Scientific Requirements for Extremely Large Telescopes
Proceedings IAU Symposium No. 232, 2005
P. Whitelock, M. Dennefeld & B. Leibundgut, eds.

doi:10.1017/S1743921306001098

Novel technologies required to meet ELT science challenges

Colin Cunningham[1] **and David Crampton**[2,3]

[1]UK ATC, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
email: crc@roe.ac.uk

[2]TMT Project, MC102-8, Pasadena, CA91125, USA

[3]National Research Council of Canada, 5071 W. Saanich Rd, Victoria, Canada

Abstract. We review the need for technology developments to meet the science cases that have been assembled for optical and infrared telescopes from 20 to 100 metres. Novel technologies can make an impact on the scientific capabilities of these ELTs, make them more affordable and decrease the operating costs. We consider those technologies highlighted by design studies and technology roadmapping exercises on both sides of the Atlantic, with particular emphasis on instrumentation. We do not consider adaptive optics (AO), which is covered by Ellerbroek & Hubin (this volume). Finally, we recommend a joint technology development programme to enable a world-wide suite of ELTs to be built.

Keywords. Telescopes – Instrumentation – Technology

1. Introduction

Plans and concepts for ELTs are at various states of development by many organisations and teams round the world. Making the step from the current generation of 8-10 metres telescopes to 20, 30 or even 100 metres primary mirrors, without costs reaching outside what might be reasonably expected from funding bodies, needs technology improvements. Previous step-changes in telescope diameter have been enabled by new technology and engineering techniques. The 200 inch Hale telescope was made possible by adopting engineering from ship design, the 8m ESO VLTs, Gemini and Subaru telescopes by computer controlled active optics and thin meniscus mirror manufacturing, and the 10m Keck telescopes by the innovative development of segmented primary mirrors. It is further development of this latter technology that will facilitate the next big step. We also expect innovations in instrument design to combine with advanced adaptive optics to vastly improve the efficiency of observations over relatively wide fields, and to enable extremely high spatial-resolution and sensitivity.

In attempting to meet the requirements flowing from the scientific ambitions for ELTs, the instrument concepts that have been considered so far are very complex and will be expensive. It is noteworthy that current costings and estimates for ELTs will not allow all these ambitions to be met. We suggest that a systems approach could be taken to meeting global astronomy requirements, where a range of telescopes could be built, each optimised for particular areas of astronomy and equipped with complementary instruments. Of course, this would only work with coordinated operations and access provisions.

2. Evaluation of technology readiness

Technology innovation is needed in astronomy for the following reasons:

- To enable new science by opening new parameter space
- To increase the efficiency of observations
- To enable the facility to be built at affordable cost
- To reduce the risk to time and budget
- To reduce operating costs and telescope down time

From a risk reduction and cost control viewpoint, we would prefer to proceed with no innovation, but it is usually impossible to make significant advances in science capability within reasonable cost bounds without using new technologies. However, as telescopes and their associated instrumentation become larger and more expensive, it is essential that technological risk is managed to ensure that costs are controlled. The aerospace industry has used the concept of technology readiness levels (TRL) for many years to evaluate status of development and the optimum timing of incorporation of new technologies into facilities and equipment. The TRL evaluation scale as used by NASA (Mankins 1995) is:

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in the operating environment
TRL 8	Actual system completed a 'flight qualified' through test and (ground or space) demonstration
TRL 9	Actual system 'flight proven' through successful mission operations

In our environment, we can replace 'space' by telescope – note that we would expect technologies to have reached TRL 7 before incorporation into an ELT, as demonstrated by operation on a 4-10 m telescope.

3. Technology roadmapping

In Europe, the OPTICON Key Technologies Network (KTN) has been developing a technology roadmap towards Extremely Large Telescopes and their instruments. OPTICON is a European Union funded programme providing telescope access, networking to promote joint infrastructures, and specific Technology Development activities (Davies 2004). The Key Technologies Network aims to:

- Identify key technology needs
- Look for opportunities that technology developments in other sectors provide for astronomy
- Encourage collaborative European technology development projects
- Provide a forum for discussing potential routes for further development, particularly looking ahead to EU Framework 7

To date, the KTN has held workshops to develop roadmaps for both technology and optical components for ELT Instruments (Spanó *et al.*, in preparation). Future workshops will concentrate on technology test-bed facilities, IR detectors, deformable mirrors and IR fibres.

