The OPTICON technology roadmap for optical and infrared astronomy

Colin Cunningham[a], David Melotte[a], Frank Molster[b]
[a]UK Astronomy Technology Centre, Science & Technology Facilities Council, Royal Observatory Edinburgh, Blackford Hill, Edinburgh, UK, EH9 3HJ
[b]NOVA, P.O. box 9513, 2300RA, Leiden, The Netherlands

ABSTRACT

The Key Technology Network (KTN) within the OPTICON programme has been developing a roadmap for the technology needed to meet the challenges of optical and infrared astronomy over the next few years, with particular emphasis on the requirements of Extremely Large Telescopes. The process and methodology so far will be described, along with the most recent roadmap.

The roadmap shows the expected progression of ground-based astronomy facilities and the technological developments which will be required to realise these new facilities. The roadmap highlights the key stages in the development of these technologies.

In some areas, such as conventional optics, gradual developments in areas such as light-weighting of optics will slowly be adopted into future instruments. In other areas, such as large area IR detectors, more rapid progress can be expected as new processing techniques allow larger and faster arrays. Finally, other areas such as integrated photonics have the potential to revolutionise astronomical instrumentation.

Future plans are outlined, in particular our intention to look at longer term development and *disruptive technologies*.

Keywords: Astronomy, Technology, Ground-based, Infrared, Optical, OPTICON, Roadmap

1. INTRODUCTION

Nearly all major advances in astronomy have been made possible by the introduction of new technology, from Galileo's discovery of the Jovian moons using his new telescope to the weighing of the black hole at the centre of our Galaxy using adaptive optics[1][2] Predicting which technologies will produce radical new capabilities and discoveries is difficult, but it is necessary to make our best attempts at this in order to make good use of limited resources for R&D programmes. In the European Union funded OPTICON network we have been developing a roadmap over the course of the Framework 6 and 7 programmes in order to guide decision making on which technologies to encourage through joint research activities.

1.1 OPTICON and the Key Technology Network

The Optical Infrared Co-ordination Network for astronomy brings together all the national and international agencies and organisations which fund, support, develop and operate Europe's facilities for optical and infrared astronomy, both night-time (classical astronomy) and day-time (solar astronomy). OPTICON provides a framework allowing joint actions to improve the quality of Europe's infrastructures, to train new astronomers, especially those from Central Europe, in modern new research methods, to develop innovative technologies to enhance research quality, to plan for future developments, and to work towards a strategic plan for Europe's future research infrastructures.

OPTICON is funded by the EU Framework 6 and 7 programmes. There is a similar programme called RadioNet covering Radio wavelengths.

Within OPTICON the Key Technology Network aims: to identify key technology needs for the future of European astronomy; transfer technologies into astronomy from other domains; encourage collaborative technology development projects and facilitate discussions on routes to further developments.

1.2 Why do we need Technology Development in Astronomy?

There are several ways that technology development can impact on the capability to do new astronomy:

- It can open new parameter space, which leads to new science. Examples are space telescopes providing access to new wavebands such as X-ray and Gamma-ray.
- It can reduce cost, and so make new capabilities and consequent new science affordable. Good examples of this are the introduction of segmented primary mirrors, which has enabled the 8m barrier to be surmounted at reduced cost per square metre, and the introduction of array detectors in the IR and submillimetre (submm) bands which enabled imaging and spectroscopy to become feasible at these wavelengths.
- It can reduce time to reach a science goal – for instance the introduction of multi-object fibre-based spectrometers enabled huge red-shift surveys which would not have been possible without such a multiplex gain.
- It can reduce the risks to a project; that is the likelihood of not delivering the performance needed to make science gains, or not meeting cost budgets or time constraints. The introduction of computer aided design and modelling is an example of new technology which reduces risk by making it easier to predict performance before a system is built. Another example is the use of new materials for large deformable mirrors to reduce the risk of accidental damage.

1.3 History of the roadmap and the KTN

Over the course of time the OPTICON Technology Roadmap has evolved through several iterations: the Smart Focal Planes Roadmap in January 2003; the OPTICON Technology Roadmap Version 1 in June 2006 and the OPTICON Technology Roadmap Version 2 in November 2008.

These have been strongly influenced by a variety of roadmaps created by other organisations including the NASA Advanced Telescope and Observatory Roadmap[3] the ASTRONET Science Vision [4] the ASTRONET Infrastructure Roadmap [5], the US Adaptive Optics Roadmap of 2008[6], and ESA's Cosmic Vision [7].

Several workshops were held, some focusing on specific technologies and others developing the more general roadmaps discussed above. The workshops held as part of the FP6 programme were:
technology roadmaps, IR detectors, smart focal planes, astrophotonics, adaptive optics, cryogenic material property measurements, optical technologies for ELT Instruments, and a joint OPTICON-ESA technology strategy meeting.

