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Abstract

This paper describes an approach to select pulsars that are visible along the path of a theoretical galactic spacecraft. The method includes determining the galactic angles relative to the rotating “lighthouse” beam as well as the use of the time delayed pulsar period to determine the spacecraft distance from the pulsar. The methods described are used for a hypothetical trip between two points in the galaxy.

1. Pulsar Galactic Navigation Theory

Galactic navigation requires the use of a common three-dimensional reference (X, Y, Z) frame referred to as the galactic – center frame. In this frame the center of the galaxy is at (0,0,0). The Sun is approximately at (0, 8500 pc, 0) (Russel, Galactic Navigation Position Data Using HI Interstellar Medium Velocity Measurements, 2018) (Russel, Earth’s Orbital Position in the Solar System using Galactic HI Measurements, 2019) (Russel, Milky Way Rotation Rate and Mass Estimation using HI Measurements, 2019). Pulsars can be plotted using the same galactic framework and therefore provide a geometric relationship that can be used to triangulate navigational positions. Pulsars also have a unique property based on the radio observable rotation rate. This rate provides a unique identifier for each pulsar and also a unique spin-down rate. The distance from the pulsar can be estimated using the observable spin-rate and then calculating the distance and therefore time based on the speed of light that it would take for the pulsar rate to be observed. (Lyne & Graham-Smith, 1990) (Lorimer & Kramer, 2005)

By developing distance solutions for multiple pulsars, it is possible to develop a model that estimates the 3 – dimensional galactic coordinates of the spacecraft. Once the model is developed the basic guide for a galactic navigator includes:

- Determine the starting point and destination galactic coordinates
- Determine the points between the start and destination that pulsar observations will need to be taken for navigation
- Determine which pulsars are visible at the navigation points
- Select the pulsars that give the small error at each navigation point (preflight)
- During flight – stop and take pulsar period observations and use the model to solve the galactic coordinate position
- Adjust course accordingly and restart flight to the next navigation point.

2. Pulsar Geometry

A pulsar is formed during the collapse of a larger star. As the star collapses the new neutron star spins faster to retain its angular momentum. The neutron star is formed with a magnetic field that has an offset from the spin axis. The magnetic field emits a radio signal that can be detected like a lighthouse by the radio telescopes. (Figure 1) The offset angle causes the radio signal to “pulse” with a detectable spin rate. The magnetic field also causes a braking effect on the pulsar spin rate. This spin-down rate can therefore be used to predict the pulsar spin rate over time. (Lyne & Graham-Smith, 1990) (Lorimer & Kramer, 2005)
A list of pulsars can be found at the Australia Telescope National Facility (Australia Telescope National Facility, n.d.) (Figure 2) and at the VizieR database (Pulsar Catalog) (Manchester, Hobbs, A., & Hobbs, 2006)(Figure 3).
The data needed from these databases include galactic latitude and longitude, distance from Earth, period at Earth, and period spin-down rate \(P_{\text{dot}}\).

3. Galactic Coordinate Navigation Model

The galactic coordinate navigation model is designed to determine a spacecraft's position as it transits from any two points in the galaxy. A theoretical faster than light (FTL) trip through the galaxy would require the spacecraft to drop out of FTL in order to detect the pulsars radio signal. Figure 4 shows the model's 3 planned stopping points between a trip between Earth and Kepler 452b, which is a super-Earth detected by the Kepler spacecraft.
Figure 4: Galactic-Centric Coordinates for Earth to K452b trip in the X-Y, X-Z, and Y-Z Plane

The calculator provides an estimate along the path in (X, Y, Z) galactic-centric coordinates. Any percent of path can be calculated by simply changing the % value. The starting and ending points can be changed by entering in the three-dimensional coordinates.
4. Model to Determine if Pulsars are Visible along the Flight Path

The nature of a pulsar is that the radio beam is not visible in all directions. The geometry of the beam is shown in Figure 5. (Lyne & Graham-Smith, 1990)

\[ \rho \approx 5.4 \frac{p^{-1/2}}{s} \]  

(1)

The beam angle (\(\rho\)) provides the basis for the model to determine if the path is in view of the pulsar.