The roadmapping process used is that developed by the Cambridge University Institute for Manufacturing (Furrukh *et al.* 2003). It is based on techniques normally used to plan timely technologies to enable products to meet market opportunities. We regard the science goals to be analogous to market opportunities, telescopes and instruments as products, and components and devices as enabling technologies. Clearly, the lower levels must be developed in good time to be applicable to the higher levels. Two simplified examples are given in Table 1.

Table 1. Two examples of technology roadmapping

First light +6	*Science Goal:* Understanding galaxy formation & structure of the Universe
First light +5	*Technique:* High-redshift galaxy surveys
First light +3	*Facility or instrument:* Wide-field MCAO and MOAO, IR MOS spectrometers
Now to 5 yrs	*Enabling Technology:* 3D energy sensitive detectors, smart focal planes, modular spectrometers, IFUs, fibres, OH suppression, MOEMS, cryomechanisms lower cost IR detectors

First light +6	*Science Goal:* Understanding extra-solar planet evolution
First light +5	*Technique:* Imaging and spectroscopy of planets near bright stars
First light +3	*Facility or instrument:* Extreme AO, coronography, differential imagers, polarimeters
Now to 5 yrs	*Enabling Technology:* High-density deformable mirrors (DMs), coronographs, modelling, control of stray light, filters, differential imaging, smooth optical components

The critical steps in this roadmapping activity are to evaluate the TRL, then determine a programme to move technologies up through the readiness levels in time for application in the telescope or instrumentation. Clearly, the choice of many telescope technologies needs to be frozen at an earlier stage than some AO and instrument technologies, which could be provided by upgrade paths or later generation instruments.

As pointed out by Ray Carlberg at this symposium, cost constraints are the key to making decisions about which technology can be adopted, and consequently what science is possible with the facility. We can ask for everything, and think of many clever technologies, but budgets will constrain what is really possible as can be seen from the TMT, OWL and Euro50 design studies. This may be visualised by the classic *cost: scope: time* triangle concept, which demonstrates that any real project has to be a compromise, i.e. optimised to deliver maximum scientific capability for an affordable cost and on a timescale competitive with, and complementary to, other facilities. Each of the three axes needs to be constrained by requirements and targets, but with enough flexibility to allow project managers and engineers to make constructive trade-offs.

4. R&D for ELTs

Two European Union funded programmes of technology development are being carried out by teams of collaborators – the OPTICON Joint Research Activities, and the ELT Design Study. In the US, the TMT and GMT projects are carrying out or funding similar programmes. Many of these are carried out by industry under contract, with the specific aim of increasing awareness and capability for ELT technologies in industry.

As part of the OPTICON programme, Joint Research Activities are being undertaken by consortia of European partners, several of which are aimed towards technologies needed by ELTs and their systems and instruments, in particular programmes on

Adaptive Optics (AO) devices & systems, AO detectors, Smart Focal Planes and volume-phase holographic (VPH) Gratings.

The European Union funded Framework 6 (FP6) ELT Design Study is undertaking a comprehensive programme of research and development on critical technologies that are independent of telescope layout. Some examples are:

- Silicon carbide mirror segments
- Large, high actuator-density deformable mirrors
- Friction drives & magnetic levitation
- Structural ropes & composite structural elements
- Instrument concepts and interaction with telescope requirements
- Integrated modelling

5. ELT technologies

5.1. *Telescope & enclosure*

From the TMT perspective, most of the technical development is incremental, and largely related to driving costs down. Examples include:

- Cost-effective manufacturing of large quantities of aspheric segments for the primary mirror,
- More cost-effective enclosure designs
- Development of a much more capable alignment and phasing system for the 738 primary segments
- A sophisticated observatory control system to optimize scientific return

Parallel developments are being carried out in Europe in the FP6 ELT Design Study with the specific aim of determining whether it is possible to build a large segmented telescope without a co-rotating enclosure, saving a considerable proportion of the overall cost. In particular, the Active Phasing Experiment (APE) and Wind Evaluation Breadboard (WEB) will develop prototype phasing metrology systems and evaluate the wind forces on a representative set of mirror segments in a realistic telescope environment.

5.2. *Adaptive optics*

All ELT designs are dependent for success on major improvements to adaptive optics systems. This topic is covered thoroughly by Ellerbroek & Hubin (this volume).

