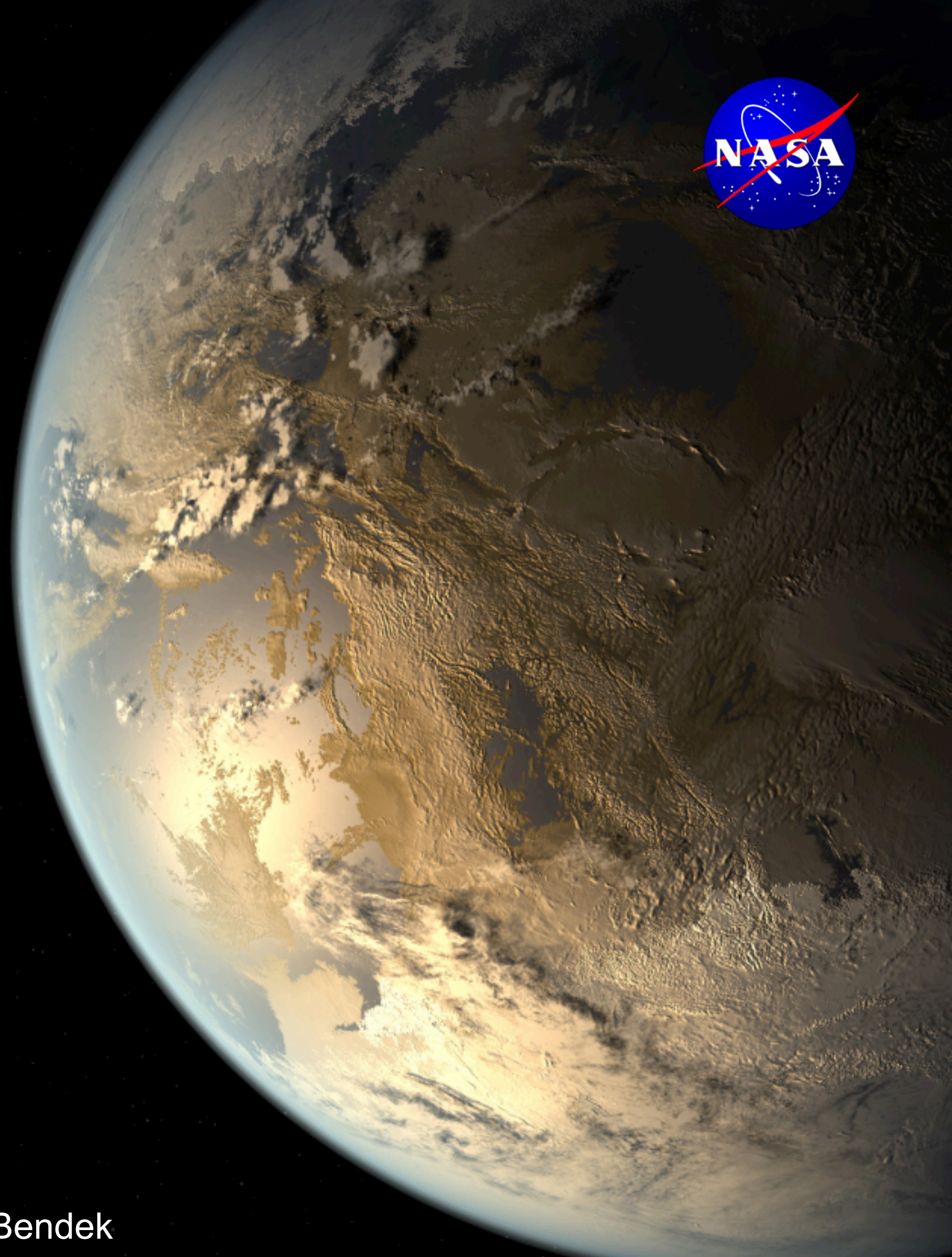
SAG-12 Astrometry for exoplanet detection



SAG-12: Chair Eduardo Bendek

Contributions of: S. Mark Ammons, David Bennett, Jim Breckinridge, O. Guyon, A. Gould, T. Henry, S. Hildebrandt, V. Makarov, F. Malbet, M. Shao, J. Sahlmann, A. Sozzetti, D. Spergel.

Exopag 11, Seattle Jan 3rd, 2015

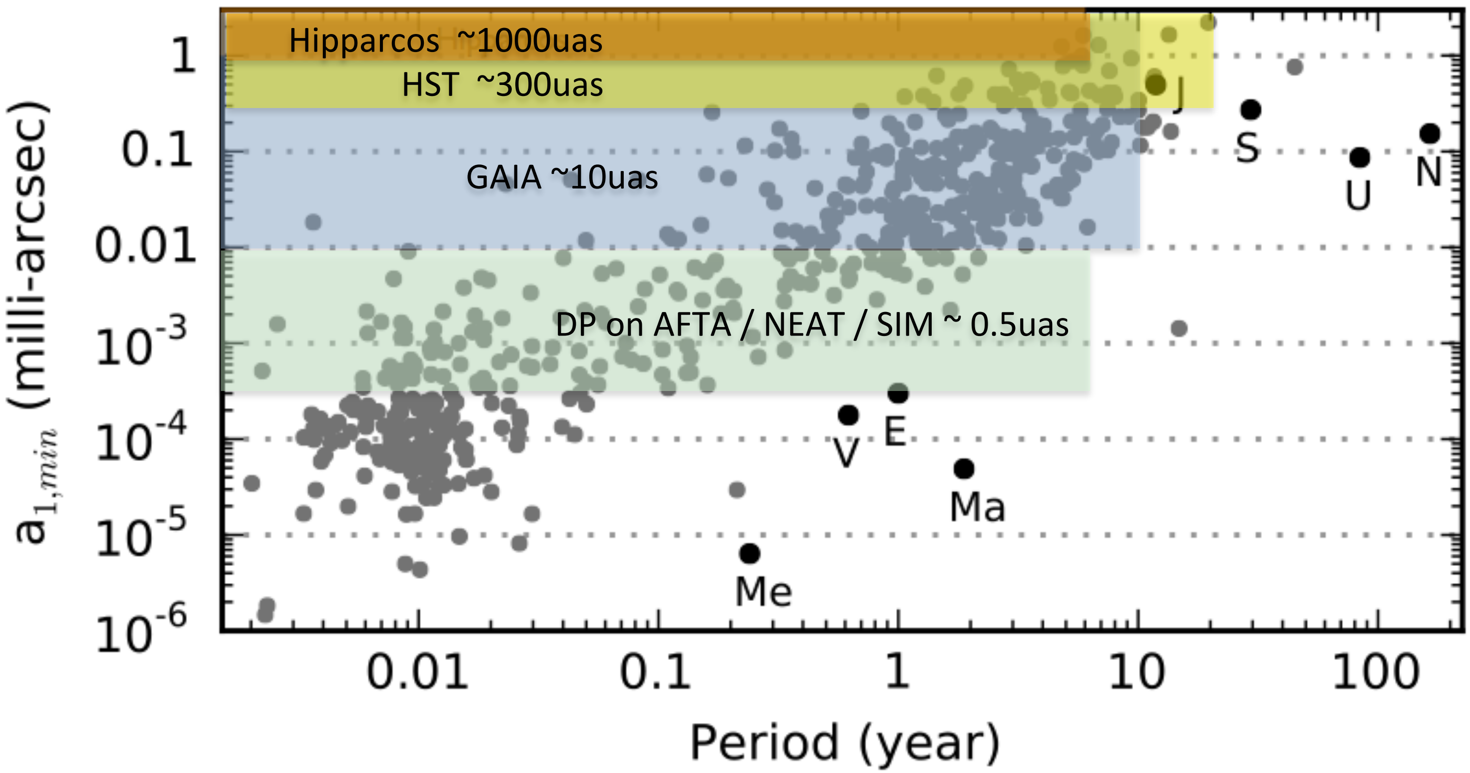
Image Credit: NASA Ames *Kepler 186f*

Overview

- Astrometry for exoplanet overview
- SAG-12 Astrometry description and questions
- Sub-areas
  - Astrometry with AFTA and other missions
  - Synergies with international missions
  - Ground and Space based astrometry
- Conclusion

