PILOT – the Pathfinder for an International Large Optical Telescope

Executive summary

The future of Australian optical/infrared astronomy depends on its ability to remain world-class. This must be achieved through the nurturing of Australian skills and talent, the identification of partnerships with international collaborators and industry, and via access to cutting-edge infrastructure. Australia produces 4% of the world's astronomical papers. It produces less that 2% of the world's intellectual property. Australia must therefore play to its strengths in all areas if it is to remain competitive in a world in which it is necessarily a small player. PILOT provides such an option.

Over the next decade, major advances are anticipated in optical/IR interferometry, adaptive optics, infrared detector technologies, and terahertz capability. Telescopes in Antarctica will be well placed to take advantage of these emerging technologies. By building upon the leadership that Australia already provides in Antarctica, PILOT represents a promising option for the future of Australian optical/IR astronomy, whilst at the same time serving broader strategic national interests.

Conditions at Dome C are known to be exceptionally favourable for astronomy, as presented in the PILOT Environmental Conditions Document. The free-atmosphere seeing, coherence time and isoplanatic angle are all twice as good as at typical mid-latitude sites, the water vapour column is several times lower, and the sky and telescope thermal emission are an order of magnitude better. The environment does present challenges, including the intensely turbulent boundary layer, the super-saturated humidity, and the rapid change of atmospheric temperature with height and time within the atmospheric boundary layer.

Through the PILOT Design Study, Australia has taken a leadership role in identifying and addressing these challenges. Further investment in the PILOT program at this stage will strengthen Australian leadership in this domain and provide a valuable option to global astronomy in a realistic plan for the development of large-scale astronomy infrastructure at one of the best sites on the planet. Moreover, should PILOT proceed to construction, it will provide Australia with a uniquely capable astronomical facility. Australian investment in PILOT is likely to provide a platform from which access to other (non-Antarctic) astronomical facilities may be negotiated, thus helping to ensure the health of Australian astronomy across the discipline whilst also forging and maintaining international partnerships in other areas of frontier science.

The specific aims for PILOT are to:

- Enable users to conduct internationally-competitive astronomical research.
- Demonstrate that large optical telescopes can be built and operated in Antarctica with reasonable timescale and cost.
- Show that the excellent natural seeing and thermal backgrounds at the site can be fully realised, and characterise the possibilities for diffraction-limited observing from the site.
- Leverage international collaboration

PILOT offers Australian astronomers the opportunity for major scientific returns, and buys the option of maintaining leadership in an emerging area of astronomy that will take maximum advantage of new optical, infrared, and terahertz technologies. The full life-cycle cost of PILOT is estimated at $129m. In order to proceed, $2.5m is requested from the ANSOC process to fund the Preliminary Design Phase, plus up to $0.9m for instrumentation studies.

No single telescope can meet all of the diverse needs of a healthy optical/IR astronomical community. At present, Australia satisfies these needs with a combination of the AAT, the Gemini telescope agreement and by purchasing time on overseas-owned facilities on an ad-hoc basis. For access to 8-metre class telescopes such as Magellan, Australia pays with cash. PILOT and its possible successors offer the opportunity to trade time between PILOT and overseas facilities to the benefit of Australian students and industry, and the international astronomical community.

Until the 1960s the summit of Mauna Kea was considered an extreme and challenging location; observing at this and similar sites is now considered routine. While once the thought of operating telescopes from space was considered fantasy, new space telescope projects are now being proposed at an ever-increasing rate. Antarctica is clearly a challenging environment, however the success of the 10 metre aperture sub-millimetre South Pole Telescope suggests that it is now realistic to plan for large optical/infrared telescopes on the Antarctic plateau on a time scale that will see the students of today using them for their research at the height of their productive research careers.

1. Introduction

The next two decades will see great progress in optical/IR astronomy, including the launch of JWST and other astronomical satellites, development of one or more ELTs, and major advances in interferometry. In addition, terahertz astronomy can be expected to mature, and to make important contributions to cosmology and to the understanding of galactic evolution.

Through the NCRIS program, Australia has identified optical and radio astronomy as a priority capability. Investments in infrastructure will be made where they maximize the skills and relationships that are also seen as key elements making up the scientific strength of the capability, measured by its productivity and impact.

The entire astronomical community in Australia is small, comparable in size to that of a single large US institution, e.g. the Harvard-Smithsonian CfA. New infrastructure investments must, of necessity, seek to focus on areas of strength and where Australia has a significant competitive or natural geographic advantage. New investments are also likely to provide the greatest return in areas where Australian astronomers can be significant partners and exercise leadership. Possible investment choices need to be carefully studied, with options where significant *prima facie* advantage is seen to exist not being ruled out prematurely.

Antarctic astronomy is one such area in which Australia currently plays a leading role. The very low infrared background of Antarctic plateau sites such as Dome C enables a telescope based there to equal the sensitivity, at some wavelengths, of a telescope over three times the diameter located elsewhere. The atmospheric turbulence above Dome C is also two to three times less than that at even the best temperate sites. These factors combine to make an optical/infrared telescope at Dome C uniquely powerful, enjoying not only a substantial advantage in both sensitivity and photometric precision, but also having a wide-field, high-resolution, high-cadence imaging capability otherwise achievable only from space.

Antarctica represents a unique opportunity for Australia. It is geographically close, and attracts significant national investment. With no space astronomy program and no high mountains, Australia has more to gain from the remarkable atmospheric conditions in Antarctica than do other countries. And, at the present time, no country challenges Australia's leadership in the development of optical/IR facilities for the Antarctic plateau. Over the coming decade, Australia can build upon this position to become a leading player in the deployment of increasingly sophisticated facilities to Antarctica. Equally, there are significant challenges that need to be addressed in order to take advantage of the unique conditions.

International interest in Antarctic astronomy is rapidly increasing. This year the IAU has become a member of SCAR, the ICSU body responsible for Antarctic science. In addition, SCAR has adopted *Astronomy and Astrophysics from Antarctica* as one of its five Scientific Research Programs, for the first time recognizing astronomy as an central theme in international Antarctic research.

PILOT is the next step in the development of international optical/IR astronomy in Antarctica. PILOT is proposed as a 2.5 m optical/infrared telescope to be located at

Dome C on the Antarctic plateau, with target first light at the beginning of 2013. The project has been endorsed by the appropriate Working Group of the European Antarctic astronomy community's ARENA network, and will be a key component of the strategy being developed by SCAR's new *Astronomy and Astrophysics from Antarctica* Scientific Research Program.

While the potential rewards from Antarctica astronomy are large, there are also significant risks – both technical and political. The PILOT Design Study placed a strong emphasis on identifying these risks and developing suitable mitigation processes.

