Galactic Navigation Position Data Using HI Interstellar Medium Velocity Measurements

Richard Russel D.Cs., Ae.E.

Deep Space Exploration Society

Abstract

This paper explores the use of HI Doppler measurements as an aid to galactic navigation. Historic HI measurements of the Milky Way are used to determine the galactic rotation rate. The location of the interstellar medium producing the HI signals can then be calculated. Knowing the location of the HI signals, the HI frequency corrections can be made for a spacecraft moving between two points in the galaxy. This data can then be used to supplement optical, pulsar and other galactic navigational aids.

Introduction

This paper explores the use of radio astronomy HI interstellar medium (HI ISM) sources to aid future navigation in the galaxy. The 21 cm HI line is used to estimate the galactic rotation at various ranges from the galactic center. The historic Doppler data can also be used to estimate the position of the HI ISM sources in the galaxy. Using both of these techniques, a thought experiment was developed using a trip from the Earth to 40 Eridani A (Keid). The experiment shows how the HI ISM data can be used for position, course and speed indicators that helps to supplement optical, pulsar and other galactic navigation aids. (1), (2), (3) (4)

Galactic Coordinate Overview

The Milky Way galactic coordinates are based on latitude and longitude with the Sun at latitude 0° and longitude 0°. The longitude plane is divided into four quadrants with the 0° longitude line directed through the galactic center, with an estimated distance of 8.0 to 8.5 kilo-parsecs (kpc) from the Sun. This distance is referred to as the Sun circle (Ro). (5) (6) (7). The Milky Way latitude is defined using +-90° above or below the galactic plane (figure 1).

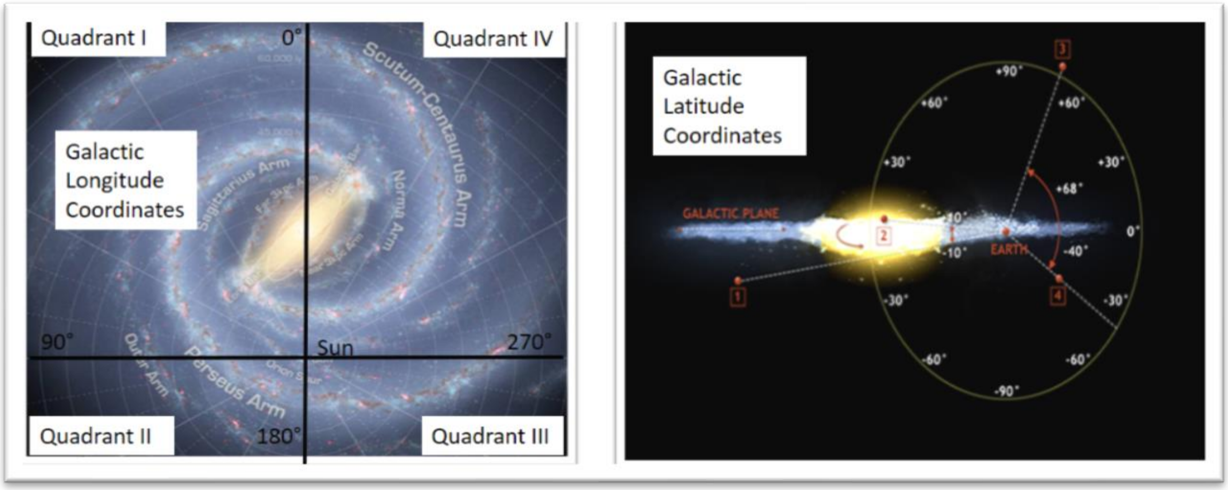


Figure 1: Milky Way Longitude and Latitude Coordinates (8), (9)

This paper starts with the standard galactic latitude and longitude helio-galactic model and then converts the data to a galactic centric model. This model will map the HI sources using Cartesian coordinates, which provides a simple way to calculate three-dimensional positions and ranges.

The analysis starts with the measurement of the Doppler shift of the HI ISM sources. Using basic geometry, the Doppler shift is converted in a rotation rate around the galactic center. Once the galactic rotation rates are found, the location of the HI ISM position in the galaxy can be estimated.

The HI ISM position data is then used to predict the HI ISM velocity measurement expected along the path of a spacecraft moving from one point in the galaxy to another, in this case from the Sun to Keid.

Rotation Rate Geometry

Radio telescopes measure the Doppler shift of the HI line of a HI ISM. This Doppler shift is a combination of the velocity components of the Earth-Sun system and the HI ISM cloud along the line of site. One technique to analyze the HI measurements is referred to as the tangent method.

The tangent method uses the geometry in figure 2 to calculate the velocity of the Sun around the galaxy (Vo), where R is the distance of the HI ISM from the galactic center and Ro is the distance of the Sun from the galactic center.

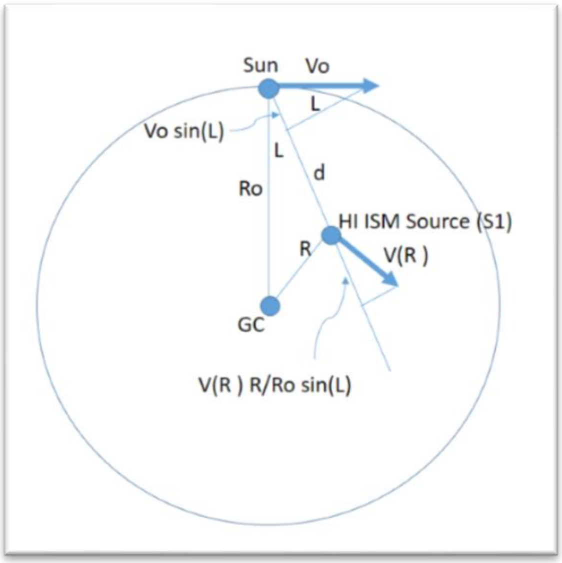


Figure 2: Geometry (10) (R< Ro)

Vo: Sun's velocity around galactic center: (220 Km/second)
Ro: Distance of the Sun to the Galactic center (8.5 Kpc; 1 pc = 3.09 x 10^{10} meters)
Distance Reference: Ro (6) 8.0 +- 0.4kpc
L: Galactic Longitude
V(R): Velocity of a cloud of gas related to R distance from the galactic center
R: Cloud distance to Galactic center, Galactic rotation radius
d: Clouds distance to the Sun

For R< Ro, the measured velocity, Vr, is calculated as (5):

$$Vr = V(R)\frac{Ro}{R}sin(L) + Vo\ sin(L) \quad Equation\ 1$$

For R> Ro the geometry is shown in figure 3:

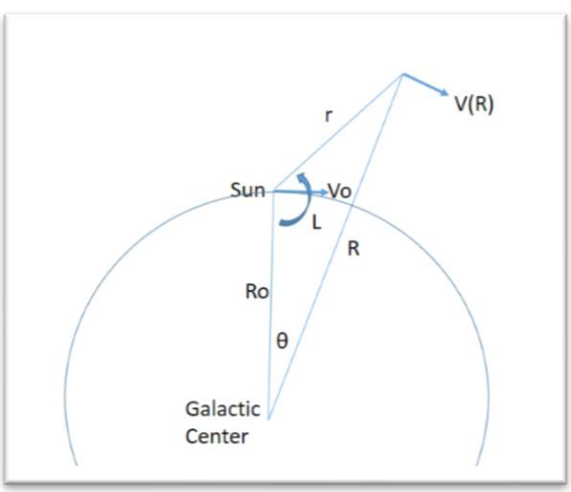


Figure 3: Geometry R> Ro

The equation (5) for R> Ro is:

$$V(R) = \frac{V_r + V_o \cos(L - 90°)}{\cos(L - \theta - 90°)} \qquad \textit{Equation 2}$$

In terms of received velocity, Vr:

$$V_r = V(R)\cos(L - \theta - 90°) - V_o \cos(L - 90°) \qquad \textit{Equation 3}$$

HI Line Doppler Data

The rotation rate can be calculated using the tangent method if the HI Doppler velocity is measured in either quadrant I or IV (10). In quadrant I, the frequency with the highest velocity is used as the closest source to the galactic center. This galactic model retrieves HI measured data and displays it based on galactic latitude and longitude as shown in figure 4.

