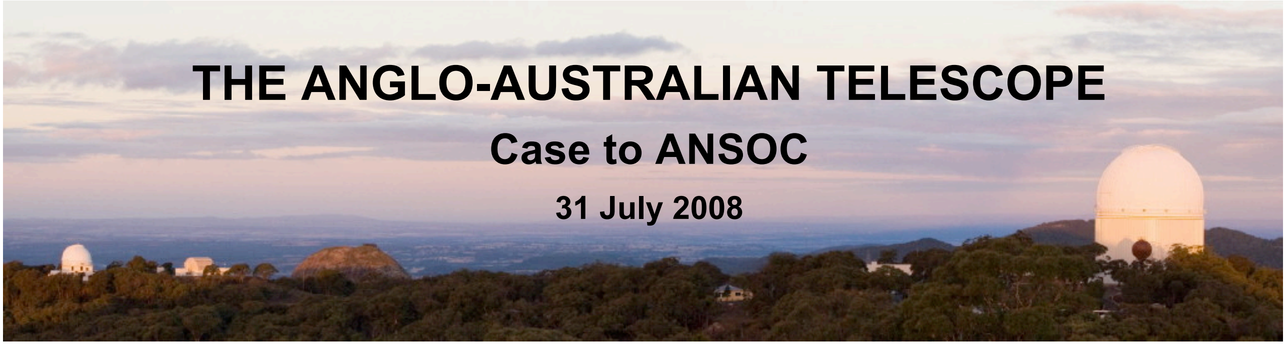
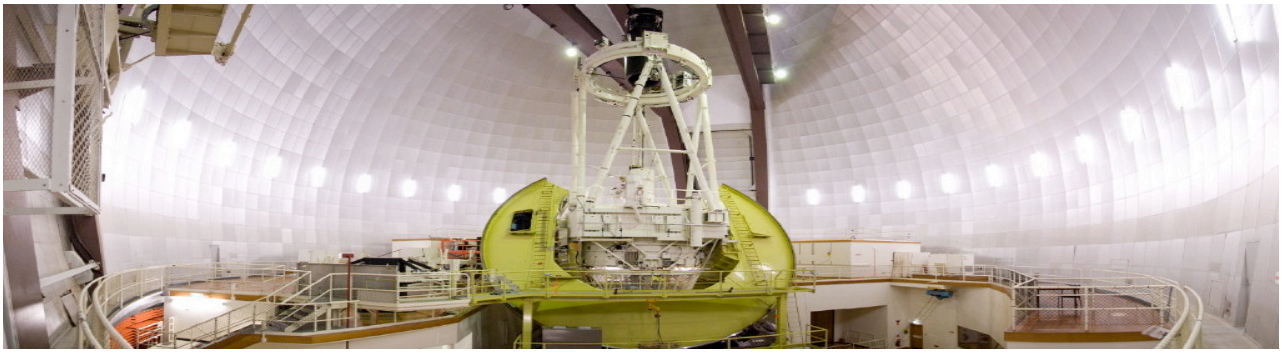


THE ANGLO-AUSTRALIAN TELESCOPE

Case to ANSOC

31 July 2008



1 SCOPE, CONTEXT AND STRUCTURE

1.1 Scope and purpose

Following the terms of reference for ANSOC, this document addresses the specific issue of the scientific return from continued operation of the 4-metre Anglo-Australian Telescope and the scientific lifetime of the facility. This is part of the wider issue of the AAO's governance and funding after the end of the AAT Agreement on 30 June 2010, which is being addressed by a Government working group.

1.2 Context

An important part of the context for this submission is the Australian Astronomy Decadal Plan for 2006-2015[1], which envisions the AAO evolving into Australia's national optical observatory. The Decadal Plan recommended that AAO's specific responsibilities include:

- Operating the AAT as Australia's major on-shore optical/infrared facility for the remainder of its lifetime, expected to be at least a decade.
- Keeping the AAT at the forefront of astronomical research by developing a major new instrument for the telescope.
- Supporting Australia's involvement in major national optical facilities, including Gemini and other 8m-class telescopes, an Extremely Large Telescope like the Giant Magellan Telescope, and potential Antarctic facilities, like PILOT.
- Maintaining a world-class astronomical instrumentation & technology program.
- Providing a focus and infrastructure for astronomical research, and contributing to the leadership of the Australian astronomical community.

Another crucial element of the context is the previous Review of the Anglo-Australian Observatory carried out by the Australian Government in 2006. A great deal of relevant information is contained in the Review Issues Paper[2] and the AAO's Review Submission[3]. The key findings of the AAO Review Report[4] (abstracted from the Executive Summary) were:

- "the AAO has consistently been one of the world's most productive telescope service providers, producing first class research outcomes for AAT users"
- "the AAO has been pivotal in helping Australian astronomers earn their reputation as respected players in international astronomy"
- "the AAO's instrumentation program is world-leading and includes exceptional technological innovations"
- "the AAO is operating in a highly cost-effective manner"
- "the AAT could continue to provide world-class observing facilities until at least 2015 if a further instrumentation enhancement was supported"

The Review Report recommended to Government that:

- the AAO continue operating the AAT until at least 2015;
- the AAT should undergo significant refurbishment;
- a major new instrument should be built for the AAT;
- the AAO should evolve to become Australia's national optical astronomy observatory and manage Australian access to current and future international optical telescopes.

The Review Report also outlined a specific funding profile for the AAO to enable it to implement these recommendations, and proposed a model for the governance of the AAO after the end of the AAT Agreement. Some of the Review's recommendations have already been implemented: funding for the refurbishment of the AAT and for the construction of a major new instrument was provided through the NCRIS Optical and Radio Astronomy grant managed by AAL, and those projects are now in progress.

1.3 Document structure

This document makes the case that the AAT has a productive scientific lifetime as a national facility until about 2018, and a subsequent role as a user-pays survey telescope. The case has the following structure:

- §2 reviews the AAT's outstanding scientific track record and the expected impact of current research programs;
- §3 evaluates the contribution the AAT makes to Australia's optical telescope capabilities, the level of demand, and the cost-effectiveness of the facility;
- §4 deals with the planned evolution of the AAT's instrumentation suite and how this will provide versatility while keeping it a world-leading facility for survey spectroscopy;
- §5 extrapolates the science that will be carried out with the AAT over the next decade and beyond;
- §6 enumerates the secondary and strategic benefits to Australia from continued operation of the AAT.

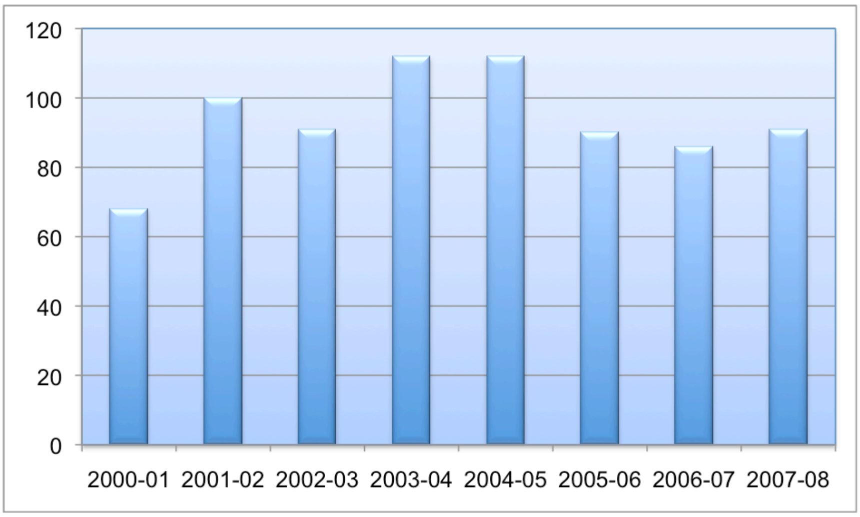
Finally, §7 provides a summary in the form of "the short answer" to each of the main questions posed by this review.

