STFC

GROUND-BASED FACILITIES REVIEW 2009

Final report

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Executive Summary

1. Through a combination of scientific leadership, instrumental and engineering brilliance, outstanding theoretical work, energetic and imaginative exploitation of facilities, and the excellence of our university departments and institutes, the UK has built up a position of remarkable impact in astronomy. With an expenditure on astronomy that is by no means exceptional as a fraction of GDP amongst advanced nations, the UK's status, as measured by publications and citations, is second only to the US. This acts as a beacon for the UK's whole scientific effort, drawing school children into science and university students into physics. The excellence of the UK's universities translates into direct economic benefit both from overseas students and from the value to the UK economy of our own graduates.
2. The Panel believes that the next decade for ground-based astronomy will be extremely exciting, that the new facilities being proposed will have an immense impact on public interest in science and on innovation in major technologies of the future, in partnership with British industry, and that the UK should seek to play a major role in these facilities. The Panel highlights the opportunities presented by new projects (such as the E-ELT and SKA); the synergies with space science and through innovation to other science disciplines; and the opportunities through facilities to engage with the public and to provide first-class training.
3. The Panel believes that in order to ensure the success of these new facilities the UK needs to have a clear strategy for its existing interests and investments and that it needs to focus upon its key strengths. This will require a planned withdrawal from some facilities or an adjustment to the level of UK participation. The Panel has included in this report recommendations for how this might be achieved.
4. The Panel emphasises the importance of the UK's subscription to ESO and,places this as its highest priority. There was very strong community support for VLT, ALMA and VISTA.
5. The Panel places very high priority on UK participation in both E-ELT (via ESO) and SKA. We see both these projects as having the potential of exceptionally high public impact, with benefits for the whole UK scientific research programme. Both projects offer great possibilities of technological innovation and knowledge transfer and can offer UK industry cutting edge involvement in the technologies of the future. There was very strong, and almost exactly equal, community support for both projects. We concur with the ASTRONET recommendation that both are of equal scientific priority, that both should go ahead. We recommend that the UK should seek a leading role in both. We expect a UK PI role in at least one E-ELT instrument, and support STFC's leadership of PrepSKA.
6. On the phasing of these two large projects, we note that E-ELT is ready for an early start, soon after the ESO Council meeting at end of 2010, if the European partners can agree on funding. SKA awaits an international community decision on its location, which is due in 2012, and also the formation of a formal SKA consortium. Construction of SKA could start in 2014, if the required international funding was available. We endorse the phasing recommended by ASTRONET,

7. On the UK membership of the Gemini Partnership, we noted that there is strong community support for, and a convincing scientific case for, continued access to a one or more 8-m telescopes in the northern hemisphere. However we found that the level of community support for Gemini, and its cost-effectiveness, is insufficient to justify continuing involvement in the Gemini Partnership at the present level.
8. The Panel recommends that STFC should investigate options for securing of order 40 open-access UK nights per year on one or more northern 8-m telescopes. The options would be to seek time on one or more of: Gemini-N, Subaru (for example by contribution to WFMOS), the Keck telescopes, or Gran TeCan. Negotiations for these northern 8-m nights should begin immediately and need to be completed before withdrawal from the current Gemini agreement.
9. Radio strategy: the Panel strongly supports the present funding agreement between STFC and the University of Manchester to support e-Merlin until 2014. The Panel encourages strong UK community participation in the SKA precursors, ASKAP and MeerKAT. The Panel recommends that STFC should agree to pay commissioning and running costs of the UK LOFAR station at Chilbolton.
10. Submillimetre strategy: assuming that SCUBA2 performance meets specification, the Panel regards it as a very high priority that JCMT be supported to 2012. The Panel felt that there was a strong case for continuation to 2014 if international partners remain on board, but at a streamlined operational cost. The Panel believes the UK heritage in submillimetre astronomy merits a UK involvement in CCAT and found the idea of provision of a refurbished SCUBA2 as a first-light instrument an attractive route.
11. Near infrared strategy: the Panel notes that the UK community will have continuing access to infrared instrumentation through ESO on VLT and NTT. There is a very strong case to support UKIRT to 2012 to complete the UKIDSS legacy surveys. The Panel believes that UK infrared survey work should focus on VISTA after 2012. The case for continuation of UKIRT in 2012-14 depends strongly on the completion of UPF by 2012. The scientific case for UPF and its science is very strong, but the Panel recognizes STFC’s financial position may make it hard to deliver UPF in the period 2010-12, without substantial contributions from other sources.
12. Recommended optical strategy: the Panel believed there is a very strong case for continuation of UK involvement (at 28%) in WHT beyond 2012, to provide access to the northern sky, to support Gaia follow-up, to support visitor instruments and to provide a test-bed for E-ELT instrument development. Continuation of WHT was a strong recommendation of NUAP. The INT is of lower priority but offers good value at a very low level of cost. We would support ESO initiatives to buy time on the AAT. The Liverpool Telescope received a low level of support from community, had lower productivity and cost-effectiveness, but is important to a small user community. We rated it at lower priority.

13. The Panel rated UK involvement in LSST at a high priority, but recognized that it would be costly to achieve a major UK role. We strongly support the exploration of an ESO involvement in LSST.
14. UK involvement in MROI: the Panel recommends continuing support of the outstanding instrumentation group working in this area. The Panel recommended supporting the group's provision of delay-lines through to completion in 2014 at high priority, provided the project finds the costs for the science beam-combiner. The Panel rated UK provision of the science beam-provider as medium high priority.
15. SuperWASP: the Panel recommends support through to 2012 at high priority. The case for continuing support for a refurbished SuperWASP beyond that date needs to be assessed in the context of broader UK exoplanet science strategy.
16. The Panel attached great importance to a continued UK role in the development of, and provision of, state-of-the-art instrumentation for ground-based telescopes. This is important for knowledge transfer and investment in the technologies of the future, as well as giving scientific leadership to the groups involved. The Panel placed at highest priority a UK PI role in at least one E-ELT instrument, then a UK 10-20% stake in WFMOS on Subaru and UPF on UKIRT.
17. The Panel believes that the work of the Wide Field Units, in support of highly-rated surveys with UKIDSS, VISTA and VST, should be rated at the same high priority as the surveys they support, but with strong oversight to ensure value for money, and to assess the required resource level. The Panel took the view that Virtual Observatory work should be tackled at an international level. Proposals for future large ground-based projects should include resources for data processing and curation, and should adopt international VO standards.
18. The Panel took the view that the university Grants line is of very high priority for the future of ground-based astronomy, both for exploitation of our facilities investments and for independent theoretical work that paves the way to new observational ideas.

Table of Acronyms

AAT	Anglo Australian Telescope
ALMA	Atacama Large Millimetre/submillimetre Array
APEX	Atacama Pathfinder Experiment
CCAT	Cornell Caltech Atacama Telescope
DES	Dark Energy Survey
E-ELT	European Extremely Large Telescope
ESA	European Space Agency
ESO	European Southern Observatory
EST	European Solar Telescope
FMOS	Fibre-fed Multi-Object Spectrograph
FUAP	Far Universe Advisory Panel
GBFR	Ground Based Facilities Review
GTC	Gran Telescopio Canarias (GranTeCan)
ING	Isaac Newton Group
INT	Isaac Newton Telescope
JCMT	James Clerk Maxwell Telescope
JAC	Joint Astronomy Centre
JIVE	Joint Institute for VLBI in Europe
LOFAR	LOw Frequency ARray
LSST	Large Synoptic Survey Telescope
LT	Liverpool Telescope
MROI	Magdalena Ridge Observatory Interferometer
NTT	New Technology Telescope (ESO)
NUAP	Near Universe Advisory Panel
RAS	Royal Astronomical Society
SALT	South African Large Telescope
SKA	Square Kilometre Array
STFC	Science and Technology Facilities Council
UKIRT	UK Infrared Telescope
VISTA	Visible and Infrared Survey Telescope for Astronomy
VLT	Very Large Telescopes
VLTI	VLT Interferometer
VST	VLT Survey Telescope
VO	Virtual Observatory
WFMOS	Wide-Field Multi-Object Spectrograph
WHT	William Herschel Telescope

1. Introduction

1.1 Background to Panel

The formation of the Ground-based Facilities Review (GBFR) Panel was announced by Keith Mason at the RAS-NAM on April 23rd 2009. Our terms of reference were:

1. establishing the key UK science aims of STFC's facility portfolio
2. setting a strategic framework for future investment decisions (for example in new instrumentation projects) for our facilities based on those science aims
3. guiding STFC strategy with regard to membership of international organisations and telescope facilities, and major projects

The key aims of the review are:

1. To identify the key science goals for ground-based astronomy at wavelengths ranging from the optical to radio in the next 10 years, taking into account science capabilities available from existing and planned space facilities, and map these to STFC and government science priorities
2. To use these science goals to provide recommendations on the UK requirements and future strategy for:
    - Involvement in the ongoing European and global development of Extremely Large Telescopes
    - Large (8-10m) class telescopes and associated instrumentation, including those for the subscription organisations of ESO and Gemini
    - Medium (~4m) class telescopes and associated instrumentation
    - ALMA
    - JCMT
    - UKIRT
    - A coherent scientific and technological pathway to the SKA
    - e-Merlin
    - Other, niche facilities in which STFC or UK groups relevant to STFC, have involvement
3. To identify any gaps in facility or instrumentation capability and recommend appropriate strategies
4. To provide recommendations on corresponding technology requirements and priorities
5. To consider whether the UK's suite of ground-based facilities matches the needs of its space astronomy programme.

We held our first meeting on April 28th and published our Consultative Document and questionnaire on June 1st, with a deadline for responses of July 31st. We published a Draft Report on September 25th and received a further 30 comments on this draft before our stated deadline of Oct 14th. We considered these comments very carefully and have made quite a few revisions. We also took into account feedback from Science Board, PPAN, NUAP and FUAP on our Draft Report. We were gratified that most of these comments on the Draft Report prefaced their remarks with positive comments on the Report.

Throughout the period since our formation, we have liaised with the newly formed STFC Near and Far Universe Panels and tried to maintain consistency with their thinking. Although five months is a very short time to have to develop a decadal strategy for ground-based astronomy, we were helped by the work that had been done previously by the Ward Committee in 2008 and by the ASTRONET review. The very positive response of the community to our questionnaire made our task much easier. We feel there is little scope for misunderstanding the recommendations of the community and of this Panel.

1.2 Economic background

This review is taking place as the UK, and the world economy, starts to emerge from a severe economic downturn. This is not an ideal time to be talking about the exciting prospects for ground-based astronomy for the next decade and to be proposing a major UK role in two very large projects. The next 2-3 years are likely to be difficult ones for the public sector and we can not expect astronomy to be immune to these problems. It would be surprising if we were not being asked to make savings in the short term.

However we would emphasize that investment in major high-tech ground-based facilities, with huge potential for knowledge transfer in the IT, communications, radar and optical-fibre technologies, and representing direct investment in high-tech UK industry, would provide a very powerful economic stimulus during emergence from a recession.

We are aware of financial difficulties facing STFC in the immediate short-term, but we have determined to stick to our brief of providing a vision and a strategy for 2012-2020. We urge that every effort is made to retain those facilities that we identify as of high priority for this period, and to seek the resources to build the key new facilities on which the future of UK astronomy depends. The vision we are presenting foresees withdrawal from some facilities around the middle of the decade in order to open funding for the new facilities.

Through a combination of scientific leadership, instrumental and engineering brilliance, outstanding theoretical work, energetic and imaginative exploitation of facilities, and the excellence of our university departments and institutes, the UK has built up a position of remarkable impact in astronomy. With an expenditure on astronomy that is by no means exceptional as a fraction of GDP amongst advanced nations, the UK's status, as measured by publications and citations, is second only to the US. This acts as a beacon for the UK's whole scientific effort, drawing school children into science and university students into physics. The excellence of the UK's universities translates into direct economic benefit both from overseas students and from the value to the UK economy of our own graduates.

1.3 Knowledge transfer, economic impact, outreach

Most professionals working in astronomy have been drawn in by the intellectual excitement of the field. In the past decade there has, however, been a growing realization among astronomers not only that we need to make the economic case for the UK's expenditure on astronomy, but also that we do in fact have a very strong case.

The then President of the RAS (and chairman of this panel) wrote in September 2006 in *Research Fortnight*:

'The astronomy and space science community have in fact worked very hard with PPARC(/STFC) over the past decade to improve knowledge transfer to industry and there have been some impressive achievements. Although our research is curiosity-driven it does have many direct links with industry, especially in the areas of astronomical instrumentation and space instrumentation, can certainly point to long-term economic benefits derived from astronomical research, and has produced some impressive short-term benefits, like commercial applications of terahertz imaging (for security and medical applications). Other examples include:

(1) A precision camera developed for gamma-ray astronomy has been used to screen cargo containers for radioactive materials being brought in at airports, border crossings and other security-sensitive areas.

(2) Superconducting tunnel junctions (STJs) that are used on telescopes to measure low levels of radiation are being developed to detect fluorescence from tagged DNA. This will improve DNA identification needed for medical and forensic techniques such as genetic profiling.

(3) One of the most successful imaging devices of recent decades has been the charge-coupled device (CCD) developed for astronomy and particle physics, which is now found in cameras bought on the high street as well as in medical X-ray equipment.

(4) Adaptive optics is a technology to compensate for the blurring of starlight by the Earth's atmosphere. It is now being applied in medical optics, where there are two distinct uses. The first application is to image the retina in unprecedented detail, opening up the possibility of early detection of disease and abnormalities. The second is to enhance someone's vision to better than normal vision.

(5) Imaging by microchannel plate camera, a standard technique in X-ray astronomy, has been developed as a sensitive camera for monitoring cancer treatment, and imaging tumours in the body.

(6) Study of reactions between ions and molecules in the interstellar medium led to the development of a technique to measure trace gases. The same technique is now used as a non-invasive method for clinical diagnosis and therapeutic monitoring (breath testing), and is also finding applications in environmental science (pollution monitoring), health and safety practice (monitoring breath following exposure to hazardous chemicals) and animal husbandry (measuring the release of noxious gases from animal waste and the sulphurous gases and fatty acids emitted by cows).

(7) Mathematical techniques designed for processing observations of the Universe as it was just after the Big Bang are being applied in forensic and medical fields. Picture enhancement was first developed and applied to astronomical images, but has been transferred to uses such as reconstructing fuzzy police photos of car number plates, and de-blurring of images of the human body taken by hospital scanners.'

Both E-ELT and SKA offer excellent examples of knowledge transfer and economic impact. The opportunities from E-ELT range from large deformable mirrors to novel IR detectors. The current R&D into large deformable mirrors has industrial partners (BAe Systems, Teer Coatings and ECM) and support from the Ministry of Defence through the Joint Grants Scheme. The study on applicability of novel IR detectors in astronomy has QinetiQ as a partner, and interest from Selex Systems Ltd. A Basic Technology research project on Ultra-precision Surfaces has resulted in development of a new facility for process development and manufacture of large optics in North Wales, driven by demanding E-ELT primary mirror segment requirements, but resulting in capability attractive to a range of industrial and space applications. In the wider context, several UK industries are involved in central E-ELT contracts on issues associated with technology proving (e.g. in prototyping construction of the primary mirror segments). Already over £6m in industrial contracts have been received in the UK as part of E-ELT studies.

The technology required for radio astronomy is, amongst all fields of astronomy, most closely aligned with the commercial market; witness that radio astronomy R&D led directly to the development of wifi. The return to the UK for its potentially large investment in the SKA is already tangible, e.g. R&D contracts let to ~17 major companies including BAe, SELEX Galileo, IBM UK, Xilinx, Roke Manor (Siemens) as part of the SKADS programme; and ~£4M to Fujitsu-UK and Global Crossing for the installation and maintenance of the e-MERLIN dark fibre network, which is testing the technology required for the SKA. The continued funding of advanced SKA R&D will lead to further contracts and will place UK companies in an excellent position to bid for and win some of the major contracts that will be let for SKA construction. UK industry has already recognized the opportunity to capitalize on the advanced technologies being developed to create new market opportunities.

