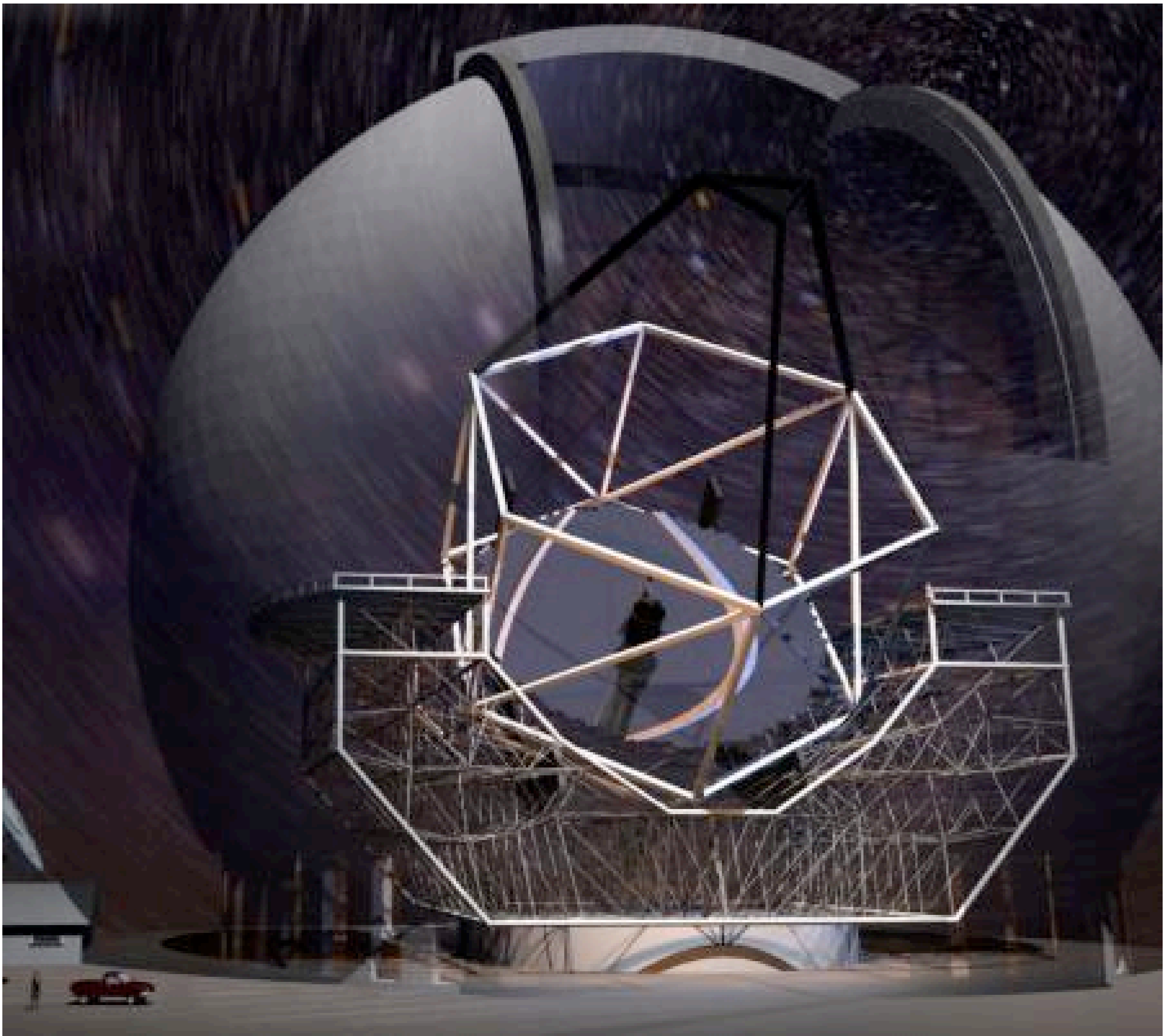

Extremely Large Telescope Roadmap

Cover figure: Artist's impression of the proposed Thirty-Meter Telescope in a cut-away dome, with a backdrop of star trails. Image courtesy of the Thirty-Meter Telescope Project, California Institute of Technology and Todd Mason, Mason Productions.

ELT Roadmap

Towards Australian Involvement in an Extremely Large Telescope

ELT Working Group

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Executive Summary

Extremely Large Telescopes (ELTs) are key future facilities for optical and infrared astronomy. Their enormous main mirrors will collect from 10 to 100 times as much light as the world's largest existing telescopes, and will produce images far sharper than those of the Hubble Space Telescope. They will be able to see the first stars forming in the universe billions of years ago and search out Earth-like planets around nearby stars for signs of life. Australia should seek a substantial share in the design and construction of an ELT (a $1 billion international project) in order to maintain its position at the forefront of astronomical research and to exploit the technological and industrial benefits from an ELT's R&D and construction programs. Australia should also explore its Antarctic advantage – the best site on Earth for large telescopes may be Dome C in the Australian Antarctic Territory. This roadmap lays out the necessary first steps for Australian involvement in an ELT. There are three main components:

1. **Smart Buyers**: Australia has the opportunity to choose which international ELT project to join. To make a well-informed choice – to be 'smart buyers' – Australia needs to understand the relative merits of each of the ELT programs in terms of their science, technology and organization. This requires close interaction with the various ELT programs and a thorough evaluation of their costs and benefits. The cost of this component for the period FY2004-7 is approximately $2.9M.
2. **Technology Leaders**: Australia offers world-leading technologies in a number of areas that have potential application to an ELT. These technologies need to be developed as potentially valuable contributions to an international ELT project, so that Australia is positioned to re-coup a significant part of its investment in an ELT through contracts to supply these technologies. The cost of the various studies in this component for the period FY2004-7 is approximately $13.4M.
3. **Antarctic Advantage**: The Dome C site in Australia's Antarctica Territory is potentially the best site on Earth for large telescopes. This potential may be realised through a three-stage approach: first, studies to extend the site characterisation and optimise the design and operational model for a telescope on the high Antarctic plateau; second, PILOT, a 2-metre telescope providing new astronomical capabilities to Australian astronomers and serving as a Pathfinder for an International Large Optical Telescope; finally, depending on the outcomes from the first two stages, an international collaboration to construct an Antarctic ELT. The cost of the first-stage studies over the period FY2004-7 is approximately $2.0M, with the PILOT facility itself costing an additional $8.0M.

Together, these components provide the essential foundation for maximizing the scientific, technical and strategic benefits of Australian involvement in an ELT.

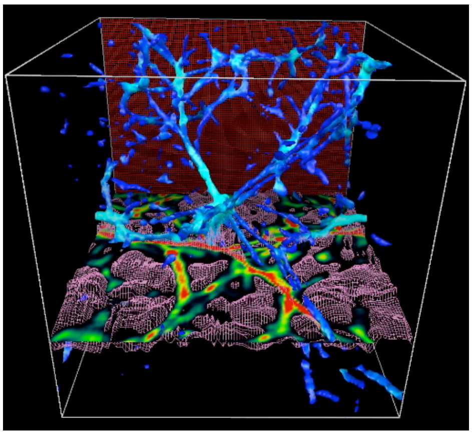
1 Purpose

The coming generation of Extremely Large Telescopes (ELTs – telescopes with main mirrors from 20 metres up to 100 metres across) represent the future horizon for optical and infrared astronomy. The purpose of this ELT roadmap is to provide a plan for the next steps towards Australian involvement in an ELT. It includes a review of the critical issues for such involvement, a summary of the case for ELTs and an overview of the international landscape of ELT projects and Australia's options for involvement. The critical element of the roadmap is the description of the work that is required to inform Australian decisions and position us to play a significant role in the next generation of these front-line astronomical facilities.

