Accuracy of Space Astrometry

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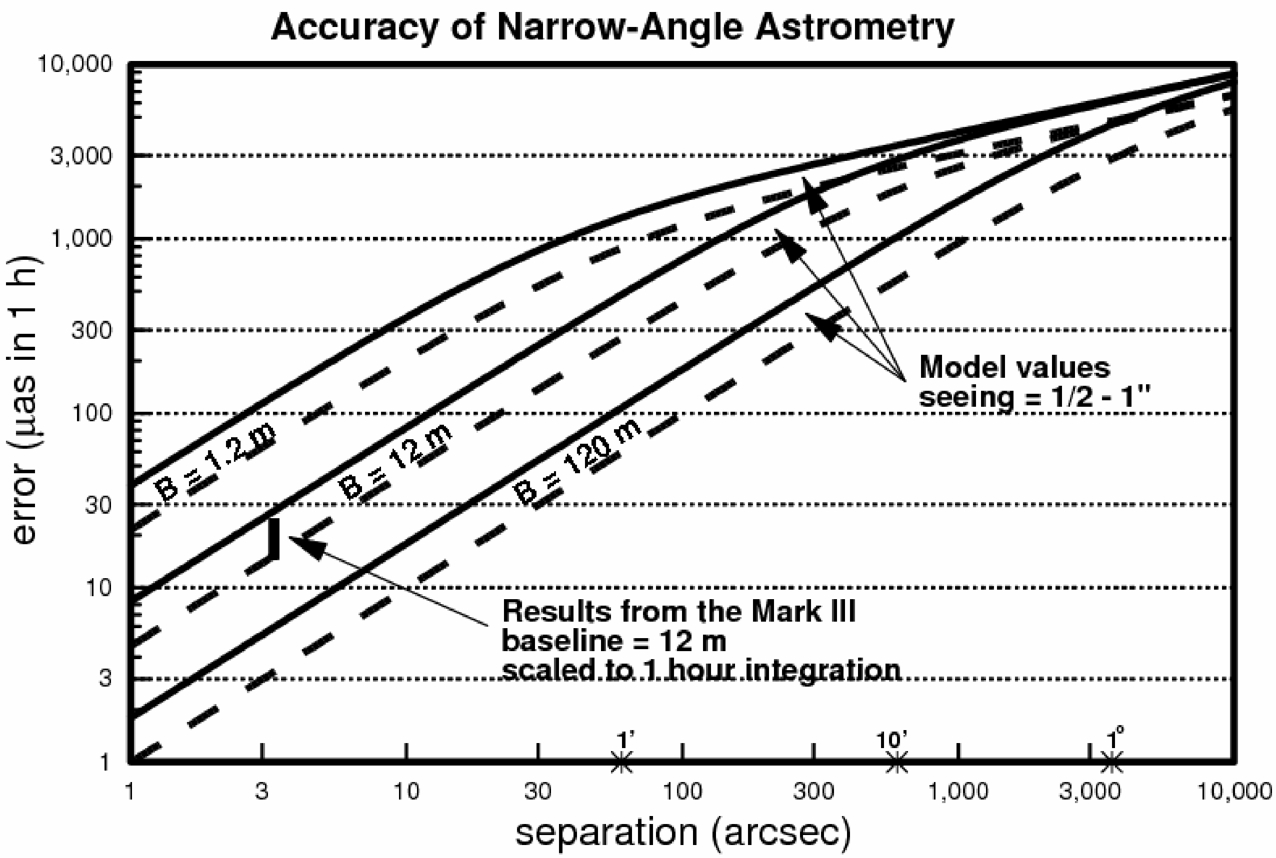
From Ground to Space



Shao and Colavita, A&A 262, 353 (1993)
Colavita, A&A 283, 1027 (1994)

The fundamental limitation to ground based astrometry is the atmosphere.

In Space the fundamental limitation is photon statistics

But very non-trivial practical limitations come from systematic errors.

Above the Atmosphere

- Very narrow angle astrometry from the ground can be very accurate. A disadvantage is that the available ref stars are in general rather faint.The major advantage to going above the atmosphere, for astrometry, is that there is no isoplanatic angle.
- Global astrometry below 1mas can only be done from space.
- Narrow angle astrometry can be done at the photon limit, while both the target and ref stars are bright. (because we can pick ref stars 1~2 deg apart instead of 20~40 arcsec apart.)

- Disadvantages of space
  - Moderately short baselines, as compared to ground based interferometers.
  - Space missions are much more expensive.

- Since instrumental errors decrease linearly with long baselines, shorter baseline space interferometers have to control instrumental error much more aggressively, to take full advantage of being in space.