1.4 Strength of UK ground-based astronomy

The UK has a very strong heritage in ground-based astronomy, stretching back to the foundation of the Greenwich Observatory and the surveys of William Herschel. In the first half of the 20th century, leadership switched to the US with the advent of the Mount Wilson 100” and Palomar 200” telescopes, but the UK played a leading role in the post-war development of radio astronomy, recognized by Nobel Prizes for Ryle and Hewish in 1974. With the construction of the AAT (1974) and the WHT (1987), two superb 4-m telescopes, the UK again became competitive in ground-based optical astronomy. The UK took a lead in infrared astronomy with the construction of UKIRT, the world's largest infrared telescope, in 1979, and took a groundbreaking lead in submillimetre astronomy with what is still the world's leading submillimetre telescope, JCMT, in 1986. The advent of the Keck 10-m optical telescope in 1993 posed a new challenge. The UK responded first by becoming a major partner in the two 8-m telescopes of the Gemini Partnership, the first of which saw first light in 1999. The growing strength of European astronomy, and the clear success of the European Southern Observatory's four VLT 8-m telescopes, proved a strong attraction for UK astronomers. The British Government agreed to support the UK's application to join ESO in 2002 and our ESO subscription is now the centrepiece of our ground-based astronomy programme.

1.5 Key role of ground-based discovery for next decade

The European funding agencies and research organisations, supported by the European Commission, have recently carried out a review of all aspects of astronomy for the next decade, under the umbrella of the ASTRONET process. The ASTRONET Science Vision document gives a very exciting list of scientific questions that can be addressed in the next decade. To realize this science vision, Europe will need both new ground-based facilities and new space astronomy missions. It is very striking from the ASTRONET Science Vision and from their Infrastructure Roadmap, how important ground-based astronomy will be to the achievement of these goals. The very highest priority is given by ASTRONET to the development of two very large ground-based facilities, the European Extremely Large Telescope (E-ELT) and the Square Kilometre Array (SKA).

The Near Universe and Far Universe Astronomy Panels are in the middle of a process of assessing the key science priorities for UK astronomy, and the implications of these for UK ground-based facilities. We have had cross-membership with these Panels and been kept informed of their evolving ideas. In our Consultative Document, we summarized the FUAP and NUAP preliminary science goals and used these in our community questionnaire. We believe our recommendations will be substantially consistent with those of NUAP and FUAP and we will have an opportunity when finalizing our report to incorporate any conclusions they have reached by then.

1.6 Synergy between ground- and space-based astronomy

One of the striking developments of the past 50 years has been the move towards multi-wavelength astronomy. To understand planets, stars, galaxies, the universe, we need observations in all the available wavebands: radio, submillimetre, infrared, optical, ultraviolet, X- and gamma-ray. This in turn requires a mixture of ground- and space-based telescopes. There is a strong synergy between ground- and space-based astronomy and it is not so much a question of one waveband being used to follow-up discoveries in another, as a combined multi-wavelength assault on the problems of interest.

There is, however, an issue of balance between the ground-based and space-based programme. For several decades space-based astronomy has been too expensive for a single group, or even a single European nation, to make a significant impact. The UK role in space-based astronomy is very much focussed on our membership of the European Space Agency (ESA). Within ESA we lobby for missions that we think are important and seek to play a major role in building the instruments needed for those missions. The subscription to ESA is the single largest item in the UK astronomy budget. Ministers have recently agreed to a substantial increase in the ESA subscription over the next decade, which will allow ESA to deliver its Cosmic Vision programme. If the UK astronomy budget does not undergo a similar increase there will be very real pressure on the rest of the programme, including participation in and exploitation of ESA missions, involvement in space exploration programmes like Aurora, and ground-based astronomy. In ground-based astronomy, too, we are moving to an era of facilities that are too expensive for a single nation to build. The ALMA millimetre and submillimetre array is the first example of a facility which has required the joint efforts of Europe, the US and Japan to achieve. The two ground-based facilities which are identified as the top priority by ASTRONET, E-ELT and SKA, will stretch European, and in the case of SKA, international, resources to the limit. The exciting vision which we are putting forward in this document, and which appears in the ASTRONET Roadmap, may require an increase in UK astronomy funding by of order 20%, in real terms, over the next decade. The ASTRONET Roadmap recommends in increase of this level across Europe, to fulfil its recommendations for ground-based and space astronomy, and astroparticle physics.

It is worth commenting that by 2020, UK astronomy will look much more like UK particle physics than it has in the past. Our programme will be very much concentrated on our ESA and ESO subscriptions, and our involvement in SKA, and the exploitation of these. Ground-based astronomy has reached the stage where our next facilities, ALMA, E-ELT and SKA, are so large that they have to be international projects. The community has made clear to us that it wants these facilities and it is important that it get behind them. The Panel recognizes that the UK can not maintain all the other existing facilities indefinitely as well.

1.7 Astronomy areas not covered by this review

The scope of this review is limited to ground-based astronomy. It perhaps needs to be complemented by a similar review of UK space-based astronomy and exploration. We were also instructed not to include: astroparticle physics (dark matter searches, neutrino astronomy, high energy cosmic rays, gamma-ray astronomy, CMB experiments), and solar-terrestrial physics, and a way needs to be found to review these areas too. A number of comments in our questionnaire responses specifically raised these areas not covered by our review.

1.8 Current facilities funded by STFC

The ground-based facilities currently funded wholly or partially by STFC, and which we have reviewed, are:

As part of our ESO subscription: a ~23% share of the 4 VLT 8-m telescopes, VLTI, the ESO 3.6m, the NTT, VISTA, VST, and APEX.
As part of the Gemini Partnership: a 25% share of the Gemini-S and Gemini-N 8-m telescopes.
The ING observatory, consisting of the WHT and INT.
The JAC on Hawaii, consisting of UKIRT and JCMT.
MERLIN, JIVE.
The Liverpool Telescope.
SuperWASP.
UK participation in the Dark Energy Survey.

(Note: Merlin, LT and SuperWASP are partially university funded)

Upcoming facilities to which STFC has already committed funding (constructed and operations about to start, under construction, or undergoing R & D):
e-Merlin, FMOS on Subaru, ALMA, MROI, E-ELT, SKA.
(Note: e-Merlin is partially university funded)

Facilities for which UK participation has, so far, been funded by UK universities: PanSTARRS1, LOFAR, SALT.

Other proposed facilities:
LSST, PanSTARRS4, LASST, CCAT, EST.

Detailed notes on each of these facilities are provided in Appendix 1. These use the corresponding notes in our Consultative Document, updated to take account of submissions from facility directors.

2. Summary of Community views

Our first act as a Panel was to write a Consultative Document to seek the community's views on the key strategic issues, published on May 1st 2009. We invited written inputs and also devised a questionnaire to try to quantify community views on ranking of science areas, ranking of existing and proposed facilities, and on the strategic questions. We held a Town Meeting at the RAS in London on July 9th 2009. Facility Directors were also specifically invited to make submissions and to answer specific questions about their facilities, including description of instrumentation suite, oversubscription, publications and citations. We have published some detailed summaries of the results from the questionnaire (web reference). Here we give a few summary tables. 440 people responded to the questionnaire, which represents about half of the total UK community. Inevitably there was a strong bias towards those who use ground-based facilities.

Table 1: Community ranking of science areas (1 = most important, 10 = least important):

	1-3	4-6	7-10
1. Galaxies	259	99	87
2. Cosmology	208	170	67
3. Exoplanets	167	142	134
4. First light	166	154	125
5. Diffuse matter, star and planet formation	153	196	96
6. Stellar astrophysics	142	176	127
7. Extreme astrophysics	129	162	144
8. Planetary interiors, surfaces and atmospheres	90	89	266
9. Space physics	78	97	270
10. Solar physics	66	99	280

Table 2: Numbers of respondents indicating >50% research in a given area:

1. Extragalactic	180
2. Galactic	65
3. Stars	61
4. Celest.mech.	34
5. Planetary	28
6. Solar/STP	7
7. Particle cosm.	6
8. Knowledge Exch.	4

Comments on science area responses:
Clearly there was a low turnout amongst particle cosmology, STP, and planetary and solar physics scientists, presumable because particle astrophysics and STP facilities were specifically excluded from this review, and because the UK planetary and solar community is primarily interested in space-based facilities. For this reason we did not evaluate the European Solar Telescope. A review whose scope included these areas, and also space astrophysics, might have resulted in different rankings.

The most strongly supported areas, amongst those who responded to the questionnaire, were cosmology and extragalactic astrophysics, and the emerging field of exoplanets.

Table 3: Community support for facilities

For each facility, figures are shown as x/y, where x= 3+4+5 (crucial), y = 1 (marginal importance)+2+no importance. List is ordered by UK perspective for next 10 years.

	importance for own research			importance from UK perspective		
	past3yrs	**next3**	**next10**	**past3**	**next3**	**next10yrs**
1. VLT	256/108	309/67	301/166	338/21	349/13(1)	332/27
2. ALMA		228/102	264/80		282/31(2)	324/9
3. SKA			250/90			306/28
4. E-ELT			230/110			305/29
5. VISTA		194/108	198/97		240/38(5)	237/37
6. LOFAR		158/147	178/132		213/71(6)	237/52
7. JCMT	160/177	176/135	147/149	232/64	251/42(4)	193/84
8. LSST			166/95			190/50
9. PnSTARRS	25/254	111/193	122/176	53/196	180/125(9)	186/104
10. GeminiN	173/158	172/176	157/177	223/109	172/176(10)	176/145
11. (e-)Merlin	105/195	158/143	137/157	141/117	191/72(7)	161/98
12. UKIRT	212/129	212/129	134/185	295/31	259/61(3)	152/155
13. CCAT			115/131			144/61
14. WHT	119/208	152/178	159/168	221/93	186/118(8)	137/159
15. GeminiS	142/191	138/205	133/159	181/142	138/205(12)	133/180
16. VST		85/170	87/168		107/125(14)	120/112
17. DES		46/195	52/187		98/115(15)	113/99
18. SupWASP	53/240	65/228	57/228	155/123	169/114(11)	102/161
19. MROI		59/156	66/150		59/156(21)	83/101
20. 3.6m/NTT	113/194	104/204	79/207	124/159	108/171(13)	81/194
21. APEX	43/220	83/172	70/177	44/153	88/104(16)	78/110
22. JIVE	55/196	70/183	66/178	76/104	81/97(17)	77/100
23. SALT	17/253	53/230	62/214	18/225	62/199(19)	64/190
24. INT	98/211	75/225	59/225	115/174	74/207(18)	58/218
25. EST			27/179			57/100
26. LT	51/238	69/219	56/221	55/203	61/193(20)	51/198

On the strategic questions:	Important, v.important, or extremely important	Unimportant, or not v.important
Role in E-ELT?	393 (141)	34 (13)
Role in SKA?	373 (120)	39 (21)
JCMT after 2012?	279 (102)	80 (28)
WHT after 2012?	256 (93)	127 (39)
e-Merlin after 2012?	244 (89)	123 (38)
UKIRT after 2012?	242 (97)	138 (38)
Role in CCAT?	214 (72)	93 (38)
Remain in Gemini?	202 (76)	197 (67)

Access to North or both hemispheres: 305 (118)
Access to South or either: 118 (41)

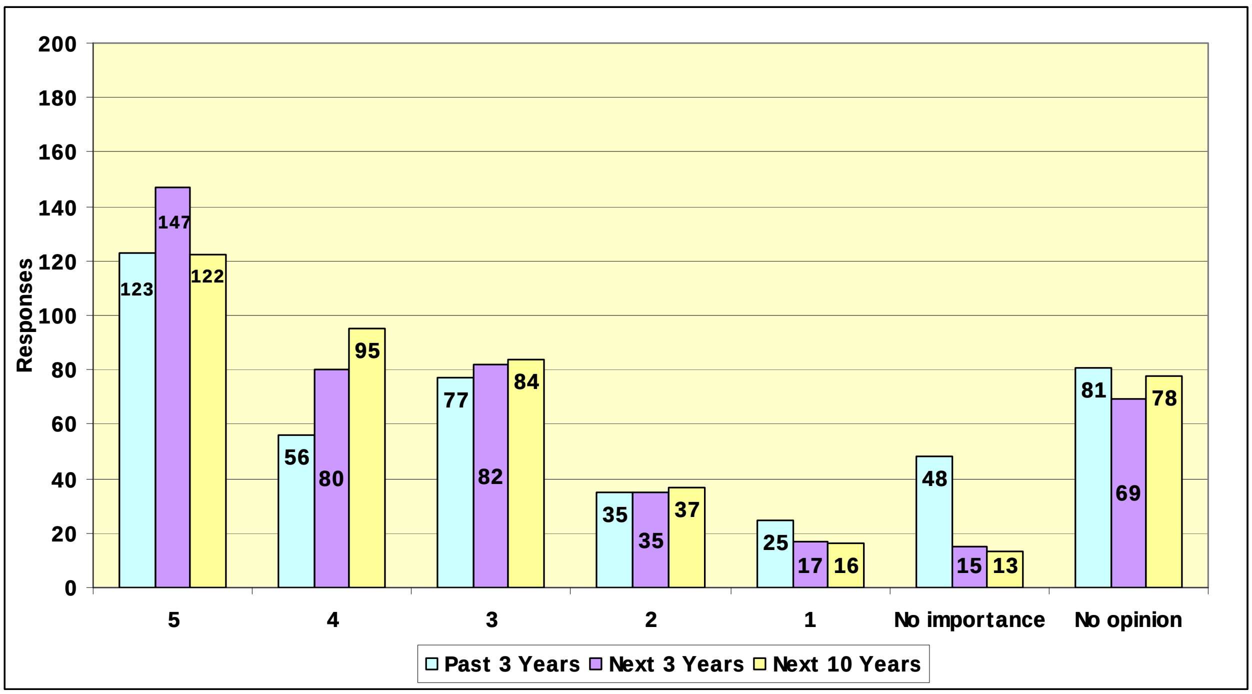
A few comments on Table 3:

1. Overwhelming support for VLT and ALMA.
2. Overwhelming support for both E-ELT and SKA.
3. Level of support for Gemini-S ~40% (compared with ~90% for VLT).
4. Continuing need for northern hemisphere access. Have to think especially of needs of Gaia, LOFAR, e-Merlin, SCUBA2 and UKIDSS.
5. Strong support for LOFAR.
6. Support for the four UK telescopes, WHT, UKIRT, JCMT, e-Merlin, is very strong over the next three years, and remains strong beyond that.
7. Support for SuperWASP is strong from UK perspective over next 3 years.
8. Strongest support for survey projects goes to VISTA, but there is significant support for LSST/PanSTARRS.

