Milky Way Rotation Rate and Mass Estimation Using HI Measurements
Latest Updates

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Abstract

The measurement of the Milky Way rotation rate is a basic for HI radio astronomy. The Deep Space Exploration Society's 60-foot dish in Haswell, Colorado has recently come online with a 1420 MHz feed and SpectraCyber system. This paper documents the conduct of the HI measurements that resulted into the production of a galactic rotation curve and a good estimate of galactic mass. This is an update to the paper in the Nov-Dec 2018 SARA Radio Astronomy Journal. Extra observations were taken to fill in the rotation curve especially closer to the galactic center.

1. Introduction

The Sun is approximately 8.05±0.45 kparsecs (Ro) from the galactic center (Sofue, 2017) traveling in an approximate circular orbit at a velocity of 238±14 km/second (Vo). The measurements of galactic HI provide a datapoint for the Doppler velocity of the HI clouds also traveling around the galactic center. The geometry is shown in figure 1.

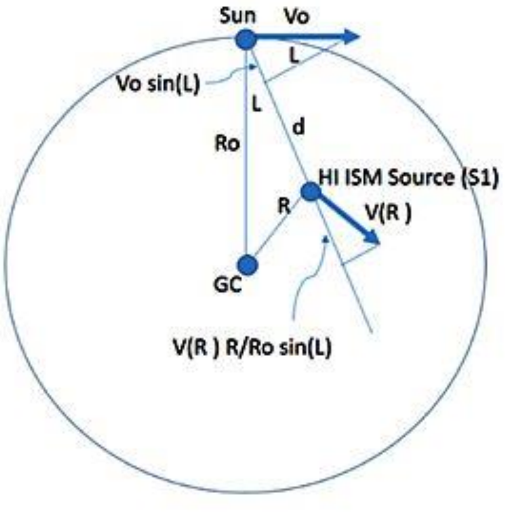


Figure 1: Galactic Rotation Rate Geometry for Quadrant 1

L: galactic longitude
Ro: Sun distance to the galactic center

R: distance of HI source (S1) from the galactic center
V(R): velocity of the HI source around the galactic center at distance R
d: distance of HI source from the Sun along the galactic longitude line

The goal is to calculate V(R) using the velocity measurements from the H1 lines (Vr). The relationship is:

$$Vr = \pm V(R)\frac{Ro}{R}\sin(L) \pm Vosin(L) \pm vlsr \qquad (1)$$

Vlsr is the contribution of velocity in the galactic longitude line-of-site do to the Earth's velocity around the Sun. Another source of Doppler is the Earth's rotation around its axis. This can be minimized if the Doppler measurements are all taken on the meridian. The signs of the equation are dependent on the geometry and galactic quadrant.

For the calculation of R, the Tangent Method is used (Sofue, 2017). This method assumes that the closest HI source to the galactic center will have either the highest or lowest Doppler measured depending on which galactic quadrant is being measured. The range (R) is therefore:

$$R = (Ro)sin(L) \qquad (2)$$

2. Observations

Two observation trips were made to the Deep Space Exploration Society's 60-foot dish at Haswell, Colorado on October 20 and November 17, 2018. (figure 2) Special thanks to Gary Agranat and Paul Berge for supporting the October 20th observations.

