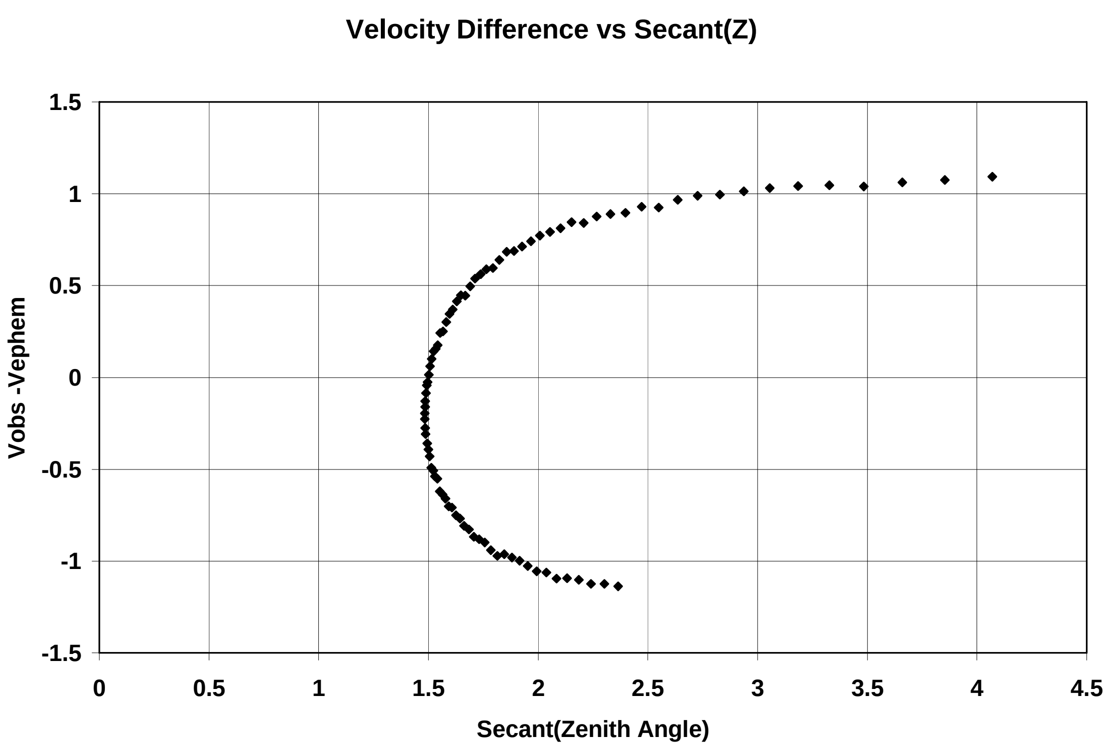

Figure 5. The velocity difference is clearly not proportional to atmospheric refraction.