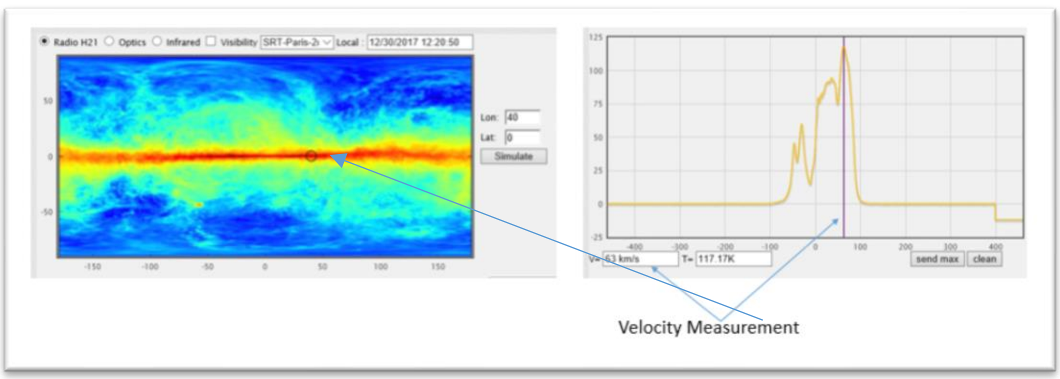


Figure 4: HI Measurement Database Query (11)

The resultant rotation rates are shown in figure 5.

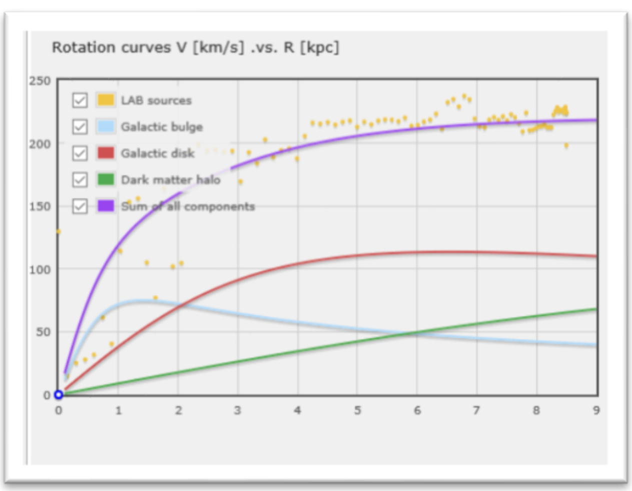


Figure 5: Baseline Galaxy Rotation Curve (10)

Use of Historic Rotation Rate to Estimate HI Source Locations

Once the rotation rate has been found, it is possible to estimate the galactic location of the HI ISM sources at 0° galactic latitude. Table 1 shows some calculated HI ISM location data from the database. (11)

G-Latitude (degrees)	G-Long (degrees)	Vr (km/s)	r (kpc)	θ (degrees)	R (kpc)	Vo(R) (km/s)	V1(R) (km/s)
0	10	13	2.2	176.54	6.34	220	220
0	20	23	2.2	173.48	6.51	220	220
0	20	120	6.5	137.44	3.28	220	220
0	30	99	6.0	138.19	4.47	220	220
0	40	65	4.5	150.24	5.82	220	220
0	50	54	5.6	138.80	6.51	220	223
0	50	11	15.0	95.73	11.56	220	220
0	60	29	11.1	107.24	10.03	220	220
0	60	2	8.3	121.06	8.41	220	220
0	60	-60	14.2	96.39	12.41	220	220
0	70	6	0.8	174.77	8.26	220	220
0	70	-71	13.1	108.09	12.95	220	220
0	80	11	4.7	149.20	8.95	220	220
0	80	-42	7.9	132.55	10.54	220	220
0	80	-67	10.5	122.86	12.31	220	220
0	90	6	2.0	166.59	8.74	220	220
0	90	-43	6.3	143.57	10.56	220	220
0	90	-80	10.3	129.52	13.36	220	220
0	100	2	0.4	177.34	8.58	220	220
0	100	-57	6.5	146.53	11.53	220	220
0	110	-3	0.3	177.83	8.63	220	220
0	110	-47	4.7	156.56	11.00	220	220
0	120	3	0.3	178.47	8.64	220	220
0	120	-52	4.8	159.03	11.69	220	220
0	130	3	0.2	178.80	8.65	220	220
0	130	-41	3.7	165.43	11.23	220	220
0	140	-2	0.2	179.33	8.62	220	220
0	140	-41	4.1	167.16	11.97	220	220
0	150	-5	0.5	178.51	8.90	220	220
0	150	-28	3.2	171.88	11.40	220	220
0	160	-28	5.2	172.40	13.54	220	220
0	170	-15	5.5	176.05	13.99	220	220

G-Latitude (degrees)	G-Long (degrees)	Vr (km/s)	r (kpc)	θ (degrees)	R (kpc)	Vo(R) (km/s)	V1(R) (km/s)	
0	190	5	1.3	181.32	9.78	220	220	
0	200	23	3.9	186.26	12.24	220	220	
0	210	41	5.5	191.72	13.55	220	220	
0	220	17	1.5	185.56	9.66	220	220	
0	230	72	7.9	203.97	14.84	220	220	
0	230	53	5.1	198.32	12.40	220	220	
0	230	19	1.6	187.18	9.58	220	220	
0	240	67	6.6	205.84	13.11	220	220	
0	240	19	1.7	188.77	9.44	220	220	
0	250	77	8.0	213.86	13.55	220	220	
0	250	22	2.3	192.89	9.51	220	220	
0	260	13	1.9	192.22	9.04	220	220	
0	260	57	6.5	213.47	11.53	220	220	
0	260	83	9.5	222.59	13.78	220	220	
0	270	62	8.2	224.10	11.84	220	220	
0	270	3	1.4	189.47	8.62	220	220	
0	280	-5	1.9	193.18	8.38	220	222	
0	290	70	13.0	251.57	12.85	220	220	x
0	290	-3	5.4	217.57	8.38	220	220	
0	300	32	11.3	253.90	10.22	220	220	
0	300	-24	5.9	222.81	7.55	220	220	
0	310	-39	7.8	239.39	6.90	220	220	
0	320	0	0.0	180.00	8.50	220	220	
0	320	-21	1.5	187.58	7.40	220	220	
0	320	-57	3.9	204.40	6.06	220	220	
0	330	0	0.0	180.00	8.50	220	220	
0	330	-41	2.9	193.34	6.19	220	220	x
0	330	-93	5.6	217.33	4.61	220	220	
0	340	-31	2.7	188.88	6.02	220	220	
0	340	-93	5.5	209.88	3.80	220	220	
0	340	-122	6.6	223.71	3.24	220	220	
0	350	-107	6.7	211.30	2.24	220	220	

Table1: Data Search for Galactic Latitude 0°

The HI ISM rotation rate was plotted against its distance from the galactic center. The formula was developed using the Excel program. (figure 6)

