2021 Joint Navigation Conference

An Experiment in Interstellar Navigation

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The New Horizons mission

- Launched 2006 Jan 19 to explore Pluto, the last of the nine planets (at that time) to be visited by a spacecraft
- Prime contractor for the spacecraft: Johns Hopkins University Applied Physics Laboratory (APL)
- Pluto encounter 2015 July 14
- Arrokoth encounter 2019 Jan 1
- Parallax images of two nearby stars taken 2020 April 22-23
- Now >50 astronomical units (au) (7.5 x 10^9 km) from the Sun

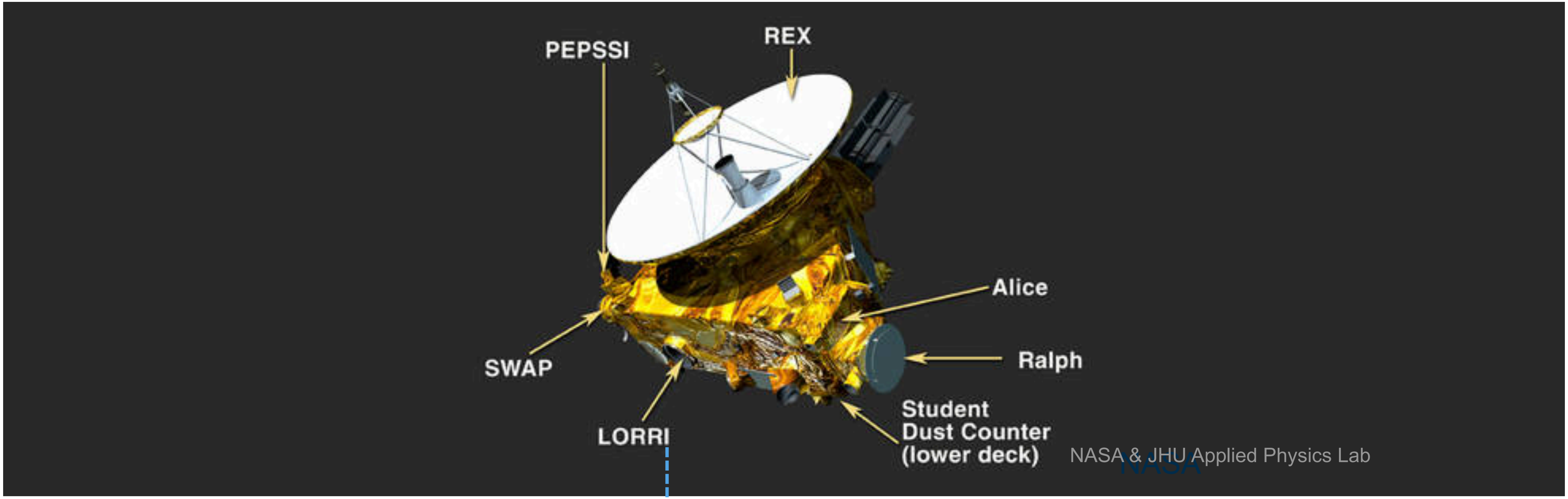
Finding New Horizons

On April 22-23 2020, NASA did a test of Celestial Navigation on the New Horizons spacecraft by observing the parallax of two stars (Proxima Centauri and Wolf 359)

The test was widely publicized, people encouraged to download the images, experiment for themselves, and then post the results to social media using #NHparallax

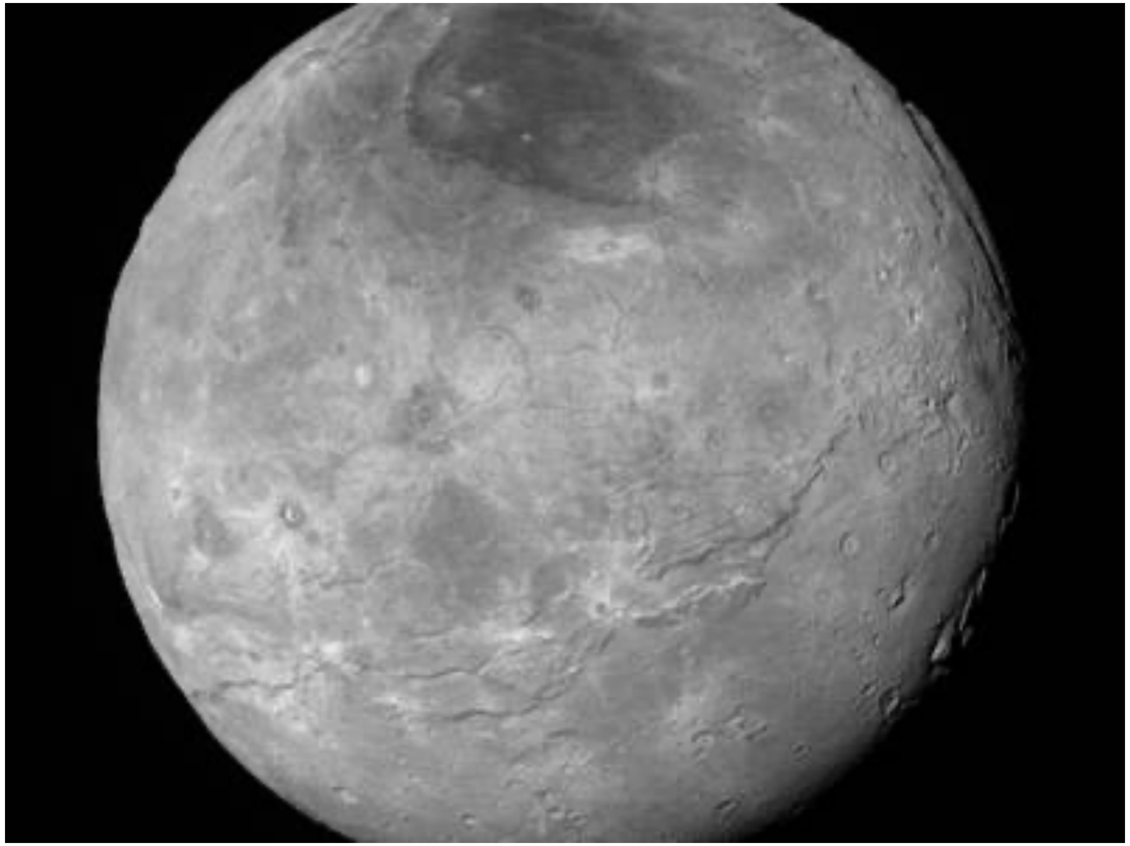
We decided to use these images in a test of Celestial Navigation algorithm