1.4 Disruptive Technology

From the beginning of astronomy as a science, discoveries have been made following the introduction of new technology. It is instructive to use the concept of disruptive technology, as it is applied to commercial markets [8] – where a new technology can completely change the market place. Disruptive technology can be defined as new technology that has a serious impact on the status quo and changes an entire way of doing things. For example, in the commercial world gramophone records were replaced by compact discs, without making fundamental changes to the market, but the next new technology, personal digital devices such as the iPod, resulted in major changes to the process of distributing music, with internet downloads almost replacing physical retail shops. Similar events can be seen in the history of astronomy:

1609	Precision glass lenses adopted to enable Galileo's telescope
1663 - 1672	James Gregory and Isaac Newton's new concepts for reflective telescopes
1864	Léon Foucault invented the silvered-glass reflecting telescope
1908 - 1948	The first large reflecting telescopes built by George Ritchey and George Ellery Hale
1975 -1990	Electronic array detectors to replace photographic plates in the visible and single detectors in the IR.
1975	The introduction of computer control enabling alt-az telescope mounts to become standard
1990	Space Telescopes
1990-1997	Segmented mirror telescopes, spun-cast mirrors and active optics using thin actuated mirrors.
1989-2010	Adaptive Optics

2. METHODOLOGY

In order to keep the roadmap tractable and fit in with the overall OPTICON programme, we have limited its scope to European optical and infrared ground-based astronomy, while recognizing synergies with space programmes and facilities at other wavelengths where appropriate. We have investigated new technologies from other research and industrial fields which can be applied in astronomy, taking note of the historical precedents such as IR detectors being adapted from military devices.

Our approach has been to use the proven Strategic Roadmapping methodology developed by Robert Phaal's group at Cambridge University [9] this is known as the *T-plan Approach.* This approach seeks to capture the interactions between the Market, Product(s) and Technology over time.

Mapping this approach to the astronomy domain gives us: Science Goals as the top level driver, analogous to the market; facilities in the middle, analogous to the products; and technology as the "bottom-up" driver.

Based around workshops using technical and scientific experts from the OPTICON partners, we developed a series of charts linking science goals to future facilities, and the enabling technologies and resources. We then used this to guide proposals for joint research activities within the OPTICON programme and to help bid for funding from other agencies such as the European Space Agency (ESA).

2.1 Learning from Workshops

We found that the Science & Facilities were well covered by the ASTRONET documents and each facility tends to have a well defined Science case. Synergies with Space astronomy were readily identified from ESA's Cosmic Vision, and by involving ESA personnel in the process. Inclusion of the funding streams was not helpful in this exercise which is about establishing technology requirements - although the output *can* be used to make a justification for funds. There is another "layer" required in the roadmap that of *instruments*; indeed looking at how technology development influences (and is influenced by) instrument choice is probably where the KTN can add the most value.

The workshops focused on the component-level technologies, for two reasons. Firstly, it was perceived that it was impossible to discuss the requirements of the systems level technologies without knowing the exact goals of the instruments where they would be found. One way to approach this impasse in the future could be to research the trends which have developed in historic instrumentation, and thereby to extrapolate to future requirements. Secondly, it was perceived that the systems level technologies would simply integrate the best available mature component technologies. This is a natural consequence of minimizing the risk of constructing an instrument.

There tended to be a focus on short term, well understood, step-wise developments & telescopes/instruments that are already planned. In the future, it will be helpful to focus on the next generation of facilities and radical new technologies.

2.2 Future approach

In the light of the experiences outlined above the approach taken for the next update of the OPTICON Technology Roadmap will be as follows. A small group will transcribe into the roadmap both: the key European facilities from existing documents (particularly the Astronet Infrastructure Roadmap); and the key planned instruments for these telescopes (using for example the ELT instrument studies). The subsequent workshop will then try to focus on the more medium and long term (> 15 years) timescales with *disruptive technology* ideas and how these might lead to new generations of instruments.

