# PILOT—securing Australia's long-term future in optical/IR astronomy through Antarctica

PILOT—the Pathfinder for an International Large Optical Telescope—is a proposed 2.4-m aperture optical/IR telescope to be sited at Concordia Station, Dome C, in the Australian Antarctic Territory.

PILOT is the first stage of a development path that leads towards larger facilities in Antarctica and a vigorous new future for Australian optical/IR astronomy. This path is consistent with both the Astronomy Decadal Plan and the Australian Extremely Large Telescope (ELT) Working Group Roadmap.

Of the five possible components of the NCRIS optical astronomy Investment Plan (8m, AAO, ELT, PILOT, and SSO), three of them (8m, AAO, and SSO) are directed at maintaining or upgrading our existing facilities. The remaining two (ELT and PILOT) are aimed at opening up new opportunities for Australian astronomy to grow into the future, and raising Australia's astronomy capabilities "to the next level".

- PILOT shares many of the desirable advantages that make the radio astronomy investment case so strong. Both PILOT and the Mileura radio telescope proposal are projects that have had strong Australian input from the beginning, and this leadership has helped shape these projects to be responsive to Australia's national requirements.
- PILOT, and the radio astronomy investments at Mileura, will create useful new facilities within the lifetime of NCRIS. These facilities will be available for Australian astronomers to use immediately upon completion. This represents productive use of NCRIS funding that is *not* contingent on additional major investment at some stage in the future in order to deliver useful infrastructure.
- As with SKA, achieving the long-term goals of the Antarctic astronomy program will require major investment. Where such facilities are located within Australian territories, there are obvious and powerful reasons—that are not astronomy related—why such investments benefit the nation and are likely to be attractive to governments and other co-investors.

**The PILOT path**

This path is a visionary one that secures Australia's leadership in optical/IR astronomy for the next 25 years. The period 2006–2010/11 begins with the construction of PILOT, and proceeds with the development of the science case for large and extremely large Antarctic telescopes, and the Conceptual Design Study of LAPCAT, an off-axis 8 metre Antarctic telescope. The final component for this period is the Design and Development phase of LAPCAT. PILOT will be partially funded through NCRIS; the latter studies will be funded through ARC, industry and international collaborative programs. The 2.4 metre PILOT telescope provides Australian astronomers with access to a facility which, due to the extremely low IR backgrounds and exceptional seeing conditions, can provide "8 meter equivalent" performance for certain science programs, thus meeting part of the demand by Australian astronomers for greater 8 metre access.

This proposal is consistent with three crucial NCRIS requirements: that world-class research infrastructure is created in an area where Australia can provide (and in fact is already providing) international leadership; that NCRIS funds are used to provide new, usable research infrastructure (i.e., the PILOT telescope itself at a cost of $8.6m); and that the NCRIS funding be directed towards maximising the strategic impact of Australian science investment at a global level.

The PILOT path uses our natural advantage of proximity to Antarctica to best effect, while simultaneously providing an internationally acceptable way for Australia to demonstrate its stewardship of the 42% of the continent that it claims. At every stage along this path, Australia is spending its money and resources in Australia, while charting a course towards eventual partnership in the most powerful ELT possible, i.e., an ELT in Antarctica At every stage, Australian astronomers are building their own uniquely powerful facilities such as PILOT and LAPCAT. And at every stage, Australia can, if desired, trade time on these facilities for time on the world's best 8 metre telescopes, and, eventually, both the Giant Magellan Telescope (GMT) and other ELTs.

**PILOT**

PILOT has been proposed by a consortium of countries including France, Italy, Germany, the UK and the US. The PILOT proposal is led by Australia, with the main support coming from astronomers at the AAO, Sydney University, Swinburne, Macquarie, and UNSW.

A number of companies around the world have expressed interest in manufacturing PILOT, including the Australian-owned EOST (Electro-Optic Systems Technologies). The EOST design is based on a 2.4 metre Nasmyth telescope, similar to the 2.4-m Lick Rocky Planet Finder. Direct drive on both axes eliminates all gears, friction wheels and other drive components to provide a simple and robust mechanical system. PILOT includes a fast tip-tilt secondary mirror to remove tower shake.

Three design studies were funded in 2004 from university development grants to ensure that a commercial off-the-shelf telescope could be adapted to Antarctic conditions without serious difficulties. These were:

- Optical design, AAO
- Engineering design study, EOST
- Telescope enclosure study, Connell Wagner

The engineering design study of the telescope confirmed that there were "no insurmountable technical challenges".