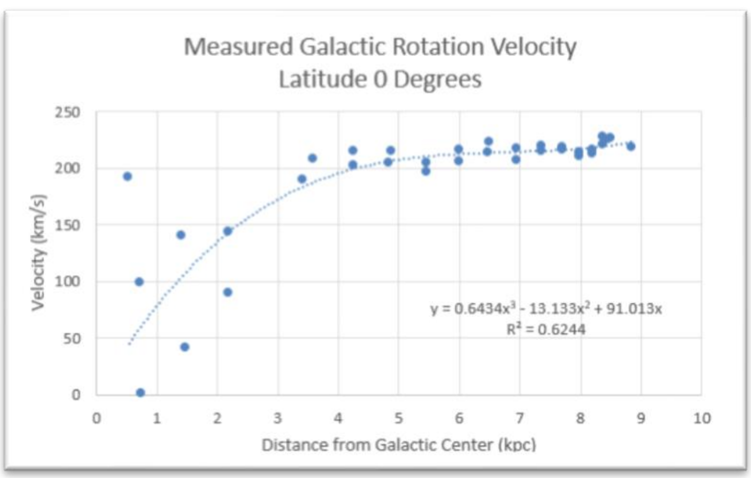


Figure 6: Rotation Rate Curve (0 Galactic Latitude)

In order to navigate away from the Sun anywhere in the Galaxy, it is important to convert the HI ISM and star data to galactic centric coordinates. The Y-axis was chosen as the Galactic Center to Sun axis with the X-axis perpendicular to the Y-axis at galactic latitude of 0°. The Z- axis is the distance above and below the Galactic disk. Table 2 shows a sample of HI ISM data positions converted to these coordinates.

Galactic Latitude (Degrees)	Galactic Longitude (Degrees)	Measured Velocity Vr (km/s)	Rotation Range (kpc)	Rotation V(R) (km/s)	X (kpc)	Y (kpc)	Z (kpc)	Calculated Velocity, V (R) (km/s)
0	10	2	1.48	41.2	0.11	7.88	0	108.0
0	15	53	2.2	89.24	0.73	5.79	0	143.5
0	20	30	0.74	0.47			0	60.4
0	25	80	0.54	191.45	2.35	3.46	0	45.4
0	30	104	4.25	214	3.17	3	0	199.0
0	35	88	4.88	214.19	3.34	3.73	0	206.2
0	40	63	5.46	204.41	2.79	5.18	0	210.1
0	45	60	6.01	215.56	3.38	5.12	0	212.3
0	50	54	6.51	222.53	0.59	8	0	213.4
0	55	36	6.96	217.21	3.08	6.35	0	214.2
0	60	28	7.36	219.53	3.26	6.62	0	215.0
0	65	16	7.7	215.39	1.8	7.66	0	215.9
0	70	6	7.99	212.73	1.06	8.11	0	217.0
0	75	3	8.21	215.5	0.5	8.37	0	218.0
0	80	11	8.37	226.66			0	219.0
0	85	5	8.47	224.16			0	219.7
0	90	6	8.5	226			0	219.9
0	95	-45			5.77	9.01	0	0.0
0	100	-57			6.36	9.32	0	0.0
0	105	-54			5.31	9.92	0	0.0
0	110	-49			4.57	10.16	0	0.0
0	115	-48			4.11	10.41	0	0.0
0	120	-54			4.37	11.03	0	0.0
0	125	-41			2.99	10.59	0	0.0
0	130	-39			2.74	10.8	0	0.0
0	135	-40			2.63	11.13	0	0.0
0	140	-42			2.75	11.77	0	0.0
0	145	-34			2.07	11.45	0	0.0
0	150	-31			1.84	11.69	0	0.0
0	155	-30			1.83	12.42	0	0.0
0	160	-29			1.89	13.7	0	0.0
0	165	-35					0	0.0

Galactic Latitude (Degrees)	Galactic Longitude (Degrees)	Measured Velocity Vr (km/s)	Rotation Range (kpc)	Rotation V(R) (km/s)	X (kpc)	Y (kpc)	Z (kpc)	Calculated Velocity, V (R) (km/s)
0	170	-15			0.96	13.96	0	0.0
0	175	-3			1.04	10.08	0	0.0
0	180	2					0	0.0
0	185	6			-0.34	12.37	0	0.0
0	190	13			-0.77	12.86	0	0.0
0	195	10			-0.48	10.3	0	0.0
0	200	21			-1.18	11.73	0	0.0
0	205	29			-1.74	12.23	0	0.0
0	210	42			-2.86	13.45	0	0.0
0	215	49			-3.47	13.46	0	0.0
0	220	59			-4.51	13.87	0	0.0
0	225	64			-5.04	13.54	0	0.0
0	230	70			-5.77	13.34	0	0.0
0	235	62			-4.96	11.97	0	0.0
0	240	67			-5.71	11.8	0	0.0
0	245	84			-8.08	12.27	0	0.0
0	250	75			-7.31	11.16	0	0.0
0	255	70			-7.2	10.43	0	0.0
0	260	83			-9.32	10.14	0	0.0
0	265	120			-16.4	9.93	0	0.0
0	270	71			-9.46	8.5	0	0.0
0	275	2	8.84	217.76	-2.11	8.32	0	222.7
0	280	-3	8.37	219.66	-0.99	8.32	0	219.0
0	285	0	8.21	212.5	-4.25	7.36	0	218.0
0	290	-3	7.99	209.73	-0.35	8.37	0	217.0
0	295	-19	7.7	218.39	-2.41	7.38	0	215.9
0	300	-24	7.36	214.53	-2.23	7.21	0	215.0
0	305	-26	6.96	206.91	-1.87	7.19	0	214.2
0	310	-44	6.48	213.27	-2.85	6.11	0	213.4
0	315	-50	6.01	205.56	-2.63	5.87	0	212.3
0	320	-55	5.46	196.41	-2.41	5.62	0	210.1
0	325	-76	4.85	204.52	-2.79	4.51	0	205.9
0	330	-92	4.25	202	-2.76	3.71	0	199.0
0	335	-114	3.59	206.98	-2.71	2.69	0	187.2
0	340	-125	3.41	188.77	-2.16	2.24	0	183.2
0	345	-84	2.2	142.94	-1.46	3.06	0	143.5
0	350	-106	1.41	139.9	-1.15	1.95	0	104.0
0	355	-79	0.73	98.56	-0.61	1.54	0	59.7

Table 2: Galactic Centric Coordinates for sample HI ISM Sources

The data is plotted in figure 7.

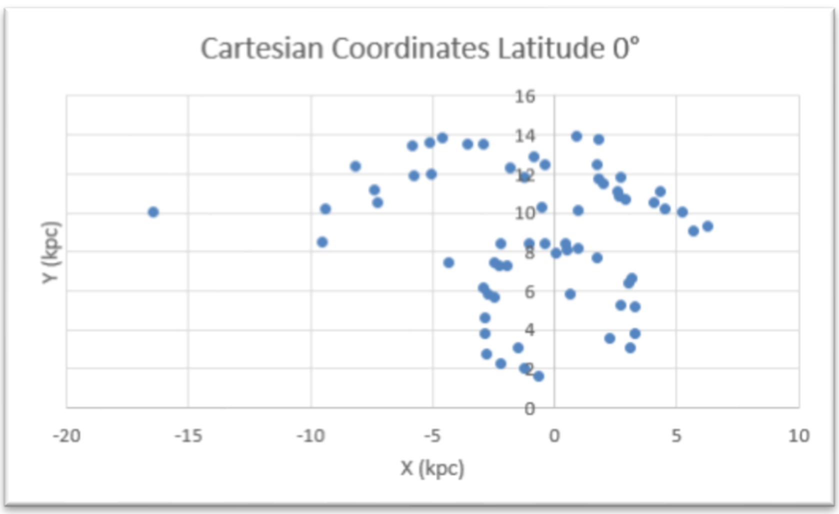


Figure 7: Galactic Latitude 0° HI ISM Coordinate Plot

Note that the current data does not include HI ISM above or below the galactic disk, Z=0. Future models will need to be developed to properly convert measured HI ISM data to galactic coordinates not on the galactic plane. However, a spacecraft traveling from the Sun to Keid will have to travel below the galactic plane. This requires converting all the data to spherical coordinates.

