Comments and responses for Ofcom CFI 'Strategic review of satellite and space use of spectrum'

Submitted by Jodrell Bank Observatory on behalf of STFC and the UK radio astronomy community.

This response is provided by Jodrell Bank Observatory, University of Manchester, on behalf of the UK radio astronomy community and in consultation with the Science and Technology Facilities Council (STFC), as the leading funder of radio astronomy in the UK and the body responsible for the payment of associated licences for Spectrum Protection, via Ofcom. JBO operate the 76-m Lovell radio telescope, two other radio telescopes on the Jodrell Bank site and the e-MERLIN array in the UK. E-MERLIN is a national facility operated on behalf of the STFC and used by almost all university astrophysics groups in the UK, as well as a large international scientific community. The Royal Astronomical Society has just given its 2015 Group Award to the e-MERLIN team.

e-MERLIN is an array of 7 radio telescopes across the UK, with a maximum separation of 217km, producing radio images of the sky at comparable resolution to the optical images from the Hubble Space Telescope. Its key science programmes, being conducted by UK and international teams, include the detection of rocky material in the process of planet formation; the physical processes of star-formation in our own galaxy; the evolution of galaxies and the role of black holes at the centres of galaxies; the distribution of dark matter and the nature of dark energy.

The Lovell telescope remains the 3rd largest fully steerable radio telescope in the world. It has a highly productive science programme as a single dish in addition to taking part in national, European and global networks.

The main research programme for the Lovell Telescope involves precision timing of pulsars to carry out experiments in general relativity and as part of a global effort to detect gravity waves. Observations with the Lovell Telescope provide an unprecedented database of pulsar timing information spanning over 40 years which has yielded new insights in the timing behavior of pulsars.

Ground based radio astronomy relies on the use of passive and protected bands for this unique scientific research. Any reduction in the degree or scope of protection would have a major impact on the ability of the UK and international scientific community to continue this research.

Jodrell Bank is also a prominent visitor destination, attracting over 160,000 visitors/yr to a new and expanding Discovery Centre (separately managed by The University of Manchester) and offering unique access to a working scientific facility. The site also hosts the global headquarters of the SKA Organisation.

Radio astronomy experiments have been carried out at Jodrell Bank since 1945 and the combination of its historical and current importance for radio astronomy is the basis for its shortlisting as a potential World Heritage Site. The Discovery

Centre has just been awarded £12M by the Heritage Lottery Fund for new facilities, showcasing the historical development of radio astronomy at Jodrell Bank.

Other UK radio astronomy facilities include LOFAR (a low frequency aperture array station at STFC's site at Chilbolton, Hampshire, which is used in conjunction with the LOFAR array in the Netherlands, France, Germany and Sweden) and AMI, a small 15 GHz array of dishes at Cambridge University.

Q1. Do you have any comments on our approach to this review?

We welcome the opportunity to comment on the value and importance of spectrum for scientific research, and we appreciate the long term outlook and international context, which are important for global observations in radio astronomy as well as Earth observation.

While we can understand the use of value chain analysis in commercial situations, it should be recognized that this approach may not fit scientific research and it may be difficult to compare the (commercial) satellite and space science sectors in this way. In particular, the 'value' may include the generation of fundamental knowledge, direct benefits in terms of spin-out technologies and training of skilled technical staff, and indirect benefits including innovation potential and the inspiration of young people into STEM subjects and career paths.

Although this CFI does consider space science and (commercial) satellite use in the same consultation, the two sectors are treated almost independently. This separation may not give full weight to the impact of satellite transmissions on radio astronomy from the ground.

Clarification is required for Section 1.6 where it says 'This does not include terrestrial science use of spectrum'. We do not understand exactly what is being excluded.

Q2 Do you have any comments on our broad overview of the satellite sector…?

It is not clear whether scientific use of GNSS should be included here. GNSS is used for global and local geodetic measurements, vertical water vapour sensing, long range time transfer and the construction of UTC, and to support a huge range of scientific programmes including radio astronomy.

Q3: Do you have any comments on our broad overview of the space science sector?...