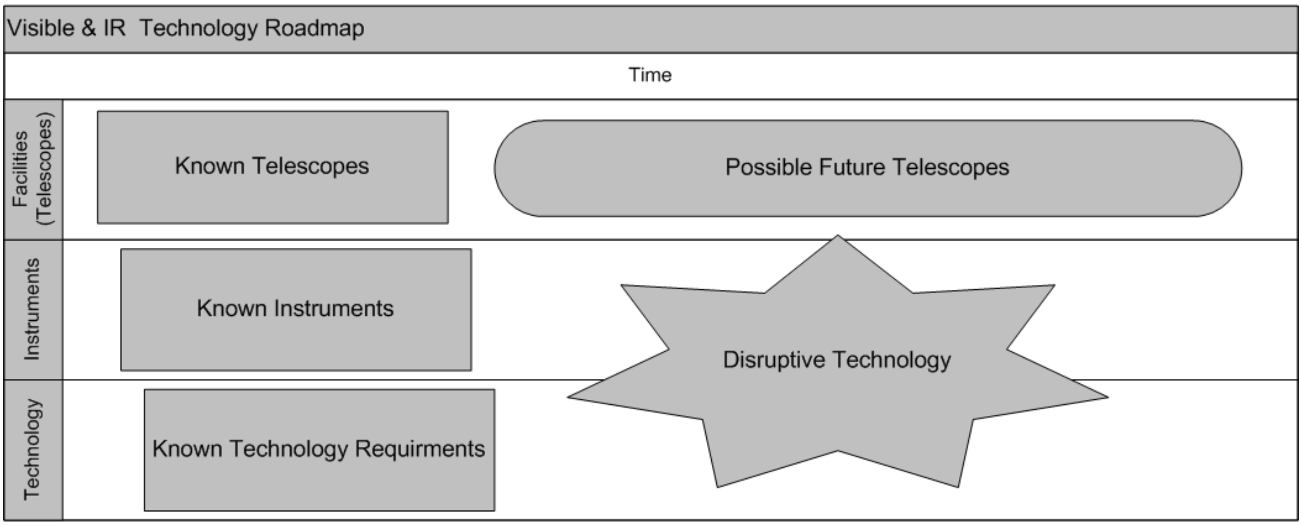

Figure 1 – Approach for the next update of the Roadmap

3. SCIENCE VISION

The scientific goals for infra-red and visible ground based astronomy form the driving force for future instrument development. The current scientific goals of the community have been catalogued through several other works. Most importantly, ASTRONET has compiled a comprehensive science vision for astronomy[4], which details the specific scientific goals to be addressed and this is outlined below. Other studies which outline the scientific goals for relevant areas of astronomy include the ESA Cosmic Vision [7] and the science case for the E-ELT [10].

Most of these studies, as should be expected, detail almost identical scientific goals:

- Exoplanets
- Galaxy Formation
- Black Holes
- Star & Planet Formation
- First Objects
- Dark Matter & Energy
- Astrobiology
- The Solar System
- Stellar Populations

3.1 The ASTRONET Science Vision

The ASTRONET Science Vision [4] and the ASTRONET Infrastructure Roadmap[5] (in the next section) are the guides for the development of European astronomy in the next 10 to 20 years. Technological development is at the heart of any of the future facilities. Flagship facilities like the E-ELT, also owe their high priority in the ASTRONET Roadmap to a long history of technology research and development. To maintain the vitality and competitiveness of European astronomy well into the next decade and beyond, it is necessary to allow for research and development in basic enabling technologies. These activities should be based on the science drivers and ideally be coordinated at a European level.

The ASTRONET Science Vision details the important science questions of today that we would like to solve in the next two decades. The main questions in astronomy can be divided in 4 groups:

1. **Do we understand the extremes of the Universe. with questions like:**

   How did the Universe begin? What is dark matter and dark energy? Can we observe strong gravity in action? How do supernovae and Gamma-ray burst work? How do black hole accretion, jets and outflows operate? What do we learn from energetic radiation and particles?

2. **How do galaxies form and evolve, with questions like:**

   How did the Universe emerge from its Dark Ages? How did the structure of the cosmic web evolve? Where are most of the metals throughout cosmic time? How were galaxies assembled? How did our Galaxy form?

3. **What is the origin and evolution of stars and planets, with questions like:**

   How do stars form? Do we understand stellar structure and evolution? What is the life-cycle of the Interstellar Medium and Stars? How do planetary systems form and evolve? What is the diversity of planetary systems in the Galaxy? Is there evidence for Life on exoplanets?

4. **How do we fit in, with questions like:**

   What can the Solar System teach us about astrophysical processes? What drives Solar variability on all scales? What is the impact of Solar activity on life on Earth? What is the dynamical history of the Solar System? What can we learn from Solar System exploration? Where should we look for life in the Solar System?

For all these questions methods are proposed to come to an answer. For some of them missions and facilities are already in the pipeline, for others new development activities have to be started. Development activities should start early in a project (or more generically, even before the specific project starts). An early outcome of the feasibility study of a certain item or aspect will help to make a well-founded go or no-go decision. The earlier in a project this can be done, the cheaper it will be in the end.

4. FACILITIES

The developments in telescope facilities will have a major impact in driving instrument development. In the short term, current facilities will directly impact the instruments which they are paired with, guiding any technology development which is required. Looking further ahead, future facilities such as the E-ELT will require a whole new instrument suite to fully exploit the capabilities of the telescope. These will have even more demanding technological requirements, and will drive technology development over long timescales.

Although current facilities already contain suites of instruments, there is the potential for new instrumentation as part of a facility upgrade path.

The table below lists both current and future major facilities to which European countries will have significant (or at least, some) access. A more detailed overview of these facilities can be found in the ASTRONET Infrastructure Roadmap [5]

	Current Facilities	Future Facilities
Key Facilities	Gemini – second and third generation instruments VLT - Third generation instruments VLTI – Second generation instruments GTC – Second generation instruments	E-ELT – First and second generation instruments Kilometre Optical Interferometer (KOI) Antarctic observatory
Other Facilities where Europe has access	SALT LBT Subaru 4m telescopes (UKIRT, VISTA etc) Pan-STARRS CHARA array MROI	Special purpose small telescopes Other ELTs LSST

Table 1- Important Facilities for European Astronomy

5. OPTICON TECHNOLOGY ROADMAP

5.1 The Combined Roadmap

A roadmap of the technology requirements for astronomical instruments has been produced. The roadmap shows the expected progression of ground-based astronomy facilities, the funding resources available and the technological developments which will be required to realise these new facilities. The roadmap highlights the key stages in the development of these technologies.