2 Science

What are the key scientific questions that can be addressed by ELTs? The answers depend on the size of the telescope…

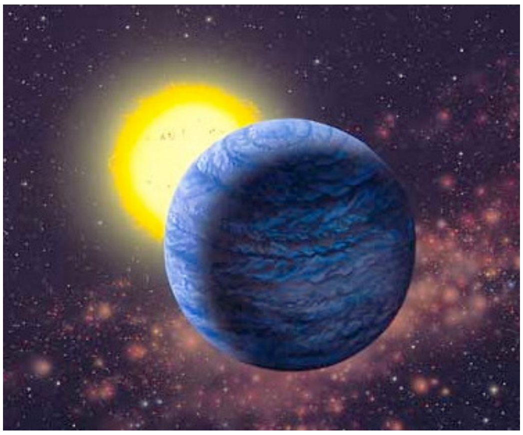
- *20-30-metre ELTs:* The science cases for 20-30-metre ELTs are spelt out in several documents, including the CELT Green Book and the GSMT Science Working Group report. Highlights include:
  - *Mapping gas, stars and dark matter in the early universe.* A 30-metre telescope can detect the absorption due to hydrogen clouds in the intergalactic medium at high redshift by using bright star-forming galaxies as background sources. A survey of a large volume of space could map these clouds' locations with sufficient resolution to allow the tomographic reconstruction of the large-scale gas distribution when the universe was only 10% of its current age. Combined with a map of the galaxies, this would reveal the distribution of dark matter at early times. It would also show how galaxies are formed from primordial gas clouds, and how elements produced in supernovae enter the intergalactic medium.



  - *The formation of galaxies.* A 30-metre telescope will be able to study the spectra of the first pre-galactic building blocks to form stars. It will measure the evolving physical properties and assay the chemical mix in the earliest generations of the stellar populations in galaxies. A different approach to the same problem will be the analysis of the archaeological record preserved in the chemical composition and orbital motions of the stars in the Milky Way and other members of the Local Group of galaxies. Identifying cohorts of stars with common chemistry and motions will allow the history of star-formation and mergers in each galaxy to be unravelled, and link the modes of formation to the present-day properties of galaxies.

- *Exploring other solar systems.* A 30-metre telescope with extreme adaptive optics will be able to image Jupiter-like gas-giant planets around other stars. Young gas giants could be imaged up to 200 light years away, and more mature gas giants at distances up to 60 light years. It will be possible to carry out spectroscopic analysis of the atmospheres of these giant planets and determine their chemical make-up. A 30-metre telescope will also be able to explore the disks of gas and dust in which new planetary systems are formed, and hunt for proto-planets by looking for the gaps in the dust rings that they produce. Together, these observations will vastly extend our understanding of the birth and properties of planetary systems.

- *50-100-metre ELTs:* In addition to the science goals above, diffraction-limited imaging and spectroscopy on a 50-100-metre telescope would allow the direct detection and characterisation not just of Jupiter-like planets but also of Earth-like planets around other stars. In order to be able to look for terrestrial planets around thousands of host stars, the telescope would need to probe stars out to 100 light years, which imposes the challenge of suppressing the star's light by a factor of 10^{10} at radii of only 20-300 milliarcseconds. Potentially, such a telescope would be able to search for signatures of life in the planetary atmospheres using bio-markers such as chlorophyll and ozone.

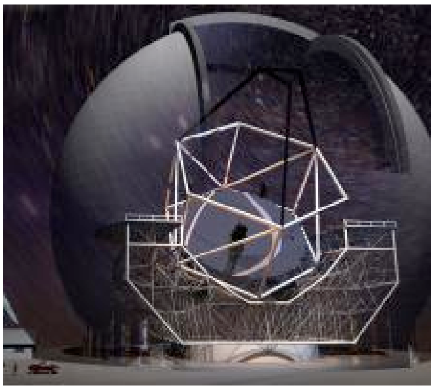


The science that we can currently predict will emerge from ELTs is exciting and fundamental, clearly justifying their construction. However experience shows that the most important scientific discoveries made by each previous generation of new and more powerful telescopes have been unexpected ones. The universe appears to be more imaginative than we are, and facilities with new capabilities invariably reveal new phenomena (like gamma ray bursts) that lead to a more expansive view of the physical universe.

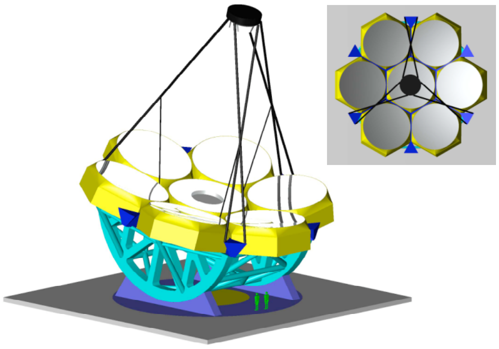
Australian involvement in an ELT will have important complementarities and synergies with other major astronomical facilities to which Australian astronomers will have access. These include existing and soon-to-be-completed telescopes (such as the Anglo-Australian Telescope, the ANU telescopes including the new Skymapper, the Parkes radio-telescope, the Australia Telescope Compact Array and the Gemini 8-metre telescopes), potential future facilities (such as the Square Kilometre Array radio telescope – SKA) and non-Australian facilities that Australian astronomers can access (e.g. the Hubble Space Telescope and Next Generation Space Telescope).

3 ELT Programs

TMT (Thirty Meter Telescope) is a partnership of the California Institute of Technology, the University of California, and the Association of Universities for Research in Astronomy in the USA, together with the Canadian Association of Universities for Research in Astronomy. TMT is 30-metre diameter optical/infrared telescope that is scheduled for completion in 2015. Design development is supported by the Moore Foundation, the USA National Science Foundation, and the Canadian Innovation Fund. The main light-collecting mirror in TMT will consist of many 1-metre diameter mirror segments.



GMT (the Giant Magellan Telescope) is a partnership between the University of Arizona, the Carnegie Institute of Washington, the University of Michigan, Harvard University, the Smithsonian Astrophysical Observatory, the Massachusetts Institute of Technology, and the University of Texas. GMT will be a 20-metre diameter optical/infrared telescope. GMT will use seven 8.4-metre diameter mirrors for its main mirror.



OWL (Overwhelmingly Large Telescope) is a concept developed by the European Southern Observatory (ESO). It is envisaged as a 100-metre diameter optical/infrared telescope. Design development is funded by ESO and the European Union. OWL is likely to be completed by 2020, and will probably have a diameter of between 50 and 100 metres. Its main light-collecting mirror will consist of many 1-metre diameter mirror segments that will each be controlled separately.

4 Issues

Based on past experience, the key features for successful Australian involvement in major astronomy facilities are…

- *Early involvement:* The early phases of a project are when the intellectual property is generated, when partners have the greatest influence in ensuring the scientific vision of the facility matches their own aspirations, and when the major decisions affecting construction contracts are made.
- *Significant share:* There is a consensus that a 5% share in a major facility is too small, and that a 10-20% share should be the minimum level of involvement.
- *Recognizable status:* The facility needs to be recognizable as a flagship for Australian astronomy, with the support of the entire astronomical community.

