SIM Space Interferometry Mission

Space Astrometry

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What is Astrometry and Why Go To Space?

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- Astrometry is the precise measurement of the positions (motions) of astrophysical objects. There are two kinds of astrometric measurements
  - Global astrometry, Position (motion) of an object in an inertial reference frame
  - Narrow angle astrometry, Relative position of an object wrt nearby reference stars
- What are the advantages of going to Space?
  - No atmosphere
    - Global astrometry limit (ground) ~ a few mas, (vs 4uas)
    - Narrow angle limitation (~20uas in 1hr) (vs 1 uas in ~10min)

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Scientific Objectives for Space Astrometry

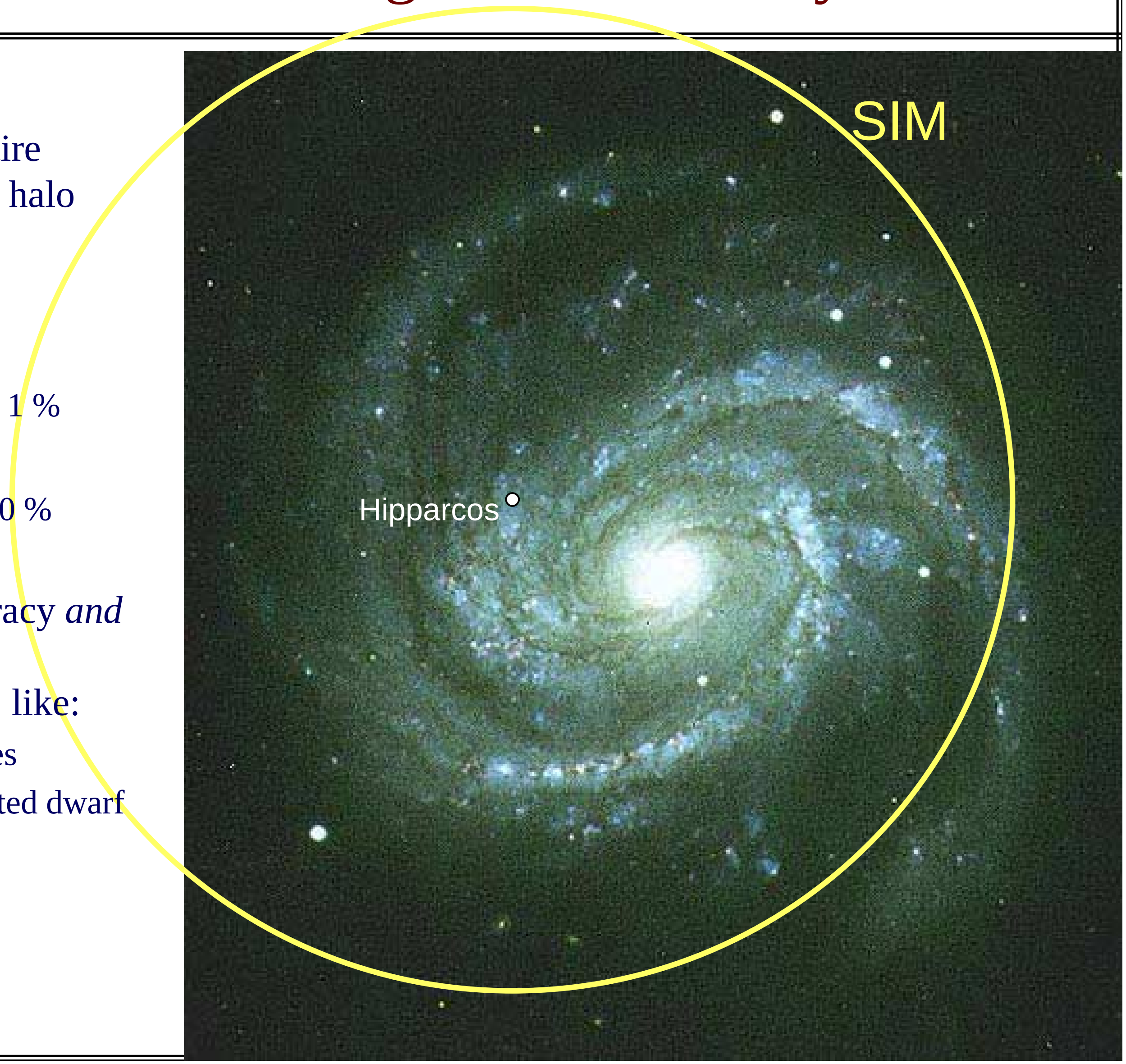
- Distances to objects
  - Standard candles (RR Lyrae, Cepheids)
  - Nearby galaxies
  - Globular Clusters
- Masses of objects
  - Measure binary/multiple object systems orbits
    - Mass luminosity for all spectral types
  - Measure gravitational lensing of background stars due to forground objects
- Discover planets orbiting nearby stars
  - Masses
  - Coplanarity

Accurate Distances Throughout the Galaxy

- SIM extends parallax distances over the entire Galaxy, including the halo

- Examples:
- G-dwarf at 3 kpc:
  - V = 17.5, accuracy 1 %
- KIII giant at 25 kpc:
  - V = 15, accuracy 10 %

- Combination of accuracy *and* sensitivity enables demanding programs, like:
  - rotational parallaxes
  - tidal tails of disrupted dwarf galaxies