The categorisation proposed here can be confusing eg radar astronomy vs active space sensing; radio astronomy carried out from satellites; geodesy via radio astronomy and GNSS; space sensing from the ground .
The distinction between the science use and TT&C can be blurred eg the technique where TT&C transmissions from probes are used to carry out scientific measurements (eg measuring wind speeds on Titan by tracking the

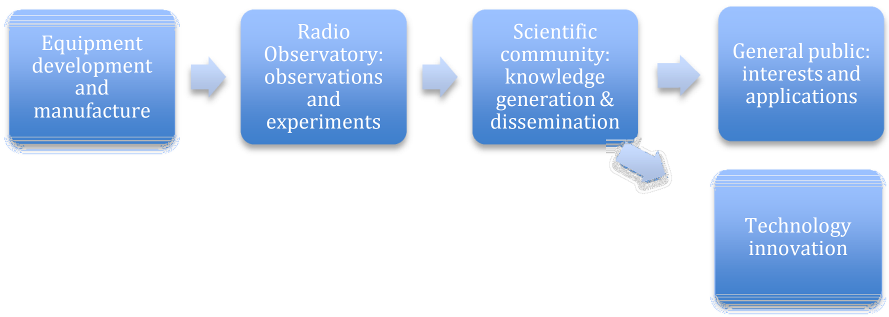
Huygens probe using Earth-based VLBI), which is increasingly being adopted in deep space missions.

Q4-10. We do not have any major comments here but note the possibility of including scientific use of GNSS in these sections.
Q11-13: assume mitigation and regulatory action addressed in Q22, Q23 & Q24.

Q14. Do you have any comments on our representation of the value chain for the space science sector?

Value chain analysis is based on a process view of organisations, looking at the primary transformation from inputs to outputs and the supporting role of secondary activities. We note that the value chain proposed is in terms of actors rather than activities as one would expect for a process-oriented view.

For radio astronomy, one could imagine a simple value chain as follows:



Radio astronomy institutes often include activities across this entire chain: developing telescopes, receivers and data processing equipment; operating and maintaining the observatory infrastructure; building a community of scientists as primary users; and delivering high quality material to the wider public via science centres and a wide range of media, including news, magazines, TV and film.

Some of these activities are 'outsourced' to industry, sometimes by partnership, and there is always a wider community of scientists involved either as primary users as in the case of national facilities or secondary users who make use of the observational data provided or published by the observatories. In the same way, typical scientists will use a multitude of research facilities to carry out their work.

The outputs are of course much wider than the public knowledge generated (as published papers and reports) and the general public interest. The economic motivation for investment in basic scientific research such as radio astronomy includes technology transfer/spin offs, explicit training in specialized and general science and engineering and inspiring future generations into STEM subject areas. This is covered in detail in the response to Q17.

Q15 What is the role of your organization in the value chain?

Primarily ground-based radio astronomy. JBO technicians, engineers and scientists are involved in development, operations , basic research (ie knowledge generation) and communication. This covers the entire value chain as discussed above.

JBO staff have played significant development roles in other space science missions, notably the ESA Planck mission, for which receivers were developed.

JBO is involved in space-based radio astronomy where we provide part of the ground segment for the Russian RadioAstron mission (not TT&C or data downlink but part of the ground array observing the same celestial objects).

JBO has provided support for ESA and NASA space probes, including searching for the Beagle lander in 2003 and remains under consideration for current and future NASA missions (e.g. Insight mission to Mars).

JBO has been involved in passive space sensing eg interplanetary scintillation measurements to study the solar wind and the receive element for active space sensing including radar of asteroids and planets.

JBO may play future roles as part of networks to carry out precision tracking of deep space probes (eg Duev et al 2012 Astronomy & Astrophysics 541, A43) and global geodetic observations for earth sensing, including precision determination of the earth rotation rate and orientation in space, continental drift etc.

Q16 For each application… provide specific frequencies etc…

<u>Ground-based radio astronomy:</u>

Ground based radio astronomy relies on the use of passive and protected bands for this unique scientific research. Any reduction in the degree or scope of protection would have a major impact on the ability of the UK and international scientific community to continue this research.

All bands listed in UK FAT and collected in footnote UK10 of the FAT (2013, issue 17) are currently or potentially used in the UK.

For information only:
The current JBO use is mainly as follows:
327 MHz; 406-410 MHz; 606-614 MHz; 1350-1720 MHz; 4600-6675 MHz and 22-24 GHz.
The current receiver bands for e-MERLIN/JBO are 406-410 MHz, 606-614 MHz, 1250-1750 MHz, 4.2-7.8 GHz and 22-24 GHz. Radio astronomy can be considered as software defined radio, making optimal use of the protected bands but also where possible taking advantage of white space (in time and frequency) between

these frequencies within the broad bands specified above. In general the input is channelized to <1 MHz as part of the signal processing.