Guyon et al., ApJ 200:11, 2012

Overview: Astrometry missions



$$a_1 \propto \frac{m_2}{d}\left(\frac{P}{m_1+m_2}\right)^{2/3}$$

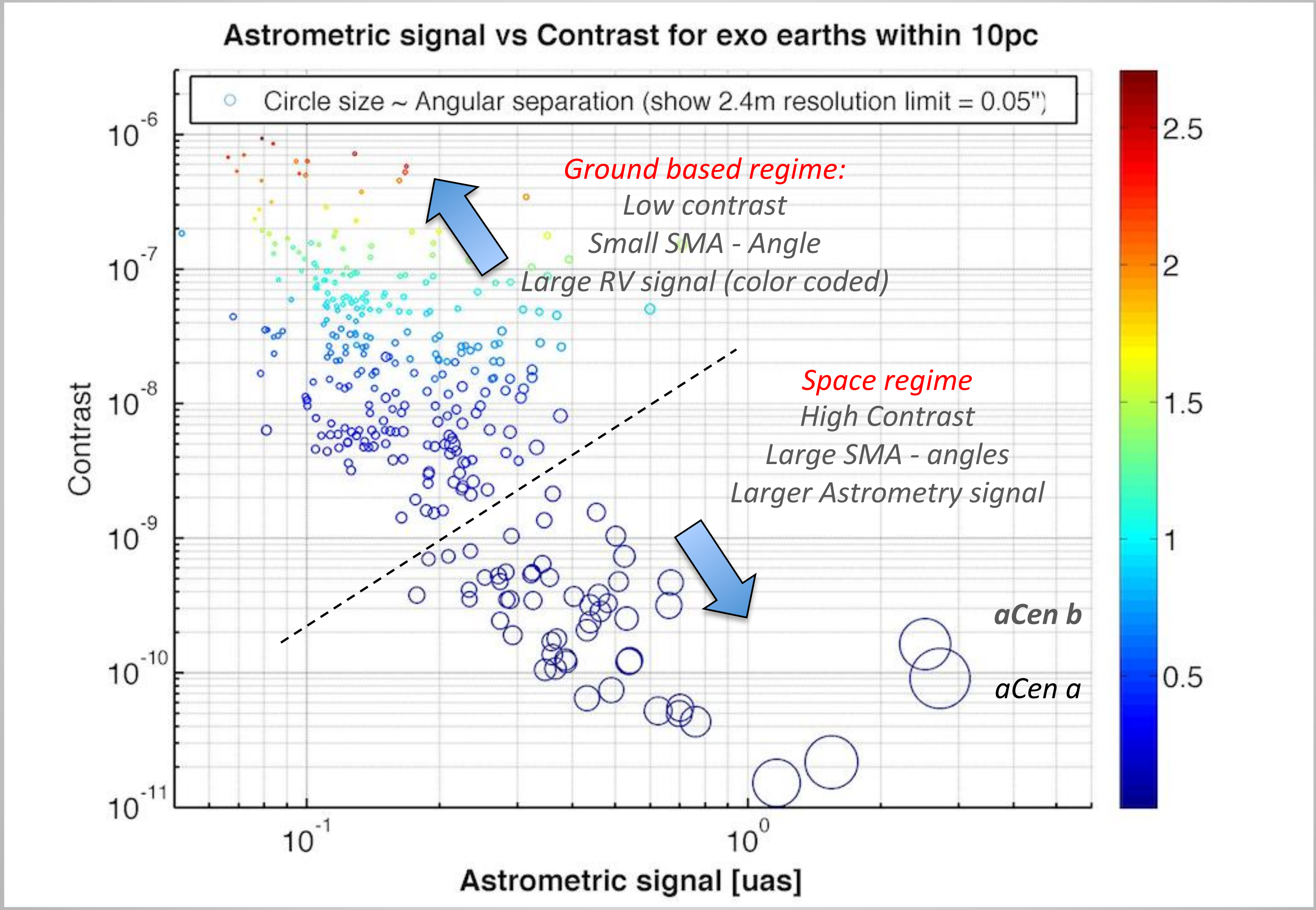
exoplanet.org

Fischer et al. PPVI

10 -100 μas astrometry required to access statistical samples of exoplanets

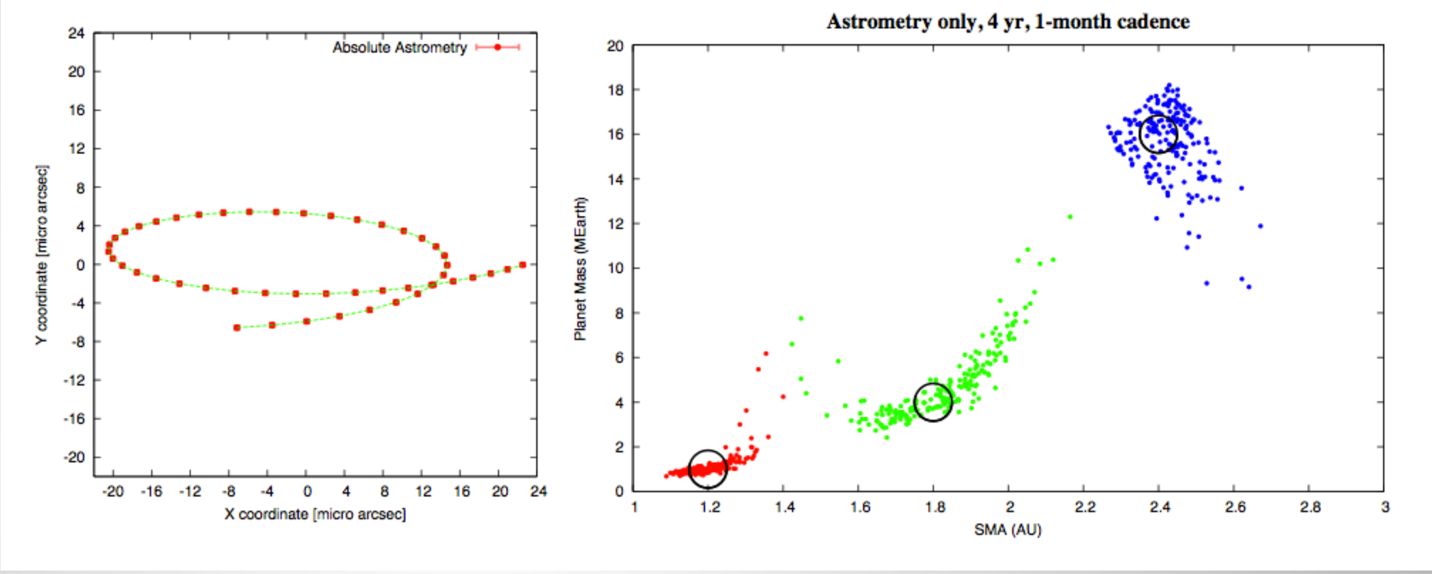
Earth twin detection requires 0.5-1 μas

Overview: Astrometry and direct Imaging

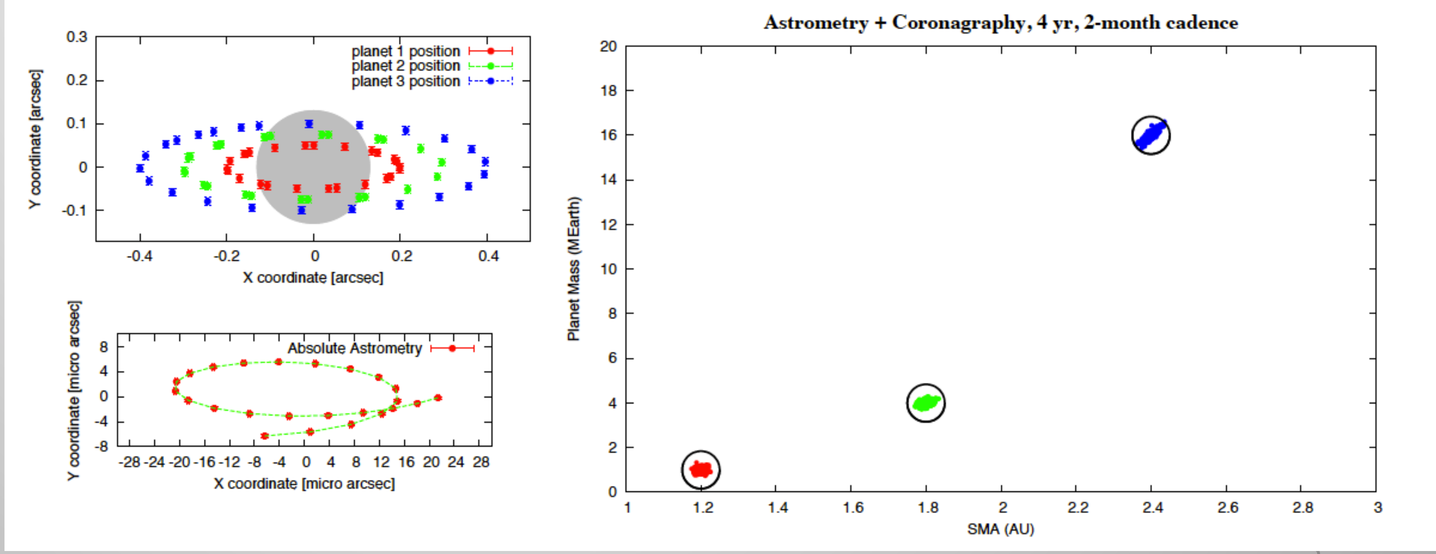


Overview: Astrometry and direct Imaging

4 Year mission,
1 Month Cadence
Astrometry only
Guyon et al, Apj 2013.

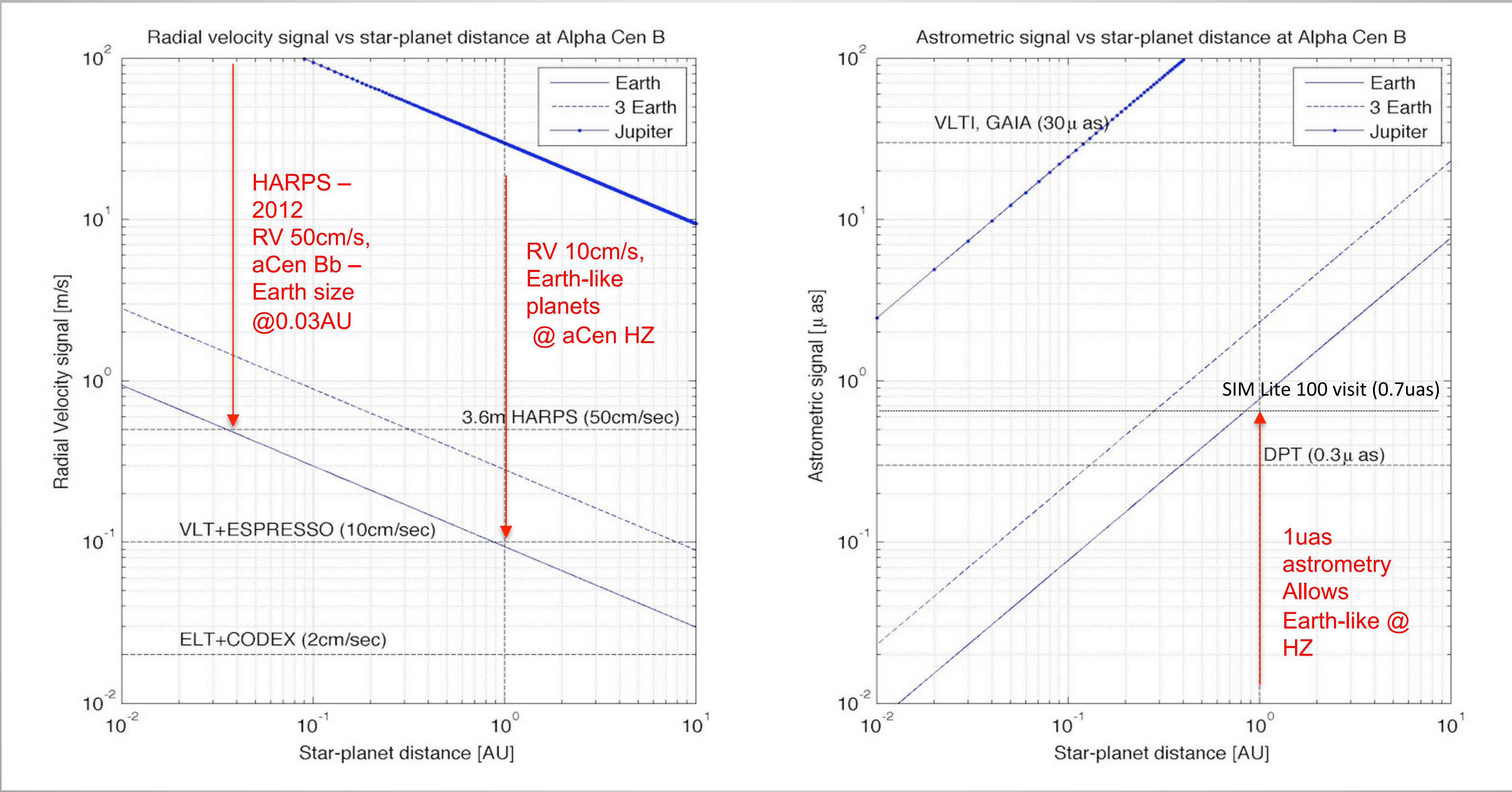


4 Year mission,
2 Month Cadence
Astrometry + Coronagraphy
Guyon et al, ApJ2013.



Overview: Astrometry and RV

- Expands the exploration envelope, complements RV
- Solves inclination ambiguity



SAG-12: Astrometry for exoplanet detection and characterization

- Potential to play an important role in the detection and characterization of exoplanets (**mass, inclination**).
- **Complement high-contrast** direct imaging surveys by allowing for improved yields.
- **Sub-microarcsecond** astrometry allows measurement of the mass and orbits of **Earth-mass planets** within 10pc.

  1μas < required for earth-like measurements
  10μas enables super-earths and Neptunes
- Complementary tool for characterizing the **demographics** of nearby planetary systems.
- **Sensitivity increases with semi-major axis**, in contrast to radial velocity and transit surveys. (WIYN, Transit spectroscopy telescopes)

SAG-12: Goals and question

Key questions and goals that this group will address are:

1) What is the scientific potential of astrometry for different precision levels? Which planets types, confirm planet candidates.

2) What are the technical limitations to achieving astrometry of a given precision? Technical challenges, observational strategies or post processing to improve the astrometry.

3) Identify mission concepts that are well suited for astrometry. Next mission after Gaia that will make exoplanet science possible? What are the requirements for such a mission?

4) Study potential synergies with current and future European astrometry missions. What are the available astrometric facilities to follow-up on Gaia (exoplanet-related) discoveries? Are they sufficient?