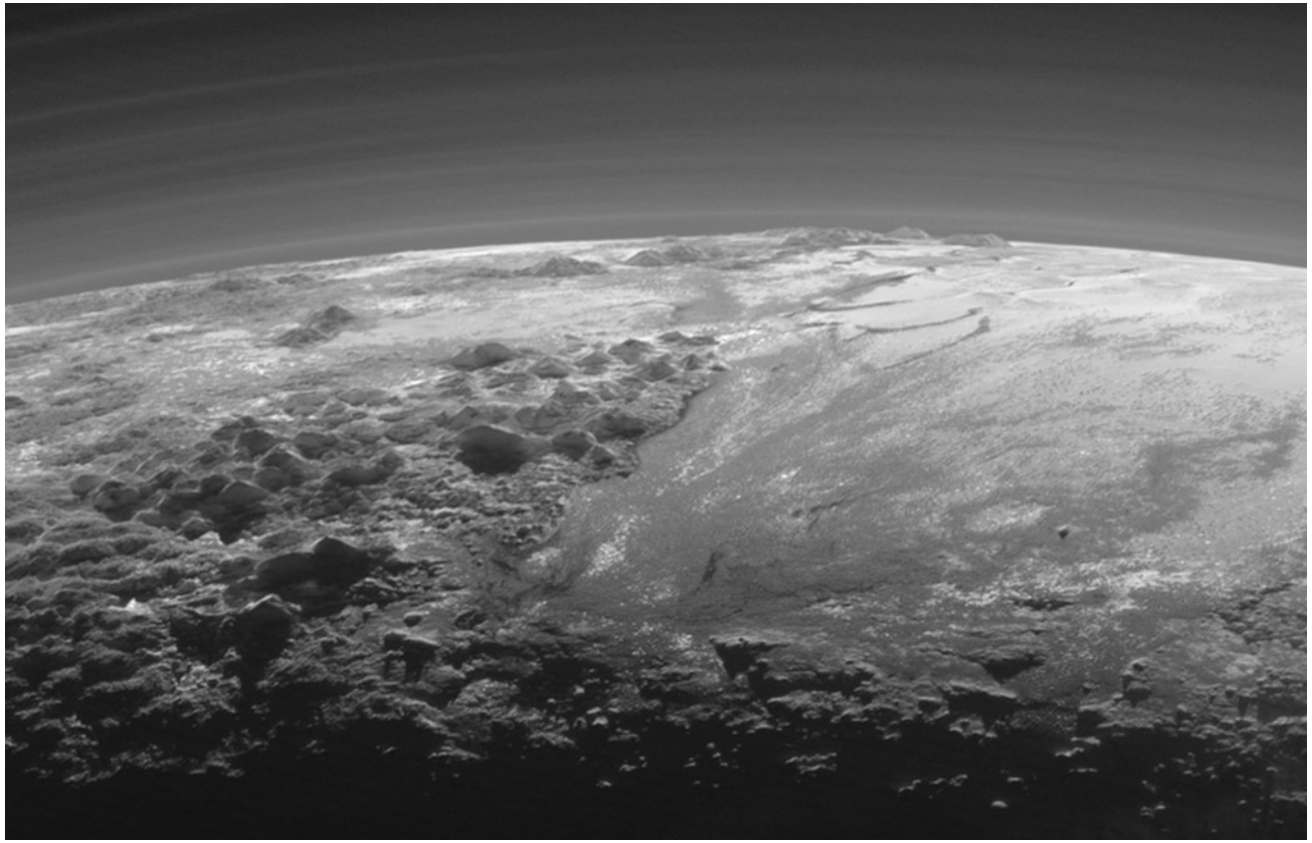
The New Horizons spacecraft



LOng Range Reconnaissance Imager (telescopic camera)