SIM Error Budget

Narrow angle astrometry means 1uas in a “single” measurement (~900sec)

Global astrometry means 4uas after a 5 yr mission (23 epochs).

Pico Error Budget

52 pm NA (1uas)

830 pm WA

Calibration Definition:
The correction of a systematic repeatable measurement bias.

42 pm
600 pm

Systematic

30 pm
560 pm

Random/nonrepeatable

- Vibrations
- Photon Statistics
- …

Errors due to translating delay line or articulating cc

27 pm
400 pm

Field Dependent Biases

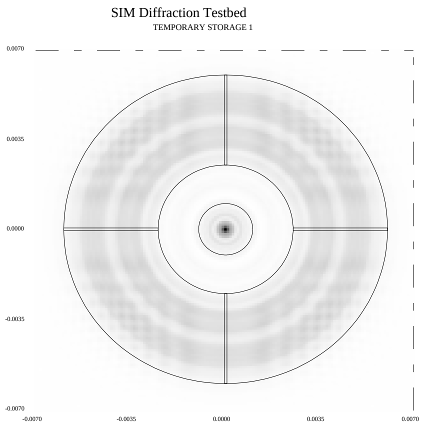
- Polarization
- Beamwalk
- Dihedral
- Diffraction
- cc Vertex Offset

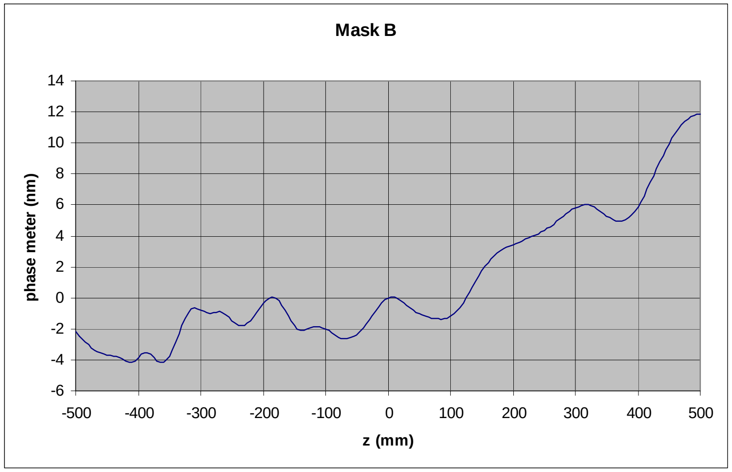
32 pm
440 pm

Field Independent Biases

- Cyclic error
  - Optical cyclic
  - Electrical cyclic
- Wavenumber
- Pointing decenter
- L*Θ*dΘ…

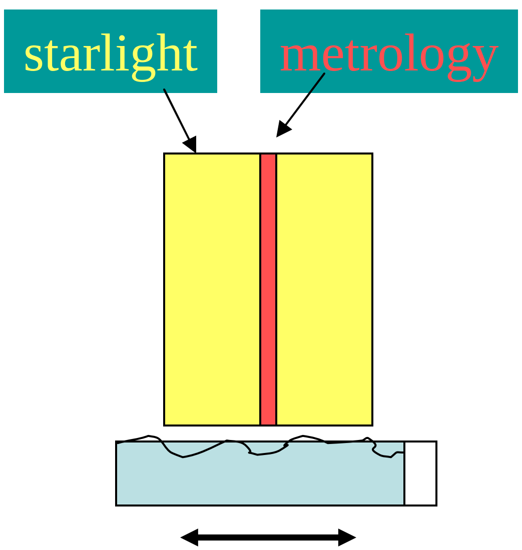
Examples of Systematic Errors





Diffraction:
The metrology beam and starlight beam are different diameters, see different obscurations.

After propagating ~10 meters the optical phase of the wavefront of metrology and starlight are different



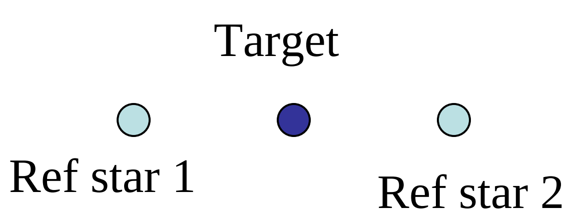
Beamwalk:

The metrology beam samples a different part of the optic than the starlight beam. If the optical surface is perfect at $\lambda/100$ rms, the surface has 6nm hills and valleys.

If we want to measure optical path to 50 picometers we have to make sure we sample the same hills and valleys everytime.