In some areas, such as conventional optics, gradual developments in areas such as light-weighting of optics will slowly be adopted into future instruments. In other areas, such as large area IR detectors, more rapid progress can be expected as new processing techniques allow larger and faster arrays. Finally, other areas such as integrated photonics have the potential to revolutionise astronomical instrumentation. Adaptive optics technologies are not included in this roadmap as they were covered in the Adaptive Optics technology roadmaps developed in 2008.

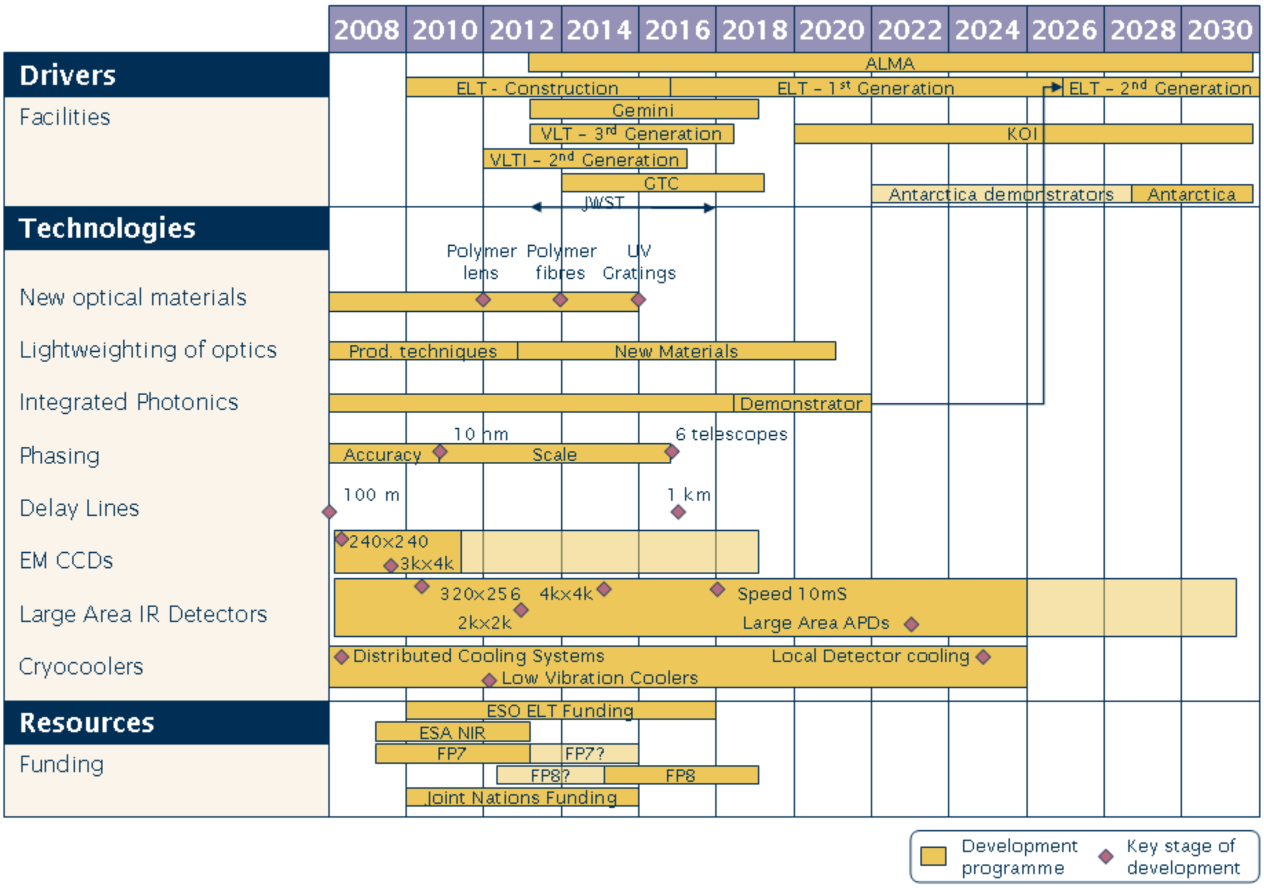

Figure 2– The OPTICON Technology Roadmap

5.2 Key instrument technologies identified

<table>
<tr><th>Optical Technologies</th><th>Interferometry</th><th>Detectors</th></tr>
<tr><td rowspan="3">Multi-Object Spectroscopy
Integral Field Spectroscopy
Fourier Transform Spectroscopy
Atmospheric Dispersion Correction
Reflective and refractive optics
Dispersive optics
Polarization Optics
Optical Coatings & Filters
Active Optics
Integrated On-Chip Spectrometers
Optical Connections
Fibres</td><td>Beam Transport & Delay Lines
Control Systems, Metrology & Phasing
Detectors
Beam Combination
Spectral Coverage</td><td>CCDs
IR detector arrays
Energy Sensitive Detectors
Single Photon Devices</td></tr>
<tr><th>Cryogenics</th><th>Cryogenics</th></tr>
<tr><td>Cryocoolers
Cryostats
Cryo-Materials
Cold Electronics
Cryo Mechanisms
Wiring</td><td>Mechanical Structures
Simulation
Calibration
Instrument control</td></tr>
</table>

Table 2 – Key instrument technologies

Further details on many of these technology areas are given in the OPTICON report [11]. The most comprehensive sections on optical technologies and detectors are reproduced here.

5.3 Optical Technologies

Optical technologies form a key part of any instrument for optical and IR astronomy. Relevant technologies range from system level, e.g. multi-object spectroscopy, to the component level, e.g. reflective and refractive optics. There is a general drive towards larger optics, which allow greater resolutions (spectral and spatial) or a wider field-of-view, but this is counterbalanced by the larger mass of these optics. Larger optics require improvements in manufacturing techniques, while novel materials have the potential to reduce the mass. Finally, novel approaches, such as integrated photonic devices, have the potential to alter the existing landscape, by achieving high resolutions without extremely large optics.

Multi-Object Spectroscopy

Multi-object spectroscopy is a system-level technology which allows one to simultaneously obtain spectra of multiple objects. There are three approaches currently in use; multi-slit systems, fibre-based systems and pick-off mirrors.

Multi-slit systems use either laser cut masks, or micro-opto-electromechanical systems (MOEMS) to select objects from a complex field. The whole field is imaged onto a spectrometer, resulting in separated spectra from each object. General improvements allowing larger optical fields to be imaged will be of interest, such as larger optics. Digital micro-mirror arrays have been developed with OPTICON assistance [12], and allow masks to be generated in situ. This technology offers some advantages as an alternative to the MOEMS shutter arrays developed for JWST NIRSPEC [13]. Fibre-based systems image the optical field onto multi-mode fibres, which are placed at selected locations either manually or automatically. These fibres then transmit the light to a spectrometer, so that spectra are obtained from each object. The fibres are either placed manually or by robotic means. Advances in fibre technology, described below, will benefit these systems.

