Earth’s Orbital Position in the Solar System

using Galactic HI Measurements

Updated to Include: Forth Observation Results with Solar System Yaw Measurements

Richard A. Russel

Deep Space Exploration Society

Abstract

The Sun moves in an almost circular path around the Milky Way. The Earth orbits the Sun at one astronomical unit in an elliptical orbit. The goal of this study is to determine if HI measurements using the Haswell, Colorado 60-foot dish and the SpectraCyber system can be used to determine the Earth’s orbit position in the solar system with reference to the Milky Way center. Multiple observations were taken of HI at the same galactic longitude degrees. The different Doppler shifts correspond to the Earth’s position at the times of observation. A Monte-Carlo model was developed to explore the Earth orbital parameters in order to match the observed Doppler shifts with the expected model. The measured results showed that the 62-degree angle of the Earth’s orbit to the galactic plane showed good correlation. This paper is an update to the February 2019 SARA Journal article. It includes the fifth measurement of HI velocity and HI measurements above the galactic plane. The b>0 measurements are to provide data to estimate the yaw of the solar system as it moves around the galaxy.

1. Introduction

The theory that the Earth’s orbital position can be estimated using the HI measurements was presented at the 2018 SARA Eastern Conference in Greenbank, WV. [1] Multiple HI Doppler velocity measurements have been taken approximately one month apart at the Deep Space Exploration Society’s 60-foot dish. [2] The theory is that the change in the received Doppler velocity of a HI measurement taken at the same galactic longitude along the b=0 galactic latitude, is caused by the Earth’s rotation and the velocity of the Earth around the Sun. The Earth’s rotation effect was minimized by taking the measurements at the meridian. This left the difference in received velocity (Vr) between monthly observations caused by the location of the Earth in orbit and its resultant velocity contribution to Vr. The measurements were mapped onto a model and the orbital position was estimated.

2. Theory

The Sun goes around the Milky Way at approximately 220 km/s at 8.5 kpc radius. The Earth rotates around the Sun in an almost circular orbit at a mean radius of 1 astronautical unit (AU). Using a pitch-roll-yaw model, the Earth’s orbit is pitched at an approximate 62 degrees in the direction of motion. The roll and yaw are considered at 0 degrees. Currently the Earth is at the closest approach to the galactic center at the summer solstice (June 22, 2018), though this will change over time. Figure 1 shows the basic geometry of the Earth and galactic plane.

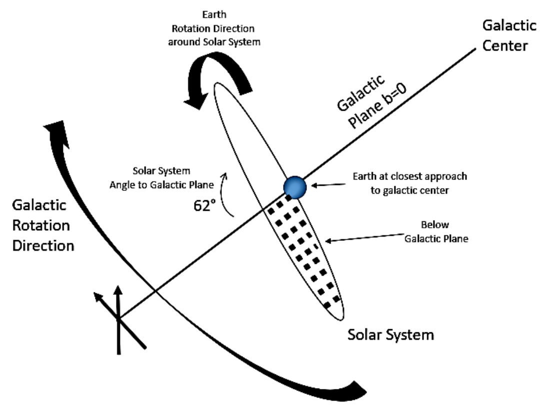


Figure 1: Earth - Galaxy Geometry

HI Doppler measurements show different velocity shifts throughout the year. The velocity change is based on the contribution of the Earth's orbital velocity to the total velocity measured (Vr).

A Monte-Carlo model was developed to show the effect of the Earth's orbital pitch to the Vr measurement. The maximum velocity contribution that the Earth's orbit can contribute is based on the velocity of the Earth around the Sun. The velocity equation for an object orbiting the Sun is:

$$V = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} \qquad (1)$$

r: radius of Earth around Sun (aphelion $152.1\text{x}10^6$ km, perihelion $147.1\text{x}10^6$ km)
a: Semimajor axis ($149.6\text{x}10^6$ km)
μ: Sun's gravitational constant ($1.32712440018\text{x}10^{20}m^3s^{-2}$)

At aphelion V=29.29 km/s, at perihelion V=30.29 km/s. So, depending on the Earth's orientation to the observation, this provides the maximum velocity contribution to Vr. Figure 2 shows the Earth angle relative to the galactic center. Based on this picture the Monte-Carlo model produces the velocity contribution to Vr of the Earth as it orbits the Sun.

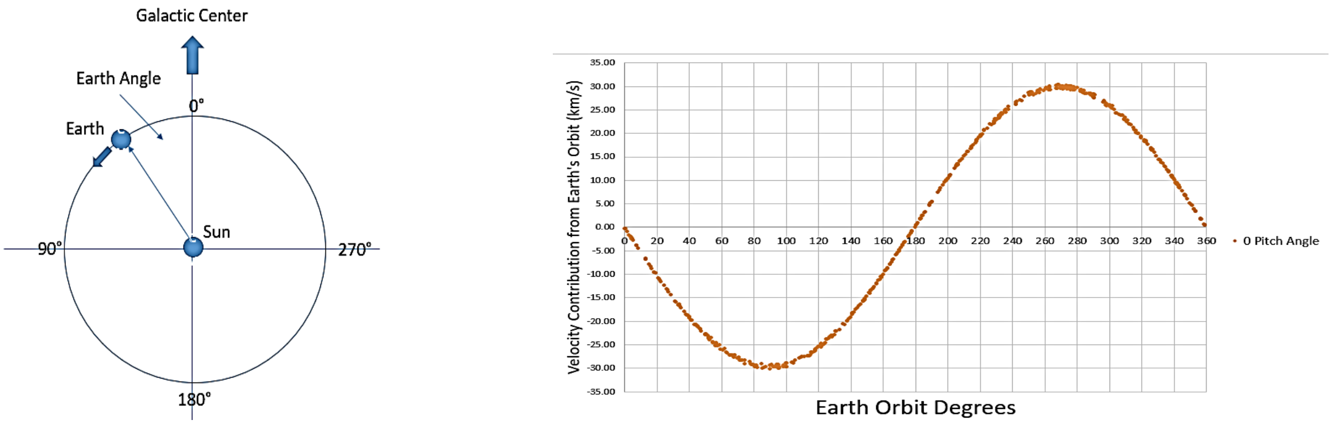


Figure 2 Earth Angle and Velocity Change Relative to the Galactic Center

The solar system is at a pitch angle of approximately 62 degrees. The contribution to Vr now gets adjusted by cos (pitch angle) as shown in figure 3. This reduces the Earth's velocity contribution to approximately ±15 km/s.

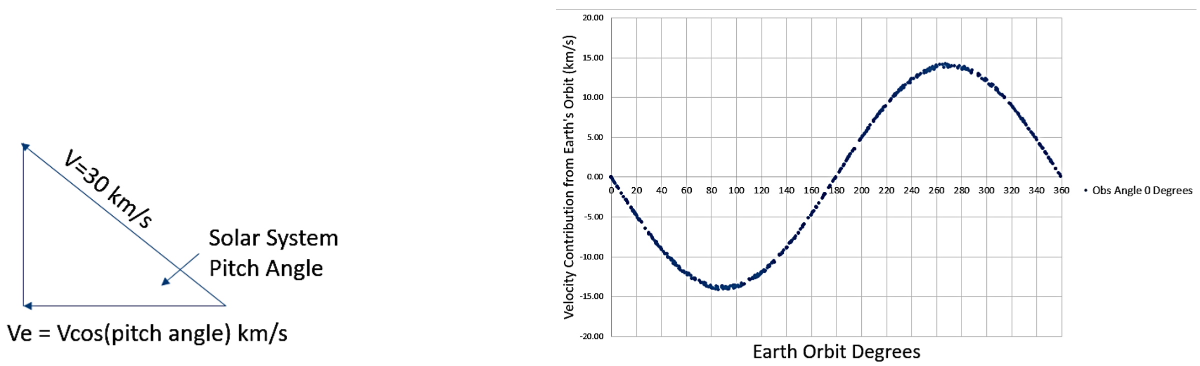


Figure 3: Effect of Pitch Angle on Velocity

Another primary parameter is the observation angle of the HI source in relationship to the galactic center. The observations were made in galactic quadrant 1 which is defined as 0-90 degrees galactic longitude from the galactic center as observed from Earth. The observation angle acts like a phase change to the sinusoid model. Figure 4 shows the shift in Earth angle based on different galactic observation angles. Note that this is assuming the 62-degree solar system pitch angle.