5.3. *Instrumentation*

It is vital that instruments are considered as part of the complete observatory system in order to ensure that ELT designs are capable of fulfilling their ambitious scientific goals. In particular, it is important that the telescope is ‘future proofed’ so that it is compatible with the more ambitious instruments that will be built following a more limited first light suite. Some of the engineering trade-offs which come into consideration when thinking of the whole system are where critical functions are carried out, including flexure control, wavefront measurement and correction, atmospheric dispersion correction, image de-rotation and field flattening. The major drivers here are overall system cost and performance. For instance there are potential cost savings for the telescope structure and enclosure by not providing gravity stable platforms, but this could result in overly complex compensation schemes within instruments, and may preclude reaching some science goals requiring high stability.

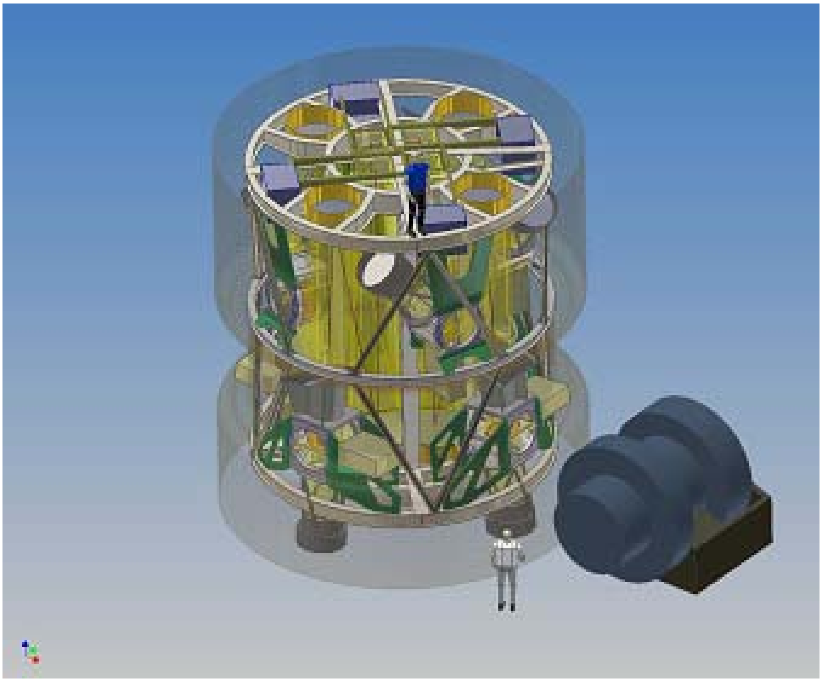

Figure 1. The WFOS concept for the TMT, shown next to the Keck-DEIMOS space envelope (Courtesy of Scott Roberts, HIA)

5.3.1. *Seeing-limited instruments*

The case for seeing-limited or ground-layer corrected instruments is particularly strong for telescopes of less than 40m aperture, and especially for spectroscopy of high redshift galaxies. However, as telescope aperture is increased, serious issues of optical apertures and final focal-ratio with available detector arrays start to make seeing limited instruments very large, difficult to design and expensive (e.g. Russell *et al.* 2003). Even for a 30m telescope such as TMT, a seeing-limited instrument with a 20 arcmin field such as the WFOS concept is nearly as big as an 8m telescope – 8m diameter and 10m high (Figure 1).

Challenges of such instruments, apart for sheer size, weight and cost, include the practical size of optical elements – 1.5m is probably an upper limit for transmissive optics due to cooling rate issues, and controlling flexure. Some of the novel optical technologies which need to be developed are:

- Light-weighted mirrors in novel materials such as carbon silicon carbide (CSiC), zero-expansion pore-free ceramics (ZPF), carbon fibre composites (CFRP) and associated advanced polishing techniques
- Large lenses & windows (see Hartmann *et al.* 2006)
- Large filters including mosaics
- Silicon immersion gratings with low scattered light
- Large volume-phase holographic (VPH) gratings
- OH suppression devices, such as fibre Bragg gratings (Bland-Hawthorn *et al.* 2004)

5.3.2. *Diffraction-limited near-IR instruments*

The size of a diffraction-limited instrument does not increase with telescope aperture, as long as the field-of-view is reduced commensurately. Hence, the information content of