Siting in Australia: There is considerable political advantage to siting in Australia. Although the Australian continent has no world-class sites for optical/infrared observing, the Australian Antarctic Territory offers enormous potential advantages for siting ELTs.

These desirable features should be matched to other expectations for ELT projects…

- *Likely cost:* Based on the studies by the US Thirty Metre Telescope (TMT) project, a 30-metre general-purpose ELT offering full adaptive optics capabilities, and built following the model of the 10-metre Keck telescopes, will conservatively cost US$750M. A 20-metre ELT offering a wide field with natural seeing or modest adaptive optics capabilities will probably cost US$500M. The 100-metre OWL concept is scoped to cost less than €1000M via a variety of unproven technical innovations; OWL is unlikely to be operational until late in the decade 2010-2020, given ESO's current funding and commitments to ALMA. The outstanding atmospheric properties of the high Antarctic plateau may mean that an 8-metre telescope there may, in some respects, perform as well as a 20-metre or 30-metre at temperate-latitude sites for particular science goals. Although the cost of building a large telescope in Antarctica has not yet been determined, it may provide much of the capacity of a larger ELT at a lower cost.
- *Likely Funding:* Australian investment in an ELT would need to be of the order of $100-200M over the next 10 years. This would provide Australia with a 10-20% share of a 30-metre ELT, a 15-30% share of a 20-metre facility, or 100% of an Antarctic 8-metre. Australia's potential share of OWL would be smaller, but this must be compared to the higher scientific aspirations, and access to the full complement of ESO’s telescopes (including the VLT and ALMA).
- *Siting Challenges:* An Antarctic location has potential scientific advantages as well as political advantages for Australia, but it also offers significant technical and logistical challenges compared to more conventional sites.

5 Next Steps

The following sections describe the work that needs to be done to prepare the ground for Australia’s involvement in an ELT. The development of ELT programs is currently at an early, but very active, stage. At least three international ELT programs are carrying out conceptual design studies and developing generic technologies. If Australia is to take advantage of the benefits of early involvement in an ELT program, it is essential that we begin our own vigorous program immediately. The Australian ELT Working Group has therefore developed a broad-front strategy with three complementary components.

The first component of this strategy is aimed at making Australian astronomers **‘Smart Buyers’**. Given sufficient resources, Australia has the opportunity at present to choose which of the various international ELT projects it would like to join, since all the ELT programs are still seeking new partners to complete their funding requirements. In order to make a well-informed choice (to be a ‘smart buyer’), the Australian community needs to understand thoroughly the relative merits of each of these ELT programs in terms of their scientific priorities, technological approaches and solutions, and the terms of any partnership or collaboration. The first set of work packages described below has the goal of equipping the Australian astronomical community with the knowledge necessary to be a ‘smart buyer’.

The second component of the roadmap strategy has the goal of establishing Australian **‘Technology Leaders’** in critical areas of ELT technology. Already world-renowned for its instrumentation expertise, Australia would invest in an ELT in part for the science it enables, but also because of the benefits that flow from involving Australian industry in cutting-edge technology programs with diverse applications in astronomy, engineering, defence and medicine. There are a number of areas in which Australia offers world-leading technology to an international ELT program, and the work packages in this second component are intended to develop these technologies to the point where they would constitute a valuable contribution to an international ELT project, so that Australia would be able to re-coup a significant part of its investment in an ELT through contracts to supply these technologies.

The third component of the roadmap strategy explores Australia's **'Antarctic Advantage'**. Long-term studies by both Australian and overseas groups have shown that the high Antarctic plateau could potentially be the best site on earth for an ELT. The advantages are the cold (low infrared background), the altitude (reduced water vapour) and the low wind (less turbulent atmosphere). In particular, the Concordia station recently established by the French and Italians at the Dome C site in the Australian Antarctic Territory has recently been shown to offer extraordinarily sharp imaging, perhaps rivalling that of the Hubble Space Telescope for some periods of time. Australia's long history of involvement in Antarctica, the world-leading research in this field by the UNSW group, and the fact that Dome C lies in Australian Antarctic Territory, together mean that Australia may be able to 'host' an ELT. The work packages in this final component of the roadmap are designed to demonstrate conclusively the quality of an Antarctic site, to examine the logistic issues associated with constructing and operating a telescope in Antarctica, and then, depending on the outcomes of these studies, build a small telescope at Dome C as a pathfinder for an ELT.

In the following sections we lay out the details of the work packages making up these three components. We provide the background motivation for the work, a description of the activities to be carried out, a summary of the outputs, outcomes and success criteria, and the top-level milestones and indicative budget for the work package. Note that the budgets cover only the first three years (FY2004-2007), even when the programs extend further. Staff costs in the budgets include a standard 100% overhead.

6 Smart Buyers

6.1 Developing Partnerships

6.1.1 Background

The quest to build the next generation of optical/infrared extremely large telescopes (ELTs) is a global activity in a state of rapid development, with consortia currently in the process of forming, and some already having formed. At the vanguard in this context are three consortia, all of whom are well underway in developing preliminary telescope designs: (1) The **Thirty Meter Telescope (TMT)** consortium, which formed from the merger of the previous Californian (Caltech and University of California), US National Optical Astronomy Observatories and Canadian groups. They are currently reanalysing each of their original telescope designs to integrate the best aspects into a TMT design that optimally addresses their core science drivers. More than US$40M is already at their disposal for research and development phases of their project over the next three years, and they have requested another US$17.5M. (2) The **Giant Magellan Telescope (GMT)** consortium, led by the Observatories of the Carnegie Institute of Washington in the US, who are progressing a conceptual design for a 20-metre multiple-mirror telescope. This consortium expects to spend on order of US$14M in the near term. (3) The **Overwhelmingly Large Telescope (OWL)** consortium involving almost all the European nations including the UK, which the European Southern Observatory is leading and whose preliminary design studies are being funded from the European Union's FP6 program. This project is even more ambitious than the TMT and GMT projects, aiming to construct a telescope in the 50-100-metre range.

Australian astronomers are already significantly involved in developing the science cases for the international ELT projects: Colless is a member of the U.S. National Science Foundation's science working group and a co-author of the report *Frontier Science Enabled by a Giant Segmented Mirror Telescope*; Sackett and Tinney are members of the European Southern Observatory's OWL science working group and contributors to *Critical Science With The Largest Telescopes: Science Drivers for a 100m Ground-Based Optical-IR Telescope*. There is also involvement by Australian institutions in the EU FP6 program *ELT Design Study*: the Anglo-Australian Observatory is carrying out two concept studies for ELT instruments, the University of NSW is collaborating on Antarctic site studies, and the Australian National University is addressing the technology behind deformable mirrors and adaptive optics. The EU evaluation report on the successful FP6 proposal noted that "[Australia's] participation is clearly justified, and the scientific team is of outstanding experience in the science and technology related to the project."

Possibilities exist for Australia to join one of these ELT consortia. Australia is already included in the European *ELT Design Study* program has received expressions of interest from both the TMT and GMT groups to join their consortia as a partner. However, Australia needs here to be a 'smart buyer' by ensuring that it is fully conversant with all the science drivers, technologies, design/performance tradeoffs, and political/funding issues that are pertinent to ELTs so it can make well-informed choices. Australia also needs to assess the viability and scientific attractiveness of each consortium, as well as the financial, operational and strategic implications of membership. It can only do so by becoming actively engaged in ELT science, design and technology development activities, and entering into detailed discussions with each consortium on the specifics of membership.