New Horizons images of Pluto

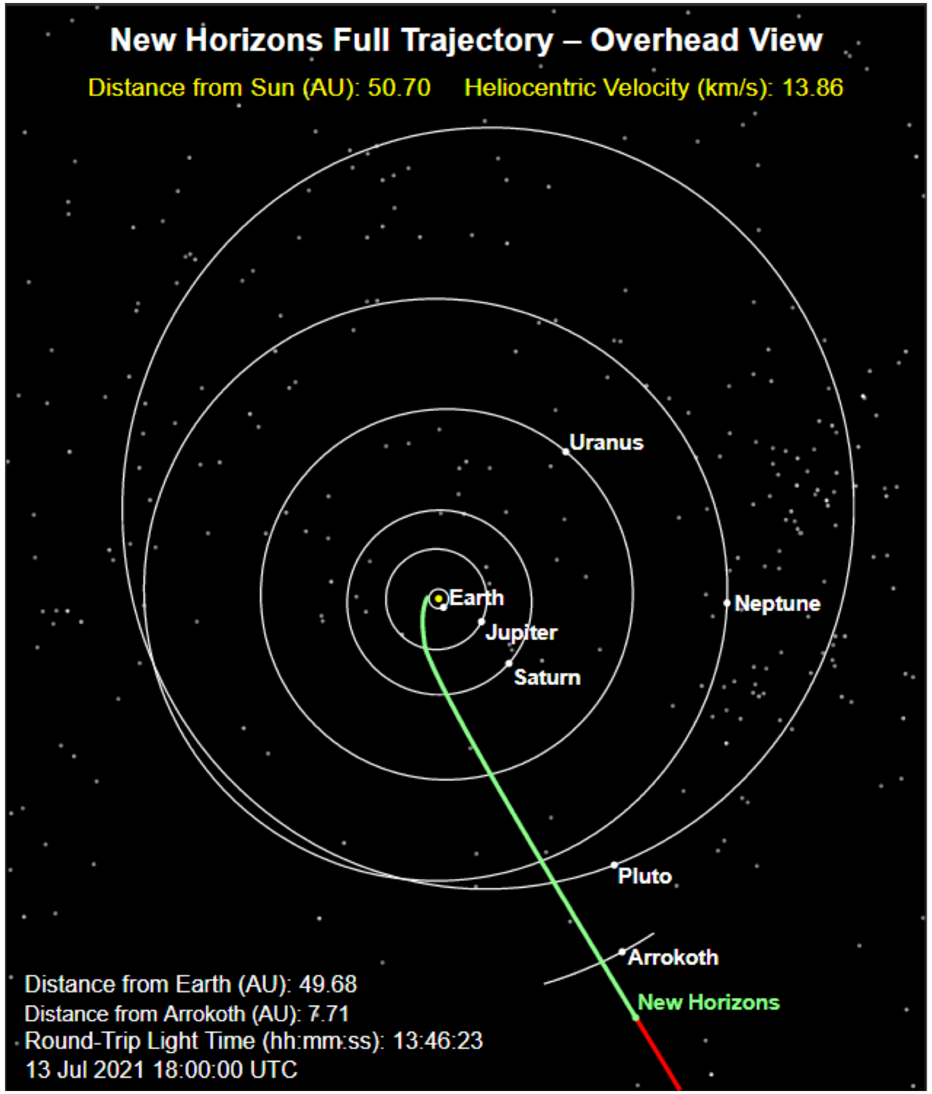




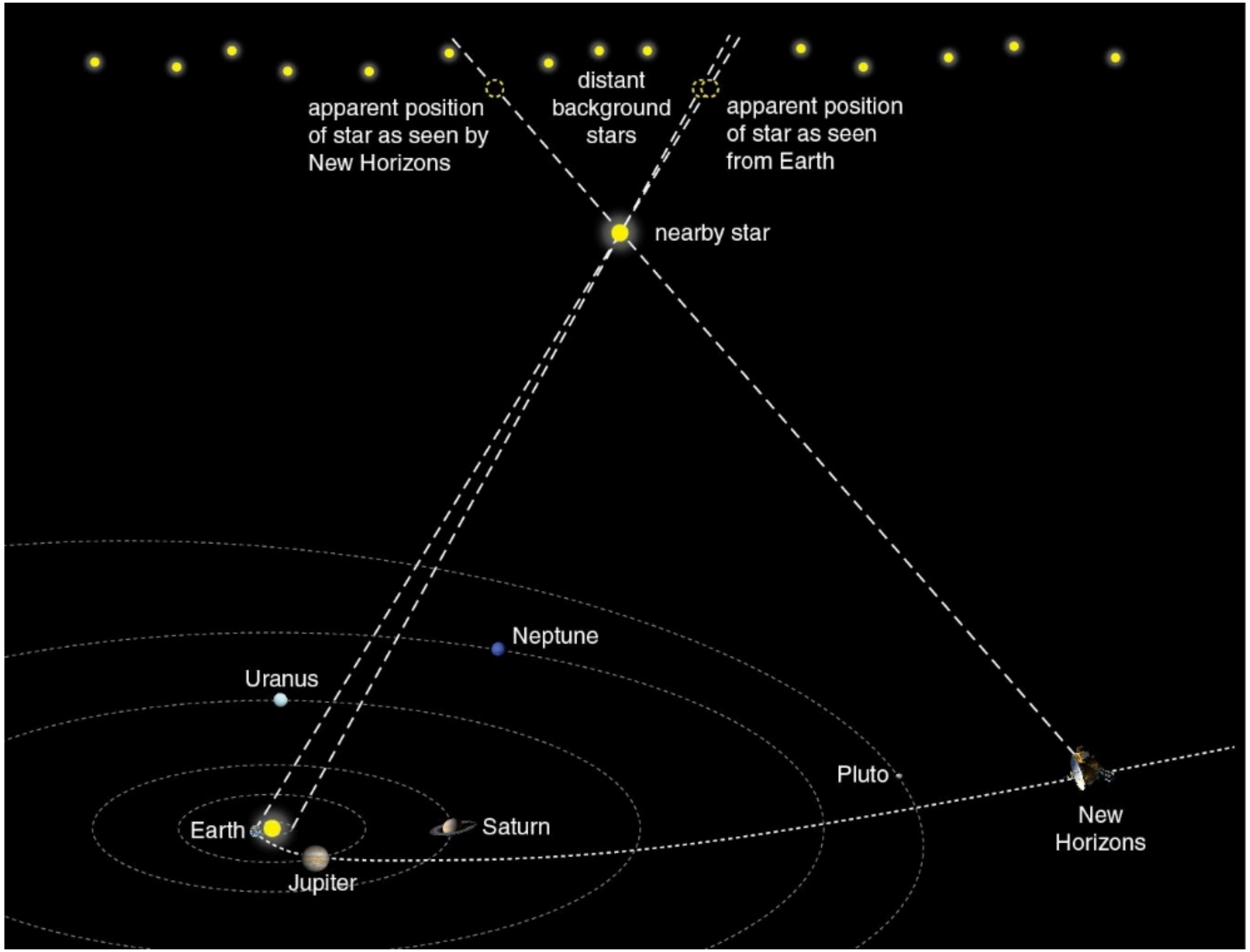
NASA images

New Horizons image of Arrokoth

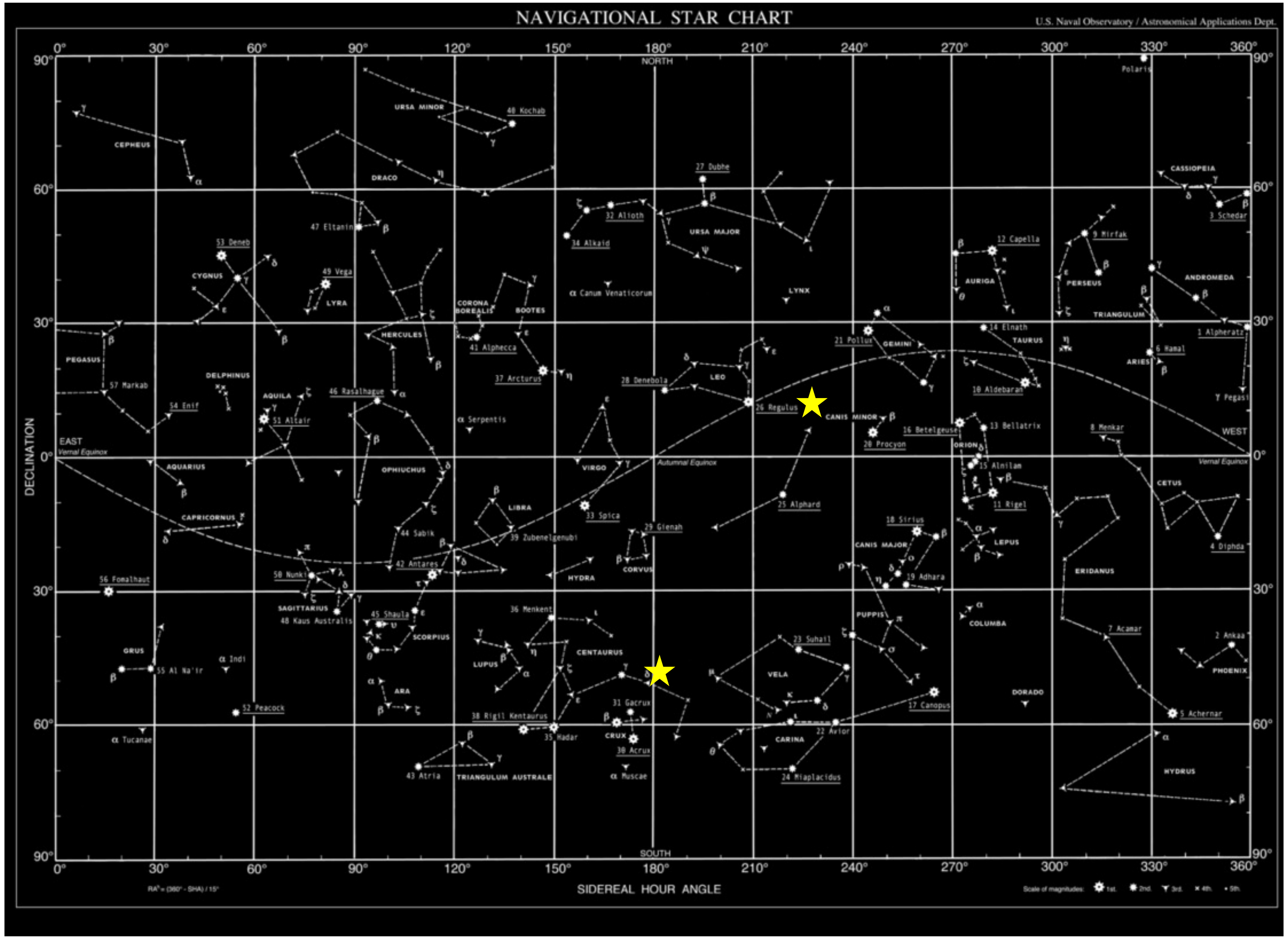
Finding New Horizons



Finding New Horizons



Positions of the two stars on the sky



Separation
RA 53.3 °
Dec 69.7 °
total 80.6 °

Wolf 359
V mag 13.5
Class M6
0.09 $M_{\odot}$

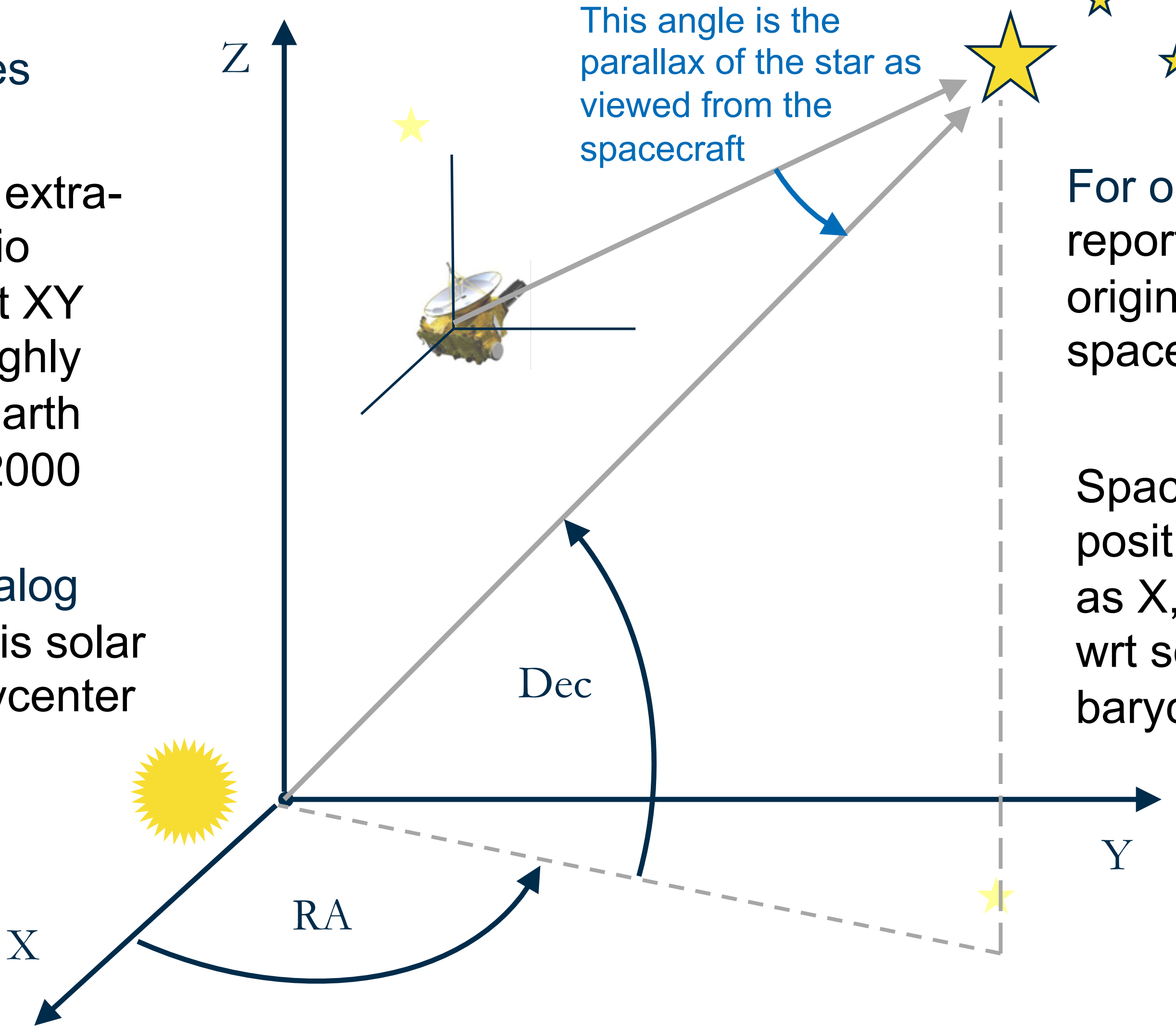
Proxima Cen
V mag 11.1
Class M5.5Ve
0.12 $M_{\odot}$