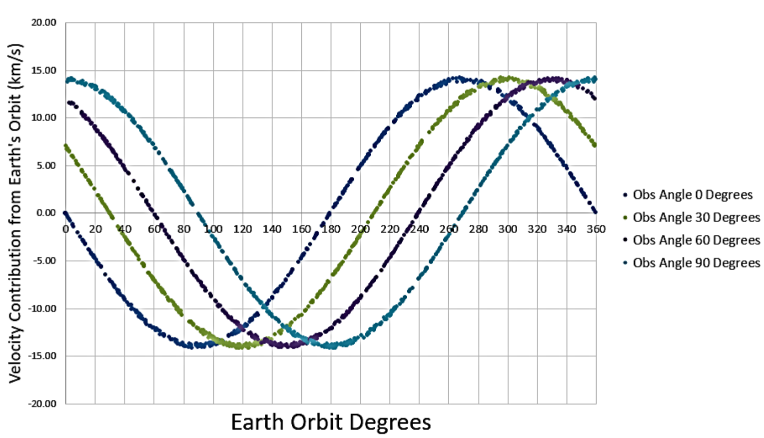


Figure 4: Galactic Longitude Observation Angle effect on Vr

The Monte-Carlo model was used to develop the appropriate plots for the HI observations made.

3. Observations

The observations of galactic HI were conducted with the Deep Space Exploration Society's (DSES) 60-foot radio telescope located near Haswell, Colorado [2]. (figure 5)

Figure 5: DSES 60-foot Dish and Communications Trailer

A SpectraCyber 1 [3] was used to receive and collect the data. The current observations were taken on 10/20/18, 11/17/18, 12/14/18, 1/18/19and 2/16/19. (figure 6)

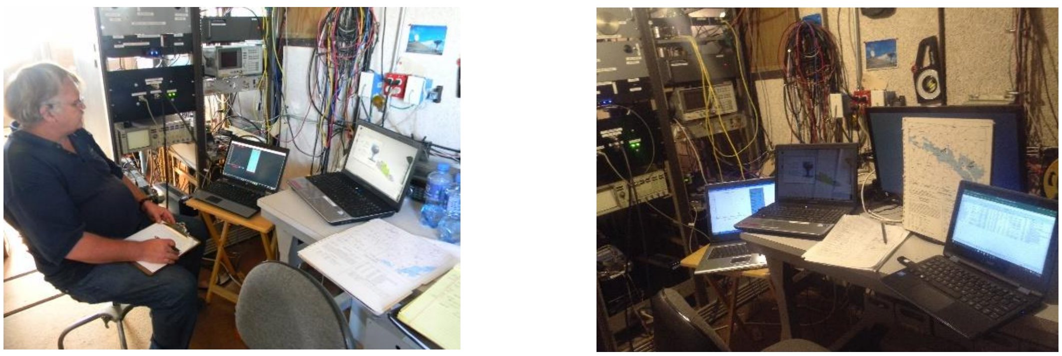
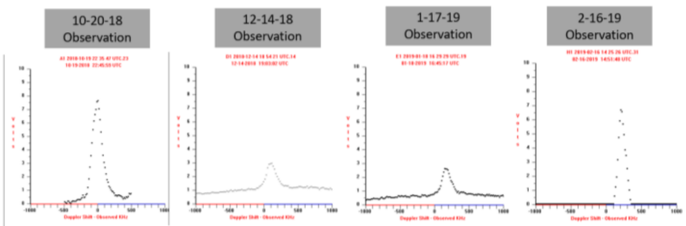


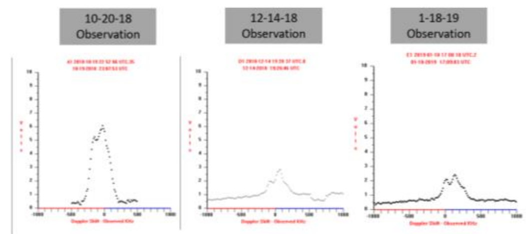
Figure 6: Operating Station in Communications Trailer

The SpectraCyber outputs are shown in figure 7. Note that the differences in signal amplitude are based on gain setting differences in order to get the voltage levels within the 10-volt maximum of the SpectraCyber. This did not affect the frequency measurements.

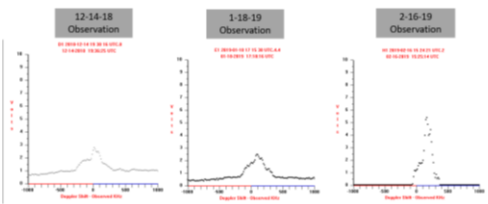
Galactic Lat 0 Long 0
RA 17h45m DEC -28d56m



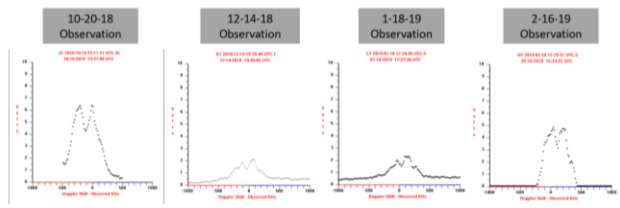
Galactic Lat 0 Long 10
RA 18h07m DEC -20d17m



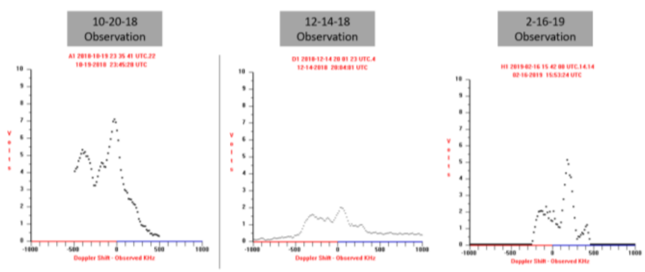
Galactic Lat 0 Long 15
RA 18h17m DEC -15d54m



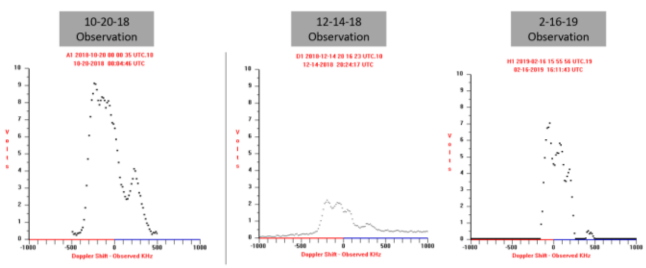
Galactic Lat 0 Long 20
RA 18h27m DEC -11d29m



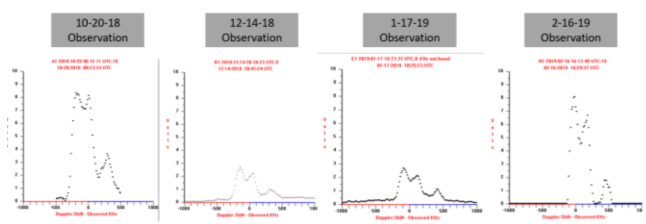
Galactic Lat 0 Long 30
RA 18h46m DEC -02d36m



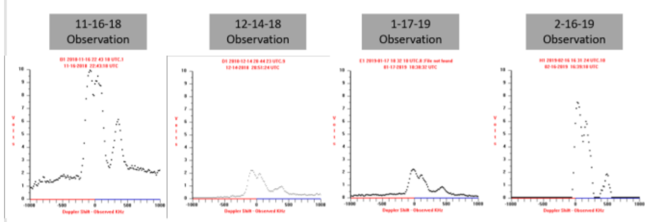
Galactic Lat 0 Long 40
RA 19h04m DEC 06d17m