LOFAR-UK (Chilboton) uses 30-80 MHz and 120-240 MHz usually in conjunction with other LOFAR stations in the Netherlands, Germany, France and Sweden.

AMI (Advanced MicroKelvin Imager) at Cambridge uses the band 13.5-18 GHz, with 6 placeable channels of 750 MHz width.

Many of the frequencies used are determined by fundamental characteristics (atomic or molecular transitions) or are chosen by international consensus. Hence there is little scope for repositioning the bands used, and interference into these bands has an impact beyond the UK.

Observations may be continuous for many years at some sites (eg 13m telescope at JBO) at the same frequency or intermittent in the sense that the frequencies may change on timescales from minutes to weeks. In general most observatories operate 24hrs/day most days of the year.

Geographical sites are as listed in the UK FAT for radio astronomy (UK10) but new sites are always under consideration.

The number of primary users for JBO and e-MERLIN facilities including EVN and VLBI is in the range 500-1000. The international LOFAR community is a similar size. The number of secondary users who make direct scientific use of the published data is likely to be several thousand, worldwide. The public interest can be gauged by the numbers of visitors to the Jodrell Bank Discovery Centre (160,000/yr) and the number of viewers for programmes such as BBC Stargazing Live, broadcast for 3 nights every year from JBO (3M/night).

Passive Space Sensing: e.g. ionospheric measurements – L-band and below.

Space-based radio astronomy: currently 327 MHz, 1600 MHz, 5 GHz, 22 GHz. Primary science community ~100 users.

Q17 How do UK consumers and citizens benefit…?

In the 1960s radio astronomy transformed our understanding of the universe: the radio sky was found to be dominated by radio galaxies and quasars, unlike anything that had been seen before, and powered by supermassive black holes, now known to exist at the centres of almost all galaxies, including our own. The discovery of pulsars revealed an entirely new form of star and state of matter. Radio astronomers detected increasingly complex organic molecules in clouds of gas and are now beginning to image the birth process of planets. The cultural and societal impact of such knowledge is immeasurable but the public's desire to understand and appreciate it can be judged from the volume of print and broadcast media devoted to astronomy in general. Astronomy as a basic science is uniquely accessible and fascinating to the general public, and in the UK, the Jodrell Bank Discovery Centre which allows visitors to approach within a few metres of the 76-m Lovell Telescope while it is operating makes radio astronomy uniquely physically accessible.

The UK undertakes a very detailed and thorough examination of the quality of university research through the Research Assessment Exercise, now the Research Excellence Framework (REF). The rigorousness of this approach is known and appreciated world-wide (Bornmann 2013, J American Soc Information Science & Technology, 64, 217) This exercise gives significant weight to the societal and economic impact of basic research and in the most recent REF the impact case for the 'public engagement in research.
The public engagement work of Jodrell Bank formed one of the case studies for research impact in the recent REF and helped the University of Manchester's School of Physics & Astronomy achieve the top grade for impact of any university physics department in the UK. This impact case is attached below.

There have been many studies analyzing the benefits of basic science to economic and social welfare including country and domain-specific studies (eg Salter & Martin 2001, Research Policy 30, 509, Martin & Tang 2007 http://core.ac.uk/download/pdf/7372156.pdf) The benefits have been highlighted in terms of increasing the stock of knowledge; training skilled graduates; creating new scientific instrumentation and methodologies; stimulating technical and social interactions; increasing scientific and technical capacity; and creating new firms. Several studies have quantified the rate of return on (government) investment in basic science, finding yields in the order of 30%. Recently there have been specific studies on the impacts of Big Science, looking at the procurement chains for organisations such as CERN and ESA (eg Autio et al 2004. *Research Policy* 33: 107–126).