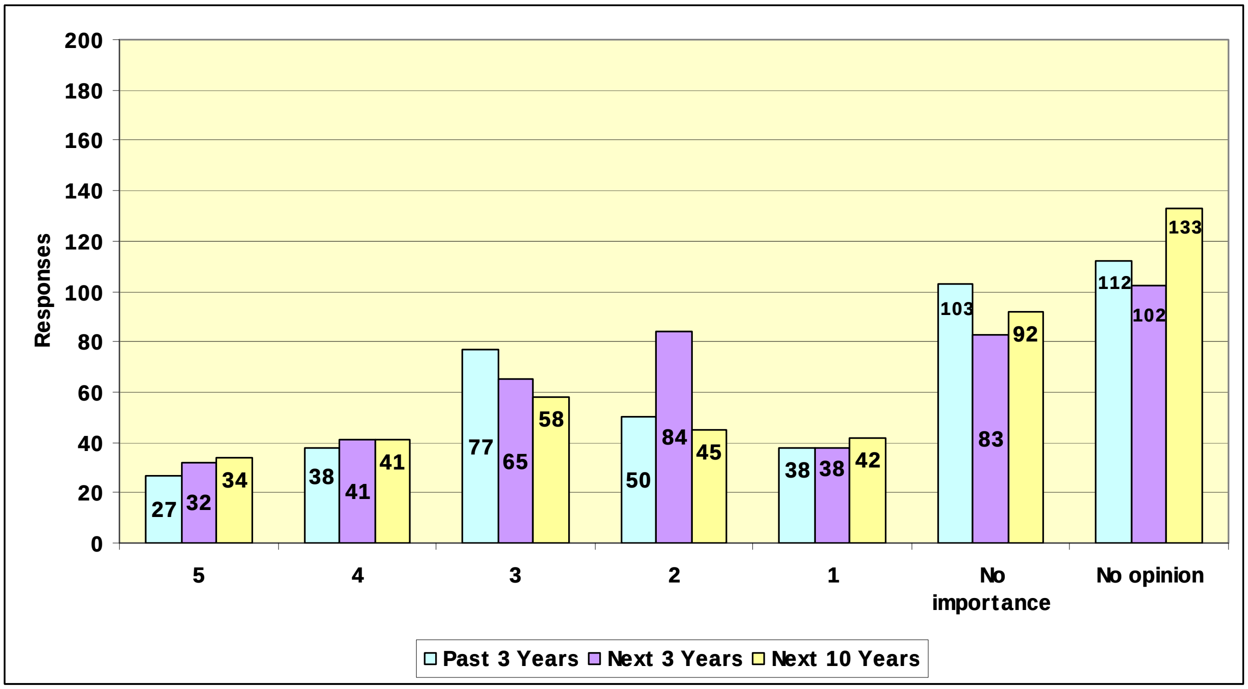
Overall, it is worth commenting that the community response to the questionnaire was extremely mature and thoughtful. People supported astronomy areas completely distinct from their own work, and made a clear distinction in their answers between 'important for my own research' and 'important for UK astronomy'. There was no clear difference between the NUAP community (categories 2-6 in Table 2) responses to strategic questions (shown bracketed) and those of the whole community. The written comments on the strategic questions amounted to some 30 pages of text when printed out, most of it highly cogent and interesting. We quote a few of these responses in Appendix 3. The figures display the responses to some of the questions in graphical form.

Ranking of VLT and Gemini-S (5=crucial):

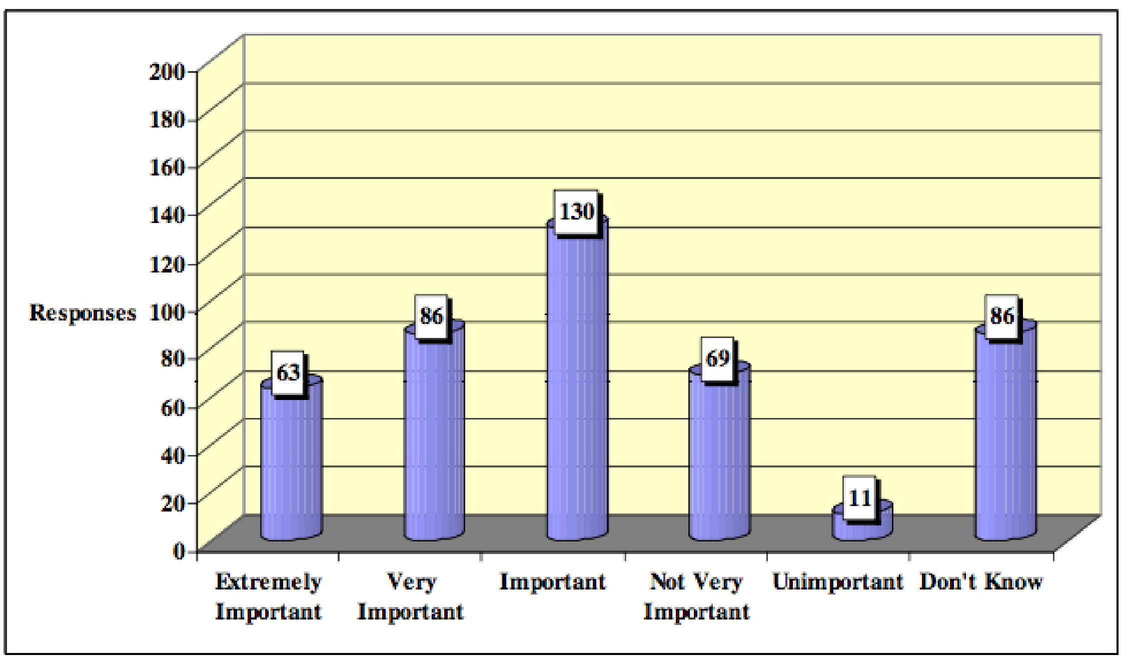
VLT



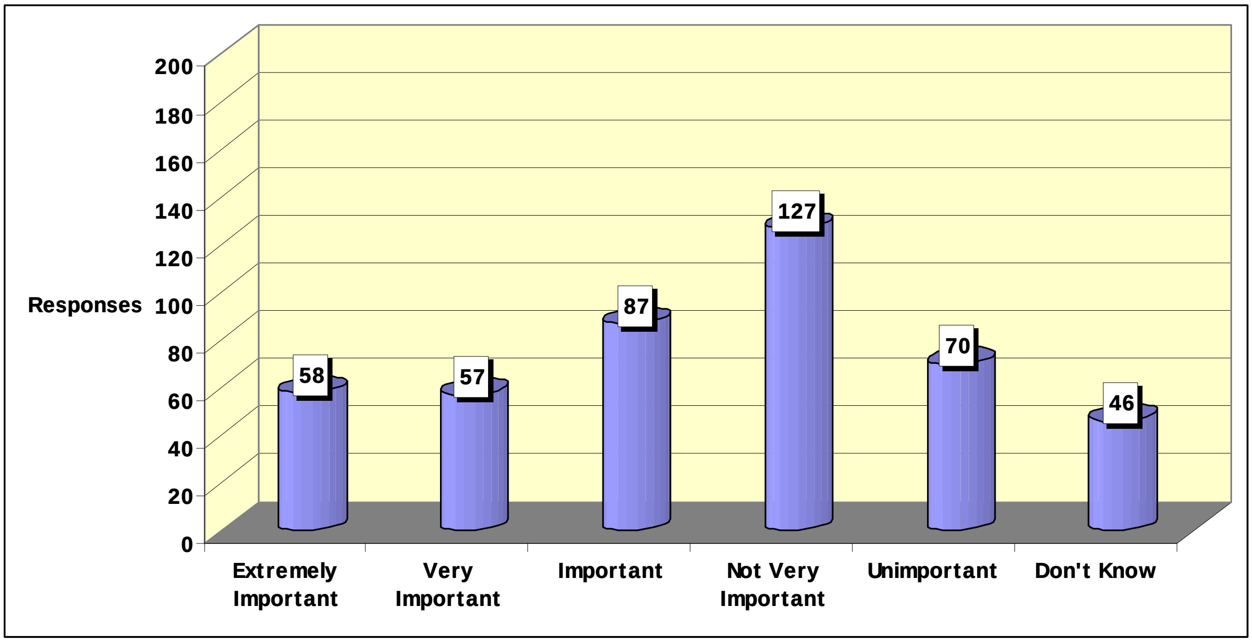
Gemini South



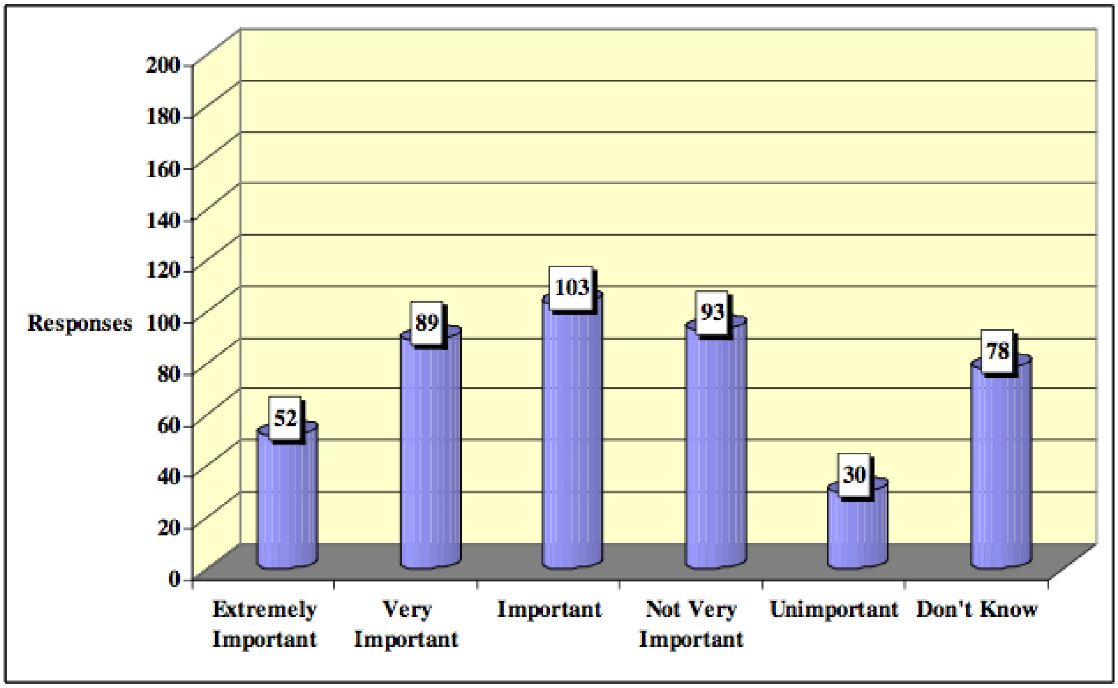
How important will it be for the UK to remain in the JCMT partnership once the first 2 years of the Legacy programme have been completed?



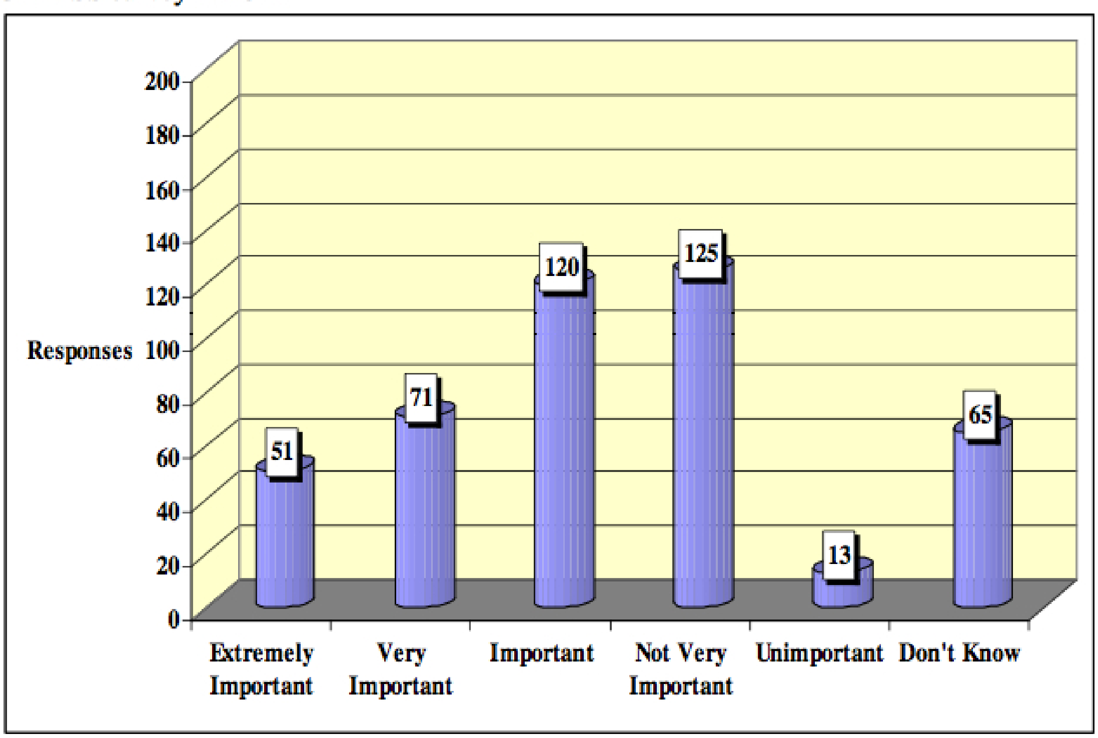
How important do you think it is to remain in the Gemini Partnership post-2012:



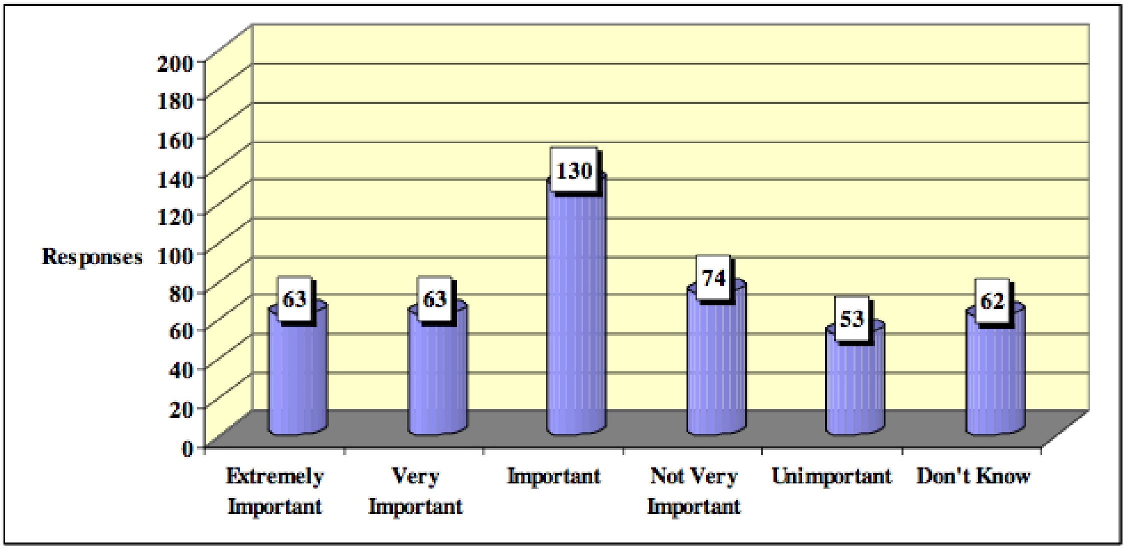
How important will it be for the UK to retain e-MERLIN once its 2.5 year Legacy programme has been completed?



How important do you think it is for the UK to retain access to UKIRT after completion of the UKIDSS survey in 2012



How important do you think it is for the UK to retain access to WHT after 2012?



3. UK Ground-based Astronomy Strategy

Here we outline our proposed strategies for UK ground-based astronomy, based on the UK's prime science goals (as identified by FUAP, NUAP and our own questionnaire), the community responses to our questionnaire, detailed comments and submissions, submissions from facility directors, and the publication and impact performance of existing facilities (Appendix 2). The prime driver in our analysis has always been the science. Other factors we took into account were balance between sub-fields, cost-effectiveness of facilities, UK leadership roles, support for space missions, balance between small, medium and large facilities. Several of our recommendations involved intensive discussion amongst the Panel and in some cases a majority view had to be found. We know from the comments we have received from the community that for almost every recommendation a counter-argument could be put. We believe that the strategy we are putting forward is one that the community can get behind, that it does represent the majority view of the community, and that it is a realistic strategy that STFC will be able to deliver.

3.1 ESO membership

There was very strong UK community support for ESO membership, with VLT rated as the highest priority facility, ALMA second and VISTA fifth (after SKA and ESO's E-ELT). The Panel believes that ESO membership is the very highest priority within the UK ground-based portfolio, with the VLT, VISTA and ALMA as the flagship facilities. The VLT instrument package is seen to be of high quality, with a high impact on cosmology, extragalactic astrophysics, stellar astrophysics and exoplanet follow-up, VISTA+VST as offering exciting opportunities for optical and near infrared surveys, with UK astronomers in leadership positions, and ALMA as a very exciting prospect for the strong UK submillimetre community. The Panel felt that the UK exoplanet community could make more use of the ESO 3.6m telescope and that the UK optical/ir interferometry community could take more advantage of VLTI.