Galactic Centric Spherical Coordinates

The galactic latitude and longitude is converted to a galactic centric framework. This allows the use of spherical coordinates to map the location of the star, and HI ISM coordinates (figure 8).

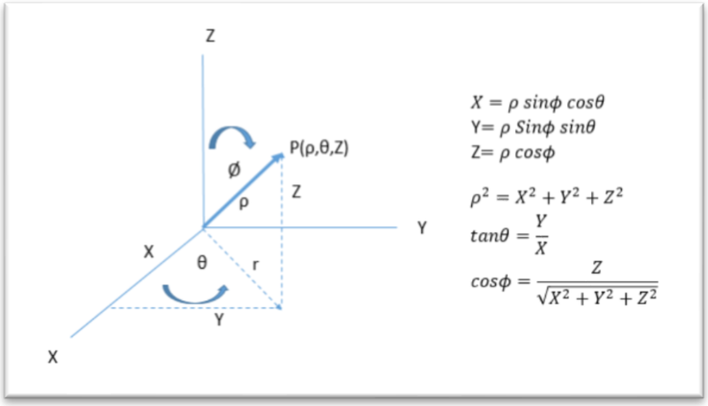


Figure 8: Spherical Coordinates

The galactic centric coordinates framework has the galactic center at (x=0, y=0, z=0). The X-Y plane is the galactic disk which is based on the longitude axis with the galactic latitude at 0°. The depth above or below the galactic plane uses the Z axis. All units are based on kilo-parsecs (kpc). The Sun is on the Y-axis at (X=0, Y=8.5, z=0). In this reference system, the angle (θ) to the Sun is 0°.

Spacecraft Geometry

A spacecraft that moves away from the Sun requires a different geometry which allows for the calculation of galactic centric angles and distances between the spacecraft (SC), HI ISM sources and the galactic center (GC). (figure 9)

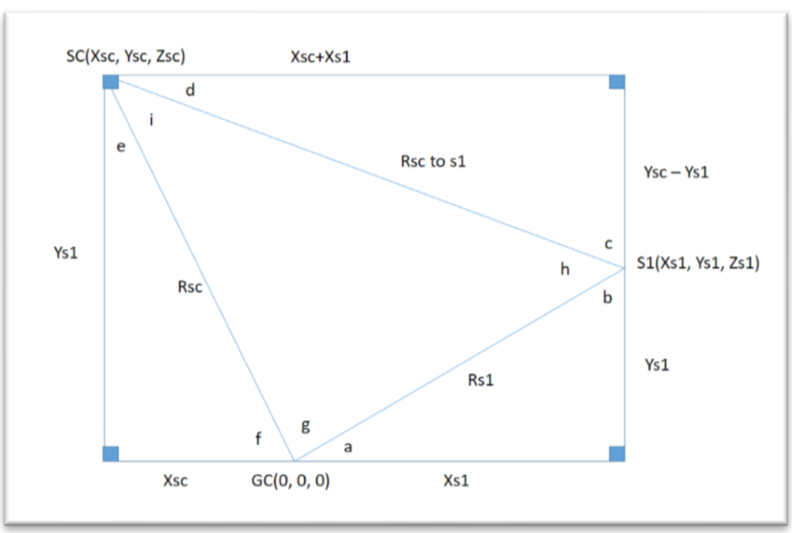


Figure 9: Spacecraft and HI ISM Source Geometry:

Assume the spacecraft position is SC (Xsc, Ysc, Zsc) and the HI ISM source position is S1 (Xs1, Ys1, Zs1) and the galactic center is defined as GC (0,0,0). In order to define the angles g, h, and I in figure 9 the following geometry formulas are derived.

$$R_{s1} = \sqrt{X_{s1}^2 + Y_{s1}^2 + Z_{s1}^2} \quad \text{Equation 4}$$

$$R_{sc} = \sqrt{X_{sc}^2 + Y_{sc}^2 + Z_{sc}^2} \quad \text{Equation 5}$$

$$R_{sc\ to\ s1} = \sqrt{(X_{sc} - X_{s1})^2 + (Y_{sc} - Y_{s1})^2 + (Z_{sc} - Z_{s1})^2} \quad \text{Equation 6}$$

$$\angle a = sin^{-1}\left(\frac{Y_{s1}}{R_{s1}}\right) \text{Equation 7}$$

$$\angle b = sin^{-1}\left(\frac{X_{s1}}{R_{s1}}\right) \text{Equation 8}$$

$$\angle c = sin^{-1}\left(\frac{X_{sc}+X_{s1}}{R_{sc\ to\ s1}}\right)\text{Equation 9}$$

$$\angle d = sin^{-1}\left(\frac{Y_{sc}-Y_{s1}}{R_{sc\ to\ s1}}\right) \quad \text{Equation 10}$$

$$\angle e = sin^{-1}\left(\frac{X_{sc}}{R_{sc}}\right) \text{Equation 11}$$

$$\angle f = sin^{-1}\left(\frac{Y_{sc}}{R_{sc}}\right)\text{Equation 12}$$

$$\angle g = (\angle a + \angle f) \text{ Equation 13}$$

$$\angle h = 180 - (\angle b + \angle c) \text{ Equation 14}$$

$$\angle i = 90 - (\angle d + \angle e) \text{ Equation 15}$$

The velocity geometry can be derived from figure 10. Assume that the spacecraft is rotating around the galactic center at V(Rsc) and the HI ISM source is rotating around the Galactic center at V(R_{s1}).

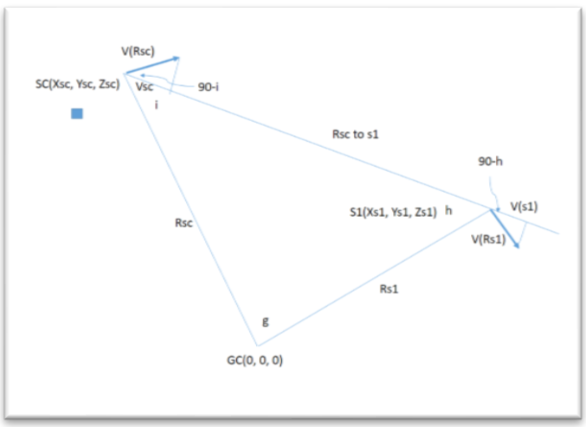


Figure 10: Velocity Geometry

The HI ISM measured velocity at the spacecraft (Vr) is calculated as:

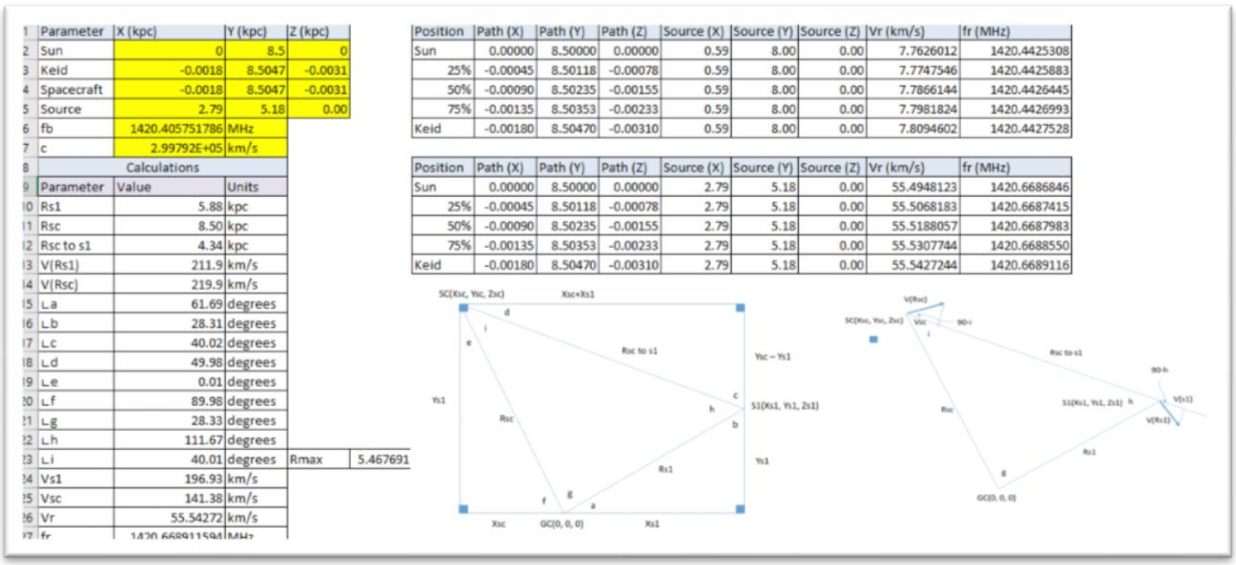
$$V_{s1} = V(R_{s1})\,cos(90 - \angle h) \; \textit{Equation 16}$$

$$V_{sc} = V(R_{sc})\,cos(90 - \angle i) \; \textit{Equation 17}$$

$$V_r = V_{s1} + V_{sc} \;\; \textit{Equation 18}$$

Note: $V(R_{s1})$ and $V(R_{sc})$ are looked up from past HI ISM rotation rate measurements.

Using these formulas, the expected V_r at any point along the spacecraft's flight path can be calculated by the model in figure 11.



	Parameter	X (kpc)	Y (kpc)	Z (kpc)
1	Parameter	X (kpc)	Y (kpc)	Z (kpc)
2	Sun	0	8.5	0
3	Keid	-0.0018	8.5047	-0.0031
4	Spacecraft	-0.0018	8.5047	-0.0031
5	Source	2.79	5.18	0.00
6	fb	1420.405751786	MHz	
7	c	2.99792E+05	km/s	
8	Calculations			
9	Parameter	Value	Units	
10	Rs1	5.88	kpc	
11	Rsc	8.50	kpc	
12	Rsc to s1	4.34	kpc	
13	V(Rs1)	211.9	km/s	
14	V(Rsc)	219.9	km/s	
15	∟a	61.69	degrees	
16	∟b	28.31	degrees	
17	∟c	40.02	degrees	
18	∟d	49.98	degrees	
19	∟e	0.01	degrees	
20	∟f	89.98	degrees	
21	∟g	28.33	degrees	
22	∟h	111.67	degrees	
23	∟i	40.01	degrees	Rmax 5.467691
24	Vs1	196.93	km/s	
25	Vsc	141.38	km/s	
26	Vr	55.54272	km/s	
27	fr	1420.668911594	MHz	

Position	Path (X)	Path (Y)	Path (Z)	Source (X)	Source (Y)	Source (Z)	Vr (km/s)	fr (MHz)
Sun	0.00000	8.50000	0.00000	0.59	8.00	0.00	7.7626012	1420.4425308
25%	-0.00045	8.50118	-0.00078	0.59	8.00	0.00	7.7747546	1420.4425883
50%	-0.00090	8.50235	-0.00155	0.59	8.00	0.00	7.7866144	1420.4426445
75%	-0.00135	8.50353	-0.00233	0.59	8.00	0.00	7.7981824	1420.4426993
Keid	-0.00180	8.50470	-0.00310	0.59	8.00	0.00	7.8094602	1420.4427528

Position	Path (X)	Path (Y)	Path (Z)	Source (X)	Source (Y)	Source (Z)	Vr (km/s)	fr (MHz)
Sun	0.00000	8.50000	0.00000	2.79	5.18	0.00	55.4948123	1420.6686846
25%	-0.00045	8.50118	-0.00078	2.79	5.18	0.00	55.5068183	1420.6687415
50%	-0.00090	8.50235	-0.00155	2.79	5.18	0.00	55.5188057	1420.6687983
75%	-0.00135	8.50353	-0.00233	2.79	5.18	0.00	55.5307744	1420.6688550
Keid	-0.00180	8.50470	-0.00310	2.79	5.18	0.00	55.5427244	1420.6689116

Figure 11: Model Results for 2 HI ISM Sources and Sun to Keid Flight Path

The plot of HI ISM sources 1 and 2 expected received velocities, Vr, during the Sun to Keid transit is shown in figure 12.

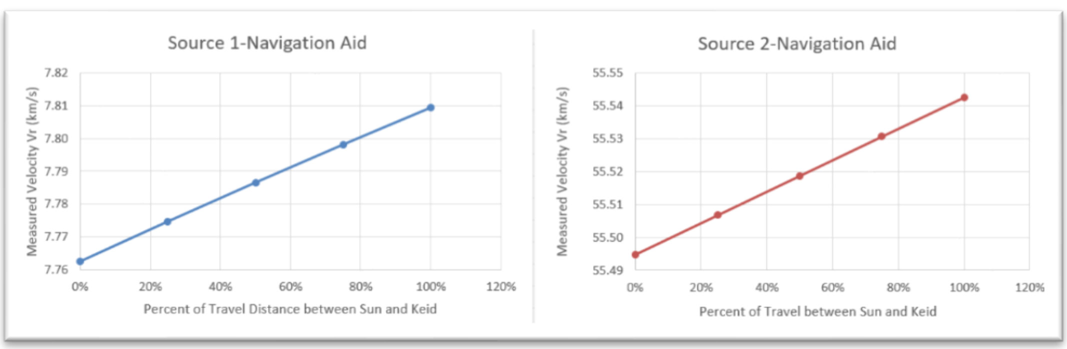


Figure 12: Sources 1 & 2 Expected Vr during Sun to Keid transit

Now the math is ready to use the HI ISM as a navigation aid for a spacecraft traveling in the Milky Way.

Navigating to Keid

The Deep Space Exploration Society (DSES) is currently assisting in a SETI project to observe frequency triplets at 40 Eridani A (Keid). A thought experiment was developed to simulate the use of HI ISM data as a navigational aid in a simulated trip from Earth to Keid.

40 Eridani A (Keid) Background

40 Eridani A is also known as Omicron 2 and Keid. In popular fiction, it is the home star of Vulcan in Star Trek and the also in the Dune series as the home star of Richese (12). The star is approximately 16.26 light years (LY) from the Sun located in the Eridanus constellation. (figure 13)

Figure 13: 40 Eridanus A (circled) (13)

The DSES organization is conducting 21 cm studies of 40 Eridani A as a SETI project (14) (15). The selection of Keid as a destination allows for further insight into the navigation requirements for the galactic trip.

Thought Experiment

Galactic navigation to Keid is conducted as a thought experiment. Some of the assumptions of the thought experiment follows:

- The trip will be non-relativistic to reduce the effects of time dilation on the data.
- The propulsion system, type of spacecraft, etc… are not being considered
- The experiment concentrated on issues associated with galactic navigation between the Sun and Keid
- The experiment only explores the use of HI ISM measured data as a supplemental navigation aid.