Fabian (Royal Astronomical Society Presidential Address 2010) has reviewed the impact of basic research in astronomy, with an international and UK perspective, highlighting the benefits in terms of specialized graduate level training, inspiration to future generations of scientists and engineers and technological spin-offs, including those from radio astronomy. There has been one early study on the technology benefits of radio astronomy (Martin & Irvine 1981 Physics in Technology 12, 204) largely based on interviews with staff at Jodrell Bank and Cambridge and their industrial contacts. This noted the very fruitful collaboration between Ferranti and Jodrell Bank, both in advanced microwave engineering and on the control of the MkII telescope by digital computer (the first large piece of machinery to be computer-controlled). It also highlights some of the early adoption of imaging algorithms developed by radio astronomers for medical imaging and tomography but concluded in general that the major benefit was from technical training rather than spin-offs. However, the report provides a typical example of how easy it is to miss the most important future developments: "Also mentioned was the use of radio signals for the purposes of very precise navigation on the earth's surface, although it is not clear whether this will have any significant benefits outside the military field". Actually, the first GPS Block I satellites had already been launched, by the mid 1980s commercial GPS surveying was becoming available, by the mid 1990s GPS was made available to the general public and now it is a ubiquitous and essential technology for all of us. Direct sales of GPS receivers are estimated at approx. $60bn in 2012 (http://www.insidegnss.com/node/3833). Another ubiquitous technology – WiFi – has its roots firmly in radio astronomy: WiFi was invented by Dr John O'Sullivan and colleagues at CSIRO using algorithms developed for searching for the signature of black hole radio emission and hardware developed for radio telescope arrays. The global WiFi market is expected to exceed $30bn by 2020 and CSIRO have earned more than AUS$400M in revenue from licensing this technology.

Here in the UK we have always led the development of scientific computing, both hardware and software to transport, manipulate and assess data. In the era of the SKA this has taken a transformational leap in the size of high performance computing and storage to deliver this exemplar Big Data project. The design of the data transport networks and high performance computing are led from the UK for this project and our academic teams are working with Cisco, IBM, Intel, NVidea, Amazon, as well as a number of SME's in the UK to deliver the design. The project has reached a design maturity which is beginning to show spin out potential.

For other comments on the benefits of radio astronomy see the ITU report ITU-R RS.2178.

Q18 What high level trends will affect the space science sector in the coming years…?

Comments on the SKA are covered in Q21.

Ground-based radio astronomy: advances in digital technology, especially high speed samplers and DSP chips will make very wide bandwidths, i.e. > 5 GHz relatively routine. Phased array feeds will be deployed on many radio telescopes increasing their field-of-view and survey speed. So radio astronomers will be observing with wider bandwidths and greater simultaneous fields of view potentially increasing their vulnerability to interference. The same technologies can also be used to mitigate interference e.g. digital filtering and adaptive beam nulling. Higher time resolution systems to search for transients are also likely to become routine – this increases susceptibility to interference transients, but also allows routes to mitigation.

The re-use of ex satellite communication antennas (e.g. Goonhilly) for radio astronomy is being widely discussed and becomes increasingly feasible as many items in the signal processing chain, including receivers and digital back-ends, become commodity items.

Q19 For each space science application, what are current trends and demand drivers…

For ground based astronomy carried out in the UK, the key trends and drivers are to increase sensitivity (via lower noise receivers), bandwidth (via wider band receivers and signal processing), frequency coverage (via new receiver bands), field-of-view (via multi-beam/phased array feeds) and resolution (via longer baselines to new telescopes in the UK and Europe).

All these developments necessarily increase the data flow produced by radio telescopes and dealing with these huge data flows has been a key factor in the UK involvement in SKA data processing. Radio astronomy is a prime example of Big Data.

There is significant interest in developing 8-12 GHz front ends for e-MERLIN.

Q20 Taking into account the drivers identified above what challenges is your organization concerned about in meeting future demand?

Threats will result from the proliferation of various technologies requiring wireless communications, including IMT, M2M/IoT and the proliferation of small-scale communications satellites. The operation of large numbers of devices in a license-free regime is a major concern.

Q21 Are there any future developments such as the radio SKA that could reduce the demand for space science spectrum in the UK?

Participation in the design, construction, management, operation and science exploitation of the SKA is without doubt amongst the highest scientific priorities identified by the UK government and STFC. The SKA is already stimulating a world-wide increase in scientific interest in radio astronomy. Access to SKA is likely to be extremely competitive. The UK has just won the international competition to host the global HQ for the SKA with significant backing from the government, research councils, universities and local government. In order to maintain credibility as a leading player in the SKA and in order for UK scientists to be in the best position in the fierce competition for SKA observing time, it is vital that the UK has a world-class national radio astronomy programme in order to train and develop the user-base, allow teams to carry out pilot studies and refine techniques etc. With the HQ at Jodrell Bank Observatory it is important that front-rank radio astronomy continues to be carried out at JBO. This is why the University of Manchester is currently investing over £15M at Jodrell Bank in support of UK government and SKA international partnership funding.