2 SCIENTIFIC PRODUCTIVITY AND IMPACT

2.1 The AAT's track record

The numbers of publications based on AAT data for each of the last 8 years are shown in Figure 1 below. Over this period the AAT has maintained an average of 94 publications per year. The high peaks in 2003-2005 correspond to the final years of the 2dF Galaxy Redshift Survey, which produced a total of 42 papers that to date have garnered 5870 citations (an average of 140 citations per paper) and include 5 papers amongst the most-cited 0.1% astronomical papers of all time.

Figure 1 – Publications from AAT observations 2000-2008



The most recent bibliometric review of the astronomical literature examining the publication and citation records of different telescopes is that of Trimble & Ceja (2008, *Astron. Nachr*., 329, 632). This extends earlier work by Trimble et al. to encompass both the productivity (number of papers) and the impact (number of citations) of all major telescope facilities based on papers published in the three years 2001-2003. The main conclusions from this study in regard to the AAT are as follows:

- The AAT is the #1-ranked 4m-class optical telescope in the world in both productivity *and* impact, achieving 2.3 times as many citations as its nearest competitor (WHT).
- Amongst optical telescopes of *any* size, ground- or space-based, the AAT is ranked #5 in productivity (behind HST, Keck, VLT and 2MASS) and also #5 in impact (behind HST, Keck, VLT and SDSS).
- Over *all* current astronomical facilities of *any* type, the AAT is ranked #8 in impact and #2 in terms of citations per paper (behind SDSS).
- The AAT provided the data for 11 of the 100 most-cited papers in astronomy from this three-year period (the top 0.1%).

2.2 Current research with the AAT

The AAT aims to maintain these outstanding levels of productivity and impact by continuing to combine unique and powerful instruments (in particular the AAT's wide-field spectroscopic capabilities) with a judicious mix of large and small observing programs. The largest are explicitly identified as Large Programs, and are typically surveys requiring commitments of a few hundred nights over a few years. These are expected to be the highest-impact programs carried out with the telescope. Together, the Large Programs are allocated at least 40% of the time on the AAT.

At present there are three Large Programs, two using AAOmega (the WiggleZ and GAMA surveys) and one using UCLES (the Anglo-Australian Planet Search):

- **The WiggleZ survey** is measuring redshifts for hundreds of thousands of distant galaxies, and will give the first measurement of the baryon acoustic oscillation scale over the redshift range z=0.5-1.0. This scale will be used as a standard ruler to trace the evolution of the equation of state for the dark energy over cosmic history, elucidating the nature of this mysterious dominant constituent of the universe. When completed in 2010, the survey will map an effective volume of 1 Gpc^3 and determine the angular-diameter distance and Hubble expansion rates in three redshift ranges with an accuracy of about 5%. It will yield the value of the dark energy's equation of state parameter, w, with higher precision than existing supernova observations and using an entirely independent technique. The combination of the WiggleZ, supernova, and cosmic microwave background datasets is forecast to give an uncertainty on the equation of state of Δw=0.07, providing a robust and precise measurement of the properties of dark energy and a crosscheck on systematic errors.
- **The GAMA survey** is looking in detail at the evolution of galaxies and the assembly of mass through a highly complete redshift survey of the low-redshift universe. The main objective of GAMA is to study structure on scales of 1 kpc to 1 Mpc. This includes galaxy clusters, groups, mergers, and structural measurements for individual galaxies (bulge-to-disk ratios). It is on these scales that baryons play a critical role in galaxy formation and subsequent evolution, and where current understanding of structure in the universe breaks down. The goal is to test the CDM paradigm of structure formation by: (a) measuring the mass function of dark matter halos for groups and clusters via group velocity dispersion measurements; (b) determining a comprehensive stellar mass function for all galaxies down to Magellanic Cloud masses in order to constrain

baryonic feedback processes; and (c) establishing recent galaxy merger rates as a function of mass, mass ratio, local environment and galaxy type.

- **The Anglo-Australian Planet Search** is looking for planets around 240 nearby stars via their Doppler reflex motions, and to date has discovered more than 25 exoplanets. The AAPS thus accounts for about 10% of all exoplanet discoveries and about 40% of all Doppler detections. The program began in 1998 and is one of the longest-running Doppler planet searches. With this long time baseline and a demonstrated velocity precision of better than 1 m s^{-1}, the AAPS is sensitive to both relatively low-mass and long-period planets (for comparison, Jupiter has an orbital period of 12 years and produces a Doppler motion in the Sun of 12.5 m s^{-1}). As well as this long-term monitoring, the AAPS is also carrying out intensive campaign-mode observations of some of the most stable stars in the main sample to search for terrestrial-like planets with masses down to a few times the mass of the Earth.

These large programs are attacking three of the most crucial questions in astronomy: the nature of dark energy, the formation of galaxies and structure, and the properties of planetary systems around other stars. All three are making, or are expected to make, a significant impact in these fields. As the WiggleZ and GAMA surveys reach completion over the next couple of years, the productivity and impact of the AAT can be expected to receive a boost similar to that witnessed during the heyday of the 2dF Galaxy Redshift Survey.

Although these are the AAT's flagship programs, up to 60% of the time on the AAT is given to smaller programs. These 'P.I.'-style programs have typical allocations of 3-7 nights in any one semester, although the average allocation for such programs is gradually increasing. This shift towards larger allocations even for 'small' programs is in part a consequence of the AAT's particular strength in wide-field multi-object spectroscopy and related survey-style science, and in part reflects the increasing share of AAT time available to a relatively stable number of Australian astronomers.

The larger average allocations have at least two beneficial effects for Australian astronomers and students: (i) researchers can undertake more ambitious programs or carry out programs more quickly over a shorter period, making their science more competitive (other things being equal); (ii) students and supervisors can have more confidence in completing thesis programs. The latter is apparent in comparing the use of the AAT and Gemini by Australian students – typically, the AAT is used for the bulk of the research and Gemini is used to 'garnish' the results where possible.

Having reviewed the AAT's track record of scientific productivity and impact, and the current and near-term programs of research, we now turn to consider the long-term future of science with the telescope. To do so, however, we must first place the AAT in its proper context amongst other Australian facilities and then map out the evolution of its instrumentation suite over the coming decade. This is because the best indicator of future scientific returns is the discovery space opened up by new instrumental capabilities and by synergies with other facilities.

3 AUSTRALIA'S OPTICAL TELESCOPE CAPABILITIES

3.1 Capability comparison

Table 1 below shows the AAT's contribution to Australia's optical telescope capability at three different times: as it is now in 2008, as it is likely to be in a reasonably optimistic scenario after the end of the AAT Agreement in 2010, and as it might be in a very optimistic scenario a decade from now in 2018. The 2010 scenario assumes that Australia doubles its share of Gemini time and maintains the current level of access to Magellan. The 2018 scenario assumes that Australia has a 20% share in Gemini, a 10% share in GMT and 100% of PILOT.