SAG-12: Structure

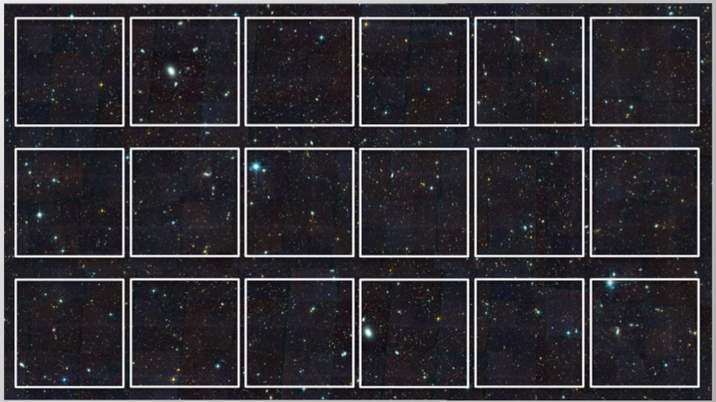
SAG-12 sub area	Questions	Name	Org	Expertise/Interest
SAG-12.1 Astrometry with AFTA and other missions	**1, 2, 3, 4**	David Spergel	Princeton University	Astrometry with AFTA, Science and calibration
		Mike Shao	JPL	Astrometry concepts performance comparisons, TPF, Diff Pupil, NEAT
		James Breckinridge	Caltech	Sources of systematic and random errors that limit astrometric precision
		Olivier Guyon	Univ. of Arizona	Imaging astrometry performance and modeling
		Todd Henry	GSI	Astrometry for exoplanet detection around nearby stars
SAG-12.2 European astrometry missions	**3, 4**	Johanness Sahlmann	ESA	Gaia, Exoplanet science with astrometry. Synergies between European and US missions
		Alessandro Sozzetti	INAF	Gaia Development
		Fabien Malbet	Grenoble	Theia, ultra-high precision astrometry
		Valerie Makarov	USNO	SIM/Theia
SAG-12.3 Ground and space-based astrometry synergies	**1, 2, 4**	Mark Ammons	LLNL	Science case for low-mass stars. Simulation of astrometric error budget, Anchoring error budgets to ground-based demos. Synergy with direct imagers on 8-10 meters and ELTs, comparison with Gaia's capabilities

SAG-12.1 Astrometry with AFTA and other missions

Interest in predict performance and develop calibrations schemes

Rich science cases for different astrometry performances

- Exoplanet detection
- Kuiper Belt Objects orbits (Gould 2014)



Main calibration challenges:

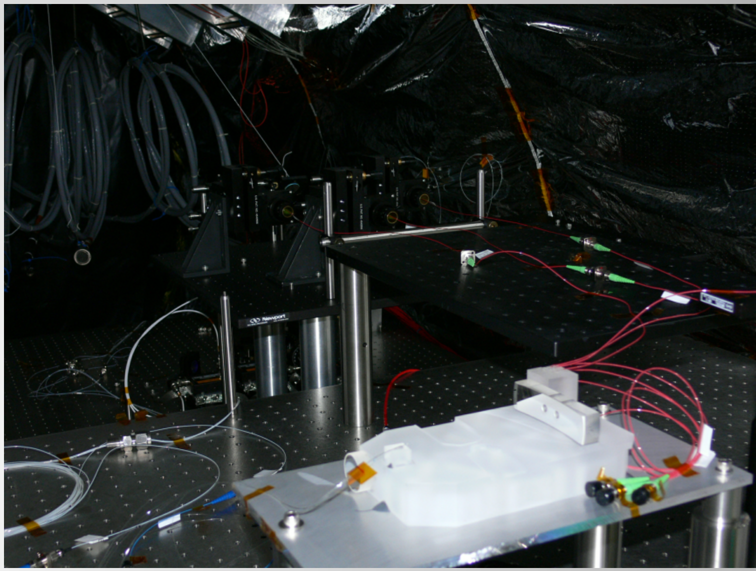
- PSF centroiding over wide field
  Difficult for precision better than 1/100th of a pixel.
- Detector pixel spatial and temporal
- Optical distortions
- Detector mounting back plane calibration
  25cm wide SiC (CTE 4ppm) focal plane. 0.01˚K gradient between the array ends can cause detector motion equivalent to ~100μas

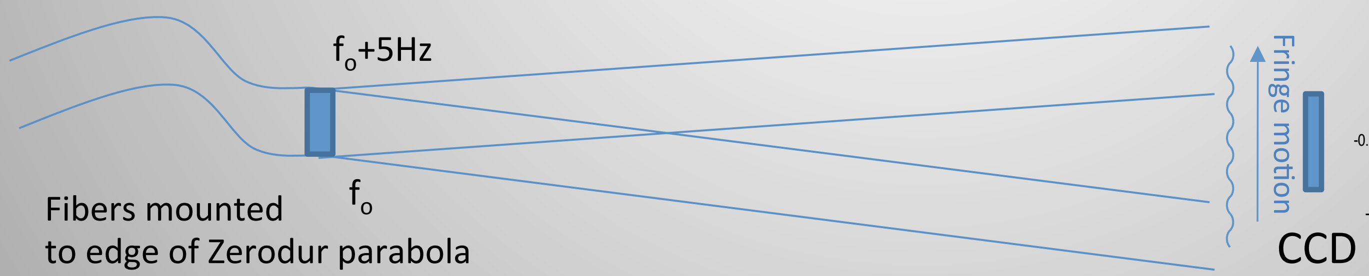
SAG-12.1 Astrometry with AFTA: μpixel Centroiding (By M. Shao)

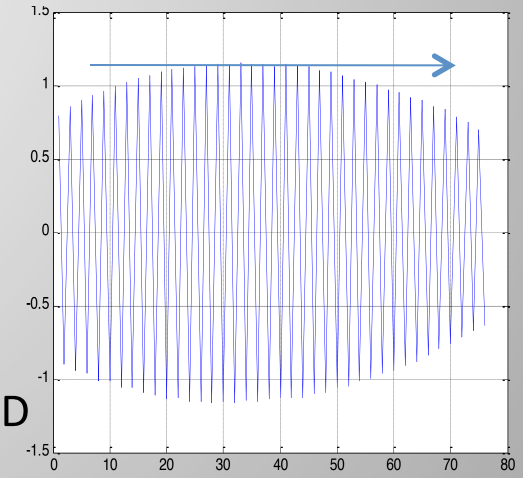
- Conventional ccd astrometry is performed by doing a least squares fit of an “assumed” telescope PSF (defined at very high spatial resolution, perhaps analytically) to the photometric values in the pixelated image.
- The CCD is calibrated with “dark” and “flat field” images.
  - Each pixel is characterized by 2 numbers.
- With current CCDs, this is sufficient for ~0.01 pixel centroiding.
- The underlying assumptions are:
  - The assumed PSF is the true PSF
  - The pixels are perfect. (Geometrically perfect, uniform QE)
- μpixel centroiding avoids the assumptions by measurements/calibration
  - Measures imperfections in the CCD (QE(x,y) within each pixel) and spacing between pixels across the whole focal plane
  - Measures the true optical PSF from the on orbit pixelated data.
    - The optical PSF might vary across the FOV

Micropixel Centroid Tesbed - Pixel Position (By M. Shao)

- The fringes move (left to right) at ~5hz, images are recorded at ~50hz.
  - If the fringe motion is uniform, then one pixel's output is C0+C1*sin(w*t + phi(I,j))
  - Phi(i,j) gives us the location of the pixel
- When the fringe spacing is >> 1 pixel we are measuring the "**position**" of the pixel, across the whole focal plane.
- When the fringe spacing is <~ 1 pixel we are measuring the **Intra-pixel QE**. Fringes with different spacing and orientation measures the Fourier transform of QE(x,y)







True Optical PSF (By M. Shao)

- Instead of "assuming" the image is a Gaussian or an airy function, or an airy function with known wave front aberrations, it is often possible to measure the true optical PSF from the pixelated data.