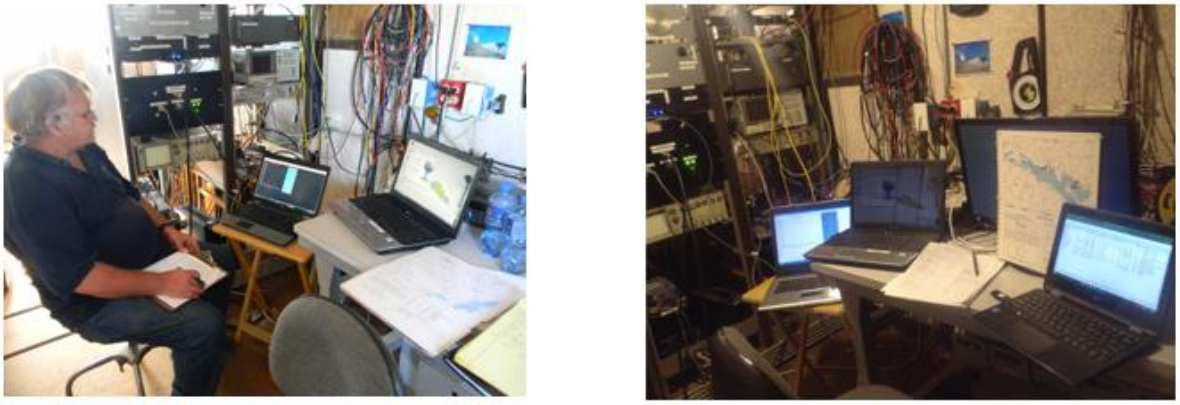


Figure 2: Observing Station for 60-foot Dish

The radio telescope was configured with a 1420 MHz feed with a cavity filter in-line with a Spectracyber 1 (Lichtman & Lyster, 2018) receiver. The observations were all taken on the meridian to reduce the Earth's rotation velocity contribution between measurements. The following spectrums were obtained (figure 3). Note that the arrow on each spectrum indicates the frequency used for the rotation rate calculations.