**PILOT instrumentation**
The table below outlines the specifications for seven possible instrument concepts that could eventually make up the imager complement of a full instrument suite for PILOT. Their fields of view are determined by the largest commercially-available array for the relevant wave-band, keeping the cost of each instrument below $2 m. Larger fields would be possible by butting several such arrays together.

| Wavebands | Wavelength (μm) | Array | Detector | Pixel Scale (arcsec) | Field of View (arcmin) |
|---|---|---|---|---|---|
| Optical: VRI (high resolution) | 0.5–1.0 | 4K | Si | 0.03 | 2.0 |
| Optical: VRI (wide field) | 0.5–1.0 | 4K | Si | 0.1 | 6.8 |
| Near-IR: JHK (high resolution) | 1.2–2.4 | 4K | HgCdTe | 0.08 | 5.3 |
| Near-IR: JHK (wide field) | 1.2–2.4 | 4K | HgCdTe | 0.30 | 20 |
| Thermal-IR: KLM | 2.2–5.9 | 1K | InSb | 0.23 | 4 |
| Mid-IR: NQ | 7–40 | 0.5K | SiAs | 0.7 | 6 |
| Sub-millimetre | 200–1000 | 64×64 | NbN | 5–25 | 5–25 |

These, and other new instruments, are within the scope of ARC LIEF funding, and could be constructed by Australian instrumentation teams, particularly RSAA and AAO. This provides opportunities to demonstrate proof-of concept of innovative technologies such as OH-suppressing fibres, and to showcase Australia's ability as a builder of quality instruments for applications that require high reliability. The initial commissioning instrument for PILOT is envisaged as a diffraction-limited optical camera with 4k × 4k pixels and a selection of broad and narrow-band filters, with a pixel scale of 0.03 arcseconds. Offers of additional instruments have also been made by our international partners (e.g., a wide-field IR camera provided by MPIA).

**PILOT science**
The PILOT science case was developed by a group of 27 leading astronomers from seven countries. It is published in the Publications of the Astronomical Society of Australia, **22,** (2005), 199–235, and outlines the broad range of astronomical problems to which PILOT could make a unique contribution. Because PILOT is an Australian-led program, Australian astronomers can determine which instruments will be built and in what order. The exact specification of each instrument will be the result of an open, consultative process within the Australian astronomical community.

JACARA, the Joint Australian Centre for Astrophysical Research in Antarctica, is a university collaboration that is advised by a working group of astronomers from seven Australian universities plus the Australian Antarctic Division. JACARA has been active for over a decade coordinating Australia's Antarctic astronomy program; most recently by organising the well-attended scientific meeting at the Anglo-Australian Observatory in 2004 from which the current PILOT science case was developed. JACARA should continue to have an advisory role on both scientific and instrumentation issues.

**International collaboration**
The PILOT team includes many of the world's leading astronomical institutions, thus ensuring that Australia gains exposure to cutting-edge technologies and satisfying the requirement of enhancing international

collaboration. With Australia providing the telescope itself, the following major contributions are also anticipated over the course of the project from our international partners:

- French and Italian National Antarctic Programs: logistic support
- Arcetri Observatory: 45-element adaptive secondary mirror
- Max Planck Institute for Astronomy: wide field IR camera
- University of Nice: observatory infrastructure and coronagraphic camera

**Costing for PILOT**

Originally envisaged as a 2.0 m telescope, PILOT can take advantage of a new EOST design to increase its aperture to 2.4 m for a modest cost increase. Several options are available for PILOT (including alternative telescope vendors), but the present proposal, for an EOST dual-Nasmyth f/10 with fast tip-tilt secondary, is:

| | |
|---|---|
| Base price of telescope FOB Los Angeles, 2008 delivery: | $6,540k |
| Winterisation | $920k |
| Shipping LA – Hobart | $140k |
| Installation and commissioning at Dome C | $480k |
| **Total** | **$8080k** |

To this must be added the cost of the mounting tower and telescope enclosure, estimated at $500k. Instrumentation for PILOT would be provided through LIEF grants (see later) and via our European partners.