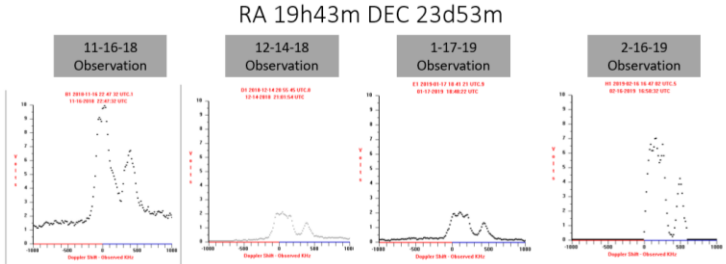
Galactic Lat 0 Long 50
RA 19h23m DEC 15d08m



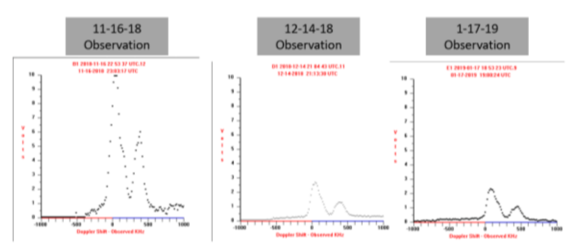
Galactic Lat 0 Long 55
RA 19h33m DEC 19d32m



Galactic Lat 0 Long 60
RA 19h43m DEC 23d53m

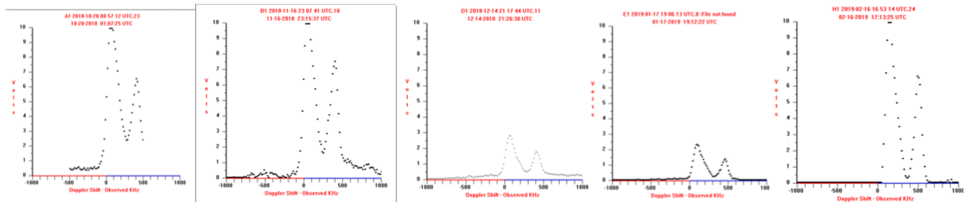


Galactic Lat 0 Long 65
RA 19h55m DEC 28d11m



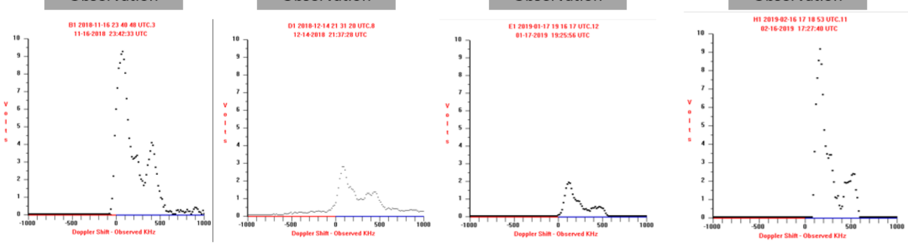
Galactic Lat 0 Long 70
RA 20h07m DEC 32d26m

10-20-18 Observation | 11-16-18 Observation | 12-14-18 Observation | 1-17-19 Observation | 2-16-19 Observation



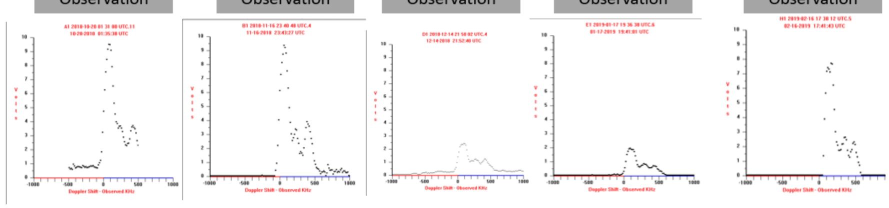
Galactic Lat 0 Long 75
RA 20h20m DEC 36d36m

11-16-18 Observation | 12-14-18 Observation | 1-17-19 Observation | 2-16-19 Observation



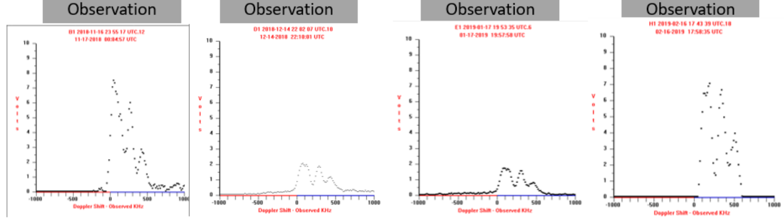
Galactic Lat 0 Long 80
RA 20h35m DEC 40d39m

10-20-18 Observation | 11-16-18 Observation | 12-14-18 Observation | 1-17-19 Observation | 2-16-19 Observation



Galactic Lat 0 Long 85
RA 20h52m DEC 44d35m

11-16-18 Observation | 12-14-18 Observation | 1-17-19 Observation | 2-16-19 Observation



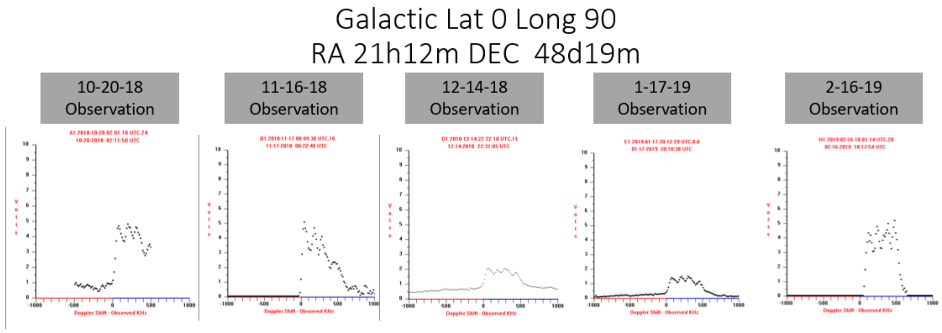


Figure 7: Hi Observations

The frequency for the left peak of each plot was measured and the velocity was calculated using the formula.

$$V = \frac{f_{base} - f_{measured}}{f_{base}} x\ c \qquad (2)$$

f $_{base:}$ HI base frequency (1,420.405,751 MHz)
f $_{measured:}$ measured frequency of observation
c: speed of light in vacuum (299,790,000 m/s)

The results for each measurement are shown in table 1.

Galactic Lat (Deg)	Galactic Long (Deg)	Most Neg Freq (Hz)	Measured Velocity Vr (km/Second)	Observation Date
0	0	1,420,405,751	0.0	10/20/2018
0	0	1,420,405,851	21.1	12/14/2018
0	0	1,420,405,891	29.5	1/18/2019
0	0	1,420,405,951	42.2	2/16/2019
0	2	1,420,405,876	26.4	1/18/2019
0	5	1,420,405,786	7.4	12/14/2018
0	5	1,420,405,861	23.2	1/18/2019
0	7	1,420,405,876	26.4	1/18/2019
0	10	1,420,405,601	-31.7	10/20/2018
0	10	1,420,405,666	-17.9	12/14/2015
0	10	1,420,405,756	1.1	1/18/2019
0	12	1,420,405,891	29.5	1/18/2019
0	15	1,420,405,651	-21.1	12/14/2015
0	15	1,420,405,831	16.9	1/18/2019
0	15	1,420,405,906	32.7	2/16/2019
0	20	1,420,405,541	-44.3	10/20/2018
0	20	1,420,405,621	-27.4	12/14/2015
0	20	1,420,405,711	-8.4	1/18/2019
0	20	1,420,405,786	7.4	2/16/2019
0	25	1,420,405,381	-78.1	12/14/2015
0	30	1,420,405,346	-85.5	10/20/2018
0	30	1,420,405,441	-65.4	12/14/2018
0	30	1,420,405,606	-30.6	2/16/2019
0	35	1,420,405,576	-36.9	12/14/2018
0	40	1,420,405,511	-50.7	10/20/2018
0	40	1,420,405,546	-43.3	12/14/2018
0	40	1,420,405,696	-11.6	2/16/2019
0	45	1,420,405,561	-40.1	12/14/2018
0	45	1,420,405,651	-21.1	2/16/2019
0	50	1,420,405,556	-41.2	10/20/2018
0	50	1,420,405,591	-33.8	12/14/2018
0	50	1,420,405,651	-21.1	1/18/2019
0	50	1,420,405,726	-5.3	2/16/2019