The UK ALMA Regional Centre was seen as necessary for effective UK participation in ALMA. Centres based on this model of distributed assistance have rarely met with universal approval but we recognise that the ALMA support group at ESO HQ will provide mainly archiving services, with perhaps limited direct support to observers or proposers, so UK astronomers would be at a disadvantage relative to astronomers in the US, the rest of Europe, and Japan, without the ARC, especially in the early years of ALMA. We recommend that the ARC's location, and the level and form of support, should be reviewed rigorously and regularly, as now, by the ALMA Oversight Committee.

3.2 European Extremely Large Telescope (E-ELT)

There was very strong support for UK involvement in E-ELT, with over 90% describing this as extremely important, very important or important. The proportion for the near universe (NUAP) community, identified by categories 2-6 in Table 2 above, was identical to that for the extragalactic (FUAP) community. The nine `Prominent Science Cases' identified by the E-ELT Science Working Group - exo-planets; stellar disks; initial mass function in stellar clusters; resolved stellar populations; black holes/AGN; the physics of galaxies; metallicity of the low-density IGM; the highest redshift galaxies; and dynamical measurement of the universal expansion – align well with the highest priority science areas identified by the UK community (eg NUAP and FUAP reports). The Panel endorses the very high priority placed on E-ELT by ASTRONET. The ESO Council is expected to reach a decision about embarking on E-ELT, and to make a decision on the site, in 2010, and to be ready to start building it soon after that, provided member states are able to raise the necessary resources. We would expect to see the UK participating at a level proportional to its GDP. Already substantial contracts have flowed back to UK industry, and we would expect STFC and BIS to ensure strong involvement of UK industry in the construction phase. We would expect to see at least one UK Instrument PI, and at least one other major instrument role. The UK is currently involved in 6/8 instrument studies and the best candidates for a UK PI role are EAGLE, HARMONI and OPTIMOS. E-ELT offers great opportunities for knowledge transfer and economic impact (see section 3.12 and Appendix 1). A significant fraction of the funding is likely to be found within ESO's existing resources or from new members. STFC would need to find some of the additional UK share of construction and instrumentation costs from its ground-based programme line.

In this Report we make the assumption that E-ELT will be located in the southern hemisphere, for consistency with ESO's other facilities. However if a northern site like La Palma were selected, both ESO and STFC would have to reconsider their northern hemisphere strategy. STFC would need to enter into discussions with ESO about ways to maintain WHT and UKIRT for the foreseeable future, and to develop their instrumentation suites. Hemisphere surveys with UKIDSS and SCUBA2 would become very attractive possibilities.

3.3 Square Kilometre Array (SKA)

There was very strong support for a strong UK involvement in SKA. Key science areas addressed by SKA Phases-1 and 2 are: (1) Mapping the Epoch of Reionization through, for example, tomography of the neutral inter-galactic medium during the 'dark ages'; (2) Studying galaxy evolution, cosmology, dark matter and dark energy through a billion-galaxy HI survey which will provide an inventory of the atomic gas content of the Universe over at least half its age, and will constrain dark matter properties (e.g. neutrino mass) and dark energy through baryon acoustic oscillation and velocity-space-distortion measurements; (3) Determining the origin and evolution of cosmic magnetism through observations of Faraday rotation towards millions of background radio sources; (4) Performing fundamental physical measurements through strong-field tests of gravity using pulsars and black holes and, via pulsar timing, detecting and characterizing gravitational waves. STFC has positioned the UK for a lead role in Prep-SKA, and the Panel endorses and supports the goal of maintaining this leadership into SKA-Phase1. The current proposal is for an above-GDP stake in SKA Phase I, and a smaller stake in Phase 2, combining to an ~11% stake in the whole SKA project. The STFC should seek ways of funding the large capital costs of constructing the SKA that do not jeopardize the similar effort for the E-ELT (and vice-versa). There are tremendous possibilities for knowledge transfer to the radio, radar, broadband and communications industries (see Appendix 1).

3.4 Phasing of E-ELT and SKA

The phasing of E-ELT and SKA is determined naturally by the technical readiness of the two projects. While E-ELT has completed Phase B and is ready to start construction soon after 2010, the SKA consortium still needs to be fully defined, with a decision on location to be made in 2012. The next few years will see a very important phase of exploitation of SKA precursors (e-Merlin, LOFAR, ASKAP, MeerKAT), in which we expect to see a very strong involvement by UK astronomers. We endorse the phasing recommended by ASTRONET, E-ELT first, then SKA. STFC should prepare a business plan to develop both these facilities, consistent with this phasing. With the various savings identified in this report, especially from 2014, the UK contribution to both projects could be afforded within the existing ground-based facilities budget over a 10-15 year time-scale, and on a shorter time-scale if help was available from the Large Facilities Capital Fund.

3.5 The Gemini Partnership

On the strategic question of whether UK should continue in Gemini Partnership at the present level after 2012, about half the community thought this was important, very important or crucial. Half thought it was less important or of no importance. Given the large cost of the Gemini subscription, the Panel did not find this level of support sufficient to justify the high cost involved. Although the rate of publications and citations had improved between 2003 and 2008 (see Appendix 2), they were still below those of the Keck, VLT and Subaru telescopes. Recent decisions about instrumentation are also a crucial factor and the decision not to proceed with PRVS and WFMOS was viewed very negatively in the UK.

Although there was a strong feeling in the questionnaire responses that the UK needed to maintain access to a northern hemisphere 8-m telescope, the support for access to Gemini-S, and for continuing involvement in the Gemini Partnership in the present form, was not overwhelming. We therefore do not recommend continuation of the current 25% share in the Gemini Partnership after 2012, though a role in Gemini-N could be one route to maintaining N-hemisphere 8-m access (see next section). This would also have implications on the continued need for a UK Gemini Office.

3.6 Northern-hemisphere 8-m access:
There was strong community support for continued 8-m access in the northern hemisphere. The Panel tried to identify the scientific case for this. With the VLT, programmes can certainly be pursued to declination $+10^0$, and in some cases probably to $+20^0$. Many groups have ensured that extragalactic and cosmological surveys are targeted at low declinations, to enable access from both hemispheres. The Panel would urge that surveys with UKIDSS, e-Merlin, LOFAR, SCUBA2, be targeted in the future, where possible, at low declinations. We expect a gradual switch of emphasis of UK survey research to the southern hemisphere, driven by VISTA, ALMA, VLT and (probably) E-ELT. We identified the following examples of the remaining need for access to dec > 20^0 sky as:

- follow-up of gamma-ray bursts detected by SWIFT (to 2015)
- follow-up of hyperluminous, high-z submillimetre galaxies detected by Planck (2012-15)
- follow-up of supernovae, asteroids, exoplanets identified by GAIA (2014-2017)
- Galactic archaeology, especially post-GAIA
- follow-up of the PanSTARRS1 survey
- follow-up of UKIDDS surveys not at dec < 20^0 (2012-2015)
- follow-up of LOFAR surveys (2011-2016)
- M31 and other Local Group galaxies
- Tidal streams in the Milky Way
- Exoplanet follow-up (from SuperWASP-N, Kepler)

The UK currently has ~70 nights per year on Gemini-N, with GMOS being the main instrument used. Some of this is used by teams working in low declination fields from telescopes in both hemispheres. The Panel suggests that STFC set a goal: to secure continued open UK access to dec > ~20^0 (one third of sky) of ~ 40 nights per year for at least a 5-year period from 2012.

The UK has access to 8 nights per year on Gran TeCan, for 3 years (to 2012), through ESO, for large survey projects (the UK did not in fact get any of this time in the first round). This does not help with post-2012 northern hemisphere 8-m access. The UK also has 30% of the nights that FMOS is on Subaru, which is estimated to amount to about 100 nights of open-access time on FMOS (a multi-object near infrared spectrograph) over the 5-7 years of the life of the instrument. We are proposing a further 40 nights of open-access time on one or more northern hemisphere 8-m class telescopes, with multi-object optical spectroscopy likely to be a key element. We estimate the cost of this to be £1.5-2.0 m/yr. This would give a total of 55-60 nights per year in total of northern hemisphere 8-m access. The reduced recommended total number of nights takes account of the fact that some programmes currently carried out on Gemini-N could be done on VLT, and the fact that the UK will need to start contributing to the build of E-ELT from about 2012. The reduction in the number of southern hemisphere nights from the loss of Gemini-S is already implicit in the decision two years ago to try to sell the UK's time on Gemini-S.

The options for the additional time needed, which needs to be negotiated for by STFC, are:

(1) Gemini-N: Pros: we are a member of the Gemini Partnership, have already contributed to the capital costs, the telescope is working well. Con: not ideal instrumentation.
(2) Subaru: seek time in return for contribution to building of WFMOS. Pros: Telescope working well. WFMOS on an 8-m would be the ideal instrument. We already have had such a collaboration with Subaru on FMOS. Buying time through contribution of an instrument offers advantages of science leadership, knowledge transfer and economic impact.
(3) Keck: Pros: telescopes are working well, excellent instrumentation. Cons: may be more expensive per night.
(4) Gran TeCan: seek time in exchange for involvement in instrumentation or for cash, combined with a deal on ING. Pros: our heritage on La Palma, future of WHT. Cons: Telescope is not fully working yet, may be risky route.

STFC need to start negotiations for this time immediately, as arrangements need to be in place at the time of the termination of the current Gemini Partnership agreement. We suggest that STFC considers appointing a senior UK astronomer as its negotiator, who could investigate objectively what possibilities are available.

3.7 Radio strategy (e-Merlin, LOFAR, JIVE):

A clear strategy to get from the current radio provision to the SKA is required. The current UK provision consists of MERLIN and JIVE, along with extensive usage of the VLA, AT, GMRT and WSRT by UK astronomers. The factor of 10-20 increase in sensitivity of the new e-Merlin array, and its Legacy Programme, has clearly attracted a much wider user-base and made possible a broader range of science. The key science areas for e-Merlin are star and planet formation, the history of star formation history and black hole growth in galaxies at low and high redshifts, AGN physics, and dark matter distributions. The Panel recommends that e-Merlin should be supported until the construction phase of SKA Phase I begins in 2014. This will allow follow-up of sources from the Legacy Programme, and from EVLA and LOFAR. The similar baselines of e-Merlin and the core of the SKA will enable valuable preparatory work for SKA's mid-frequency science.

The Panel is encouraged by the significant involvement of UK astronomers in the science programme with the SKA pathfinder experiments, as evidenced in the initial round of

ASKAP survey projects. This should continue with the other pathfinders when opportunities arise such as MeerKAT.

The UK's involvement in LOFAR via a consortium of universities received strong support and will allow UK astronomers to be involved in a wide range of survey and time-domain studies. As one of the principal pathfinders for the low-frequency part of the SKA, this will enable the UK to gain valuable experience with the new techniques involved in such a digital telescope, using new aperture array devices. The panel recommends that STFC should fund the commissioning and running costs of the Chilbolton LOFAR station. There is community support for the provision of a second UK station, but we did not feel in the present financial climate we could recommend provision of a second station at this time.

The support for, and productivity of, the European VLBI effort of JIVE/EVN was not high. Although, there are prospects for further development through e-VLBI the panel believes that support for JIVE/EVN is at a lower priority. The international coordination aspects of the JIVE programme should be pursued within the SKA activities.

3.8 Submm strategy (JCMT, APEX, ALMA, CCAT):

The UK's overwhelming priority for ground-based submillimetre astronomy in the 2012-20 timeframe is the Atacama Large Millimetre/submillimetre Array (ALMA), which promises to truly revolutionise our understanding of the obscured Universe, providing unrivalled spatial and spectral resolution and sensitivity. In the nearby Universe, ALMA will study the processes of star and planet formation, revealing the details of young, still-forming stars, and is expected to show young planets still in the process of developing. ALMA will also explore the complex chemistry of the giant clouds of gas and dust that spawn stars and planetary systems. On the cosmological scale, ALMA will study the first stars and galaxies that emerged from the cosmic dark ages. Our strategy should be to enable optimal exploitation of ALMA, thus maintaining the dominant position that UK scientists were able to attain via SCUBA on the UK/Canada/Netherlands 15-m James Clerk Maxwell Telescope (JCMT). This will also ensure that UK industry can play a vigorous role in the next generation of ALMA instrumentation, e.g. the Band-1 receivers (30GHz), and in the development of complementary space facilities, e.g. ESA's Far-Infrared Interferometer (FIRI) and the FIRI Antarctic testbed.

The uniquely capable SCUBA2 camera, which begins commissioning on JCMT in September 2009, will give the UK a leadership role in the ALMA era, feeding both representative and rare targets from its world-leading legacy programme to the interferometer. From mid-2011, SCUBA2 will be complemented by the ARTEMIS 200-450um imager on the 12-m Atacama Pathfinder EXperiment (APEX), in which the UK has a small stake via ESO. There is a strong case for continuing with JCMT to the end of 2014, probably with SCUBA2 as the sole instrument complement, to complete the Legacy Programma, so long as the cost of operations can be reduced significantly and our international partners remain on board. If that is not possible, there is scope to significantly accelerate the SCUBA2 elements of the JCMT legacy programme prior to 2012.

Beyond 2014, the transformational potential of ALMA makes it difficult to foresee whether the need for wide-field submillimetre imaging or spectroscopy with a single dish will be as important as it is now. The 25-m Caltech-Cornell Atacama Telescope (CCAT), due for construction in the 2012-2017 timeframe, has no realistic competition and will be equipped with a wide-field MOS, competitive with ALMA as a redshift machine, and a camera. Given the UK's leading role in submillimetre astronomy during the past decade, it would be appropriate for the UK to seek a stake in CCAT. An attractive possibility would be to offer a refurbished SCUBA2 as a first-light instrument. We advise that the UK maintains its watching brief on this development with a view to an appropriate involvement.

3.9 Near-infrared strategy (UKIRT, MROI):
The main goal for near-infrared astronomy in the period 2012-20 is UK involvement in E-ELT. UK astronomers have access to a suite of near infrared imaging and spectrographic instruments on VLT and NTT, and some of the facilities in section 3.9. UKIRT has been an outstanding near infrared telescope. After 2012 it is expected that the impetus on near-ir surveys will switch to VISTA, in which UK astronomers have a strong stake. Continuation of UKIRT past 2012 is therefore strongly dependent on delivery of the UKIRT Planet Finder (UPF). The Panel strongly supports the science case for UPF and recognizes that quantification of the frequency of terrestrial-mass exoplanets would be a tremendous achievement. The science goal for UPF is to survey 1000 M-type stars, and it is expected that 30 terrestrial mass planets would be found in 5 years, if UPF is being used in parallel with a hemisphere survey with UKIDSS. This could be compressed to 2-3 years if UPF was the only instrument on UKIRT. These terrestrial-mass exoplanets would then be prime targets for spectroscopy with JWST. The Panel recognizes that finding funding of £5.6m in the time-frame 2010-2012 will be extremely difficult for STFC. If the majority of the funding could be found from another source, the Panel would support keeping UKIRT open from 2012-2014 to exploit UPF.

The UKIRT Board also advocates a hemisphere survey with UKIDSS as worthwhile activity post-2012, particularly to support Pan STARRS1, and it may be worth seeking other partners to fund this. The Panel did not support a major UK investment in a northern hemisphere UKIDSS survey in the same time-frame that UK astronomers will be heavily involved in VISTA surveys. However assuming JCMT is funded to 2014, the JAC Director could explore a low-operations-cost, multi-partner, model for UKIRT.

The MROI attracted significant support from the ~60-strong section of the community that requires sub-milliarcsecond near-IR imaging capability. The Panel rates at high priority continuing the current grant for completion of the delivery of the delay lines, to secure the 30 nights per year access for UK astronomers, provided the project finds alternative funding for the Beam-Combiner. We rated the additional request for STFC funds to build the Science Beam Combiner in the UK at medium priority. We recommend that STFC seek an agreement with Cambridge on an appropriate fraction of general-user access to the 30 nights/year.

