Challenges for Quantitative Astronomy with ELTs

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New Science with ELTs

- ELTs will expand many astronomy frontiers and open entirely new areas
- In order to reach an ELT's potential, errors need to be controlled to tighter tolerances on larger components
  - Lots of these error terms: same type as for previous generation of telescopes and AO systems, but their magnitude needs to be smaller
  - In some cases, effects that could be ignored altogether become important
  - We want to anticipate as many of these as possible, designing to new specs is always better than retrofitting
- Intellectually challenging problem, but it's solvable. Output:
  - Best possible design of observatory as a system
    - Telescope, AO system, instruments, enclosure, structure, …, even facilities
  - Prescription for observers on how to do very high accuracy/precision measurements

“Quantitative Astronomy”

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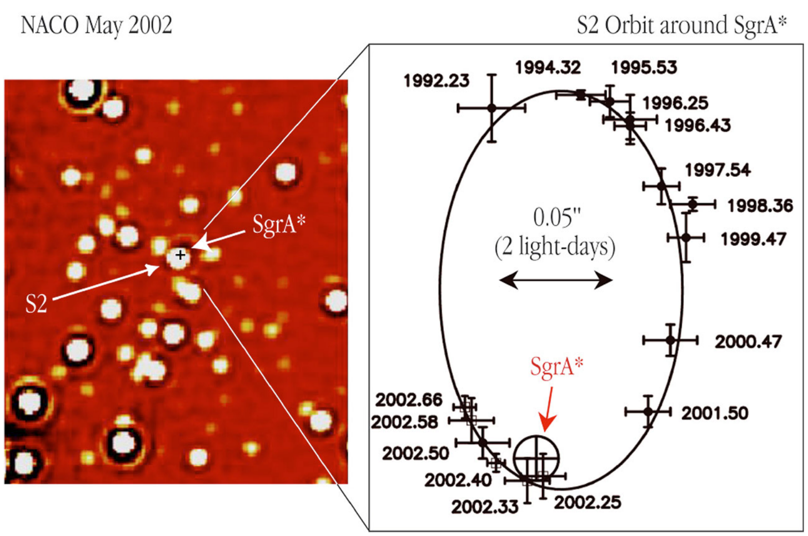
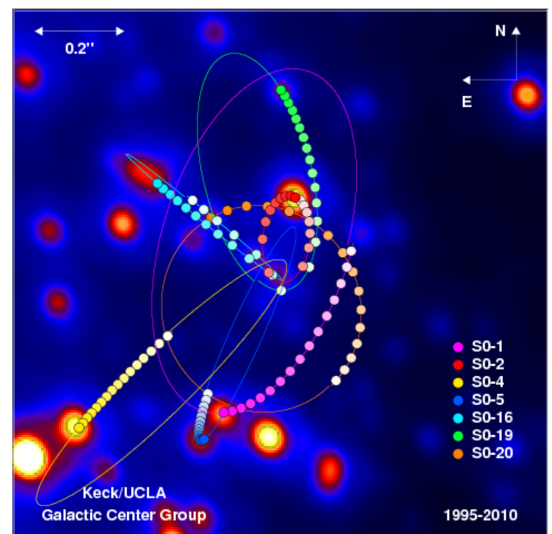
- Most astronomy is quantitative in some way
- Challenging examples:
  - High-contrast AO
    - discussed later in this conference
  - Direct measurement of the expansion of the Universe
    - Requires extreme instrument stability over long times (many years to decades)
  - Photometry
- For this talk, I will concentrate on astrometry with AO



Credit: ESO press release eso0226

Credit: UCLA Galactic Center Group, A. Ghez et al.



Astrometry with ELTs

- Astrometry:
  - Measuring the positions of stars
  - Highest precision: relative measurements in fields with lots of stars
- Revisit same fields many times, often months or years apart
- As a general rule, observers take many short exposures
  - In order to control variable effects (distortions etc.)
  - But too short is problem, S/N & overhead
- Exposures are combined after coordinate transformation
  - Takes out low-order distortions

Irregular dwarf galaxy NGC 1569
APOD 29 Dec 2008

Astrometry with ELTs

- Precision Astrometry on current telescopes: ~100-300 μas differential astrometry
  - Lots of papers out there on how to do that, and some error budget papers
- TMT NFIRAOS requirement:
  - 50 μas differential astrometry for 100s exposure on 30” FoV in H band
  - Error falling as $t^{-1/2}$ to a systematic floor of 10 μas (1-dim)
- Challenging constraints on all parts of the opto-mechanics, such as:
  - Control of telescope, AO system and instrument distortions, and in particular their temporal variations
  - Atmospheric dispersion correction
  - AO system performance, stability
  - Detector noise, pixel size and pixel irregularities