The first phase of SKA to be built in 2018-2022 will not have baselines beyond about 100km. Long baseline, high resolution radio astronomy will be provided by existing networks of large radio telescopes in the UK, Europe, and elsewhere. These European facilities will continue to provide northern-hemisphere sky coverage not visible to the SKA throughout the SKA era. There is a strong desire to establish a global network connecting the SKA to the large dishes in Europe, bridging the gap by bringing other telescopes in Africa into operation.

The European Parliament (Written Declaration 45 “on Science Capacity Building in Africa: promoting European-African radio astronomy partnerships”) and

African Union ("Assembly/AU/Dec.407 CXVIII") and the South African Government, through its investment in SKA SA, recognise radio astronomy as a driver of technological development in a wide range of research and industry sectors.

For all these reasons, radio astronomy demand in the UK is likely to increase rather than decrease as we enter the SKA era.

Q22, Q23 Potential mitigations

The very high sensitivity and wide area coverage of radio astronomy facilities make mitigation challenging in general. Reducing out of band emission and reducing transmission power wherever and whenever possible should be seen as key design features for satellite and terrestrial systems to reduce their impact on radio astronomy.

Q24 additional regulatory actions

Although in our response to Q16 it has been indicated that radio astronomy observations take place over frequency ranges greater than the protected bands, it is extremely important that the protected and passive bands are maintained interference free to the agreed ITU levels. Otherwise, not only are the measurements within the protected bands degraded at some considerable financial cost to the RAS, but it becomes impossible to correctly calibrate all of the acquired data.

To this end it is very desirable that the existing ITU Radio Regulations are strongly enforced.

In a current situation in which it has been clearly demonstrated that a SECONDARY service is radiating out-of-band into a PRIMARY RAS band, no real attempt to stop this seems to have resulted and there does not appear to be an acceptable change in the situation on the horizon.

Institution: The University of Manchester

Unit of Assessment: 9

Title of case study: Public engagement with the research of Jodrell Bank

1. Summary of the impact (indicative maximum 100 words)

For decades Jodrell Bank has been a world-leader in both radio astronomy research and public engagement with science. The Lovell Telescope in particular, whilst still remaining one of the world's foremost active research instruments, has become an icon for UK science and engineering. In this case study we show how Jodrell Bank research has had a significant impact on society, culture and creativity, including economic impacts of tourism, educational impacts from engagement with schools, and cultural and creative impacts in television, music and the arts. Our approach to delivering this impact is varied and wide-ranging but a key vehicle is the Jodrell Bank Discovery Centre. The Centre has a significant impact on the regional economy and has attracted 496,000 visitors (including 43,000 school pupils) to engage with our research over the REF period Jan 2008-Jul 2013.

2. Underpinning research (indicative maximum 500 words)

The impact is based on a wide body of research carried out at Jodrell Bank during the past 20 years. Over this time Jodrell Bank astronomers have made a number of seminal contributions to astrophysics, particularly in radio astronomy, and to the technical development of observing techniques. A few selected research highlights are listed below with key staff in each area identified. These few examples are drawn from the wide-ranging research programme carried out by our whole group. The breadth and depth of this programme, coupled with the long-term appeal of Jodrell Bank, enables us to play a leading role in public engagement with astrophysics research.

- The significant volume of ongoing world-leading work on pulsars using the Lovell Telescope (LT), including the discovery and analysis of the double pulsar from 2004 onwards, providing the most stringent test yet of General Relativity (e.g. paper [1]) and resulting in the award of the 2005 Descartes Prize. [Prof. Andrew Lyne(from before 1993 till 2011), Prof. Michael Kramer (1999-2008), Dr Ben Stappers (2005-date), Dr Patrick Weltevrede (2009-date)]
- The development of our radio-linked interferometer MERLIN (which includes the LT) and its upgrade to an optical-fibre linked network e-MERLIN [2], providing high-sensitivity radio images comparable in resolution to those of the Hubble Space Telescope. The application of fibre technologies and signal synchronisation techniques have led to e-MERLIN being designated as a pathfinder for what is planned to be the world's largest radio telescope, the Square Kilometre Array (SKA). [Prof. Simon Garrington (throughout), Prof. Phil Diamond (1999-2010), Dr Tom Muxlow (throughout), Dr Rob Beswick (2002-date), Dr Anita Richards (throughout), Prof. Tim O'Brien (1999-date), Dr Bryan Anderson (to 2006), Prof. Ralph Spencer (to 2010)]
- Observations of the cosmic microwave background over many years, for example developing in collaboration with the University of Cambridge the Very Small Array which made early observations of the power spectrum [3] and recently through building ultra low-noise amplifiers for LFI on the Planck spacecraft and leading on the analysis of "foreground" radio emission in the Planck consortium. [Prof. Rod Davies (to 2004), Prof. Richard Davis (throughout), Prof. Richard Battye (2001-date), Dr Clive Dickinson (2007-date)]
- The work on gravitational lensing following discovery of the first lens by a group led from Jodrell Bank, leading to the significant CLASS survey [4], which provided