Field Independent Errors
Thermal Drift and Chopping

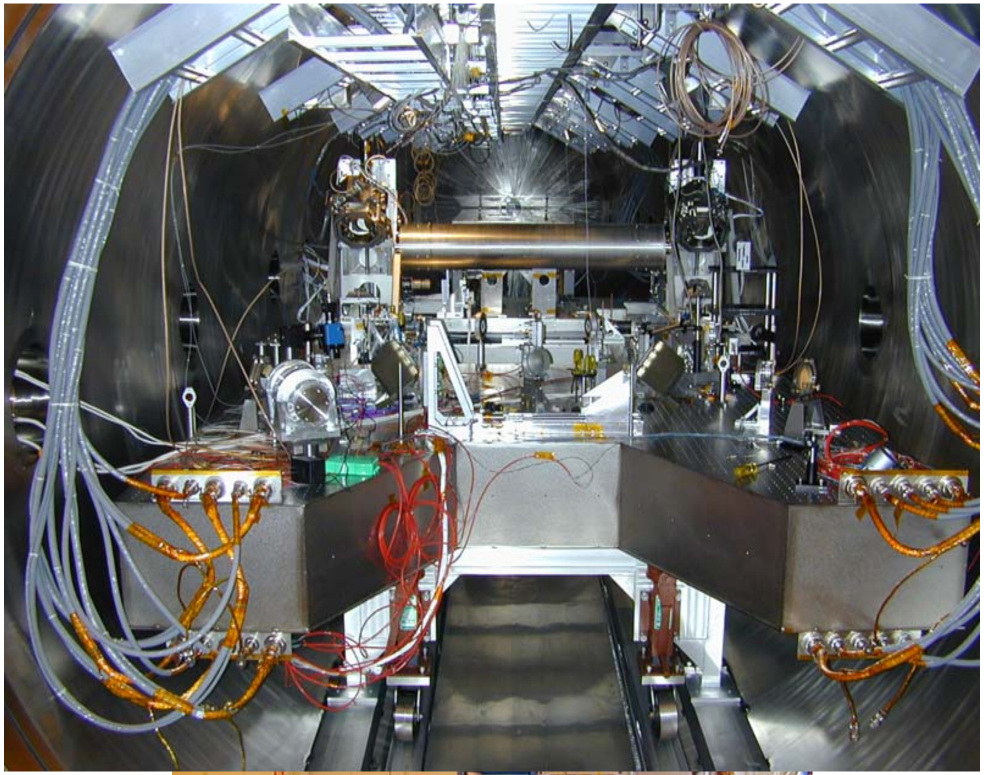
- Standing still is not standing still. If we do not move any optics on purpose, at the picometer level, they still move.
- Field independent errors are differences in the optical path of starlight versus the optical path of metrology light when everything is nominally stationary.
  - Many field independent errors are associated with thermal drift of something. (temperature gradient across a mirror mount, of an optical fiber etc.)
  - We get around drift errors by chopping

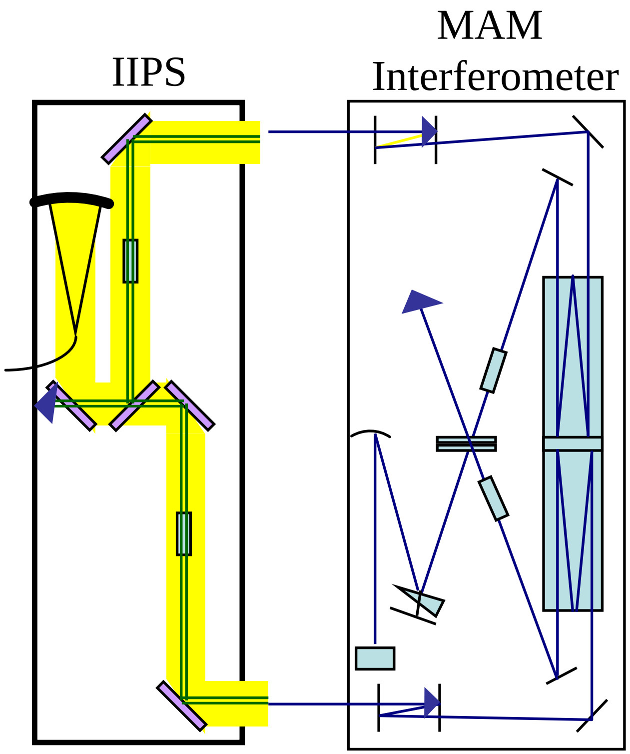


T, R1, T, R2, T, R1 …...

