Challenges for Quantitative Astronomy with ELTs

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Abstract. Extremely large telescopes will push the limits of astronomical observations to a level not achievable with the current generation of telescopes. It will be possible to observe to fainter magnitude limits and, with adaptive optics, with higher angular resolution due to the sizes of the primary mirrors. In addition, it is expected that "quantitative techniques" such as astrometry and photometry will achieve levels of accuracy not possible today. This requires controlling the error sources affecting such measurements, for example distortions caused by all parts of the optics, to a higher level of accuracy for much larger components than on current telescopes. It may also be necessary to develop new calibration procedures, observing techniques and post-processing methods in the more challenging cases. In this paper, we give an overview of the challenges this presents for the design, construction and operation of ELTs, concentrating on the example of precision astrometry.

1 Introduction

The coming generation of extremely large telescopes (ELTs) will expand many astronomy frontiers and open up entirely new areas that are currently inaccessible even with 10-meter class telescopes [see L. Simard's presentation at this conference]. This is achieved by the combination of the larger collecting area and the smaller size of the point spread function (PSF) in adaptive optics (AO) mode. It does, in turn, also mean that errors need to be controlled to tighter tolerances on larger components if the theoretical performance limit of an ELT is to be reached. When trying to estimate how close to this limit we can get for a specific science case, we find that many of the terms in an error budget are the same as those present for the previous generation of telescope, with the main difference being that their magnitudes need to be smaller, in some cases significantly. There are, however, also some error terms that were previously not taken into account because they were either negligible or because they did not apply to earlier systems and instruments.

Anticipating and evaluating this latter category of errors presents a particular challenge for producing a complete and accurate error budget. It is, however, necessary not only for estimating the expected performance of the system, but in particular for identifying potential show stoppers in the design of the telescope, AO system or instruments that would prevent us from reaching the full potential of the ELT. As designing to specifications is (almost) always preferable over retro-fitting, significant effort should be put into verifying the feasibility of the most challenging science cases. This can only be achieved by designing the observatory as a system and evaluating the combined performance of the telescope, AO system, instruments, structure and enclosure, even of the facilities and data pipelines in some cases. The result of such an effort is the best possible design for the specific ELT. As a "side effect" it will also yield prescriptions for observing procedures and data analyses for producing the best possible science result in the minimum amount of observing time.

1.1 Quantitative Astronomy

Most astronomy science observations are quantitative in some way. They might involve measurements of science object magnitudes, colors, positions, velocities, compositions, numbers or number densities, to name just a few. In general, we want to measure these quantities with errors that are as close to the theoretical limitations imposed by the perfect telescope of diameter D. With D being significantly larger for ELTs than for current telescopes, we thus expect to have much smaller errors for all important

ELT science cases involving these sorts of quantitative measurements. Among the most challenging measurements being thought of today are:

– High-contrast AO: resolving and characterizing faint objects very close to much brighter objects, such as planets in orbit around stars, presents unique challenges for the AO system(s), instruments and telescope. This is the subject of several other presentations at this conference and is therefore not described here.
– The expansion of the universe can, in principle, be measured directly with ELTs by looking for the change in the radial velocities of distant objects over extended amounts of time. This requires extreme absolute stability of the spectrometers used over times of many years or even decades.
– The planned ELTs have very stringent requirements for high precision and accuracy photometry and astrometry. These requirements are among the most difficult to meet, as well as to estimate, because they involve all parts of the observatory and their interactions and correlations.

For the remainder of the paper, we will concentrate on high-precision astrometry as an example of the challenges faced when trying to evaluate the performance of an ELT for one of these science cases. For the most part, the treatment is done in a general sense, although the case of high-precision relative astrometry with the Thirty Meter Telescpe (TMT) first-light AO system, NFIRAOS, is sometimes used as an example.

2 Astrometry with ELTs

One of the exciting prospects of studying the universe with an ELT is the potential for direct observations of movement of almost any kind of astronomical object. High precision astrometry, that is, measuring the exact positions of the science objects, is therefore one of the main drivers for the technical requirements of the planned ELTs. In the example of TMT, NFIRAOS is required to produce 50 micro-arcsec differential astrometry in 100-second exposures over a 30 arcsec field of view in the H Band. This error is supposed to fall as $T^{-1/2}$ to a systematic floor of 10 micro-arcsec, where T is the integration time. Thus, errors need to be controlled to two to three orders of magnitude smaller than the diffraction limit. By comparison, precision astrometry on current telescopes reaches levels of 100—300 μarcsec (and even below that in special cases), a similar factor below their diffraction limit (see, for example, [1–4]).