Galactic Lat (Deg)	Galactic Long (Deg)	Most Neg Freq (Hz)	Measured Velocity Vr (km/Second)	Observation Date
0	55	1,420,405,671	-16.9	11/17/2018
0	55	1,420,405,651	-21.1	12/14/2018
0	55	1,420,405,726	-5.3	1/18/2019
0	55	1,420,405,771	4.2	2/16/2019
0	60	1,420,405,766	3.2	10/20/2018
0	60	1,420,405,701	-10.6	11/17/2018
0	60	1,420,405,711	-8.4	12/14/2018
0	60	1,420,405,771	4.2	1/18/2019
0	60	1,420,405,831	16.9	2/16/2019
0	65	1,420,405,771	4.2	11/17/2018
0	65	1,420,405,786	7.4	12/14/2018
0	65	1,420,405,816	13.7	1/18/2019
0	70	1,420,405,791	8.4	10/20/2018
0	70	1,420,405,771	4.2	11/17/2018
0	70	1,420,405,801	10.6	12/14/2018
0	70	1,420,405,831	16.9	1/18/2019
0	70	1,420,405,876	26.4	2/16/2019
0	75	1,420,405,821	14.8	11/17/2018
0	75	1,420,405,831	16.9	12/14/2018
0	75	1,420,405,861	23.2	1/18/2019
0	75	1,420,405,906	32.7	2/16/2019
0	80	1,420,405,841	19.0	10/20/2018
0	80	1,420,405,806	11.6	11/17/2018
0	80	1,420,405,801	10.6	12/14/2018
0	80	1,420,405,831	16.9	1/18/2019
0	80	1,420,405,861	23.2	2/16/2019
0	85	1,420,405,791	8.4	11/17/2018
0	85	1,420,405,816	13.7	12/14/2018
0	85	1,420,405,831	16.9	1/18/2019
0	85	1,420,405,876	26.4	2/16/2019
0	90	1,420,405,826	15.8	10/20/2018
0	90	1,420,405,791	8.4	11/17/2018
0	90	1,420,405,801	10.6	12/14/2018
0	90	1,420,405,831	16.9	1/18/2019
0	90	1,420,405,861	23.2	2/16/2019

Table 1: Vr Observations

4. Analytical Technique

The analysis technique developed was to curve fit the observation Vr data onto a model that included the pitch angle, observation longitude angles, and the Earth radius velocity.

The first step is to use Monte-Carlo Model to produce a velocity vs. Earth orbit angle curve for each longitude angle measured. The expected pitch angle of the Earth's orbit to the galactic plane was added. Both the longitude angles and the pitch angle were spread to account for uncertainties. This was simply done by adjusting the minimum and maximum values in the Monte-Carlo model. The pitch angle selected between 60.2 degrees [4] and 63 degrees [5]. The longitude measurement angle was ±1 degree based on antenna beamwidth and pointing error. (figure 8)

Figure 8: Monte-Carlo Input and Output for 70 Degree Galactic Longitude Measurement

Step two was to plot the VR measurements and visually curve fit them to the plots. Another model was developed that allowed for the Vr measurements to be plotted on the Monte-Carlo curve. (Figure 9)

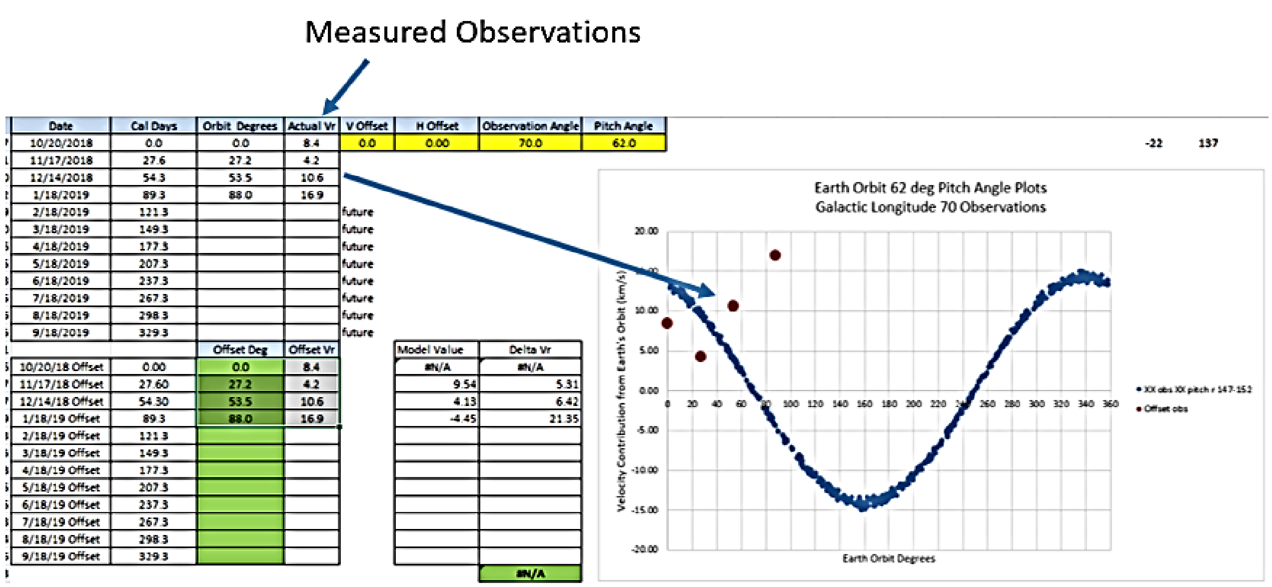


Figure 9: Measured Vr Observations Plotted on Curve

Step 3 is to shift the raw measured values horizontally and vertically in order to get the most accurate curve fit. An added tool was developed to compare the shifted measurements with the curve and provide an indicator of the least difference between the values. (figure 10)

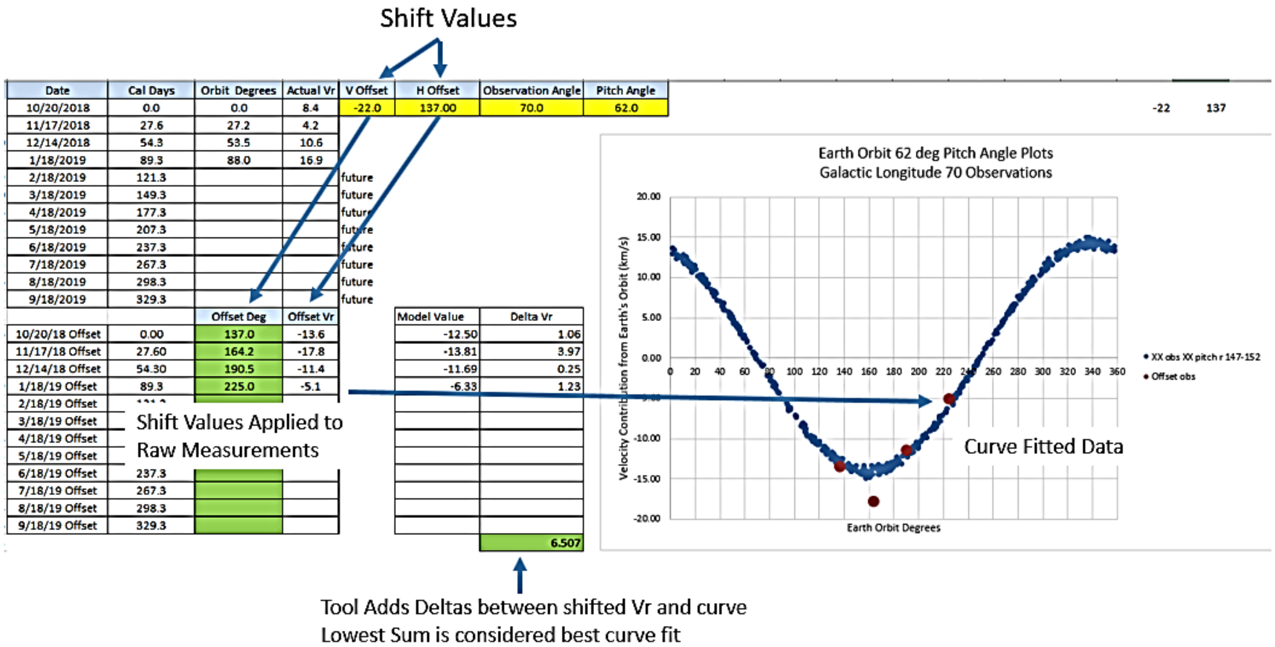


Figure 10: Curve Fitting the Raw Vr onto Curves

This technique was conducted on the four days of observations. Note that the more observation days measured should provide more data to get a good curve fit. (figures 11-24)