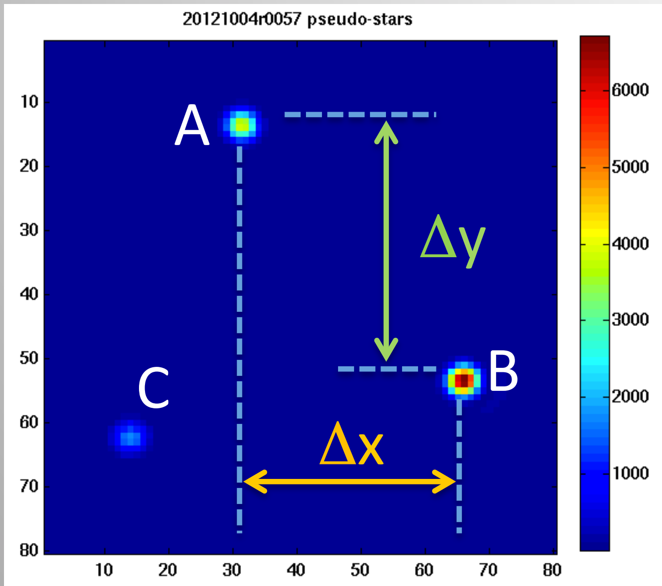
- The simplest way is if the focal plane in Nyquist sampled (>2 pixels per (λ/ D)). If the pixels under sample the PSF (as in WFIRST) one can perform sub-pixel dithering. Take several images where the image is moved a fraction of a pixel. Accurate dithering is not necessary if there are many stars in the FOV and the optical PSF is only slowly varying across the FOV.

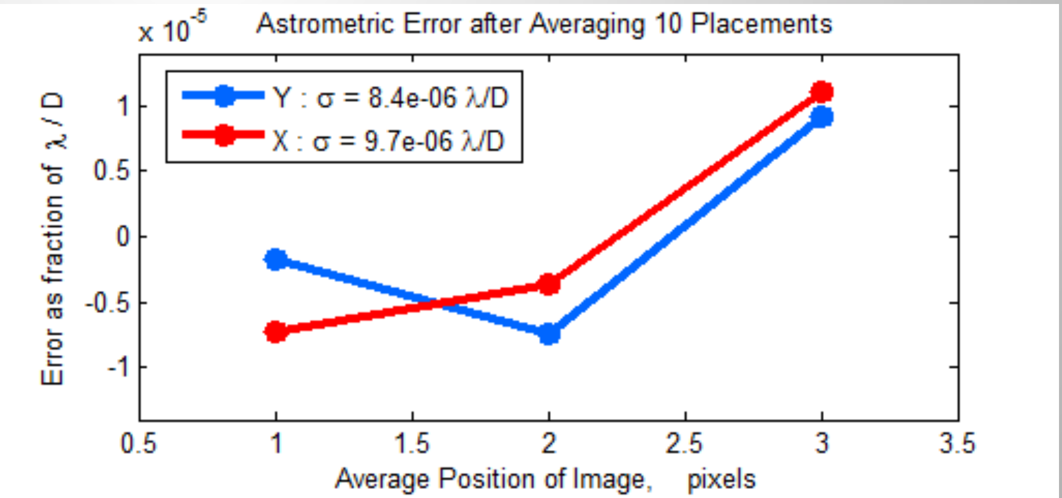
  – It is necessary to measure the pixel array geometry (location of the pixels) and sub-pixel QE variations for each pixel. The number of terms to specify sub-pixel QE increases as image is not Nyquist sampled.

- For astrometry, long range errors in the focal plane are important, the spacing between pixels is not uniform over 1000's pixels and there can be a large discontinuity between pixels in adjacent chips in a mosaic focal plane.
  – Laser fringes can span the whole focal plane, providing geometric accuracy over 1000's of pixels and across different chips on a mosaic.

Centroiding Test 10^{-5} λ/D (By M. Shao)

- Three diff limited spots are moved across multiple pixels on a backside CCD. The separation of the images should not change.
- Images were oversampled (3.5~4 pixels / λ/D). Images were moved ~30 positions. The separation of the two images (A B) were constant to 1e-5 l/D when 10 positions were averaged. Astrometry with a single image was ~1.2e-4 pixels.



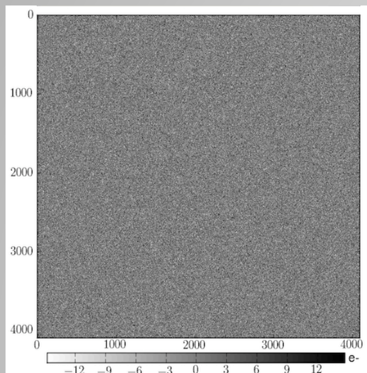


SAG-12.1 Astrometry with AFTA:

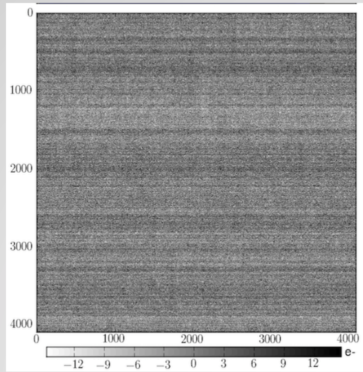
EFFECT OF DETECTOR NOISE IN ASTROMETRY

By SERGI R HILDEBRANDT (JPL/CALTECH)

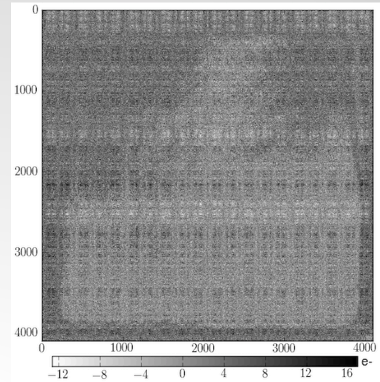
WHITE NOISE (RMS 4e$^-$)



WN + PINK NOISE



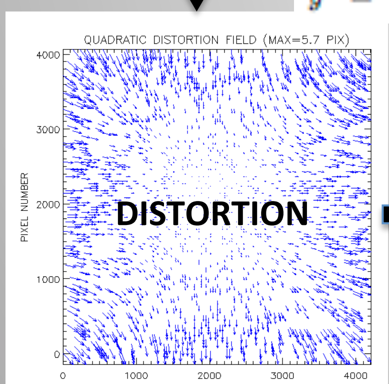
WN + NON-STATIONARY NOISE



… 196 INDEPENDENT NOISE REALIZATIONS OF REALISTIC H4RG (BERNARD RAUSCHER, GODDARD)

FOCAL PLANE GEOMETRY MODEL (EXAMPLE)

$$x = x_0 + \alpha^x_x (i - i_{rf}) + \alpha^x_y (j - j_{rf}) + \beta^x_{xx} (i - i_{rf})^2 + \beta^x_{xy} (i - i_{rf})(j - j_{rf}) + \beta^x_{yy} (j - j_{rf})^2,$$
$$y = y_0 + \alpha^y_x (i - i_{rf}) + \alpha^y_y (j - j_{rf}) + \beta^y_{xx} (i - i_{rf})^2 + \beta^y_{xy} (i - i_{rf})(j - j_{rf}) + \beta^y_{yy} (j - j_{rf})^2,$$



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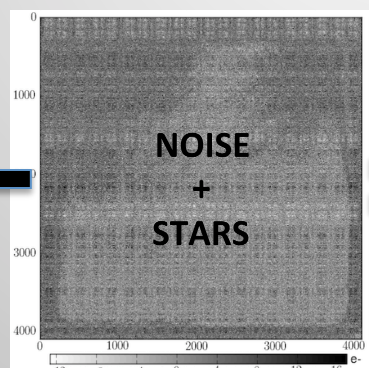