Such a precision, both for ELTs and the current telescope generation, can only be reached for differential astrometry in fields with many stars and with sophisticated data analysis techniques. In most cases, this is accomplished by taking many, relatively short exposures in order to control effects that change during an exposure, such as distortions caused by moving optics, rotator errors or atmospheric dispersion corrector residuals. Of course, exposures cannot be too short, as that would cause problems with the signal-to-noise ratio and observing overhead. Individual exposures are then combined, often by putting them onto a common grid through coordinate transformations that eliminate low-order distortions, and run through the data processing algorithm.

Even with complex post-processing techniques, astrometric errors can only be reduced to the tens of micro-arcsec level, if the input uncertainties are very tightly controlled. This imposes very challenging constraints on all parts of the opto-mechanics, including but not limited to the control of telescope, adaptive optics and instrument distortions and, in particular, their temporal variations; atmospheric dispersion correction accuracy and residuals; AO system performance and stability; and detector noise, pixel size and pixel irregularities.

3 Astrometry Error Budget

A detailed discussion of the 10 most important terms in the E-ELT astrometry error budget has been published in [5]. In a similar fashion, an error budget for astrometry with TMT is currently being developed. The TMT astrometry working group started by attempting to identify all potential sources of astrometric error, irrespective of their magnitude. These errors are currently being evaluated quantitatively, in order to identify dominant terms and potential methods for reducing them in the observatory design or by optimizing observation and post-processing procedures.

There are, of course, many different ways to set up such a budget, because many sources of error affect different aspects of the astrometric measurement and its precision. For example, the Strehl ratio delivered by the AO system, and thus the ratio of light in the core and halo of the PSF, determines the signal-to-noise ratio of the image, the effect the halo has on nearby sources and the potential to resolve faint sources next to brighter ones, among other things. In setting up an astrometry error budget, it is not important how exactly these different effects are categorized, as long as all of them are included. As the purpose of the astrometry error budget for TMT, at this time, is to serve as a design tool, we set up the budget as an “engineering budget”. That is, terms are organized by their causes, rather than by the effect they have in the focal plane. They are divided into 5 categories:

– Reference source and catalog errors
– Atmospheric refraction correction errors
– Other residual atmospheric effects
– Opto-mechanical errors
– Focal plane measurement errors

One of the first things one notices when working on this error budget is the dependence of almost every single term in the error budget on the details of the astrometry observations, such as whether absolute or differential astrometry is the goal, whether one observes a sparse or crowded field, what the time scales of interest are, etc. This causes not just quantitative changes in the magnitude of the errors, but qualitative differences as well. One also notices that many of the error terms are correlated and interconnected and cannot simply be added in quadrature. Some of these complications are described in the following sections, others will be detailed in a future publication once the TMT astrometry budget has been completed.

3.1 Reference source and catalog errors

This section describes astrometry error budget terms that are caused by differences between the real and assumed properties of the reference sources. Here, ‘reference sources’ refers to the objects in the science fields, most commonly stars, that are used to put the images onto a common grid. These can be the science objects themselves, or other sources that are also visible in the science field but are not physically associated with the science objects. Distant background galaxies/quasars or masers are examples of this latter category.

If the assumed properties of the reference sources have errors, this will cause errors in the astrometric data analysis. The most obvious case is the position of the stars themselves as taken from reference catalogs, as well as their proper motions. These cause direct errors in the astrometric grid, although their effect is different for absolute and differential astrometry. Depending on the science case, they can also be systematic (e.g. observations of the same field during the same night or of fields in which proper motions are correlated) or random (observations of many different fields or proper motion uncertainties that are randomly distributed in observations spanning several epochs). Uncertainties of the colors of the reference source and variability also causes errors, most notably through their coupling with differential atmospheric refraction or other chromatic effects.