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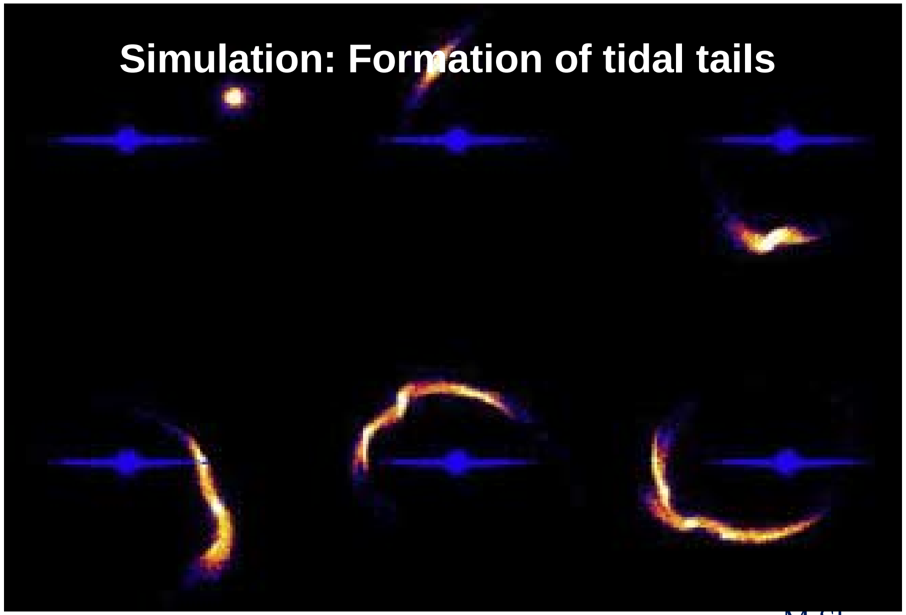
Mass of the Galaxy (Dark Halo)

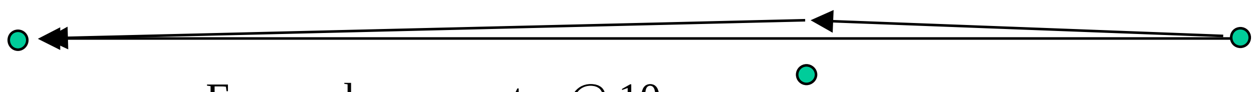
- Parallax and proper motion measurements give precise velocities in outer Galaxy
- SIM can determine mass vs. radius to *R* > 200 kpc via complementary methods:
  - **Jeans Equation**: ~1000 random field giants, Galactic globulars and satellite galaxies
  - Stars in **tidal streams** (e.g., Sagittarius): Milky Way potential from true 3-D orbits



Masses of Stars

- The combination of astrometry and radial velocity (of binaries) can measure the masses the components of binary systems.
- Mass of MACHO objects can be determined by a combination
  - Measure the astrometric Macho signature
  - Measure the Macho light curve from Earth and from a space observatory 0.5~ 1AU from the Earth.
- Masses of single stars (with high proper motion) can be made by looking at the change in astrometric microlensing signature.

A forground star seems to “push” a
Background star away as it moves
In between the background star and
Observer



For a solar mass star @ 10pc
The deflection is ~ 2arcsec @ 0.5mas impact parameter.
~200uas deflection @ 5 arcsec

Astrometric Planet Detection
What's Measured?

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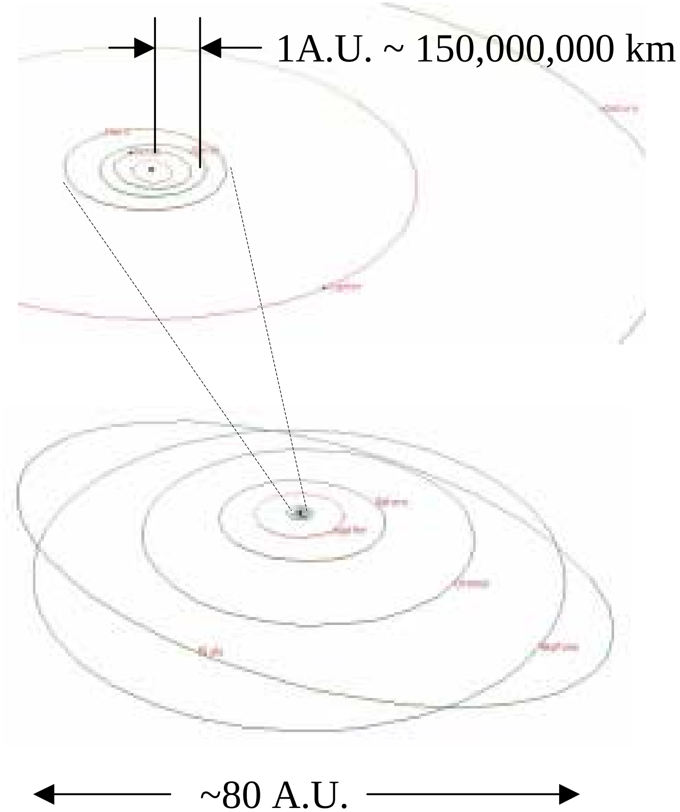

Astrometry can measure all of the orbital parameters of all planets.

Orbit parameter	Planet Property
Mass	atmosphere?
Semimajor axis	temperature
Eccentricity	variation of temp
Orbit Inclination	Coplanar planets?
Period	

All planets have an astrometric signature =>
An absence of a signal means absense of Planet

Basic mission is 5 years, with an additional 5 year extended mission, which will help characterize planets with longer periods.

Sun's reflex motion (Jupiter) ~500 μas
Sun's motion from the Earth ~0.3 μas

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Astrometric Planet Detection

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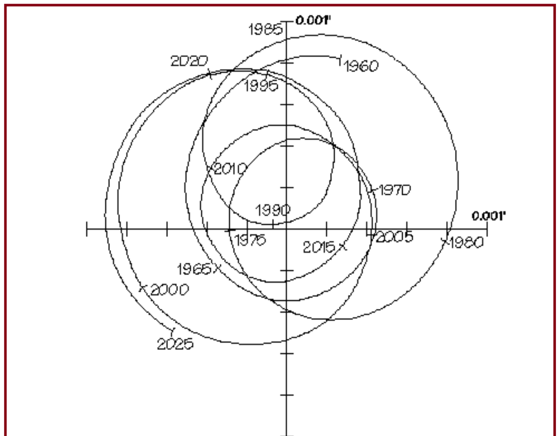