The table lists the share of each facility, the number of nights available on the facility, and a figure of merit that combines the size of the telescope and the amount of access (namely, the product of aperture and nights, normalized to a 100% share of the AAT). In very broad terms, aperture-nights are a measure of a facility's scientific capability, while nights are a measure of how widely that capability can be distributed over the user community.

In 2008, Australia's share of the AAT accounts for 85% of Australian nights on large optical telescopes, and 58% of the aperture-nights. In 2010, even with somewhat optimistic assumptions about Australia's 8m-class telescope access, full ownership of the AAT means that it still accounts for 79% of the total large-telescope nights and 48% of the aperture-nights (slightly more than is provided by a 12.4% share in the two Gemini telescopes).

Table 1 – Australian optical telescope capabilities

2008 : 85% of AAT + 6.2% of Gemini + 15 Magellan nights p.a.

Telescope	D (m)	Share (%)	Nights (p.a.)	Nights (%)	D^2 x Nights	D^2 x Nights (%)
AAT	3.9	85.0%	281	84.6%	0.85	58.3%
Gemini	8.2	12.4%	36	10.8%	0.48	33.0%
Magellan	6.5	4.5%	15	4.5%	0.13	8.7%
			331	100.0%	1.46	100.0%

2010 : 100% of AAT +12.4% of two Gemini telescopes + 15 Magellan nights p.a.

Telescope	D (m)	Share (%)	Nights (p.a.)	Nights (%)	D^2 x Nights	D^2 x Nights (%)
AAT	3.9	100.0%	330	79.2%	1.00	47.9%
Gemini	8.2	24.8%	72	17.3%	0.96	46.1%
Magellan	6.5	4.5%	15	3.6%	0.13	6.0%
			417	100.0%	2.09	100.0%

2018 : 100% of AAT + 20% of two Gemini telescopes + 10% of GMT + 100% of PILOT

Telescope	D (m)	Share (%)	Nights (p.a.)	Nights (%)	D^2 x Nights	D^2 x Nights (%)
PILOT	2.5	100.0%	300	38.7%	0.37	6.3%
AAT	3.9	100.0%	330	42.5%	1.00	16.8%
Gemini	8.2	40.0%	116	14.9%	1.55	26.1%
GMT	22.5	10.0%	30	3.9%	3.03	50.8%
			776	100.0%	5.95	100.0%

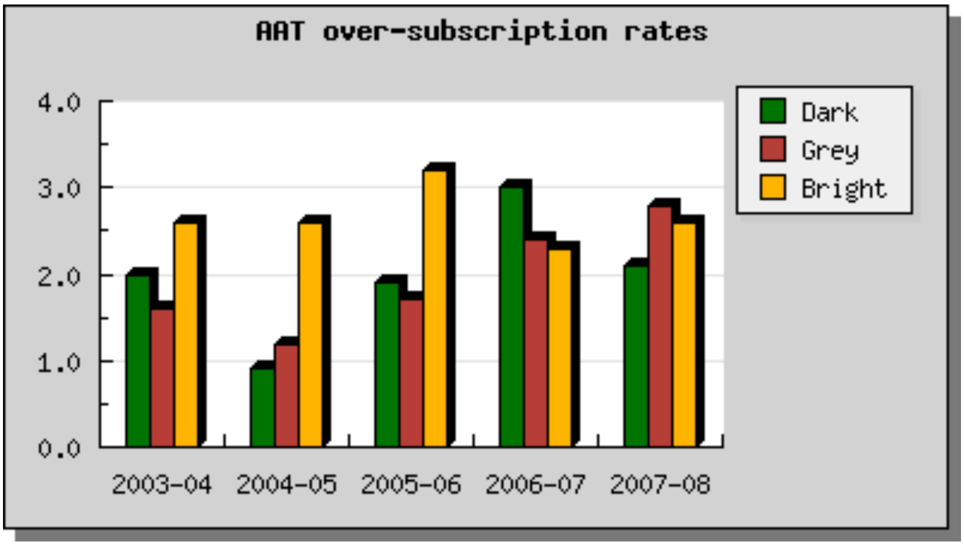
Thus until new facilities are made available to Australian astronomers, the AAT will continue to provide about half of Australia's capability in large optical telescopes and about 80% of the nights on such facilities. Without the AAT, the number of nights on large telescopes available to Australian astronomers is reduced by a factor of 5, to significantly less than one night per astronomer per year.

In 2018, even if we assume that Australia achieves all it wishes for in terms of new optical facilities over the next decade, the AAT will still be providing both a unique capability for wide-field spectroscopy as well as more than 40% of the nights available to Australian optical astronomers. In any less optimistic scenario the importance of the AAT to Australia's optical telescope capabilities can only be greater.

3.2 Demand and usage

The high level of demand for AAT time is illustrated in Figure 2, which shows the over-subscription factors for time on the telescope for each of the last 5 years.

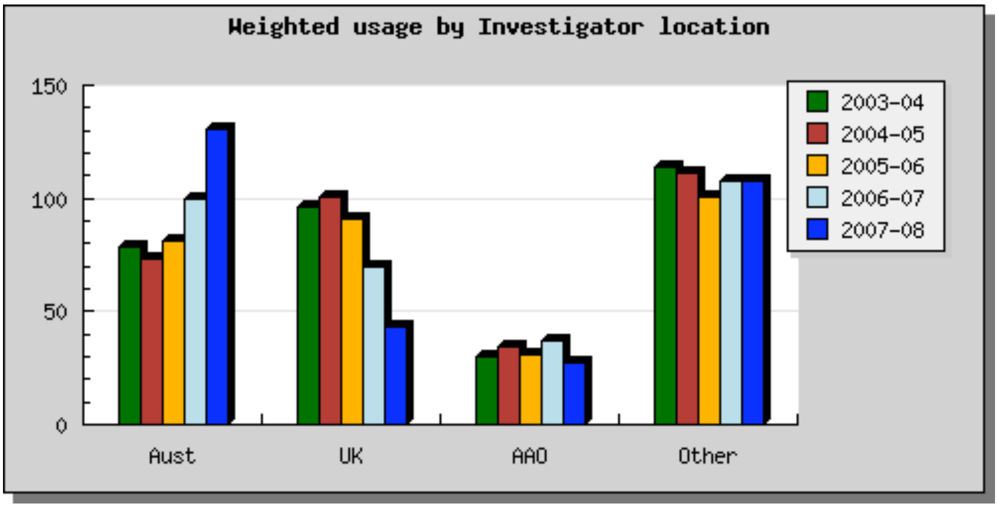
Figure 2 – AAT over-subscription factors 2003-2008



Since AAOmega was commissioned in early 2006, the over-subscription factors for dark, grey and bright time have all been consistently in the range between 2 and 3, indicating strong demand and a healthy level of competition for access.

AAT usage is shown in Figure 3, which gives the numbers of Australian, British, AAO and Other (third-country) investigators awarded AAT time in each of the last 5 years.

Figure 3 – Numbers of Australian, British, AAO and Other AAT users 2003-2008



The obvious trend is the increase in the number of Australian users and the decrease in the number of British users as the Australian share of AAT time has increased and the British share decreased. However the two important points to note from this figure are that: (i) the increase in the number of Australian users implies that demand for AAT time in Australia has not saturated, but rather that there was unmet demand that is now being satisfied; (ii) the continuing strong demand from third-country users is a good indication that the AAT remains competitive on the international scene, and not just relative to the other resources available to Australian astronomers.