International optical/IR astronomy will undergo a significant expansion in capability in the next five years. In considering the role of PILOT on the international scene, it is essential to consider a world in which SOFIA, Herschel, VISTA, ALMA, WISE and PanSTARRS are all operational. Within Australia, PILOT must also sit comfortably in a radio astronomy environment that will be enhanced first by ASKAP and MWA, then ultimately perhaps by the SKA. The science that PILOT delivers must be world-class. In the event that none of the future options in Antarctica is adopted, PILOT should have proven itself to be a cost-effective scientific investment by the end of its ten-year scientific-program life.

PILOT must also create opportunities for Australia in a world well beyond 2013, a world that will eventually see the launch of the JWST, EUCLID and JDEM space missions, construction of the SKA and possibly one or more ELTs. Over the next decade, major advances in astronomical technology will occur. Importantly, telescopes in Antarctica can take greater advantage of many of these new technologies than can telescopes at temperate sites. By retaining and building upon the leadership that Australia already provides in Antarctica, a promising option can be developed that maximises the competitive advantage offered by Australia's access to, knowledge of, and experience in Antarctica. For example, were negotiations between Australia and ESO to recommence, the experience, IP and infrastructure owned by Australia in Antarctica could be an important consideration.

2. PILOT technical summary

The PILOT facility is based on a 2.5m f/10 Ritchey-Chrétien telescope, with twin Nasmyth foci, and 1° field of view. The aperture is determined by commercial availability and timescales, by the limits for passive mirror support, and by the limits for effective fast guiding. The focal length is set to match the pixel scale to the median free seeing. The PILOT design, including the mirror coating, assumes a ten-year science-program life.

The telescope will be installed on a tower, above most of the turbulent atmospheric surface layer. The 30m height of the tower is such that any residual surface layer turbulence above the telescope be correctable, via the tip-tilt system, down to a level much smaller than the free seeing. The tower design is extremely stiff to twisting and bending, with a fundamental frequency of ~3Hz and an expected windshake of ~0.1". This windshake is mostly corrected by the tip-tilt.

Apart from surface layer turbulence, the other major challenges at Dome C are the enormous vertical temperature gradient, (~1°C/m at surface level and ~0.15°C/m even at 30m), and the supersaturated humidity. To solve these problems, a temperature and humidity-controlled enclosure is proposed. This enclosure will be continuously flushed with sub-saturated air, matched in temperature to the external air at the dome aperture. This air is drawn from closer to the surface of the snow, and is heated using largely the waste heat from the instrumentation. A further advantage of this scheme is the delivery of excellent dome seeing, as the temperatures can be closely matched and the external airflow suffers minimum disruption – as demonstrated by computational fluid dynamics (CFD) models.

The imaging specifications for the PILOT telescope are that it should be capable of taking diffraction-limited images over small fields at 1 μm in the best conditions; and that the imaging over wide fields, longwards of 0.4μm, in normal conditions should be limited by the median free (tip-tilt-corrected) seeing and/or diffraction, rather than by imperfections in the telescope itself.

The gains in seeing, isokinetic angle and coherence time over existing sites collectively mean that, in terms of suitable guide stars per isokinetic patch, Dome C enjoys a 20-fold advantage over, e.g., Mauna Kea. This means that there are enough guide stars at r and i-bands to map the entire atmospheric deflection field, at a level giving negligible anisokinetic error. This means median image quality ~0.25" is achievable over arbitrarily large fields, using tip-tilt correction for high-level turbulence via Orthogonal Transfer CCDs.

3. PILOT science case

An optical/infrared telescope at Dome C would occupy a unique position in parameter space, enjoying not only a substantial advantage in sensitivity and photometric precision, but also having a wide-field, high-resolution, high-cadence imaging capability otherwise achievable only from space. The science case for PILOT must also consider the smaller fraction of dark time and the limited sky access of high-latitude sites. The key science objectives of PILOT are discussed in detail in the PILOT Science Case Document PILOT_SPE_001_B. Some of these science goals are summarised here, grouped into six themes.

3.1 First light in the Universe

This theme aims to measure the signatures of the final evolutionary stages of the first stars to form in the Universe, and the properties of the first galaxies.

Pair-instability Supernovae (PISNe) are predicted to be extremely powerful explosions that occur in massive progenitor stars formed in low metallicity environments, and should thus be numerous amongst the first Population III stars. While there is a large range of expected brightness and frequency of these events, PILOT should be capable of finding PISNe out to a maximum redshift in the range z = 7–10, via a dedicated search in the near-infrared. PILOT and JWST will be the only facilities capable of detecting such high-redshift objects; both telescopes will probe a separate region of PISNe parameter space.

Because of their high intrinsic luminosity, gamma ray bursts (GRBs) offer a powerful probe of the Universe at a range of cosmological distances. The highest redshift GRB so far detected is at $z = 6.3$; theories suggest that they should be numerous at even higher red-shifts in the range $z = 10 - 20$. While current high-energy satellites find hundreds of GRBs per year, there is a paucity of uniform optical/infrared afterglow observations. Via a near-infrared follow-up of every GRB alert in the observable sky at Dome C during winter, with a high sensitivity and a wide wavelength coverage, PILOT is expected to find several $z > 6$ GRBs per season and at least one $z > 10$ GRB in a few years.

The low sky thermal emission and the wide field of view should allow a PILOT wide-area 2.4 μm K_d survey to find more distant galaxies at lower limiting masses than possible with other facilities. Additionally, the combination of PILOT *K*-band survey data with higher wavelength Spitzer warm mission observations, would allow the identification of significant numbers of Balmer break galaxies in the redshift range $z = 5 - 7$. These evolved galaxies represent the very earliest stellar populations to form in the Universe.

3.2 The equation of state of the Universe

This theme will probe the evolution of dark matter and dark energy via the observation of weak gravitationally-lensed galaxies.

The determination of the ellipticities of a very large sample of weak gravitationally-lensed galaxies via a wide-area (~4000 deg^2) optical survey will allow PILOT to measure the evolution of the power spectrum, and hence the equation of state of the Universe. The overall speed of a weak lensing survey varies as the fourth power of the observed image size. With a stable point-spread function, a wide-field camera, and a high spatial resolution, the PILOT survey should be competitive in terms of survey speed with surveys for planned large aperture ground-based facilities such as LSST and proposed spaced-based missions such as Euclid (formerly DUNE). Additionally, by covering the same sky region as the sub-millimetre South Pole Telescope (SPT), PILOT could obtain, via strong lensing, an independent calibration for a subset of the SPT cluster masses determined by the Sunyaev-Zeldovich effect.