1) The maximum value of 2\(\rho\) is 90°. A larger angle would violate the light cylinder around the pulsar in which the magnetic field lines break before reaching the speed of light.
2) The Earth is within the 2\(\rho\) angle because we currently observe the pulsar. The model assumes that the Earth is on the edge of the beam and that beam can be seen along the path across the entire 2\(\rho\) angle. This is the worst-case high value; therefore, the model can limit the angle by any percent needed. However, for the following exercise, the entire 2\(\rho\) value will be used for each pulsar.
3) Each pulsar will have a unique \(\rho\) angle based on its period. The model will show a green alert if a pulsar is visible along the path. The model can show the path position anywhere along the path. The entire pulsar database alerts for are then updated so that the visible pulsars can be selected.

A navigation path using a single pulsar is shown in Figure 6. The use of multiple pulsars that also have visibility throughout the trip, provides greater navigation accuracy and ambiguity resolution.
The Earth, destination, and pulsar form a triangle for each plane (Figure 7). The database provides the estimated distances from the Earth and pulsar (line c-d). The distance between the Earth – destination (line b), and pulsar – destination (line a) are easily calculated. The important angle is angle A. This is the angle that corresponds to the 2\(\rho\) beam angle of the pulsar. If angle A is < 2\(\rho\) then the pulsar should be visible at the destination. Figure 7 shows the derivation of the angle A value. This was used in the model and compared to the 2\(\rho\) angle for each of the three planes.

\[
\frac{c + d}{a} = \frac{a}{c} \quad \text{P 105 Geometry Cliff Notes}
\]
\[
c = \frac{a^2}{c+d}
\]
\[
d = (c+d)-c
\]
\[
e = \sqrt{|a^2 - c^2|}
\]
\[
A = \arcsin\left(\frac{e}{a}\right)
\]
\[
B = \arccos\left(\frac{d}{b}\right)
\]
\[
C = \arcsin\left(\frac{c}{a}\right)
\]
\[
D = \arcsin\left(\frac{d}{b}\right)
\]

Figure 7: Angle Geometry

The master pulsar database automatically calculates the geometry of the pulsar to the navigation point and calculates three angles. If the angles are less than the 2\(\rho\) angle, they are colored green, otherwise they are colored red (Figure 8).
The calculations of angles were added to the master pulsar database. This provides a quick reference for the selection of pulsars that are visible at any position in the galaxy. (Figure 9)
### Model to Calculate Galactic Angles

**Figure 9: Master Pulsar Model**

<table>
<thead>
<tr>
<th>Data from Database</th>
<th>Calculation of pulsar Base Period</th>
<th>X-Y Plane Calculations</th>
<th>X-Z Plane Calculations</th>
<th>Y-Z Plane Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculation of ( \rho ) angle</td>
<td></td>
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</tbody>
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### Table

| Pulsar | Galactic Coordinate | Pulsar Period | Spin Period | Spin Axis | Distance | Speed | Mass | Age | V_z | V_\perp | V_\parallel | V_\perp \| V_\parallel | V_\perp \| V_\parallel | V_\perp \| V_\parallel | V_\perp \| V_\parallel |
|--------|---------------------|--------------|-------------|-----------|----------|-------|------|-----|-----|--------|----------|----------------|----------------|----------------|----------------|----------------|
| 1      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 2      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 3      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 4      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 5      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 6      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 7      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 8      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 9      |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 10     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 11     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 12     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 13     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 14     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 15     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 16     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 17     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 18     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 19     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 20     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 21     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 22     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 23     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 24     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 25     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 26     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |
| 27     |                     |              |             |           |          |       |      |     |    |        |          |                 |                 |                 |                 |                 |

### Calculation

- **Data from Database**: Information extracted from various sources related to pulsars.
- **Calculation of Pulsar Base Period**: Determines the period at which the pulsar emits radiation.
- **X-Y Plane Calculations**: Involves coordinates and velocities in the X-Y plane.
- **X-Z Plane Calculations**: Involves coordinates and velocities in the X-Z plane.
- **Y-Z Plane Calculations**: Involves coordinates and velocities in the Y-Z plane.

### Conversion

- **Conversion to Galactic-Centric Coordinates**: Converts the pulsar's position and movement to a galactic-centric system.
- **Calculated Period at Navigation Point**: Provides the pulsar's period at a specific navigation point.

### Alerts

- **X-Y Alert**: Alerts related to X-Y plane calculations.
- **X-Z Alert**: Alerts related to X-Z plane calculations.
- **Y-Z Alert**: Alerts related to Y-Z plane calculations.
The pulsars that are visible can now be defined. The next step is to select the pulsars and use their periods and $P_{\text{dot}}$ values to calculate the 3-dimensional galactic coordinates. The pulsars that meet the requirements of having a beam of $2\rho$ diameter beam width that is visible along the entire path are shown in Figure 10.