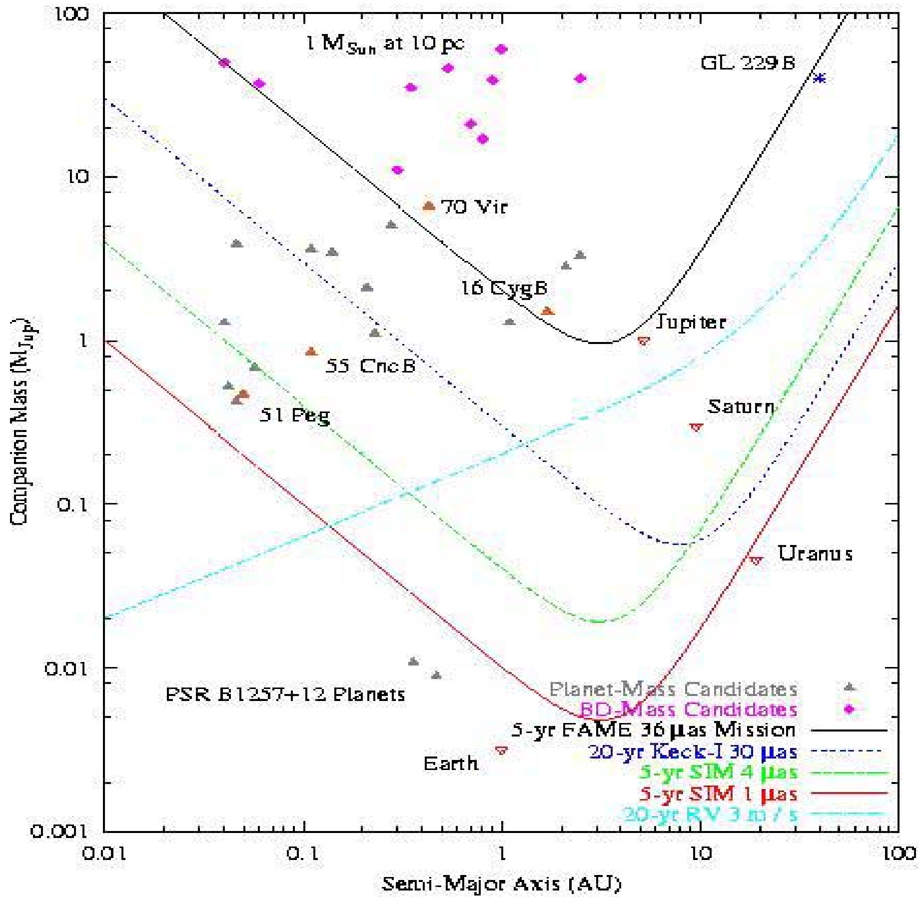

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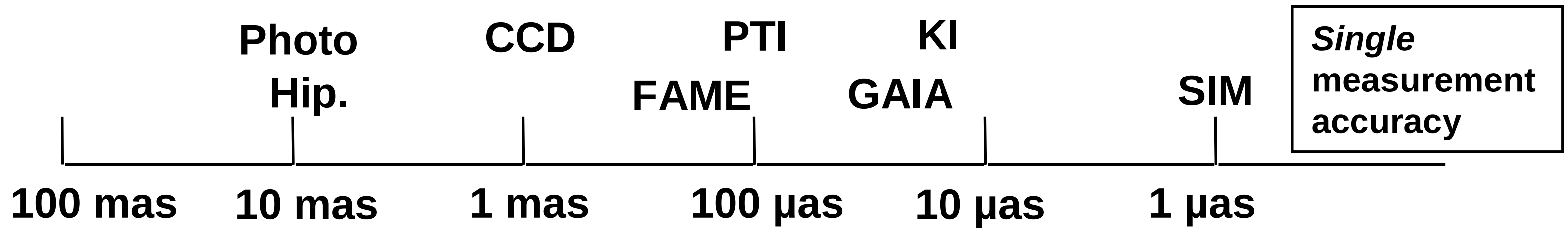
Detection Limits

SIM: 1 µas over 5 years (mission lifetime)

Keck Interferometer: 20 µas over 10 years

Planet Detection Comparison



- FAME and GAIA are scanners - no control over observations
- SIM is a pointed spacecraft - optimize for planet detection
- SIM is much more sensitive than other planned future astrometry missions
- Accuracy comparison:
  - Hipparcos mission accuracy: 1 mas
  - FAME mission accuracy: 36 μas
  - GAIA mission accuracy: 4 μas
  - SIM equivalent mission accuracy: 0.2 μas
    - In a local reference frame, after 50 measurements

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SIM Planet Science

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- The SIM planet science program has 3 components.
- One is a search of ~250 nearby stars for terrestrial planets, in its **Deep Search** at (1 μas). (1 Earth mass @ 3pc, 3Earth Mass @ 10pc, 1AU orbit)
  - **SIM will characterize targets for Terrestrial Planet Finder**
- The second is a search of ~ 2000 stars in a **Broad Survey** at lower but still extremely high accuracy (4 μas) to study planetary systems throughout this part of the galaxy.
  - **If planets are found via other means (direct imaging in visible or IR using TPF), SIM can determine masses a factor of ~3 smaller than survey mode limit since orbital parameters are known**
- Achieves the goal of studying the birth of planetary systems around **Young Stars** so we can understand how planetary systems evolve.
  - Do multiple Jupiters form and only a few or none survive during the birth of a star/planetary system?
  - Is orbital migration caused primarily by Planet-Planet interaction or by Disk-planet interaction?
  - **Suitable information for young stars cannot be obtained from radial velocity studies due to effects of rotation and stellar active** (starspots limit survey to Jupiter masses)

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What does a stellar interferometer measure?