6.1.2 Activities

These requirements dictate a rapid deployment of effort by Australian scientific staff on three fronts: (i) first and foremost, to establish formal communications with each of the three major consortia, through their peak bodies and/or the appropriate personnel; (ii) to establish an Australian presence on the scientific and project management committees of the various ELT consortia, be it as a full participant or with 'observer' status; and (iii) to conduct an information gathering and exchange process with the relevant groups around the world, to obtain a complete picture of ELT science, design, technological, political and funding issues.

In combination, these activities must address the following specific questions in relation to the three existing ELT consortia, or any other potential ELT opportunity:

- *Scientific benefits*: What are the main scientific opportunities and how well are they aligned with Australian priorities? What opportunities will there be for Australia to set scientific agenda? What is the 'discovery potential' through access to new areas of observational parameter space?
- *Instrumentation and technologies*: Will the technical characteristics of the ELT cater to the scientific interests of the Australian community? How comprehensive/limited will capabilities be (particularly the first generation of instruments)? What unique capabilities are envisaged? What is the dependence on high-risk technologies? How well matched are they to Australia's areas of strength and expertise?
- *Funding*: What are the mechanisms, timescales, and success probabilities? What are the true costs? What risk mitigation strategies are in place?
- *Membership conditions*: How large a share-partner could Australia become? How would the associated operations costs be calculated, and how much would they be? What operational model will be used for the telescope? How would time be allocated? What management/governance structure would be adopted? How

would the instrumentation program be organized? What potential would there be for Australian institutions to be awarded construction contracts?

- *Site selection*: Is a site identified and/or available? Would Antarctica be considered as a suitable site? What is the timescale for making a site selection decision? What are the site characteristics and hence the expected performance of the telescope?
- *Strategic benefit*: Will partnership lead to future developments of strategic interest to Australia? Would the same partnership consider a future Antarctic telescope?
- *Access to other facilities*: Will ELT involvement give access to other telescopes? At what cost?

6.1.3 Outputs and Outcomes

This work package will produce the following outputs:

1. Documentation providing an overview of global ELT opportunities and associated scientific, technological, design/performance, funding and political issues.
2. Documentation providing a detailed evaluation of the merits of Australian involvement in the TMT, GMT and OWL projects, based on the above criteria.

The outcomes of this work will be:

1. A clear and properly informed understanding of the best options for Australia in terms of ELT involvement.
2. Establishment of Australia as a high-profile community on the international ELT scene, who is a serious, credible, and thus desirable, consortium partner.
3. Establishment of formal lines of communication to all the existing major ELT consortia, with a clear understanding on both sides of the 'terms of engagement' and in what areas Australia could add value to the partnership if it were to join.
4. Establishment of an Australian presence on the key science and design working groups of the major consortia, providing the opportunity for its scientific aspirations to be injected into the early phases of ELT technical design.

6.1.4 Budget

The above activities require the full-time services of two scientific staff over the next three years. Specifically this would involve an ELT Project Scientist (PS) – a senior Australian astronomer who would represent Australia at the various meetings and in the negotiations with the various ELT consortia – and a Deputy Project Scientist (DPS) – a more junior person whose primary responsibility would be to assist the PS in the information gathering and assembly of documentation. Both would need to undertake a significant amount of travel, both international and domestic, and this also needs to be budgeted for.

Developing partnerships	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Scientist (0.5 FTE)	100	100	100
Deputy Project (1.0 FTE)	160	160	160
Travel	35	35	35
Total	**295**	**295**	**295**

The Australian Astronomy Board of Management for the Astronomy MNRF is expected to provide funding for the Project Scientist through the current MNRF award.

6.2 Telescope Designs

6.2.1 Background

Three international ELT consortia are actively developing preliminary telescope designs. The TMT consortium has formed from the merger of the previous CELT, GSMT, and VLOT groups, and so combines US private, US public and Canadian national groups. They are currently reanalysing all aspects of the telescope system design to integrate the best aspects of each original design into a TMT design that optimally addresses the TMT core science drivers. This is occurring through daily telecons within the TMT partnership that report the results of multiple technical investigations. The GMT consortium is progressing a similar conceptual design, albeit at a more relaxed pace due to present funding realities. ESO is progressing the preliminary design of the OWL telescope through ESO and EU FP6 funding. Australia needs to participate in these design developments in order to gain in-depth understanding of technical design trades, inject Australian scientific priorities into these discussions, and secure appropriate technical studies for Australian institutions and industry.

At the same time, Australia also needs to establish the possible advantages of siting large telescopes on the high Antarctic plateau. If Dome C proves to be as good an observatory site as the preliminary indications suggest, an 8-metre telescope at Dome C may provide many of the capabilities of an ELT at a temperate-latitude site. It is therefore important to compare the costs and benefits of an 8-metre telescope in Antarctica relative to those for a 30-metre ELT at some temperate-latitude site.

6.2.2 Activities

The ELTWG needs to secure participation of Australian scientific and technical staff on appropriate ELT technical groups. This is likely to be through observer status of a small technical group during technical telecons and participation in international ELT technical meetings.

It is proposed that a design staff consisting of two opto-mechanical engineers initially obtain, review, and critically assess technical documentation prepared by the three ELT consortia, and participate in the on-going technical design develops of the three groups. These design staff will perform technical design studies as appropriate in order to participate to the greatest extent possible in the development of each telescope design, and alert Australian institutions and industry to wider design development possibilities as they arise.

This group, together with astronomers, will also carry out a comparative study of an 8-metre telescope at Dome C and an ELT on the best temperate-latitude site. This study will compare the relative costs, benefits and scientific capabilities, drawing on both the Dome C site study and the scientific cases carried out under the 'Antarctic advantage' work package in order to determine which would be the most effective option, relative to the specific inherent risks.

6.2.3 Outputs and Outcomes

This work package will produce the following outputs:

1. Review documentation of existing ELT technical designs, contrasting their areas of relative strengths and weaknesses.
2. Technical design study documentation for specific aspects of ELT designs.
3. A report on the relative merits of an 8-metre telescope in Antarctica compared to an ELT at a temperate site.

The intended outcomes are:

1. Australian scientific aspirations will be injected into early phases of the technical design development and so ensure that the telescope caters to these aspirations to the greatest extent possible.
2. Improved understanding will be developed of the technical trades that constrain ELT designs.
3. Improved understanding will be developed of the technical aspirations of ELT partners.
4. Specific areas will be identified in which Australian institutions and industry can make technical contributions to ELT developments.
5. Australia will be seen internationally as being a desirable and active potential ELT partner.
6. Australian astronomers will understand the relative merits of an ELT and an Antarctic 8-metre telescope, and make informed choices based on the available opportunities.

This work package will be successful if Australian scientists and engineers become involved in ELT design work and gain a deeper understanding of the technical trades being addressed by international ELT groups and secure some of that activity for Australia.

6.2.4 Budget

Involvement in technical design development should be on-going through the preliminary design phase and extend through the construction phase of the telescope consortium that Australia ultimately joins; the budget presented here only covers the three-year period to the end of FY2006-7.