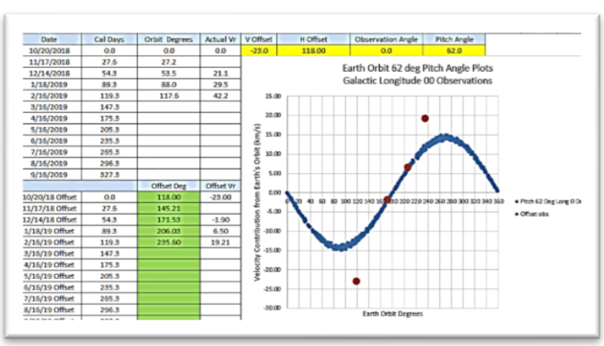


Figure 11: 0 Degrees Longitude Angle

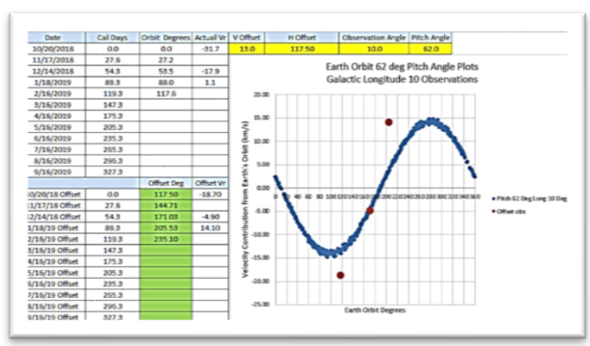


Figure 12: 10 Degrees Longitude Angle

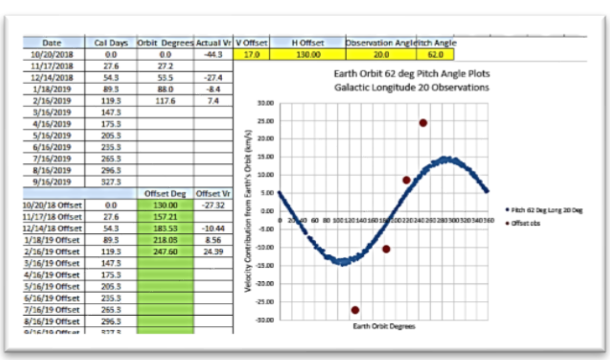


Figure 13: 20 Degrees Longitude Angle

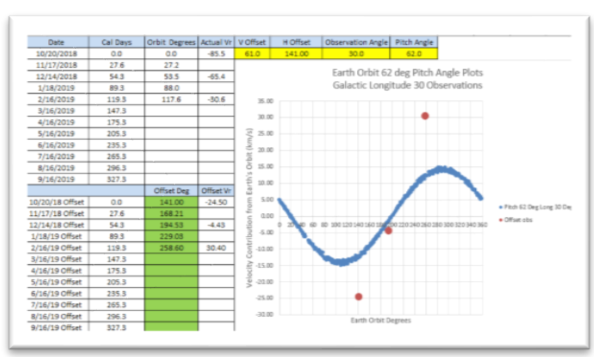


Figure 14: 30 Degrees Longitude Angle

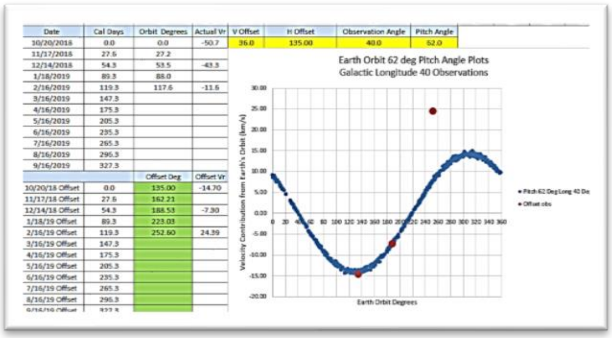


Figure 15: 40 Degrees Longitude Angle

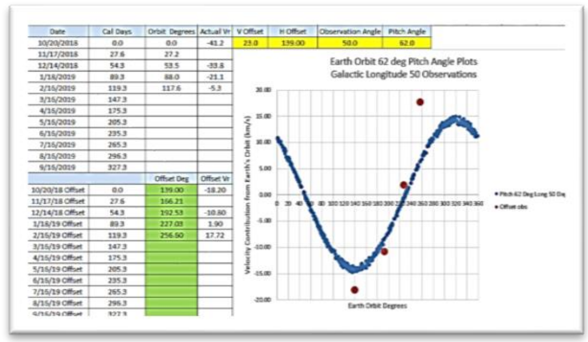


Figure 16: 50 Degrees Longitude Angle

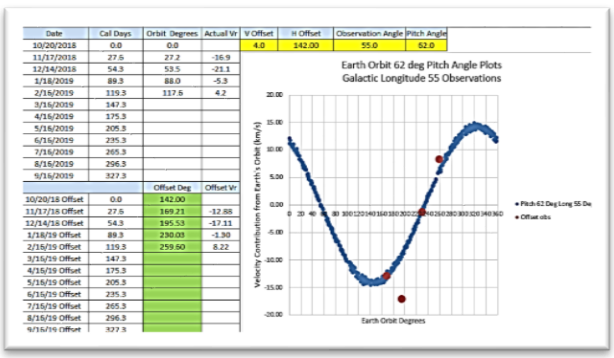


Figure 17: 55 Degrees Longitude Angle

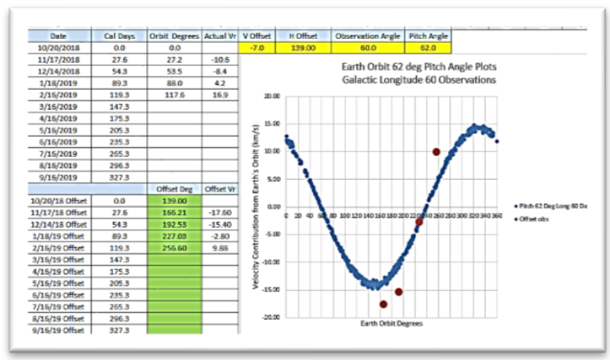


Figure 18: 60 Degrees Longitude Angle

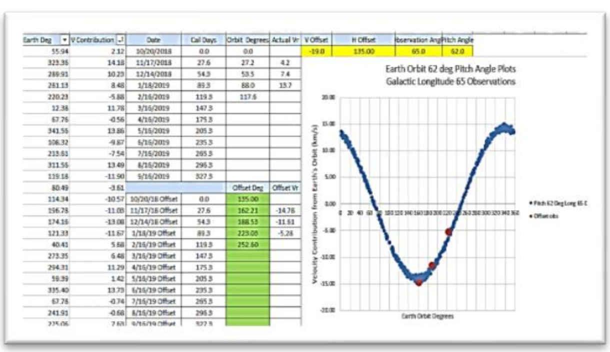


Figure 19: 65 Degrees Longitude Angle

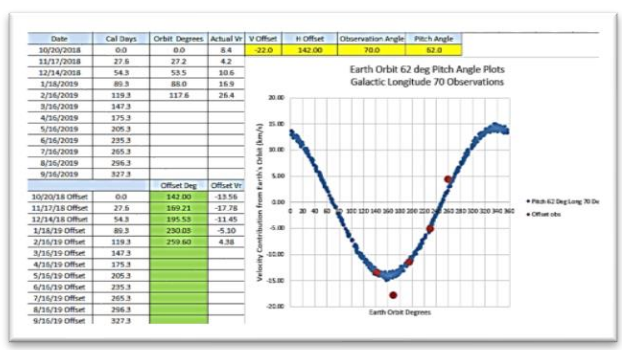


Figure 20: 70 Degrees Longitude Angle

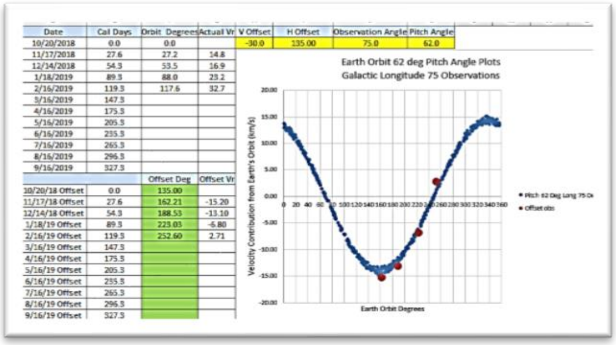


Figure 21: 75 Degrees Longitude Angle

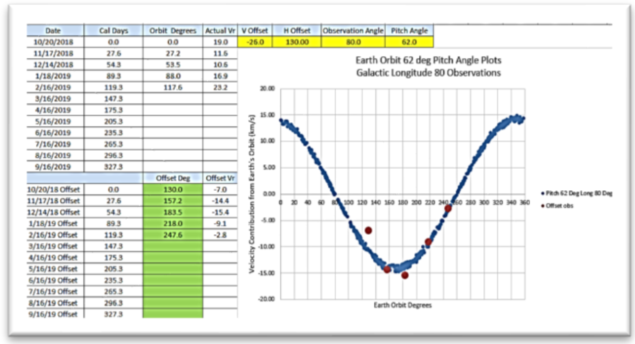


Figure 22: 80 Degrees Longitude Angle

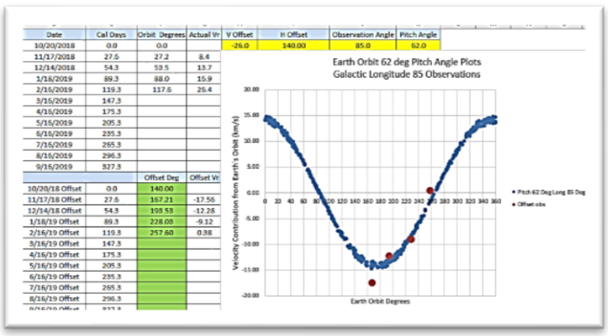


Figure 23: 85 Degrees Longitude Angle

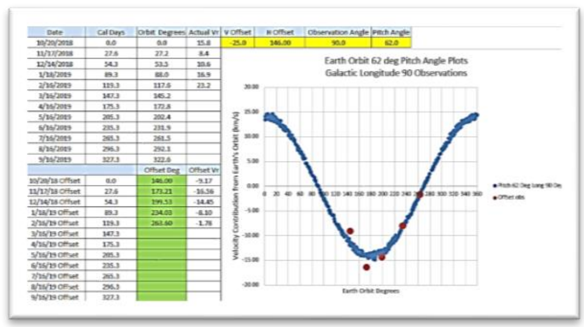


Figure 24: 90 Degrees Longitude Angle

The curve fitted results were correlated and the average value of the Earth angle was calculated for each observation day in order to come up with the best Earth position on that day. (table 2)

Pitch Angle	Galactic Longitude Observed	Earth Degrees at 10/20/2018	Earth Degrees at 11/18/18	Earth Degrees at 12/14/18	Earth Degrees at 1/18/19	Earth Degrees at 2/16/19
62	0	118.0	145.2	171.5	206.0	235.6
62	10	117.5	144.7	171.0	205.5	235.1
62	20	130.0	157.2	183.5	218.0	247.6
62	30	141.0	168.2	194.5	229.0	258.6
62	40	135.0	162.2	188.5	223.0	252.6
62	50	139.0	166.2	192.5	227.0	256.6
62	55	142.0	169.2	195.5	230.0	259.6
62	60	139.0	166.2	192.5	227.0	256.6