3.3 Cost-effectiveness comparison

For the purposes of this particular comparison, we take the operating cost of the AAT to include the full cost of Siding Spring operations plus appropriate proportions of the AAO's corporate, administrative and IT costs, but we exclude instrument development. This leads to an estimate of the AAT's operating cost of $4.8M p.a., or $14.5k per available night (note that the AAT provides 330 nights p.a. to users).

The AAT's current operating model, on which this cost is based, provides a high level of support to users, keeping down-time resulting from technical problems below 3% and providing both full-time night assistants and support astronomers for at least the first night of every run (and longer where necessary). Such high-quality support obviously requires a more staff than models providing lower levels of service. However both AAO staff and AAT users believe that this high level of support is, along with the competitive instrument suite, one of the major factors in making the AAT the most productive and high-impact 4m-class telescope in the world (see §2.1 above). And in fact the AAT staff levels and operating costs compare favourably to those of other national 4m-class telescopes serving general users (see Tables 2.2 and 7.1 of the AAO's Review Submission[3] in 2006).

It is also worth comparing the cost-effectiveness of the AAT relative to the 8m-class telescopes to which Australia has access. Based on the figures in the ANSOC proposal for 8m-class telescope access†, the cost of a Gemini night is $64.4k and the cost of a Magellan night is $51.1k. Scaling these costs per night by the aperture of each telescope, the relative costs are AAT : Gemini : Magellan = 1.00 : 1.03 : 1.21. Thus the AAT is good value for money based on this simple figure of merit. Even if the AAT's operating costs were available to buy Gemini or Magellan time, using the money in that way would not only greatly reduce the number of telescope nights available to Australian astronomers (by a factor of more than 2) and the diversity of the available instrumentation, it would also slightly decrease Australia's overall optical capability in terms of the aperture-nights figure of merit.

This cost comparison in fact under-values the AAT in another way, since it is based on comparing *share* in the AAT and *nights* on Gemini and Magellan. Share confers additional benefits in terms of ownership, decision-making and control that buying nights does not – consequently, buying additional share in a facility is in general significantly more expensive than buying additional nights.

Another way to evaluate cost-effectiveness is based on the scientific productivity of a telescope relative to its operating costs. For example, the two Gemini telescopes have just recently produced their 500th refereed paper, nine years after science operations began on Gemini-North (eight years for Gemini-South). Allowing Gemini a 3-4 year ramp-up period and assuming these papers were produced over just the past five years, this gives an average productivity of 50 papers per year per telescope at a cost of approximately $9M p.a. (i.e. $180k per paper). Over the same period, the AAT has produced 370 refereed papers, corresponding to 74 papers per year at a cost of $4.8M p.a. (i.e. $65k per paper).

† Note that for Gemini this *excludes* the cost of the Aspen new instrumentation program (which comes at an additional cost to Australia), but for Magellan it *includes* access to new instruments built by the Magellan partners (from which Australia benefits at no additional cost); this difference contributes to the apparently higher cost of Magellan in this comparison.

4 THE EVOLUTION OF THE AAT INSTRUMENT SUITE

4.1 Refurbishment of the AAT

NCRIS has provided $4.1M for the refurbishment of the AAT. This is allowing the AAO to deal with high-likelihood risks that have potentially serious impact on the continued operation of the AAT (in terms of lost observing time, disruption to services, personnel safety and/or cost). Following this refurbishment the AAT is expected to be able to continue reliable and efficient operations through to at least 2015, provided that ongoing routine maintenance continues to be supported through the AAO's operational funding at about the current level.

While it is possible that there are unforeseen risks or that the funding to retire the known risks proves inadequate, such potential problems could be mitigated by seeking additional funding through either the ARC's LIEF scheme or a subsequent NCRIS round. However at this time the AAO believes that the refurbished AAT will be able to continue scientifically effective operations for another decade.

4.2 Competitive lifetimes of current instruments

The AAT currently has a broadly-capable instrumentation suite comprising an optical wide-field low-to-medium resolution multi-object spectrograph (2dF+AAOmega), an optical integral field spectrograph (SPIRAL+AAOmega), a near-infrared imaging spectrometer with multi-object capability (IRIS2), a high-resolution, high-stability single-object optical spectrograph (UCLES), and an ultra-high resolution optical spectrograph (UHRF).

Figure 4 – Nights allocated to each AAT instrument 2003-2008

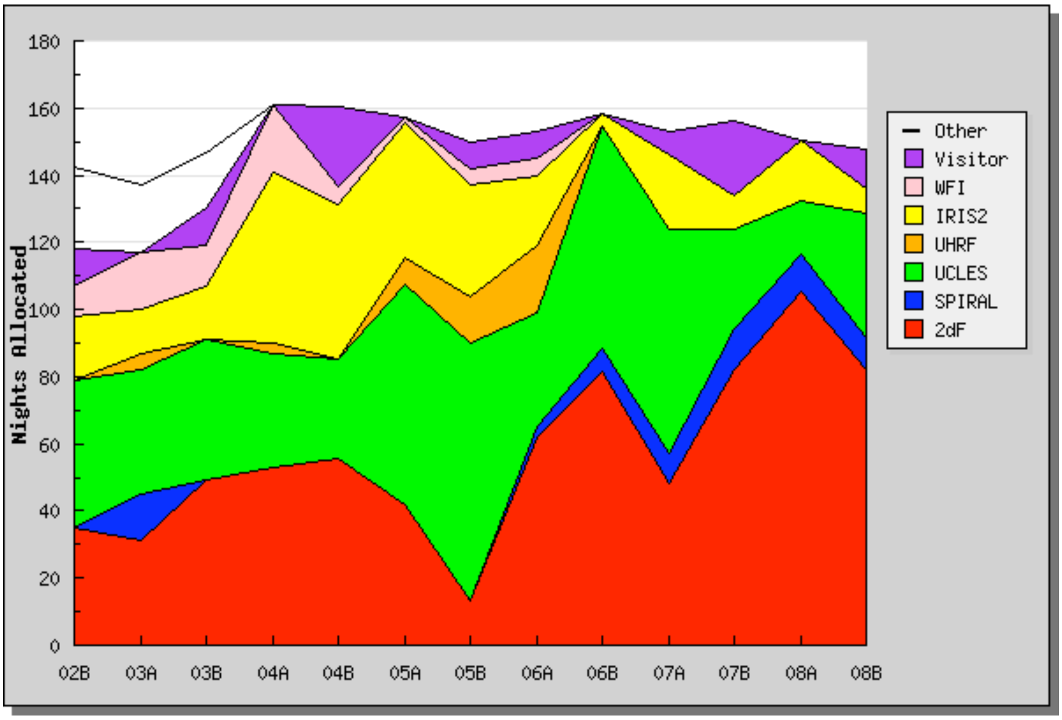


Figure 4 shows the numbers of nights allocated to each AAT instrument over the past five years. The most obvious trends are the strong increase in the numbers of 2dF and SPIRAL nights since the commissioning of AAOmega in 06A, the continuing large fraction of time going to UCLES, and the diminishing share going to IRIS2. No time has been awarded on WFI or UHRF since 06B, and WFI has since been decommissioned. There is still moderate use of visitor instruments on the AAT (mainly the Semel polarimeter).

Of the current instrument suite, AAOmega clearly has a long productive lifetime ahead of it – five years would be conservative and ten years is entirely credible. UCLES will also continue to generate moderate demand for several years, particularly if the CYCLOPS upgrade is funded (see §4.3 below). The long time baseline of the Anglo-Australian Planet Search using UCLES also provides good motivation for maintaining the instrument for some time to come. While UHRF has little demand, there is no reason to decommission it while UCLES remains in service.