Telescope designs	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Management (0.25 FTE)	50	50	50
Project Scientist (0.5 FTE)	100	100	100
Opto-mechanical engineers (2.0 FTE)	400	400	400
Systems engineer (0.5FTE)	0	100	50
Instrument scientist (0.5FTE)	0	100	50
Travel	15	15	15
Total	**565**	**765**	**665**

7 Technology Leaders

7.1 Adaptive Mirror Technologies

7.1.1 Background

The most efficient way for ELTs to achieve their full potential for high-quality imaging is to incorporate adaptive mirror elements into the telescope itself, thus making the telescope mirrors adaptive. Ultimately, all telescopes will be made with adaptive primary and secondary mirrors. However, on the timescales of the first ELTs it is unlikely that adaptive mirror technologies will have progressed to the point where adaptive primary mirror segments can be used. Adaptive secondary mirrors are far more realistic on these timescales, but even these present significant technical challenges. The only adaptive secondary mirror in routine operation is the 600 mm diameter mirror on the 6.5m MMT. Another is being constructed for the Large

Binocular Telescope, and design studies are under way for adaptive secondary mirrors for the Magellan, VLT, and Gemini telescopes.

The maximum achievable size of an ELT adaptive secondary mirror directly affects the telescope and instrument complexity. The TMT design baseline is a 4m diameter rigid secondary mirror that feeds a 20-arcminute diameter field having a linear extent of 2.6m. The maximum diameter currently contemplated for continuous faceplate mirrors is about 2m, so extending this technology to a 4m diameter adaptive secondary mirror for TMT will require the challenging development of segmented adaptive mirror technology. The alternative of restricting the adaptive secondary diameter to 2m is equally challenging because it increases the image plane scale, which doubles the linear extent of the TMT field to over 5m. This in turn presents severe design challenges for the natural seeing, wide field, multi-object spectrograph instrument that has to accept this enormous field. No member of the TMT partnership currently has adaptive secondary mirror expertise, so a strategic opportunity exists for Australia in this area.

The GMT will use seven monolithic primary mirrors that will each be held to micron precision. This is insufficient to phase the full array, so the secondary mirror will be both segmented and adaptive to correct residual focus error in the individual primary mirrors as well as correcting higher order atmospherically induced wave front errors.

More generally, segmented adaptive secondary mirror technologies should be directly appropriate to the future development of large segmented adaptive primary mirrors. ANU is already collaborating in an EU FP6 work package with Arcetri Observatory to experiment with techniques for producing glass membranes for optical quality, low cost, adaptive mirrors that could be used in the spherical aberration correctors of the 100-m diameter OWL telescope.

7.1.2 Activities

Segmented adaptive mirror technologies will be developed in a staged way. Our goal will be to first design and manufacture a 250mm diameter single faceplate adaptive secondary mirror for the ANU 2.3 m telescope. The design will then be extended to address a 1m diameter segmented mirror that would potentially be suitable for the Gemini telescopes. This will simultaneously position Australia to compete for a possible future Gemini adaptive secondary mirror contract and demonstrate Australia's prowess in this area to ELT consortia. Ultimately, we expect to extend this development to a 2m diameter segmented adaptive mirror, and finally to address the challenges of a 4m diameter segmented adaptive secondary mirror, although this is beyond the scope of the present proposal.

Segmented adaptive mirrors will be complex optic systems requiring careful design of optical, mechanical, thermal, electronic, and software systems. It is expected that commercial voice coil actuators and drive electronics will be available for the smaller mirrors. Integrating the various subsystems is a significant challenge that will be addressed in developing the relatively small mirror for the 2.3metre ANU telescope. Design development for the larger segmented mirrors will concentrate on manufacturing the individual off-axis thin glass membrane mirror segments, controlling their lateral positions, controlling the axial positions of their edges, and managing the higher thermal load associated with larger numbers of actuators. This may require the development of new types of actuators.

This development could draw on and extend expertise available within Australian industry. CPE Systems (Victoria) has control systems expertise and has expressed a strong desire to become involved in ELT developments. Electro-Optic Systems (NSW) is one of the largest manufacturers of medium-sized telescopes in the world. Adaptive mirror technologies could be incorporated in their product range. This commercial involvement has not been budgeted for in the present proposal.

7.1.3 Outputs and Outcomes

This work package will produce the following outputs:

1. Documentation of the design and fabrication method for a 250mm diameter single faceplate adaptive secondary mirror.
2. A functional adaptive secondary mirror for the ANU 2.3-metre telescope at Siding Spring Observatory, NSW.
3. Documentation of the design and fabrication method for a 1m diameter segmented faceplate adaptive secondary mirror.

The outcomes from this work will be as follows:

1. Existing infrastructure on the ANU 2.3-metre will be enhanced by the addition of an adaptive secondary mirror. This will improve the image sharpness obtained by this telescope, increasing its scientific output.
2. Australian infrastructure for the fabrication of large optics will be expanded.
3. Australia will assert its technical expertise internationally in the area of adaptive mirrors and position itself to secure future ELT work in these areas.
4. Australian technologists will gain broader experience in the area of high tech optics, opto-mechanics, control systems, and systems integration.
5. Closer ties will be forged between Australian universities and industry.
6. Potential non-astronomical applications of adaptive mirrors may be identified in space-based remote sensing and surveillance applications, telescopes for satellite laser ranging applications, high resolution imaging systems for defence applications, and possibly in future satellite downlink telescopes.

7.1.4 Budget

The development of adaptive mirror technologies will require significant personnel and hardware investment; at least one mechanical engineer, one optician, one control system engineer, one electronics technician, and two software engineer for three years, and hardware for each of the adaptive mirrors.

Adaptive mirrors	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Management (0.5 FTE)	100	100	100
Mechanical engineer (1.0 FTE)	200	200	200
Optical technician (0.5 FTE)	100	100	100
Control system engineer (0.5 FTE)	100	100	100
Electronics technician (0.5 FTE)	75	75	75
Software engineer (1.0 FTE)	200	200	200
Hardware	500	1000	1000
Total	**1275**	**1775**	**1775**

7.2 Adaptive Optics Technologies

7.2.1 Background

Adaptive optics is needed to remove the image blur induced by the Earth's atmosphere so that ELTs can achieve the sharpest possible images. This will be essential for ELTs to deliver many of their core science objectives. Adaptive optics is one of the main challenges faced by ELT designers.

A variety of adaptive optics capabilities are needed for ELTs: (i) Multi-Conjugate Adaptive Optics (MCAO) will produces the sharpest possible images over modest fields of view; (ii) Ground Layer Adaptive Optics (GLAO) will produces modest improvement in image sharpness over much wider fields of view; (iii) Multi-Object Adaptive Optics (MOAO) has recently been proposed as a way of obtaining the sharpest possible images over small individual fields each spaced widely over a much larger field; (iv) Extreme Adaptive Optics (ExAO) is needed to achieve the extremely high contrast ratios required to detect planets around nearby bright stars.

A proposal for a Research Network for Adaptive Optics is currently under consideration by the Australian Research Council. ANU is working with adaptive optics groups in the Gemini partnership as part of the development of the NIFS and GSAOI instruments, and RSAA has a limited collaboration with the European Southern Observatory to model the adaptive optics performance of ELTs. The University of New South Wales is also investigating the application of adaptive optics to astronomical observations in the Antarctic.

7.2.2 Activities

Adaptive optics systems for ELTs are complex systems that require new approaches to modelling the effect on light propagation of the Earth's atmosphere, new approaches to the design of optical wave front sensors, development of powerful lasers to form artificial guide stars at high altitudes in the atmosphere, and new ways of implementing algorithms that control large numbers of mirror actuators. These areas will be developed in collaboration with international adaptive optics groups through the participation of one scientist, one opto-mechanical engineer, and one control systems engineer in the detailed design of the four classes of adaptive optics systems required for ELTs.