62	65	135.0	162.2	188.5	223.0	252.6
62	70	142.0	169.2	195.5	230.0	259.6
62	75	135.0	162.2	188.5	223.0	252.6
62	80	130.0	157.2	183.5	218.0	247.6
62	85	140.0	167.2	193.5	228.0	257.6
62	90	146.0	173.2	199.5	234.0	263.6
	Average	135.0	162.2	188.5	223.0	252.6
	STDev ±	8.6	8.6	8.6	8.6	8.6

Table 2: Curve Fit Results

5. Visualizing the Results

The results can be represented like a clock face with noon being the direction of the galactic center. The Earth is rotating counter-clockwise. Based on these results, the Earth is now starting back toward the direction of the galactic center. (figure 25)

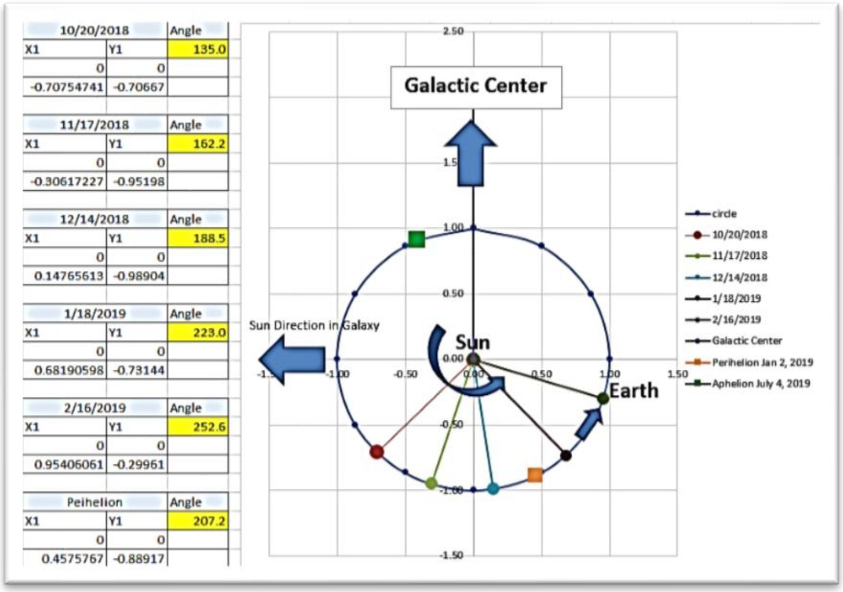


Figure 25: Average Earth Position in Orbit for each Observation Day

6. Error Analysis

Error Analysis is based on the effect of the frequency, Ro, Vo, and pointing ranges on R and V(R). The estimates were made by substituting the error ranges into the calculations and determining the change of each result [6]. The results of this analysis are shown in table 3.

Parameter	Value	±Error	Units
Vo	238	14	km/s
Ro	8.05	0.45	Kpc
frequency	1,420,405,751	10	hz
Pointing		0.17	deg
Beamwidth		0.86	deg
Total Pointing Error (X-Axis)		**1.03**	**deg**
V (R) Error (Ro)		0.00	km/s
V(R) Error (pointing)		2.10	km/s
V(R) Error (Vo)		12.1	km/s
V(R) Error (freq)		2.00	km/s
Total V(R) Error		**16.20**	**km/s**
Percentage Error (Y-Axis)	Based on 243.3 km/sec	**6.7%**	**km/s**

Table 3: Error Analysis

The results are close to expected values; however, the curve fitting approach should get more accurate with more observations. Figure 26 shows the galactic longitude 0 measurements overlaid on the model. Note that the measurements indicate that the Earth was the farthest from the galactic center on approximately 12/5/18 at the Earth angle of 180 degrees.