3.3 Star and planet formation.

These studies aim to investigate the molecular phase of the Galaxy and to search for the signatures of circumstellar discs around young and low-mass stellar objects.

PILOT should be able to map the mid-infrared emission from the rotational lines of H_2 at 12 and 17 μm in the typical warm environment of molecular clouds at a spatial resolution of ~2″ over a wide region of the Galactic plane. This spatial resolution is more than an order of magnitude better than achievable with mapping surveys using millimetre-wave telescopes, and is nearly two orders of magnitude better than the current best southern Galactic plane molecular survey.

The study of circumstellar disks specifically around young stellar objects and young brown dwarfs offers an opportunity to explore planet formation. PILOT offers a unique capability to perform a large-scale mid-infrared molecular cloud survey, in regions such as the Chamaeleon dark clouds complex, at a reasonable spatial resolution. By mapping this region at a range of mid-infrared wavelengths the most complete initial mass function for this complex can be obtained, and the physical characteristics of a large sample of circumstellar disks can be explored in detail.

3.4 Stellar properties and populations

These projects aim to increase our understanding of stellar evolution, star formation processes, and galaxy formation and evolution.

The wide-field, high spatial resolution, and wide wavelength coverage capabilities of PILOT are essential to studies tracing stellar populations both in the crowded inner regions and in the outer parts of nearby galaxies. A program of deep, wide-field imaging of a sample of galaxies out to ~10 Mpc with PILOT will produce further understanding of the relationship between extended disks, inner disks, bulges, and halos, and provide input into simulations of galaxy formation and evolution over a range of cosmological distances.

The study of stellar oscillations, known as asteroseismology, allows the interiors of stars to be probed. The large field of view, nearly continuous temporal coverage, and high photometric precision required for such studies are uniquely satisfied by PILOT. Several programs of long-time-series observations of nearby globular and open stellar clusters are planned to study age-metallicity relationships and test aspects of stellar evolution theory.

3.5 Exoplanet science

These projects aim to directly detect low-mass "free floating" objects and to characterise the atmospheric properties of hot Jupiters.

The observation of a free-floating planetary-mass object allows it to be characterised in much greater detail than is possible for an exoplanet that orbits a host star. The wide-field, near-infrared survey capabilities of PILOT should allow the identification of the coolest "T dwarf" members of nearby star clusters and the direct methane imaging of objects as low in mass as a few Jupiter masses.

The collection of multiple, high photometric precision, exoplanet primary transit and secondary eclipse light curves at infrared wavelengths can be used to determine the presence of secondary lower mass planets, to constrain the planet molecular composition, to measure the planet thermal emission, and to infer planetary atmospheric circulation regimes. To obtain such data requires a high temporal cadence and a very stable infrared background. The Antarctic plateau is the only location on the ground to deliver this combination.

3.6 "Lucky Imaging" science

This technique uses fast-readout CCDs to select only the best frames, and includes programs to demonstrate the atmospheric conditions at the site and to perform high-resolution observations currently only possible with the HST.

With the inevitable demise of the HST, only Lucky Imaging systems will be able to consistently produce HST-quality images from the ground. The unique atmospheric characteristics at Dome C should deliver higher spatial resolution, over a larger fraction of the sky, and at shorter wavelengths than systems on mid-latitude telescopes. This creates opportunities for a range of projects in high-resolution imaging in the optical over small fields, including solar system science and emission-line mapping of galaxy centres.

3.7 Beyond PILOT

The depth and breadth of science proposed for the PILOT facility, despite its modest 2.5 m aperture, are a direct result of the unique characteristics of the Dome C site. These same characteristics will also benefit future, larger telescopes, for which PILOT acts as a pathfinder. For example, an 8–10 m class telescope would be uniquely powerful for very high-resolution optical imaging and spectroscopy over small fields, and very deep infrared imaging over extremely wide fields. This facilitates a range of science including the direct imaging of exoplanets, a detailed exploration of the first stars to form and the epoch of reionisation, and the investigation of the acceleration of the universe via supernovae studies.

4. PILOT costs

4.1 Cradle-to-grave costing

Care has been taken to identify the full cradle-to-grave cost of PILOT, including costs which would normally be hidden or absorbed as overheads by a hosting organization or infrastructure support agency. The costing assumes an agreement can be negotiated for access to Concordia Station, with PILOT paying its full share of operating costs. However, no allowance has been made for capital depreciation. Instead, the investment is considered to be written off during the life of the project, and any replacement facility will need to seek new funding.

No assumption has been made about the likely degree of support from national or international infrastructure agencies. For example, the cost estimates include provision of a new 100 kW solar power installation at Concordia, and the purchase of a Caterpillar tractor and three sleds for deployment and subsequent support. The costs also include the new buildings required in Antarctica and Australia, and all support staff both in Antarctica and Australia (including in-house astronomers) for the life of the project.

In practice, many of these costs can be reduced by appropriate resource sharing, partnership agreements, in-kind contributions, and ultimately by selling shares in the facility to other organisations and countries. Section 4.3 provides a strawman example of how this might be done, but stresses that any funding model and collaborative structures will be dependent on the political and scientific considerations of the time. There are two key points: firstly, as the lead partner, Australia can make its own decisions on how it wishes to engage with potential partners; secondly, there is demonstrated strong interest in this project by prestigious institutes in North America, Europe and Asia, so Australia is likely to be able to choose its partners.

Each of the three first-generation instruments is costed at $9m including software. There is no "Antarctic factor" here, as the instruments operate in a controlled environment within the telescope dome. All modern astronomical instrumentation must be built to extremely high standards of reliability, regardless of where it is located. The cost of PILOT's instruments is therefore directly comparable to that of similar instruments at other observatories. While the total cost of all three instruments is included in the budget, some or all of the instruments might be contributed by international consortia, at zero cost, in return for share. Again, these decisions can be made by the PILOT Board at an appropriate time.

The total cost of the PILOT, based on an on-sky science program life of ten years, is $129m (in 2008 dollars). The costing model provides for PILOT to be dismantled and removed from Antarctica in accordance with Treaty provisions after ten years. An amount equal to half the cost of commissioning has been provided for this. However, it is more likely that PILOT will continue to operate well beyond its initial ten-year program as a special-purpose facility, possibly in a non-astronomical role such as monitoring near-earth satellite debris.