the majority of known lenses at the time and is continuing in projects such as SuperCLASS with e-MERLIN. [Prof. Ian Browne (to 2012), Prof. Peter Wilkinson (throughout), Dr Neal Jackson (1994-date)]

- The observations of the Hubble Deep Field with MERLIN+LT from 1997 onwards showing that high-redshift galaxies are resolved in the radio, hence providing part of the inspiration for the SKA [5]. [MERLIN group as above]
- The MERLIN observations of radio stars, which were key to linking the Hipparcos Catalogue to the International Celestial Reference System (ICRS) and hence enabling a fundamental astrometric reference frame to be constructed [6]. [MERLIN group as above]

3. References to the research (indicative maximum of six references)

Research from the Jodrell Bank group has consistently been rated as of international quality (e.g. RAE 2008). Six examples of underpinning research cited in Section 2 are listed below. All appear in leading journals for the astrophysics community. Three of the references which best exemplify the research quality are:

[1] *A double-pulsar system: A rare laboratory for relativistic gravity and plasma physics*, Lyne et al inc. Kramer, Science, 303, 1153-1157 (2004), DOI: 10.1126/science.1094645 Journal article, 362 citations and leading to a further 173 publications from groups worldwide whose title includes the name of the object.

[2] *e-MERLIN*, Garrington et al inc. , in "Ground-based Telescopes", eds. Oschmann, Jacobus M., Jr., Proceedings of the SPIE, Vol. 5489, pp. 332-343 (2004), DOI: 10.1117/12.553235 Technical journal article, currently 50% of time e-MERLIN is conducting significant legacy programmes, applications for which involved 325 astronomers from over 100 institutes in more than 20 countries.

[3] *High-sensitivity measurements of the cosmic microwave background power spectrum with the extended Very Small Array*, Dickinson et al inc. Battye, Davies, Davis, MNRAS, 353, 732-746 (2004), DOI: 10.1111/j.1365-2966.2004.08206.x Journal article, 194 citations.

A further three references are included to show the breadth of our research and its applications:

[4] *The Hubble constant from the gravitational lens CLASS B0218+357 using the Advanced Camera for Surveys*, York et al inc. Jackson, Browne, MNRAS, 357, 124-134 (2005), DOI: 10.1111/j.1365-2966.2004.08618.x Journal article

[5] *High-resolution studies of radio sources in the Hubble Deep and Flanking Fields*, Muxlow et al inc. Richards, Garrington, Wilkinson, Anderson, Monthly Notices of the Royal Astronomical Society, 358, 1159-1194 (2005), DOI: 10.1111/j.1365-2966.2005.08824.x Journal article

[6] *The HIPPARCOS catalogue as a realisation of the extragalactic reference system*, Kovalevsky et al inc. Garrington, Astronomy & Astrophysics, 323, 620-633 (1997), Journal article

4. Details of the impact (indicative maximum 750 words)

Introduction : Public engagement with our research has led to impacts on the economy and on society, culture and creativity. We have stimulated public interest in science and engineering and inspired thousands of schoolchildren by including our research in their education programmes. We achieve this impact through a strategic approach to developing a high national and international media profile combined with a purpose-built facility at Jodrell Bank to welcome visitors and engage them directly with the actual research going on at the site. This engagement with live science and active researchers at a working observatory is a key element in our delivering impact. Another key element of our approach is that the engagement programme is directed by designated members of staff – currently Prof. Tim O'Brien (1999-date; Associate Director Jodrell Bank Observatory) and Dr Teresa Anderson (2006-date; Director of Jodrell Bank Discovery Centre) and, until 2007, Prof. Ian Morison (retired 2010). Some specific examples of this impact during 2008-13 are listed below.