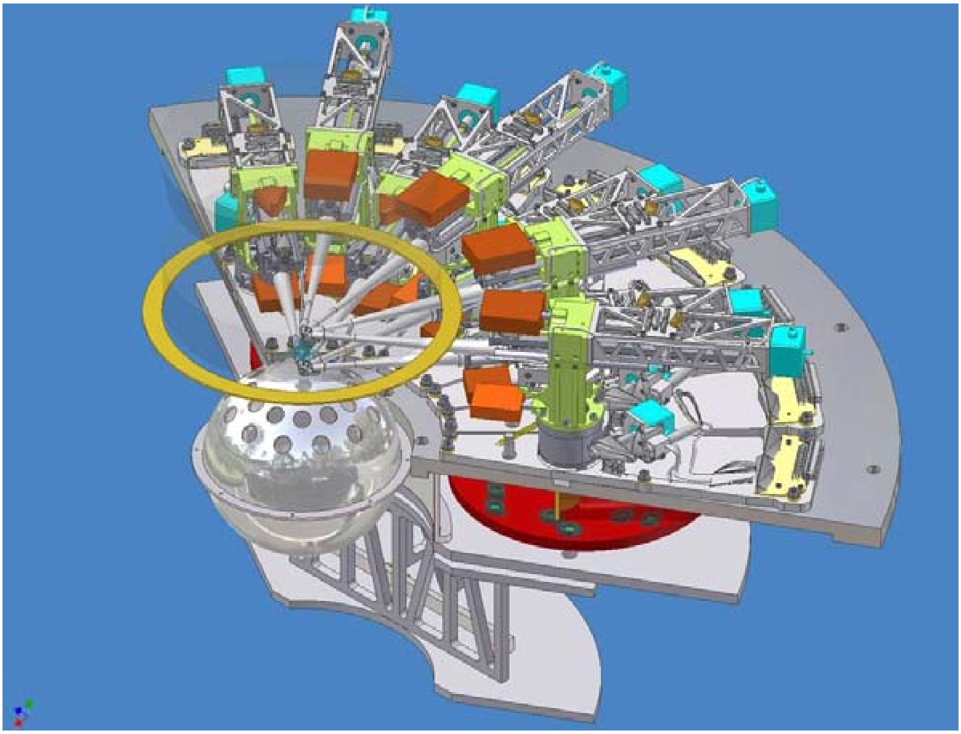

Figure 2. The KMOS smart focal plane, showing one third of the pick-off arms.

the field of view remains constant. The design of 8-10m instruments such as KMOS for the VLT (Sharples *et al.* 2004) could be adapted to meet this requirement. Naturally there is pressure to increase the field-of-view within the practical limits of wide-field adaptive optics capabilities, in order to improve the multiplex capability to maximise the science output of these very expensive ELT facilities. Technology solutions which are needed to readout such high information content include very large mosaic arrays of IR detectors (with the consequent need to reduce their cost), and the Smart Focal Plane devices such as cryogenic beam-steering mirrors, robotic pick-off mirrors and programmeable MOEMS slit masks being developed under the OPTICON programme (Cunningham *et al.* 2004). Challenges for all near-infrared (NIR) diffraction-limited instruments are in maintaining image quality, controlling wavefront errors to less than 50nm, controlling vibrations and understanding AO PSFs well enough to carry out efficient sky subtraction.

5.3.3. *Challenges: Thermal IR diffraction-limited instruments*

There is a strong science case for thermal IR on a ground-based telescope of more than 30m diameter, particularly to complement the JWST MIRI instrument by providing high spectral resolution capabilities not available on JWST. However, operating from 5 to 28 microns provides challenges in minimizing the emissivity of the telescope and associated warm optical systems, while sky subtraction becomes more difficult as large secondary mirrors are unlikely to offer chopping capabilities. To compete with space based facilities, it is likely that low-order adaptive optics systems will be needed, and these may have to be operated within the cryogenic environment with consequent challenges for development of deformable mirrors.

5.4. *Challenges: Detectors*

Exploitation of the maximum scientific potential of ELTs in the IR may be limited by the cost and performance of IR detectors. Current 2k by 2k science arrays show impressive performance but are still some way from ideal high-quantum efficiency and low-noise performance, and are much more expensive than equivalent CCDs. Alternatives to the current hybrid devices using direct growth of HgCdTe on silicon may offer cost and systems integration advantages (e.g. Hall *et al.* 2004). Wavefront sensing at the same wavelength as the observing instrument has some advantages (Owner-Petersen & Goncharov 2004), but IR detectors with 5e noise at high readout rates of up to 500Hz need more development.