Pick-off-mirror systems use small mirrors in the image plane to select objects of interest from the field, sending the images to separate spectrometers.

Integral Field Spectroscopy

Integral field spectroscopy allows selected regions of the optical field to be reformatted so that spectra can be taken simultaneously of each spatial element of the field. Three designs can be used to achieve this: Fibres or fibre-bundles, lenslet arrays, or image slicers. Of these, image slicers are currently believed to be the key technology, as this allows efficient smaller instruments.

Fibre-bundles will benefit from advances in fibre technology, lenslet arrays from the manufacture of plastic optics and image slicers from better precision manufacturing and metrology techniques.

Fourier Transform Spectroscopy

Fourier transform spectroscopy is a system-level spectroscopy which varies the length of an optical cavity to separate the frequency components of an image over time. This allows a spectrum to be obtained. Although this technology is used in some space instruments, it is of limited use for terrestrial astronomy.

Atmospheric Dispersion Correction

Atmospheric dispersion correction removes the distortions introduced by light propagating through the atmosphere at non-zenith angles. These distortions are dispersive and refractive. Current systems use matched pairs of prisms of up to 300mm in size. Larger sizes of optics (up to 1m) will allow corrections over a larger field.

Reflective and refractive optics

These optics are a part of any optical instrument. While many optics are commercially available, there are serious issues with the production of large optics over 1m. In particular, blanks for the IR in this size are difficult to obtain. Generally, reductions in the mass or cost, or improvements in the speed of manufacture would be beneficial. For small optics, the reproducibility is a key issue.

Technologies which could impact the manufacture of these optics include processing techniques (e.g. for aluminium surfaces), light-weighting, the development of new optical materials which allow better replication, and GRIN (Graded Refractive Index) lenses.

Dispersive optics

Dispersive optics spatially separate light according to its wavelength. Current technologies are gratings, volume phase holograms and prisms. Efficiency for gratings is currently limiting in the UV and thermal IR (aim is to achieve >80%), but not in the visible. Larger effective sizes will allow better spectral resolution, and this can be achieved either through larger gratings, or by embedding the gratings in a medium of higher refractive index.

Improved replication and better fabrication of grating mosaics will be beneficial.

Polarization Optics

Polarization optics alter the polarization of light, or separate and combine polarizations. Currently, telescope designs degrade the polarization information of the incoming light. Compensatory optics could potentially correct this, as could better telescope design. Size is a key issue for large birefringent optics as they are difficult to manufacture. Novel birefringent materials would be of great use. Polarization gratings are a relatively new technology which can achieve high efficiencies.