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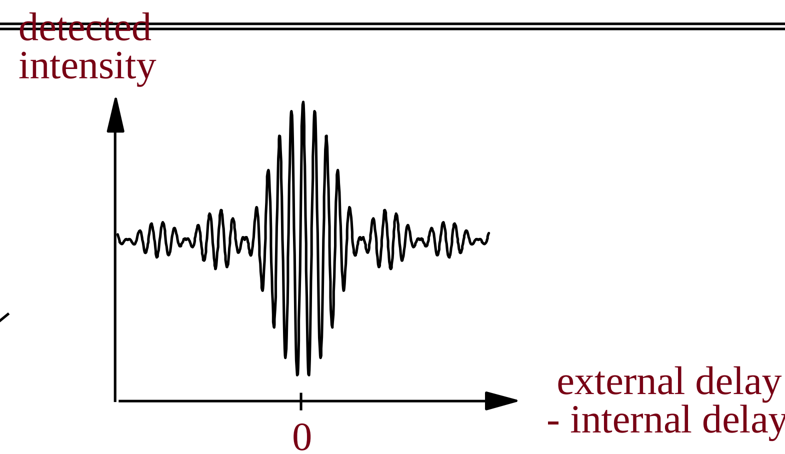

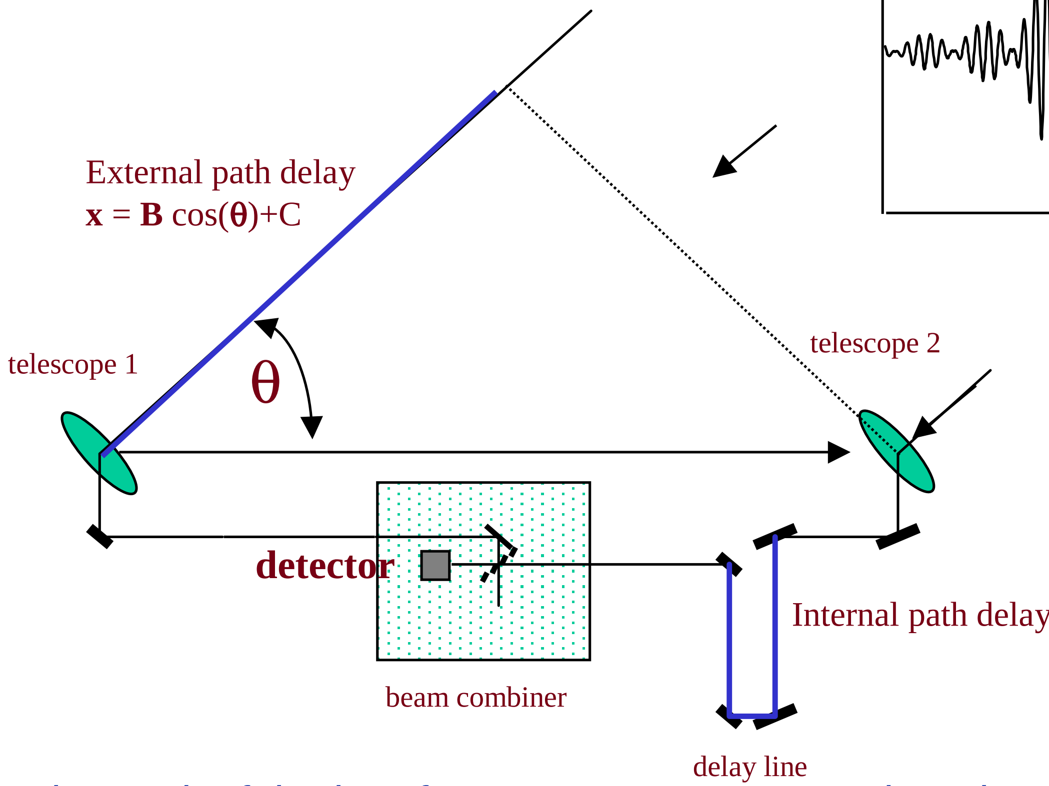

An interferometer measures the dot product of the baseline vector and a unit vector to the star.

Or, the project of the star vector in the direction of the baseline

The peak of the interference pattern occurs when the internal path delay equals the external path delay

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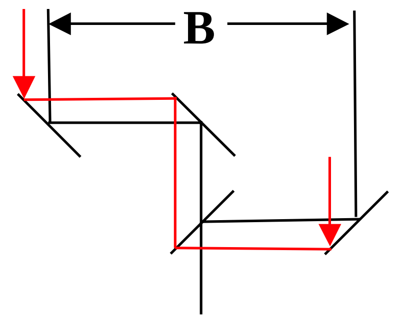
What's Measured

- Delay = S*B + c +/- 1~4 uas error
  - 1uas (10m baseline) = 50pm (picometers)
  - S is a unit vector to the Star
  - **B** is the baseline vector
- Ground vs Space
  - A ground based interferometer's baseline can be as stable as the rotation of the Earth. (after modeling solid earth tides etc.)
  - In space there is no large mass to anchor the baseline to. As a result we need to fix the baseline using "guide" interferometers.
    - Can't fix the baseline using "strap on star trackers" ~ 1arcsec
    - Can't fix the baseline using "gyroes" 1arcsec/hr (HST)
- From wide angle (relative) measurements to coordinates in an inertial reference frame
  - A grid of stars to cover the sky
  - Tie to QSO (or dynamical ref frame)

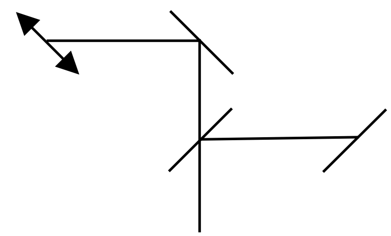
Instrument Definitions

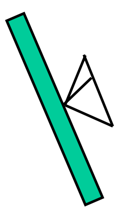
- Optical paths have to be measured to 50pm
- When we measure an optical path length, we measure from x, to y, what is x and y? (that are defined with a precision of < 50pm)
  - In VLBI the baseline is the vector joining two telescopes
    - In space interferometry the telescopes are ~35cm in diameter, what part of the telescope defines the end point of the baseline?
- Optical fiducials (with pointline characteristics) define the baseline, not optical surfaces, or mechanical structures.
  - In VLBI the end point of a baseline is the intersection of the antenna's az and el axes. (This type of mechanical definition fails at the um level.)
  - In SIM (and also Keck) the vertex of a retro reflector defines the baseline end point.
    - Show that this definition obeys the basic astrometric equation
    - Model imperfections in the retroreflector

Astrometric vs Imaging Baseline



- Imaging baseline is the lateral shear of the combined beams. The imaging baseline is related to the measurement of spatial coherence of the source.
- An astrometric baseline satisfies the equation Delay = S*B+c. We define an astrometric baseline as the vector joining the vertices of Cube corners, at the center of siderostats
  - Note that translation of a siderostat along its surface will change the baseline vector (for astrometry) but not for imaging.





