Smart instrument technologies to meet extreme instrument stability requirements

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ABSTRACT

The performance requirements for the next generation of ground-based instruments for optical and infrared astronomy on current telescopes and future ELTs are generating extreme requirements for stability, for instance to carry out precise radial velocity measurements, imaging and spectroscopy with high contrast, and diffraction-limited performance at a level of tens of milliarcsecond. As it is not always possible to make use of a gravity-invariant focal station, flexure must be accommodated while still minimising thermal loads for cryogenic instruments. Variable thermal loads are another source of dimensional changes. High stability will require the minimising of the effects of vibration sources, either from the telescope systems or mechanical coolers. All this must be done while maintaining mass budgets, an especial challenge for large, wide-field, multi-object spectrographs.

Keywords: Flexure, Smart Structures, Active Instruments

INTRODUCTION

The theme of this SPIE symposium is Synergies between Ground and Space. It is instructive to think about the commonalities and differences between design constraints for astronomical instruments deployed on the ground and in space. Similarities abound in terms of spectrograph and imager optical designs, detectors, optical components such as dispersing elements and filters, data acquisition and so on, but there are also big differences. The very different operating and deployment environments include both the lack of atmospheric distortion and the need for artificial vacuum in space, and the varying gravitational force and its influence on the structural stability of ground-based instruments. There are also very different space, mass, thermal and cost constraints.

Four of the most critical design parameters for any instrument are mass, size, cost and dynamic error, where we define dynamic error as the effect on scientific performance of variable forces acting on the instrument during operation, such as vibration and varying gravity forces.

Space instruments generally need to be light and small to reduce launch costs, and dynamic errors are usually less critical than the need to be strong enough to survive launch loads. Absolute cost is usually higher than for ground-based instruments, although the constraints on cost can be severe – but we can safely assume that cost issues are more pressing for ground-based instrument teams. Current space instruments at visible- and IR-wavelengths do not have strong constraints on dynamic errors, but note that the James Webb Space Telescope has a fully-active, segmented, primary mirror to control wavefront errors [1].

On the ground, space envelope and mass constraints are less severe (but still cause problems for instrument designers). The main difference is that many instruments are mounted in a way that results in a variable gravity vector as the telescope tracks a field in the sky, causing flexure of the mechanical system and hence errors in the optical alignment.

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However, these differences do not mean that there are no lessons to be learnt from space instrument design which could benefit the next generation of ground-based instruments, particularly those needed for Extremely Large Telescopes (ELTs), as we shall show in later discussion of monolithic optical structures. We will now review current strategies for dealing with the effects of flexure, outline where further work is needed and finally propose a toolkit of 'smart' techniques which can be brought to bear on the problem. By 'smart' techniques we mean active elements and structures – actuators and metrology, new materials – lightweight optics and stiff and fully elastic structures, and new optical concepts which can enable more compact instruments. A combination of lighter optics, more compact optical layouts and fully elastic and stiff structures results in less and more predictable flexure – then we bring active elements into play to complete the solution.

THE NEED FOR ACTIVE INSTRUMENTS

As we moved from 4- to 8- and 10-metre class telescopes on the ground, dealing with flexure has been a serious concern for many instruments as their physical size and mass increased. The deflection of a structure due to gravity depends on the mass supported, the elastic modulus of the structure, and its linear dimensions. A very simple model would be a mass (M) supported on a cantilever beam of length L, where deflection is given by:

$$d = M.g.L^3 / 3.E.I$$

with E being the Young's Modulus and I the moment of inertia of the beam. Of course, a real structure is much more complex than this, but the very strong dependence on linear dimensions is still likely to be present. We can see that reducing the passive flexure of optical instruments can be achieved by reducing the mass of the optical elements, and using stiffer support structures, but this simple model indicates that even greater impact on deflections due to gravity can be made by reducing the dimensions of an instrument.

To what lengths this can be taken is determined by the spatial resolution mode in which the instrument operates [2]. The size of an instrument which is seeing-limited is proportional to the aperture of the telescope, giving rise to very large instruments such as the WFOS concept for TMT. At the other extreme, the size of a diffraction-limited instrument is independent of telescope aperture, as long as the field-of-view is also reduced proportionally. This consideration leads to the idea of exploiting photonic technologies to build swarms of tiny instruments [3].