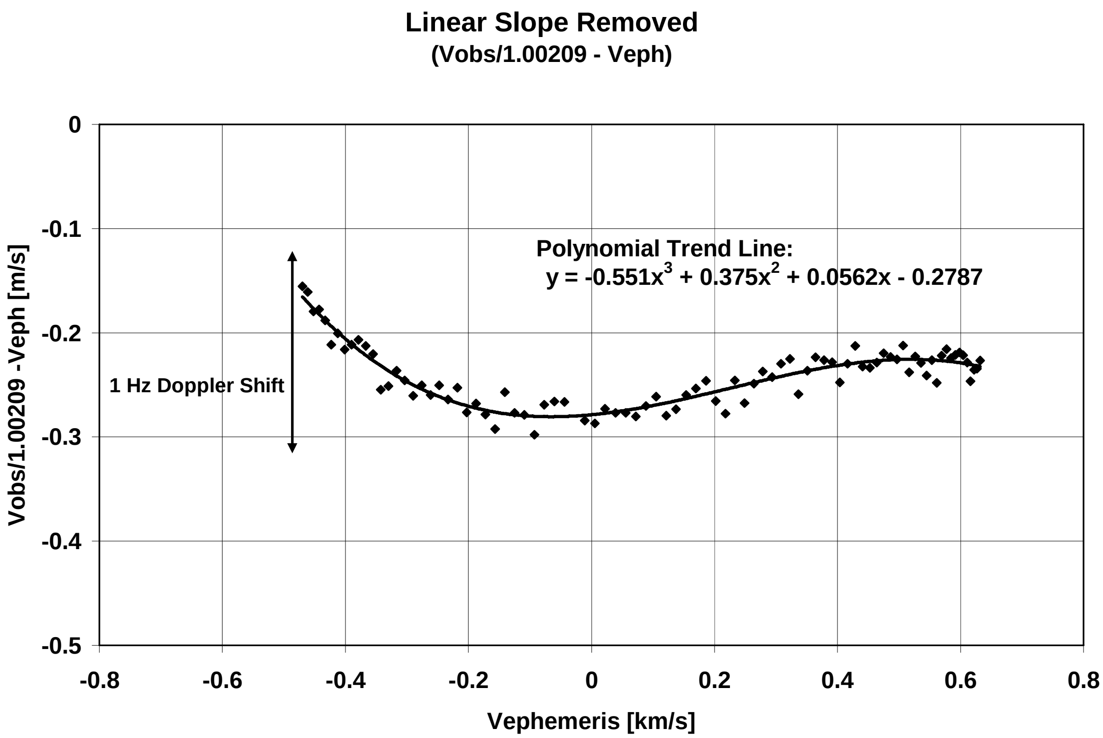

Figure 6. Removing the trend seen in Figure 4 reduces the error by a large factor, but still leaves systematic errors well above the measurement errors.

An Excel spreadsheet is available with the detailed calculations.

GPS Satellite CW Tones
2. Comparison with Published GPS Satellite Coordinates

Mike Davis
March 14, 2006

Radial velocity residuals for satellite NP24 measured on November 15, 2005, reported in my earlier memo, are shown in Figure 1 (small squares). The present ATA Ephemeris routine was not designed to provide extremely accurate Doppler shift corrections, so this memo recalculates the expected velocities using the NGS Geodetic Toolkit with data from the GPS 'Final' ephemeris. This ephemeris, accurate to about 5 cm, is available online with a delay of about two weeks. The resulting disagreement of about 0.2 m/s (~1 Hz) shown in Figure 1 (large squares) is much less, ~0.02 %, but is still highly systematic.

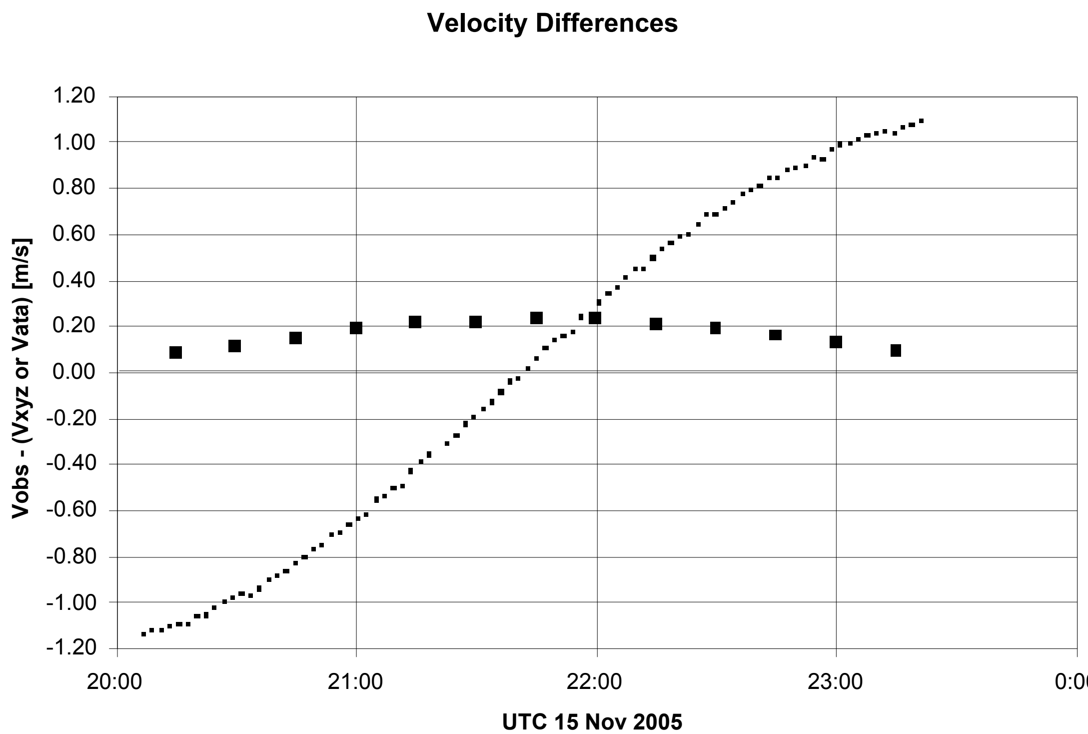

Figure 1. The velocity differences are shown between observed and ephemeris values, for both the 'Predicted' (small squares) and 'Final' (large squares) ephemerides.