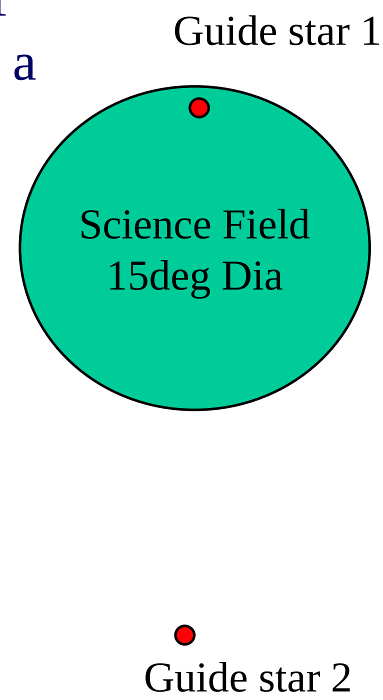
For a space interferometer like SIM, the imaging baseline
And the astrometric baseline are identical to ~6 decimal places,
The astrometric baseline is defined to ~ 11 decimal places.

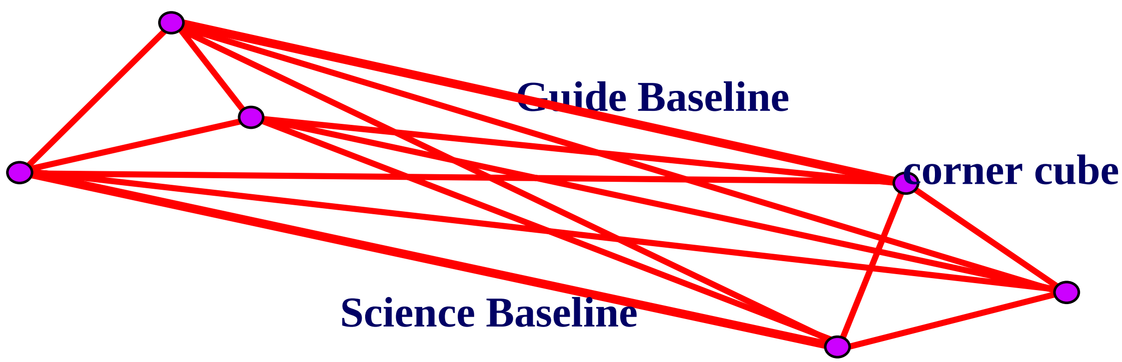
What needs to be measured?

- For accurate astrometry several quantities need to be measured very precisely.
  - The optical delay of the starlight (or the change in optical delay as we switch from star to star)
  - The motion of the baseline vector end points, as the spacecraft floats in space.
    - A solid body has 3 rotational degrees of freedom. In SIM where the science baseline and guide baselines are colinear, two of those rotations have to be know (wrt an inertial ref frame) at the uas level.
    - The two rotational degrees of freedom are measured with 2 "guide" interferometers.
    - The guide interferometers are tied to the science interferometer with a laser interferometer optical truss.

Guide Interferometers

- Science and Guide interferometers nominally parallel
- Two guide interferometers measure the spacecraft attitude at the microarcsec level.
- As the spacecraft drifts, (~ 1arcsec) the knowledge of baseline motion is used in data analysis to synthesize a regularized baseline that is stable at the uas





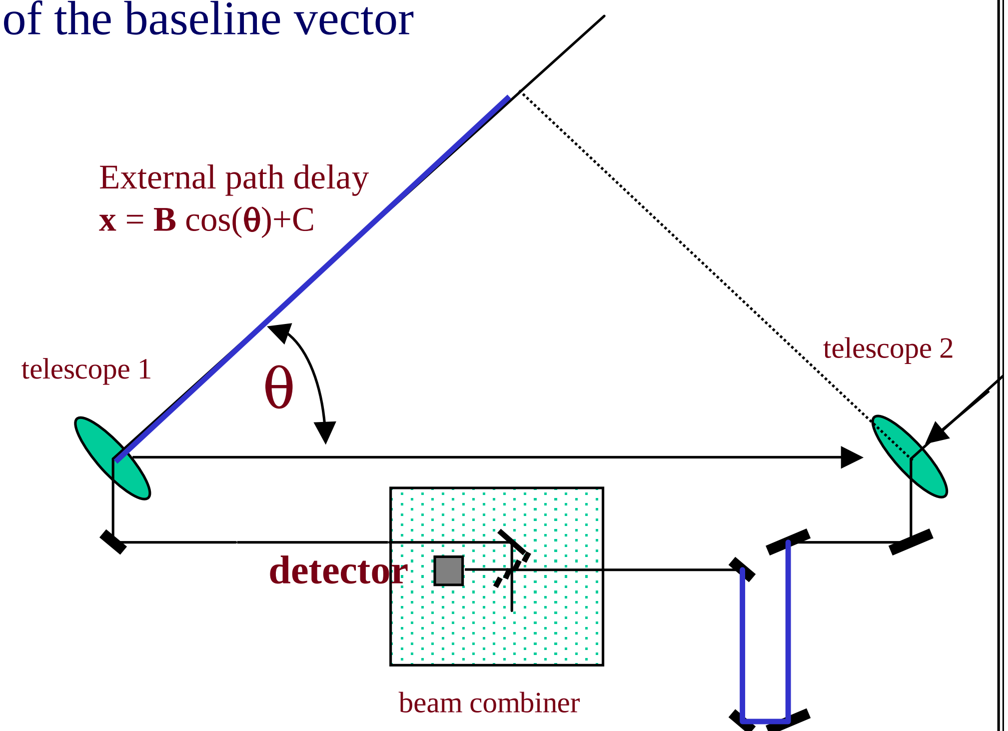
Measuring the Optical Delay of Starlight

- The delayline is moved so that we see the central fringe at the combiner. What's involved in measuring the starlight optical delay at the 10's of picometer level?
  - Measuring the white light fringe position
  - Measuring the position of the delay line
  - Measuring the end points of the baseline vector

Each of the three measurements can be quite difficult (at the 10's pm level)

Each of the three measurements can have significant systematic errors, that need to be calibrated and removed in data analysis

Even with nothing moving (intentionally) stability of a 10m interferometer at the 5 parts per trillion is challenging.