Basic Trip Geometry

Keid is in the Eridanus constellation (13):

<u>Keid (O2 ERI – 40 ERI) – HIP19849</u>

J2018.0 Galactic Latitude: -38° 03’ 27.9”
Galactic Longitude: -159° 14’ 26.7”
RA: 4h 16m 7.26s
DEC: -7° 37’ 05.4”
Distance: 16.26 Light Years (LY)

The 3-dimensional position is shown in figure 14. It is located in galactic quadrant III and is therefore both at R> Ro and slightly below the galactic disk.

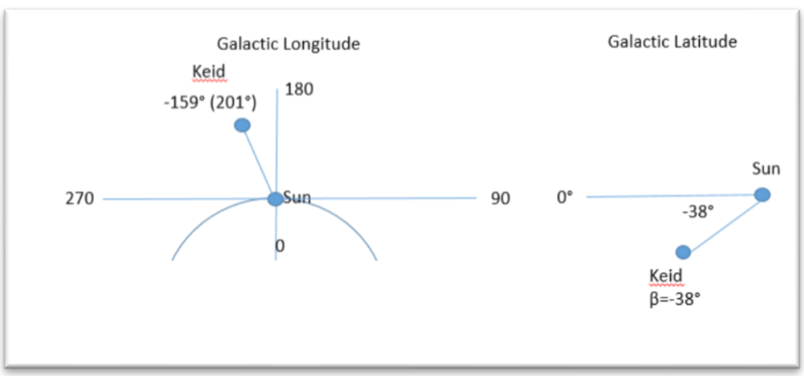


Figure 14: Geometry of Sun and Keid

The galactic – centric coordinates for the Sun and Keid are shown in figure 15.

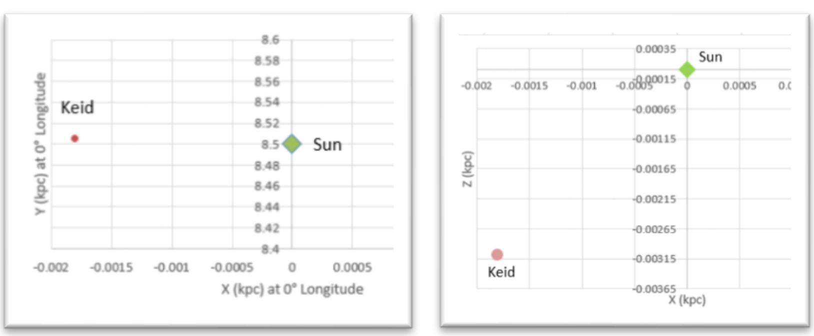


Figure 15: X-Y and X-Z Coordinate Plots

The coordinates for the closest HI ISM measurements are shown in figure 16.

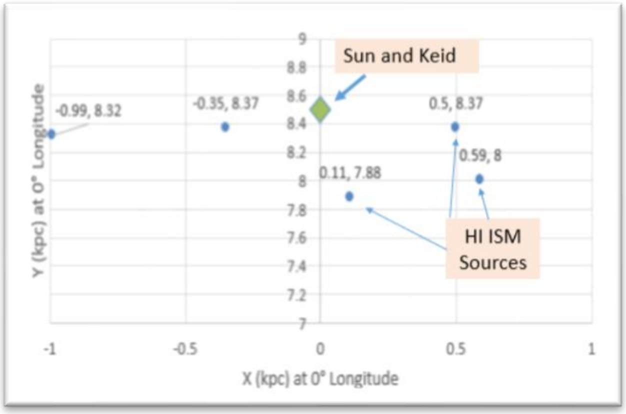


Figure 16: Closest HI ISM Sources to Sun - Keid Flight Path

Keid's distance from the Galactic center is:

$R = \sqrt{(Ro + \Delta y)^2 + (x)^2}$ = *8.50037 kpc*   *Equation 19*

Based on this, assume that Keid's galactic rotation is approximately the same as the Sun. Vo=V1(Rsc)=220 km/s.

Determining Galactic Position

By comparing the measured with the expected Vr from multiple HI ISM sources, the Galactic position can be plotted. As an example, two HI ISM sources were selected and modeled as shown in figure 17.

Source 1

Parameter	X (kpc)	Y (kpc)	Z (kpc)
Sun	0	8.5	0
Keid	-0.0018	8.5047	-0.0031
Spacecraft	-0.0009	8.50235	-0.00155
Source	0.59	8.00	0.00
fb	1420.405751786	MHz	
c	2.99792E+05	km/s	
Calculations			
Parameter	Value	Units	
Rs1	8.02	kpc	
Rsc	8.50	kpc	
Rsc to s1	0.78	kpc	
V(Rs1)	217.1	km/s	
V(Rsc)	219.9	km/s	
∟a	85.78	degrees	
∟b	4.22	degrees	
∟c	49.63	degrees	
∟d	40.37	degrees	
∟e	0.01	degrees	
∟f	89.99	degrees	
∟g	4.23	degrees	
∟h	126.15	degrees	
∟i	49.62	degrees	
Vs1	175.31	km/s	
Vsc	167.52	km/s	
Vr	7.78661	km/s	
fr	1420.442644538	MHz	

Position	Path (X)	Path (Y)	Path (Z)	Source (X)	Source (Y)	Source (Z)	Vr (km/s)	fr (MHz)
0%	0.00000	8.50000	0.00000	0.59	8.00	0.00	7.7626012	1420.4425308
25%	-0.00045	8.50118	-0.00078	0.59	8.00	0.00	7.7747546	1420.4425883
50%	-0.00090	8.50235	-0.00155	0.59	8.00	0.00	7.7866144	1420.4426445
75%	-0.00135	8.50353	-0.00233	0.59	8.00	0.00	7.7981824	1420.4426993
100%	-0.00180	8.50470	-0.00310	0.59	8.00	0.00	7.8094602	1420.4427528

Source 2

Parameter	X (kpc)	Y (kpc)	Z (kpc)
Sun	0	8.5	0
Keid	-0.0018	8.5047	-0.0031
Spacecraft	-0.0009	8.50235	-0.00155
Source	2.79	5.18	0.00
fb	1420.405751786	MHz	
c	2.99792E+05	km/s	
Calculations			
Parameter	Value	Units	
Rs1	5.88	kpc	
Rsc	8.50	kpc	
Rsc to s1	4.34	kpc	
V(Rs1)	211.9	km/s	
V(Rsc)	219.9	km/s	
∟a	61.69	degrees	
∟b	28.31	degrees	
∟c	40.03	degrees	
∟d	49.97	degrees	
∟e	0.01	degrees	
∟f	89.99	degrees	
∟g	28.32	degrees	
∟h	111.66	degrees	
∟i	40.03	degrees	
Vs1	196.94	km/s	
Vsc	141.42	km/s	
Vr	55.51881	km/s	
fr	1420.668798268	MHz	

Position	Path (X)	Path (Y)	Path (Z)	Source (X)	Source (Y)	Source (Z)	Vr (km/s)	fr (MHz)
0%	0.00000	8.50000	0.00000	2.79	5.18	0.00	55.4948123	1420.6686846
25%	-0.00045	8.50118	-0.00078	2.79	5.18	0.00	55.5068183	1420.6687415
50%	-0.00090	8.50235	-0.00155	2.79	5.18	0.00	55.5188057	1420.6687983
75%	-0.00135	8.50353	-0.00233	2.79	5.18	0.00	55.5307744	1420.6688550
100%	-0.00180	8.50470	-0.00310	2.79	5.18	0.00	55.5427244	1420.6689116

Figure 17: Sources 1 & 2 Example Measured Data

If a velocity measurement is taken at the spacecraft at time (T=0000) of HI ISM Sources 1 & 2, the expected position along the spacecraft's path can be plotted (figure 18).