Many instruments for future ELTs will be somewhere between these two extremes, with either seeing-enhanced modes of operation or Multi-Object Adaptive Optics (MOAO) over relatively wide fields [4], providing significant size and hence flexure challenges. Using extreme aspheres can help address these challenges by enabling more compact optical layouts. Reducing the size of optics in this way will also tend to reduce the mass, and will therefore multiply the benefit. Another proposed technique to reduce the size of seeing-limited ELT spectrographs is pupil slicing [5].

All these considerations push us towards big instruments – potentially as large as current telescopes. If we make these instruments from conventional materials such as steel, aluminium alloys and glass, then they will be very heavy, and this self-weight may induce unacceptable flexure even with the stiffest support structures. The problem becomes worse in cryogenic IR instruments, where support structures also encounter thermal constraints, so have to be relatively long and of reasonably small cross-sectional area even if made from low-thermal conductivity composites. The consequences of such big and heavy instruments are:

- Handling becomes awkward and adds expense
- Access to instruments is complicated
- Large Nasmyth platforms add to telescope and enclosure cost
- Additional mass makes flexure worse, resulting in heavier support structures – a vicious circle
- Thermal loads become greater due to increased thermal conductance of supports, and thus requiring heavier cooling engines (although it is only below 10K that conduction loads become a significant proportion of overall load)
- Thermal cycle time becomes greater increasing integration and test time – as well as causing logistical problems on the telescope

- Cost tends to increase proportionally with mass (although many methods used to reduce mass but not volume are also expensive)

There is an interesting parallel here with the design strategies taken with telescope structures over the last century. The 200 inch Palomar telescope was big and heavy, relying as it did on shipbuilding technology. Maintaining alignment of the primary and secondary mirrors was a critical challenge, which was solved by an engineer called Mark Serrurier[†] in 1935. He used a back-to-back arrangement of trusses in a ‘V’ arrangement, so that flexure of the top end of the telescope was equal to flexure of the primary mirror cell, and the primary and secondary mirrors moved parallel to each other, so that only focus adjustment was needed as the telescope tracked. This solution was almost universally applied until Ray Wilson’s development of the active telescope. ESO’s New Technology Telescope (commissioned in 1989) used wavefront sensors and a thin meniscus primary mirror which was corrected by applying forces to the back and sides of the mirror – combined with tip-tilt and focus drives on the secondary [6]. This solution became the default for most of the 8-10m class telescopes which followed it. So if this is so successful for telescope optics and structures, why have such solutions not become universal for correcting flexure in instruments? As we shall see, this is partly because it has been possible to get away with conventional solutions until now, but also because active instruments have had many practical problems to overcome. We contend that most of the next generation of instruments will have to adopt active solutions if they are to remain within sensible mass limits.

There are three basic types of instruments which need high stability:

- Spectrographs with high spectral resolution aimed at radial velocity measurements such as exoplanet studies or even direct measurements of temporal variation of interstellar absorption lines to directly measure the expansion of the universe as planned for CODEX on E-ELT [7]
- High contrast imagers with XAO for exoplanet imaging– EPICS on E-ELT [8]
- Large seeing-limited wide-field spectrographs – WFOS on TMT [9]
- Large multi-object spectrographs with MOAO – EAGLE on E-ELT [4]

Diffraction-limited, AO-fed imagers and spectrographs such as HARMONI and MICADO on E-ELT should be no more of a challenge than similar instruments on current telescopes, but they are likely to provide alternative modes with lower spatial resolution to exploit poorer atmospheric conditions when diffraction-limited performance is not possible, and science cases where non-spatially-resolved spectroscopy of very faint sources is required. Therefore, size, mass and hence flexure will be issues for nearly all ELT instruments.