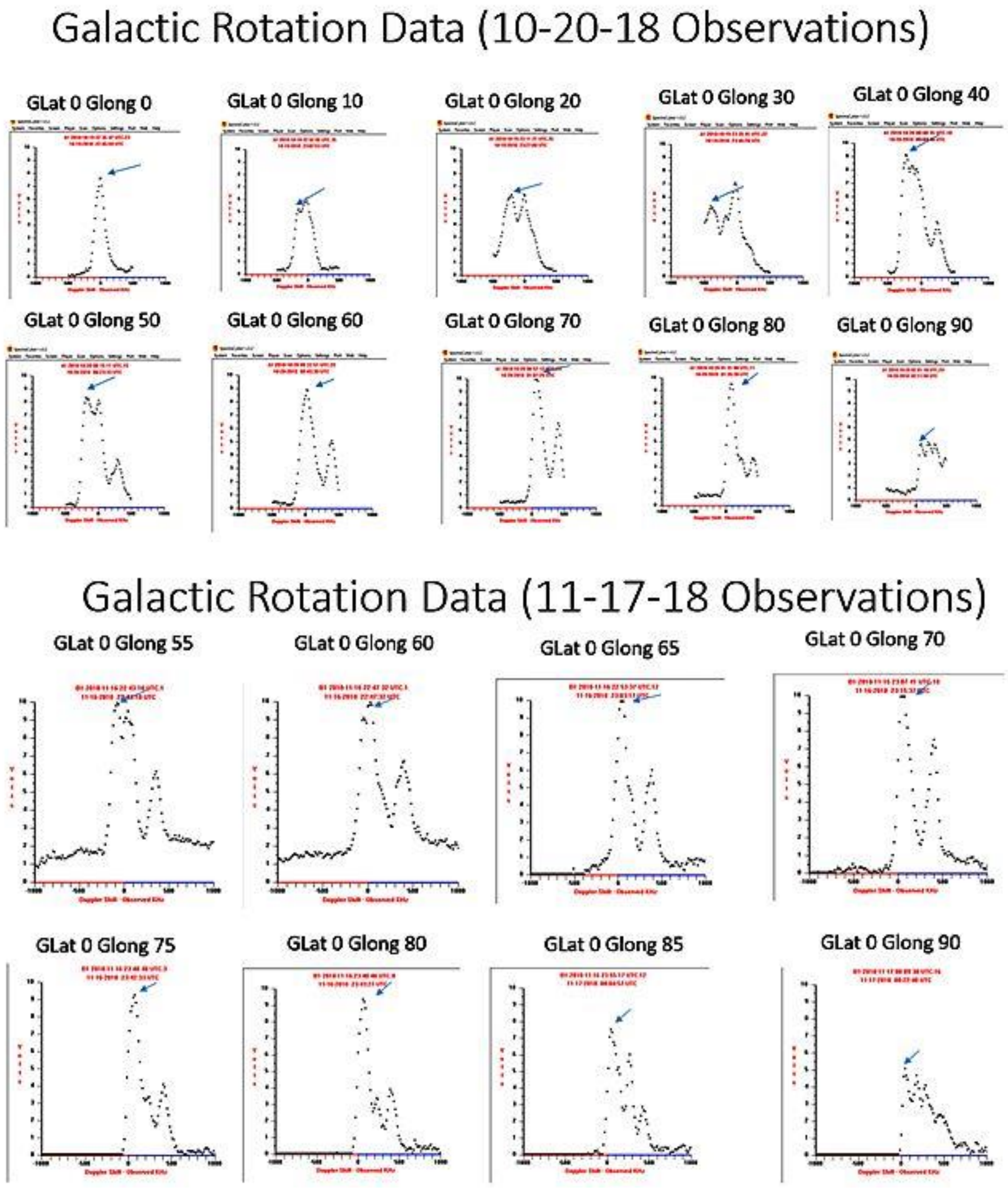
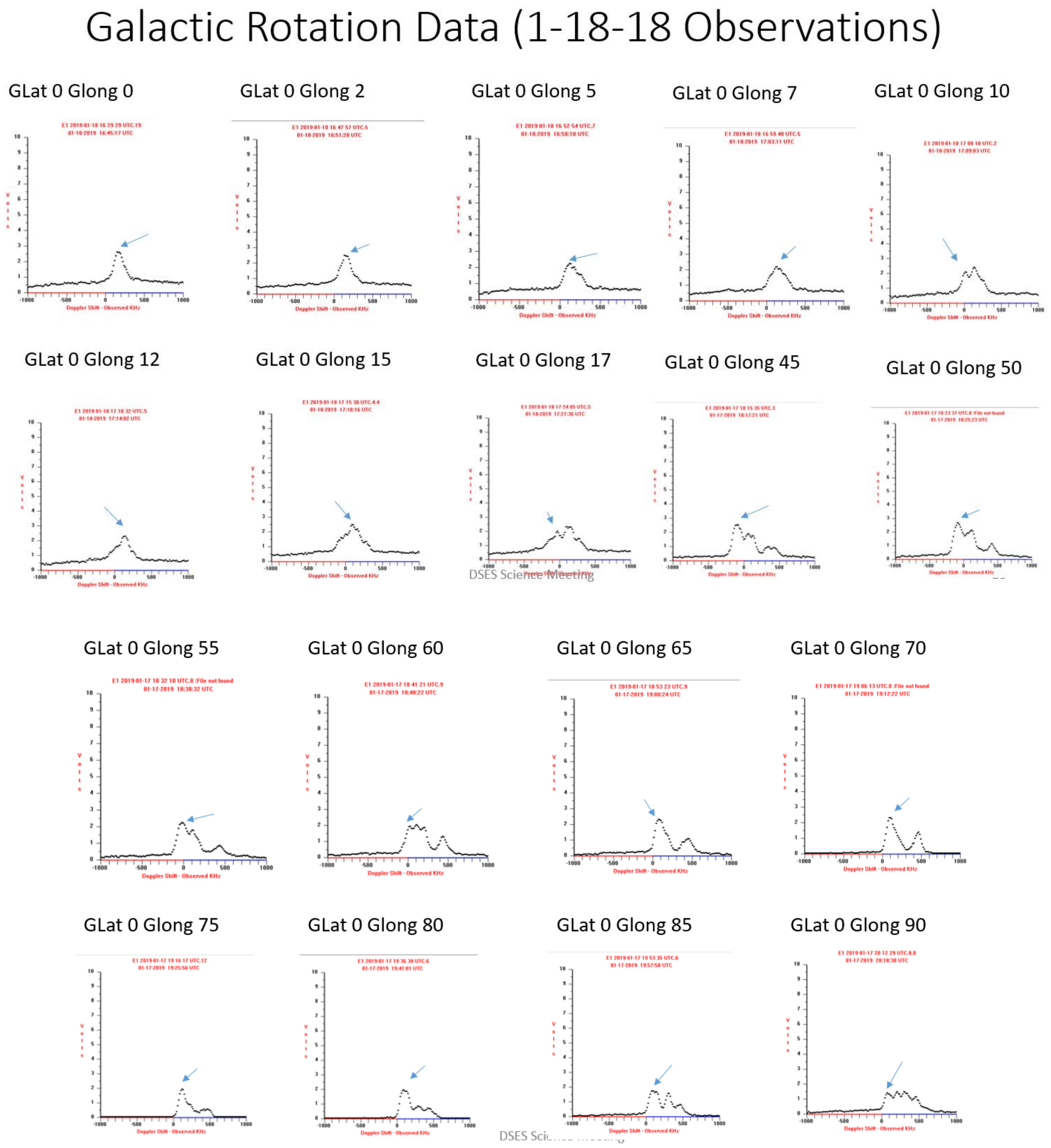


Figure 3: Haswell HI Spectrum Observations



Galactic Rotation Data (1-18-18 Observations)