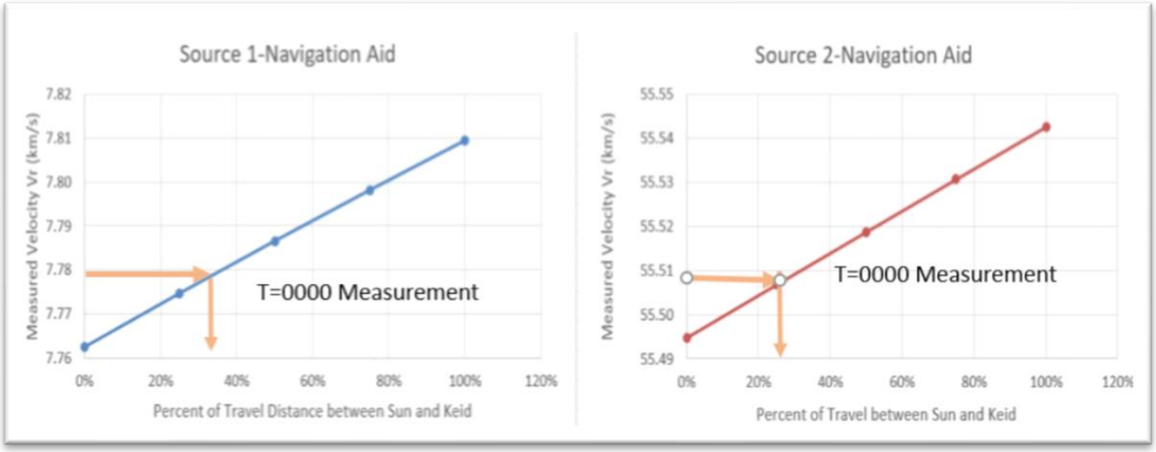


Figure 18: Velocity to % Path Measurement for Sources 1 & 2

Note that Source 1 indicates 35% and Source 2 indicates 25% along flight path. Plotting these positions from the known Galactic positions of sources 1 & 2 will provide the spacecraft position at T=0000. (figure 19)

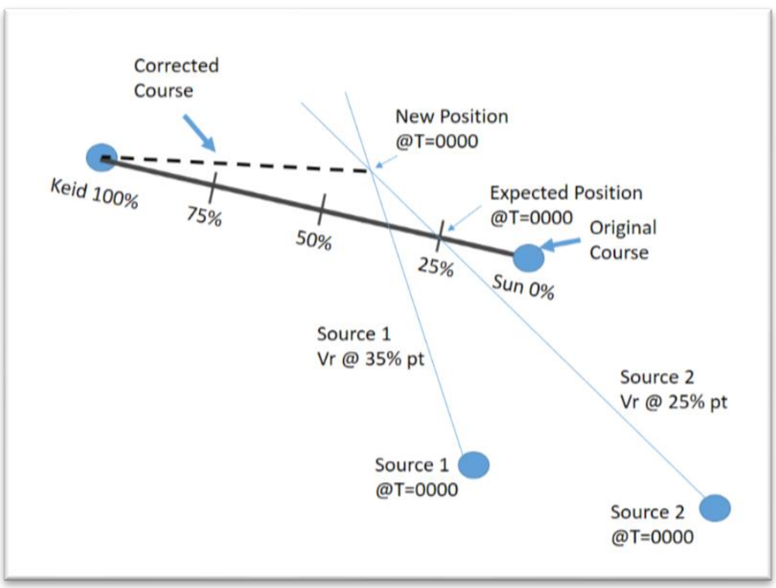


Figure 19: Example Use of Vr Measurements for X-Y Position Data

The position of the spacecraft can be calculated in all three dimensons with more sources at different positions. The accuracy of the position is dependent on the number and measurement accuracy of the source data.

The actual three dimensional velocity of the spacecraft can be calculated based on the time difference of the position data. Course corrections and velocity adjustments can therefore be calculated.

Velocity and Course Deviation Indicator

The use of the HI ISM line frequencies can also be used to provide velocity and course deviation data to a spacecraft. A basic geometry using a source that is directly inline and parallel to the spacecraft path shows that the $V_{measured}$ data will change with a change of spacecraft velocity, Vsc. (figure 20)

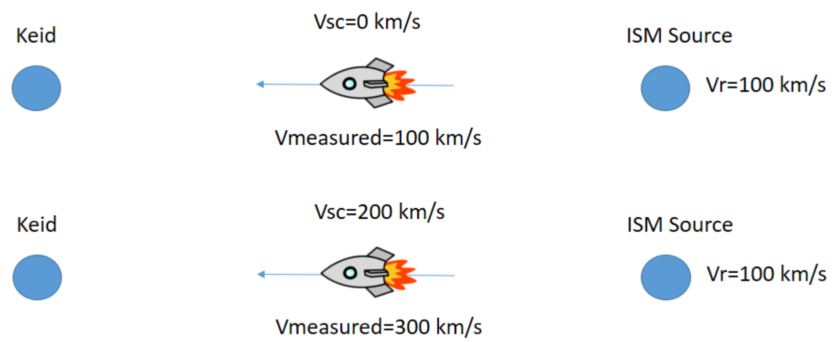


Figure 20: Velocity Deviation Indicator

Course offsets can also be detected when the received velocity measurement decreases below Vr+Vsc of the HI ISM source. (figure 21)

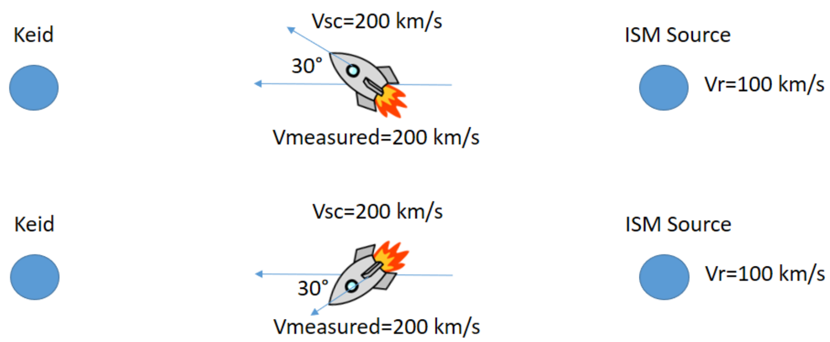


Figure 21: Course Deviation Indicator

Note that more accurate knowledge of the HI ISM source positions and galactic center distance will allow for better accuracy of this 3-dimensional model.