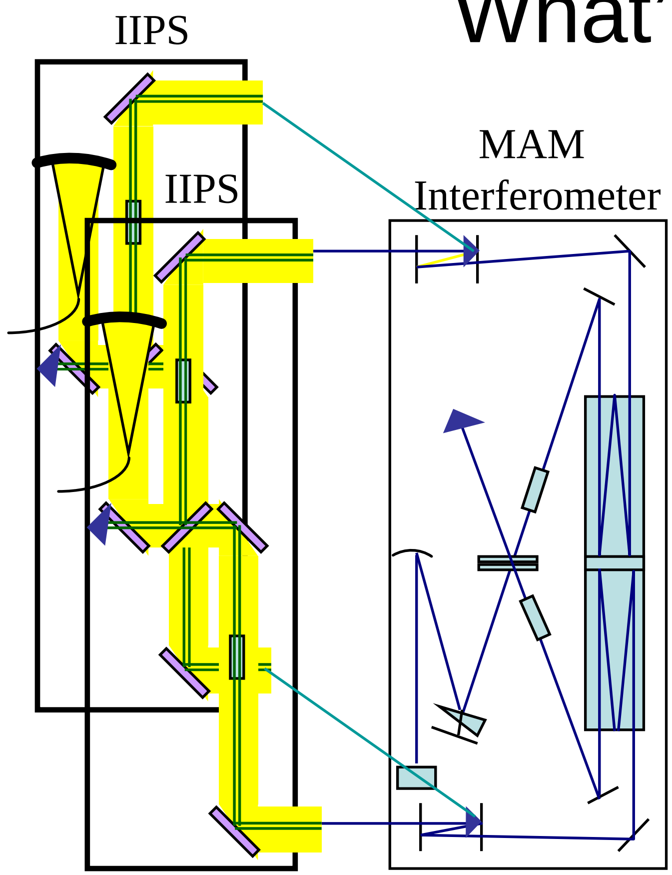
30 sec, 15 slew, 30 sec 15 slew ...

The Micro Arcsec Metrology Testbed





What’s Tested



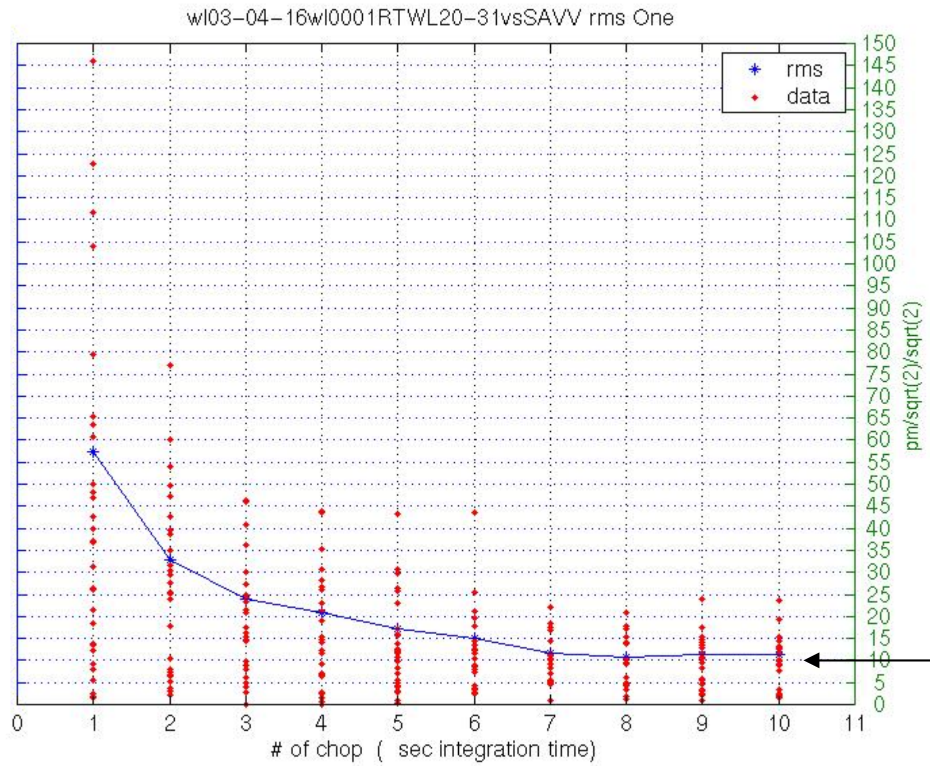
The IIPS represents the star

The metrology on the IIPS measures the position of that star.

The interferometer independently, measures the star’s position.