The X-Y plane position of the selected pulsars are shown in Figure 11.

5. Math Model to Determine the Galactic Position

The following sequence of equations were used to establish a multiple equation and multiple unknown problem to determine the ship’s galactic position by observing the pulsar periods during flight along the path. Equations 1-2 use the base period ($P_{\text{base}}$) and spin down rate ($P_{\text{dot}}$) to calculate a range from a pulsar to the ship’s position based on an observed period of the pulsar ($P_{\text{observed}}$).

$$P_{\text{base}} = P_{\text{observed}} + P_{\text{dot}} \times (\text{distance in light years}) \quad (1)$$

$$\frac{P_{\text{base}}}{P_{\text{base}} - P_{\text{observed}}} = \text{Pulsar 1 observed distance (LY)} \quad (2)$$

The EXCEL Solver program provides iterations on Trial $X$, $Y$, and $Z$ galactic coordinates. The distance to the known pulsar to the Trial coordinates is calculated in Equations 3-5. Note that the actual model used 8 pulsars.

$$\sqrt{(\text{Trial } X - \text{Pulsar 1 } X)^2 + (\text{Trial } Y - \text{Pulsar 1 } Y)^2 + (\text{Trial } Z - \text{Pulsar 1 } Z)^2} = \text{Trial Pulsar 1 distance (LY)} \quad (3)$$
\[
\sqrt{(\text{Trial } X - \text{ Pulsar } X)^2 + (\text{Trial } Y - \text{ Pulsar } Y)^2 + (\text{Trial } Z - \text{ Pulsar } Z)^2} = \\
\text{Trial Pulsar 2 distance (LY)} \quad (4)
\]

\[
\sqrt{(\text{Trial } X - \text{ Pulsar } 3 X)^2 + (\text{Trial } Y - \text{ Pulsar } 3 Y)^2 + (\text{Trial } Z - \text{ Pulsar } 3 Z)^2} = \\
\text{Trial Pulsar 3 distance (LY)} \quad (5)
\]

The difference error between the observed distance and the trial distance is calculated with equations 6-8.

\[\begin{align*}
\text{Pulsar 1 observed distance (LY)} - \text{Trial Pulsar 1 distance (LY)} &= \text{error 1} \quad (6) \\
\text{Pulsar 2 observed distance (LY)} - \text{Trial Pulsar 2 distance (LY)} &= \text{error 2} \quad (7) \\
\text{Pulsar 3 observed distance (LY)} - \text{Trial Pulsar 3 distance (LY)} &= \text{error 3} \quad (8)
\end{align*}\]

The EXCEL solver iterates the Trial X, Y, and Z coordinates until it reduces the sum of the errors to 0 or runs out of iterations. (Equation 9).

\[\text{Solver set to find solution so that: error 1 + error 2 + error 3 = 0} \quad (9)\]

6. Using Pulsar Period and Pulsar Spin down rate to determine distance to a pulsar.

A model was developed in EXCEL to meet the following requirements:

- Observe the pulsar period at the spacecraft position
- Determine the distance from the pulsar using the difference between the base period and the observed period.
- Use multiple pulsar observations to refine position.
- The following model was developed to determine the 3-dimensional galactic-Centric position using multiple pulsar measurements. (Figure 12)
Solver Model to Calculate Distances
The Excel Solver program was used to calculate the best solution. Figure 13 shows the solver setup with the options selection that provided increased accuracy to the solution.

**Figure 13: Solver Parameters**

7. Error Analysis

The solver accuracy was tested using known values of the path galactic coordinates. The accuracy was tested by increasing the number of pulsars used in the solution. The results are shown in Figure 14.

**Figure 14: Error Analysis**

The error analysis indicates that the model requires at least three pulsars to get accurate results. Figure 15 shows the relative distance that the error indicates. With an 8-pulsar observation, the solar system can be found compared to the next closest solar system, Alpha Centauri. The error should be able to be reduced using a better solver program. This will be explored in future research.
Using the above models, the following steps can be used to plan the galactic navigation using pulsars.

- Determine the start and destination of the galactic trip
- Determine the location of the path stops to obtain navigation data
- Based on the path stop location, determine which pulsars meet the alpha angle criteria (visible to the spacecraft at the stop point)
- Select Pulsars that have beams that intersect the path
- Select pulsars that provide a minimal AOU along the path
- Identify multiple points along the path to stop and take navigation data – FTL flight will not allow pulsar observation
- Adjust course and speed based on updated navigation position.
- Secondary – look for new pulsars that may not have been observable from Earth before.