4.1 Cost breakdown by stage

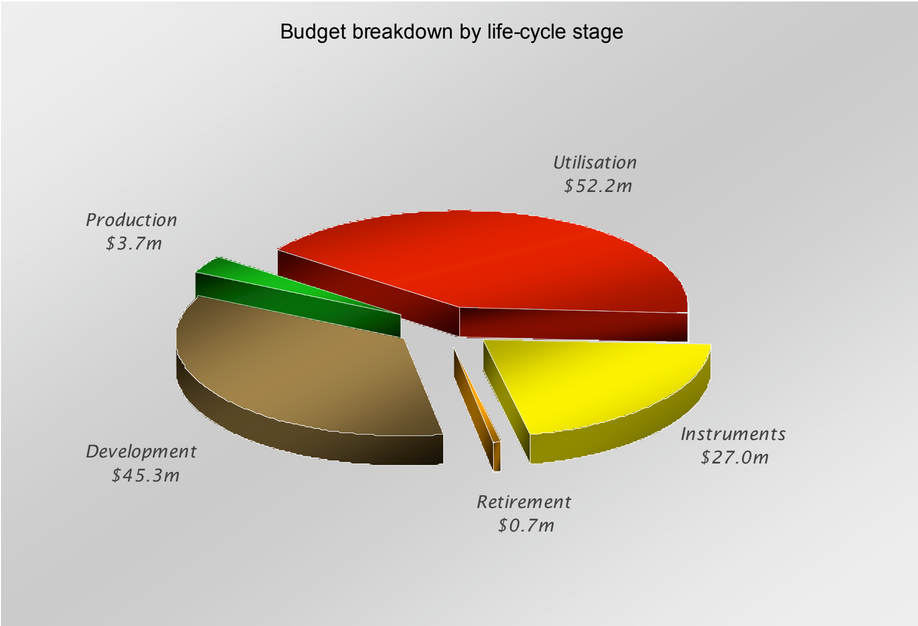

Figure 1.

ISO 15288 standard nomenclature is used for the life-cycle stages, and adapted by amalgamating the *Utilisation* and *Support* stages, and inserting an additional stage called *Instruments*. The PILOT project is now ready to begin the *Development* stage, which includes the remaining preliminary and final design stages, plus construction of the telescope and other major items. *Production* means shipping, installation and commissioning.

In Figure 1 expenditure at each stage of the project is identified, assuming an on-sky science-program operational life for PILOT of 10 years.

4.2 PILOT spend profile

The life-cycle funding profile, in A$m, of PILOT is shown in Figure 2. NCRIS funding for 2008 – 09 and 2009 – 10 is assumed, followed by the allocation of new resources in the 2010 Federal budget. This is an aggressive schedule, based on the timely resolution of funding agreements and contractual arrangements.

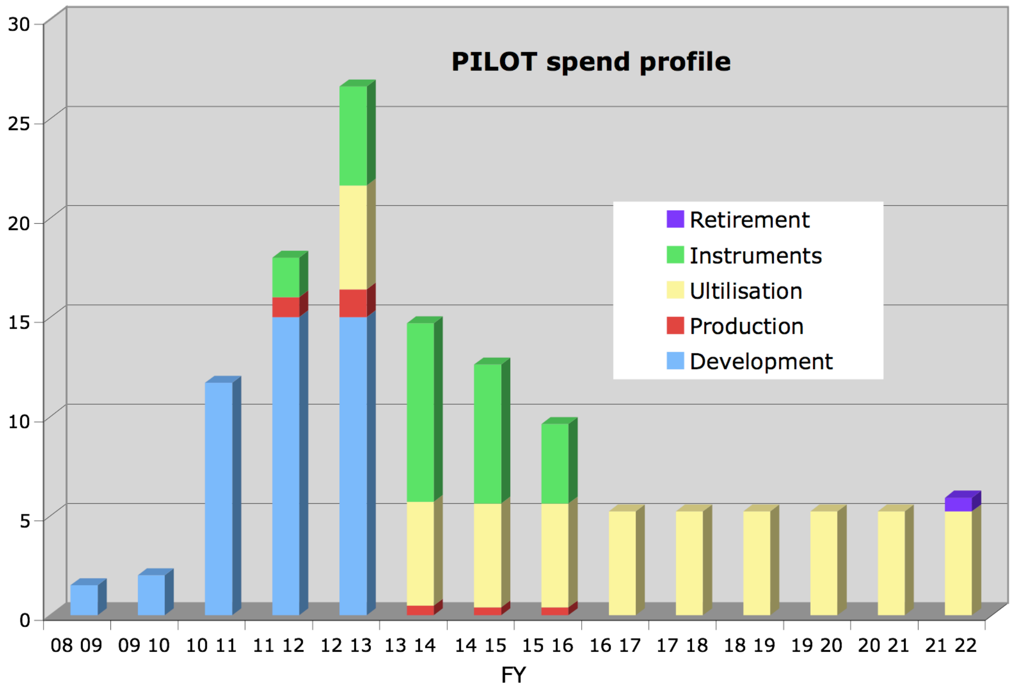

Figure 2

4.3 A strawman funding model

The full life-cycle cost of PILOT can be broken down as follows:

- Project Management and Systems Engineering (staff)
- Telescope, tower and enclosure (hardware)
- Instrumentation (hardware)
- Observatory and Antarctic infrastructure (hardware)
- Software (staff)
- Software support and instrument support (staff)
- Observing support (staff)
- Logistic support (Antarctic costs)

This leads to one possible funding model, shown below, which sees an initial cash injection of $32m for hardware. Project management, software development and support are funded through a continued budget line to the AAO, and logistic support through an enhanced budget line to the AAD. Continuing IPEV and PNRA logistic support of the station at the current level is identified as a contribution equivalent to 20% of the project, in return for share. Instruments are funded and built by individual consortia made up of Australian and international institutions and industrial partners.

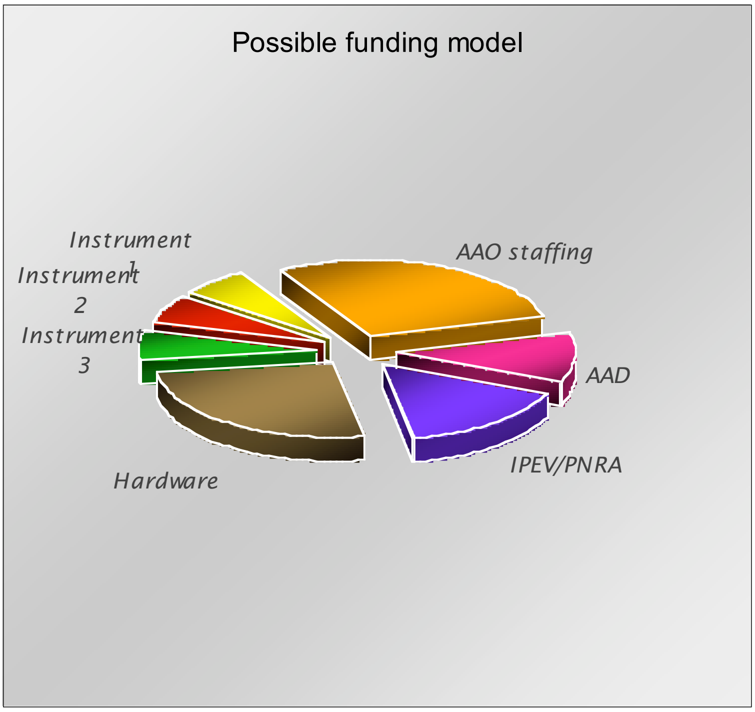

Figure 3.