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Example of some types of systematic errors

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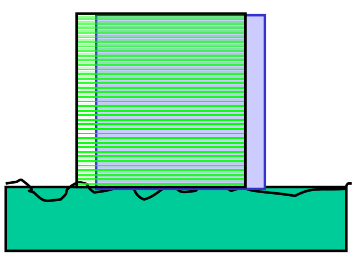
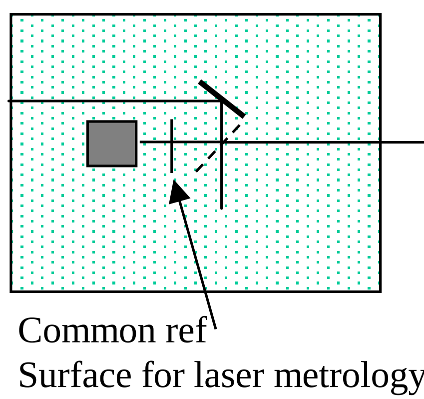
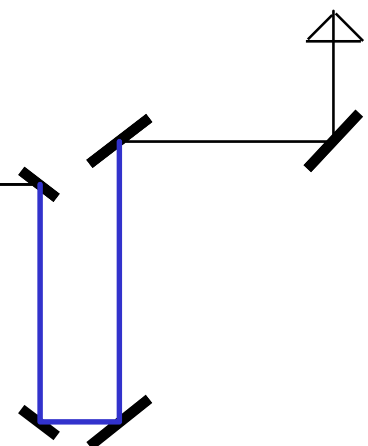
- Imperfect optics
  - A precise optical surface is accurate to λ/100, ~6nm. At the levels (50pm) we care about, a flat mirror (λ/100) is anything but flat.
  - We can make differential optical delay measurements between stars, only if the stellar footprint on the optic doesn't change (~ 1%).
  - Similarly the metrology footprint can't change.
  - In theory (with perfect alignment) the only optical footprints that "have" to change are the articulating optics. (siderostat/corner cube)







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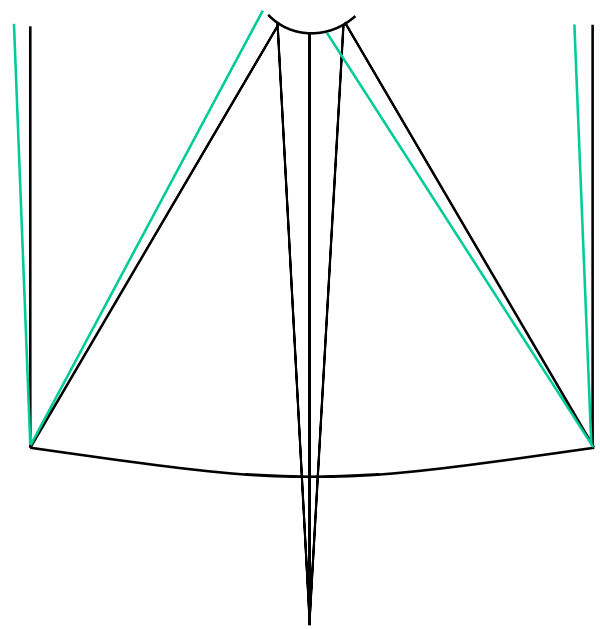
Examples of the same effect in an astrometric telescope

- In a conventional telescope, an offaxis star will sample different parts of the optical train. Imperfections in the optical figure must be calibrated to ~λ/10,000 for ~1uas astrometry.
- This is particularly difficult for wide angle astrometry.



Unavoidable Footprint changes in an astrometric interferometer

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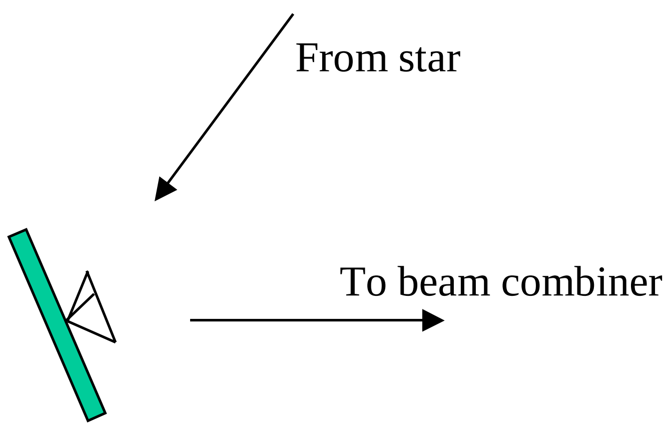
- Optics that undergo large angular motion produce the largest systematic biases (due to imperfect optics) in an astrometric interferometer
- Siderostats, and attached Corner cube (baseline fiducial)

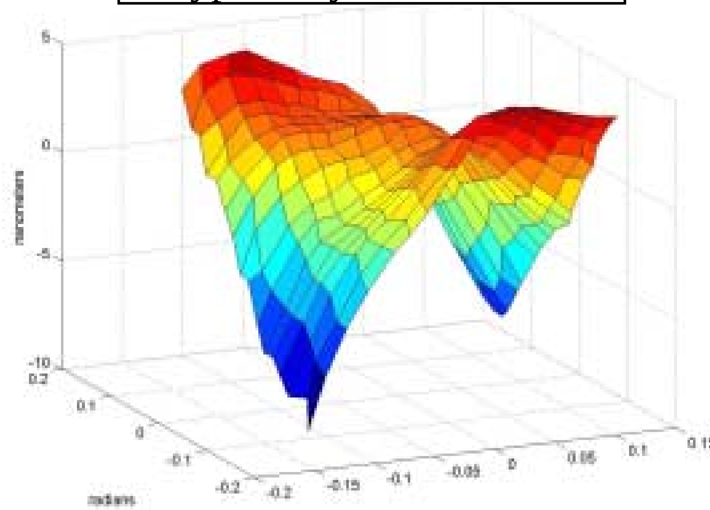
Important effects

CC-Mirror offset
Siderostat stellar footprint
Polarization effects in CC
CC dihedral errors
Wavefront errors in CC



15 deg astrometric field
=> ~7.5 deg mirror rotation

Typical Systematic Bias



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From Delay Measurements to RA/DEC

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- Delay = S*B + c - calibration(θ,φ)
- The conversion of delays into stellar positions are slightly different for global astrometry and narrow field astrometry
- Narrow angle astrometry observations and data reduction is based on the existance of a “grid” of stars whose global positions are known, at lower (but still single digit uas) level of accuracy.
- Global astrometry is primarily a very large least squares fit.
  - Choose a “grid” of well behaved stars in a regular patter that covers the sky.
  - Make “relative measurements of this grid in a series of overlaping “tiles”
  - Repeat several times/yr over a period of >3 yrs (5 for SIM) so that proper motion and parallax have roughly orthogonal astrometric signatures.
  - Put the data into a large least squares fit.