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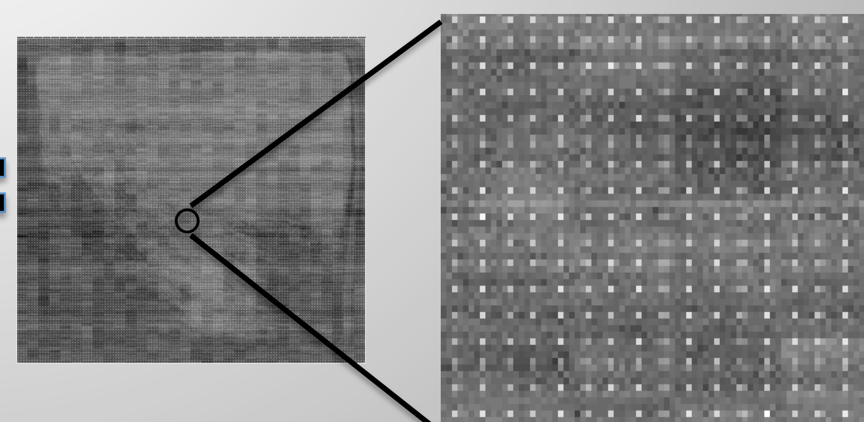
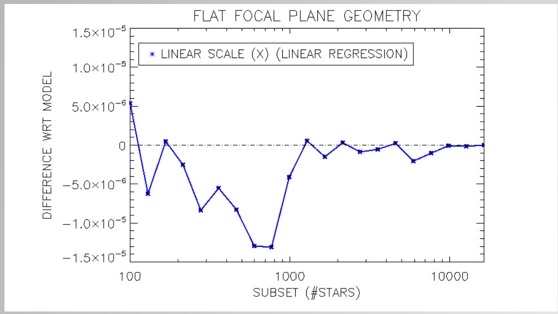
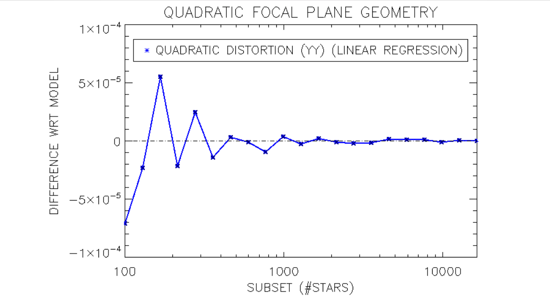


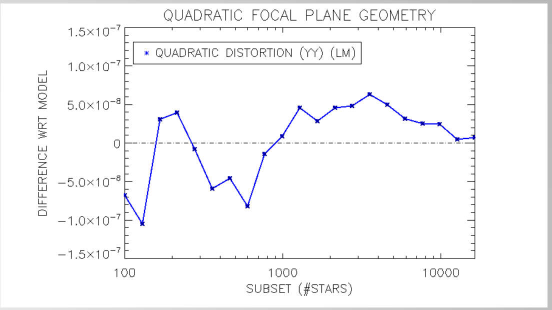
(*) SERGI R HILDEBRANDT (JPL/CALTECH)

SAG-12.1 Astrometry with AFTA:
EFFECT OF DETECTOR NOISE IN ASTROMETRY
By SERGI R HILDEBRANDT (JPL/CALTECH)

CONVERGENCE OF COEEFICIENTS WITH THE NUMBER OF STARS

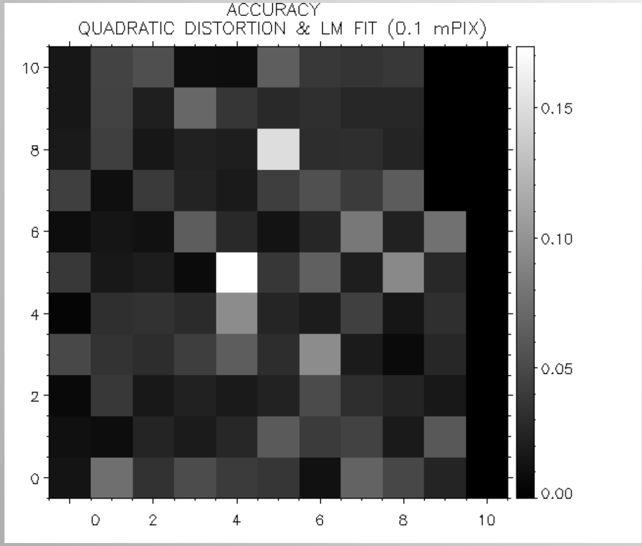






STUDIED BOTH **ACCURACY**: SYSTEMATIC EFFECTS AND **PRECISION**: STATISTICAL ERRORS FOR SEVERAL MAGNITUDES AND ACROSS THE FOCAL PLANE.

RESULTS: Median values for each of the 106 noise types

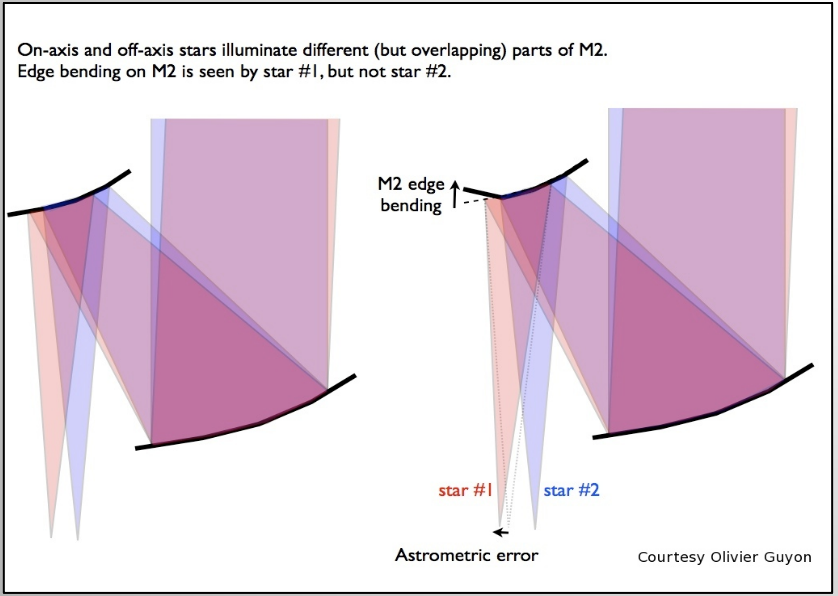


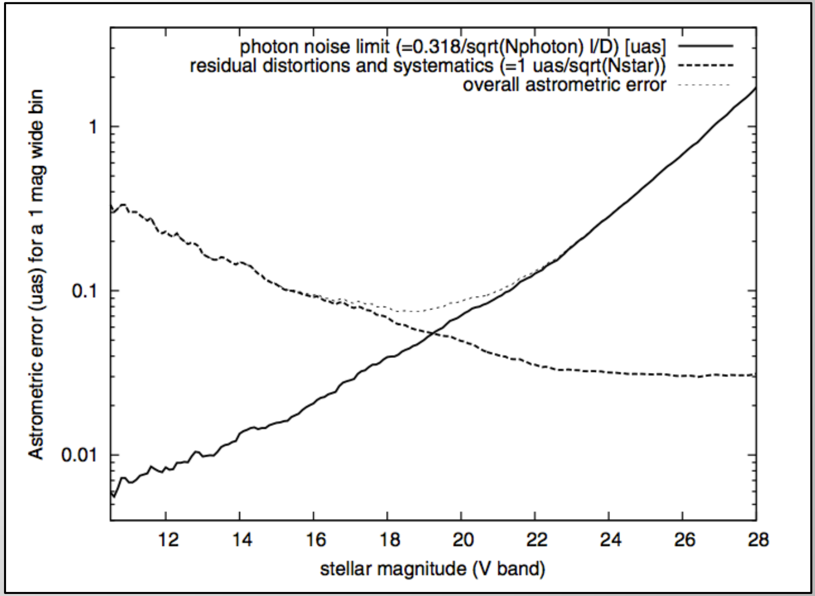
GENERAL CONCLUSIONS:

- **GOOD NEWS FOR ASTROMETRY**
- **EFFECTS OF ORDER 0.1 \`MILLIPIXEL' (m<24, H FILTER).**
- **IDEAL ASTROMETRIC LIMIT OF SCAN MODE ASTROMETRY WITH WFIRST = 0.1 mPIX (DAVID N. SPERGEL)**
- **MORE REALISTIC SIGNAL UNDER STUDY**