4.4 Exchange rates

The following exchange rates, which were current in late July 2008 have been used:

- AUD 1 = USD 0.965
- AUD 1 = EUR 0.611

The majority of funds over the life of the PILOT project would be spent in Australia, providing a solid barrier to exchange-rate fluctuations. The main item of expenditure outside Australia is the mirror. To the maximum extent possible, renewable energy will used to power PILOT, minimising the impact to the project from rises in the cost of oil.

5. PILOT Development Stage

To proceed to the next stage, the PILOT project seeks $2.5m – $3.4m from the NCRIS Strategic Options fund.

Following its Design Review on 24 – 25 July 2008, the PILOT project seeks to move into the *Development* stage (ISO 15288 nomenclature), which begins with the preliminary design phase. This phase is valuable in its own right, delivering both science and unique IP to Australian industry as the most significant risks to the project are bought down through component design, modelling, protoyping and research studies. Traditionally, major projects invest 5% of the capital cost into preliminary design. Accordingly, for PILOT itself, 5% of $45m, or $2.5m, is sought.

In addition, there is clear merit in establishing Australian institutions and industry as the prime contractors for at least the first two instruments for PILOT. At $9m per instrument (including software), the 5% design phase for these instruments would require a further investment of $0.45m each. This investment would have clear benefits in maintaining the health of Australia's astronomical instrumentation capability, with the bulk of the funding going to Australian industry and institutions.

The top-level Work Breakdown Structure for the project for the next phase is outlined in the PILOT Delivery Plan Document PILOT_PRM_04_D. Sufficient funding is required to establish a full-time PILOT team, which will maintain a project office at an existing Australian institution such as the Anglo-Australian Observatory. Subject to satisfactory progress, the project could seek major funding as early as the 2010 – 11 Federal budget to proceed to the final design phase and construction. During the preliminary design phase, an estimated 75% of the funds will be spent in Australia.

6. ANSOC Terms of Reference

In this section, the ANSOC terms of reference are addressed directly and a brief overview of PILOT's potential contribution to Australia's Optical and Radioastronomy capability is provided.

6.1 The potential for novel scientific returns and for contribution to the resolution of the key scientific and technical challenges in 21st Century astronomy

Scientific Returns
The PILOT science case is based on several key projects of crucial importance to contemporary astronomy, ranging from studies of near-earth objects to measurement of fundamental cosmological parameters. These are described in more detail in Section 3 and in the PILOT Science Case Document PILOT_SPE_001_B.

This science case has been developed over the past decade, with earlier versions being published in 2001 and 2005. The most recent version (the PILOT Science Case Document) has contributions from 39 authors in eight countries and will shortly be submitted for publication in a peer-reviewed journal.

The PILOT science case should ideally be sufficiently compelling that PILOT can proceed on the basis of "no regrets". In other words, should all subsequent future options in Antarctica not be available, or not be adopted, PILOT would have proven itself to be a cost-effective scientific investment by the end of its ten-year program.

Scientific and Technical Challenges
The fundamental technological challenge to twenty-first century optical/infrared astronomy is to mitigate, to the maximum extent possible, the deleterious effects of the earth's atmosphere. PILOT addresses this challenge by paving the way for future telescopes to be deployed to sites with significantly better atmospheric conditions. This opens a new era in astronomy, where developments in adaptive optics, telescope aperture, detector technology and instrumentation can be used to greater advantage than at a temperate site.

PILOT is a pathfinder for future Antarctic facilities, as the name suggests. The option that PILOT buys is one that may have unparalleled potential to further our exploration of the universe. Development of the detailed science case for next-generation (post-PILOT) Antarctic telescopes has only just begun, but examples for an 8 m high-dynamic-range telescope include direct imaging of "hot Jupiter" extrasolar planets, for an interferometer include characterisation of zodiacal dust discs out to the distance at which future space missions plan to study earth-like planets, and for a terahertz antenna include the first complete census of the interstellar medium. Looking to the distant future, a 30 metre-class telescope in Antarctica could carry out much of the ambitious science envisaged for the original 100m OWL telescope.

To make any of this possible, PILOT must solve the key technological challenges of operating a telescope in Antarctica. These include the intense cold, a supersaturated atmosphere (though one that is exceptionally dry in absolute terms), limited logistic support, an exceptionally strong (though low elevation) temperature inversion layer, and rapid temperature fluctuations.

The challenges can be compared to those faced by astronomers a few decades ago when Mauna Kea was first developed for astronomy. In the case of Mauna Kea, few would doubt that the pioneering struggles to overcome what were then formidable technological obstacles have delivered handsome dividends. The difficulties of high altitude and logistic support of a remote location are common to both sites. PILOT has taken care to learn from, and build upon, the Mauna Kea experience. For example, Peter Gillingham, who was the Operations Director at the W.M Keck Observatory during the commissioning of both the "Kecks", is the PILOT Project Engineer.

In developing solutions to the technological challenges, Australia is likely to create IP which is important to all future Antarctic telescopes. This should place Australia in the position of preferred partner for any future international telescope venture in Antarctica. This has already happened with AST3, a Chinese-led project to place three 0.5m Schmidt telescopes at Dome A. Australia has been invited to join the AST3 team, creating an new international partnership that could prove valuable to Australia as China pursues her ambitious plans to build a new, permanent station at Dome A within a decade.

6.2 The potential to develop Australian astronomy and enhance its world position

PILOT will provide Australian astronomers with a powerful new facility offering some capabilities that are unmatched by any existing or planned ground-based telescope. PILOT will provide Australian astronomers with opportunities to involve international collaborators to maximise scientific return. Through these collaborations, Australia stands to benefit from the close interaction with the best researchers in the field at any time.