3.10 Optical strategy (VLT, NTT, 3.6m, WHT, INT, LT, AAT):

There is a very high high level of community support for participation in the E-ELT and continued access to the ESO VLT with its 4 x 8.1m telescopes. ESO also provides access to suite of 2-4m class telescopes including the 3.6m and 3.5m NTT. The ESO 3.6m is operated with a single instrument, HARPS, for exoplanet searches. UK astronomers have been slow to take advantage of this but we expect that this will increase. The ESO NTT is a useful general purpose 4-m telescope providing optical and near-IR imaging and spectroscopy.

The 4.2m WHT on LaPalma has a comprehensive optical and near-IR imaging and spectroscopic instrumentation suite, some of which employ AO and it also includes support for visitor instruments. The WHT has strong user support with a broad science case from planets to cosmology. It is notable that community support for the WHT was significantly higher than for the comparable aperture ESO 3.6m and NTT. Under the current funding arrangements, the UK has 28% of INT and WHT time with the rest shared with Netherlands and Spain.

The science case for continued access to the WHT is somewhat similar to that for UK access to a northern 8-m, particularly GAIA follow-up, where the relatively bright targets are especially well-matched to 4-m follow-up. The WHT will also provide follow-up capabilities for sources detected with LOFAR, e-Merlin, Herschel and Planck. In time-domain and transient astronomy such as GRB follow-up, the longitude of La Palma compared with continental USA and Hawaii is highly important. With this in mind, a new optical imager/spectrograph (ACAM) mounted permanently at a Cassegrain focus has been recently built and commissioned in June 2009.

With several instrument stations including 2 stable Nasmyth foci the WHT is an ideal test-bed for new instrumentation, and has been proposed for testing E-ELT instruments. Current oversubscription is ~3. It is extremely good value at a current cost of £0.8M/year and even with no new instrumentation the Panel felt that the case for support post-2012 is strong. The Near Universe Advisory Panel was especially strong in its support for the continuation of the WHT. We propose that if the UK E-ELT program requires long-term access to the WHT that funding from the ELT funding line could be earmarked for the WHT.

Negotiations are taking place to host the Harvard built HARPS-NEF high precision spectrograph from 2010/11 onward and this may give an additional source of funding, as well as opportunities for UK astronomers especially for exoplanet studies. It is proposed with a wide-field MOS be built for the WHT at a cost of 13Meu, shared between the three international partners and this is discussed in section 3.13 below.

The WHT remains a valuable facility and we consider continued support of the WHT as both a scientific and strategic priority, especially now that Spain is a member of ESO and UK access to the GTC may satisfy the UK Community needs for 8-m Northern access in post 2012 when the current Gemini agreement ends. There is also a possibility that the E-ELT could be located on La Palma. Also, as UK access to Northern hemisphere 8-m telescopes is reduced, we would expect an increase in the demand for WHT time. We have set the end-date for the WHT as 2017 to be consistent with the needs of GAIA. This would need to be kept under review in the light of the level of over-subscription for the telescope.

The 2.5m INT with its two mature but still effective instruments, the Intermediate Dispersion Spectrograph(IDS) and Wide Field Camera(WFC), is operated at low cost with no support astronomer or telescope operator (<3% of the ING operations costs) and after SDSS the INT is the most productive 2-m class telescope in the world, with good publications and an excellent (and currently increasing) impact. Although it did not receive very high level of community support, the saving gained from withdrawal would be small.

The 2.0m Liverpool Telescope has a small user community that rates it highly and considers it important for their research, but it did not attract broader community support and did not appear to have yet achieved a strong publication and citation record, though this is still improving. It has done important work on gamma-ray bursts, time-domain astronomy and exoplanet follow-up, and it has an excellent public outreach programme. However it does not appear to cost-effective compared with other telescope in its class and we believe most programmes could be pursued on other telescopes. In transient and time domain astronomy its eastern longitude is as much a merit as its robotic nature.

Finally, the AAT was mentioned by many respondents to the questionnaire and though perhaps not quite the high impact facility that it was 5 years ago (see Appendix 2) it is still a valuable facility. UK access to time on AAOmega could be via an ESO wide field spectroscopic initiative or where UK astronomers leverage access to AAOmega via collaborative follow-up programs for the UK led VST and VISTA surveys.

3.11 Optical-nir survey strategy (UKIDSS, VISTA, VST, PanSTARRS, LSST)

Optical and near infrared multi-band photometric surveys are crucial for addressing questions of large-scale structure and the nature of dark matter and dark energy, and this has been a real strength of UK astronomy. Ground-based surveys are seen both as the precursors of, and complementary to, space-based surveys with the proposed EUCLID mission. The Panel supports the completion of the UKIDSS legacy surveys but believes that after 2012, UK survey effort should shift to VISTA and VST surveys, in which the UK has secured a strong science role. We did not find a hemisphere 2-band (J, K) survey, proposed to be carried out from 2012-14 with UKIDSS, represented a good strategy for UK astronomy. Such a survey would be valuable to PanSTARRS, giving them extra photometric leverage for photometric redshift determination, and the Director of UKIRT is encouraged to see whether funding for this can be secured from US sources.

Both PanSTARRS4 and LSST were strongly supported in the questionnaire. We received a specific submission about UK involvement in LSST. We recognize that LSST is an exciting project, but so far it is primarily a US one, and it is hard to see how a UK leadership role can be secured except at very high cost. We rated such a proposal highly, but below Northern hemisphere 8-m access, JCMT, WFMOS, e-Merlin and UKIRT. We urge that ESO explore a European involvement in LSST. We did not have enough information to evaluate a possible UK involvement in Pan STARRS4.

3.12 Wide field units, virtual observatory

We received submissions in respect of CASU and WFAU, arguing that cuts brought in last year would harm delivery of data products for UKIDSS, VISTA and VST. We feel that it was an error to rate these units at a low priority: they should be rated at the same level as the surveys that they support. However there does need to be strong oversight to ensure that they deliver value for money, and to determine the correct level of resource.

The International Virtual Observatory Alliance, with UK involvement, successfully established common international standards for data curation and access and established the framework for integrating data collections and user tools within a Virtual Observatory. Astrogrid also facilitated the dissemination of some useful tools including the widely used TOPCAT application. We believe that future VO activity needs to be coordinated at an international level, organized and funded by ESO or the EU. We encourage UK projects to adopt international VO standards for data products. Otherwise projects need to deal with their own data processing and curation, and the associated costs need to be included as part of the original project plan.

3.13 Instrumentation

Astronomical breakthroughs are driven by technological advances in facilities and instrumentation. The UK's lead in submillimetre cosmology was due to the development of JCMT and SCUBA; the 2dF Galaxy Redshift Survey relied on an innovative spectrograph developed at AAO; the MPE group leads the world in resolved spectroscopy of z~2 galaxies (with SINFONI/SPIFFI) and studies of the Galactic Centre (with e.g. CONICA on VLT). The proliferation of UK PIs amongst VISTA's survey programme is a good example of how the UK benefits from leadership roles in both a facility and an instrument, and the same should be true for SCUBA2/JCMT, FMOS/Subaru, KMOS/VLT and e-MERLIN. UKIDSS provides a good example of how much the world values the UK's ability to innovate and deliver high-quality, well-engineered, common-user instruments - Japan bought in by contributing funds for detectors and ESO participated as part of the UK's entry fee.

The opportunity to set the scientific agenda, seize a scientific leadership role - and to involve UK industry - are possible only via significant scientific and technological involvement in instruments and facilities, partly because of the system used by organisations such as ESO to allocate Guaranteed Time. Unless the UK is involved in instrumentation, the UK will not find itself leading the obvious early science programmes. For these reasons, we attach a high level of importance to the health of instrument groups throughout the UK.

The last decade saw university instrument groups rise in number and size, matched initially by the number of new facilities and instruments. The inexorable advance in detector QE has now stalled and recent years have seen a significant shift towards fewer, larger and more complicated instruments, typically involving institutes in several countries. To remain attractive partners, our groups must deliver unique R&D and/or engineering expertise, as well as industry-standard systems engineering, and must receive sufficient support from STFC. In the current model, universities often supply scientific leadership and lead innovative R&D programmes, calling on UK ATC or RAL for world-leading engineering and/or manufacturing expertise, and for professional instrument scientists. We believe this is a good model.

Instruments that have been proposed recently for STFC funding need to be assessed under two different headings - (i) what are the scientific priorities - what science/instruments will be so important that we want to develop them, even if it is "only" for astronomy? (ii) what technologies are promising, both as a basis for providing the next generation of instruments and having wider applications that will help STFC meet its EI strategy?

The E-ELT instrument programme scores highly across the board, with superb science drivers and technology development in many areas, including photonics (e.g. modal control in fibre optics via refractive index modification, one application of which is OH suppression; miniaturisation), adaptive optics (deformable mirrors and fast, low-noise IR detectors) and robotic control. It is our highest priority amongst the ongoing and proposed instrument development programmes and we suggest the UK should continue a significantly broad involvement in E-ELT instrumentation to guarantee a major role in at least one of the chosen instruments - preferably two, one at first light and a future "work-horse". The E-ELT instrumentation programme is seen as having very high potential for knowledge transfer and economic impact, especially in the photonics area.

WFMOS on Subaru scores well in both categories, appealing to the Galactic archaeology community as well as the cosmology and galaxy-formation communities. It is also capable of driving the photonics EI agenda. It is likely to be expensive, so we recommend involvement at the ~10-20% level, preferably in exchange for access to Subaru's full instrument suit.

The scientific priorities of the growing exoplanet community are driving technology development in several ways. e.g. coronography and nulling interferometry. UPF on UKIRT would be an ultra-stable spectrograph that utilises the development of laser comb technology for wavelength calibration, while driving it to broader bandwidth and longer wavelengths. The UK has a head start via our role in earlier studies, e.g. PRVS for Gemini, ensuring that we can be the first to measure the exoplanet mass distribution, using the biggest telescope on which the large amounts of observing time required can realistically be afforded. We therefore concur with the high scientific ranking assigned to UPF but note that timely delivery requires investment during the difficult 2010-12 period.

MROI promises a major advance in high-resolution IR interferometry. The Cambridge group leads the world in this area and MROI ranks highly in both categories. The full cost of MROI is considerable and funding to date has progressed in a haphazard fashion. However, we believe the scientific case is exciting and that the technology has much potential. We believe STFC should continue to support the group's delivery of the delay lines provided credible plans are in place for provision of the science beam combiner and for operations, from outside the STFC budget.

The panel received news from the Director of ING of a wide-field MOS that will be proposed for WHT. This scores poorly using either criteria relative to WFMOS/Subaru, but it may be of interest to the UK if a significant role in WFMOS does not prove possible. A proposal for Durham involvement in a German-led wide-field MOS on AAT or the Calar Alto 3.5m was received after we had drafted the preliminary version of our Report. European needs for wide-field spectroscopy will be reviewed by an ASTRONET survey currently under way and this may provide useful recommendations over the next year.

Finally, the panel notes that the UK's lead in submillimetre instrumentation - and its hopes of playing a significant role in space facilities such as SPICA and FIRI, and future ground-based developments such as CCAT - will be jeopardised unless we maintain an programme of R&D in this area.

3.14 Other university funded facilities

We have noted the large number of university initiatives supporting ground-based facilities. It is clearly excellent for the programme that universities are able to supply this additional source of funding. Several of these have evolved to secure STFC funding. However this can generate additional pressure on an already overstretched programme and we advise that universities ensure they have identified the full costs of involvement, including running costs, or have submitted proposals to STFC. We have already discussed LT, e-Merlin, LOFAR, PanSTARRS, and LSST, in earlier sections.

SuperWASP

SuperWASP attracted support not only from the growing exo-planet community, but from the community in general, especially for the next 3 years. For transits across bright stars it is an ideal instrument, and has detected 30% of the known transiting exoplanets to date. After 2012, the emphasis in exoplanet searches will shift towards space-based missions such as Kepler and, if selected by ESA, PLATO. Characterization of exoplanets will be by HARPS on the ESO 3.6m, AO imaging on the VLT, JWST, and eventually E-ELT. There could be a role for a refurbished SuperWASP post-2012, in detecting smaller ice-giant planets around brighter stars. The panel strongly supports the continued running of SuperWASP until at least 2012, though it believes operation costs could be streamlined. The case for continuing support for a refurbished SuperWASP beyond that date needs to be assessed in the context of broader UK exoplanet science strategy.

SALT

SALT received a modest amount of support. No STFC funds have been requested for this project and as such it should remain a purely University funded project.

4. Priorities 2012-2020

Here we give the Panel's conclusions in the form of a table of priorities for 2012-2020. Our detailed recommendations are given in section 3, and a summary is contained in our Executive Summary. Table 3 in section 2 quantifies the community's views on UK ground-based facilities over the next decade. Here we break facilities down into three categories by cost: high cost (>£5m per year), medium cost (£1-4m per year) and lower cost (<£1m per year). We then categorize facilities in each class as very high priority, high priority, medium high priority, and 'good science, but lower priority'. Within each category we have placed the facilities in priority order. Our ordering differs slightly from Table 3 because of detailed strategic considerations discussed in this document. We emphasize that all these facilities have been peer-reviewed as excellent science. This priority table needs to be read in conjunction with the discussion given in section 3.

Table 4 : Panel's final priority list for UK-funded facilities:

	High cost(>£5m/yr)	Medium cost(£1-4m/yr)	Lower cost(<£1m/yr)
Very high priority	ESO subscription (VLT, ALMA, VISTA etc) SKA, E-ELT	ELT instruments	
High priority		N.Hemisphere 8m access JCMT to 2014 WFMOS on Subaru e-Merlin to 2014 UKIRT(if UPF) to 2014 LSST (UK Role)	WHT to 2017 LOFAR running costs SuperWASP to 2012 Wide field units Alma Regional Cent. MROI CCAT
Medium high priority	25% share in Gemini partnership	MOS on WHT	MROI beam-combnr
Good science but lower priority			INT JIVE LT Gemini support

5. Schedule for Proposed Decadal Plan

2009-14

The ground-based programme will contribute to STFC's short-term funding problems in two ways: the completion of payment of the ESO joining fee in 2012 will save ~£10m per year thereafter and replacement of the current Gemini agreement (~£5m) with the purchase of 40 northern 8-m nights (~£2m) will save a further ~£3m per year. Only small savings can be made in the period 2009-2012 without disproportionate damage to the programme, but over a five-year period the ground-based programme would contribute its pro rata share of savings, even with a start-up of funding for the build of E-ELT in 2012.

2014-2017

The proposed closure date for JCMT, e-Merlin and UKIRT of 2014 has been partially dictated by the need for funding to open for E-ELT and SKA. For each facility a good scientific case can be made for extending them further, but the case for involvement in E-ELT and SKA is stronger, and choices have to be made. The telescope that we identify as most valuable for support of GAIA (2014-17) is the WHT and so we recommend keeping the WHT open to 2017, but with no recommendation on new funding for instrumentation. If the start of the construction phase of SKA were to be delayed, then the case for extending JCMT, UKIRT and e-Merlin beyond 2014 should be looked at again.

2017-2020

Towards the end of the decade, the UK ground-based programme will be realized mainly through ESO (VLT, ALMA, E-ELT, and other smaller ESO telescopes) and SKA. In addition we propose a small UK involvement in CCAT. Other opportunities may arise through ESO, for example LSST, or through bilateral partnerships, for example PanSTARSS4.

6. Concluding remarks

The next decade will be an exciting one for astronomy, and ground-based astronomy will be at the forefront of new developments. Ground-based astronomy has reached a level of maturity such that the next facilities, from ALMA onwards, will be massive international collaborations, with a scope and cost comparable to large space missions or accelerators. In its response to our questionnaire, the UK community showed that it is ready for this challenge and is committed to moving in this direction. We have set out strategies for the different ground-based observational wavebands that continue and complete exploitation of past UK investment in ground-based facilities and their instrumentation, while at the same time preparing the way for the facilities of the future. While some additional funding will be needed to deliver the major UK role in construction of E-ELT and SKA that we are recommending, most of what we recommend can be delivered within the present ground-based astronomy funding level. The power of these facilities is such that observing runs may be measured in minutes rather than nights. The impact on public interest in science and as a stimulus to UK advanced technology will be immense.