Multi-Object Adaptive Optics is particularly relevant to Australian scientific aspirations. This technique uses atmospheric tomography (like medical imaging tomography) to form a 3D model of atmospheric turbulence. Then it efficiently uses multiple small adaptive optics systems positioned on interesting science targets to obtain sharp images of just these objects over the field, ignoring the empty sky regions between. This concept mates naturally with the integral-field and multi-object spectroscopy work packages described below; combined with MOAO, these technologies will allow astronomers to record multiple spectra across the faces of several distant galaxies simultaneously.

7.2.3 Outputs and Outcomes

The adaptive optics work package will lead to:

1. An understanding of the AO requirements for a variety of scientific drivers for an ELT, and of the performance of AO systems in meeting these requirements.
2. The establishment of an Australian adaptive optics network linking universities and industry for the purpose of designing and constructing AO systems for ELTs.
3. The development of MOAO systems suitable for integral-field and multi-object spectroscopy, complementing the work packages in these areas.

This work package will be successful if it enables Australian astronomers to evaluate the effectiveness of the different AO systems proposed for the various ELT designs; if the Australian adaptive optics network is able to bring universities and industries together to provide the necessary infrastructure of knowledge and technology to support Australian AO systems for ELTs and ELT instruments; and, specifically, if the MOAO development combines with the other instrumentation technology work packages to provide world-leading ELT instruments.

7.2.4 Budget

Adaptive optics	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Management (0.5 FTE)	100	100	100
Project Scientist (1.0 FTE)	200	200	200
Opto-mechanical engineer (1.0 FTE)	200	200	200
Control system engineer (1.0 FTE)	200	200	200
Hardware	500	500	500
Total	**1200**	**1200**	**1200**

A small portion of these activities may be funded through a current bid to the Australian Research Council for an Adaptive Optics Research Network.

7.3 Integral Field Unit Development

7.3.1 Background

The Gemini NIFS instrument and the WIFES spectrograph for the ANU 2.3 m telescope have established the ANU team in the forefront of integral field unit (IFU) technologies. Many of the science cases for ELTs require highly multiplexed diffraction-limited integral field spectrograph capabilities. How best to provide this capability at both optical and infrared wavelengths is an active area of research.

7.3.2 Activities

Reductions in the size, mass, and cost of current integral field spectrographs will be required to achieve large multiplex gains. Techniques for miniaturizing IFU designs will be explored by investigating alternative optical designs and methods for manufacturing image slicers. Manufacturing procedures will be refined by trialling methods for manufacturing toroidal mirrors and mirror arrays. Optical designs will be studied that integrate the IFU function and the spectrograph function more thoroughly. Alternative methods for feeding multiple IFUs will be devised.

7.3.3 Outputs and Outcomes

1. Australia will assert its technical expertise internationally in the area of deployable integral field spectroscopy and position itself to secure future ELT instrumentation design and construction work in this area.
2. Australian technologists will gain experience in high-tech optics, opto-mechanics and fabrication, and closer ties will be forged between universities and industry.
3. Potential non-astronomical applications of integral field spectroscopy may be identified in remote sensing imaging spectroscopy, sample analysis in pathology and medicine, and target recognition in surveillance applications.

This work package will be successful if Australian scientists and engineers develop new optical designs for integral field spectrographs and demonstrate that they can be manufactured with existing techniques.

7.3.4 Budget

The proposed work plan will require one mechanical engineer and one optical designer for two years to develop new designs, an optician for one year to experiment with new image slicer manufacturing methods, and funds to out-source the fabrication of toroidal mirrors.

Integral Field Units	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Management (0.25 FTE)	50	50	0
Mechanical engineer (1.0 FTE)	200	200	0
Optical designer (1.0 FTE)	200	200	0
Optician (0.5 FTE)	100	100	0
Outsourced optical fabrication	200	200	0
Hardware	200	200	0
Total	**950**	**950**	**0**

7.4 Multi-Object Spectroscopic Concepts

7.4.1 Background

In order to take advantage of the power of either an ELT or a comparably performing Antarctic 8-metre, it is desirable to be able to obtain spectra for many targets simultaneously within a given field of view. Multi-object spectroscopy (MOS) is applicable to both a wide, seeing-limited field (>20 arcmin) or to a modest, diffraction-limited field (~2 arcmin). A variety of methods are under development, and will be compared in order to derive optimum solutions for each MOS application.

7.4.2 Activities

The Anglo-Australian Observatory (AAO) will perform studies of fibre-positioning technologies, fibre-optic performance capabilities, and beam-steering technologies applicable to multi-object spectroscopic facilities on an ELT. This effort will build upon the AAO's existing engagements with other ELT studies (such as the Opticon FP6 Smart Focal Plane study of Starbug devices). Development of operational prototype devices is required, particularly for cryogenic and beam steering mechanisms. An exploration of alternative fibre-optic photonic technologies for UV, optical, and IR application will also continue. The AAO will explore instrument designs for a variety of ELT and Antarctic 8-metre concepts that will utilize these MOS pickoffs. The AAO will also explore and develop atmospheric suppression methods, in particular in relation to the auroral and OH emission.

7.4.3 Outputs and Outcomes

This work will lead to the following outputs:

1. A comparison of the technologies available and under development, contrasting their performances and capabilities.
2. Development of prototype actuators carrying beam-steering mirrors in closed-loop operation at room and cryogenic temperatures.
3. Instrument concepts for a range of ELT and Antarctic telescope designs.
4. Documentation of technologies available for suppressing the night-sky emission.

The outcomes from this study should be:

1. Australia will extend its world-leading position in MOS-related technologies.
2. Australian astronomers will be viewed as a compelling instrumentation partner for MOS-related instruments on ELT facilities.
3. Australian astronomers will develop expertise and a world leadership role in night-sky emission suppression.

7.4.4 Budget

MOS concepts	($k) 2004/5	($k) 2005/6	($k) 2006/7
Project Management (0.25 FTE)	50	50	50
Project Scientist (0.5 FTE)	100	100	100
Scientists (2.0 FTE)	400	400	400
Opto-mechanical engineer (0.5 FTE)	100	100	100
Electrical engineer (0.5 FTE)	100	100	100
Software engineer (0.25 FTE)	50	50	50
Hardware	50	50	50
Travel	15	15	15
Total	**865**	**865**	**865**

7.5 Inertial Drives

7.5.1 Background

Eliminating the impact of wind buffeting on ELT structures has been identified as one of the biggest challenges facing the development of ELTs. Wind buffeting does not just shake the telescope, resulting in a linear displacement of the image, but produces as well a deformation of the telescope structure that impairs the telescope's ability to produce an aberration-minimised image. It is acknowledged that an adaptive mirror is likely required to compensate for the image distortion produced by the wind. One European study has even stated that the adaptive-optics correction of wind buffeting is more difficult than correcting atmospheric distortion of the image.

The AAO has proposed a potential solution for wind buffeting that uses inertial drives located at critical nodal positions in the telescope structure. Such drives would dampen the wind-induced oscillations, minimising the image distortion produced. This approach may solve, or at least ameliorate, the wind-buffeting problem.

7.5.2 Activities

The AAO will work with the various ELT groups to develop and implement inertial drives suitable for the ELT structures. Finite element analysis (FEA) will be required to understand how theoretical inertial drives might reduce the problem, and where they should be located within the telescope structure for optimal effect. The ELT designs would be modified to make best use of inertial drives. The study also entails the development of a prototype and tests; it would also evaluate the cost savings for an ELT. These studies will be made in collaboration with Australian industry.