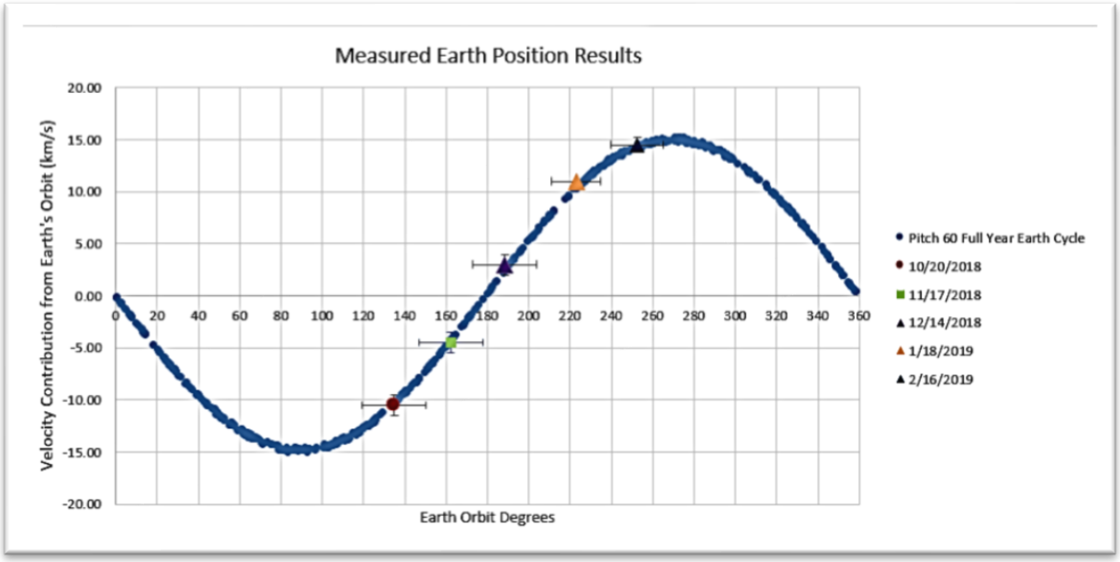


Figure 26: Observation Day Earth Positions with Error Ranges Plotted on a 0 galactic Longitude Observation Angle Curve

7. Estimating the Date of the Earth's Closest Approach to the Galactic Center

The Earth's closest approach to the galactic center can now be estimated using the Earth degrees and the observation dates. The Earth calendar days are therefore:

$$Calendar\ Days = \frac{\text{365 Calendar Days}}{360\ Earth\ Orbit\ Degrees}\ (Measured\ Earth\ Orbit\ Degrees)\ \ (2)$$

The results indicate that the average Earth angle from the galactic center on 2/16/19 was 252.6 degrees. This is equivalent to 256 calendar days since the galactic center closest approach. This puts the Earth's next closest approach to the galactic center in at June 5, 2019. The standard deviation of the data range is shown in figure 26 as 7.7 degrees or 7.8 calendar days. The range of closest approach is therefore between 5/28/19 and 6/13/19. The next expected galactic center closest approach is June 21, 2019 [7] which corresponds to the North American summer solstice. The HI measurement approach appears to be trailing the expected date of closest approach.

8. Determining the Solar System Yaw Angle to the Galactic Center

Observing the HI measurements at galactic longitude (b=0) does not provide enough geometry input to determine the yaw axis angle. Therefore, a series of observations were taken between galactic latitude 70 and 0 at galactic longitude 0. The results of these observations are shown in table 4.

Galactic Lat (Deg)	Galactic Long (Deg)	Most Neg Freq (Hz)	Measured Velocity Vr (km/Second)	Observation Date
70	0	1,420,406,011	54.9	1/18/2019
70	0	1,420,406,011	54.9	2/16/2019
60	0	1,420,405,996	51.7	1/18/2019
60	0	1,420,406,011	54.9	2/16/2019
50	0	1,420,406,011	54.9	1/18/2019
50	0	1,420,406,011	54.9	2/16/2019
40	0	1,420,405,996	51.7	1/18/2019
40	0	1,420,406,011	54.9	2/16/2019
30	0	1,420,405,981	48.5	1/18/2019
30	0	1,420,406,011	54.9	2/16/2019
20	0	1,420,405,966	45.4	1/18/2019
20	0	1,420,405,996	51.7	2/16/2019
10	0	1,420,405,936	39.0	1/18/2019
10	0	1,420,405,981	48.5	1/18/2019
0	0	1,420,405,751	0.0	10/20/2018
0	0	1,420,405,851	21.1	12/14/2018
0	0	1,420,405,891	29.5	1/18/2019
0	0	1,420,405,951	42.2	2/16/2019

Table 4: Galactic Latitude (b>0) HI Measurements

A model for each galactic latitude measurements was developed, and the results were plotted, and curve fitted on figures 27 – 31.