Concordia Station costs €4.5m/year to operate. Agreement must be reached with Italy and France (who will be funding the on-going operation of Concordia regardless of whether PILOT is built or not) to include PILOT as one of the station's scientific key facilities in return for 50% of the observing time. Exactly such an agreement was reached in 2001, and must now be revisited and updated. Australia's commitment of $8.6m would be roughly matched by the Europe partners picking up the full deployment costs and operational cost for 7 years. Funding for a project office (2007–2010) and for an ongoing project scientist position once PILOT is commissioned (2010– ) must also be provided, and will be sought from university resources.

**Upscaling and down-sizing**

Community input is required to determine the optimum level of Australian commitment to Antarctic astronomy. The cost of PILOT is most readily reduced by reducing the diameter to 2.0 m or even 1.8 m. Other partners could be found to share the cost, including co-investors from industry. On the other hand, PILOT could be built to meet even more demanding goals; e.g., a tight wavefront error specification (in order to achieve diffraction limited imaging in V without adaptive optics) could increase the cost by a further $1.7 m.

**Current status of Dome C site testing**

The conditions at Dome C have now been studied over two separate winters, as asked for in the ELT Working Group Roadmap. Measurements have just begun for a third winter. The consistency of the results from the first two years gives confidence to the conclusion that Dome C is the world's best optical/IR site, especially considering that two different teams were involved and that four different experimental techniques were used. In 2004, a MASS/SODAR combination demonstrated an average free-atmosphere seeing of 0.27 arcsec and a possible turbulent boundary layer no more than 30 m thick. In 2005, a combination of a DIMM and microthermal balloons delivered an average free-atmosphere seeing of 0.24 arcsec and set the height of the turbulent boundary layer at 36 m±19m. Clear-sky statistics first measured robotically in 2003 at a lower limit of 74% were found in 2005 to exceed 90%. Concordia Station at Dome C is now operating year-round. The benefits offered by the site are:

| **Parameter** | **Advantage over other sites** | **Performance Impact** |
|---|---|---|
| Isoplanatic angle | 2–3× | 4–9× in AO sky coverage and corrected field |
| Coherence time | 2.5× | 1 magnitude in guide star required brightness |
| Low IR background | 20–100× | 1–3 magnitudes in point source sensitivity |
| Image size | 2–4× | 2–4× spatial resolution in visible; 0.5–1.5 magnitudes in point source sensitivity |
| Scintillation | 3–4× | 3–4× gain in photometric and astrometric precision |

**Beyond PILOT**
PILOT is described as a "pathfinder" as it is the essential next step to the development of larger and more capable Antarctic facilities. Building a 2 metre class telescope at Dome C consolidates Australia's lead in this field for many years to come. The reason for this is that PILOT will be the "last common ancestor" of a wide range of new facilities that are currently under discussion, including a two-telescope nulling interferometer (ALADDIN), a multi-telescope Fizeau interferometer (KEOPS), an 8 metre off-axis telescope (LAPCAT) and even a 12 metre terahertz telescope (ASO). Intellectual Property and know-how developed through experience with PILOT will be invaluable for all of these future projects.

Of these future projects, the most interesting for Australia is LAPCAT, the Large Antarctic Plateau Clear-Aperture Telescope. LAPCAT has been proposed jointly by Australia and the University of Arizona, and offers Australia the opportunity to lead a new 8 metre telescope project. LAPCAT will use an 8.4 metre mirror identical to the offset segment recently cast for the Giant Magellan Telescope (GMT) as a completely unobscured f/2.1 primary. With a cooled deformable Gregorian secondary in a dewar following prime focus, LAPCAT will allow for diffraction-limited imaging with only a single reflecting surface at ~220K, and thus the lowest possible thermal background obtainable from the ground. LAPCAT would be the most sensitive infrared telescope on earth by a wide margin.

**Beyond LAPCAT**
By providing a test bed for many of the GMT technologies in an Antarctic environment, LAPCAT also paves the way for the eventual construction of a second GMT at Dome C. Such a telescope would have unparalleled capabilities compared both to ELTs at temperate sites and to JWST.

**Space debris detection tracking**
In addition to PILOT's role in astronomy, it could also be used for extending searches for satellite debris in low-earth orbit. Dome C's geographic location is close to optimum for detection of polar orbiting and high-inclination satellites and debris, and the long duration of twilight at high latitudes greatly increases the observability of such objects. This is a "space environment" issue of growing importance, with some 100,000 objects between 1 cm and 10 cm in diameter posing an ever-increasing risk to the space industry. Successful trial observations by PILOT in this mode could lead to the rapid deployment of a PILOT clone dedicated to debris tracking, or a potential long-term role for PILOT once astronomers have moved on to larger telescopes. While such an application is not of particular interest to astronomers, it creates important opportunities for private sector co-investment.