7.5.3 Outputs and Outcomes

The results of this work package will be:

1. FEA studies showing how to best design the telescopes and inertial drives.
2. Development of a prototype inertial drive for testing on a telescope.
3. Documentation of the performance of the prototype inertial drive.
4. Evaluation of the cost savings of an inertially-compensated ELT structure.

The desired outcomes are:

1. Australia develops a potential solution for one of the most fundamental challenges facing the development of ELT facilities.
2. Australian industry is positioned to make a significant and valued contribution to the construction of an ELT.

7.5.4 Budget

Inertial drives	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**
Project Management (0.25 FTE)	50	50	50
Project Scientist (0.25 FTE)	50	50	50
Opto-mechanical engineer (0.25 FTE)	50	50	50
Travel	15	15	15
Total	**165**	**165**	**165**

8 Antarctic Advantage

We envision a three-stage program of work packages for realizing Australia's Antarctic advantage.

8.1 Stage 1

8.1.1 Background

The high Antarctic plateau may be the best site on Earth for an optical/infrared telescope. Studies carried out at Dome C in the Australian Antarctic Territory show extremely promising results in terms of the transparency and clarity of the atmosphere at this high, dry, still site. The sharpness of the images that can be obtained there may occasionally rival those taken with the Hubble Space Telescope. A detailed site study is currently underway, but even while that is proceeding, Australian astronomers should be moving quickly to exploit this potential opportunity.

This can be achieved by carrying out, in parallel with a comprehensive characterisation of the site properties, two studies providing the critical information needed to exploit most effectively the advantages of the site. The first of these would examine the scientific cases for telescopes of sizes ranging from 2 metres up to 30 metres; the second would evaluate the costs of a 2-metre telescope through a detailed preliminary design study.

With these studies in hand, Australian astronomers could decide the most effective route to an Antarctic ELT: to immediately build a 2-metre telescope and/or carry out a detailed design study for an 8-metre Antarctic telescope that would have many of the capabilities of a 30-metre telescope at some other site, but at a fraction of the cost. Implementing the chosen strategy forms the Stage 2 work package.

8.1.2 Activities

The design study for Antarctic telescopes would encompass the following activities:

1a. **Site study of Dome C**: Characterise Dome C as a telescope site, to the level required for a potential ELT site. This would include studies of the outstanding 'seeing' (the turbulence properties of the atmosphere relevant to sharp imaging) and how best to take advantage of it, and exploration of site and logistic issues affecting the use of optical/infrared telescopes.

1b. **Science case for Antarctic telescopes**: Evaluation of the science cases for 2-metre, 8-metre and 30-metre telescopes at Dome C, with particular emphasis on the differentials between telescopes of different sizes. This study would draw on the site studies, and would consider whether there were significant qualitative steps in the science capabilities as telescope aperture is increased.

1c. **Fully-costed design for a 2-metre telescope**: Perform a fully-costed design study for building a 2-metre telescope at Dome C. Working with one or both of the two potential contractors, EOS (Australia) and TTL (UK), the study would start from existing telescope designs, and would include instrumentation. The study would also examine in detail the logistical and operational issues and costs associated with siting a telescope at Dome C. The study should also, in partnership with the Australian Antarctic Division, explore agreements with France and Italy (who jointly operate the Concordia base at Dome C) allowing for the logistical support of the telescope.

8.1.3 Outputs and Outcomes

The outputs from this work package are the three study reports. The immediate outcomes will be a clear understanding of the properties of the Dome C site, a differential measure of scientific capabilities based on telescope size and a design and costing for a 'winterised' 2-metre telescope suitable for operation at Dome C. The ultimate outcome is that the Australian astronomical community will be ideally positioned to exploit the Dome C site, with a comprehensive basis for a well-informed decision on how best to proceed at the second stage of the program.

Stage 1 of this program will be a success if (i) all three studies described above are completed on time and on budget; and (ii) the studies provide sufficient information to make a clear decision on the best way to proceed in Stage 2.

8.1.4 Milestones

Stage 1 of this program requires 2 years to complete.

- **Sep 2004** – initiate site study, science case study and preliminary design study
- **Jun 2005** – complete science case study
- **Sep 2005** – complete design study for 2-metre telescope
- **Sep 2006** – complete site study after two Antarctic nights (winters), 2005 & 2006

8.1.5 Budget

	($k)	**($k)**	**($k)**
1a. Site Study	**2004/5**	**2005/6**	**2006/7**
Project manager (0.25FTE)	25	50	13
Project scientist (0.5FTE)	50	100	25
Opto-mechanical engineer (1.0FTE)	100	200	50
Hardware	75	75	0
Travel	10	25	5
1b. Science Case	**2004/5**	**2005/6**	**2006/7**
Project manager (0.25FTE)	25	0	0
Astronomers (3x0.25FTE)	75	0	0
Travel	10	0	0
1c. Preliminary Design	**2004/5**	**2005/6**	**2006/7**
Project manager (0.25FTE)	25	50	0
Project scientist (0.5FTE)	50	100	0
Opto-mechanical engineer (1.0FTE)	100	200	0
Systems engineer (1.0FTE)	100	200	0
Instrument scientist (0.5FTE)	50	100	0
Hardware	25	50	0
Travel	10	10	0
Total	**730**	**1160**	**88**

8.2 Stage 2

8.2.1 Background

The studies carried out under the Stage 1 work package, together with the outcomes from the 'Smart Buyers' work package, will provide the information required for Stage 2: exploiting the Australian Antarctic advantage for ELT science. The two components of Stage 2 are:

2a. Construction of PILOT, a 2-metre telescope at Dome C in order to immediately exploit the scientific opportunities of Antarctica and as a pathfinder facility for a subsequent 8-metre telescope or ELT (PILOT = Pathfinder for an International Large Optical Telescope).

and/or

2b. Begin a detailed design study for an 8-metre telescope at Dome C as a scientifically effective alternative to a temperate-latitude ELT, but available sooner and with a larger share of the facility for a fixed cost.

8.2.2 Activities

The activities for the two components are:

2a. **PILOT: a medium-sized telescope at Dome C**. Based on the design and costing produced in Stage 1, construction of a 2-metre telescope for Dome C would be initiated in 2006. This telescope, to be called PILOT (Pathfinder for an International Large Optical Telescope), would be expected to have a total capital cost, complete with instrumentation, in the range $8-10M. The annual operational budget would be of the order of $1-2M (not included in the roadmap budget as it is beyond the 3-year horizon). PILOT will have three roles: to demonstrate the technologies required to operate in Antarctic conditions, to provide unequivocal demonstration of the advantages of the Dome C site, and to carry out world-class science programs for the Australian community.

2b. **Antarctic 8-metre telescope**. A design process is begun in 2007 for an 8-metre telescope at Dome C. The design phase would last 1.5 years and cost approximately $5M. Subsequently, construction would begin in the summer of 2008-9 and cost of order $100M (this cost may be shared with international partners). The goal would be for the telescope to see first light in 2012, before any of the existing ELT programs expect to begin operations. Annual operating costs would be of the order of $5-10M.

8.2.3 Outputs and Outcomes

The result of the Stage 2 activities will be an operational telescope at Dome C (PILOT) and/or a detailed design for an Antarctic 8-metre telescope. The criteria for success are:

- An operating telescope in Antarctica, delivered on time and on budget.
- Outstanding scientific results emerging from the telescope.
- Australia established as the leading nation in Antarctic optical/infrared astronomy.
- Australia in a strong position to capitalise on this position with a larger Antarctic telescope at the next stage.