SAG-12.1 Astrometry with AFTA: Optical distortions (Guyon, Bendek)

- How distortions affect astrometry
  - Cause local plate scale changes
  - Bias the astrometric measurements
  - Impact on multi-epoch astrometry





SAG-12.1 Astrometry with AFTA and other missions

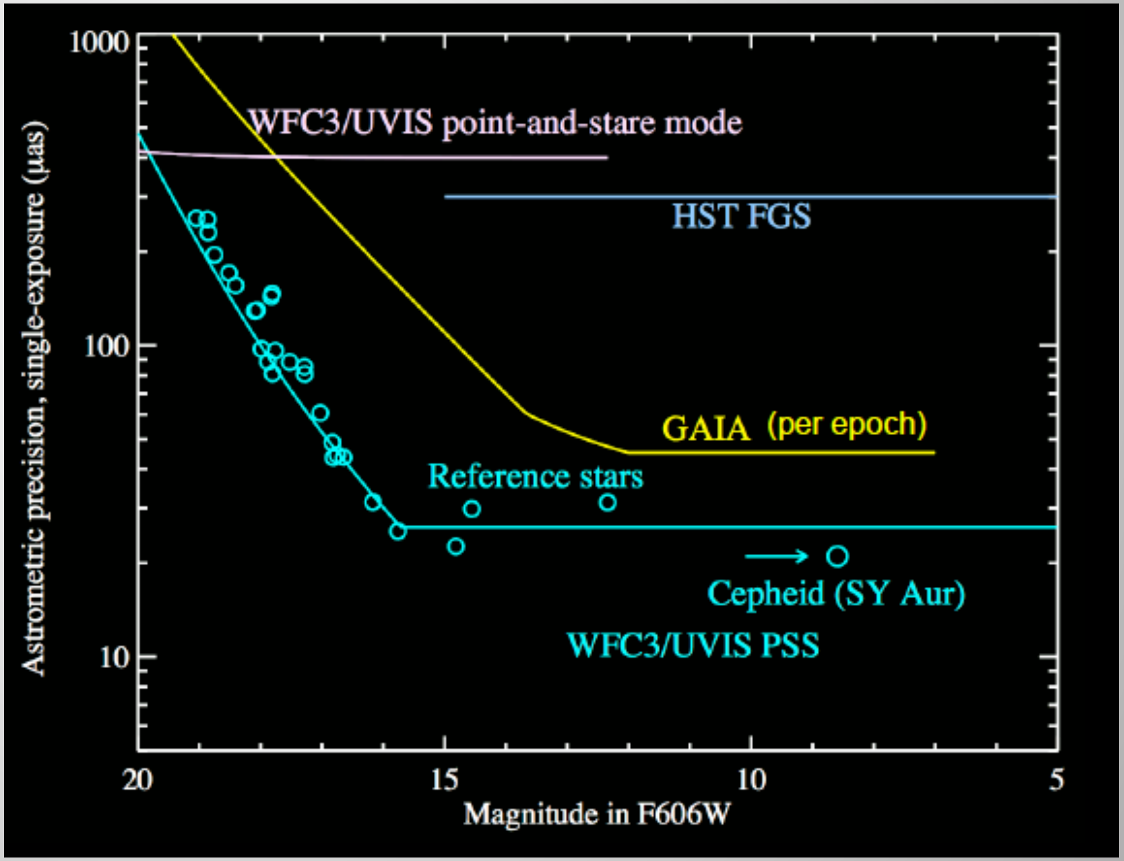
Other missions: HST Astrometry (From Adam Reiss)

Wide field

- WFC3/UVIS Point and stare mode ~ 400µas
- HST FGS ~ 300µas

Narrow field

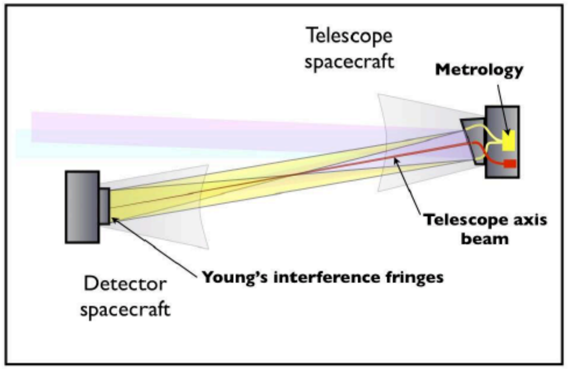
- Precision Astrometry with Spatial Scanning ~25µas

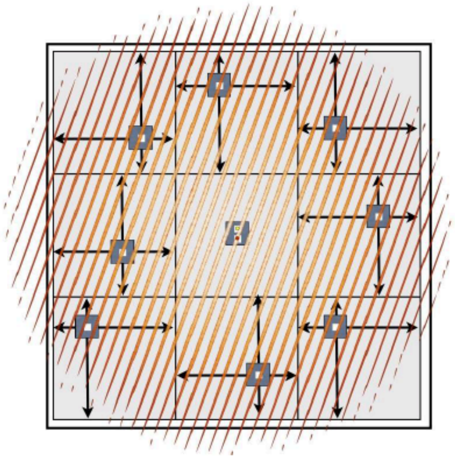


SAG-12.1 other missions: NEAT, Theia

From Malbet F., Leger A., Shao M., et al.

- Remove non-pupil optics: 2 spacecrafts, 1m off-axis aperture
- Add interferometric calibration for detectors and pixels.





Mission name	Mirror diameter	Focal length	Field of view diameter	Focal Plane size	Ref. star mean magnitude	DMA in 1h	# targets for a given mass limit		
	(m)	(m)	(deg)	(cm)	(R mag)	(μas)	$0.5 M_\oplus$	$1 M_\oplus$	$5 M_\oplus$
NEAT plus	1.2	50	0.45	40	11.5	0.7	7	100	200
NEAT	1.0	40	0.56	40	11	0.8	5	70	200
NEAT light	0.8	30	0.71	35	10.5	1.0	4	50	200
EXAM	0.6	20	0.85	30	10.1	1.4	2	35	200

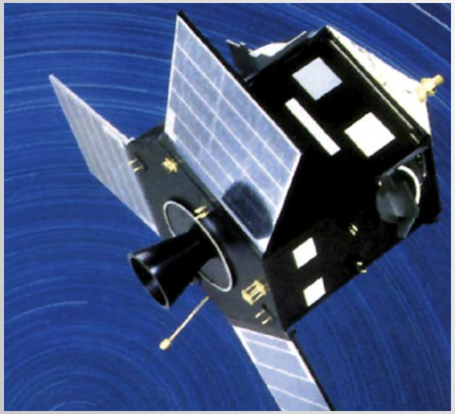
DMA = Differential astrometric Measurement Accuracy (rms)

SAG-12.2 Synergies between U.S. and international astrometry efforts

3) Identify mission concepts that are well suited for astrometry. Next mission after Gaia that will make exoplanet science possible? What are the requirements for such a mission?

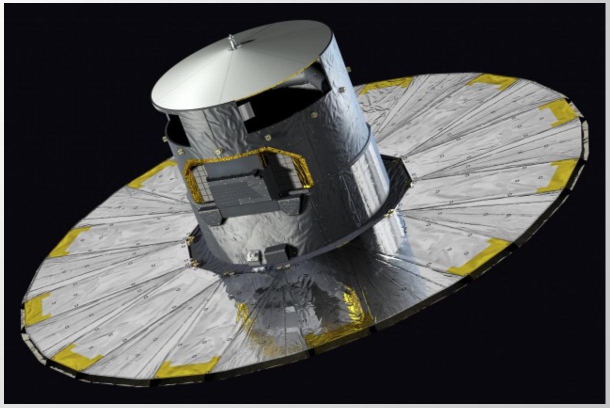
4) Study potential synergies with current and future European astrometry missions. What are the available astrometric facilities to follow-up on Gaia (exoplanet-related) discoveries? Are they sufficient?