Appendix 1: UK Ground-based Facilities

In this section we give some notes on existing and UK ground-based facilities with strong UK involvement, listed in wavelength order from optical to radio.

ESO optical/IR facilities

The European Southern Observatory (ESO), operates 11 optical-IR telescopes (including 4 auxiliary VLTI telescopes) at the Paranal and La Silla observatories in Chile, on behalf of its 14 member countries. The UK joined the partnership in 2002 to enable UK participation in ALMA and E-ELT, and to provide access to increased access to 8m-class telescopes. The current annual cost of ESO membership (including ALMA costs) for the UK is £18.3 M/yr, with an additional £9 M/yr residual contribution to entry costs being paid until 2012.

The current flagship ESO facility is the Very Large Telescope (VLT) at the Paranal Observatory in northern Chile, comprising four 8.2-m Unit Telescopes (UTs), equipped with 11 facility-class instruments that deliver imaging and spectroscopy at optical, near- and mid-IR wavelengths. Recent developments include the successful commissioning of the X-Shooter spectrometer and the first on-sky demonstration of wide-field adaptive optics (MAD). The VLT as well as the 3.6m and NTT provide access for visitor instruments. UK instruments; UltraCam and DAZLE have made use of the VLT visitor focus; UltraSpec and LuckyCam have used the NTT.

The VLT has an active instrumentation programme and there are currently six second generation VLT instruments under development or in planning. The UK is leading the construction of KMOS, a cryogenic near-infrared multi-object spectrograph [delivery date to the VLT in 2011]. Other instruments under construction are MUSE, a multi-unit optical integral field spectrograph with a field of view of 1’×1’ [delivery date to VLT in 2012] and SPHERE, the VLT planet imager with a delivery data in 2010. EXPRESSO, a high resolution, high stability fibre fed spectrograph for the combined focus of the VLT is under study. Two further instruments are under assessment: one for multi-object optical spectroscopy and an adaptive optics imager to make best use of the adaptive optics facility under development for UT4.

The VLT Interferometer (VLTI) brings the light from either the UTs or four 1.8-m auxiliary telescopes(ATs) to a coherent focus, enabling near- and mid-IR interferometry. Current instruments include the near-IR AMBER which combines 3 beams at once with a sensitivity at H of 7 with the UTs or 5 with the ATs at medium spectral resolution (low and high also available). Spectrally resolved visibilities are measured on baselines up to 100 to 200 m giving information on 2 milli-arcsecond scales. MIDI operates in the mid-IR and combines 2 UT beams with a sensitivity of about 1 Jy at 12 microns. Future instruments planned are a 4 beam thermal-IR instrument, MATISSE and astrometric instruments PRIMA and GRAVITY, whilst plans for a new 4-way near-IR beam combiner VSI are on hold.

Two new survey telescopes have also been constructed at Paranal: the VLT Survey Telescope (VST), a 2.6-m telescope for optical surveys, and the Visible and Infrared Survey Telescope for Astronomy (VISTA), a new 4.0m-class wide-field telescope, constructed by a UK consortium and funded via the UK Joint Infrastructure Fund (JIF). Final VISTA commissioning is now nearing completion and the start of ESO science operations is scheduled to commence on 30th Oct, 2009. Planned VISTA near infra-red surveys range from ultradeep surveys in small areas to surveys of the entire southern sky. Seven of the eight approved public surveys with VST and VISTA have a UK Principle Investigator.

The La Silla Observatory comprises the ESO 3.6-m, the 3.5m New Technology Telescope (NTT) and shared-time on the 2.2-m telescope which is on loan from the Max Planck Gesellschaft(MPG). La Silla operations have been restructured in recent years, leading to a more cost-effective, efficient observatory that continues to deliver high-impact, highly-cited science. While technical and logistical support is provided on site, no support astronomer will in general be available on site.

The 3.6m telescope has a single instrument permanently mounted at the Cassegrain focus. This instrument is a high resolution spectrograph; High Accuracy Radial velocity Planet Searcher (HARPS) for studies of extrasolar planets. The NTT has two instruments permanently mounted at the two Nasmyth foci: SofI, a near infrared spectrograph and imager including polarimetry and EFOSC-2 a optical spectrograph (including MOS mode) and imager including polarimetry. ESO access to the MPG 2.2m has been agreed until Mar 31, 2013. The ESO fraction of night 15% per year, with the remaining 85% shared between MPG(75%) and Chile(10%) as host country. There are two ESO supported instruments permanently mounted on the 2.2m; FEROS, a bench-mounted fibre fed high resolution Echelle optical spectrograph and WFI, a wide field CCD mosaic optical imager with a field of view of 34’× 33’.

ESO also provides access to the 10.4m Gran Telescope de Canarias(GTC) until 2012 through the accession agreement of Spain into ESO. A total of 122 clear nights are available for large programs (minimum request is 20nights) at a rate of up to 40 nights per year.

While E-ELT is ESO's overwhelming priority in the optical/infrared waveband for the foreseeable future, and the Director General will not countenance any expenditure that slows its development, the community has been pushing for a wide-field spectroscopic capability. As a result, a Call for New Instrumentation and large scale spectroscopic public surveys is imminent.

E-ELT

ESO are now in the advanced design stages of a 40m-class European Extremely Large Telescope (E-ELT), which will be the largest optical-IR telescope (0.36-24 μm) in the world. IR observations near the diffraction limit will provide images more than five times sharper than those from the JWST. When coupled with the 16-fold increase in collecting area compared to current telescopes, this will provide a dramatic increase in discovery power, enabling European scientists to address some of the most fundamental questions in astronomy and physics. The nine `Prominent Science Cases' identified by the E-ELT Science Working Group are exo-planets; stellar disks; initial mass function in stellar clusters; resolved stellar populations; black holes/AGN; the physics of galaxies; metallicity of the low-density IGM; the highest redshift galaxies; and dynamical measurement of the universal expansion.

The E-ELT Basic Reference Design was endorsed by ESO Council in December 2006, leading to the start of the telescope Phase B in Jan 2007. The UK has been a key partner in this activity, leading instrument studies and development of the science case, partly funded by FP6 and FP7 programmes, technology R&D in partnership with industry, and industrial design studies funded directly by ESO. STFC has invested £3.2M since May 2005 into targeted technology development, including participation in the initial instrumentation studies. In this phase, technology development has been focused on critical areas where UK research groups and industry can add significant value: large adaptive mirrors, adaptive optics simulation and on-sky validation and IR detectors.

If the UK aspires to take a major role in building and exploiting E-ELT, it must lead in the development of the instruments needed to do the science. UK groups currently lead the evaluation and further development of its science capabilities through a Design Reference Mission, and are developing and proving critical adaptive optics and instrument technologies. The aim is to maintain and expand UK leadership in instrumentation and adaptive optics, as well as develop opportunities for UK industrial participation as the project moves towards the construction phase from 2011 onwards.

Indeed, E-ELT provides a range of important opportunities for knowledge transfer, ranging from large deformable mirrors to novel IR detectors. The current R&D into large deformable mirrors has industrial partners (BAe Systems, Teer Coatings and ECM) and support from the Ministry of Defence through the Joint Grants Scheme. The study on applicability of novel IR detectors in astronomy has QinetiQ as a partner, and interest from Selex Systems Ltd. A Basic Technology research project on Ultra-precision Surfaces has resulted in development of a new facility for process development and manufacture of large optics in North Wales, driven by demanding E-ELT primary mirror segment requirements, but resulting in capability attractive to a range of industrial and space applications. In the wider context, several UK industries are involved in central E-ELT contracts on issues associated with technology proving (e.g. in prototyping construction of the primary mirror segments).

The recent ASTRONET Infrastructure Roadmap identified the E-ELT as one of Europe's two top-priority facilities for the coming decade, the other being SKA, and a construction proposal will be presented to the community in 2010, with the start of operations planned for 2018. The UK is one of the major partners in the project, involved in Phase-A studies for four E-ELT instruments, industrial studies for elements of the telescope design (e.g. the dome) and continued leadership and development of the science case.

There are several other competing development programmes working towards large telescopes in the 20-40m class. In the US, two projects (TMT, GMT) are under way. In Canada, ACURA has been formed, and is currently working with TMT to implement an ELT with major Canadian Fund for Innovation support. Japan, Korea, China, and Australia are also possible partners in TMT and/or GMT.

Gemini

The Gemini Observatory consists of two 8.1-m telescopes, the Gemini South telescope on Cerro Pachon in Chile, and the Gemini North telescope on Mauna Kea, Hawaii. The telescopes were designed to provide the best image quality possible from the ground together with the lowest possible emissivity, for optimal infrared observing.

Both Gemini telescopes are equipped with GMOS - workhorse optical imagers and multi-object spectrographs, which also have optical IFUs. Gemini North also employs Altair - a natural/laser guide star adaptive optics system which feeds a near-IR imager (NIRI) and a 3"x3" IFU (NIFS). Uniquely, NIFS is also equipped with a coronograph, designed for spectroscopy of extra-solar planets. Depending on instrument switching, Michelle - a mid-IR imager and spectrometer is also available, although demand is low. By 2010A it is expected that a repaired GNIRS (a cross-dispersed near-IR spectrograph) will be operating at Gemini North. Before instrument problems in 2007B, GNIRS was one of the most requested instruments on Gemini.

At Gemini South, together with GMOS there is a high-resolution near-IR echelle spectrometer (Phoenix), a mid-IR imager and spectrograph - TeRECS, and NICI - an near-IR coronagraphic imager designed to detect Jovian planets around nearby stars. GMOS remains the most requested instrument on Gemini-South. By 20010B it is expected there will be a new MCAO-fed near-IR imager and multi-object spectrometer (2'x6' FoV), FLAMINGOS-2 on Gemini South. The Gemini Planet Imager (GPI), with some UK participation, is expected to be commissioned in late 2010 or 2011. It is designed to obtain direct images and low resolution spectroscopy of young, bright, gas giant planets orbiting nearby stars. The GPI shares similar science goals to the VLT Sphere instrument, which will be commissioned on the same timescale. Unfortunately the Gemini Board have not taken up their options to progress beyond the study phase a number of high-profile instruments - PRVS, HRNIRS, GLAO and WFMOS – several of which had significant UK participation.

Membership of the Gemini Observatory also enables access to the 8m-class Subaru telescope, at a low level (3 nights/semester), through a programme of time exchange - a very popular option for wide-field imaging.

The current cost of membership to STFC is approximately £5.4M/yr, though this will not be sufficient to cover the full cost of future instrumentation upgrades. UK support is provided by the Gemini National Office in Oxford, at a cost of 0.4 M/yr.

ING (INT+WHT)

The ING is comprised of 3 telescopes: the 4.2m WHT, 2.5m INT and 1.0m JKT. The WHT is an alt-az mounted telescope and is equipped with nasmyth platforms able to support substantial instruments. The WHT was constructed in the mid 1980's and has developed a comprehensive instrument suite able to deliver observations at both optical and near-IR wavelengths. The WHT also has a natural and laser-guide star AO imaging and spectroscopy instrument suite. These instruments serve a broad user community (solar system to cosmology). It is expected that the high precision stabilized spectrograph, HARPS_NEF, will begin commissioning in 2010. This will be used for follow up of candidates from NASA's Kepler satellite in the search for Earth-like exoplanets. The WHT has also attracted many privately owned, specialist instruments. This includes SAURON, PNS, UltraCAM amongst others. The WHT AO infrastructure is to be used as an e-ELT AO testbed. Since its inauguration, the WHT has remained one of the UK's most over-subscribed telescopes (still a factor of 3).

The INT is a fork mounted equatorial telescope. It is equipped with a Wide field camera and cassegrain spectrograph. It has been used to conduct a number of wide-field surveys. Running costs for the telescope are extremely low, absorbing just 3% of the (current) ING budget (the cost to the UK in 2008 was 99.5K). The INT is one of the most productive 2m telescopes. The JKT has been withdrawn from service (to the UK community).

The UK share of telescope time on ING telescopes has been declining in recent years from 60 to 28%. This is in line with the reduction in the UK contribution (2009/10 0.8M/yr). As the support model for the telescopes has evolved the ING have combined their Student Education Scheme with visitor introductions on the INT to good effect. The UK share will further decline as Harvard University (the lead partner in the HARPS-NEF project) buys up to 50-60 nights per year (with a UK contribution of about 20 nights).

Liverpool Telescope (LT)

The Liverpool Telescope (LT) is a fully robotic instrument owed by the Astrophysics Research Institute of Liverpool John Mores University. It was constructed on La Palma using funds made available from the European Union and JMU. STFC currently provides operational costs (0.6M/yr) for the telescope in return for 40% of the available time (allocated through a PATT committee). The telescope became fully robotic in 2003. Down time on the telescope is generally around 3-5% - which is competitive with a classically staffed facility.

Using the faculty optical and IR imaging instruments the telescope executes proposals over all areas of science ranging from solar system objects to active galactic nuclei. The LT's robotic control makes it ideal for exploitation of the time domain and proposals are executed that require observations on all timescales from seconds to years.

In addition to the workhorse imaging camera, JMU have provided some novel instrumentation, such as RINGO which was built to detect polarisation signatures in GRB's. The RISE (high speed imaging camera) is heavily used by the UK Exoplanet community. The faculty integral field spectrograph (FrodoSpec) is currently being commissioned. JMU also have plans for a second generation, wide field, optical/IR imaging instrument.

The LT’s active outreach and schools program makes use of 5% of the available telescope time provided by JMU.

SuperWASP

The SuperWASP experiment originated amongst a group of UK universities with the purpose of detecting large extrasolar planets via the transit technique. As the problem required dedicated and novel equipment, the WASP consortium raised funds locally for the construction of 2 nearly identical facilities on La Palma (commissioned in 2004) and at SAAO (2006). The £1.5M funding for this came mostly from local SRIF awards. STFC originally supported the project at a low level through the grants line but in 2008 a Project grant was awarded (£0.38M/yr during 2008-10). This supports all aspects of the operations including improvements to the hardware and software infrastructure. The STFC award also provides support for the development of a public archive (along with interrogation tools). The WASP consortium have generated a number of highly cited exoplanet press releases over the last 2 years and generated much publicity from TV appearances etc.

Each facility has a field of view of nearly 500 square degrees and is designed to detect variations in stellar brightness of just a few millimags. A recent upgrade has led to a significant reduction in noise sources and hence significantly smaller planets are now detectable. WASP planets are amongst the brightest transiting planets and are therefore usable as targets on other facilities eg atmospheric studies with HST and, soon, JWST. Thanks to the STFC award, the WASP project is now the world leading source of bright transiting exoplanets (>30% of known transiting planets). This will continue even in the CoRoT/Kepler era - their fields of view are much smaller than SuperWASP and hence their candidates are, in general, much fainter.

MROI

The Magdalena Ridge Observatory Interferometer (MROI) is a near-IR (JHK) imaging interferometer being built in New Mexico. It will consist of six 1.4 m telescopes in a reconfigurable Y shape with baselines out to 350 m. The capital funding (~$70M) is mostly coming from New Mexico Tech. A team at the University of Cambridge has led the design of the system and is building the delay lines. The total STFC investment since 2002 has been £1.2M and a further £1.1M is required to take the project to completion for which 30 nights p.a. for 10 years would be available to UK astronomers. Together with St Andrews, an additional request to STFC has been made to build the science beam combiner at a cost of £2.1M.

Science input to the design was received from a broad team of UK astronomers. The design aims to deliver a sensitivity of 13.5 magnitude at H or K and model-independent imaging of targets at sub-milli-arcsecond resolution. In comparison to AMBER at the VLTI, this would be over an order of magnitude more sensitive, and 6-way beam combination allows for the recording of visibilities - and hence high-fidelity imaging - 5 times faster than AMBER. Low (R~35) and medium (R~300) resolution spectral modes will be available, with first light in 2011 and operation of the full array in 2014. Upgrade paths will be available for high spectral resolution, an extension to optical wavebands, and an increase to ten telescopes. The main science areas for the UK community are the imaging of planet formation and accretion phenomena in proto-planetary discs, mass-loss in evolved stars and the broad-line region in AGN.