8.2.4 Milestones

2a. The milestones for the **PILOT** project are:

- **Nov 2005** – initiate construction of telescope and instruments
- **Nov 2005** – begin construction of infrastructure at Dome C

- **Feb 2006** – end of first summer of construction phase
- **Nov 2006** – begin second summer of construction
- **Feb 2007** – complete construction of telescope
- **Dec 2007** – complete construction of instruments and ship to Dome C
- **Apr 2008** – first light and commissioning of telescope and instruments
- **Jun 2008** – first scientific observations; beginning of operational phase

2b. The milestones for the **Antarctic 8-metre telescope** option are:

- **Jan 2007** – initiate design study for telescope and first-generation instruments
- **Jun 2009** – telescope design study completed
- **Sep 2009** – construction of essential infrastructure at Dome C begins
- **Dec 2009** – instrumentation design studies completed
- **Jan 2010** – instrument construction begins
- **Mar 2010** – end of first summer of construction phase
- **Sep 2010** – construction of telescope begins
- **Mar 2011** – second summer of construction phase ends
- **Sep 2011** – construction of telescope continues
- **Dec 2011** – instrument construction completed and delivered to Dome C
- **Mar 2012** – third summer of construction phase ends
- **Jun 2012** – first winter operations; first light and commissioning

8.2.5 Budget

An accurate estimate for the cost of the PILOT 2-metre telescope will be determined by the design study carried out in Stage 1, but is expected to be approximately $8-10M. The cost of an Antarctic 8-metre telescope is expected to be in the range $50-100M.

8.3 Stage 3

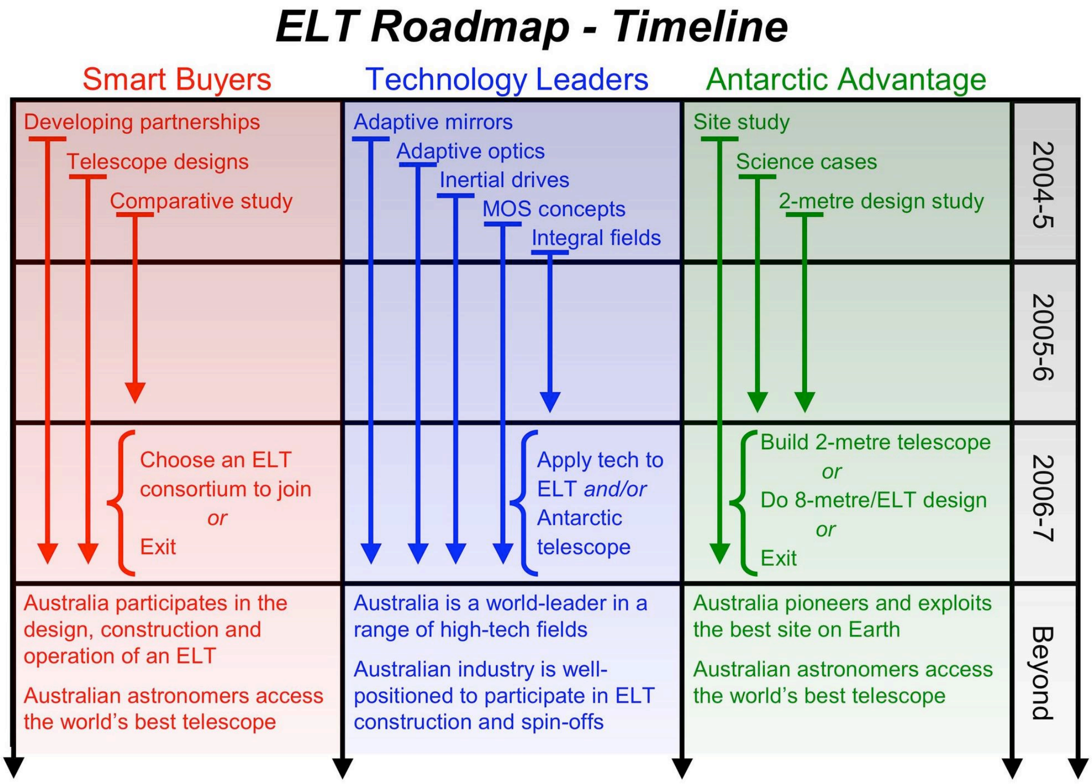
Stage 3 represents the culmination of the Antarctic component of the Australian ELT program. The goal of this stage depends on the outcome of earlier stages, as does the timing. There are two likely options:

3a. **Antarctic 8-metre telescope**. This option would be one possible development following the establishment of the PILOT 2-metre telescope at Dome C and/or the 8-metre telescope design study carried out in Stage 2. Building an 8-metre after the 2-metre has the advantage conferred by the experience of operating the PILOT facility, and the disadvantage that the delay means having to compete with ELTs on temperate sites from day one. The capital cost of this option would be in the range $50-100M, with annual operating costs of $5-10M.

3b. **Antarctic ELT**. Based on the experience obtained with PILOT and/or with an Antarctic 8-metre telescope, Australia joins an international collaboration to build a 30-metre ELT in the Antarctic. This would be a second-generation ELT since, starting late, it would begin operations after the first-generation ELTs on temperate sites. However the superior site conditions at Dome C would make it the most capable telescope on Earth. Australia's share of the capital cost of this $1000M facility might be $100-200M, with the share of the annual operating costs amounting to $10-20M.

9 Summary

The diagram below shows the timelines for the work packages in each of the three components over the 3-year period covered by this roadmap. The diagram also shows the decision points that occur and the intended longer-term outcomes.



The budget in the table below brings together the individual work package budgets to give the cost of each of the three components of the roadmap program for the period 2004-2007: the Smart Buyers component is $2.9M, the Technology Leaders component is $13.4M, and the Antarctic Advantage component is $10M ($2M for Stage 1 and $8M for Stage 2). The overall cost of the roadmap program is $26.3M.

ELT Roadmap Budget 2004-2007	**($k) 2004/5**	**($k) 2005/6**	**($k) 2006/7**	**($k) Total**
Smart Buyers	**860**	**1060**	**960**	***2880***
Developing partnerships	295	295	295	*885*
Telescope designs	565	765	665	*1995*
Technology Leaders	**4455**	**4955**	**4005**	***13415***
Adaptive mirrors	1275	1775	1775	*4825*
Adaptive optics	1200	1200	1200	*3600*
Integral field units	950	950	0	*1900*
MOS concepts	865	865	865	*2595*
Inertial drives	165	165	165	*495*
Antarctic Advantage	**730**	**1160**	**8088**	***9978***
Antarctic stage 1	730	1160	88	*1978*
Antarctic stage 2	0	0	8000	*8000*
Total	**6045**	**7175**	**13053**	***26273***

The final figure, below, shows four possible long-term scenarios resulting from the roadmap program. In the first scenario, the Smart Buyers and Technology Leaders components lead directly to Australia joining an international ELT consortium for the purpose of constructing an ELT. In the second, the Antarctic Advantage and Technology Leaders components lead initially to an Antarctic 2-metre telescope and eventually to an Antarctic 8-metre or ELT. The third is a hybrid of the first two scenarios, and envisages an Antarctic 2-metre preceding the construction of an ELT as part of an international consortium. The fourth and final scenario emphasises that the roadmap program will provide Australia with sufficiently broad information and capabilities to allow us to respond appropriately to any other unexpected opportunities that may emerge.