The most vulnerable instrument is IRIS2 is already uncompetitive as an infrared imager and single-object spectrograph compared to other facilities around the world; it will soon be uncompetitive relative to other instruments to which Australian astronomers have access, such as the FLAMINGOS-2 imaging spectrograph on Gemini and the FourStar imager on Magellan. FLAMINGOS-2 will also share IRIS2's previously unique role as an infrared multi-object spectrograph. The useful lifetime of IRIS2 is probably at most five years, although it does remain the only imaging instrument on the AAT now that the WFI camera has been decommissioned.

4.3 Future instruments and upgrades

NCRIS has provided $5.9M in funding for a major new AAT instrument to maintain the scientific competitiveness of the telescope out to 2015 and beyond. After a comprehensive exploration of a range of instrument options, and close consultation with the user community, the AAO has selected the HERMES concept for design and construction. HERMES is a multi-object high-resolution (R=30,000) optical spectrograph fed by the 400 fibres of 2dF. The primary science driver is Galactic archeology, but it has a wide a range of applications including studies of stars, the interstellar medium and the Galaxy. A detailed description of HERMES is given in the recent SPIE paper by Barden et al.[5], while §5.1 includes further discussion of the science that HERMES will do.

HERMES passed its Conceptual Design Review in May 2008 and science observations are planned to begin in 2012. The only competitive instrument in the world will be Hectochelle on the MMT (in the northern hemisphere), and of all currently-planned instruments only the high-resolution mode of WFMOS on Subaru (also in the north) will be significantly superior. Note that WFMOS is not expected to be available until 2015 at the earliest, and is yet to complete its concept design study and obtain full funding from the Gemini partners and Subaru. HERMES can therefore reasonably be expected to produce high-impact science for at least five years (the usual period for a competitive instrument), and perhaps up to ten years (as for an almost-unique instrument like 2dF/AAOmega).

HERMES is the centrepiece of the AAO's instrumentation plans for the AAT, which also involve upgrades to existing instruments and another major new instrument:

- **CYCLOPS** In collaboration with UNSW, the AAO is seeking ARC LIEF funding in 2009 for CYCLOPS, a fibre feed for the UCLES spectrograph that will simultaneously increase both its spectral resolution and its throughput, and keep that instrument competitive for the next several years.
- **SPIRAL+** The next upgrade proposed is SPIRAL+, providing a doubling of the sky coverage of the integral field unit that is the alternative feed for AAOmega and HERMES. SPIRAL+ could also be funded by an ARC LIEF grant.
- **HERMES+** There is an upgrade path to HERMES+ that adds a mode in which it could be fed by 40 of the 400 2dF fibres (or by SPIRAL+) and produce spectra at substantially higher resolution (R=50,000). This mode broadens further the range of science that can be undertaken with HERMES, while also making UCLES largely

redundant. These additional capabilities are beyond the currently available funding for HERMES, so the AAO is exploring a possible collaboration with the Korean Astronomy and Space Science Institute (KASI) to carry out this upgrade; KASI would providing funding and effort in exchange for AAT time.

- **NG1dF** Looking beyond HERMES to a future major instrument, the AAO is carrying out a feasibility study in collaboration with the University of Durham on the NG1dF concept. NG1dF is a massively-multiplex (N=10,000), low-resolution (R=1000), imaging spectrograph for the AAT's prime focus that has as its primary science driver million-galaxy surveys to relatively deep limits over large volumes of the universe. This concept was, after HERMES, the most strongly supported new instrument for the AAT in the recent consultative process. It pushes to new limits the AAT's focus on wide-field spectroscopy, and would keep the AAT at the forefront of survey astronomy for the foreseeable future. It is ideal for following up the imaging surveys planned with new facilities like SkyMapper and ASKAP, and would be well-adapted to a future in which the AAT ultimately retires as a general-purpose telescope and is reshaped as a specialised survey-spectroscopy machine carrying out large programs on a user-pays basis (see §5.2). NG1dF demonstrates that the AAT could be potentially extend its competitive scientific lifetime well beyond 2015.

Table 2 outlines the planned evolution of the AAT's instrument suite over the next decade (see also Figure 5 below). The table lists the suite of instruments available on the AAT in 2008, those expected to be available in 2012 (by which time CYCLOPS, SPIRAL+ and HERMES should be available, and IRIS2 may be decommissioned), and those proposed if the AAT's lifetime was extended beyond 2015 (an upgrade to HERMES, the retirement of UCLES, and the addition of NG1dF).

Table 2 – The planned evolution of the AAT's instrument complement

Year	Instruments & upgrades
2008	AAOmega (2dF & SPIRAL), UCLES, IRIS2
2012	AAOmega & HERMES (2dF & SPIRAL+), UCLES (CYCLOPS)
2016	AAOmega & HERMES+ (2dF & SPIRAL+), NG1dF

Table 3 gives estimates of the cost of each of these new instruments and upgrades, together with an indication of the known or expected sources of funding.

Table 3 – Instrument program costs and funding

Instrument/upgrade	Cost estimate	Funding source
HERMES	$9M	NCRIS ($6M), AAO ($3M)
CYCLOPS	$0.8M	ARC LIEF
SPIRAL+	$0.7M	ARC LIEF
HERMES+	$3M	KASI ($2M), AAO ($1M)
NG1dF	~$10M	Not yet identified

The cost of the proposed NG1dF instrument is uncertain until the initial design study is completed at the end of 2008, but is expected to be on the order of $10M. Funding sources for this instrument have not yet been identified, but would probably involve international collaboration, with at least a 50% Australian share.