UKIRT

The 3.8-m UK Infrared Telescope (UKIRT) is operated on behalf of STFC by the Joint Astronomy Centre. 15% of time on UKIRT is made available to the University of Hawaii in return for the lease of the Mauna Kea site. Recebtly, University of Hawaii agreed to commit half their time to UKIDSS observing in return for membership of the UKIDSS consortium. 18 nights per year are sold to a Korean research group and 8 nights peryear are sold to Japan. The continuing search for international partners, along with the withdrawal of the Cassegrain instrument suite in February 2009, reflects recent pressure to reduce UKIRT's operating costs. Currently engineering and operational costs are shared with JCMT.

Citations and publication rates for the UKIDSS near-IR survey of the northern sky show that UKIRT remains at the peak of its productivity. WFCAM, the wide-field survey camera behind UKIDSS, is currently UKIRT's sole operational instrument.

The completion of the UKIDSS survey is the highest priority for UKIRT over the next few years (to 2012). The science goals of UKIDSS are: the coolest and nearest brown dwarfs, young star clusters, high-redshift dusty starburst galaxies, elliptical galaxies and galaxy clusters at redshifts 1‹z‹2, and the highest-redshift quasars, at z=7. There would be demand for additional surveys beyond the present planned end-date of 2012. A further opportunity exists to exploit UKIRT's unrivalled performance by equipping it with a fibre-fed high-resolution spectrometer - the UKIRT Planet Finder (UPF). UPF will search for earth-mass planets orbiting in the habitable zones of nearby cool stars by measuring radial velocities via their near-infrared stellar spectrum. With an operating model closely integrated with that of WFCAM and scientific requirements perfectly matched to UKIRT's modest collecting area and high efficiency, UPF would maintain UKIRT as a productive facility beyond 2012.

JCMT

The JCMT is the world's largest single-dish submillimetre telescope. It is a partnership between the UK as owners (55%), Canada (25%) and the Netherlands (20%). The University of Hawaii has access to 10% of nights as a site tax. JCMT is a member of the RadioNet consortium, which offers transnational access to European astronomers. The management and operation of the facility by the Joint Astronomy Centre is widely viewed to be exceptional, with a current cost of £1.4M/yr.

The JCMT Legacy Survey will exploit the unparalleled mapping speed of JCMT's flagship instrument, SCUBA-2, as well as the HARP/ACSIS heterodyne imager. SCUBA-2 should be operational by the end of 2009 with a deadline for Shared-Risk Observing Proposals in late October. The Legacy Survey, which is open to all UK astronomers, comprises: SCUBA-2 All Sky Survey, SCUBA-2 Cosmology Legacy Survey, Nearby Galaxies Survey, JCMT Galactic Plane Survey, Gould Belt Survey, Spectral Legacy Survey and Debris Disk Survey.

The high-frequency receiver, RxW, provides access to, e.g., high-J lines of CO and has provided a glimpse of what ALMA will be capable of in the middle of the next decade. Membership of JCMT also offers access to eSMA, though the delivery of this option has been severely delayed and is now of little interest to the UK community.

The future of the international partnership needs to be reconsidered well before the current agreement expires, in 2012, and depends critically on the performance of SCUBA-2. There is a strong case for extending operations to 2014 to allow completion of the full originally conceived 5-year Legacy Survey. This would enable JCMT to map large areas of sky to the confusion limit and much of the accessible sky to a shallower level, thus providing the UK with a competitive edge in the early ALMA era.

JCMT must be judged against the 12-m Atacama Pathfinder EXperiment (APEX) and the proposed 25-m Cornell-Caltech Atacama Telescope (CCAT), though CCAT will not be completed until well into the next decade.

APEX

The Atacama Pathfinder EXperiment (APEX) is a modified VERTEX prototype 12-m ALMA antenna on the high-altitude Llano Chajnantor site in Chile. UK astronomers have access through ESO, which has a 27% stake. It is, or soon will be, equipped with heterodyne receivers in the 211--270, 275-370, 375-500 and 1250-1384-GHz windows, and with the 295-pixel LABOCA submm (870-um) camera. Artemis, a wide-field 200-

350-450-micron imager with 2048 bolometers, is expected to be commissioned in 2011.

CCAT

The 25-m Cornell-Caltech Atacama Telescope is to be built in the 2013-17 timeframe on an excellent high-altitude site for sub-mm observations in Chile, is designed to provide the wide-field complement in the era when ALMA becomes fully operational. The main scientific priorities are to carry out deep, wide-field surveys in the 200-450-micron range to unprecedented depth - this being a region critical to understanding the high-redshift Universe and how stars form and evolve - and to work as a `CO redshift machine', via a wide-field MOS. Although the UK is formally a partner in the CCAT project, our contributions at the present time are only through relatively small-scale design studies. A more serious commitment could be justified by the UK's heritage in submillimetre astronomy.

ALMA

The Atacama Large Millimeter/Submillimetre Array (ALMA) is currently under construction at an altitude of 5km in the Chilean Andes. ALMA is a global endeavour - a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile - an array of 66 reconfigurable antennas with a correlator capable of 1016 operations per second and receivers covering every atmospheric window between 0.3 and 9.6mm, providing an impressive combination of sensitivity, angular resolution, spectral resolution and imaging fidelity.

In the nearby Universe, ALMA will study the processes of star and planet formation, revealing the details of young, still-forming stars, and is expected to show young planets still in the process of developing. ALMA will also explore the complex chemistry of the giant clouds of gas and dust that spawn stars and planetary systems. Further a field, ALMA will study the first stars and galaxies that emerged from the cosmic dark ages.

UK astronomers played a key role in the development of the ALMA science case and the technological development that has made it a reality. Professor Richard Hills is the ALMA Project Scientist. Several UK groups are making key contributions to the water vapour radiometer calibration system, the data transmission system, the software that allows astronomers to plan and execute their observations, and the archiving system. The UK also hosts the European Front End Integration Centre.

UK astronomers have access to ALMA via the subscription to ESO. Time allocation procedures have yet to be hammered out, but a call for Early Science programmes will be made in late 2010 when the array is expected to have 16 antennas with receivers for bands 3, 6, 7 and 9 (3, 1, 0.85 and 0.45mm).

The ALMA support group at ESO HQ will provide archiving services, and some direct support to observers or proposers. UK, and other partners, have all planned for local support structures (ARClets) to aid in the expected large number of non-specialist users of this facility. The UK's ALMA Regional Centre (ARC) is based at the Jodrell Bank Centre for Astrophysics in Manchester and benefits from their interferometry experience. Without this Centre, UK astronomers would be at a disadvantage relative to astronomers in the US, other European countries, and Japan. The cost is £0.3M/yr.

In the future, the UK aspires to design and build the Band 1 (9.6mm) receiver system, and there is keen interest in the science possible in that waveband, e.g. wide-field unbiased surveys of redshifted CO(J=1-0) to complement those possible with E-VLA at lower frequencies and searches for prebiotic molecules in circumstellar disks.

e-MERLIN

e-MERLIN is the UK's array of six 25-32m radio telescopes with baselines up to 217 km operating at wavelengths of 1, 6 and 20 cm. Recent upgrades worth £8M have increased the sensitivity by a factor of 10 compared to the old MERLIN array, mainly through the use of broad bandwidth optical fibre connections provided by the telecommunications company Global Crossing Europe, as well as upgraded receivers and a new correlator. At 6 cm a further factor of two increase in sensitivity is achieved with inclusion of the re-surfaced 76 m Lovell Telescope on payment of a £2.5k per day access charge. This provides imaging at the microJy level on baselines that are similar to those that will form the core of the SKA. The combination of this sensitivity with an angular resolution (40 milli-arcseconds at 6 cm) that is 8 times that of the EVLA at cm wavelengths enables a wide range of science to be addressed as illustrated by the recent Legacy Programme awards. These will take up half of the available time and address topics such as galactic star and planet formation, star formation history and black hole growth in galaxies at low and high redshifts, AGN physics and dark matter distributions. The previously small user base for MERLIN has been expanded to 325 users from 20 countries for the e-Merlin Legacy Programme. First light fringes with e-Merlin have been achieved and full operations will start in 2010 for an initial operating period of up to 2014. Post-2014 e-Merlin could be seen as complementary to JWST, until the arrival of SKA-Phase 1.

JIVE/EVN

The Joint Institute for VLBI in Europe (JIVE) is the umbrella organization for the coordination of the European VLBI Network (EVN). UK participation in this organization currently costs STFC £100k/year. The EVN is the most sensitive VLBI network in the world (except for times when the GBT combines with the VLBA), with potentially the highest angular resolution when utilizing intercontinental baselines to China and/or South Africa. The extremely high angular resolution provided has allowed e.g. structural studies of extragalactic supernovae, high redshift radio galaxies and H_2O masers in the early universe. The EVN has also developed the first large-scale open e-VLBI system, in which the data are correlated in real time; the system can routinely correlate at data rates of 1 Gb/sec or higher. The e-EVN is recognized as a pathfinder to the long-baseline aspects of the SKA.

In a global context, the key competition comes from the VLBA, which is a VLBI array in the USA operated by NRAO. The VLBA is less ad-hoc than the EVN, but has not implemented e-VLBI. Several other smaller VLBI arrays are available across the world.

As well as technical coordination, JIVE provides user support (even at the level of assistance with writing proposals and analyzing data) and travel support for visitors (via European Trans-national access funding).

LOFAR(-UK)

LOFAR is a Dutch-led low-frequency (30-240 MHz) software telescope currently under construction and has issued its first call for proposals (with full capability to be offered by 2011). LOFAR is also the major pathfinder for the low-frequency component of the SKA, and the only major SKA pathfinder under construction in Europe. LOFAR-UK is a consortium of more than 20 UK institutions, the majority of which are university astronomy groups, which have contributed collectively enough money (~£1.2M), in combination with SEPNET (South-East Physics Network, funded by HEFCE) to buy a first LOFAR station for the UK. This station will be installed at Chilbolton, an STFC site, and LOFAR-UK are looking to STFC for commissioning and operations costs (approximately £300k / year initially), and have ongoing aspirations for further stations. PPRP did support the idea of STFC funding for a second station but the funding situation did not permit this. The return for the existing investment will be considerable UK involvement in LOFAR science, as well as training in the use of 'next generation' radio technology and the associated very large data volumes. LOFAR has six key science projects, *The Epoch of Reionisation*, *Surveys*, *Transients and Pulsars*, *Cosmic Rays*, *Solar* and *Cosmic Magnetism*. The UK consortium is involved in all six of these KSPs, with a particularly strong involvement (i.e. leadership) in *Surveys* and *Transients*. Starting in 2010, the ratio of guaranteed KSP to open time will be 90:10, evolving to >50% open by 2014.

In the context of world facilities, the VLA and GMRT offer observations within the LOFAR band, but will not be competitive in terms of sensitivity or fields of view (by more than two orders of magnitude). The MIT-led Australian Murchison Wide-field Array (MWA) is comparable to a short-baseline version of the high-frequency end of LOFAR, but will not have open access. The US Long-Wavelength Array (LWA) will operate at comparable frequencies to the low end of LOFAR but is not currently fully funded. In short there is no strong direct competition for LOFAR. In terms of science goals some are being tackled by other facilities (e.g. searching for the direct HI signal of Epoch of Reionisation), but many are unique to LOFAR. For example, in the context of deep and wide extragalactic surveys, nothing will supersede those performed by LOFAR prior to the SKA.

SKA

The Square Kilometre Array (SKA) is the primary goal for most of the world's radio astronomy community and is a transformational facility with an extremely diverse science case. The final SKA will consist of three separate types of receptor (a sparse low-frequency aperture array, a dense mid-frequency aperture arrays, and high-frequency dishes) sharing the same infrastructure (fibre links, computing). A choice will be made around 2011-12 between proposed sites in South Africa and Australia, both of which are currently constructing ~$200M GHz-frequency pathfinders (MeerKAT and ASKAP respectively). Following the site decision, work will begin on the *Phase-1* SKA, which is the initial deployment of the array, providing 10-20% of the array collecting area at intermediate frequencies. *Phase-1* should start to deliver scientific data from 2017 and be complete around 2018/19; it will be followed by *Phase-2,* the full deployment of low- and intermediate frequencies. The implementation of the highest frequencies, SKA *Phase-3,* up to 25 GHz or higher, will take place in the 2020s.

Key science areas addressed by SKA Phases-1 and 2 are: (1) Mapping the Epoch of Reionization through, for example, tomography of the neutral inter-galactic medium during the 'dark ages'; (2) Studying galaxy evolution, cosmology, dark matter and dark energy through a billion-galaxy HI survey which will provide an inventory of the atomic gas content of the Universe over at least half its age, and will constrain dark matter properties (e.g. neutrino mass) and dark energy through baryon acoustic oscillation and velocity-space-distortion measurements; (3) Determining the origin and evolution of cosmic magnetism through observations of Faraday rotation towards millions of background radio sources; (4) Performing fundamental physical measurements through strong-field tests of gravity using pulsars and black holes and, via pulsar timing, detecting and characterizing gravitational waves.

The SKA is being designed as a general purpose facility with the specifications being defined by the requirements of the key science areas. However, with a sensitivity of more than 50 times the EVLA, e-MERLIN or LOFAR and with a survey speed that will be up to 10^6 times greater than the EVLA it will be capable of a range of science far greater than that encapsulated in the key science areas.

The current funding model for the SKA requires, in 2007 Euros, €300M for Phase 1 and an additional €1200M for Phase 2. These costs are being refined through aggressive R&D by the global SKA team. The costs for Phase 3 will be determined in the next decade. The mid- to long-term funding proposal for the SKA within the UK is to continue the R&D programme at the current ~£3M/year level followed by a ramped uplift to ~£10M/year when the phase-1 construction begins in around 2014/15 and continuing at that level to 2019. The ~£2M/year from running costs for phase-I begin in 2017, rising to ~£3m/year in 2019.

The UK currently holds a leading role within the European programme of R&D development towards the SKA, with a current major focus on developing mid-frequency-range aperture arrays as well as electromagnetic design, signal processing and communication technologies. The international SKA Program Development Office is based at The University of Manchester and the EC-funded, but global, SKA Preparatory Study (PrepSKA) is led by the STFC. During PrepSKA, the UK will lead more technical work packages than other contributors across the full range of technologies to be employed by the SKA.

The technology required for radio astronomy is, amongst all fields of astronomy, most closely aligned with the commercial market; witness that radio astronomy R&D led directly to the development of wifi. The return to the UK for its potentially large investment in the SKA is already tangible, e.g. R&D contracts let to ~17 major companies including BAe, SELEX Galileo, IBM UK, Xilinx, Roke Manor (Siemans) as part of the SKADS programme; and ~£4M to Fujitsu-UK and Global Crossing for the installation and maintenance of the e-MERLIN dark fibre network, which is testing the technology required for the SKA. The continued funding of advanced SKA R&D will lead to further contracts and will place UK companies in an excellent position to bid for and win some of the major contracts that will be let for SKA construction. UK industry has already recognized the opportunity to capitalize on the advanced technologies being developed to create new market opportunities. Additionally, UK involvement in a project such as the SKA will attract the best and brightest students into UK universities thereby enhancing the training of people essential to the long-term health of the economy.

Theory, high performance computing and virtual observatory

Although the issue of science exploitation is beyond the scope of this review, it is worth stating that investment in facilities is pointless without strong support from the grants line for exploitation and theory. Many of the facilities discussed here involve huge data volumes and innovative techniques will be necessary to process these data. Both theoretical modeling and data processing are likely to generate demand for high performance computing. The international Virtual Observatory represents a way forward to tackle some of these data processing and data access issues. ASTROGRID is the UK contribution to the world-wide Virtual Observatory activity. Phase 1 of ASTROGRID development is complete, but further development and maintenance may be needed over the next decade.