Astrometry Error Budget

- Attempt to identify all potential sources of astrometric errors, irrespective of their expected magnitude
  - Many different ways to slice up the error budget
- E.g. 5 categories:
  - Reference star and catalog errors
  - Atmospheric refraction
  - Other atmospheric effects
  - Opto-mechanical errors
  - Focal plane measurement errors
- Many terms are correlated or interconnected
  - They cannot simply be added in quadrature
- Almost every error term depends on the details of the astrometry observations
  - Absolute vs. differential astrometry, sparse vs. crowded fields, short vs. long times scales, …

Astrometry Error Budget
Reference Star/Catalog Errors

- Differences between real and assumed properties of reference stars:
  - Position errors in reference catalog
    - Depend on field of view and number of stars
  - Proper motion uncertainties
  - Differential aberration (compression of field due to motion of Earth w.r.t. light velocity)
  - Other or unknown motion, e.g.:
    - Binaries
    - Gravitational lensing (by stars, galaxies or the Sun)
  - Color errors and variability
    - Couple with differential atmospheric refraction and other effects
  - Non-point-source references require special attention
- Apply to both reference field stars and AO guide stars

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Astrometry Error Budget
Atmospheric Refraction

- Differences between observed and physical zenith angle of objects
  - Absolute value of refraction
    - Absolute astrometry, for the most part
  - Achromatic differential refraction
    - Due to differences between zenith angles of different objects
  - Chromatic differential refraction (dispersion)
    - Due to wavelength dependence of index of refraction
    - Requires atmospheric dispersion corrector (ADC), and most likely a different ADC for each wavelength band
    - Might even be necessary to narrow down wavelength band further
    - A posteriori corrections may be required for highest-precision astrometry

Astrometry Error Budget
Other Atmospheric Effects

- Residual atmospheric tip/tilt after (MC)AO correction
  - Absolute value
    - For the most part, only affects absolute astrometry without reference source
  - Differential atmospheric tip/tilt
    - Depends on integration time as $T^{-0.5}$
    - Can be reduced significantly using reference star positions
- Higher order residual turbulence
- Halo effect
  - Seeing-limited halos of other stars cause background gradients
- Elongated PSF due to anisoplanatism after AO correction
- Variable atmospheric effects (during exposure):
  - Couple, for example, with image motion to cause astrometric uncertainties
  - E.g., transparency or Strehl ratio variations

Example: First Simulation of Astrometry Errors Due to Incompletely Averaged Residual Turbulence

- Residual tip/tilt errors computed for 7x7 stars in a 30" square FoV at 800 Hz for a 20 second simulation of NFIRAOS
- Low order (polynomial) modes of distortion removed using "field stars"
  - 0^{th}, 1^{st}, 2^{nd}, or 3^{rd} order calibration
  - Low order modes fit to either 4x4 or 7x7 field stars
- Residual errors (in μarc sec) after 20 second integration