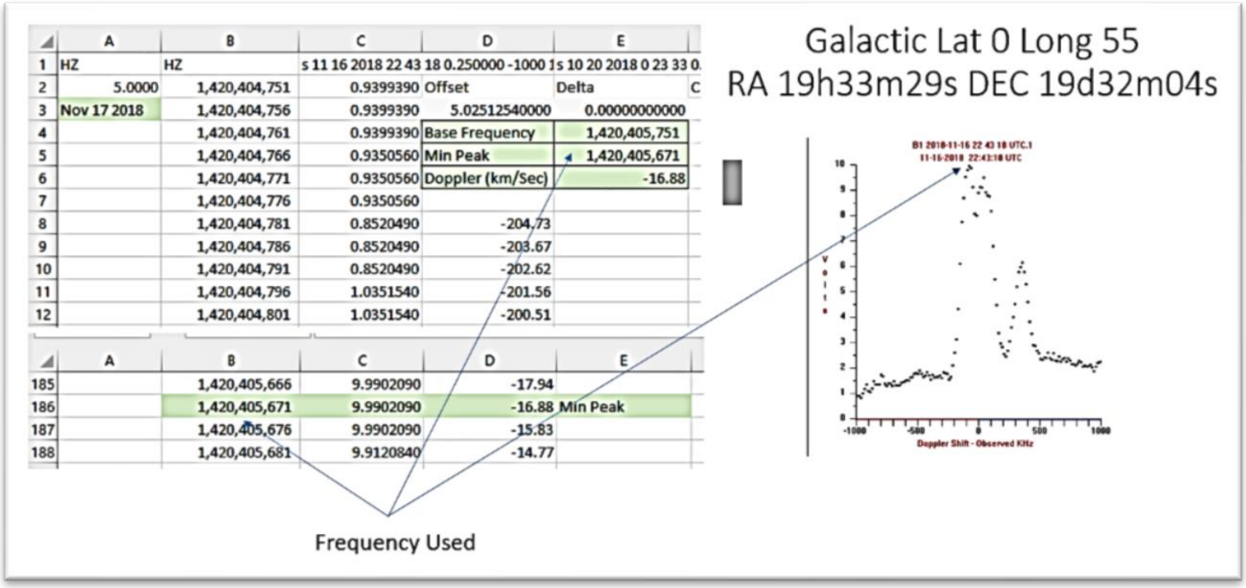
Figure 4: Galactic Rotation Data (1-18-19 Observations)

3. Data Reduction

The SpectraCyber 1 outputs the data for each observation in a csv file. Each observation was set with a frequency sweep range and appropriate gains in order to ensure that the signal level was within the plot. The most negative frequency (f) signal spike was selected for each measurement and then converted to velocity by the equation:

$$\mathrm{Vr} = \frac{(f - 1420{,}405{,}751\ hz)}{1420{,}405{,}751 hz}\left(299{,}790{,}000\,\frac{km}{sec}\right) \quad (3)$$

The SpectraCyber output and the conversion of the frequency level spike to Vr is shown in figure 4.



	A	B	C	D	E	
1	HZ	HZ	s 11 16 2018 22 43 18 0.250000 -1000 1		s 10 20 2018 0 23 33 0.	
2	5.0000	1,420,404,751	0.9399390	Offset	Delta	C
3	Nov 17 2018	1,420,404,756	0.9399390	5.02512540000	0.00000000000	
4		1,420,404,761	0.9399390	Base Frequency	1,420,405,751	
5		1,420,404,766	0.9350560	Min Peak	1,420,405,671	
6		1,420,404,771	0.9350560	Doppler (km/Sec)	-16.88	
7		1,420,404,776	0.9350560			
8		1,420,404,781	0.8520490	-204.73		
9		1,420,404,786	0.8520490	-203.67		
10		1,420,404,791	0.8520490	-202.62		
11		1,420,404,796	1.0351540	-201.56		
12		1,420,404,801	1.0351540	-200.51		

	A	B	C	D	E
185		1,420,405,666	9.9902090	-17.94	
186		1,420,405,671	9.9902090	-16.88	Min Peak
187		1,420,405,676	9.9902090	-15.83	
188		1,420,405,681	9.9120840	-14.77	