A relatively unexplored field of astronomy is high time-resolution astronomy, which will be much more feasible with the increased sensitivity of ELTs. Instruments to record single photon events at time resolution of up to 30ns require new generations of fast CCDs and avalanche photo-diode arrays. At longer wavelengths, current state of art submm arrays such as developed for SCUBA 2 have a maximum pixel count of around 6000. Producing a submm camera for a 50-100m telescope at 200 or 450 microns would require development of much higher density arrays and readout systems.

It is noteworthy that nearly all astronomical detectors are limited to measurement of the intensity of light. Development of energy sensing detector arrays, with pixel counts well beyond current superconducting devices, could open-up new opportunities for simpler spectrometer optical designs, with much of the spectral resolution being provided by direct measurement of photon energy. In future, new modes of science may be opened up by development of sensors which also measure phase, energy, polarization, photon arrival time and even angular momentum.

5.5. *An integrated instrument suite – based on smart focal planes*

One estimate of the real cost of operating an ELT is $300k per night. There is an obligation to make cost-effective use of available observing time, and to exploit periods with the best weather and seeing conditions. It is worth considering if the multi-object concept could be enhanced so that pick-offs could be used to observe objects in field simultaneously with different 'instruments' using a range of spatial and spectral resolutions and wavebands. It is worth considering whether there are compelling science cases for such a 'Smart Instrument Suite', observing multiple objects in a common AO corrected field, perhaps exploiting variations in spatial resolution across the field to optimise the deployment of instruments as in Figure 3. Of course, there would be considerable additional operational and hardware cost for such a complex arrangement.

6. Critical technologies for ELTs

In summary, we regard developments in these areas as critical to achieving cost-effective and scientifically productive ELTs:

- AO-systems, WFS, large deformable mirrors, miniature high actuator-density DMs, laser guide stars;
- Lightweight segment materials, high-throughput manufacture and metrology;
- Durable mirror coatings;
- IR detectors – science & WFS;
- High performance control systems;
- Instrument components – beam steering, cryogenic DMs, large lenses & filters, VPH gratings, IR fibres, in-fibre Bragg gratings.

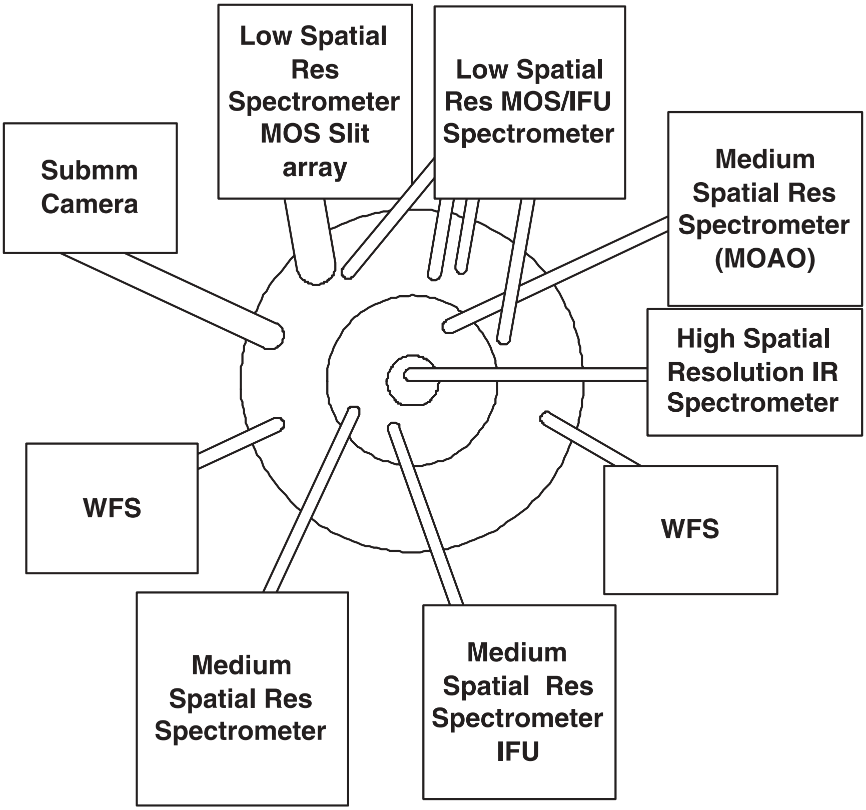

Figure 3. A smart instrument suite.