**Contribution to other capability areas**
PILOT, and telescopes at Dome C that evolve from PILOT, are well situated to perform "dual use" observations. For example, hydroxyl (OH) measurements from Dome C would be a byproduct of PILOT's routine near-IR observations and would give valuable data on stratospheric temperatures at polar latitudes, which in turn are a key ingredient of climate models. In addition to incidental measurements of atmospheric parameters, a small fraction of PILOT time could be dedicated to specific observations, for example, studies of stratospheric ozone and trace gases that are crucial for climate change modeling.

## Specific questions from Town Hall meeting:

**1. How realistic is the costing of PILOT?**
The cost is based on a detailed estimate obtained from EOST on 13 May 2006, and is consistent with the actual cost of similar telescopes (e.g., the 2.4m Lick Rocky Planet Finder, currently being completed). The CEO of EOS (EOST's parent company) has successfully deployed his own experiment to South Pole and is fully acquainted with conditions there, while the Control Systems Manager of EOST has also spent a summer at South Pole with the Viper telescope. It is important to realize that the cost of building a telescope in Antarctica is no greater (and in most cases less) than building it at a good temperate site. Although there are significant costs associated with adapting designs to the low temperatures (which have been included in the EOST estimate), there are also substantial savings since all the site infrastructure is already available, site preparation costs are minimal, and there is no need to provide protection against high winds, earthquakes, rain, lightning, animals or vandalism. This has been confirmed by a decade of telescope construction and operation at the South Pole by CARA (Center for Astrophysical Research in Antarctica), comparisons between the DASI (South Pole) and CBI (Atacama) mm-wave telescopes, and more recently by the construction of the US$25m 10 metre diameter submm-wave South Pole Telescope.

**2. "What are the risk-mitigation strategies?"** See below.

## General questions from Town Hall meeting:

**Describe the infrastructure that the facility would provide, and the timescale.**
PILOT, a 2.4m optical/IR Antarctic telescope, will be operational towards the end of the NCRIS funding cycle.

**Describe how access to the infrastructure will be allocated (e.g. time assignment committees; what fraction will be available to what constituency, etc).**
The basis for negotiation with the European community is that time on PILOT will be split 50% Australia, 50% Europe. All Australian time will be available for open competition on the basis of merit. Proposals will be assessed by a nationally-constituted body such as ATAC.

**Describe the likely outcomes (refereed papers, PhD completions, etc.) over the next 5 or 10 years.**
Based on the past performance of Australia's Antarctic astronomy program (21 refereed papers over 5 years, for an investment of $150k/year), at least 30 instrument science publications could be anticipated during the development of PILOT. Once operational, PILOT should produce at least a dozen high impact astronomical papers per year. Opportunities created for university departments across Australia in the development of LAPCAT, plus Australian involvement in other international Antarctic astronomy programs, could easily double this in the second 5 years.

The UNSW Antarctic astronomy work has, over the past five years, produced more PhD students in optical/IR instrumentation than any other astronomical program in Australia. The scale of the instruments and the originality of the research lend themselves perfectly to research training in instrumentation. PILOT will create opportunities for many other university teams to also engage postgraduate students in this area, perhaps doubling or tripling the present numbers. Once operational, PILOT gives Australian PhD students a unique facility on which to base, or supplement, their research. A conservative estimate (2 weeks observing time/year each) would be at 12 students at any time.

**Other outcomes (industrial partnerships, technology development, engineering expertise)**

- The Australian company EOS sees opportunities for developing a robust, Antarctic-capable element into their product line, and to invest in a satellite debris tracking program.
- Arcetri Observatory has offered to provide a complete adaptive secondary mirror as in-kind support to the PILOT project. It is only because of the unique capability that PILOT offers that a world-leading AO team is interested in sharing this technology with Australia.
- PILOT will be Australia's first telescope at a competitive site at which we can explore innovative new technologies.