Optical Coatings & Filters

Optical coatings are used to coat surfaces with either metallic or dielectric coatings to produce a reflective surface, or a wavelength selective element. Filters may additionally use a frequency selective absorptive element. Coatings for extreme angles of incidence are difficult to produce.

Increased size, efficiency and wavelength range together with improved temperature stability and reduced coating distortion effects would be beneficial. This could be achieved through novel manufacturing methods or novel materials.

Active Optics

Active optics consist of optical surfaces which can be moved or deformed on timescales greater than 1s to deal with thermal or gravitationally induced errors. Current technologies are not currently limiting, but there are some barriers to adoption within instruments, where improvements to actuators would be beneficial, as well as the associated metrology systems and modelling tools.

Integrated On-Chip Spectrometers

A miniaturised complete spectrometer on a chip would enable great simplification and increased functionality of multi-object instruments, and is seen as the key novel technology for instrument design. Current designs plan to collect the light from objects of interest in multi-mode fibres, and send these to an integrated photonic device. This device would convert the multi-mode input to single-modes, pass each of these through a spectrometer and detect the signal on a single integrated linear array.

It is also be possible to suppress OH sky emission in the single mode stage, using fibre Bragg gratings [14].

Development is targeting 2018 for inclusion in the Second Generation ELT instruments.

Optical Connections

Optical connections allow switching between many optical channels, each contained in fibres. Ideally, one would like to send any combination of input in *n* fibres to any combination of *m* output fibres ($n>m$). Telecoms technologies can already do this for single-mode systems, but this needs to be extended to multi-mode for it to be applicable for astronomy.

Fibres

Optical fibres can be used to transport light efficiently. Current systems are efficient in the telecoms wavebands, but less efficient in the Infra-red. Improvements in wavelength range and cryogenic properties would be beneficial. Photonic crystal fibres could be a key technology, as they introduce no dispersion.

Multimode fibres cause a degradation in etendue (focal ratio degradation) on transmission and materials which would reduce this effect would be beneficial.

5.4 Detectors

In the period 1975 to 1990 developments in astronomical technology and the resulting observations and science were dominated by the increasing linearity, size and sensitivity (as well as the reducing cost) of Charge Coupled Devices (CCDs). In the last couple of decades attention has switched to other wavelengths and in particular the Infrared with perhaps the most important development thread being the desire for “CCD-like” IR detector arrays. There is also a wide variety of possible developments of superconducting devices which can measure the energy of incoming photons.

CCDs

Charge Coupled Devices operate by incoming photons promoting electrons between energy bands in suitably doped silicon. The energy band gap corresponds to a wavelength of 1.1 μm and therefore CCDs cannot be used at longer (NIR) wavelengths.

CCDs already offer the astronomer high quantum efficiency, linearity and large array sizes so it seems unlikely that there are many fundamental developments to be made in this area, although cost reductions are always in demand. Array sizes of around 6kx4k are already possible and going to much bigger arrays is likely to produce yield issues that would adversely affect cost.

However there are some niche developments (described below) of interest.

Electron multiplication CCDs (also known as EM CCDs or L3CCDs) contain a gain register in which the number of electrons is increased by means of impact ionization. This is useful for detection at low light levels (at higher light levels the stochastic nature of the multiplication process effectively reduces quantum efficiency). In principle this register could be added to any size or geometry of CCD, the main issue is cost.

It would be convenient for certain telescope geometries to have a curved detector to be used in a curved focal plane. With current technology it is estimated that a 5m radius of curvature might be possible. Curvature (say approx 300mm concave radius of curvature) would be required to be useful in most telescopes.

IR detector arrays

Because of the 1.1 μm cut-off in Silicon most IR detector arrays use a detector wafer constructed from some other semi-conductor and Indium bump bonded to a Silicon Read-Out integrated Circuit (ROIC). This “hybridisation” is necessary to make use of the conventional (Silicon based) solid state electronics in the readouts. The problem with hybridisation is that differential thermal contraction can cause high stresses when the detector is cooled. In addition it is suspected that the bonding process itself can introduce internal stresses which may be responsible for reliability issues. The semi conductor most commonly used for the detector is Mercury Cadmium Telluride (HgCdTe or MCT). The MCT is normally grown onto a substrate of Cadmium Zinc Telluride and this can limit the size of array which can be produced.

The main issues facing European astronomy are the ability to source detectors within Europe and the size of the detector available.

Currently the main suppliers of IR detectors to Astronomy are Teledyne Scientific Imaging, based in the US and to a lesser extent Raytheon also based in the US. This is of concern to European funding organisations such as ESA (who have a formal policy of sourcing within member states where possible) and ESO (who also try to source within Europe). As future space and ground based telescopes are likely to need significant numbers of IR arrays there is a strong desire to develop a European manufacturer. This would also ensure continuity of supply which could be threatened by any change or reinterpretation to the ITAR regulations, since the detector technology used by Astronomers is essentially the same as that used by the military. ESA are making a considerable investment (€8M over the next 4 years) into IR detector and readout controller development in Europe, the aim being to develop European suppliers as well as addressing the size limitations.