Galactic "Current" Indicator

The galactic rotation rate changes during the flight. It is uncertain the effect of this rotation on an individual spacecraft moving in the medium. This effect is similar to an ocean traveling ship subjected to a current. The current pushes the ship off of a direct path, even though the steered course does not change. (figure 22)

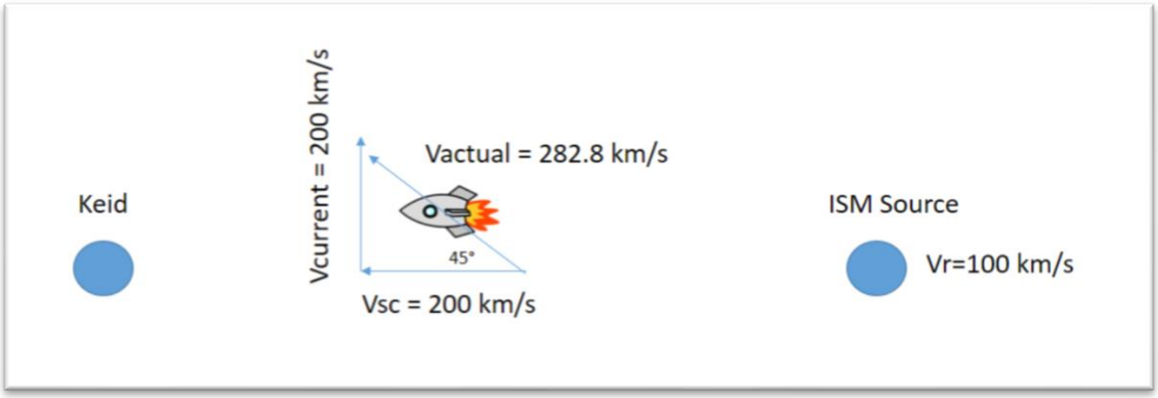


Figure 22: Example of "Current" effect on spacecraft

The galactic "current" in this example is the same as the galactic rotation rate at a distance R from the galactic center, V(R). This current will also change with the spacecraft transiting above or below the galactic disk. It is unclear how this current affects the spacecraft. The rotation rate of the stars and HI ISM are the result of billions of years in this rotation current. A spacecraft transiting through different rotation rates may not be "pushed" by this current and may maintain the original rotation velocity based on its starting point. This is just one of the issues that were uncovered during the thought experiment.

Issues to be Resolved

This thought experiment also unveiled more questions and improvements to be followed-up on:

- What is the rotation rate of the galaxy at different distances above and below the galactic plane Z-axis?
- Is the spacecraft pushed along the rotation rate of the galaxy as it moves through different rotation regions?
- The current basic model needs to be improved to calculate the received velocity for different spacecraft course and speed changes.
- The current model requires more accurate position data for HI ISM sources. The model should also add CO radio sources.
- The model should be improved to include relativistic spacecraft velocities. This model should include all possible spacecraft velocities up to the speed of light plus the time dilation correction incurred.
- The model needs to be improved to include the measured velocity correction from the Earth's rotation and the Earth's orbit velocity around the Sun.

Mapping the Earth's Location

The next experiment will encompass the current basic model to plot the Earth's position around the Sun and its coordinate position in the galaxy throughout a one year period. This experiment will require more accuracy since the ranges are +- 8 light minutes. Figure 23 shows a basic representation of the use of HI ISM sources to map the Earth's location around its orbit.

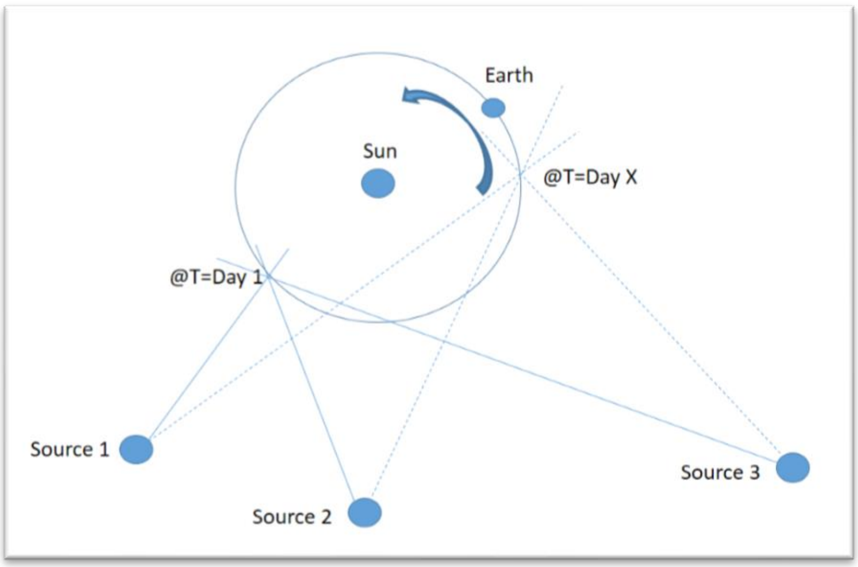


Figure 23: Earth's Path Around the Sun HI ISM Model

The accuracy requirements for this experiment will require:

- Improved logging of HI ISM frequency and velocity measurements at the Earth stations to include precise location and time measurements of each observation.
- Improved rotation rate data for the HI ISM sources chosen and the Sun's rotation around the galactic plane.
- Improved value for the Sun to galactic center distance. The research articles found so far range from 8.0 to 8.5 kpc.
- Improved precision for the location data for selected HI ISM sources mapped to galactic coordinates. These sources will need to be selected to allow for good triangulation geometry throughout the Earth's orbit.

Summary

This paper reviewed the use of HI source data to determine the Milky Way rotation rate. The historic rotation rates were then used to estimate the HI source locations in the galaxy. It was then shown that it would be possible to calculate a spacecraft's location in the galaxy by using the Doppler measurements from these HI sources. A Galactic model was developed to use the HI source locations as Galactic navigation aids for a trip from the Sun to the 40 Eridani A (Keid) star system.

The techniques developed from this thought experiment can be extended to the development of a navigation system using not only HI ISM sources but any other Galactic sources with known positions and stable frequency outputs.

References

1. Reid, M.J. and Dame, T.M. On the Rotation Speed the Milky Way Determined from HI Emission. [Online] 2016. https://arxiv.org/pdf/1608.03886.pdf.

2. Carraro, Giovanni. The Milky Way Disk. [Online] 2015. https://arxiv.org/pdf/1502.03151.pdf.

3. Nakanishi, Hiroyuki and Sofue, Yoshiaki. Three-dimensional distribution of the ISM in the Milky. [Online] 2003. https://arxiv.org/pdf/astro-ph/0304338.pdf.

4. Ray, Paul S., Wood, Kent S. and Wolff, Michael T. Characterization of Pulsar Sources for X-ray Navigation. [Online] 2017. https://arxiv.org/pdf/1711.08507.pdf.

5. Sofue, Yoshiaku. *Galactic Radio Astronomy.* s.l. : Springer, 2017. ISBN 978-981-10-3444-2.

6. Eisenhauer, F., et al. A Geometric Determination of the Distance to the Galactic Center. [Online] 2003. https://arxiv.org/pdf/astro-ph/0306220.pdf.

7. Lockman, Felix J. HI and Galactic Structure. [Online] 2002. https://arxiv.org/pdf/astro-ph/0203210.pdf.

8. Charting the Milky Way From the Inside Out. [Online] 2015. https://www.nasa.gov/jpl/charting-the-milky-way-from-the-inside-out.

9. Galactic Navigation. [Online] http://chandra.si.edu/build/navigation.html.

10. Rudolph, Alexander. Understanding the Rotation of the Milky Way Using Radio Telescope Observations. [Online] http://euhou.obspm.fr/public/.

11. Rotation Rate Simulator and Database. [Online] http://euhou.obspm.fr/public/simu.php.

12. Stars and Plenetary Systems in Fiction. [Online] https://en.wikipedia.org/wiki/Stars_and_planetary_systems_in_fiction#40_(o²)_Eridani.

13. 40 Eridani. [Online] https://en.wikipedia.org/wiki/40_Eridani.

14. *Narrow Bandwidth Radio Bursts Observed using the Green Bank Forty Foot Telescope and Home-built Five Meter Telescopes.* Crilly, Skip. Prescott, AZ : SARA 2016 Western Conference, 2016.

15. *Shannon Entropy Measurements of Radio Telescope Signals.* Crilly, Skip. Green Bank, W.V. : SARA, 2015.