Frequency Used

Galactic Lat 0 Long 55
RA 19h33m29s DEC 19d32m04s

Figure 4: Data Retrieval and Conversion into Velocity Example

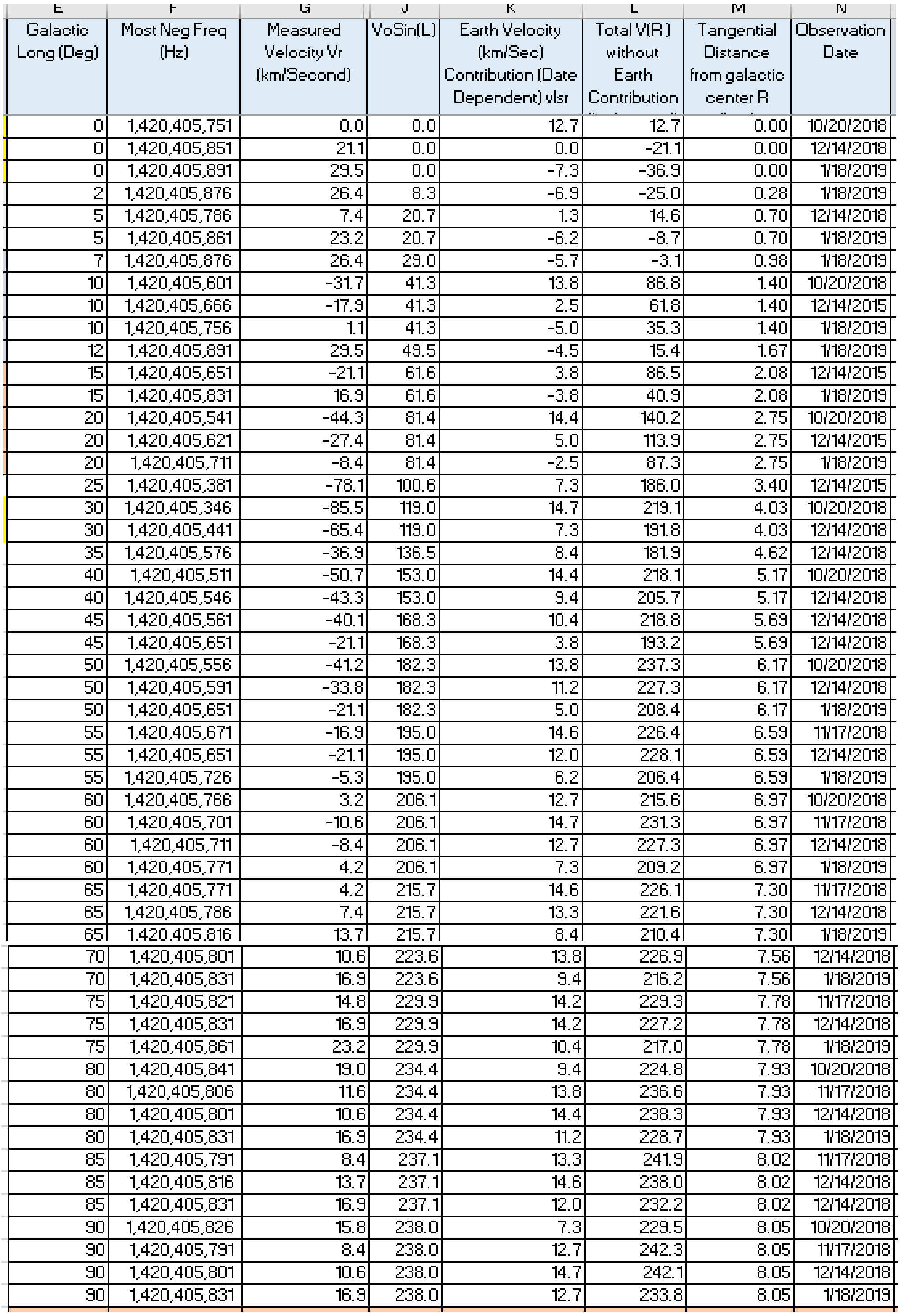
The Earth's orbital velocity contribution to the observation (VLSR) is calculated for each galactic longitude and time of year (Russel R. A., 2018).

The final frequency measurements and calculations are shown in table 1. The signs of each term from equation 1 were determined to be:

$$V(R) = \frac{-Vr + VoSin(L) - vlsr}{\frac{Ro}{R}\sin(L)} \quad (4)$$

Note that for the tangent method: $\frac{Ro}{R}\sin(L) = 1$

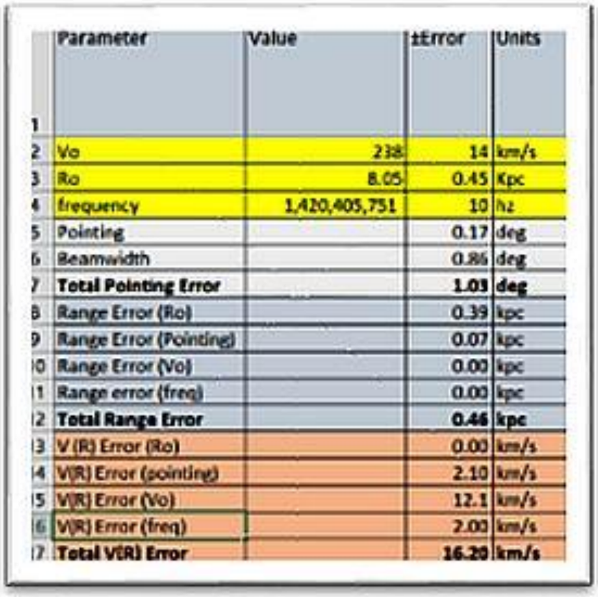
Therefore: $V(R) = -Vr + VoSin(L) - vlsr$ (5)



E	F	G	J	K	L	M	N
Galactic Long (Deg)	Most Neg Freq (Hz)	Measured Velocity Vr (km/Second)	VoSin(L)	Earth Velocity (km/Sec) Contribution (Date Dependent) vlsr	Total V(R) without Earth Contribution	Tangential Distance from galactic center R	Observation Date
0	1,420,405,751	0.0	0.0	12.7	12.7	0.00	10/20/2018
0	1,420,405,851	21.1	0.0	0.0	-21.1	0.00	12/14/2018
0	1,420,405,891	29.5	0.0	-7.3	-36.9	0.00	1/18/2019
2	1,420,405,876	26.4	8.3	-6.9	-25.0	0.28	1/18/2019
5	1,420,405,786	7.4	20.7	1.3	14.6	0.70	12/14/2018
5	1,420,405,861	23.2	20.7	-6.2	-8.7	0.70	1/18/2019
7	1,420,405,876	26.4	29.0	-5.7	-3.1	0.98	1/18/2019
10	1,420,405,601	-31.7	41.3	13.8	86.8	1.40	10/20/2018
10	1,420,405,666	-17.9	41.3	2.5	61.8	1.40	12/14/2015
10	1,420,405,756	1.1	41.3	-5.0	35.3	1.40	1/18/2019
12	1,420,405,891	29.5	49.5	-4.5	15.4	1.67	1/18/2019
15	1,420,405,651	-21.1	61.6	3.8	86.5	2.08	12/14/2015
15	1,420,405,831	16.9	61.6	-3.8	40.9	2.08	1/18/2019
20	1,420,405,541	-44.3	81.4	14.4	140.2	2.75	10/20/2018
20	1,420,405,621	-27.4	81.4	5.0	113.9	2.75	12/14/2015
20	1,420,405,711	-8.4	81.4	-2.5	87.3	2.75	1/18/2019
25	1,420,405,381	-78.1	100.6	7.3	186.0	3.40	12/14/2015
30	1,420,405,346	-85.5	119.0	14.7	219.1	4.03	10/20/2018
30	1,420,405,441	-65.4	119.0	7.3	191.8	4.03	12/14/2018
35	1,420,405,576	-36.9	136.5	8.4	181.9	4.62	12/14/2018
40	1,420,405,511	-50.7	153.0	14.4	218.1	5.17	10/20/2018
40	1,420,405,546	-43.3	153.0	9.4	205.7	5.17	12/14/2018
45	1,420,405,561	-40.1	168.3	10.4	218.8	5.69	12/14/2018
45	1,420,405,651	-21.1	168.3	3.8	193.2	5.69	12/14/2018
50	1,420,405,556	-41.2	182.3	13.8	237.3	6.17	10/20/2018
50	1,420,405,591	-33.8	182.3	11.2	227.3	6.17	12/14/2018
50	1,420,405,651	-21.1	182.3	5.0	208.4	6.17	1/18/2019
55	1,420,405,671	-16.9	195.0	14.6	226.4	6.59	11/17/2018
55	1,420,405,651	-21.1	195.0	12.0	228.1	6.59	12/14/2018
55	1,420,405,726	-5.3	195.0	6.2	206.4	6.59	1/18/2019
60	1,420,405,766	3.2	206.1	12.7	215.6	6.97	10/20/2018
60	1,420,405,701	-10.6	206.1	14.7	231.3	6.97	11/17/2018
60	1,420,405,711	-8.4	206.1	12.7	227.3	6.97	12/14/2018
60	1,420,405,771	4.2	206.1	7.3	209.2	6.97	1/18/2019
65	1,420,405,771	4.2	215.7	14.6	226.1	7.30	11/17/2018
65	1,420,405,786	7.4	215.7	13.3	221.6	7.30	12/14/2018
65	1,420,405,816	13.7	215.7	8.4	210.4	7.30	1/18/2019
70	1,420,405,801	10.6	223.6	13.8	226.9	7.56	12/14/2018
70	1,420,405,831	16.9	223.6	9.4	216.2	7.56	1/18/2019
75	1,420,405,821	14.8	229.9	14.2	229.3	7.78	11/17/2018
75	1,420,405,831	16.9	229.9	14.2	227.2	7.78	12/14/2018
75	1,420,405,861	23.2	229.9	10.4	217.0	7.78	1/18/2019
80	1,420,405,841	19.0	234.4	9.4	224.8	7.93	10/20/2018
80	1,420,405,806	11.6	234.4	13.8	236.6	7.93	11/17/2018
80	1,420,405,801	10.6	234.4	14.4	238.3	7.93	12/14/2018
80	1,420,405,831	16.9	234.4	11.2	228.7	7.93	1/18/2019
85	1,420,405,791	8.4	237.1	13.3	241.9	8.02	11/17/2018
85	1,420,405,816	13.7	237.1	14.6	238.0	8.02	12/14/2018
85	1,420,405,831	16.9	237.1	12.0	232.2	8.02	12/14/2018
90	1,420,405,826	15.8	238.0	7.3	229.5	8.05	10/20/2018
90	1,420,405,791	8.4	238.0	12.7	242.3	8.05	11/17/2018
90	1,420,405,801	10.6	238.0	14.7	242.1	8.05	12/14/2018
90	1,420,405,831	16.9	238.0	12.7	233.8	8.05	1/18/2019