Other facilities

Other projects and facilities in which the UK has an interest include:

DES (Dark Energy Survey): a US-UK-Spain-Brazil wide area galaxy optical multi-waveband photometric survey to estimate dark energy properties. DES will be carried out from late 2011 to early 2016, using 525 night of guaranteed time with a new 3 degree FOV CCD camera on the CTIO 4.0m Blanco telescope.. The DES:UK consortium includes UCL, Cambridge, Edinburgh, Nottingham, Portsmouth and Sussex. STFC supported UK participation by contributing to funding of the DES camera including a significant part of the DES optics work which is carried out by UCL. Funding is also provided by UK universities (e.g. Nottingham, Portsmouth).

PanSTARRS1: one 1.8m telescope, 7 square degree FOV, dedicated survey telescope located at Haleakala. In operation, 3.5 year survey combining all sky (30,000 square degrees) and medium deep surveys. The PS1 Science Consortium is funding the operations and data management costs for the 3.5 year science mission (2009-2012), including the UK institutes Edinburgh, Durham and QUB. Cost to the UK consortium is \$1.5M (there are no STFC operating costs).

PanSTARRS4: a proposed array of four 1.8m telescopes surveying whole sky at fortnightly intervals, allowing even larger galaxy surveys than DES and with additional science goals like near-earth asteroid (main funding justification) and supernova searches. The PS1 universities (Edinburgh, Durham and QUB) have aspirations to be involved either in PanStarrs4 or LSST. PS4 aims to run 2014-2024, and requires a further \$55M approximately capital costs for site development and hardware construction. The science consortium to fund and operate the mission has not yet been decided and opportunities exist for entry. The approximate operation costs per year is likely to be \$5-10M. It will be sited on Mauna Kea. The UK PS1 partners fund approximately 15-20% of PS1 operations costs, approximately pro-rata for the number of UK scientists involved. PS4 involvment for the UK community would need substantially more.

LSST (Large Synoptic Survey Telescope): This is a proposed 8.4m survey telescope to be sited on Cerro Pachon in Chile. Its science drivers encompass understanding dark energy and dark matter, a solar system inventory, transients and galactic maps. When fully commissioned it will be equipped with a single 3.2 Gpixel camera covering a 3.5 degree FOV. The camera will generate 20-30Tb per night. The UK could obtain access to this facility either as a single partner or through ESO membership.

SALT (South African Large Telescope): several UK universities (Central Lancs, Southampton, Nottingham, Keele, OU and Armagh Observatory) have formed a consortium to participate in this 10-m telescope, the largest in the southern hemisphere.

GTC (Spanish Gran Tecan 10-m telescope on La Palma): ESO provides access to the 10.4m Gran Telescope de Canarias(GTC) until 2012 through the accession agreement of Spain into ESO. A total of 122 clear nights are available for large programs (minimum request is 20 nights) at a rate of up to 40 nights per year.

Appendices

Appendix 2 shows publications and citations data for UK facilities, with selected international comparisons, taken from the study by Trimble and Ceja (2008). The publications are from the years 2001-2003, and the citations refer to the three years after publication. These give a snapshot from over five years ago, but may be of interest, at least for facilities which were well-established at the period being analyzed. Virginia Trimble has also undertaken, at our request, an analysis of publications from facilities for the period Jan-June 2008, and of their citations during the year following publication. This gives a much more recent snapshot of the impact of UK, and comparable international, facilities.

Papers that use data from more than one facility are assigned a fractional contribution. The new data for papers published in January-June 2008, and cited in the following 12 months, have been scaled so that they correspond to the same time period as the 2001-6 study. However we recognize this will not give as accurate picture as a 3-year compilation.

Appendix 2. Publications and citation rates of UK facilities, with selected international comparisons:

Facility	no. of papers 2001-2003	citations/paper next 3 years	no. of papers Jan-Jun 2008 x6	citations/paper next 12 mnths x3
8-m				
Gemini (2)	36.4	17.25	205.8	9.45
VLT (4)	345.5	16.49	834.6	9.75
Keck (2)	*365.5*	*23.33*	*357.6*	*16.77*
Magellan (2)	*27.6*	*17.39*	*92.4*	*12.45*
Subaru	*109.1*	*13.07*	*198.0*	*12.54*
4-m				
AAT	170.2	26.98	138.0	10.03
WHT	158.6	12.69	117.0	8.46
NTT	128.0	12.69	114.0	8.52
UKIRT	130.3	11.50	94.8	10.26
ESO 3.6m	117.0	10.90	68.4	10.53
KPNO 4m	*79.2*	*15.71*	*69.6*	*12.12*
CFHT	*123.8*	*15.07*	*228.0*	*12.00*
Palomar 5m	*57.8*	*12.53*	*77.4*	*9.75*
CTIO 4m	*96.0*	*12.48*	*76.8*	*12.42*
2-m				
INT	87.8	11.10	49.2	15.72
Liverpool Tel.			<24	
ESO 2.2m	60.9	11.02	<24	
Las Campanas 2.5m	*56.7*	*12.93*	*30.6*	*14.13*
U Hawaii 2.2m	*53.3*	*12.51*		
Calar Alto 2.2m	*49.1*	*11.34*		
Radio				
Merlin	56.2	8.9	26.7	12.81
EVN	27.0	7.6	42.6	8.04
VLA	*582.2*	*14.6*	*774.6*	*9.21*
AT/ATCA	*139.4*	*12.2*	*139.2*	*6.09*
VLBA	*105.2*	*11.0*	*103.2*	*9.06*
Westerbork	*61.3*	*10.5*	*66.9*	*7.17*
GMRT	*36.1*	*5.7*	*90.0*	*6.21*
Submm				
JCMT	178.1	18.1	159.9	13.95
CSO	*31.5*	*14.6*	*52.2*	*9.66*
IRAM 30m	*113.2*	*14.0*	*217.8*	*14.22*

[Data from V.Trimble, J.A.Ceja, 2008, Astron.Nachr. 329, 632; Trimble, 2009, pers.comm]

Appendix 3: Some selected responses to the GBFR Questionnaire

[Note that comments on impact refer to data from 2001-3.]

What other facilities/instruments should the UK be involved in?

- I cannot resist noting that the AAT has a higher impact per paper than any of the above; we should never have severed connections. Even a part-share would remain a much better use of UK money than e.g. the Liverpool Telescope or JIVE.

  I also have an interest in seeing a UK involvement in Subaru. Since Gemini has chosen not to pursue the WFMOS instrument, we should do this in direct partnership with Japan.

- How the UK cannot consider future ground based facilities such as CTA (the Cherenkov Telescope Array) is baffling. The STFC consultation documents states The Panel has been instructed not to include astro-particle, CMB or STP facilities in its review, yet two lines down it continues 'The ASTRONET Roadmap emphasizes that astronomy has become a multi-wavelength science, requiring front-rank facilities in all wavebands.' You cannot ignore a facility like CTA which addresses many of the key science goals listed above. Future facilities such as Alma and SKA will (not maybe) conduct multi-wavelength campaigns with CTA and satellites. It is crucial that the UK consider such a facility within its ground-based astronomy remit, if it truly wants to be a leader over the next 10 years in the areas outlined.

- The UK should consider expanding OPTICON funding so that it can have a pooled operation of ALL non-ESO European <4m telescopes (UKIRT, WHT, Calar Alto, CFHT, etc). This would allow each facility to find its own niche and avoid having to offer the full suite of instruments that each observatory is currently obliged to.

- The UK also has an opportunity to participate in the U.S. led Advanced Technology Solar Telescope which will see first light in 2016, approximately 3 years earlier than EST. While EST is being designed to provide a complementary facility to the ATST, ATST will have a somewhat broader scope, including the capability to measure the coronal magnetic field; a quantity that would enable many current models of energy storage and release in the solar atmosphere to be significantly constrained. The UK has been approached on several occasions to provide detectors and camera systems, as well as an adaptation of QUB's ROSA instrument as part of the focal plane instrumentation. Clearly a substantial role in both EST and ATST is unrealistic, but the possibility of some level of involvement that gives the UK access to both facilities should be considered.

- Good science will probably be done with the SKA pathfinder experiments. I'd rate both the SA and Aus versions of those as having a more significant potential future return than LOFAR-UK to the UK community not least in building international collaborations on a worldwide of the kind needed for the SKA era.

- It remains essential to have access to facilities to many facilities such as JWST, IRAM, VLA/GBT, ATCA etc that the UK does not pay directly for. STFC should remember that many of these facilities provide access to international PIs as a courtesy to the astronomical community, and actions that damage the UK's standing and reputation as a reliable and considerate collaborator will have many knock on effects that potentially imperil telescope access essential to complement STFC funded facilities and fully exploit their data.

Comments on strategic questions:

- A key instrument is becoming available on Gemini-South which was previously instrument-poor with respect to Gemini-North (which I believe does not have any new instruments planned). This is a near-infrared multi-object slit spectrograph (FLAMINGOS-2) and is absolutely key for probing the full redshift desert and for obtaining much needed kinematics at an epoch where stellar mass estimates have extremely large uncertainties. A study of the redshift desert is timely and would place the UK in the forefront of the study of galaxy formation and evolution and would play on particular UK strengths developed at lower redshifts (i.e.- detailed studies of elliptical galaxy kinematics).

- My other argument for maintaining access to 4m telescopes is follow-up of the massive harvest from GAIA. Amongst many things, GAIA will enable the discovery of vast numbers of objects that today are rare, and very likely entire new classes. GAIAs limiting magnitude is around V=20; much follow-up of these objects can be accomplished on 4m telescopes. It could also be carried out on 8m telescopes, but for bright objects, 4m telescopes are far better value for money. I think this is an argument for maintaining access to one or more 4m; in my view the WHT would be top of the list of 4m-class facilities for its aperture, optical instrumentation (better than the NTTs) and as a primarily UK-led facility. I think any consideration of the smaller telescopes needs to take GAIA into account. For much of galactic astronomy, GAIA will have the same importance as Hubble's Law for extra-galactic astronomy.

- It is very important that the UK maintains a steady flow of new instrumentation projects to be able to train and keep these skills in the UK community

- It is very important to have the infrastructure to support large ground based facilities. We need data centres to do the processing and archiving of the data efficiently or scientists will be spending all their time repeating the same processes as each other on vast amounts of data rather than doing science. Currently these data centres are having their budgets squeezed instead of

- The future of optical/near-IR astronomy is ELT supported by some smaller/niche instruments. The future of near-IR surveys is in space. The future of sub-mm is ALMA/CCAT. The future of radio is SKA. We just need an evolving path to get there.

- In the era of ELT/SKA the cost of facilities will approach that of major space missions. This will require taking the lesson from such missions that emphasis on the value to UK industry is vital.

- Whatever the final decision, the strategy will fail if the UK does not give all aspects of Human Resources the highest priority.

- Aside from M31 and M33, there are many key features of the Milky Way that can only be studied in the northern hemisphere. Thanks to SDSS (and eventually to Pan-Starrs), a multitude of debris streams and ultra-faint satellites have been identified in the north that require deep follow-up to understand their nature and origin, as well as details of the Milky Way potential in which they live. It will be many years before a similar census exists for the south.

- A key strategic issue which I would like to highlight is the vital role that theoretical research plays in the scientific exploitation of the facilities mentioned in this survey. UK theory is generally regarded as world class. Yet, this position is threatened by current STFC policies and priorities. One example is the appalling delay of a programme to provide HPC facilities for the UK theory community which, 3 years after 13 million pounds of direct government funding was promised to PPARC, has yet to be implemented

- However this must not be done on the basis of a priority list of what people like, or what facilities are voted most important in the drop-down list. It needs to be a strategic plan. For example, a move to completely shift to the southern hemisphere, with phased withdrawal from the North and significant reinvestment in the south (e.g. ESO, LSST, ELT, SKA) would not be unreasonable. Investment in ESO and ELT are the highest priorities. If it is at all possible, then some retention of a northern facility is highly desirable, but 2nd priority
- Buying influence early is dangerous if you cannot maintain commitments throughout the development phase, influence will be eroded and the earlier spend could be wasted

Comments on knowledge transfer and economic impact:

- e-MERLIN/JIVE/SKA has direct industrial links with digital signal processing and data transport (i.e. high-bandwidth networking). Knowledge transfer with UK

- It should be noted that much of the UK expertise in terahertz imaging comes through our technical heritage in the millimetre and sub-millimetre bands. Terahertz imaging is increasingly being used in airport security screening and has a number of healthcare applications.
  Data reduction and image processing algorithms are of value in areas such as medical imaging, e,.g. the work of Alan Heavens at ROE in reconstructing MRI images.

- A strong technical development base in imaging technology can be used to drive forward imaging applications, e.g. e2v technologies and applications in space hardware. As digital imaging becomes more and more pervasive in society (e.g. cameraphones) ways of dealing with images will become more and more important.

- There is significant opportunity for economic impact from synergistic working between radio astronomy and STP. The ionosphere-plasmasphere system is an important constraint on many radio-based technologies including radar surveillance of space objects, space radar monitoring of Earth's surface and satellite navigation. Thus there is world-wide interest in maintaining awareness of conditions in the ionosphere and plasmasphere through a complementary mix of advanced modelling and real-time measurements. Future radio astronomy systems can gain impact by contributing to that mix – and could also benefit by gaining access to a wider set of information on ionospheric conditions.

- Advanced Astronomical Instrumentation projects such as Adaptive Optics have a clear potential for industrial impacts. The AO work here in Durham has already generated two spin off companies: Starpoint and Durham Smart Imaging, the latter applying AO technologies to bio-medical imaging. We have also recently received CASE studentship funding with Culham to explore applications in Fusion Plasma diagnostics and begun discussions on common future requirements for real-time processing hardware with the UK advanced communications industry. This potential could be exploited further by expanding UK Adaptive Optics capacity (not just at Durham!) to enable both strong UK participation in forthcoming astronomical AO projects, but also to facilitate future spin-off and KT. Right now, existing UK astronomical AO capacity is fully committed to those current E-ELT AO projects with UK involvement (CANARY/EAGLE). Capacity expansion would be most timely and effective in an area of high potential impact. Perhaps a UK AO Centre, which could and probably should be geographically distributed, but able to tackle both future Astronomical and wider industrial projects in a fully coordinated way?

- Radio telescopes and facilities are an ideal and very accessible showcase for world-class astronomy being carried from the UK and Europe. These facilities

Appendix 4: Declarations of interest

M.Rowan-Robinson:
Deputy PI, Spitzer-SWIRE Survey
Co-I Herschel-SPIRE, Planck-HFI

R.Fender
PI LOFAR-UK, PI LOFAR Transients Key Science Project
UK representative LOFAR International Working Group
Co-I VOTC
Member SKADS Oversight Committee

D. Pollacco
P-I SuperWASP-N
Chair LT Oversight Committee
Chair ING Science Advisory Committee
PI PLATO
Past Chair LT TAC, ING TAC

R.McMahon
Ex-chair Gemini TAC
PI VISTA Survey
CoI DES
CoI ASTROGRID, VOTC
Grant holder LSST science case development
CoI VISTA data flow system

M.Hoare
Member SKA International Science WG
PI eMerlin Legacy Survey
Contributor MROI case
Chair JCMT Survey Oversight Committee

R.Ivison
ESO: STC member; instrument scientist for KMOS study phase
ALMA: Chair, UK ALMA Oversight Committee; European Science Advisory Committee; ALMA Science Advisory Committee
Gemini: instrument scientist, GMOS-S; project scientist, HRNIRS study phase
CCAT: UK Project Associate
JCMT: past Chair, UK and International TACs; past Chair, JCMT Survey Steering Group; SCUBA-2 GT team member; past member, JCMT Board
eMERLIN: Chair, Legacy Steering Group
LOFAR-UK: management council
FIRI: Cosmic Vision proposal, co-PI
Herschel/SPIRE: Associate Scientist
UK ATC staff