For reference, the detailed steps leading to comparison of the observed and expected radial velocities shown in Figure 1 are given in the Appendix.

APPENDIX

Published Satellite Coordinates

GPS satellite positions are published for each satellite going back many years, at http://www.ngs.noaa.gov/GPS/GPS.html . Each file contains data for all satellites for one 'GPS Week'; the files are named by week number. Conversion from date to GPS week is given at http://www.ngs.noaa.gov/CORS/Gpscal.html . Observations were made on 2005 11 15, which is GPS Week + Day of Week: 1349 2. The directory contains both rapid and final orbit data. The 'final' ephemeris file is igs13492.sp3c.Z. It appeared on 02-Dec-2005. It gives the following XYZ values for satellite NP24 during the observing run:

GPS Time	Satellite	X [km]	Y [km]	Z [km]
19:30:00	PG24	3444.207	-25577.773	-5508.578
19:45:00	PG24	3824.968	-25996.826	-2687.792
20:00:00	PG24	4119.768	-26116.649	180.049
20:15:00	PG24	4364.859	-25928.103	3044.772
20:30:00	PG24	4597.804	-25431.057	5856.571
20:45:00	PG24	4855.790	-24634.377	8566.893
21:00:00	PG24	5173.984	-23555.566	11129.287
21:15:00	PG24	5583.984	-22220.081	13500.186
21:30:00	PG24	6112.443	-20660.372	15639.617
21:45:00	PG24	6779.890	-18914.669	17511.832
22:00:00	PG24	7599.818	-17025.574	19085.848
22:15:00	PG24	8578.050	-15038.522	20335.893
22:30:00	PG24	9712.409	-13000.155	21241.762
22:45:00	PG24	10992.698	-10956.685	21789.075
23:00:00	PG24	12400.985	-8952.293	21969.446
23:15:00	PG24	13912.182	-7027.626	21780.556
23:30:00	PG24	15494.888	-5218.443	21226.145
23:45:00	PG24	17112.477	-3554.453	20315.916

Note that GPS time does not use leap seconds. It was 13 seconds ahead of UTC on the date of the observations.

http://www.ngs.noaa.gov/CORS/Coords.html describes the satellite coordinates:

> Since January 11, 2004, the National Geodetic Survey (NGS) and the other Analysis Centers of the International GPS Service (IGS) have been providing GPS satellite orbits (ephemerides) that are referred to a new terrestrial reference frame, called IGb 2000 (or IGb00 for short). This new frame strictly based on GPS observations was designed to be consistent 'on average' with the International Terrestrial Reference Frame of 2000 (ITRF 2000 or ITRF00). … Despite the different designations, users can treat IGb00 and ITRF00 as equivalent.

The difference between the NAD 83 and ITRF00 coordinate systems at the Hat Creek site is of order one meter, and is therefore not critical. However, the difference between NAD 27 and NAD 83 is about 93 meters (see below).

ATA Telescope Coordinates

The PTA dishes 1 and 3 were used at separate frequencies (see Table). The ATA telescopes are surveyed in UTM (Universal Transverse Mercator coordinates) based on the NAD 27 and NGVD 29 horizontal and vertical coordinate systems. Hat Creek is in UTM zone 10. UTM values for the GPS receiver and the three PTA dishes are:

UTM [m] NAD1927	Name	E	N	H	dE	dN	dH
GPS Receiver	Ref	629137.74	4519255.30	1024.94			
1574.397 MHz	pta1	629140.02	4519520.9	1018.609	2.28	265.57	-6.33
Not used	pta2	629129.16	4519520.89	1018.68	-8.58	265.59	-6.26
1576.443 MHz	pta3	629115.95	4519503.8	1018.767	-21.79	248.53	-6.17

Following are the steps to convert UTM telescope coordinates based on NAD 27 and NGVD 29 coordinate systems to NAD 83 and NAVD 88 latitude, longitude and height, and then to XYZ coordinates matching those published for GPS satellites. The NGS Geodetic Toolkit http://www.ngs.noaa.gov/TOOLS/ provides the necessary conversions.