The Jodrell Bank Discovery Centre : In April 2011 we opened a new £2.9M Discovery Centre (funded by external grants from the Regional Development Agency and the European Regional Development Fund) replacing remaining parts of the public science centre which had been on site since the mid 1960's but reduced in size in 2003. The new Centre has a broad remit of enhancing public engagement with our research combined with providing out-of-classroom education aimed at inspiring the next generation of scientists and engineers. From Jan 2008 to Jul 2013, 496,000 people visited the Centre. From 2008 until it closed for rebuilding in Sep 2010, numbers were around 70-80,000 per year, but since re-opening in 2011 annual visitor numbers have risen to 128,000 (Aug 2012-Jul 2013). (A)

Current exhibits highlight our research, including the work of the Lovell Telescope, pulsars, e-MERLIN, the CMB, black holes, gravitational lensing, the evolution of stars and the search for life. The latest exhibit on the science & technology of Big Telescopes (including the work of VLT and ALMA, and plans for E-ELT and SKA) will open in Oct 2013. Our researchers work closely with the Centre e.g. in daily "Ask an Expert" talks/Q&A during school holidays (which have attracted 5,500 attendees from July 2011 to April 2013) and in public lectures such as the Lovell Lectures (held every 2-3 months, each attracting sell-out audiences of around 125). (A)

The Centre was awarded Tourism Attraction of the Year by Marketing Cheshire in 2012 (B). Evidence of impact of our activities at the Centre can be found in a consistent appetite for our events and exhibitions throughout the REF period (note visitors paying for entrance provide a current annual income of around £600,000 which is ploughed back into the Centre and its operations), audience growth at the new Centre (from 94,000 visitors in first full year 2011/12 to 128,000 in 2012/13), positive feedback and repeat visits from schools and the general public. For example, 82% of visitors rate the quality of the venue and the content of the exhibition as good or very good; whilst in a Girls Night Out event targeted at young women, 91% said they were more interested after the event whilst 94% said they'd come again; quotes include "My 12 year old loved it, as did I"; "It was extremely exciting and when I go back to school it will help me with my studying". A national online survey carried out by Harris International in 2008 showed that 54% of the UK population recognise Jodrell Bank as a UK science facility – a 'brand' recognition unparalleled amongst active UK science centres and indicative of the impact of our public engagement. Another Harris survey in 2012 found 76% of our visitors are very likely or absolutely certain to recommend a visit to friends (C).

Music & Science – Live from Jodrell Bank : New audiences are engaged with our research in innovative events such as the Live from Jodrell Bank music/science festivals. The first event in July 2011 attracted 5,000 people from the UK and beyond, in 2012 this increased to 12,000. In 2013 we held the event over two weekends in July and August. The first on July 6/7 attracted a total of about 12,000 attendees. Aimed at reaching out to a different audience, postcode analysis of ticket holders showed 65% of the attendees travelled further than 60 miles (including some from overseas), whereas 94% of our usual visitors come from within 60 miles. Alongside the Music Arena with the main stage we also have a Science Arena which showcases Jodrell Bank research with exhibitions and talks from our researchers, as well as others from the UK community, including STFC, IoP, RCUK and the Wellcome Trust. Our research is also delivered from the main stage between bands by Prof. O'Brien. This includes descriptions of scientific results from use of the Jodrell telescopes and, in 2012, a live video link to the telescope platform at the VLT in Chile. For the 2013 event, although 68% of people had primarily come to see the bands, 81% of people surveyed said they had learnt something about science whilst 87% would definitely visit Jodrell Bank again (D).

Live From Jodrell Bank 2011 was awarded Best Outdoor Event at the national Event Awards in 2012; the 2012 event received an award for 'Extreme Creativity' from a panel of industry judges at the 2012 UK Festival Awards for its extra activity of integrating science into the music event (E).

Job creation & economic impact of tourism : As of July 2013, 26 jobs have been directly created in the new Discovery Centre (6 of them specifically for science engagement & education), plus 7 have been safeguarded and more will follow both directly and indirectly. As part of the funding process, the Regional Development Agency commissioned an assessment from EKOS (economic & social development consultants) which found the Centre is likely to provide an additional £27M economic impact to the region over the decade from opening in 2011 i.e. ~£6M over the REF period (F). Although no similar analyses exist, the economic impact of visitors during 2008-11 will also have been significant.