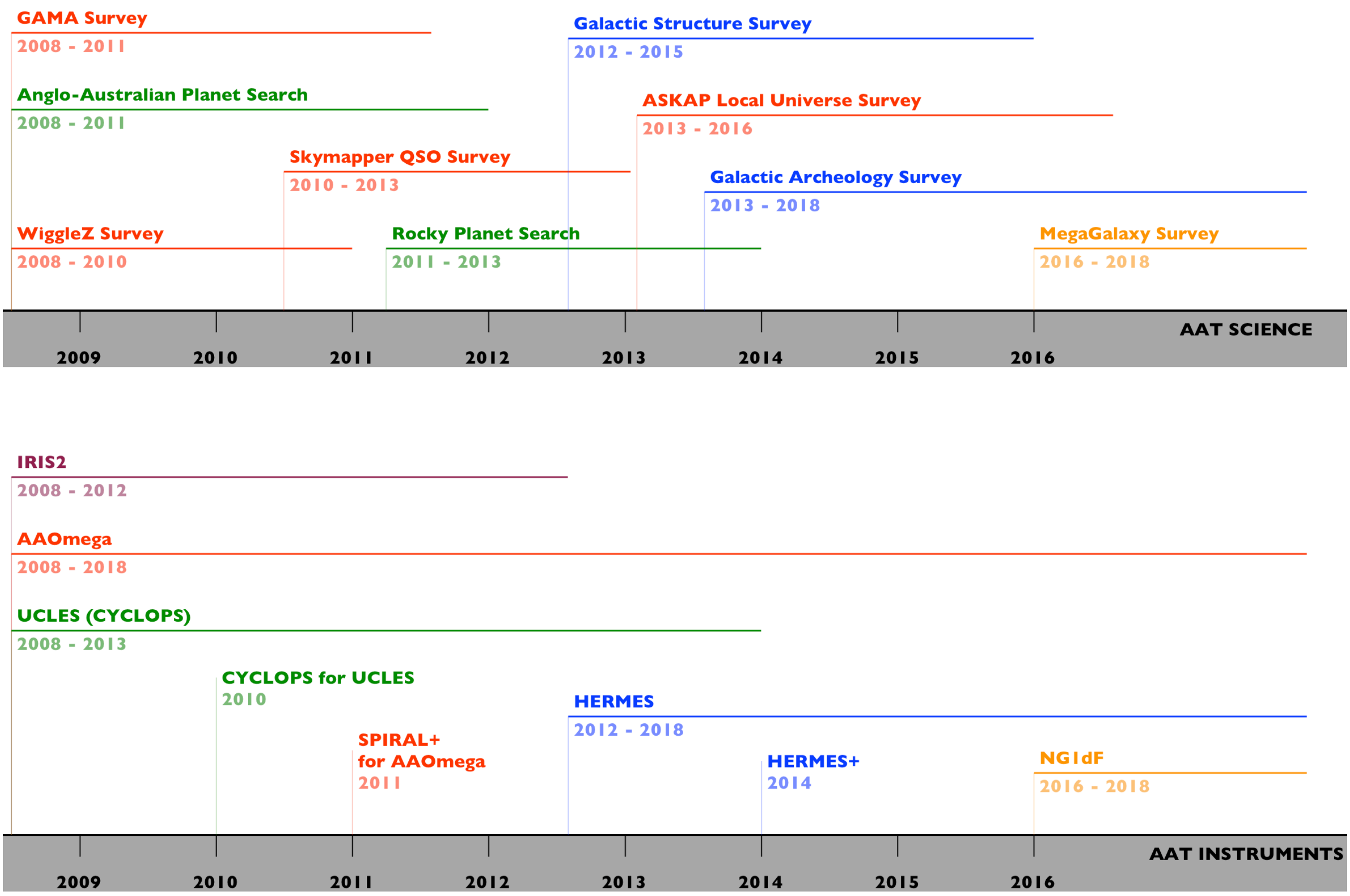
5 THE FUTURE OF THE AAT

5.1 Future science with the AAT

The AAT's diverse instrumentation suite, and the highly competitive capabilities of AAOmega and HERMES in particular, will continue to enable a wide range of high-quality science. A picture of the science that will be done with the AAT over the next decade can be extrapolated from the present state of the field, the capabilities and competitive advantages of the planned instrument suite, and the synergies to be expected with other new facilities that will come on-line during this period in Australia and around the world.

Figure 5 shows timelines for existing and expected major science programs supported by the evolving suite of instruments on the AAT over the next decade. The lower half of the timeline shows the anticipated lifetimes of current and future instruments (and their upgrades) following Table 2, while the upper half of the timeline shows the major observational programs expected to be carried out on the telescope, colour-coded by the instruments that they utilise.

Figure 5 – Timelines for AAT science and instrumentation 2008-2018
(colours link observing programs to the instruments they employ)



Wide-field, multi-object optical spectroscopy is the AAT's greatest strength, and also one of the most-used instrument capabilities on telescopes of all sizes around the world. With the increasing number of all-sky imaging surveys becoming available, the demand for spectroscopic follow-up is expected to increase strongly in coming years. AAOmega remains highly competitive with respect to other multi-object spectrographs, occupying a strong position in the crucial discovery space of entendue (AΩ = aperture times field of view) and multiplex (number of objects observed simultaneously) relative to other facilities – both those currently available and those expected to be available for at least the next five years. The AAT's strength in wide-field spectroscopy will be broadened by HERMES to cover stellar and Galactic astronomy, and would be further enhanced in extragalactic astronomy by the tremendous multiplex advantage and efficiency of NG1dF.

AAOmega After the WiggleZ and GAMA surveys, the future for AAOmega will mainly be about spectroscopic follow-up of the monumental new imaging surveys of the southern hemisphere that are just about to begin using the ANU's SkyMapper telescope at optical wavelengths, ESO's VISTA telescope in the near-infrared, and the Australian SKA Pathfinder (ASKAP) in the radio. These all-sky surveys will generate vast samples of a wide variety of interesting sources, all requiring spectroscopic follow-up. AAOmega's potent combination of 400 fibres, a 2-degree field and a 4-metre aperture will make it the instrument of choice for such programs.

HERMES The major science driver for HERMES is Galactic archeology. The RAVE survey on the UKST is currently measuring the radial velocities and basic stellar parameters for hundreds of thousands of stars over the whole southern sky, with the goal of exploring the dynamics of the various Galactic stellar populations and starting to unravel the formation history of the Milky Way. After its launch in 2012 (the year that HERMES sees first light), the GAIA satellite will map the positions, proper motions and radial velocities of hundreds of millions of stars and greatly expand this work. However it is not possible to untangle the many galactic building blocks and star-forming associations from which the Milky Way assembled using phase space (position-velocity) information alone. HERMES provides a powerful extension of this approach by measuring a chemical abundance 'signature' that identifies those stars that formed together out of the same cloud of gas and dust. Combining the abundance signatures and phase space locations for millions of stars will provide an extraordinarily detailed insight into the formation and structure of the Milky Way.

HERMES will provide the AAT with a virtually unique capability – only Hectochelle on the MMT will be comparable, and that in the northern hemisphere. As well as carrying out the large Galactic archeology surveys that are its primary science driver, HERMES is expected to generate a goldmine of data for stellar astronomers, supporting significant advances in studies of stellar evolution, nucleosynthesis and internal mixing, the identification of rare kinds of stars, accurate ages for subgiants of different populations, tests of mixing length theory across the Hertzsprung-Russell diagram, and an ideal database for deriving the primordial helium abundance.

The Big Questions Table 4 below shows the AAT's impact on the Big Questions highlighted in Table 4.1 of Australia's Decadal Plan for Astronomy 2006-15[1]. The AAT appears in this table as Australia's national optical facility, and contributes 'key investigations' to three of the nine Big Questions and 'supporting investigations' for another five. The three Big Questions where the AAT provides key investigations correspond to existing and future Large Programs studying dark energy (e.g. WiggleZ), Galactic assembly and evolution (e.g. GAMA & Galactic Archaeology), and planetary systems (e.g. Anglo-Australian Planet Search) – see Figure 5 above.

Table 4 - The AAT's impact on the Big Questions in Australia's Decadal Plan

	Facilities and their Investigations					
	University	**National**		**International**		
The Big Questions		Optical	Radio	8-m	ELT	SKA
Dark energy & dark matter	•	(••)	•	••	••	••
First stars	•	•	•	••	•	••
Galaxy assembly & evolution	•	(••)	•	••	••	•
Pulsars & gravity			••			••
Origin of magnetism		•	••	•		••
Supermassive black holes	•	•	••	•	••	••
Making stars and planets	•	•	•	•	•	•
Planetary systems	•	(••)		••	••	
Building blocks of life	•	•		••	••	

Legend: •• Key Investigation • Supporting Investigation ( ) AAT Large Programs

5.2 The AAT as a user-pays survey telescope

The above discussion demonstrates that the AAT has a future as a general-purpose telescope for Australian astronomers for at least another decade. Beyond that time, however, the AAT will have a continuing role as a specialized spectroscopic survey telescope, operated on a user-pays basis to carry out a small number of massive surveys of stars (with HERMES) or galaxies (with AAOmega or NG1dF).