The fundamental coordinate system

ICRS axes

Defined wrt extra-galactic radio sources, but XY plane is roughly parallel to Earth equator of 2000

For star catalog data, origin is solar system barycenter



Background stars

For observations reported here, origin is at the spacecraft

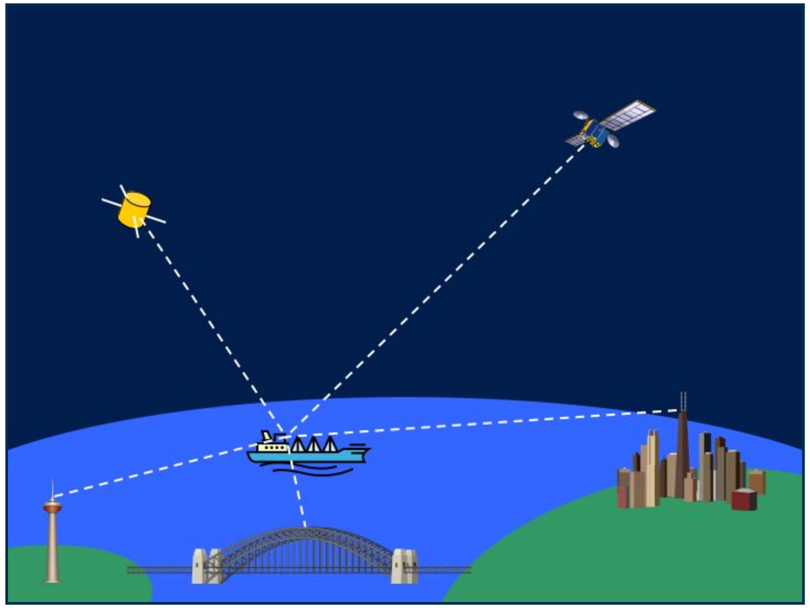
Spacecraft position is given as X,Y,Z (in au) wrt solar system barycenter

Finding 3D position by triangulation

Our algorithm Requires:

(1) Position coordinates of objects observed (assumes these objects can be identified); and

(2) Measurement of directions toward the objects, converted (if necessary) to the same coordinate system in which their position coordinates are expressed.



The result is a number of lines-of-position (LOPs) in 3D space that converge toward a point that represents the observer's position.

Algorithm characterization

Our algorithm is in the category of

Angles-Only Navigation AKA
Bearings-Only Navigation AKA
Image-Based Navigation AKA
Vision-Based Navigation

A variety of techniques whereby position, velocity, and/or attitude information for an observer is passively obtained from measurements of the apparent angles, or angular rates, of objects at finite distances

Contrast to

- Time-of-arrival (TOA) systems like GPS and LORAN (trilateration)
- Active range-measuring systems such as radar and sonar
- Inertial navigation systems
- Traditional celestial nav — stars assumed to be at “infinite” distance, requiring reference to local vertical (or horizon)

Observing near-against-far objects

There are *considerable* simplifications in both the observations and the analysis if we can restrict ourselves to observing <u>near objects relative to far objects</u>, if coordinates are known for both.

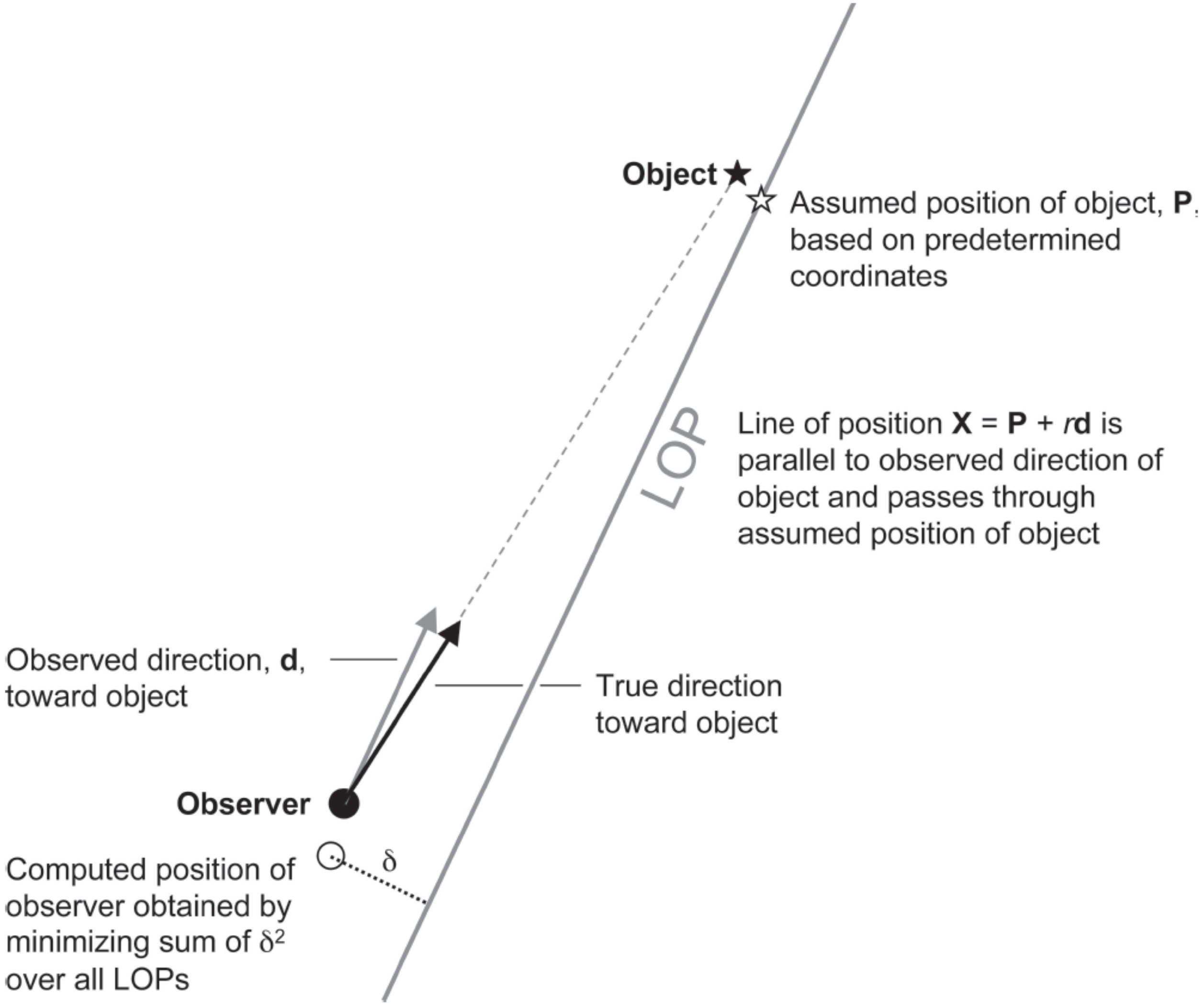
A simple closed-form solution is then available.