Order	**4x4 stars**	**7x7 stars**
0	168	167
1	56	55
2	17	16
3	8	7

Astrometry Error Budget
Opto-Mechanical Errors

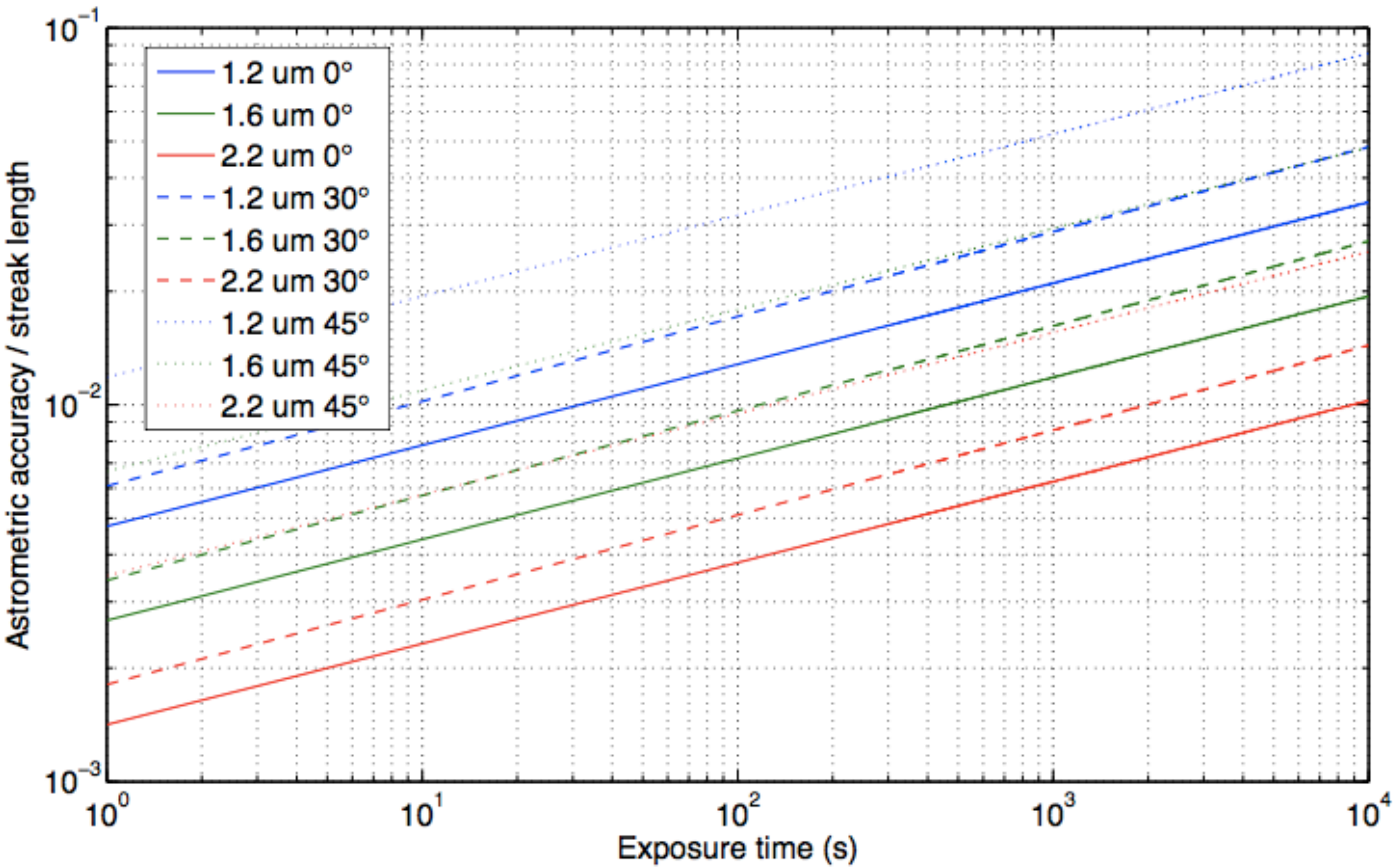
- Distortions have direct effect on astrometry:
  - Plate scale errors and variations due to guide probe positioning
  - Plate scale errors and variations due to focus uncertainties and variations
  - Previous design of NFIARAOS: OAP relay distortions
  - Rotator errors
  - Atmospheric dispersion corrector imperfections
  - Telescope or instrument distortions
  - Any other distortion in the opto-mechanical train
- Low-order distortions:
  - Can, to a large part, be corrected by coordinate transforms in fields with many reference sources
  - But it is always better not to have them in the first place, especially because:
- Time variability of distortions of particular importance

Example: Seeing and Transparency Variations Coupled with Image Motion

- Seeing and transparency variations during exposure
  - Couple to image motion
  - Produce astrometric errors
- Astrometric error:
  - Typically 2-6% of image motion for transparency variations (wavelength independent)
  - Typically 1-10% of image motion for seeing variations (wavelength dependent)
- Errors increase with exposure time

- Main result: differential image motion should be <<1 mas for precision astrometry.

Effect of Seeing Variations



Astrometry Error Budget
Focal Plane Measurement Errors

- Photon, detector, background noise
  - Statistical errors that average out in time if random
  - More difficult if, for example, the background has structure
- Flat field and dark current calibration errors
- Pixel size effect
  - Finite size of pixels causes a measurement error
- Pixel shape and intra-pixel sensitivity irregularities
- Detector non-linearity calibration errors
  - Unlike almost all other errors, this one is larger for brighter objects
- Confusion
  - Unresolved faint stars change measured position of brighter stars

Summary

- ELTs will provide a lot of exciting new science capabilities
- In order to reach an ELT's potential, errors need to be controlled tightly
  - We want to anticipate as many of these as possible, designing to new specs is always better than retrofitting
  - No errors are better than known errors
- This is an intellectually challenging problem, but it's solvable
  - For TMT, we have found no show-stoppers, but it has, in a few cases, affected the design (or, more often, confirmed that we are on the right way)
- Will also result in instruction for observers how to do very high accuracy/precision measurements
  - Observation preparation
  - Calibration
  - Observations (e.g. observe at same LST, short exposures, narrow bands, ….)
- Photometry: when system optimized for high-precision astrometry, photometry performance will also be ideal (or close to it)