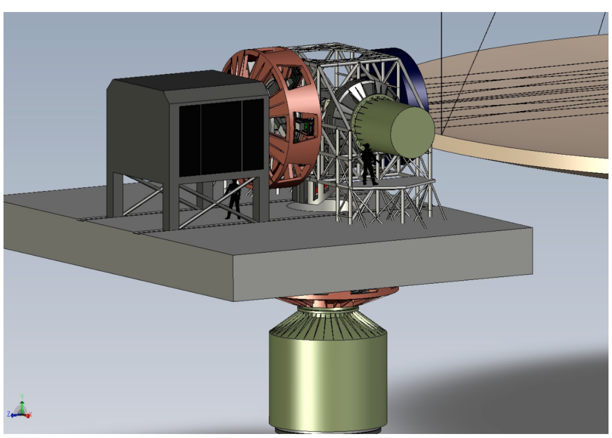

Figure 1 E-ELT Instrument Platform (ESO)

Consideration of size and flexure problems for instruments has led the three ELTs currently under intensive study to take different approaches. Both the E-ELT and the TMT have large Nasmyth platforms. However, the need to remove field rotation means most instruments will need to be mounted on rotators, with the consequent one-dimensional variable gravity forces. The ESO E-ELT team decided to implement two upward-looking instrument ports, where instrument rotation will not induce variable forces. The E-ELT also has a Coudé focus for ultra-stable high spectral resolution instruments. The Giant Magellan Telescope team have taken a different approach – all their instruments are mounted at the ‘Cassegrain’ focus behind the primary mirror, so will have to deal with two axes of variable gravity vector. However, this enables the GMT team to take advantage of the lack of Nasmyth platforms by having a very compact and stiff telescope, and a smaller and cheaper dome. These telescope architectures mean that all three ELTs will have to deal with gravity-induced flexure to a greater or lesser extent.

[†] Who later won an Oscar for his work on the *Moviola* film editing machine.

PREVIOUS WORK

The move from 4m to 8-10m class instruments resulted in many groups proposing solutions to the instrument flexure challenge, as summarised in Table 1. D'Arrigo et al [10] outlined the issues and proposed an active solution for a high-resolution spectrograph at the Gemini Cassegrain focus. This approach turned out to be too much of a challenge and the instrument was eventually implemented as a conventional fibre-fed instrument mounted off the telescope.

Table 1 Approaches to flexure control

Telescope	Instrument	Technology	Status	Reference
Gemini	GNIRS	Passive mechanical compensator	On Sky	Passive compensation of gravity flexure in optical instruments Hileman et al [11]
VLT	FORS	Passive	On Sky	FORS: a workhorse instrument for the ESO VLT Seifert et al [12]
Gemini	GMOS	Two-axis translation stage driven in open loop	On Sky	Scientific and technical performance of GMOS: the Gemini Multi-Object Spectrograph Crampton and Murowinski [13]
Keck	ESI	Tip-tilt collimator mirror driven in open loop	On Sky	Active flexure compensation software for the echellette spectrograph and imager on Keck II Kibrick et al [14]
Keck	DEIMOS	Tip-tilt mirror driven in closed loop	On Sky	The DEIMOS flexure compensation system: overview and operational results Kibrick et al [15]
VLT	X-Shooter	Tip-tilt mirror driven in closed loop	Under Development	X-shooter UV- to K-band intermediate-resolution high-efficiency spectrograph for the VLT: status report at the final design review D'Odorico et al [16]
LBT	MODS	Tip-tilt collimator mirror, driven in closed loop with IR laser reference source	Under Development	An Image Motion Compensation System for the Multi-Object Double Spectrograph Marshall et al [17]

Approaches used for dealing with flexure are:

- Fix the instrument in a gravity-invariant position and feed light to it via fibres or an optical relay
    - not always possible, particularly for medium to large fields-of-view, and IR fibres are still problematic
- Fix instrument on Nasmyth platform and remove rotation using K-mirror
    - Takes up space and adds more optical surfaces, suitable only for small fields-of-view
- Fix instrument on Nasmyth platform and remove rotation by software re-sampling
    - Only works for fast read-out imaging (not spectroscopy), and will add noise to the images
- Build instrument with very stiff materials so the flexure is less than that required for particular science needs
    - Results in heavy instruments and high thermal loads – which in turn increase the complexity of the cooling mechanisms for cryogenic instrument
- Build in passive compensation
    - Sensitive to vibration (if using pendulum type compensators) and non-elastic effects
- Apply open-loop compensation by tip-tilt mirrors or detector translation stages
    - Proven, reliable and relatively simple and cheap

- Sensitive to errors and temporal variations in flexure models – in particular non-elastic behaviour such as hysteresis in joints, backlash in mechanisms and thermal effects, so limited in accuracy of compensation
- Dynamic range limited