Buoy relative to bridge pier

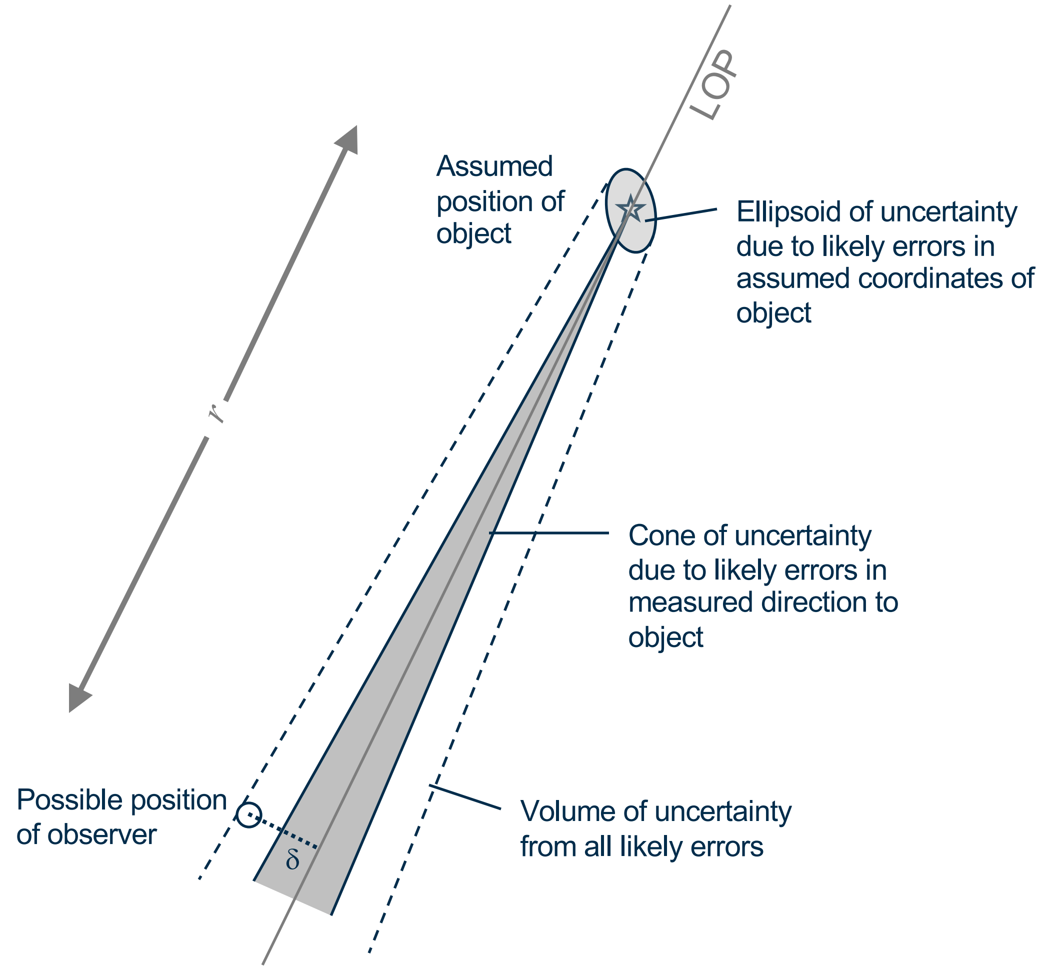
GPS satellite (SV51) relative to stars

“Nearby” star relative to more distant stars

Basic Geometry



Error propagation along LOP

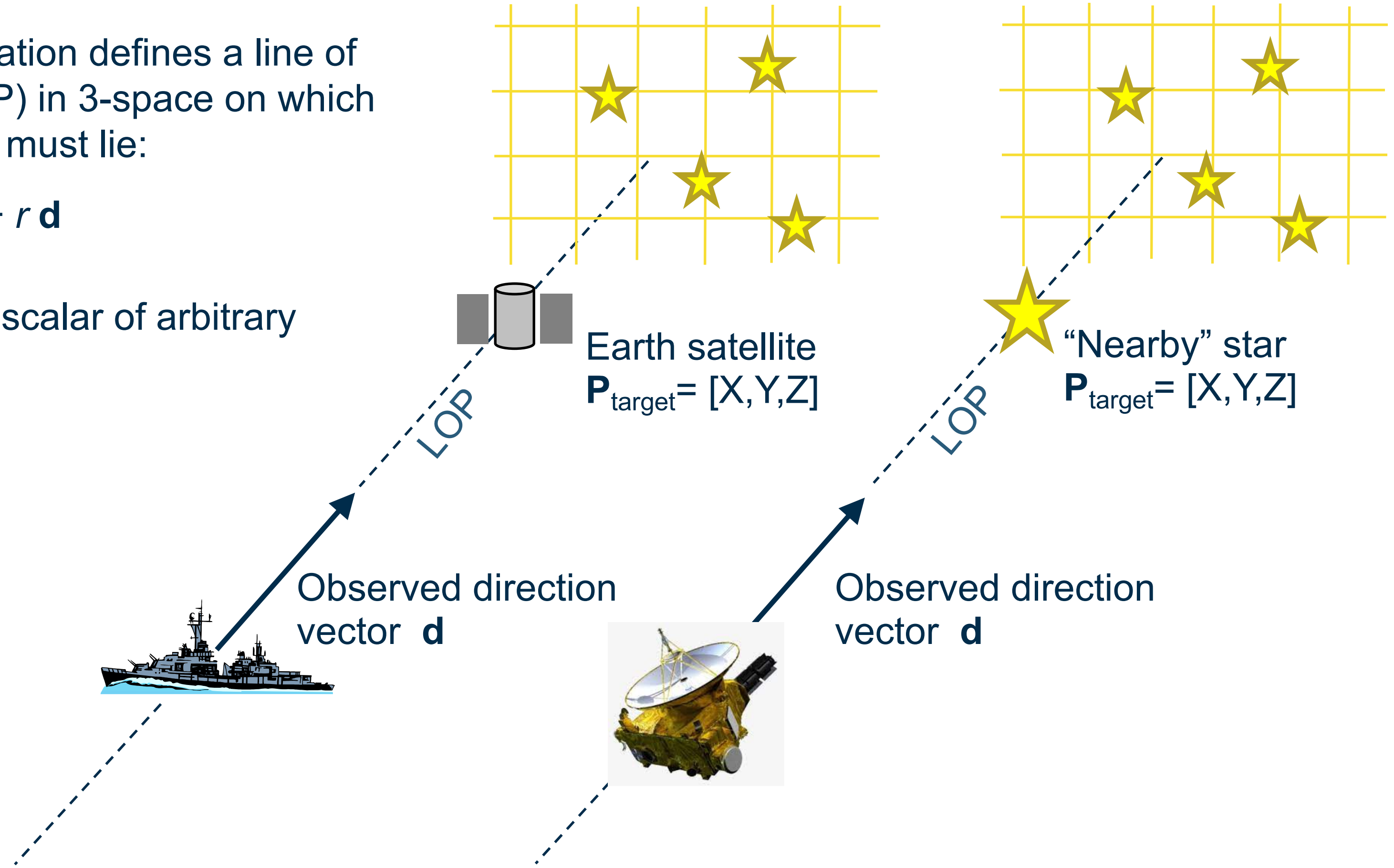


Observation Geometry

Each observation defines a line of position (LOP) in 3-space on which the observer must lie:

$\mathbf{X}_{obs} = \mathbf{P}_{target} + r\,\mathbf{d}$

where r is a scalar of arbitrary magnitude

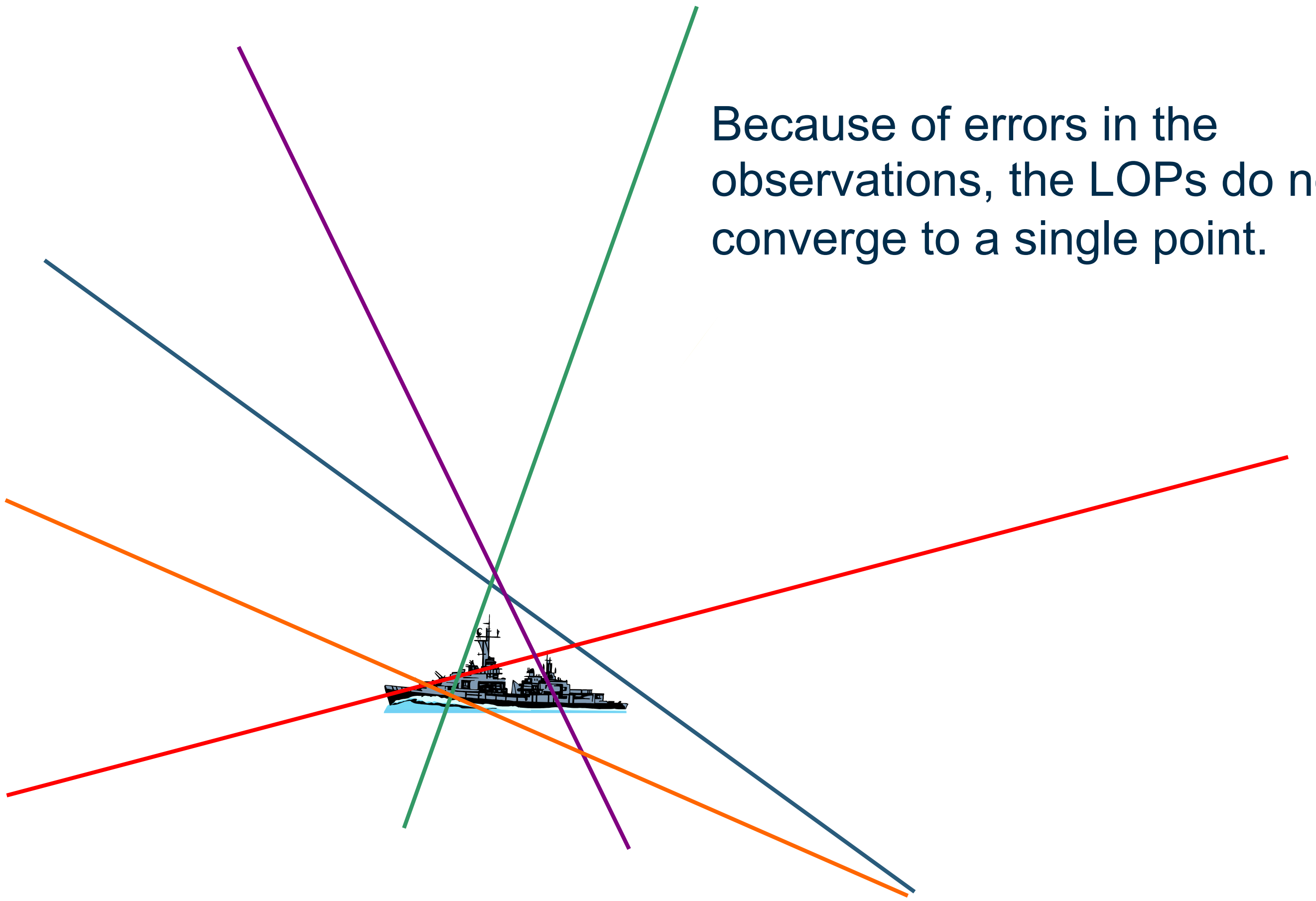


Form of solution for stationary observer

$$\begin{pmatrix} n-[{d_{i_1}}^2] & -[d_{i_1}d_{i_2}] & -[d_{i_1}d_{i_3}] \\ -[d_{i_1}d_{i_2}] & n-[{d_{i_2}}^2] & -[d_{i_2}d_{i_3}] \\ -[d_{i_1}d_{i_3}] & -[d_{i_2}d_{i_3}] & n-[{d_{i_3}}^2] \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} [P_{i_1} - (\mathbf{d}_i \cdot \mathbf{P}_i) d_{i_1}] \\ [P_{i_2} - (\mathbf{d}_i \cdot \mathbf{P}_i) d_{i_2}] \\ [P_{i_3} - (\mathbf{d}_i \cdot \mathbf{P}_i) d_{i_3}] \end{pmatrix}$$

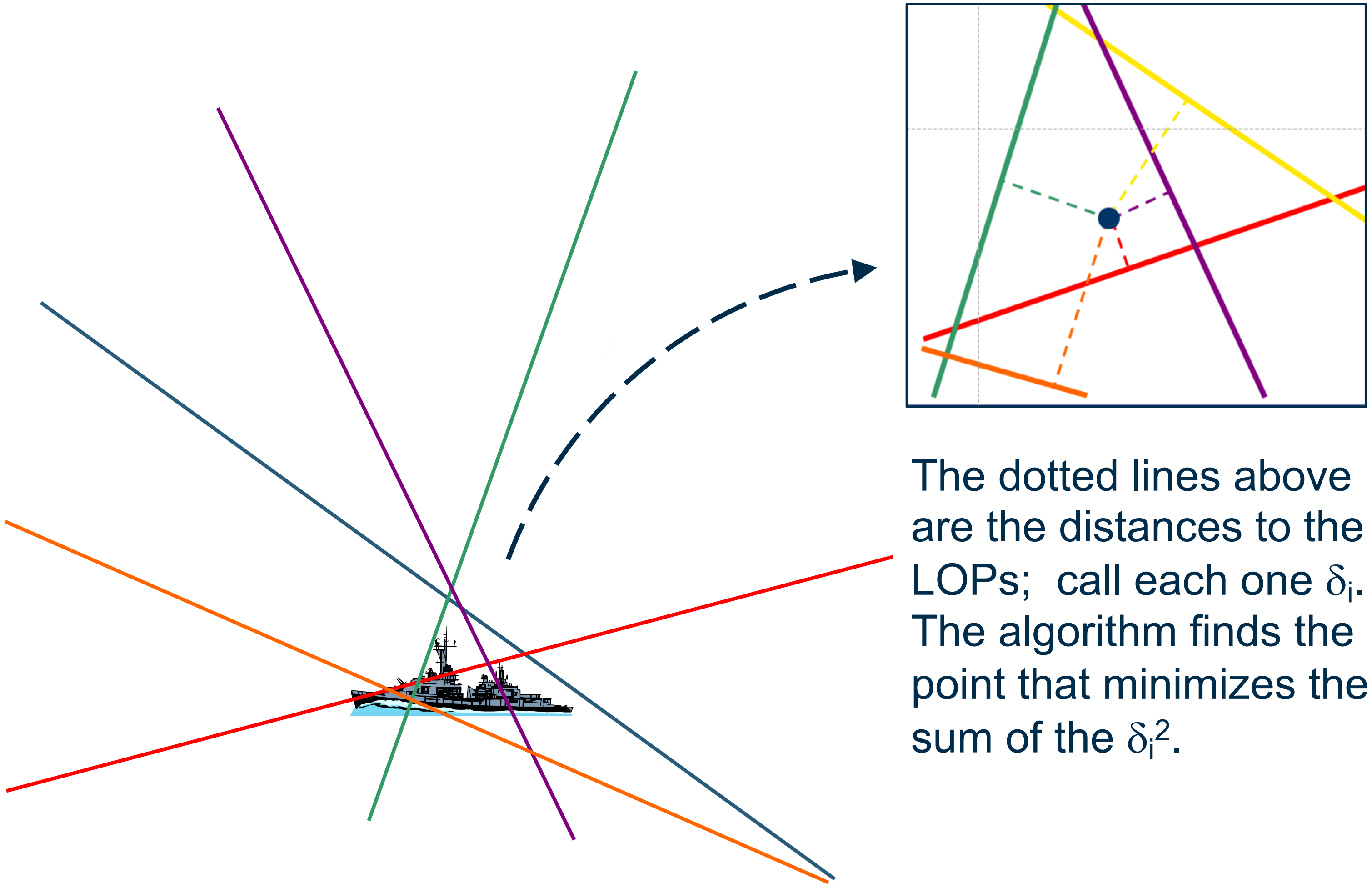
- (x_1, x_2, x_3) is position vector to be solved for
- Elements of 3×3 matrix on left and 3×1 matrix on right are sums of combinations of quantities from each observation
- Position vector will be expressed in same coordinate system as observation vectors and object coordinates
- Inverse of 3×3 matrix on left is unscaled covariance matrix of solution
- Inherently a “lost in space” algorithm — no initial guess of position is used
- Previously published by Bomford (1971), *Geodesy*

Stationary observer solution



Because of errors in the observations, the LOPs do not converge to a single point.

Stationary observer solution



The dotted lines above are the distances to the LOPs; call each one δ_i. The algorithm finds the point that minimizes the sum of the δ_i^2.