These two measurements should be the same. +/- a few microarcsecs

Field Independent Error Test



Caveats:

Bright target and ref stars
(instrument errors only)

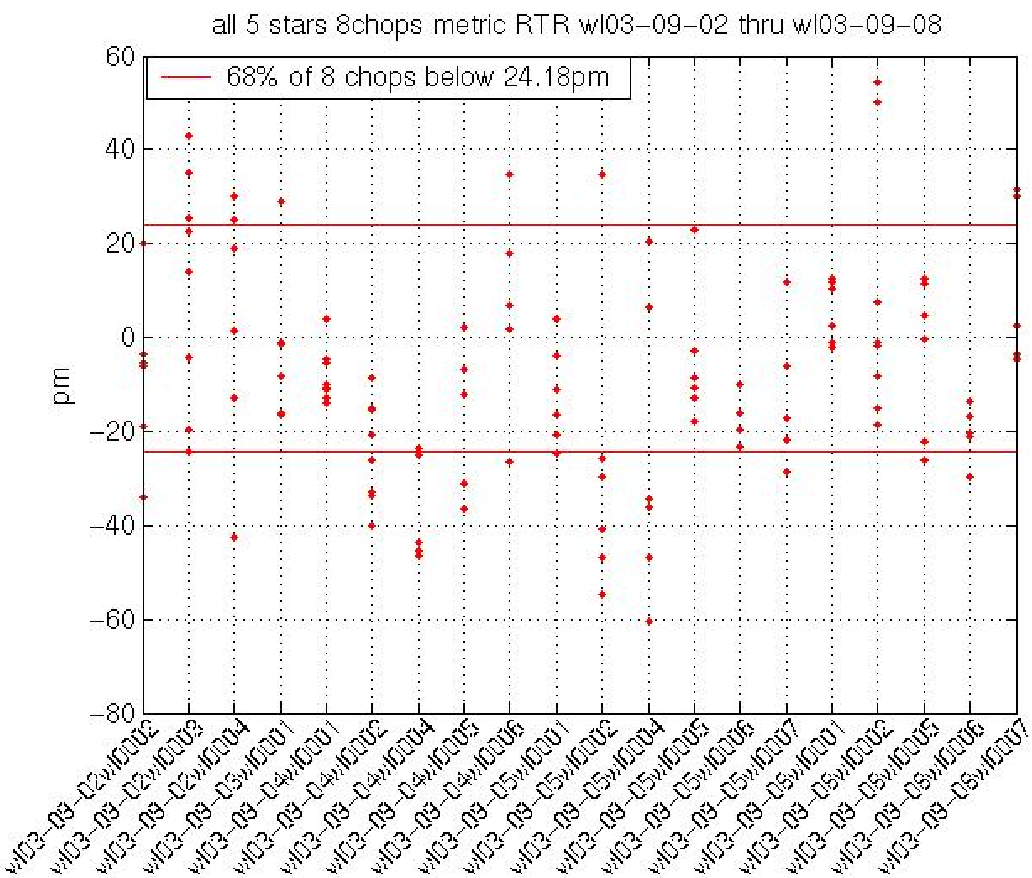
Field Dependent errors are repeatable
planet detection => diff astrometry
Needs stable optics/alignment
(long term milli K stability)

Field independent errors ultimately
limit accuracy.

10 pm (0.2 μas) in 300sec integration

Sqrt(N) From 1 Chop to 10 chops

- Our story is 100% solid. The data we showed at the SIMTAC is not 3uas in 1 chop, it’s 1uas in 3 chops