Table 1: Velocity Calculations

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. The results of this analysis are shown in table 2.



1	Parameter	Value	±Error	Units
2	Vo	238	14	km/s
3	Ro	8.05	0.45	Kpc
4	frequency	1,420,405,751	10	hz
5	Pointing		0.17	deg
6	Beamwidth		0.86	deg
7	**Total Pointing Error**		**1.03**	**deg**
8	Range Error (Ro)		0.39	kpc
9	Range Error (Pointing)		0.07	kpc
0	Range Error (Vo)		0.00	kpc
1	Range error (freq)		0.00	kpc
2	**Total Range Error**		**0.46**	**kpc**
3	V (R) Error (Ro)		0.00	km/s
4	V(R) Error (pointing)		2.10	km/s
5	V(R) Error (Vo)		12.1	km/s
6	V(R) Error (freq)		2.00	km/s
7	**Total V(R) Error**		**16.20**	**km/s**

Table 2: Error Analysis

The plot of the results with error bars is shown in figure 5.

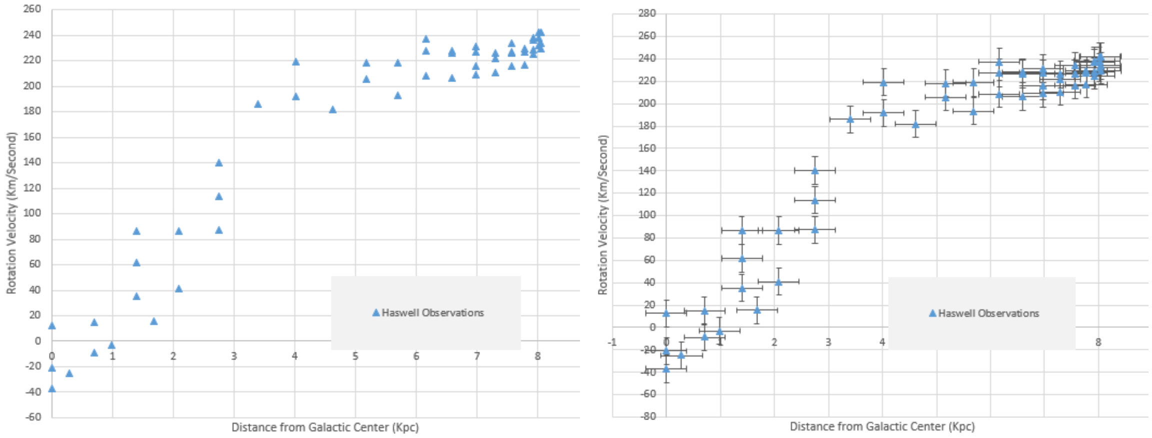


Figure 5: Galactic Rotation Plot

4. Calculating the Mass of the Milky Way

The mass of the galaxy can be calculated using the formula:

$$M = \frac{V^2 R}{G} \quad (5)$$

M: Mass of galaxy (kg)
V: Velocity of the galaxy at distance R (km/second)
R: distance from galactic center (m)
G: Gravitation constant $6.67x10^{-11}m^3kg^{-1}s^{-2}$