More subtle effects are introduced through other unknown motions, such as binary star motion or gravitational lensing. If a sufficient number of observations can be taken during different epochs, it should be possible to characterize this kind of motion, but it might not always be possible if only a few observations are available. It can also significantly complicate data processing in crowded fields.

Finally, differential aberration and the use of non-point-source reference need to be considered. Aberration is the compression of the field (in one direction) due to the relative directions of the Earth’s motion and the velocity vector of the light coming from the reference sources. Fortunately, this effect is negligible once the lowest order terms have been removed in post processing. If non-point-source references (for example, distant galaxies) need to be used as reference sources, their finite size causes a random astrometric error. This error averages out in time, but the use of very long integration times and thousands of such references may be necessary to reduce it to the level of tens of micro-arcsec [5].

3.2 Atmospheric refraction correction errors

Atmospheric refraction is separated out from other atmospheric effects because it is one of the largest potential astrometry error sources, at least for some astrometry science cases. It causes differences between the observed and physical zenith angles of the observed objects and contributes an absolute term (which is irrelevant to most science cases) as well as two differential terms to the astrometry error budget:

– Achromatic differential refraction is due to the fact that different objects in the field are at different zenith angles. This term is large but consists mostly of low-order terms that can be taken out with coordinate transformations.
– Chromatic differential refraction (dispersion) is due to the index of refraction being a function of the wavelength of light. Thus, stars of different color exhibit different offsets due to atmospheric refraction. This error can be reduced in post-processing, if the colors of the stars and the atmospheric properties are known. However, any error in our knowledge of either causes astrometric errors.

In order to reduce refraction errors to acceptable values, it has been shown that atmospheric dispersion correctors (ADCs) are necessary [6, 5]. In fact, most likely a different ADC is needed for each wavelength band. Moreover, narrow-band observations might be required for the highest precision astrometry observations, although post-processing might take care of much of the residual errors in cases when the star colors are either all similar (such as in globular clusters) or well known.

Even with all these precautions, residual errors enter through several mechanism:

– Uncertainties in our knowledge of the star colors.
– Uncertainties in our knowledge of the atmospheric properties. This applies to both the absolute values of temperature, air pressure and humidity at the observatory site and the shapes of their profiles above the site.
– The residual atmospheric refraction after ADC correction even for the perfectly built and controlled ADC.
– Errors caused by imperfect manufacturing and positioning (rotation angle) of the ADC. In our budget, we count this as an opto-mechanical error, it is only listed here for completeness.

All of these potential error sources change in time, albeit at different timescales. We therefore get changing astrometric errors and uncertainties on time scales from intra-exposure to inter-epoch. The magnitudes of these effects range from negligible to large (compared to ELT astrometry requirements) and need to be considered on a case by case basis. In the end, some of these considerations will drive the observing procedures for different science cases.

3.3 Other residual atmospheric effects

Other (non-refraction) atmospheric effects include residual atmospheric distortions after AO correction, the “halo effect”, PSF elongation due to anisoplanatism and variable atmospheric effects such as transparency or the seeing. Residual atmospheric turbulence after AO corrections has several effects on astrometry:

– The absolute value of the residual tip/tilt mostly only affects absolute astrometry. It does have an effect on differential astrometry through the reduction of the signal-to-noise ratio and Strehl ratio of the observations, but this is generally a small contribution to the error budget.
– Differential residual tip/tilt causes changes in the plate scale of the images. These can be reduced to very small residuals through the aforementioned coordinate transformations.

- Higher-order residuals cause local distortions in the image plane. They are smaller in magnitude and average out faster than low-order modes, but can be one of the dominant error sources, especially in short-exposure images, if they are not well corrected. This is were the turbulence correction achieved by the AO system matters most. The higher-order the correction is, and the more uniform over the science field, the smaller is the residual astrometric error. Conversely, this translates into a shorter integration time to average out these errors to the same level. Note that all types of AO correction are preferable over no correction for this, and the smaller the residual the better, as the corrected wavefront always has a lower residual than that caused by atmospheric turbulence without correction. [The possible exception here are quasi-static effects, but those are generally caused by non-common path aberrations rather than elements inside the AO loop, as the latter average out in time.]
- Atmospheric residuals also cause PSF irregularities and the PSF is elongated in the direction away from the tip/tilt guide star(s), both of which cause errors and uncertainties in the determination of the center of the PSF.