Acknowledgments

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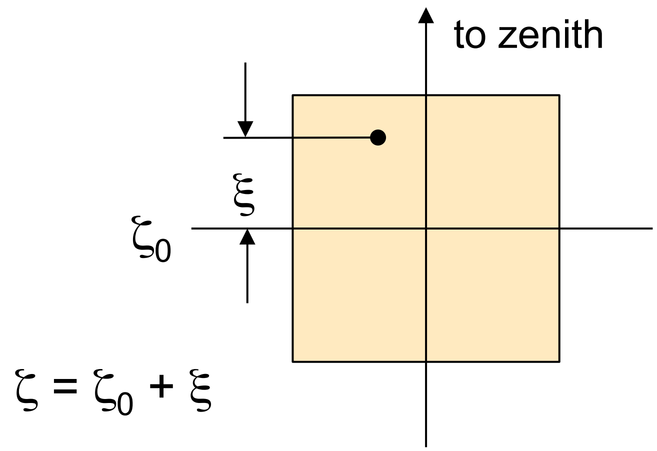
Astrometric Science with ELTs

- Black holes (BHs)
  - Relativistic orbit precession in Galactic Center (GC): general relativity, central mass distribution, accurate distance to GC.
  - Evolutionary history of GC BH from proper motion of Sgr A*
  - Stellar orbits around supermassive BHs in M31, Cen A, etc.
  - Search for intermediate-mass BHs in galactic star clusters
  - Proper motion in extragalactic jets: origin and evolution of active galactic nuclei
- Dark matter
  - 3-d stellar orbits in dwarf galaxies: cold dark matter and variants (warm dark matter, etc)
- Star formation
  - Proper motions for cluster membership: determination of initial mass function (IMF) for a range of environments
  - Astrometric microlensing: precise measurement of stellar masses
- Extrasolar planets
  - Astrometric detection of planets
  - Accurate mass determinations

Example: Atmospheric Refraction

- Image stretched in direction of zenith
- Axis rotates during exposure
- Tracking removes offset
- MCAO can remove linear term
- Quadratic term small - reduce by modeling?

$\Delta\zeta \approx 0.00025 \tan\zeta$

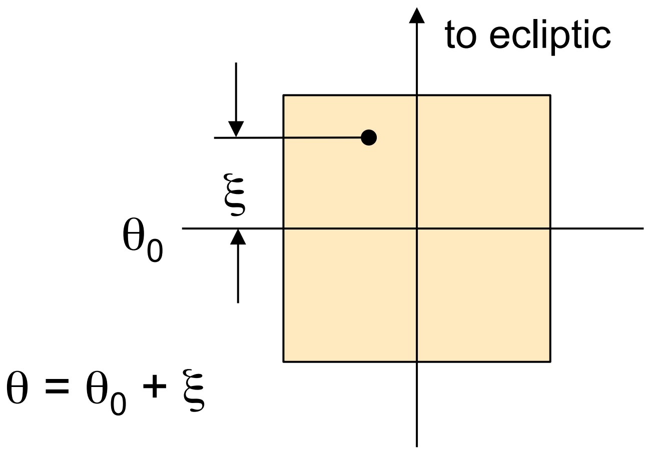


Expansion term	Type	$\zeta_0 = 45°$, $\xi = 1'$
$0.00025 \tan\zeta_0$	offset	~ 1'
$+ 0.00025 \sec^2\zeta_0 \, \xi$	anamorphic distortion	~ 35 mas
$+ 0.00025 \sec^2\zeta_0 \tan\zeta_0 \, \xi^2$	quadratic distortion	~ 10 μas
$+ 0.00008 (1 + 3 \tan^2\zeta_0) \, \xi^3$	cubic distortion	negligible

Example: Aberration

- Image compressed in direction of Earth's motion
- Slow, small, change during exposure
- Tracking removes offset
- MCAO can remove linear term
- Unimportant!

$$\Delta\theta \approx 0.00010 \tan\theta$$



Expansion term	Type	$\theta_0 = 45°, \xi = 1'$
$0.00010 \cos\theta_0$	offset	~ 14"
$+ 0.00010 \sin\theta_0\, \xi$	anamorphic distortion	~ 4 mas
$- 0.00005 \cos\theta_0\, \xi^2$	quadratic distortion	~ 0.6 μas
$+ 0.00002 \sin\theta_0\, \xi^3$	cubic distortion	negligible