From the measured results in table 3, the calculated velocity of the galaxy at 8.05±0.46 kpc is 243.3±16.2 km/s. Entering these values into equation 5 with the appropriate conversions:

$$M = \frac{\left(243.3\frac{km}{s}x\frac{10^3m}{km}\right)^2(8.05kpc)\left(\frac{3.09x10^{19}m}{1kpc}\right)}{(6.67x10^{-11}m^3kg^{-1}s^{-2})} = 2.21x10^{41}kg \qquad (6)$$

$$M = (2.21x10^{41}kg)\left(\frac{1\ M_{Sun}}{2x10^{30}kg}\right) = 1.10x10^{11}M_{Sun} \qquad (7)$$

The error range was calculated by substituting the Vo and Ro error ranges into the formulas which results in a total error range of:

$$\mathrm{M}= 1.10x10^{11} \pm 0.22x10^{11}M_{Sun} \qquad (8)$$

The estimate for the mass of the Milky Way has been estimated as (Sofue, 2017):

$$M = (1.0x10^{11})M_{Sun}\left(\frac{R}{Ro}\right) \qquad (9)$$

The observed measurements, therefore, encompass the historic values of the Milky Way's mass.

5. Analysis

The Milky Way rotation rate curve was calculated using Doppler velocity measurements of the HI line measured by the DSES 60-foot dish. The rotation rates are comparable to similar galactic rotation curves documented. (Reid & Dame, 2016) (Rotation Rate Simulator and Database) (Santo & Uddin, 2013) (Sofue, 2017) (Rudolph) (Russel R. , 2018) Note that the flattening of the curve after R>4 kpc is theoretically due to the dark matter contribution to the galactic mass.

6. Future Observations and Analysis

The goal of future observations is to continue to refine the measurements near the galactic center for R < 4 kpc. The duplication of measurements for all other galactic latitudes may reveal Doppler velocity changes due to the time of year. This will allow estimation of the Earth's orbital position around the Sun. This could be used to estimate the Earth's orbital position in relation to the galactic plane, (Russel R. A., 2018)

This experiment was an outstanding learning opportunity that can be conducted by amateur and professional radio astronomers alike.

Special thanks to Dayton Jones, Jeff Lichtman (Lichtman & Lyster, 2018) and Ralph Boyd (Boyd, 2018) for their review and recommendations on this paper.

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Deep Space Exploration Society, www.dses.science

References

Boyd, R. (2018). HIghQ Software Group. Retrieved from https://sites.google.com/site/highqsoftwaregroup/home

Lichtman, J., & Lyster, C. (2018). Radio Astronomy Supplies. Retrieved from https://www.radioastronomysupplies.com/

Reid, M., & Dame, T. (2016). *On the Rotation Speed the Milky Way Determined from HI Emission.* Retrieved from https://arxiv.org/pdf/1608.03886.pdf

Rotation Rate Simulator and Database. (n.d.). Retrieved from http://euhou.obspm.fr/public/simu.php

Rudolph, A. (n.d.). *Understanding the Rotation of the Milky Way Using Radio Telescope Observations.* Retrieved from http://euhou.obspm.fr/public/

Russel, R. (2018). Galactic Navigation Position Data Using HI Velocity Measurements. Society of Amateur Radio Astronomers 2018 Western Conference. Retrieved from www.radio-astronomy.org

Russel, R. A. (2018). Earth Orbital Position Using Galactic HI Interstellar Medium Velocity Measurements. *Society of Amateur Radio Astronomers Eastern Conference. June 10-13, 2018*, pp. 68-77. Green Bank, West Virginia: Society of Amateur Radio Astronomers. Retrieved from www.radio-astronomy.org

Santo, T. R., & Uddin, S. A. (2013). Mapping the Spiral Structure of the Milky Way Galaxy at 21cm Wavelength Using the SALSA Radio Telescope of Onsala Space Observatory . *International Journal of Astronomy*, 37-42. Retrieved from https://vale.oso.chalmers.se/salsa/sites/default/files/10.5923.j.astronomy.20130203.03.pdf

Sofue, Y. (2017). *Galactic Radio Astronomy.* Singapore: Springer.