The AAT will be competitive in this mode due to its unique combination of aperture, field of view, instrumentation and availability – a combination that would be extremely expensive and time-consuming to duplicate with a purpose-built facility. Indeed, given that the AAT already exists and is available, it would be prohibitively difficult to justify duplicating its capabilities. In this role the AAT would remain a unique asset that generated real value for the whole Australian astronomical community through selling or swapping time and so generating access to other facilities.

Although this mode of operation is relatively uncommon at present, the RAVE survey on the UKST and the HARPS survey on the ESO 3.6m provide good examples of what is likely to prove an increasingly common approach in an increasingly globalized astronomy community.

5.3 Synergies with other facilities

The AAT is a superb survey spectroscopy telescope and it will be highly effective and scientifically productive in following-up imaging surveys at other wavelengths, such as SkyMapper in the optical, VISTA in the near infrared, and ASKAP in the radio. The AAT has a strong synergy with PILOT, the proposed Antarctic telescope, which is optimized for carrying out deep, wide-field imaging surveys in the optical and infrared, requiring spectroscopic follow-up surveys on both 4m and 8m telescopes.

The AAT also has a particular role to play alongside 8m-class telescopes, as a 'feeder' facility that can more readily and cheaply carry out the elements of large projects that do not really require an 8m telescope. This will allow Australian astronomers to make more efficient use of their 8m-telescope access, and also make them more competitive in preparing proposals for time on 8m telescopes and other high-demand facilities.

6 OTHER BENEFITS OF THE AAT

6.1 Teaching and training

The AAT provides Australian research students with an excellent opportunity for hands-on observing experience on a large telescope with complex instrumentation. The larger telescopes to which Australian astronomers currently have access (mainly Gemini and Magellan) are either queue-scheduled, with little or no direct observational involvement for the student (e.g. Gemini), or are a relatively scarce resource (e.g. Magellan). Until now, smaller telescopes have been a mainstay of student training, but with loss of the telescopes on Mount Stromlo, the closure of the ANU 40-inch, and the limited national access to the ANU's 2.3m telescope, the AAT now provides the greatest opportunity for Australian students to spend substantial amounts of time at a telescope gaining direct practical understanding of observing techniques and front-line instrumentation.

The AAT's relative ease of access for Australian students (compared to the smaller amounts of time available on 8m-class telescopes) means that it remains the workhorse facility for observational theses in optical/infrared astronomy. Over the last five years, 41 Australian students (and 84 students in total) have used the AAT for their research, while AAO staff have co-supervised a total of more than 25 students with researchers from Australian universities. The AAO provides top-up scholarships for three PhD students each year who are working on projects involving AAO staff, and co-sponsors (with Macquarie University) two Honours scholarships each year in astronomy and instrumentation. Astronomy graduates are in great demand not only in the field but also in a wide range of industries, where they are valued for the breadth of their mathematical and physical training and their pragmatic problem-solving skills. Students trained on the AAT have not only gone on to distinguished careers in astronomy, but also in engineering, commerce, and the IT industry.

6.2 Instrumentation development

The AAT is the one large telescope in which Australia has a controlling interest. It therefore provides Australian astronomers and instrument scientists with an excellent test-bed for developing new astronomical instruments and technologies. Examples of innovations prototyped or significantly developed on the AAT include: optical fibre feeds, multi-object spectroscopy, fibre positioning robots, and nod & shuffle imaging. These technologies underpin the success of the AAO's existing (and future) instrumentation suite, and the instruments that the AAO has designed and/or built for other telescopes (e.g. OzPoz for the VLT, DAZLE for the VLT, Echidna for Subaru, and WFMOS for Gemini/Subaru).

AAT instruments provide obvious direct benefit for Australian observers, but the instruments built for other telescopes also provide a variety of benefits, ranging from access to other facilities (e.g. VLT time for OzPoz, Subaru access for Echidna), to the ability to do unique science (e.g. high-redshift galaxies with DAZLE), or spin-off instrumentation (e.g. 6dF was built as the prototype for OzPoz). These external instrumentation contracts also provide revenue that maintains the AAO's instrument-building capacity and contributes to the AAO's investment in new instrumentation for the AAT.

The AAO continues to develop new technologies from astronomical instrumentation. Current examples include the Starbugs positioner technology and fibre Bragg gratings for OH sky-line suppression. Other more ambitious 'astrophotonics' devices are in the pipeline, including integrated photonic spectrographs – the first prototype of these astronomical ‘spectrographs on a chip’ was recently designed and tested by the AAO. These new technologies are highly relevant to the 8m-class telescopes and Extremely Large Telescopes (ELTs) for which AAO will be building future instruments, as they provide opportunities for both quantitatively new capabilities and a way to break the standard scaling of instrument cost with telescope size.

6.3 A valuable and tradeable resource

The AAT has a number of properties that make time on the telescope a valuable and tradeable resource: (i) it has a 2-degree field of view on a 4-metre telescope exploited by powerful and versatile instruments (AAOmega and HERMES), making the AAT one of the world’s premier facilities for wide-field spectroscopy; (ii) it has a highly stable high-resolution spectrograph (UCLES) that is ideally suited to planet searches; and (iii) it is located at a longitude and latitude that makes it a crucial part of a global telescope network for some types of monitoring programs.

Although the AAT does not *require* international support, its unique capabilities mean that international users are willing to pay for or swap time in exchange for AAT access. Current opportunities include:

OPTICON The AAT is part of the European OPTICON Access program, under which the AAO is paid for access to the AAT by EU astronomers up to an agreed number of nights per year. This program is slated to continue in the EU’s FP7 funding round.

HERMES+ The AAO is exploring the possibility of a collaboration with the Korea Astronomy and Space Science Institute (KASI) to build the HERMES+ upgrade. Under this arrangement, KASI would provide funding and manpower in exchange for access to HERMES+ on the AAT.

European Southern Observatory The AAO is discussing with ESO the possibility of obtaining VLT time in exchange for providing access to the AAT’s wide-field spectroscopic facilities (AAOmega now and HERMES in future).

US National Optical Astronomy Observatories The NOAO is undertaking a program (called ReSTAR) to develop a prioritized, quantitative, science-justified set of capabilities appropriate for telescopes with apertures less than 6 metres, In this context, the AAT has been mentioned as part of a world-wide network of small and mid-sized telescopes that might make their varied instrument complements available to each other’s user communities by either selling or swapping time. Such a network would allow the AAT to trade its particular strengths for access to facilities, such as high spatial resolution imaging, that it cannot offer to Australian astronomers.

6.4 Strategic advantages of the AAT

As well as the secondary benefits described above, there are some strategic benefits to the continued operation of the AAT for another decade.

First, there is considerable value to the Australian astronomical community in having a large on-shore optical telescope that is wholly Australian owned and controlled. Not only does this have a number of practical advantages (such as facilitating training and providing a test-bed for instrumentation), it is also – in the eyes of a large section of the Australian public and its government – a clear and visible symbol of a national commitment to optical astronomy, in a way that off-shore facilities are not. While ultimately our goal must be to educate the public and government on this point, so that off-shore facilities are clearly recognised as national resources, we have not reached that point here yet. In the interim, having the AAT on Australian soil is a significant public relations and political advantage.