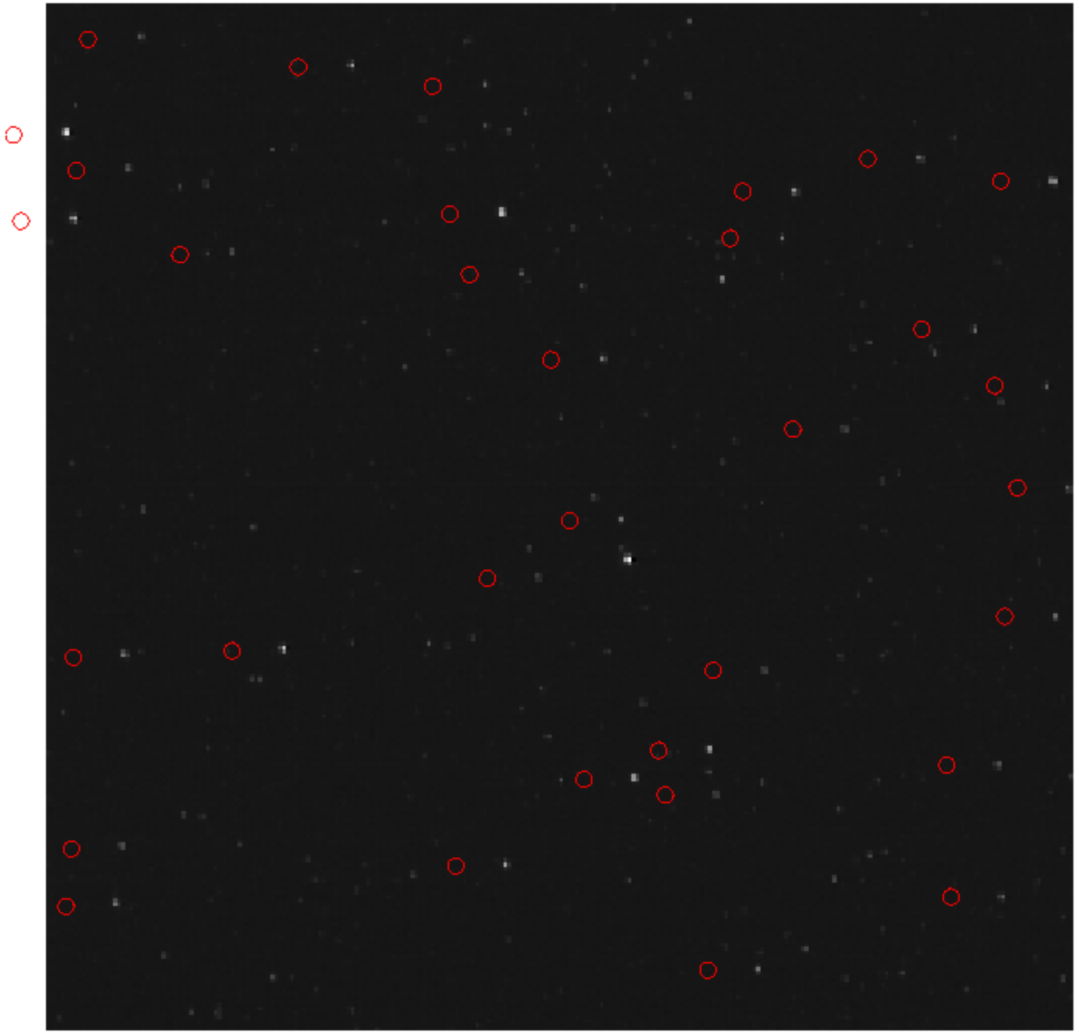
Algorithm available in other forms

- Position solution for moving observer at known velocity
- Velocity solution for moving observer at known position at one specific time
- Position and velocity solution for moving observer

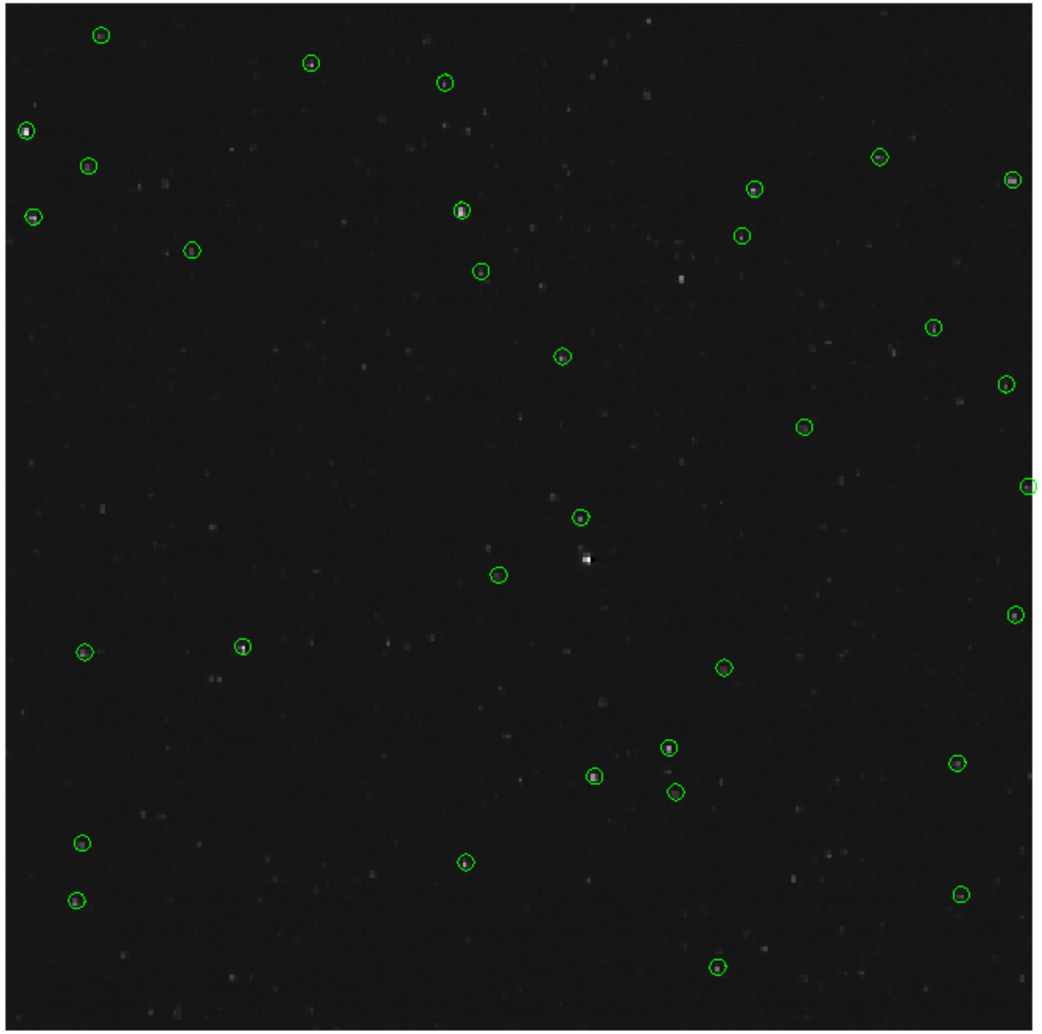
… assuming observations are suitably distributed in time

For an observing moving on or near the Earth’s surface, corrections for the curvature of the Earth can also be built in.

Bad Astrometry



Good Astrometry



WCS headers

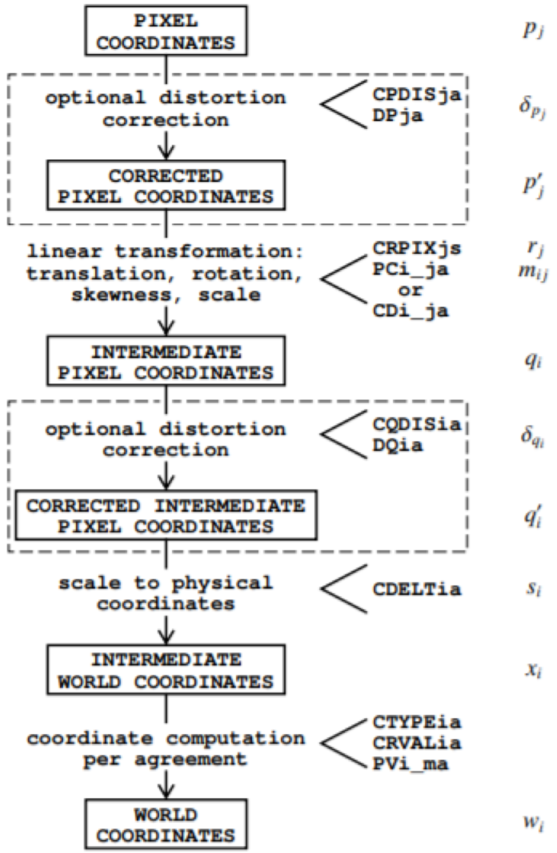


Fig. 1. Conversion of pixel coordinates to world coordinates showing optional distortion corrections enclosed in the dashed boxes. For later reference, the mathematical symbols associated with each step are shown in the box at right.