Publications

Australia's Antarctic astronomy program has already shown itself to be a very productive astronomical investment in terms of published output per dollar. Importantly, almost all of these publications arise from Australian-led programs and have Australian first authors. With NCRIS funding there has been a surge in activity.

Because of the nature of the PILOT Design Study, the outputs have largely been in IP, technical reports and conference papers. Innovation in astronomical instrumentation is presented at conferences, notably the Astronomical Instrumentation meeting of SPIE (Society of Photo-Optical Instrumentation Engineers) held every two years. The resulting proceedings are recognized by ADS. Australia's Antarctic astronomy program has been responsible for the following publications in *Proc. SPIE:*

Year	*Number of SPIE papers*
2000	2
2002	4
2004	5
2006	6
2008	11 (in press)

The surge in publications in 2008 is in part due to NCRIS funding of the PILOT design study. Antarctic astronomy now plays a major role in maintaining Australia's international reputation as an innovator in astronomical instrumentation. At the most recent SPIE meeting (June 2008, Marseilles), Antarctic astronomy accounted for some 50% of papers presented by Australian authors.

Antarctic astronomy has been an Australian strength for over a decade, with Australians invited to join scientific organising committees, chair conference sessions, participate in discussion panels, and give invited talks. In addition to peer-reviewed papers, from 1998 – 2008, over 90 full-length conference papers were presented by Australians and published on Antarctic astronomy. Australians have been asked to write the entries for *"Astronomy"* and *"Infrared Astronomy"* in the Routledge Encyclopedia of Antarctica (2007), plus articles for New Scientist and European and Chinese popular astronomy magazines.

Student Training

There can be few other areas of research that offer students such a challenging combination of science, innovative instrumentation, project management and individual self-reliance in one of the world's harshest environments. Opportunities are created at undergraduate, postgraduate and postdoctoral level.

Although UNSW's program has until now been conducted at only a small scale, former students and postdocs are now in senior positions at the ATNF and in industry. For example, Dr Craig Smith is currently CEO of EOS Space Systems Pty Ltd, Canberra. Others have gone overseas, where they act as ambassadors for Australia's scientific prestige and strengthen international links with Australian researchers. Some of Australia's Antarctic astronomy "alumni" are now at:

- Thirty Metre Telescope Project, California
- Harvard Smithsonian, Massachusetts
- James Clerk Maxwell Telescope, Hawaii
- Boston University, Massachusetts
- Cornell University, New York
- Cardiff University, Wales
- Planetary Science Institute, Arizona
- Las Cumbres Observatory Global Telescope Network, California

- Gemini Observatory, Chile

Advancing Industry
As an Australian-led program, PILOT is in a unique position in its ability to engage Australian industry to best advantage. Astronomy can play an important role as a demanding customer, challenging industry to achieve ever greater performance and precision. Antarctic astronomy throws down still more challenges, including ruggedness, reliability, and operation under extreme environmental conditions. Australian industry can build PILOT – the primary mirror is the only major component that needs to be sourced overseas.

From the perspective of industry, PILOT is a relatively small project with limited opportunity for annuity income – which is the life blood of companies. However, PILOT will demand the development of novel and innovative technologies that may be expected to have impacts well beyond astronomy. New materials, techniques and processes will be needed to bring PILOT into operation. These may be expected to have application in broader areas of human activity and their associated markets. PILOT offers the potential to become a marker project in the context of realising the anticipated outcomes of the current review of the National Innovation System.

Specific industry sectors that may be expected to benefit from Australian investment in PILOT may include:

- Mechatronics and autonomics, notably as they may be applied in harsh and remote environments
- Large structure design, construction and maintenance techniques as they may be applied in harsh and remote environments
- Broadband communications, coding and other schemes, especially as they relate to satellite communications
- Renewable energy
- Systems engineering, complex modeling and simulation

International engagement
For the past decade, Australia has been an acknowledged world leader in Antarctic astronomy. Australians hold key positions in the international ICSU bodies IAU and SCAR. Australia is the only non-European member of ARENA, an EU FP6 Coordinating action involving 21 institutions in eight countries to study the options for Dome C.

Australia has also strong links with China through the PLATO observatory, built in Australia and deployed to the highest point on the Antarctic plateau, Dome A, earlier this year. PLATO is spearheading the Chinese drive into Antarctica, building upon Australian know-how and experience. Like PLATO, the PILOT project positions Australia to be a significant partner in future Chinese observatories in Antarctica.

Inspirational Science
Antarctic astronomy has always enjoyed a strong media profile in Australia. The popular appeal of astronomy combines with the lure of Antarctica to create a ready stream of material for schools, TV, and magazines. With this in mind we have included in our PILOT budget the salary of a part-time outreach officer.

6.3 The feasibility and robustness of the proposed design and costing (for both construction and operation)

Throughout the PILOT Design Study, the project has engaged closely with leading industrial companies to ensure that the resulting design is feasible and can be rigorously costed. In keeping with ISO 15288, a project at the present stage of development can be expected to have costs known to within 35%.

Design of the deployment and operation phases of PILOT has been carried out with the assistance of the Australian Antarctic Division, which has over 50 years of experience in Antarctic operations. Advice on operational costs of Concordia, and deployment costs to Concordia from Hobart, comes directly from the French polar agency IPEV.

The detailed costing of PILOT, and the basis for those cost estimates, is presented in the PILOT Project Delivery Plan Document PILOT_PRM_04_D.

6.4 The risks associated with the option and the quality of the proposed mitigation strategies.

The first activity of the PILOT project in early 2007 was to commission the project management company SKM to hold a risk workshop. The resulting risk report identified 29 risks, of which 8 were classified as "high" according to the procedures of Australian Standard AS4360 – 2004. This report was used to establish the risk register that has guided the project throughout its development.

The Design Study has been a process of buying down the most significant of these risks and identifying new ones. The risk register was last reviewed on July 23, 2008. Assuming appropriate mitigation steps are taken, of those risks considered "high", two are associated with contracts, five with management, two with safety, and three are associated with technical issues. Full details are presented in Sections 4.7 – 4.15 of the PILOT Delivery Plan Document PILOT_PRM_04_D.

In addition, the telescope manufacturer EOS Technologies performed its own detailed risk analysis for the telescope itself as part of their PILOT subcontract. EOST concluded that the only technical items for which the risk was "high" were those associated with the operation of the drive trains and encoders at very low temperatures, and the possibly of shock loads during transport. Both these risks will be addressed during the preliminary design phase.

At the present stage there is no agreement in place for the installation of PILOT at Concordia Station. This agreement must be negotiated during the next phase of the project, or an alternative site identified and characterised.