All atmospheric turbulence residuals average out in time, most of them with a $T^{-1/2}$ dependence on integration time, T. This means that the averaging process is slow and that starting with the smallest possible residual in the first place is highly desirable.

The so-called halo effect is caused by stars being located on the halos of other stars in crowded fields. Uncertainties in our knowledge of the PSF, local irregularities of the halo and changes thereof in time then cause (variable) background gradients and thus astrometric errors. As with the errors above, the best counter measure is the highest possible AO correction and stability, both in time and across the field.

Finally, variable properties of the atmosphere such as overall transparency that, on first look, don't seem to have any effect on image position can also cause astrometric errors. Transparency variations cause the flux received by the detector to vary. If, at the same time, image motion is present (for example due to opto-mechanical distortions), we get astrometric errors. These errors are random if either the transparency variations or the image motion are random, but can be systematic if both are systematic during an exposure. An unintuitive property of this process is that even the random errors increase with the integration time of individual exposures. Strehl ratio variations due to turbulence strength changes have a similar effect.

3.4 Opto-mechanical errors

Any sort of distortion in the opto-mechanics directly causes an astrometric error. If these errors are low-order (such as those caused by the relative position of the primary and secondary mirror or focus errors), they can largely be corrected for with coordinate transformations during the data analysis process. Another example of a low-order distortion is the natural guide star probe arm positioning error in an MCAO system. This causes changes in the plate scale that can be taken out entirely if a sufficient number of stars is available in the field. Thus, it is only an issue for absolute astrometry or very sparse fields.

Rotator errors, atmospheric dispersion corrector imperfections or any other kind of distortion in the telescope or instrument can also cause astrometric errors that can be large compared to the desired astrometric precision [7]. These distortions are usually calibrated by observing a reference grid, such as a pinhole mask inserted into the focal plane or a known star field, and taken out in post-processing. Stability from calibration to calibration is then the main property driving this astrometric error.

3.5 Focal plane measurement errors

The statistical one-dimensional uncertainty caused by photon noise is given by

$$\frac{\lambda}{\pi D}\frac{1}{\mathrm{SNR}}, \tag{1}$$

where λ is the observation wavelength, D is the telescope diamter and SNR is the signal-to-noise ratio of the observation. This error is random and averages out as $T^{-1/2}$. Flat fielding and dark current also need to be taken into account. Both can cause random as well as systematic errors for astrometry.

The discrete nature (pixelization) of the detectors enters the astrometry error budget in two ways. First through the effect of the pixel size itself, as determination of the center of the PSF is only possible to a certain fraction of the pixel size. A second contribution is through pixel irregularities, both their shapes and intra-pixel sensitivity variations. These errors need to be assessed through careful, sub-pixel characterization of the detector.

The detector sensitivity is non-linear, especially as the fluxes get close to saturation. This non-linearity is usually carefully calibrated, but even a small calibration error can cause astrometric errors if the PSF is not centered exactly on a pixel, or between two adjacent pixels. It is interesting to note that this error increases with star brightness, contrary to most other errors.

In dense star fields, there often exist many stars that are too faint to be resolved close to the brighter stars in the field. This is known as confusion. Their flux is small compared to the brighter sources, but causes astrometric errors and uncertainties if they lie on the part of the PSF of the resolved sources that is used for position estimating. This error is systematic in the same field during the same epoch. It is random between different fields and can become random for the same field if the sources move with respect to each other from epoch to epoch. As with many other errors, the best way to deal with this error is through high-order stable AO correction, such that as many of these background stars as possible can be resolved.

4 Summary

The coming generation of extremely larger telescopes will provide many new exciting science capabilities. In order to reach an ELT's potential, it is necessary to reduce errors to much smaller levels than for the existing generation of telescopes. A large effort should therefore be spent on estimating the performance of the ELT and developing the error budgets for all science cases, but in particular for the most challenging ones. In this paper, we have described the terms that go into such error budgets, and the difficulties in estimating them, using the example of precision astrometry with adaptive optics. This is a challenging problem, but it is a necessary process in order to arrive at the best possible design given the science goals of the ELT. It will also result in instructions for calibration, observing and data processing methods for achieving very high accuracy and precision astrometric results.

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