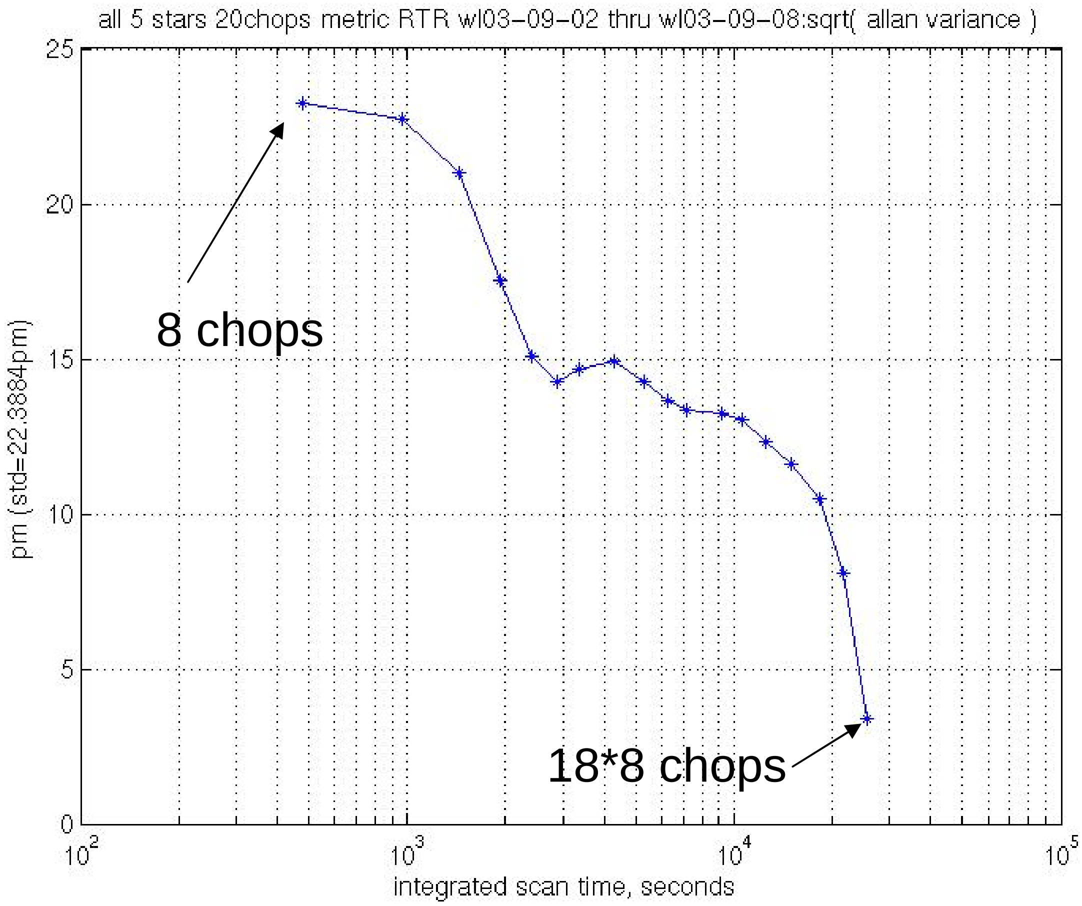
1 uas total error
0.7 to photon noise
0.7 to instrument
0.5 to science interf