The ability to create larger arrays is important since the alternative of creating "mosaics" has several limitations as the required detector sizes get larger. Currently array sizes of 2k x2k and above are possible from US sources but not yet from Europe. Firstly however good the design there will always be gaps between the arrays, this is not a great problem for imaging since the telescope can simply be moved but it creates problems for spectroscopy. Secondly the complexity and cost of wiring, integrating and individually characterising many arrays can become prohibitive. Thirdly the mechanical positioning of large numbers of arrays in a mosaic can be challenging, for instance a flatness specification of ~10-20 µm can be difficult to achieve. Sizes up to at least 4k×4k are required.

In an attempt to address the above two issues the following technologies are being developed: Selex (European) are using a Gallium Arsenide substrate to grow the MCT onto and QinetiQ (European) are developing a way to grow MCT islands directly onto the Silicon ROIC. This latter non-hybridised approach could bring benefits in persistence, cost and reliability but the fill factor needs to be improved.

For many years it has been suggested that the drive to produce ever faster processors might lead the microprocessor industry to start using Gallium Arsenide (which allows a higher transistor switching speed) or other semiconductors. Were this to be the case then it might open up the possibility of a CCD (with detector the same material as ROIC) which operates at IR wavelengths. However currently "Moore's Law" is being maintained with the use of Silicon and there is not sufficient resources to develop a new semiconductor technology for Astronomy alone.

Energy Sensitive Detectors

These are difficult to use at visible and IR wavelengths. The best current performance using superconducting tunnel junctions only provides spectral resolution (R) of about 30 [15]. Improvement to R~200 could result in a completely solid state low-loss spectrometer.

Possible technologies include:

TES (Transition Edge Sensors) is currently the best candidate. ESA have demonstrated R~25 at 500 nm but as R is proportional to √E it will be harder to get good resolution at longer wavelengths.

KIDs (Kinetic Induction Detectors) are not currently available under 20 microns however they have potential for the future, especially for longer wavelengths. They consist of a series of resonant cavities, when a photon is absorbed it changes the resonant frequency and the signal on resonance peak changes. Many cavities can be read simultaneously, as they are detuned from each other.

Nanowires are currently at a very early stage of development but they may be of use in the future.

Fast APDs

Avalanche Photodiodes are high gain photo detectors. Faster APD arrays would enable high time-resolution spectrometry and polarimetry.

Multi-band QWIPs

Quantum Well Infrared Photo-detectors operate by having incoming photons excite electrons to a higher energy band within a quantum well. They have a very narrow spectral response. Multi-band QWIPs give greater spectral range by integrating several QWIP stacks into a single array structure. Multi-band QWIPs exist now but have not been used for astronomical devices. It may be possible to develop these by 2014.

Single Photon / Photon Counting Devices

Possible technologies include:

Single-Photon Avalanche Diodes or *SPADs* can be used for photon counting. This has been explored in the QuantEYE concept study.

DROIDs (Distributed Read Out Imaging Devices) are position and energy sensitive Superconducting detectors. At its simplest a DROID consists of a1-D linear absorber with a TES at each end. When a photon strikes the absorber the sum of the TES signals gives the energy of the photon and the difference gives the position. This can be extended to a 2-D surface with readouts at corners. Thus you can get large area detectors without the requirement for separate readouts for each pixel.

Quantum Dots are a young technology with potential in photon detection.

5.5 November 08 Roadmap Contributors

The roadmap was compiled by Robert Pfab and Dave Melotte of the UKATC using the input from the contributors:

Jeremy Allington-Smith (Durham University); Colin Cunningham (STFC - UK ATC); Gavin Dalton (STFC – RAL); Tim Gledhill (University of Herefordshire); Pierre Kern (LAOG); Didier Martin (ESA); Frank Molster (NOW); Suzanne Ramsay (ESO); Lars Venema (ASTRON); Martyn Wells (STFC - UK ATC); Adam Woodcraft (University of Edinburgh); Fillipo Zerbi (INAF-Brera).

6. OUTCOMES FROM THE OPTICON KTN PROGRAMME

The roadmapping activity within the OPTICON Key Technology Network has stimulated several important new activities in Europe. Some examples are:

6.1 AstroPhotonica Europa

The application of photonics in astronomy was highlighted at one of the first OPTICON roadmapping workshops in FP6. This topic has been taken up as a workpackage in OPTICON FP7, as described in a paper in this conference by Jeremy Allington-Smith [16].

AstroPhotonica Europa is a partnership to exploit photonic principles for astronomy. The primary goal is to make instruments for Extremely Large Telescopes affordable and practicable by exploiting photonic principles. It is based around the principle of adapting devices and techniques developed by the telecommunications industry. It acts as a coordinating focus for many activities funded outside the OPTICON programme, in particular the new innoFSPEC institute in Potsdam and the concentration of novel photonic developments in Sydney . Examples of devices and techniques under development are miniature photonic spectrometers, selective fibre filters (for example for OH suppression), and 3D beam combiners for interferometry.