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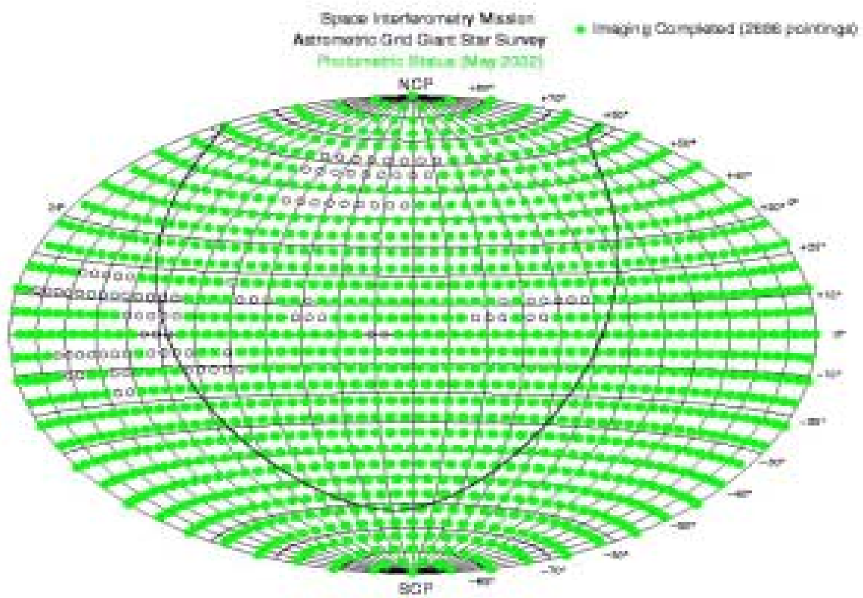
What is the Grid?

- A regularly spaced set of ~12 mag stars that cover the whole sky, along with 25~50 QSO's that form a reference frame for SIM global and narrow angle obs



- Grid stars: Moderately bright (12 mag) ~1300 stars in a regular grid pattern
  - K giants were chosen because they are intrinsically bright, hence distant, 1~2 Kpc

Relative Observations in Overlapping Tiles

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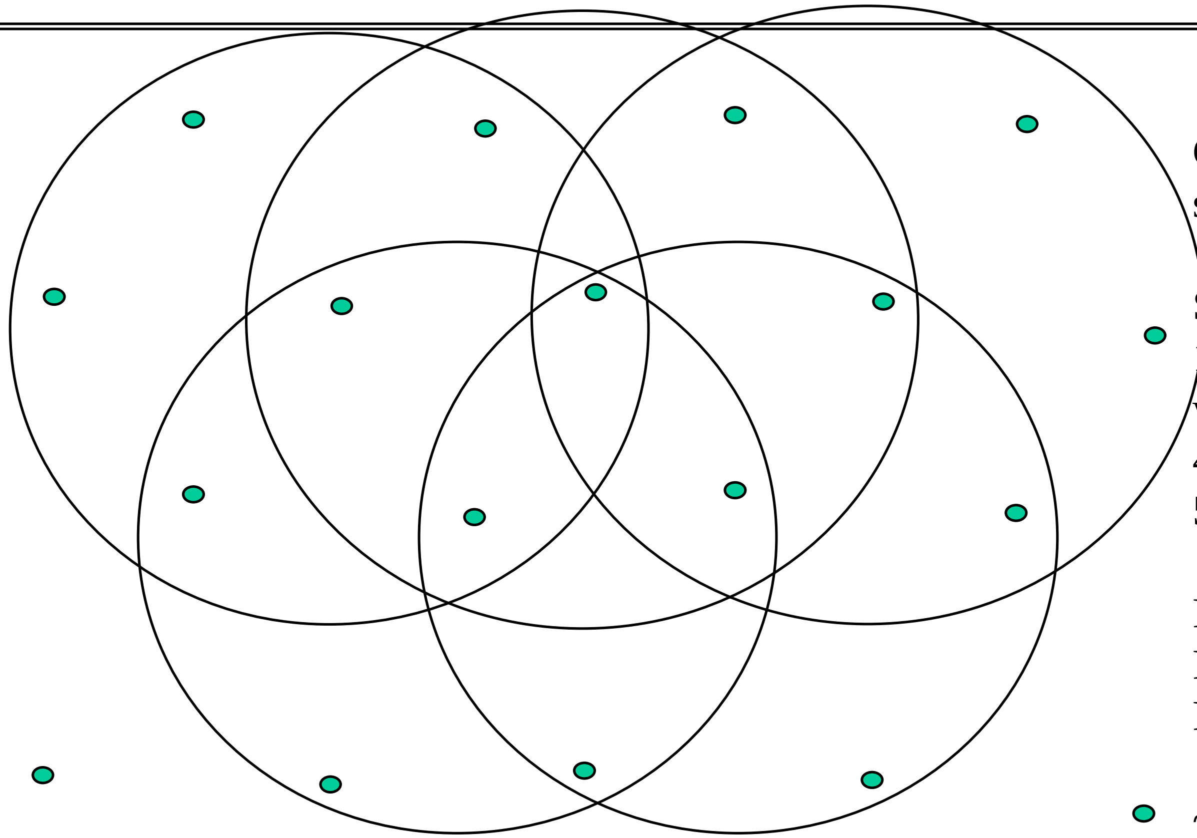