- Apply closed-loop compensation using integrated metrology
  - Needs light source such as pin-hole, laser or fibre and detector system.
  - May introduce stray light to science channels. Some designs use an out-of band source/detector combination, such as a NIR laser for an optical spectrograph [17]
- Dynamic observing modes – using smarter detectors
  - It is possible to use clever shuffle modes to correct image motion, but this is unlikely to be a noise-free process particularly at IR wavelengths

CASE STUDIES

We now look more closely at two approaches taken for open-loop and closed-loop flexure control. A successful example of the use of open-loop compensation is found in the GMOS seeing-limited multi-object optical spectrographs on both Gemini telescopes. They use a combination of careful mechanical design and active adjustment of the detector position in three orthogonal directions. The optical support structure was designed to minimise rotation or tilt of the image, and achieve elastic performance with low hysteresis. The detector arrays (CCDs) were mounted to a translation stage, driven by stepper motors, which incorporated mechanical advantage and a mechanism based on flexure hinges to provide mechanical advantage and hence the required sub-micron translation step increment. Flexure compensation using regularly calibrated look up tables enables the spectrographs to maintain image stability of better than 3 µm per hour, to achieve spectral stability of 2km/s at R=5000 [13]. This is probably the limit of what can be achieved with open-loop compensation due to the non-linear effects discussed earlier.

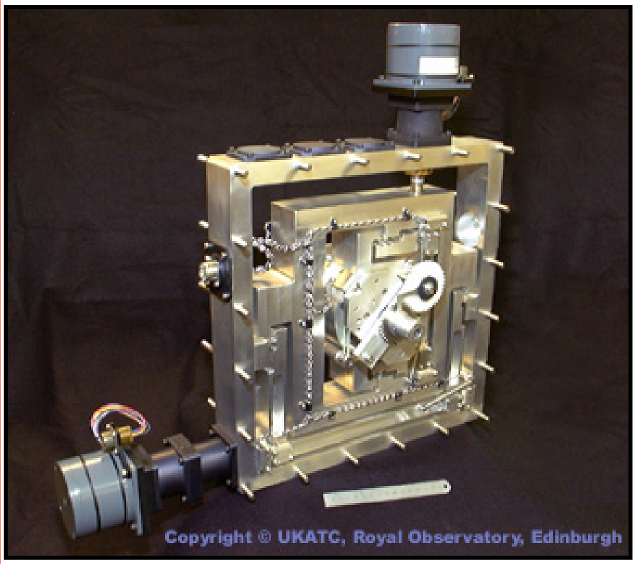

Figure 2 GMOS Detector Mount

An example of the application of closed-loop compensation is the X-Shooter UV-NIR wide band spectrograph now being assembled and tested for the VLT [16]. The need to maintain alignment of the slits of a three-arm spectrograph mounted at the Cassegrain focus results in stability requirements of 0.08 arcsec (0.04 goal) perpendicular to the slit, which equates to 0.72 (0.36) µm. Although FE modelling suggest this is just possible, active adjustment using piezo-driven tip-tilt mirrors in two arms of the spectrograph is incorporated to ensure that the specification is met. These active adjustments are carried out by minimizing the amount of shift between lines in arc spectra taken using a 250 µm (0.5 arcsec) pinhole in the A&G mirror, and similar spectra taken with a pinhole in each of the three slit units. It is planned that measurements will be taken after slewing the telescope, or every hour for long observations [18].

USUAL CONCLUSION

Despite these successes, it is notable that the requirements on stability for these two instruments are not very challenging compared with those of the proposed optical and IR high-resolution spectrographs, seeing-limited MOS and diffraction-limited AO-fed ELT instruments. The usual conclusion is that mounting high-precision instruments on non-gravity stable platforms is too difficult, and we should design our telescopes to incorporate gravity-stable focal positions if stability is really important. This results in big Nasmyth platforms, however, and major additional cost to the enclosure and telescope structure. The GMT team have taken a different approach, which is going to make life harder for their instrument builders, and we have seen that both TMT and E-ELT will have to deal with the effects of flexure to some extent.