6.2 Near IR Arrays

Another successful workshop with significant outcomes was held by the OPTICON KTN on IR arrays in the summer of 2008. Representatives from instrument building teams, industry and the agencies (both ESA and ESO) attended and came to the conclusion that significant capability was available in European industry and was ripe for investment in order to take forward technology developed for military applications into astronomy. It was seen that the instruments envisaged for both the ESO E-ELT programme and ESO's Cosmic Vision needed European development of both science and wavefront sensing detectors. Particular needs were for large area, lower cost but high performance science detectors, and fast low-noise IR detectors for natural guide star wavefront sensing.

As mentioned earlier, ESA have started industrial studies on HgCdTe IR arrays based on alternative substrates to the conventional CdZnTe, and offering potential advantages in array size and integration with read-out electronics. Also, ESO have placed contracts with Selex-Galileo to demonstrate IR avalanche-gain arrays for wavefront sensing.[17]

6.3 William Herschel Telescope Test-bed

Right at the beginning of the OPTICON KTN activities, we concluded that there was a real need for a cost-effective test-bed where prototype instruments and novel devices could be tested on-sky. We highlighted that the William Herschel Telescope on La Palma was an ideal candidate, with four key advantages:

1. It has excellent infrastructure, including two large Naysmith platforms fitted with experimental chambers
2. The telescope performs extremely well
3. It is conveniently situated for access by European development teams
4. The telescope board encourages this important role for the WHT

Following this conclusion, several proposals were developed for experiments and test facilities on the WHT, and OPTICON support under FP7 gained for a Multi-Object Adaptive Optics on-sky demonstrator: CANARY [18]. It was designed to use the existing Rayleigh laser guide star (RLGS) to construct a 10:1 Scale model of the E-ELT, making use of the fact that the RLGS can be gated to generate a guide star at a range of altitudes. Thus it can form a GS at one tenth of the Sodium layer height, corresponding to the fact that the WHT aperture is on tenth of that of the E-ELT. Of course, it is not a perfect scale model, as we cannot scale the atmospheric profile. However, it will be a very valuable proof-of-concept for MOAO in the configuration envisaged by the EAGLE concept [19]. It will also provide experience of real-time control techniques and calibration in a realistic environment, significantly de-risking the EAGLE project.

There are also proposals to take CANARY forward as a general purpose test-bed for laser guide star based adaptive optics systems and concepts.

7. OPTICON KEY TECHNOLOGY NETWORK: OBJECTIVES AND FUTURE

7.1 OPTICON Key Technology Network: Objectives Achieved

Objective	How achieved
Identify key technology needs	IR Detectors, Large Optics, Astrophotonics, Adaptive Optics components and systems, Smart Instrument Technologies
Look for opportunities which technology developments in other sectors provide for astronomy	Astrophotonics, IR Detectors
Encourage European collaborative technology development projects	WHT Test-bed, Astrophotonics, Smart Instrument Technologies, Adaptive Optics
Provide a forum for discussing potential routes for further development	Through 16 Meetings & Workshops

Table 3– The OPTICON Key Technology Network Objectives

7.2 Workshops in OPTICON FP7

The programme for FP7 will consist of several workshops focused on particular technology areas and then later a workshop to update the roadmap with the emphasise being on disruptive technologies as described earlier.

- Position sensing – held in Edinburgh on 21st June 2010
  - 11 attendees from UK, Netherlands, France, ESO and Switzerland, including 5 from industry
  - Aim: to identify common challenges and look for new solutions from industry offering higher performance or lower cost
  - Concentrated on ELT mirror segment position sensing and cryogenic instrument rotating mechanism sensing
- Polarimetry techniques and devices – to be held in Spring 2011, organised by Frank Molster & Christoph Keller
- Deformable Mirrors
  - Aimed at reviewing status of European technologies and encouraging further collaboration
- High Performance Real-Time computing
  - Aimed at encouraging collaboration with industrial partners and SKA
- Disruptive Technologies (such as energy sensitive detectors)

Anyone wishing to contribute to these workshops should contact the authors: (Colin.Cunningham@stfc.ac.uk; dave.melotte@stfc.ac.uk) and molster@strw.leidenuniv.nl

8. SUMMARY

Advances in technology are vital to ensuring the success of future astronomical telescopes and instruments. The OPTICON KTN provides a useful forum for identifying what the critical technology needs are for the future, examining technology from other domains and building collaborations for the timely development of technology. The OPTICON Technology Roadmap has been a valuable tool to facilitate and record these discussions.

Examples of technologies which have been identified as being of particular importance include adaptive optics, multi-object pick-off devices, integrated photonic spectrometers, and NIR detector arrays.

The next revision of the roadmap will focus on disruptive technologies which have the potential to revolutionise astronomy in the longer term.

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