Grid Least sq solution

Start with individual 1D measurements with ~ 12 uas err
4.5orange peels/yr
5 yrs

Positions ~ 2.5 uas
Proper mot ~1 uas/yr
Parallax ~ 2.5uas

~1300 stars in the grid

Each grid star position(2), proper motion(2), parallax (1)
Each tile baseline orientation (2)
Per orange peel baseline length(1)
~25 QSO sprinkled through the grid of stars.
Cover the whole sky except for sun exclusion (~45 deg)

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Well Behaved Grid Stars

- Well behaved stars are ones whose motion can be modeled to <3uas with just proper motion and parallax.
  - K giants are ideal candidates, intrinsically bright
  - At 12 mag they are 1~2 Kpc distant
  - Progenitors are G stars, whose planetary companion statistics are known
  - Stellar mass companions can be eliminated by Radial velocity surveys
  - Very short period (jovian mass) planets have as astrometric signature << 3 uas. Very long period (jovian mass) companions have only “linear” motion. Only a small fraction of the most massive planets will present non-linear motion > 3uas because these stars are 1~2Kpc away.

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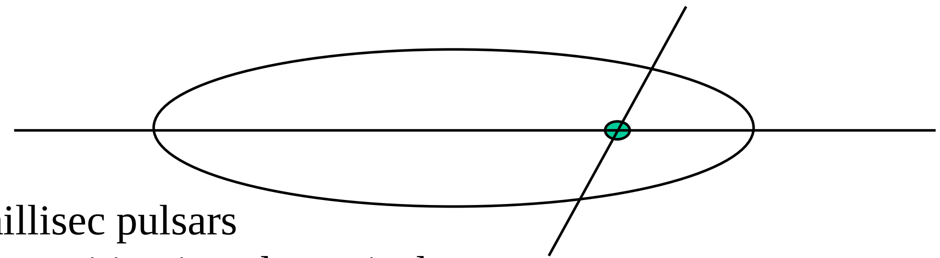
Defining an inertial reference frame

- There are two (or more) approaches to defining an inertial reference frame
  - One is based on using a collection of QSO's and argueing their net rotation is zero. (Inertial ref frame is defined by the matter in the universe.)
  - The other is a "dynamical reference frame" defined by two bodies orbiting each other. The plane of the orbit and the line along the semimajor axis of the elipse define a coord frame.

Our solar system defines a dynamical reference frame



Timing measurements of millisec pulsars can be used to measure their position in a dynamical reference frame at the uas level.

That can be compared to a ref frame define by QSO's.

Narrow Angle Astrometry

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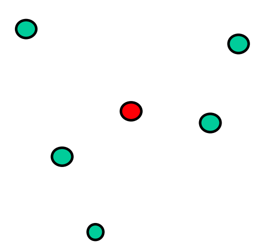
- Space based narrow angle astrometry with interferometers at 1uas is slightly different than astrometry at the 100uas to 1000mas level with single telescopes (Palomar, Alleghany, HST etc.)
- In single telescope astrometry, an imaging detector can measure the positions of all the objects simultaneously. An interferometer however must observe the reference and target objects sequentially.



In a telescope the field of view is set by the size of the detector array (or distortion in the optics).
In general none of the ref stars are in a precise (at the mas or uas) catalog.
The ref stars define the ref frame (center of the frame, the plate scale, (x,y), the orientation of the frame)
Motions of the ref stars can give rise to apparent non-linear motion of the target, even if the ref stars and the target are only moving in straight lines.

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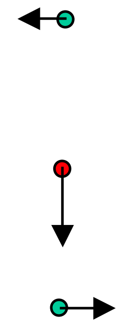
False Non-linear motion

- With a small number of reference stars, the ensemble of stars, if they all are moving in a straight line, will have some net rotation.
- That results in a ref frame that is rotating, which combined with a large proper motion of the target gives rise to a coreolis type effect, a false curved motion of the target.
- This is not an issue for astrometry at the 100uas level but is very serious for 1uas astrometry



Ref star, 1mas/yr
Target star ~0.5 arcsec/yr
Field ~ 10 arcmin
Frame rot ~0.3arcsec/yr

false curved motion
> 10uas in 5yrs

The solution is to use a "local" reference frame that rotates a lot less than 0.1 arcsec/yr

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Reference Frames, uas Narrow Angle Ast

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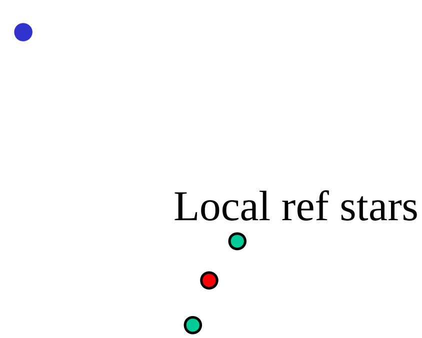
The rotation of the ref frame is not a problem if we’re looking for a planetary signature with a period << the mission duration.

The false curve motion caused by a rotating local ref frame is a problem for planetary orbits comparable to the mission length. (where the false curved motion can produce large errors in the derived orbit parameters.)



- Grid stars with proper motions known to 1uas/yr (rather than 1mas/yr)

- Grid stars 6~7 deg away define the orientation and scale of the ref frame
  Local ref stars are used to define only the zero point of the ref frame.
  Linear motion of the local ref stars only result in linear motion of the frame zero point.
  Rotation of the frame is controlled by the extremely accurate proper motion of the grid stars, and the larger field (15 deg vs 10arcmin)

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Summary

- Space Astrometric Interferometer
  - Directly measures delay = S*B +c + noise (uas)
  - The delay has biases (50~100 uas in wide angle and 3~5 uas in narrow angle) that have to be calibrate and removed in data analysis
  - Some of the biases can be calibrated on the ground
  - Some biases vary with time and need to be calibrated on orbit
  - Measurements over ~15 deg, of ~1500 grid stars with 25~50 QSO's with overlapping tiles, are used in a large least squares fit to solve for global positions with 3~4 uas positional accuracy, uas/yr proper motion and 3~4uas parallaxes.
  - The grid stars provide a non-rotating reference frame for narrow angle astrometry at the 1 uas level.
  - The zero point of the narrow angle frame is set by nearby "reference" stars. Nearby so that instrumental biases are small and accurately calibrated.