6.5 The feasibility that the international support necessary to deliver the option will be forthcoming on a timescale relevant to Australian decision making.

If Australia decides to take full ownership of the PILOT project, no international funding is needed. However, agreement must be reached with France and Italy on access to Concordia Station. The PILOT proposal is costed on the assumption that Australia would pay for all costs associated with the use of the station, and this could form the starting point for negotiation of a tenancy agreement. In terms of the necessary skill and experience, the project is not dependent on any international support. The Australian-owned company EOST is a leading constructor of 2.5 m class telescopes and telescope enclosures. Finally, the total cost of PILOT (capital, instrumentation, deployment operation and decommissioning) is within Australia's capability to fund in its entirety.

Nevertheless, there are strong reasons, both scientific and political, why Australia should seek to partner other nations in the PILOT project. For example, the preferred site for PILOT is the Concordia Station at Dome C operated by France and Italy, making these two countries desirable partners. The success of the AAO has shown the clear benefits of an equal partnership with a nation of scientific peers. There is also obvious benefit in a collaboration with the US, a nation which combines leadership in astronomy, technology (especially in infrared detectors) and satellite communications. Other countries, such as China and Japan, may also represent highly desirable partners for both scientific and political reasons.

In parallel with the NCRIS-funded PILOT Design Study, the ARENA Network has been assessing the potential for astronomy at Dome C. As the only non-European member of ARENA, Australia has worked closely with European partners to ensure that PILOT meets the common goals of the two communities. At a minimum, an agreement must be negotiated with France and Italy for use of Concordia infrastructure. Indications are that such an agreement would be welcomed by Europe, with the negotiations to be conducted during the Development stage of PILOT.

Acknowledgement
The PILOT Design Study is part of an initiative of the Australian government being conducted as part of the National Collaborative Research Infrastructure Strategy.

Submitted to Astronomy Australia Limited, 31 July 2008
Professor J.W.V. Storey, PILOT Project Leader, on behalf of the PILOT team.

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A1. Glossary

AAAAC	Australian Antarctic Astronomy Advisory Committee
AAD	Australian Antarctic Division (Australian national Antarctic agency)
AAO	Anglo-Australian Observatory
AAT	Anglo-Australian Telescope
ADS	Astrophysics Data System (NASA)
ALMA	Atacama Large Millimetre Array
ANSOC	Astronomy NCRIS Strategic Options Committee
ARENA	Antarctic Research: a European Network for Astronomy (an EU FP6 network)
ASKAP	Australian Square Kilometre Array Pathfinder
AST3	Antarctic Schmidt Telescope (which consists of 3 units)
ATNF	Australia Telescope National Facility
CCD	Charge-Coupled Device
DUNE	Dark UNiverse Explorer (now part of Euclid)
ELT	Extremely Large Telescope
EOS	Electro-Optic Systems
EOST	Electro-Optic Systems Technologies
ESO	European Southern Observatory
Euclid	European Cosmic Vision space project merging DUNE) and the spectroscopic all-sky cosmology explorer (SPACE).
Herschel	European far-infrared space mission due for launch 2009
GRB	Gamma Ray Burst
IAU	International Astronomical Union
ICSU	International Council for Science (formerly “of Scientific Unions”)
IPEV	Institut Paul Émile Victor (French national Antarctic agency)
ISO	International Organization for Standardization
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
LSST	Large Synoptic Survey Telescope
MWA	Murchison Wide-field Array
NCRIS	National Collaborative Research Infrastructure Strategy
OWL	Overwhelmingly Large Telescope (an earlier European ELT proposal)
PanSTARRS	Panoramic Survey Telescope and Rapid Response System
PISNe	Pair-Instability Supernova(e)
PLATO	Plateau Observatory (a robotic site-testing observatory currently operating at Dome A)
PNRA	Programma Nazionale di Ricerche in Antartide (Italian national Antarctic agency)
SCAR	Scientific Committee on Antarctic Research
SKA	Square Kilometre Array
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPIE	Society of Photo-Optical Instrumentation Engineers
SPT	South Pole Telescope
UNSW	University of New South Wales
VISTA	Visible and Infrared Survey Telescope for Astronomy
WISE	Wide-field Infrared Survey Explorer (a space mission due for launch in 2009)

A2. PILOT papers presented at SPIE meeting, Marseilles, June 2008

- The PILOT Telescope facility
- The proposed PILOT instrumentation
- The PILOT operational challenges

A3. List of PILOT Design Study documents

The key project documents are available on the PILOT public website:

http://www.aao.gov.au/pilot/pilot_status.htm

The full set of documents is only available on the PILOT password-protected website.

In the "core system documentation" sub-directory:
- Science Case Document
- Environmental Conditions Document
- Delivery Plan Report, including Risk Register/Issues Log
- Design Study Report

In the "spie papers" sub-directory:
- The PILOT Telescope facility
- The proposed PILOT instrumentation
- The PILOT operational challenges

In the "supporting documentation" sub-directory:
- Systems Engineering
  - Science Requirements Document
  - Operations Concept Document
  - Functional Performance Requirement Document
- Technical notes
  - A large collection of raw design and technical notes developed during the design study on specific PILOT issues, systems and components, plus reports from contractors.
  - Zemax files
    The working Zemax files for the telescope, plus the near-IR and optical wide-field instruments.

A4. AAAAC membership

Prof. Tim Bedding	
Mr. Brett Biddington	Chair
Prof. Brian Boyle	ATNF Director
Dr. Iver Cairns	
Dr. Martin Cole	AAL Board
Prof. Matthew Colless	AAO Director
Mr. Roger Franzen	
Ben Galbraith	Tasmanian Government
Prof. Karl Glazebrook	
Dr. Charles Jenkins	
Dr. Michael Stoddart	AAD Chief Scientist
A/Prof. Mark Wardle	
Vacant	Bureau of Meteorology

A5. PILOT Design Review panel members

Brian Boyle (Chair)
Director of the CSIRO Australia Telescope National Facility

Dr Brian Boyle completed his PhD at the University of Durham in the UK. He held positions at the University of Edinburgh, the Anglo-Australian Observatory, the University of Cambridge and was Director of the Anglo-Australian Observatory from 1996 to 2003, before his appointment to CSIRO Australia Telescope National Facility's Director in July 2003. Dr Boyle has published more than 300 papers in astronomy.

His primary research interests are in the fields of quasars, active galaxies and cosmology. While at the AAO he led the 2dF QSO redshift survey program, and is currently involved in the Australia Telescope Large Area Survey (ATLAS). He plays a major role both nationally and internationally in the Square Kilometre Array (SKA) program; a project to build the world's largest cm-wavelength radio telescope.