0.5uas ~25 pm

Meet 25pm in 8 chops

Each dot is an 8 chop average

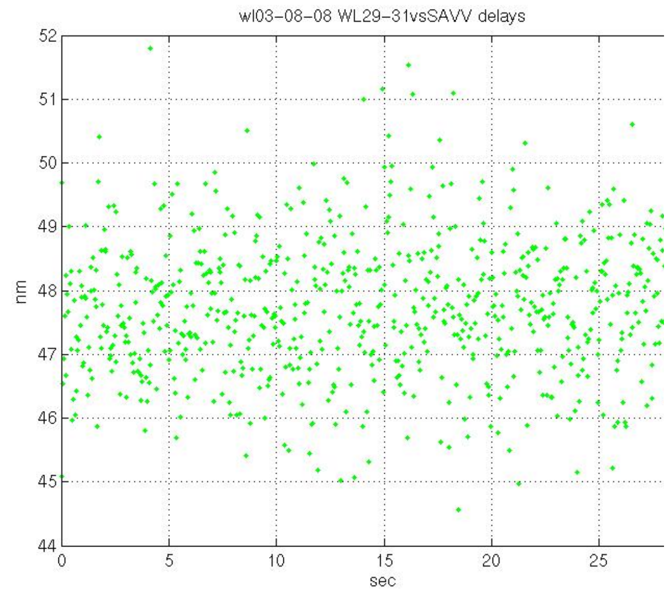
Sqrt(N) Multiple Epochs



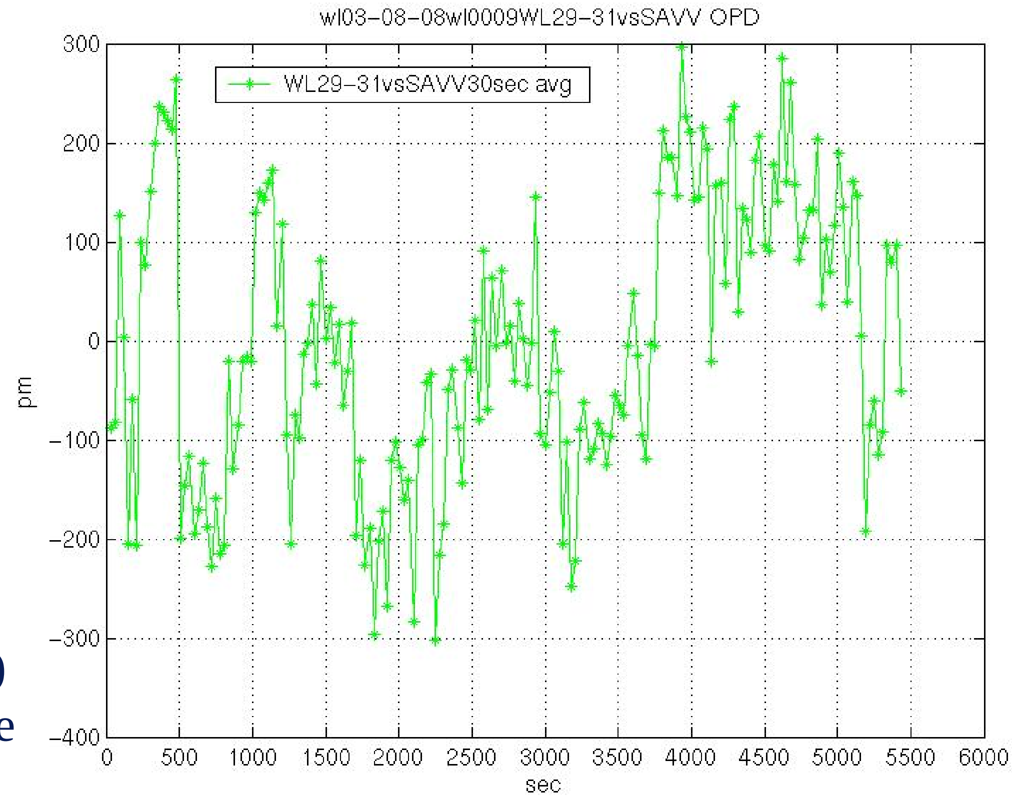
The data does show
That averaging multiple
8 chop data does improve
Accuracy.

Small number statistics at
long integration
Times make a definitive
Statement difficult.

There was enough data to calculate allen variance and get some idea whether multiple epochs will get sqrt(N).

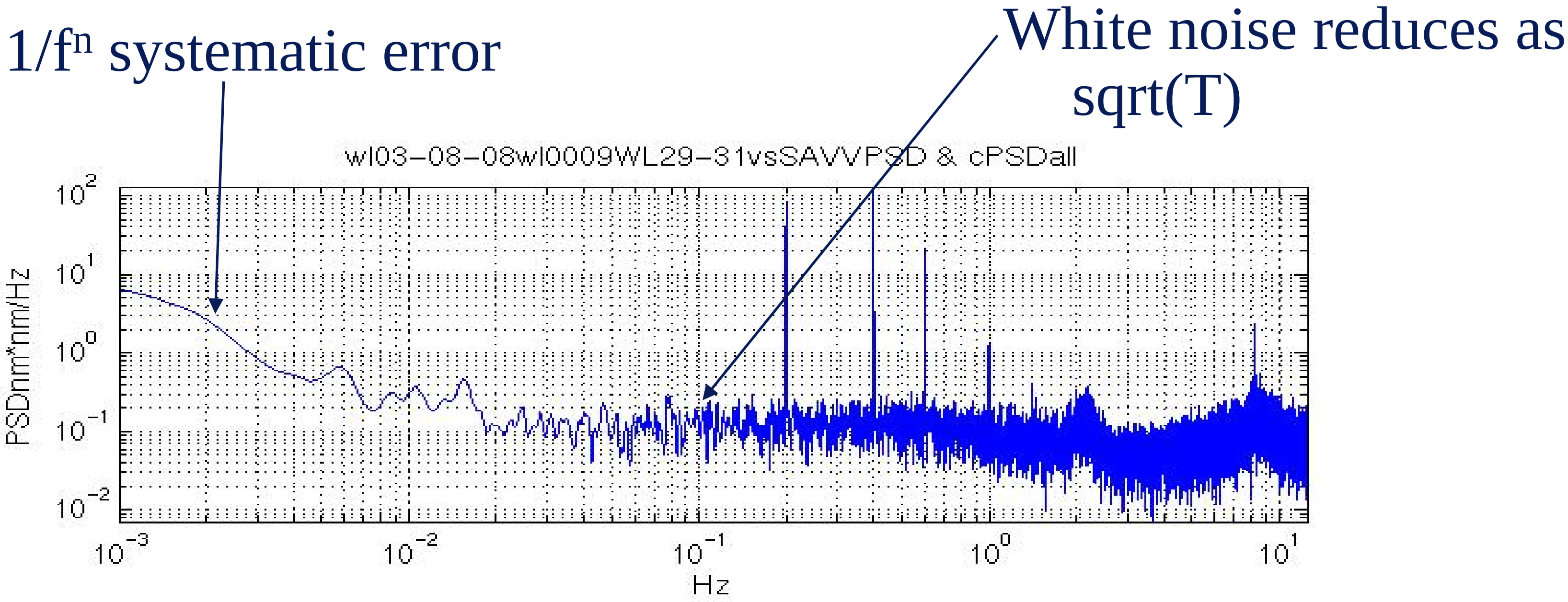


Testbed data @ 25 hz (40msec)
at high freq, the noise looks like
Gaussian white noise