**What evidence is there of demand for the facility?**

- The PILOT science case included contributions from 27 co-authors in 7 different countries. Some 25 major scientific programs were identified—even with a small instrumentation suite.
- The 30 CIs and PIs who submitted the ARC Centre of Excellence proposal in 2004 to build a 2 metre telescope at Dome C include many of the world's leading astronomers, whose awards include a Federation Fellowship, two Pawsey medals, a Fulbright scholarship, the Wolfgang Paul Prize, Italian CNAA Medal, Prix du Rayonnement Francais, two Millikan Fellowships, a Packard Fellowship and a MacArthur Fellowship.
- The SPIREX telescope at South Pole, *despite being only 60 cm in diameter and using an engineering-grade detector array,* attracted a large number of Australian proposals from across Australia. SPIREX data was obtained for nine of these fourteen proposals; these data contributed to three Australian PhD theses. The average citation impact of the first four Australian-authored SPIREX science papers is exactly the same as for the first four Australian-authored Gemini papers (ADS statistics). However, *all* of these SPIREX papers had Australian first authors, while *none* of the Gemini papers did.
- Other international teams are now forming to develop proposals for optical/IR Antarctic telescopes. For example, the recently formed European ARENA network has over 100 members from 8 countries. The US-led "Xian" project has a team of 16 people from China, Italy, US and Australia.
- The development of Dome C (which lies within the Australian Antarctic Territories) creates a major new opportunity for Hobart, potentially leading to a substantial economic gain for Tasmania. Already, Antarctic-related activities contribute $90m/year to the Tasmanian economy. The world currently spends about $1billion per annum on polar activities, suggesting major growth potential for Tasmania's Antarctic support industries. The Tasmanian government's stated vision for Hobart is for it to be *"...recognized globally as the world's pre-eminent gateway to the Antarctic..."*

- The Tasmanian Polar Network is an industry association set up to promote Tasmanian industry capability, and can be expected to lead efforts to capture the maximum return for the state's economy from the expansion of activities at Dome C.
- Dome C is the ideal location from which to study low-earth-orbit high inclination space debris; studies of major potential benefit to the space industry.
- Australia's presence in Antarctica has been judged to be in the national interest and will continue into the indefinite future. Astronomy adds substantial value to this investment, while increasing the visibility of Australia's presence in Antarctica in an internationally acceptable manner.
- Construction of PILOT will create new opportunities for instrument development and adaptive optics research at RSAA and AAO.

**Identify the major risks for the proposal, a risk mitigation strategy, and any major milestones.**
A Risk Analysis carried out in 2004 identified the main risks as political rather than technical. For example, will Australia continue to maintain an active presence in Antarctica? Can long-term access to the Concordia site be guaranteed?

Since that time, the federal government's commitment to the Australian Antarctic Territories has been confirmed by the allocation of $46.3m to create a new air-link between Hobart and Casey. PILOT will add scientific value to this investment.

Australia's importance to the European plans for Concordia is underlined by the fact that Australia is the only non-European member of the ARENA FP6 Network. Successful deployment of PILOT will itself further establish Australia as an indispensable partner. As with all major projects, the development of PILOT will need to be covered by an appropriate formal agreement that guarantees a fair return to Australia over the useful lifetime of the facility. Such agreements are common in Antarctica, where international science programs are regularly negotiated at a national level by agencies such as the Australian Antarctic Division.

For PILOT itself, expenditure of NCRIS funds would be contingent on satisfactory achievement of the usual milestones (design and readiness reviews). If at any stage the project needs to be cancelled, for whatever reason, unused NCRIS funds could be used to purchase time on foreign-owned telescopes (e.g., Gemini) to partially compensate for the loss of the planned PILOT science.

**What NCRIS funding is required, and how is the estimate based and phased over 2007–2011?**
The total requested for infrastructure is $8.6 m, see above. The phasing is approximately

| **Year:** | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|
| **$m** | 1 | 2 | 4 | 1 | 0.6 |

**What other sources of funding can be anticipated to augment the NCRIS funds?**

- National Antarctic agencies: IPEV, PNRA, AAD
- European FP7 funds
- *Antarctic Tasmania* (Tasmanian government Department of Economic Development)
- Tasmanian Polar Network
- Space industry; space insurance industry
- UNSW and other Australian universities
- ARC Discovery Project & LIEF grants

## Key Principles of the NCRIS Investment Framework, as set out in the NCRIS Roadmap:

These have been addressed in the main body of the document.

John Storey, 14 May 2006.