PROPOSED SOLUTIONS

We propose a two pronged approach. Firstly, reducing size and mass will help reduce flexure to within controllable limits, although there are limits to the dimensions of seeing-limited instruments defined by spectral resolution and field-of-view. Secondly, we propose development of better active devices and techniques to control residual errors. A more radical future solution is to use photonics technology and fibre feeds to reduce dramatically the size of spectrographs by massive multiplexing [19] [20].

Reducing mass can be achieved through a combination of ultra-lightweighted metal optics as described by ter Horst at this conference [21], and the use of lower-density optical and structural material, such as SiC, CSiC and novel alloys such as aluminium/beryllium[22].

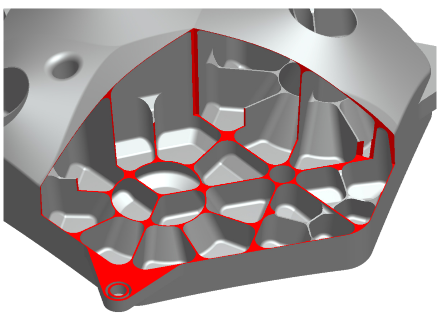

Figure 3 Ultra-lightweighted metal mirror (NOVA-ASTRON)

We can also increase the stiffness of support structures, by passive or active techniques. There is some scope to increase structural stiffness by using new composite materials, but this is often compromised by the lack of availability of data on materials properties, particularly at cryogenic temperatures. The most effective method is to make use of active components to increase the apparent stiffness. Lay at this conference promotes an idea for zero CTE trusses using an actuator and range gating (sub nanometre) sensor combination [24]. These active actuators can also include feedback by tracking of the deflections of optical images and spectra through the system, this will also have the benefit of removing the effects of non-elastic behavior.

A final piece in the armoury to enable highly stable instruments are the integrated modeling tools needed to design an optimize these complex opto-mechanical systems and their operation within a overall telescope and adaptive optics system. Several groups have made progress with such integrated modeling tools, but considerable work is still needed to make such tools more accessible and responsive to the needs of instrument engineers.

CONCLUSIONS

Many of the technologies needed to produce light, stiff and active instruments exist today. A question worth asking is - could we use them to build high-stability radial velocity spectrographs for applications such as exoplanet studies at non-gravity stable foci? This is very challenging – for instance the specification for the E-ELT CODEX instrument is 2 $cm.s^{-1}$ over ten years, equivalent to a stability requirement at the focal plane of a few thousandths of a μm. Returning to themes of Space-Ground synergy, there is the example of the GAIA instrument, where extreme stability is obtained by building an optical bench and reflective optics from one material, and having no moving parts in the optical path. However, reaching such stability is much easier in space, where the whole instrument can be at the same temperature, and there is no air to generate thermal gradients and turbulence. On the ground the equivalent is the HARPS instrument, where all components are held in a fixed-position vacuum chamber and never disturbed. It is hard to see how building a complete instrument and its supports could be done with a cryogenic IR instrument, except perhaps for a fibre-fed spectrograph. It is generally concluded that the only practical approach is to avoid gravity-variant locations when extreme stability is required.

However, for intermediate-stability instruments such as medium- and wide-field spectrographs we are starting to develop a range of tools to confront the challenges presented by ELT instruments. We have a proposal for the next phase of the OPTICON programme within the EU Framework 7 programme to develop these tools to make the improvements necessary for the next generation of challenging ELT instruments, summarised in Table 2. The programme will be a combination of evaluation of existing techniques as applied to ELT instrument concepts and development and prototyping of novel solutions.

Table 2 Smart Instrument Toolkit

Technique	**Technology**	**Partners**
Active Focal Planes	motor and piezo drives, flexure mounts	ASTRON, UKATC, CSEM
Active Structures	Piezo actuated tip-tilt mirrors	UKATC, ASTRON
Active Mirrors	Piezo actuated deformable mirrors	LAM, UKATC
Built-in metrology	Position and extension sensing, fibre and pin-hole illumination	UKATC, LAM
Highly Aspheric Mirrors	Compact spectrograph designs	LAM
Optical modelling of highly aspheric surfaces	Extensions to Zemax to allow modelling of extreme aspheres	LAM
Integrated Modelling Tools	To pull all technologies together	UKATC
New materials and corresponding characterisation data	To enable use of these materials	UKATC, ASTRON, ESO

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