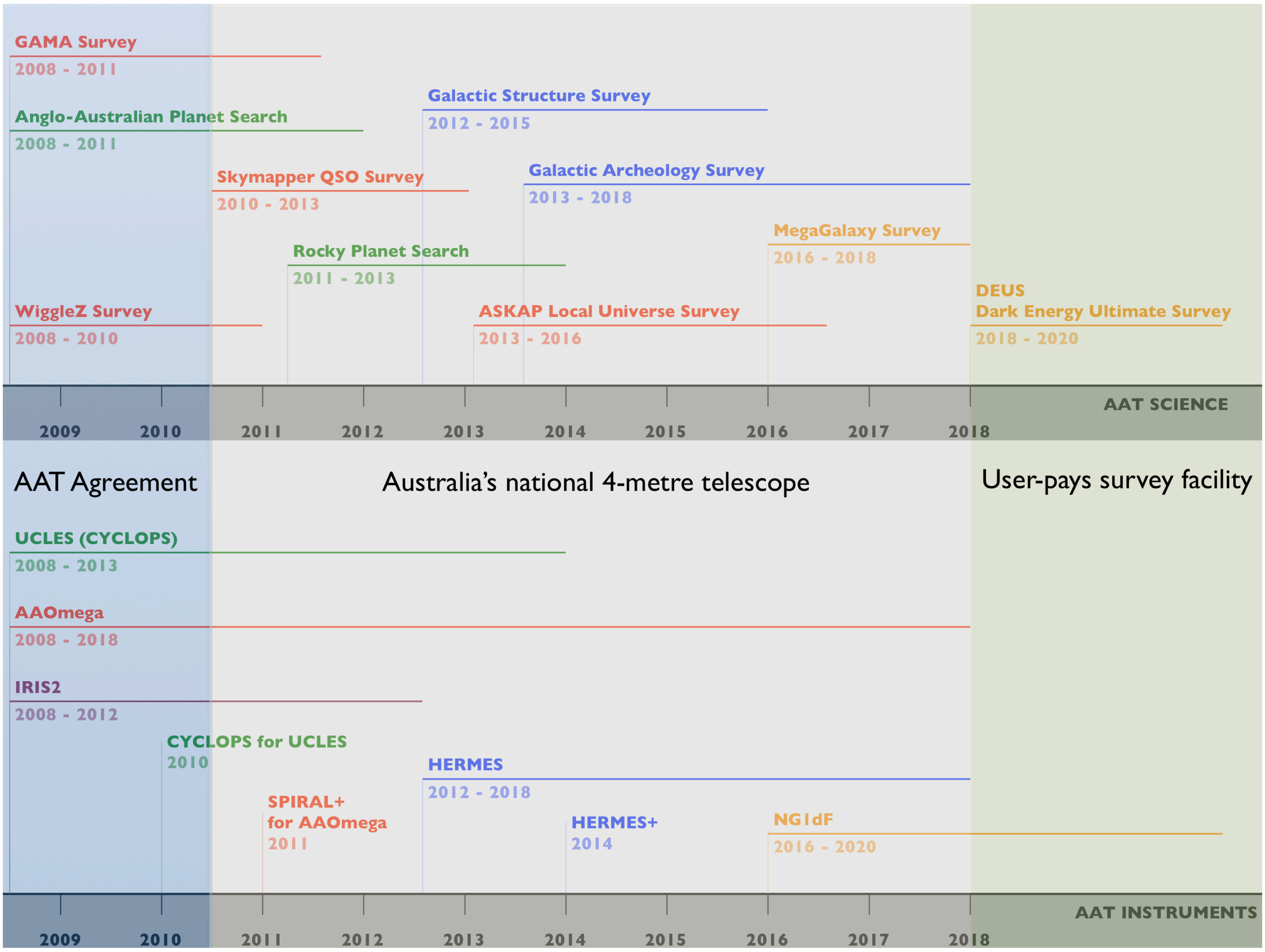
Second, having the AAT continue to operate for another decade means that it would remain available as a potential 'trade-in' for future facilities. One possibility that has been explicitly discussed is that operational support for the AAT could plausibly be transferred to operational support for the GMT, since the full operational cost of the AAT and a 10% share of the estimated operating cost of the GMT are very similar. This might occur around 2018, when the GMT is expected to start scientific operations.

7 THE SHORT ANSWERS

7.1 What is the future of the AAT?

The future of the AAT is summarised in Figure 6. This timeline shows the three phases of the AAT's remaining lifetime: (i) the period to 30 June 2010 under the AAT Agreement; (ii) the period from 1 July 2010 to about 2018, during which the AAT is Australia's national 4-metre telescope and premier on-shore optical facility, with an evolving instrumentation suite allowing it to carry out a range of high-impact observing programs; and (iii) the telescope's final phase beyond 2018 as a specialized user-pays survey-spectroscopy facility, lasting as long there is demand and funding.

Figure 6 – The future of the AAT



7.2 What is the lifetime of the AAT?

The AAT has a scientifically competitive and cost-effective lifetime as a national observatory of about 10 years. The current and ongoing refurbishment of the telescope will ensure efficient and reliable operations over the next decade. The instruments and upgrades planned for the AAT are outlined in the lower half of Figure 6, and will maintain it throughout this period both as a versatile general-purpose telescope for the whole Australian community and as one of the world's most potent facilities for survey spectroscopy. Up until GMT begins operations around 2018, the AAT will provide half of Australia's national optical telescope capability and 80% of the nights available to Australian astronomers (see Table 1).

7.3 What science will the AAT do in future?

As a national facility with broadly capable instrumentation, the AAT will do a mix of large and small programs having high impact across a wide swathe of astronomy and addressing eight of the nine Big Questions posed in the Decadal Plan (see Table 4). The flagship programs are mapped out in the upper half of Figure 6, and provide key investigations into three of the Big Questions: the nature of dark matter and dark energy, the assembly and evolution of galaxies, and the study of other planetary systems. The AAT will have strong synergies with new Australian facilities coming on-line in the next few years, providing spectroscopic follow-up surveys of sources discovered by SkyMapper and ASKAP. In the long term, the AAT has a potentially valuable role as a user-pays facility carrying out massive survey programs.

7.4 How much will this cost?

The AAT itself costs $4.8M p.a. to operate, so over the 10 years from 2009 to 2018, the total cost of operations would be $48M (in 2008 dollars). The cost of the planned AAT instrumentation program (excluding NG1dF) is $13.5M, of which $6M has already been provided by NCRIS, $1.5M is sought from the ARC, and $2M would be provided by collaborators, leaving $4M to be found over about 5 years from the AAO's instrumentation program. The NG1dF instrument, for which funding sources have not yet been identified, would cost about another $10M.

7.5 Is the AAT cost-effective?

The AAT is a highly cost-effective facility in terms of both capability and productivity. The cost-effectiveness of a telescope's *scientific capability* can be compared using the cost per night scaled by aperture as the figure of merit. By this measure, the AAT is good value for money: the relative costs per unit capability for the AAT, Gemini and Magellan are 1.00, 1.03 and 1.21 (see §3.3) Another figure of merit, based on *scientific productivity,* is the average number of refereed papers per year relative to the annual cost of operating the facility. Over the past five years, Gemini produced an average of 50 papers per year per telescope at a cost of $9M p.a., while the AAT produced an average of 74 papers per year at a cost of $4.8M p.a. (see §3.3).

7.6 What other benefits does the AAT provide?

As Australia's only national, on-shore, general-purpose large optical telescope, the AAT provides a unique training facility for graduate students in astronomy, a test-bed for developing new astronomical instrumentation technologies, and a valuable resource that can be traded in exchange for access to other international research facilities. The AAT also provides strategic advantages as a highly visible national icon and a focus for the AAO's evolving role in supporting optical astronomy.

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