Same data integrated to 30sec. The noise
No longer looks like white noise, it looks
like 1/f noise, systematic error that would not
average down as sqrt(T)

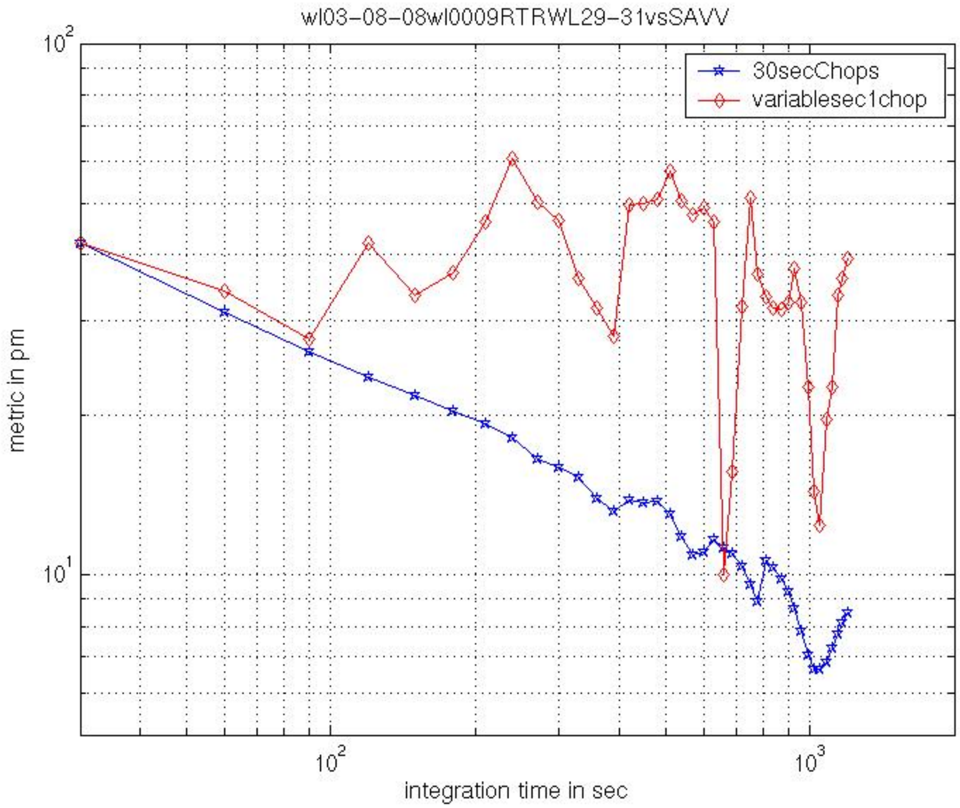
Freq Domain Description of Systematic Error



- The power spectrum of the instrumental errors provides a quantitative description of both random and systematic errors.
- Chopping is a standard way of removing the systematic effects of 1/f noise. Where the 1/f noise intersects the white noise sets the minimum chopping frequency.

Looking for a Periodic Signal

Avoids systematic error limitations



Diff measurement (1 chop) shows accuracy does not improve with integration time

Chop after 30sec integration show sqrt(T) improvement even in the presence of systematic error (1/f noise)

This data from field independent error test on MAM. Represents errors from guide interferometers.

Summary

- Accuracy of astrometry from space is limited by instrumental systematic error and stellar photon noise.
- For global astrometry, single epoch accuracy ~10uas translates to mission accuracy of ~ 4uas for bright stars. (bright means < 13 mag)
  - At 13 mag, photon noise and instrumental error are roughly balanced. 4uas accuracy at fainter magnitudes will require longer integration time (30 sec/visit, 200 visits over 5 years)
- Narrow angle astrometry is also limited by instrumental error and photon noise. The two roughly balanced at ~10 mag. 1uas accuracy per visit, ~800 sec integration time.
- The goal is that systematic errors will be controlled, through instrument and observing sequence design, so that narrow angle accuracy will improve as sqrt(N_visits) down to ~0.1 uas.