1. Convert UTM (Zone 10) to NAD 27 Lat/Long using tool UTM at
http://www.ngs.noaa.gov/cgi-bin/utm_getgp.prl

NAD 27		Lat [deg min sec]	Long [deg min sec]
	Ref	40 48 57.83393	121 28 7.74751
1574 MHz	pta1	40 48 59.58207	121 28 7.46228
Not used	pta2		
1576 MHz	pta3	40 49 5.90342	121 28 8.49204

2. Convert NAD 27 to NAD 83 Lat/Long using tool NADCON at
http://www.ngs.noaa.gov/cgi-bin/nadcon.prl

NAD 83		Lat [deg min sec]	Long [deg min sec]
	Ref	40 48 57.41310	121 28 11.67256
1574 MHz	pta1	40 48 59.16127	121 28 11.38735
Not used	pta2		
1576 MHz	pta3	40 49 5.48267	121 28 12.41722

3. Heights are treated separately. Convert NGVD 29 to NAVD 88 Height using tool VERTCON at http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl

NAD 83 + NAVD88		H [NGVD 29]	lat [NAD 83]	long [NAD 83]	H [NAVD 88]
	Ref	1024.94	40 48 57.41310	121 28 11.67256	1025.92
1574 MHz	pta1	1018.609	40 48 59.16127	121 28 11.38735	1019.58
Not used	pta2	1018.68			
1576 MHz	pta3	1018.767	40 49 5.48267	121 28 12.41722	1019.74

4. Convert Lat/Long/Height to X1,Y1, Z1 using tool XYZ at
http://www.ngs.noaa.gov/cgi-bin/xyz_getxyz.prl

XYZ		X1 [m]	Y1 [m]	Z1 [m]
	Ref	-2523985.692	-4123629.932	4147646.484
1574 MHz	pta1	-2523959.081	-4123599.261	4147683.159
Not used	pta2			
1576 MHz	pta3	-2523913.182	-4123478.032	4147830.861

<u>Comparison</u>

1. Derive the radial distance

$$R = \sqrt{((X\text{-}X1)^2 + (Y\text{-}Y1^{\wedge 2} + (Z\text{-}Z1)^2)},$$

2. Compute the velocities by fitting a 4th order polynomial five points at a time to R. The interpolation formula is

$$V_0\ [m/s] = (2*(R_{+1}\text{-}R_{-1})/3 - (R_{+2}\text{-}R_{-2})/12)/dT,$$

where dT, the time step, is 900 seconds.

GPS Time	PTA1 Range [m]	PTA3 Range [m]	PTA3-PTA1 dR [m]	PTA1 Velocity [m/s]	PTA3 Velocity [m/s]	PTA3-PTA1 dV [m/s]
19:30:00	24272287.477	24272442.106	154.628			
19:45:00	23779626.430	23779768.143	141.713			
20:00:00	23314705.304	23314831.717	126.413	-495.223	-495.242	-0.011
20:15:00	22893418.183	22893526.951	108.767	-438.073	-438.094	-0.012
20:30:00	22531035.268	22531124.203	88.935	-364.576	-364.599	-0.013
20:45:00	22241450.662	22241517.881	67.219	-276.705	-276.730	-0.015
21:00:00	22036388.895	22036432.967	44.072	-177.302	-177.328	-0.015
21:15:00	21924659.603	21924679.685	20.082	-69.972	-69.999	-0.016
21:30:00	21911568.614	21911564.550	-4.064	41.154	41.128	-0.015
21:45:00	21998586.725	21998559.094	-27.631	151.750	151.725	-0.015
22:00:00	22183340.005	22183290.104	-49.901	257.665	257.641	-0.014
22:15:00	22459925.927	22459855.695	-70.232	355.262	355.241	-0.012
22:30:00	22819497.868	22819409.769	-88.099	441.668	441.649	-0.011
22:45:00	23251017.456	23250914.333	-103.123	514.893	514.878	-0.009
23:00:00	23742061.529	23741946.460	-115.069	573.839	573.828	-0.007
23:15:00	24279586.086	24279462.247	-123.839	618.203	618.195	-0.005
23:30:00	24850581.526	24850452.079	-129.448			
23:45:00	25442588.275	25442456.277	-131.998			

3. Interpolate the observed PTA3 velocities at the GPS times, using a quadratic fit to the closest nine values. Compute the velocity differences shown in Figure 1.

UTC	Vobs [m/s]	Vobs-Vxyz [m/s]
19:29:47		
19:44:47		
19:59:47		
20:14:47	-438.005	0.089
20:29:47	-364.485	0.114
20:44:47	-276.581	0.149
20:59:47	-177.136	0.192
21:14:47	-69.7804	0.219
21:29:47	41.34936	0.222
21:44:47	151.9621	0.237
21:59:47	257.8798	0.238
22:14:47	355.4511	0.210
22:29:47	441.8407	0.191
22:44:47	515.0404	0.162
22:59:47	573.9573	0.129
23:14:47	618.2903	0.096
23:29:47		
23:44:47		
	Std Dev	0.053