Education & inspiration : During the REF period 2008-2013, 43,000 pupils have visited Jodrell Bank as part of school groups, taking part in workshops relating to our research and targeted at the curriculum. The new programme, launched in Sep 2012, attracted 13,000 pupils in its first year and also includes teacher-training and short courses for adults. 97% of teachers rate these sessions as either good or excellent. We also regularly deliver talks and workshops in schools; targeting disadvantaged schools in particular. For example, we reached around 1500 Cumbrian pupils in an outreach event in 2010 alongside one of our research conferences (A).

Media impact : Jodrell Bank research has attracted the attention of the media for many years stimulated in part by our active publicity programme. From 2008, we have produced more than 80 press releases and news items (available on our website) and, from monthly Google News searches, there were over 1,500 mentions of Jodrell Bank in print and web news stories (G).

TV producers in particular have been attracted to our work, resulting in our scientists and facilities appearing many times in a wide range of programmes. The most significant recent example is the incredibly successful BBC2 "Stargazing Live" series broadcast from Jodrell Bank in Jan 2011, 2012 and 2013.The programme typically attracts over 3 million viewers on each night of 3 consecutive nights, remarkable for a science subject. In 2012, it was the most viewed programme on BBC Two, Channel 4 or Channel 5 during the week of transmission and its audience share was 53% higher than the timeslot average (H). The programme always features our research and technology (e.g. pulsars, starburst galaxies, radio jets, masers, SETI, e-MERLIN and SKA). The impact has been clear: many positive reviews; astronomy equipment was reported as selling out in major retailers; a record-breaking 2.3 million downloads of the BBC Stargazing Guide; in 2011, 3,800 viewer photos and 5,000 questions were submitted; the website had 450,000 views; 13,000 people took part in interactive chat; 40,000 people attended 330 linked events nationwide; and astronomy societies reported significant boosts in membership and website traffic (H).

Podcast : A popular feature of our outreach programme is "The Jodcast", a twice-monthly podcast which has been produced since Jan 2006 by a team primarily composed of research students. The show features news, interviews with our researchers and others, and audience Q&A . There have been more than 170 episodes and special programmes, including reports from National Astronomy Meetings and occasional video episodes (e.g. featuring e-MERLIN and LOFAR). The shows are regularly downloaded by over 4,000 listeners (this is a lower limit as it does not include syndicated outlets such as astronomy.fm). When surveyed in 2010, 95% of 195 respondents said they would recommend it to others, 85% said that it had increased their interest in astronomy, whilst 94% said they had learnt something worthwhile. Quotes include "The interviews are my favourite part because you talk to an expert at length rather than editing them down to short sound bites"; "You always inspire and intrigue". (I).

World Heritage Site : In 2011, Jodrell Bank Observatory was added to the UK Tentative List for World Heritage Site status demonstrating a major societal impact of our research. The panel recognised that the site is "impressive tangible evidence of a major modern scientific development which has greatly enlarged human understanding of the Universe" (J).

Conclusion : Our aim with the programme of public engagement from Jodrell Bank is to harness the strong public interest in curiosity-driven research by directly engaging them with scientific research at a major UK facility, providing a legacy for decades by inspiring a wide audience including the scientists and engineers of the future.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Records of visitor numbers, event attendees and feedback from Jodrell Bank Discovery Centre
[B] Marketing Cheshire Visitor Attraction of the Year 2012 – p1 and 6 of PDFs
[C] Harris International nationwide and visitor surveys of 2008 and 2012
[D] Testimonial letter from MD of Ground Control, event organisers of Live from Jodrell Bank confirming event details, attendees etc
[E] Event Awards 2012 – Best Outdoor Event – p5 of PDF; UK Festival Awards 2012 – Extra-Festival Activity Award – p4 of PDF
[F] Independent feasibility assessment of case for funding of Discovery Centre produced for NWDA by EKOS p35, inc. testimonial letters of support from Cheshire East Council, Marketing Cheshire (the regional tourism agency) and the Right Hon. David Rutley, MP for Macclesfield
[G] Monthly analysis of mentions of Jodrell Bank in Google News searches since 2008
[H] Testimonial from BBC Executive Producer inc. Stargazing Live campaign review
[I] Jodcast 2010 listener survey results inc archive of episodes at http://www.jodcast.net
[J] Panel report on Jodrell Bank's successful application for placement on UK Tentative List for World Heritage Site status – p52-53 of PDF