Plan
- Plot path using galactic coordinates
- Choose pulsars that are visible along entire path

Underway Observations
- Stop and take observations
- Calculate new position
- Make course corrections accordingly

9. Practical example of a flight from Earth to Kepler 452b

The flight path from Earth to Kepler 452b is set up with three stops for navigation observations at 25%, 50% and 75% along the path. The model calculates the expected galactic coordinates at these points as shown in Figure 16. The coordinates are shown in the X-Y, X-Z, and Y-Z planes. Note that the 25% highlight in the model allows the path % to be transferred to the rest of the models features.
Using the model’s pulsar database, select pulsars that have a beam that encompasses the expected galactic position along the path. Note, that it is not necessary that the same pulsars be used along the entire path. Figure 17 shows the selected pulsars that meet the visibility path along the entire path.
During flight, the first stop at the 25% point results in the following pulsar periods being observed. (Figure 18)
Run the Solver program for these pulsar periods to determine the spacecraft position. (Figure 19)

The trial position result is plotted in Figure 20 for the X-Y plane. Note, that the ship is off course! The navigator will need to plan a new course in order to hit the planned 50% point.
The X-Y, X-Z and Y-Z plane course adjustments are shown in figure 21.

This process is completed as often as necessary in order to successfully use pulsars to navigate.
10. Follow-On work to improve the navigation accuracy

The paper provides a basic approach to using pulsars to determine the galactic position using observed period measurements. The model is rudimentary and requires upgrades to reduce the error. These include:

- Characterize the beam cone in the model – this will provide better predictions of beam detection
- Get better pulsar spin down models that account for historical and predicted glitches and other timing anomalies.
- Add pulsar range errors: this will provide a more realistic area of uncertainty around the trial position.
- Develop a better “Solver” program to get a more precision that will allow for navigation within the solar system.
- Add GAIA astronomical catalog to improve accuracy of the galactic navigation data. GAIA provides positions, parallactic distances and proper motion for millions of galactic stars with precisions as good as a few micro-arcseconds. (Jones D. D., 2019)
- Each of the above Effects will only make small corrections to the Pulsar’s Timing, but for Navigational purposes will become very important for long distance navigation.

1. Doppler Shift Correction - the space craft is at a different Galactic Position and will be affected by the rotation of the Galaxy. (Boyd, 2019)

2. Dispersion - As the RF signal passes through the ISM it will pass through different Interstellar Clouds causing time delay at the lower Pulsar frequencies. This needs to be corrected in order to detect the proper Pulsar. In some cases, the Dispersion can completely "smear out" the Pulsar's signal altogether. The Navigator could miss the chosen Pulsar. (Boyd, 2019)

3. Lastly and most interesting is the effect of Gravity on measuring Time. As the space craft travels towards the Center of the Galaxy it will encounter a stronger Gravity Field. The Spacetime Curvature of the Gravitation Field will cause the Navigator’s clock to change relative to the that of the Pulsar's. This is exactly what happens with GPS satellites at high altitudes above the Earth. So, a Relativistic Correction needs to be made by the Navigator. At the same time the Gravity Field can also be affected by any nearby locally massive object. So, it may be wise for the Navigator to choose waypoints that are not near any massive objects. The same effect works even when the space craft travels further away from the Galactic Center. (Boyd, 2019)

11. Summary

The use of pulsars for galactic navigation is a viable option for futuristic FTL space flight. The precise measurements of the pulsar period and spin-down rate provide the ability to calculate distance to the pulsar. The distance of the pulsars from the Earth has a significant error range that needs to be refined. The agreement on the pulsar base period will also provide more accuracy to the trial range estimates. The calculated base periods for the ATNF database was calculated by the model and is available from the author.

12. Student Exercises using this Model

The exercise of using pulsars for galactic navigation is an excellent way to teach the properties of pulsars, galactic coordinates, light speed, and modeling.
1) Take observed pulsar observations and determine the Earth’s position. This is similar to using HI measurements to determine the Earth’s position. (Russel, Earth’s Orbital Position in the Solar System using Galactic HI Measurements, 2019)
2) Develop a pulsar message to another planetary system that uses only the pulsar periods observed from the Earth to provide a unique galactic position. This is similar to the Pioneer pulsar map which was developed by Frank Drake. (Russel, Galactic Navigation using the Pioneer Spacecraft Pulsar Map, 2019)

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References


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