Hipparcos – ESA 1989 - 1993



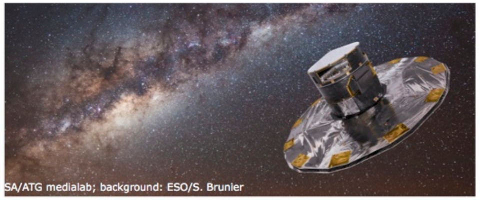
- 0.001 µas for 117,000 stars
- 0.03 as for 2.5 million stars (Tycho2)
- 2.5 million stars
- 300Ly range

GAIA ESA 2013 - 2018



- **8µas for stars $6 < m_v < 12$**
- **25µas for stars $m_v = 15$**
- 70 visits in 5 years.
- 1000 million stars, 30.000Ly range

GAIA, ESA'S GALACTIC CENSUS



Gaia will deliver high-precision astrometry of ~1000 million stars (+ photometry, spectroscopy)

All-sky survey, $G < 20$ mag, ~70 observations per star, 5 year mission at L2

Launched 19 December 2013

Status:
- Nominal mission since July 2014
- Spacecraft in good health. Science data being collected, downlinked, and processed nominally
- Unwanted surprises: stray light (affects performance on faint stars), mirror contamination with water (source not yet exhausted), larger than expected basic angle variation. These are being investigated/mitigated to minimize science impact.
- Photometric science alerts are live: http://gaia.ac.uk/selected-gaia-science-alerts

First catalogue release planned for mid-2016

http://www.cosmos.esa.int/web/gaia/

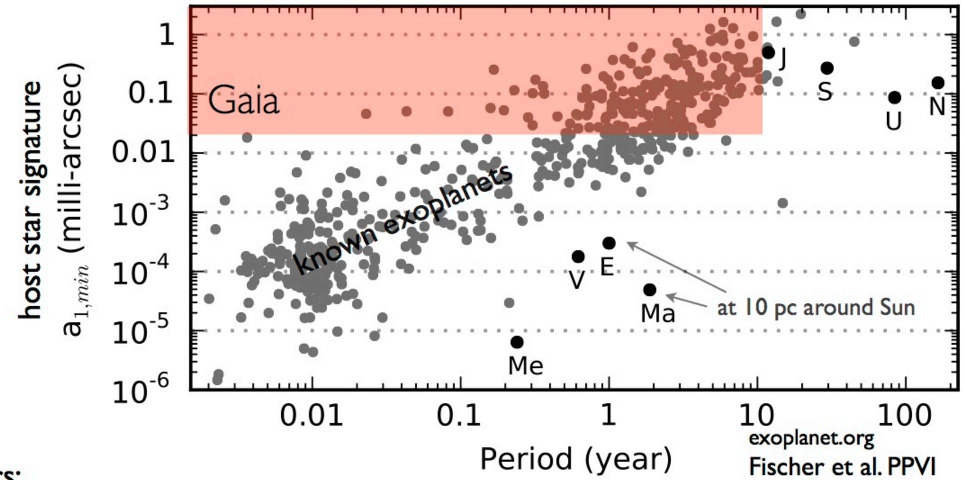
Perryman et al. 2001, de Bruijne 2012, Mignard 2011, Lindegren 2010

GAIA'S EXOPLANET DISCOVERY POTENTIAL

Gaia single-measurement precision for bright (G<13) stars is expected to be ~30 micro-arcseconds (not affected by stray light).

This is sufficient for giant exoplanet detection around stars within ~500 pc.

Several studies estimate the exoplanet yield:



exoplanet.org
Fischer et al. PPVI

Giant exoplanets (15-30 $M_{Jupiter}$ > M > 1 $M_{Jupiter}$) around single stars:
- Casertano et al. 2008, A&A: 4000 - 8000 planets around FGK stars
- Sozzetti et al., 2014, MNRAS: 2000 - 3000 planets around M dwarfs
- Perryman et al. 2014, ApJ: 21000 +/- 6000 planets around stars within 500 pc

Giant exoplanets (30 $M_{Jupiter}$ > M > 1 $M_{Jupiter}$) around binary stars:
- Sahlmann et al., 2015, MNRAS: 100 - 500 circumbinary planets around binary stars with FGK primaries (<200 pc)

Gaia will thus discover (tens of) thousands of extrasolar planets by detecting the orbital motions of the host stars in the sky plane.

This will allow us to study the occurrence of giant planets and their orbital parameters as a function of stellar mass, spectral type, age, evolutionary state, metallicity, ...

SAG-12.3 Ground and Space based astrometry synergies (S. M. Ammons)

Goals

1. **Science case for low-mass stars**, such as M dwarfs and brown dwarfs: **Matching planet formation theory at higher masses**, synergy with high-contrast imaging programs of brown dwarfs (using LGS).

2. **Simulation of astrometric error budget**, including use of common position-finding codes (StarFinder) and distortion correction schemes

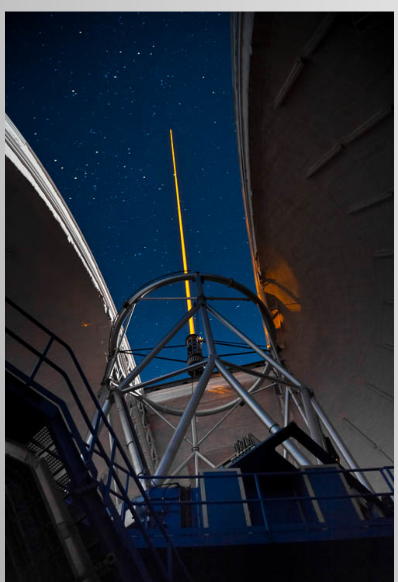
3. **Anchoring error budgets to ground-based** demos on GeMS, ShaneAO, etc

4. **Synergy with direct imagers on 8-10 meters and ELTs**, comparison with GAIA's capabilities

SAG-12.3 Ground and Space based astrometry synergies

Ground based telescopes astrometric performance

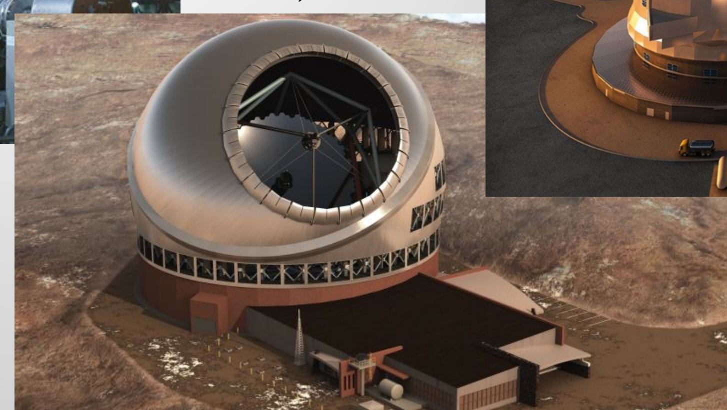
Observatory	Instrument	Performance	FoV	Comments	Ref
Gemini	GEMS +GSAOI	0.2mas monoepoch + 0.4 multiepoch	2'	Crowded wide	Neichel et al 2014 (MNRAS)
VLT	FORS	50µas	Narrow	Crowded	Lazorenko et al 2009 (A&A)
TMT	IRIS	25µas	17"x17"	Galactic center	Yelda et al 2013
EELT	MICADO	40µas	Narrow	Crowded	Trippe et al 2009



Gemini South, GEMS

VLT, FORS1, 2.

TMT, IRIS



EELT, MICADO

Conclusion

SAG-12 Astrometry has been started

- What is the scientific potential of astrometry for different precision levels?
- What are the technical limitations to achieving astrometry of a given precision?
- Identify mission concepts that are well suited for astrometry.
- Study potential synergies with current and future European astrometry missions.

Sub-areas has been identified

- Astrometry with AFTA and other missions
- Synergies with international missions
- Ground and Space based astrometry

We are seeking for members of the community