Wolfgang Ansorge
RAMS-CON

Wolfgang Ansorge has spent more than 40 years of his professional life in project management, Systems Engineering, quality assurance and system safety management of large international commercial as well as research infrastructure projects. Today he is owner of a consulting company specialist on the above mentioned subjects for scientific and research organizations and projects. He participated in a number of large projects in EU FP6 and FP7.

Ansorge was key member of the project management team of the ESO Very Large Telescope project from 1990 to 2000. He introduced Systems Engineering into this €1 billion astronomical observatory project and initiated the introduction of the System Engineering discipline worldwide in the astronomical infrastructure community. Since many years he is invited speaker on Systems Engineering at the international SPIE conferences on astronomical infrastructures and instrumentation.

Peter Gray
Assistant Project Manager, TMT

Peter Gray has a bachelor of science degree in physics and a bachelor of engineering degree in mechanical engineering from the University of Sydney. He has over 26 years of experience of engineering design and operations support for many of the world's major observatories and large telescope projects. His early career at the Anglo-Australian Observatory was in the design and construction of astronomical instrumentation, particularly multi-object fiber spectrographs, where he helped pioneer this technology. Gray moved to the University of Arizona where he was involved in many projects at the Mirror Lab, MMT, and LBT telescopes. He later led the assembly and integration phase for ESO's four VLT telescopes at Paranal Observatory in Chile, where, as head of engineering, he established engineering operations support. He has worked on system engineering for the ALMA project, and most recently served as Associate Director of Engineering at the Gemini Observatory, where he successfully led the engineering team during the transition from commissioning to science operations.

Geraint Lewis
Associate Professor, School of Physics, University of Sydney

A/Prof Geraint Lewis undertakes a broad spectrum of research. On the largest scales, his program involves looking at the influence of dark energy and dark matter on the evolution and ultimate fate of the Universe.

Another aspect of his research uses the phenomenon of gravitational lensing to probe the nature and distribution of the pervasive dark matter, and employing individual stars to magnify the hearts of quasars, the most luminous objects in the Universe.

Closer to home, Geraint's research focuses upon Galactic cannibalism, where small dwarf galaxies are torn apart by the much more massive Milky Way and Andromeda Galaxy. Using telescopes from around the world, including the 10-m Keck telescope in Hawaii, he has mapped the tell-tale signs of tidal disruption and destruction, providing important clues to how large galaxies have grown over time.

Peter Yates
Telecommunications Engineer, Australian Antarctic Division

Peter Yates has been involved in Antarctic operations for over 25 years. He wintered at Mawson in 1983 and 1986, as an engineer operating and updating the Cosmic Ray Observatory. From 1987 until 1998 he managed the AAD Science Support Electronics Section, participating in projects including Glaciology Ice radar survey in the Prince Charles Mountains, development of Automatic Weather Stations, and development of the LIDAR now in operation at Davis.

In 1998 he was appointed as the Engineer in Charge of the AAD Telecommunications Section, which provides all of Australia's Antarctic Telecommunications and IT. Recently he has filled the role of Chief Engineer at the AAD, responsible for the maintenance of Australia's four Antarctic Stations.

A6. PILOT Design Review

Review Team Report: 25 July 2008

The review team commends the PILOT design study team for the work they have completed to date on the design for a diffraction-limited optical/infrared telescope at the Dome C site in Antarctica.

The review team consider that the design team have conducted the most detailed examination to date of the feasibility of placing a diffraction-limited moderate-to-large aperture optical/infrared telescope on the high plateau of Antarctica. They have also developed a competitive science case with broad community engagement and established a comprehensive set of project management/system engineering practices relevant to successfully continue with a project of this scale.

Australia is well placed to build on this initial study and undertake a comprehensive Preliminary Design for a significant optical/IR telescope on the high Antarctic plateau.

We understand that a 2.5m telescope is the first phase of a longer-term strategic program to develop and exploit the Australia's Antarctic Territory as a world-class astronomy observatory site.

The over-arching recommendation of the review panel is therefore that, if resources are available, the PILOT project should be carried forward to a full Preliminary Design stage to be completed no later than September 2010. This would be best achieved by establishing a distinct Project Office with additional resources for contractual work, including additional environmental studies.

Based on an extrapolation of the current resource levels, the review team estimate that a minimum of 10-15FTE yr would be required to reach this milestone. Particular attention should be placed on achieving broader engineering skill set and technical depth in the design study team. Closer relationships need to be developed with key stakeholders and collaborators with knowledge essential for the successful delivery of the project, in particular the Australian Antarctic Division and the Concordia Organization.

The Project Team should engage with international partners on the basis of its leadership position in this area.

In taking this study forward to a full Preliminary Design, the following issues that have emerged from the existing study would need to be critically addressed:

Technical

- Outstanding telescope/tower design issues (control dynamics, wind affects, optical coatings etc).
- Explore alternative solutions and to perform detailed investigation in order to eliminate or minimize to an acceptable minimum the risks identified in the Design Study.
- Complete site verification programme with emphasis on issues that critically affect the design of the telescope and the delivery of the scientific programme (e.g. rapid variation in temperature).

Managerial

- Establish an appropriate balance between resources devoted to Project Management, Systems Engineering, and technical design for the scale and stage of the project
- Clarify and complete the requirement definition process
    - user/stakeholder requirement identification
    - preparation of a System Requirement Specification
    - preparation of other documents supporting the System Requirement Spec, e.g. Environmental requirement Spec, Interface Spec.
- Prepare concise but detailed project management documents, e.g.
    - design and development plan, project schedule, Statement of Work, Work Breakdown Structure WBS, etc.

Scientific

- Develop a motivated long-term scientific program
- Focus on competitive and differentiated areas of parameter space (deep K band imaging, long-term monitoring, high-res optical) seeking to maximise scientific impact.
- Develop a sensitivity matrix to drive the phased implementation of telescope scientific functionality

Operational

- Develop the current scope of the Operations Plan, including more detailed consideration of staffing, functional skills, costs, transport, communications, maintenance and logistic support issues relevant to the design and operational costs of the system.

Strategic

- Consider carefully potential reliance on small number of suppliers in the key technology areas, particularly the telescope.
    - Investigate cost implications of worst-case scenarios (cost v risk)
- Continue to broaden ownership of PILOT science goals amongst community
- Develop non-astronomy aspects for case for astronomical infrastructure in Australian Antarctic Territory

Relationships

- Develop clarity around potential international partnerships involving the delivery of both the PILOT 2.5m telescope project and the long-term strategic program.
- Clarify contractual relationship with Concordia site.