In order to build ELTs with the best performance for the least expense, it is essential that a balance of scope, innovation and feasibility is achieved. It is necessary to evaluate Technology Readiness Levels to decide when to freeze technology and hence telescope, AO and instrument concepts to give adequate time for design and build phases, and to control risk. Equally, innovation is necessary to enable ELTs and their systems at reasonable cost and to the high levels of performance demanded.

The best route to successful development of these technologies to a usable TRL would be through a coordinated global programme, in particular for optical materials, laser guide stars and detectors, where development costs are very high. A model for such global development could be the European collaborative programmes funded by the EU. Such a coordinated R&D programme could be the first step towards a world-wide ELT project, possibly aimed at developing a suite of telescopes optimised to specific science cases.

7. A global systems approach to addressing science goals

Given the intense interest world-wide in developing ELTs over the next decades, and the very high capital and operating cost of such facilities, there is a strong incentive for pooling resources. The current crop of 8-10m telescopes have been developed in a competitive environment with little cross-collaboration – although there is some evidence for this changing as the next generation of ambitious instruments is planned. It would be attractive from a cost-effectiveness point of view to move to a more collaborative model. Several ELTs could be built, all attempting to cover a very wide range of science at visible to submm wavelengths, and from high spatial-resolution narrow-field to wide-field seeing-limited. This will be very expensive, and possibly unfundable. An alternative might be to fund a global ELT suite, where each telescope is based on common technology, but specialises in terms of waveband and field-of-view. This could be especially attractive in avoiding driving site choice and telescope emissivity to suit long-wavelength observation for each telescope. An option might be three specialised telescopes chosen from:

(*a*) High-redshift Galaxy & Cosmology Explorer (complement SKA, WFMOS): Wide-field, GLAO, MOAO, 30-50m

(*b*) High-resolution Planet and Stellar Explorer (complement Darwin, TPF): Narrow-field, low scattered-light, high spatial and spectral resolution, 20-50m

(*c*) Mid IR and Submm Explorer (complement JWST, ALMA): Low emissivity, dry site, no or minimum AO, 50m

(*d*) Blue-optimised Explorer – although that would be better addressed by a large UV/blue space telescope

Such an approach would have some downsides: not being able to independently confirm results if only one of the ELT suite can do a particular observation; sky coverage would be an issue; and it may reduce healthy competition during build phase. However, taking a systems engineering approach to providing a global astronomical ELT facility is worth careful consideration. At least, it would be very advantageous to set up a global R&D programme to address some of the common issues outlined here. It has been suggested that this could be done through an ELT club which would act in a coordination role and enable a larger market to be presented to industrial manufacturers.

8. Acknowledgement

OPTICON has received research funding from the European Community's Sixth Framework Programme under contract number RII3-CT-001566.

References

Bland-Hawthorn, J., Englund, M. & Edvell, G. 2004, *Optics Express* 12, 5902

Cunningham, C.R., Atad, E., Bailey, J., Bortoletto, F., Garzon, F., Hastings, P., Haynes, R., Norrie, C., Parry, I., Prieto, E., Ramsay Howat, S.K., Schmoll, J., Zago, L. & Zamkotsian, F. 2005, *SPIE* 5904 in press

Davies, J.K. 2004, OPTICON: The EU Optical Infrared Co-ordination Network. *Proceedings of the 2004 Joint European Astronomy Meeting, Granada, Spain*, in press

Farrukh, C., Phaal, R. & Probert, D. 2003, *International Journal of Technology Management* 26

Hall D.J., Buckle, L., Gordon N.T., Giess, J., Hails J.E., Cairns, J.W., Lawrence, R.M., Graham, A., Hall, R.S., Maltby, C. & Ashley, T. 2004, *SPIE* 5406, 317

Hartmann, P., Döhring, T., Jedamzik, R. & Loosen, K.-D. 2006, *AN* in press

Mankins, J.C. 1995, *Technology Readiness Levels: A White Paper, Advanced Concepts Office*, Office of Space Access & Technology, NASA

Owner-Petersen, M. & Goncharov, A.V. 2004, *SPIE* 5489, 507

Russell, A.P.G., Hawarden, T.G., Atad, E., Ramsay Howat, S.K., Quirrenbach, A., Bacon, R. & Redfern, R.M. 2004, *SPIE* 5382, 684

Sharples, R.M., Bender, R., Lehnert, M.D., Ramsay Howat, S.K., Bremer, M.N., Davies, R.L., Genzel, R., Hoffmann, R., Ivison, R.J., Saglia, R. & Thatte, N.A. 2004, *SPIE* 5492, 1179