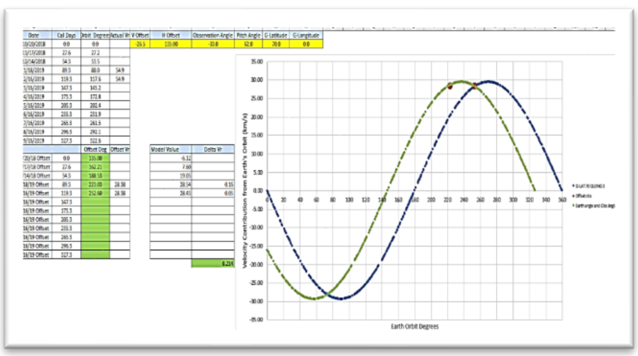


Figure 27: Galactic Latitude 70 Curve Fit

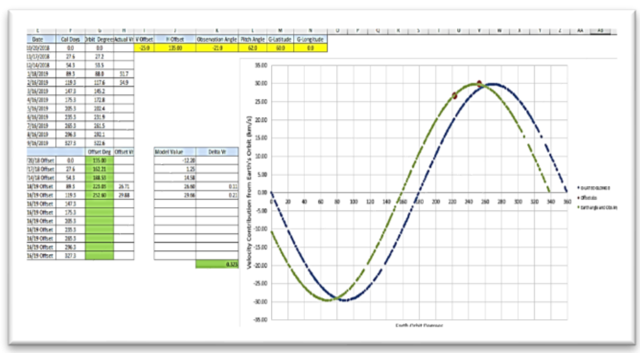


Figure 28: Galactic Latitude 60 Curve Fit

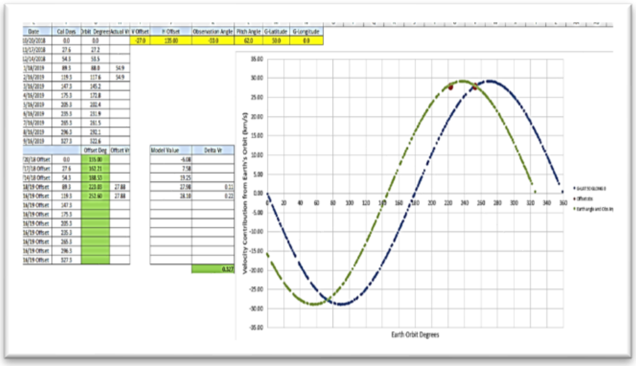


Figure 27: Galactic Latitude 50 Curve Fit

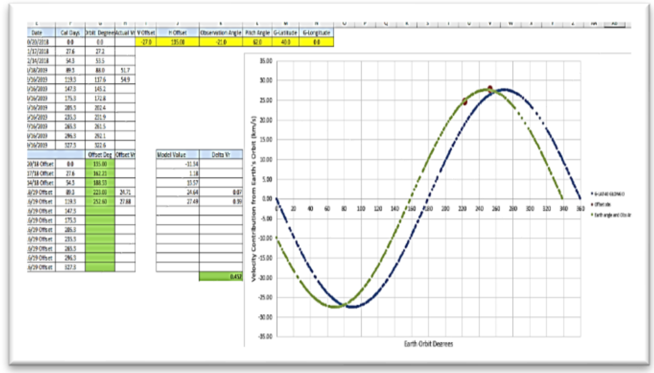


Figure 28: Galactic Latitude 40 Curve Fit

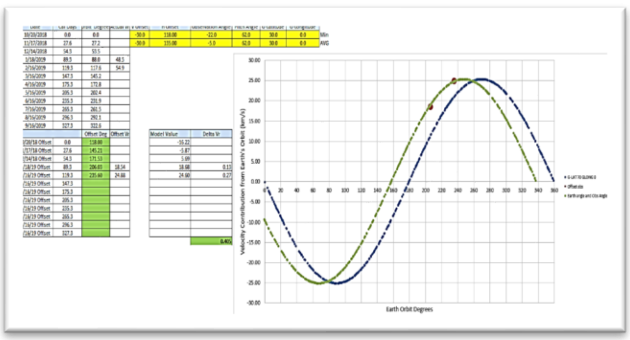


Figure 29: Galactic Latitude 30 Curve Fit

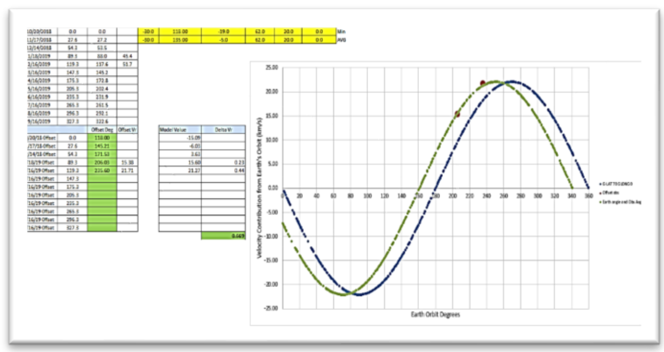


Figure 30: Galactic Latitude 20 Curve Fit

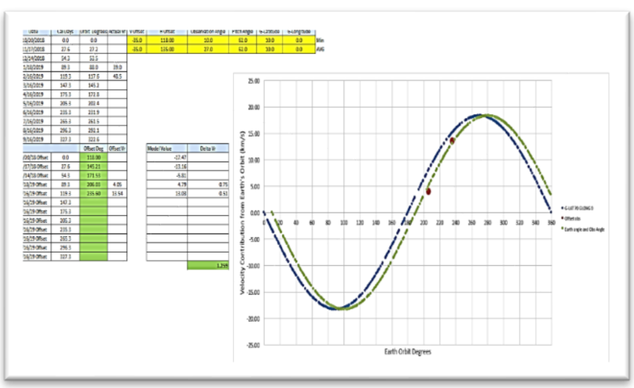


Figure 31: Galactic Latitude 10 Curve Fit

Plotting the minimum and average results indicate that the yaw angle is between -21 to -50 degrees from the galactic center. The results are shown in figure 32.

Gal Latitude	Min Obs Angle	AVG Obs Angle
10	10	27
20	-19	-5
30	-22	-5
40	-38	-21
50	-50	-33
60	-38	-21
70	-50	-33

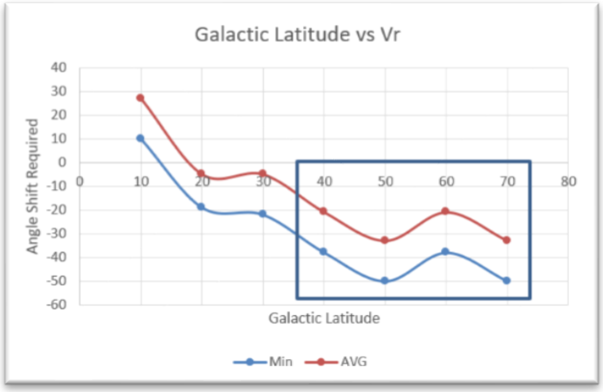


Figure 32: Galactic Latitude vs. Vr Measurement Summary

The values for Latitudes 40 to 70 were used because they were consistent. This decision needs to be reevaluated after more observations are made.

The preliminary results indicate that the Earth's orbit yaw angle is between 21 and 50 degrees to the right of the galactic center. This assumes that the best measurements are from 40-70 degrees galactic latitude. This is a preliminary result and will require more HI measurements to improve the curve fit on the models. The interpretation of the results are that the highest point the Earth reaches above the galactic plane is between the Earth angles of 310 and 339 as shown in figure 33.

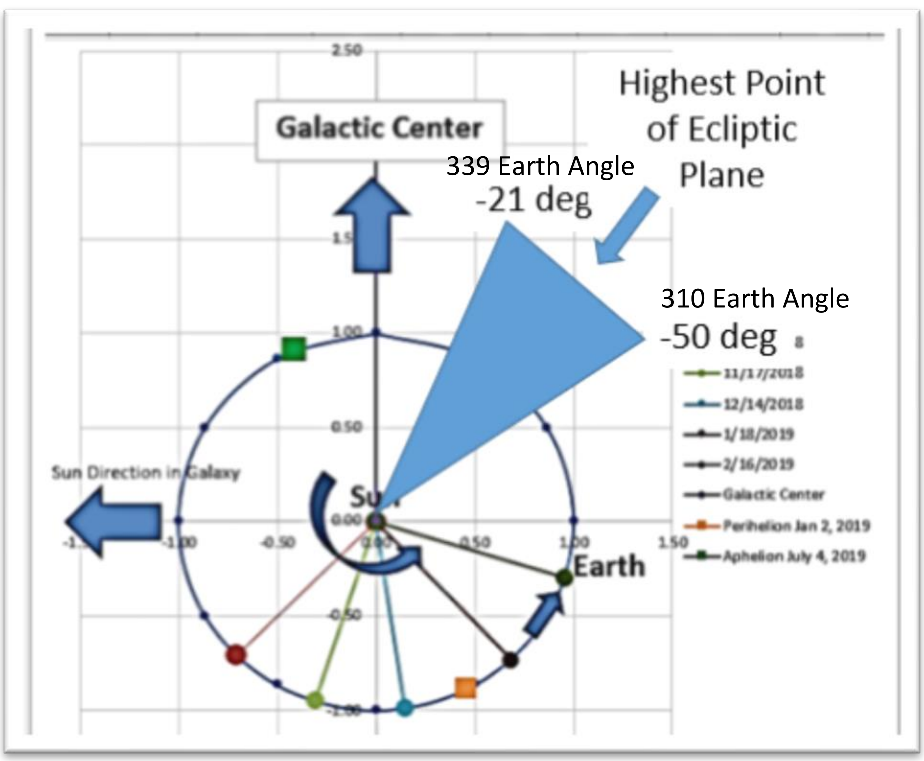


Figure 33: Preliminary Yaw Results

9. Summary

The use of galactic HI measurements to estimate the Earth's position around the Sun is promising. The results show good fit of the Vr measurements to the Monte-Carlo models. The position of the Earth in the model, based on HI Doppler measurements, appears to be properly moving in its orbit. The data supports the Earth's orbit having a pitch angle of between 60.2 and 63 degrees. Future observations need to be made to get the maximum and minimum Doppler readings over a year.

In order to determine the angle where the Earth is at the highest point above the galactic plane (yaw angle), HI measurements were taken over two observing sessions at b=0 to b=70 degrees at 0 degrees galactic longitude. The preliminary model results indicate the yaw angle is between earth angles 310 to 339 degrees. This yaw value represents the highest the Earth moves in its orbit above the galactic plane. More measurements should provide better curve fits and may enable reducing error range of the yaw angle.

This technique is excellent for educational purposes. It provides the student with an experiment that uses real radio astronomy data to show the position of the Earth in the solar system. Further refinement of the technique may also lead to a detailed estimate of the Earth's orbital parameters.

For more information:

Dr. Richard Russel DrRichRussel@netscape.net

Deep Space Exploration Society: www.DSES.science

References

[1] R. A. Russel, "Earth Orbital Position Using Galactic HI Interstellar Medium Velocity Measurements," in *Society of Amateur Radio Astronomers Eastern Conference*, Green Bank, West Virginia, 2018.

[2] "Deep Space Exploration Society Website," 2018.

[3] J. Lichtman and C. Lyster, "Radio Astronomy Supplies," 2018.

[4] "Orientation of the Earth, Sun and Solar System in the Milky Way," 2018.

[5] "Are the planes of solar systems aligned with the plane of the Galaxy? (Intermediate)," 2018.

[6] R. A. Russel, "Milky Way Rotation Rate and Mass Estimation Using HI Measurements," *Radio Astronomy,* Vols. November-December 2018, 2018.

[7] "The Old Farmers Almanac," 2019. [Online]. Available: https://www.almanac.com/content/first-day-summer-summer-solstice.

[8] S. Brunier, 2019. [Online]. Available: https://commons.wikimedia.org/wiki/File:Motion_of_Sun,_Earth_and_Moon_around_the_Milky_Way.jpg.