Algorithm

Fix WCS Headers

Extract P Cen and W359 positions from Gaia DR3

Propagate positions to time of observation

Convert RA, DE into position vector in units of AU

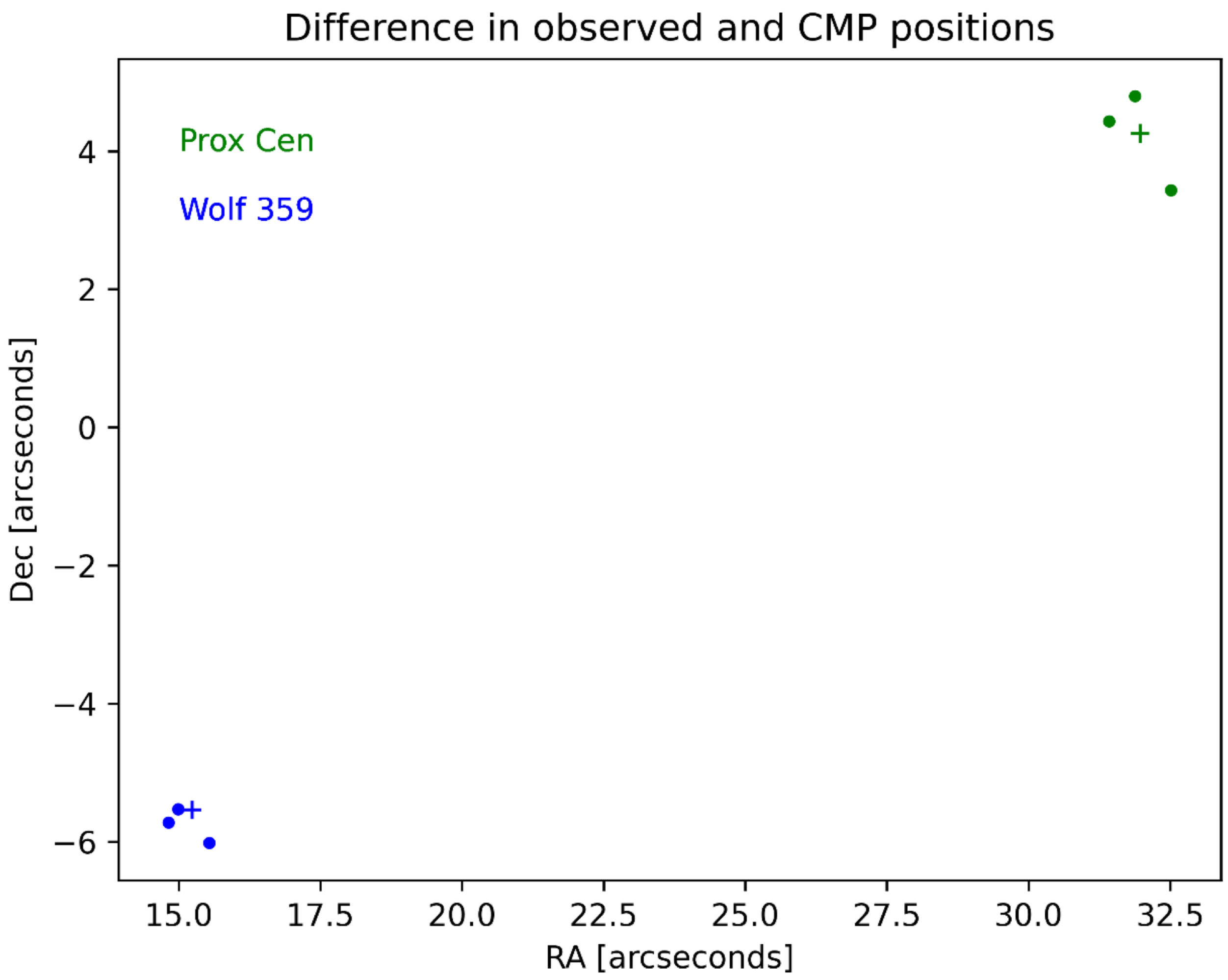
Use SourceExtractor to calculate x,y,ra,de,errors

For each of six frames, collect observed value (d) and calculated position (P)

Plug into algorithm. Rinse. Spin.

Compare calculated answer with JPL Horizons position (plot)

Data

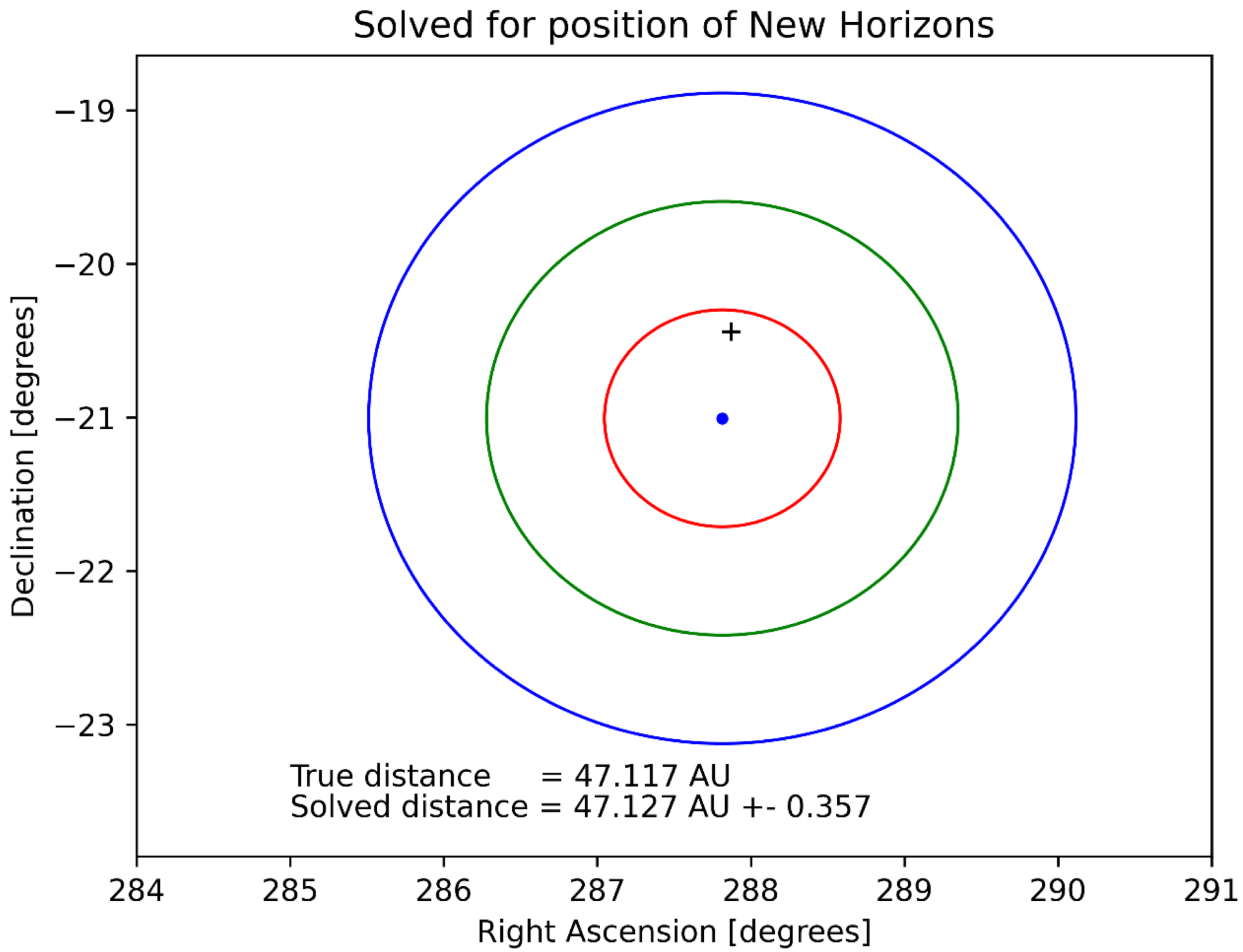

Difference in observed and CMP positions
Prox Cen
Wolf 359
4
2
0
−2
−4
−6
Dec [arcseconds]
15.0
17.5
20.0
22.5
25.0
27.5
30.0
32.5
RA [arcseconds]

Solved-for New Horizons Position

	X	Y	Z	dist
Calculated from obs	[13.459	-41.886	-16.893]	47.127
True from JPL tracking	[13.549	-42.018	-16.456]	47.117
Difference	[-0.090	0.132	-0.436]	-0.011
Calculated 1σ err	[0.462	0.332	0.418]	

Calculated RA/DEC/DIST	(287.8136, -21.0057, 47.127)
True RA/DEC/DIST	(287.8722, -20.4433, 47.117)
Error	(0.5890, 0.4983, 0.357)

Solved-for Position



Conclusions

- Modern star catalog data from the ESA Gaia mission provides an accurate 3-dimensional model of the stars in the solar neighborhood to support deep-space or interstellar navigation by spacecraft imaging of nearby stars
- Accuracy of nav solution is limited by centroiding accuracy of star images taken by spacecraft, not the star catalog data
- Relatively simple closed-form navigation algorithms are adequate for the problem
- In our experiment, centroiding 1σ accuracy of ~0.5 arcseconds gave a final positional accuracy of about 0.4 au ~6 x 10^7 km.
- While crude, this accuracy is sufficient to get from Sun to any nearby star!