FINAL REPORT

Impact evaluation of CSIRO's collaboration with the Five hundred metre Aperture Spherical Telescope (FAST)

Prepared for
CSIRO

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THE CENTRE FOR INTERNATIONAL ECONOMICS
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CANBERRA

Centre for International Economics
Ground Floor, 11 Lancaster Place
Majura Park

Canberra ACT 2609
GPO Box 2203
Canberra ACT Australia 2601

Telephone +61 2 6245 7800
Facsimile +61 2 6245 7888
Email cie@TheCIE.com.au

Website www.TheCIE.com.au

SYDNEY

Centre for International Economics
Level 7, 8 Spring Street
Sydney NSW 2000

Telephone +61 2 9250 0800
Email ciesyd@TheCIE.com.au

Website www.TheCIE.com.au

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Glossary

ACAMAR	Australia-China Consortium for Astrophysical Research
ASKAP	Australian Square Kilometre Array Pathfinder
CAS	Chinese Academy of Sciences
CASDA	CSIRO ASKAP Science Data Archive
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FAST	Five hundred metre Aperture Spherical Telescope
GW	Gravitation waves
HI	Neutral hydrogen atom gas clouds
ISM	Interstellar medium
L-band	The range of frequencies in the radio spectrum from 1 to 2 gigahertz
MOU	Memorandum of Understanding
NAOC	National Astronomical Observatories of China
OH	Hydroxyl
PSRDA	Parkes Pulsar Data Archive
PTA	Pulsar timing arrays
RFI	Radio frequency interference
SKA	Square Kilometre Array
VLBI	Very Long Baseline Interferometry

Summary

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) in Guizhou Province China, is the largest single dish radio telescope in the world following its completion in 2016. Broadly speaking, FAST will help to enhance our understanding of the interstellar medium (ISM) life cycle, cosmology, galaxy evolution, star formation and exoplanets.

This report provides an evaluation of CSIRO's involvement with FAST, via the 19-beam receiver, and ongoing scientific collaboration under the research Memorandum of Understanding (MOU) between CSIRO and National Astronomical Observatories of China (NAOC), operators of FAST. Costs and benefits are calculated from an Australian perspective.

The net present value of CSIRO's involvement with FAST is estimated to be $13.2 million over 20 years (2014-2034), with a benefit-cost ratio of 3.1. This considers capital expenditure costs and estimated operational (employee) costs. Unknown maintenance costs are not considered.

In order of highest value, the quantifiable benefits include, publications and citations, NAOC contract revenue, cultural benefits to Australia, learning by doing benefits, human capital benefits and benefits from CSIROs expanded scientific footprint.

Inputs and activities

CSIRO was commissioned by NAOC to design, build and install FAST's primary multi-beam receiver, known as the 19-beam array receiver for L-band (19-beam receiver). The total project cost was $5.4 million. This included 15.6 full-time equivalent staff (FTE) working an estimated combined total of 18.3 FTE years.[1] CSIRO received $3.74 million from NAOC for this project.

CSIRO receives hypothecated funding from NAOC to undertake research and analysis of FAST related data/discoveries. FAST has purchased about 2 000 hours of observing time over three years on the Parkes facility, as part CSIRO's on-going collaboration with NAOC. This is approximately 10 per cent of observing time in that period and makes NAOC CSIRO's second biggest customer in terms of sale of telescope time over that period.[2] CSIRO has also executed several bespoke contracts with NAOC to provide additional research and specialist advice associated with FAST.

1 Hayman, D (2017), *CASS Project Review Board 128 – FAST Multibeam Receiver*, CSIRO, October, and CSIRO excel file 'FASTProjCosts'.xls

2 CSIRO personal communication

CSIRO and NAOC staff have spent numerous hours networking at their respective partner facilities. This includes:

- initial site visit to FAST by 3 CSIRO staff for approximately 1 week to unpack and undertake laboratory testing of the 19-beam array receiver
- two CSIRO scientists to install the 19-beam receiver at FAST and participate in on-antenna tests for approximately 4 weeks[3]
- numerous visits by Di Li to the Australia Telescope National Facility Marsfield site in Sydney as part of the 19-beam array program
- George Hobbs and Di Li running the Parkes facility remotely from Guizhou to confirm FAST pulsar candidates over several days,[4] and
- five international PhD exchange students to date, analysing FAST data/observations at the Parkes facility.[5]

Outputs and outcomes

The key outputs of CSIRO's involvement with FAST include:

- FAST's primary receiver, the 19-beam receiver
- an established database of observations/discoveries, which:
  - provides data for scientists to test various theories in radio astronomy
  - provides international recognition to Australian scientists and programmers, and
  - links professionals together through common data, which is most prominently displayed in CSIRO's collaboration with NAOC, and
- educational benefits to scientists and programmers, such as through:
  - programming skills in storing, using and analysing FAST data/discoveries, and
  - scientific skills and advances through analysis of FAST data/discoveries to confirm theoretical understanding or produce new theories.

Impact value

The greatest impact of CSIRO's involvement with FAST is its ability to enhance an understanding of the universe and improve Australia's reputation and connections with the international research community. We estimate a total impact value of $19.4 million (present value) associated with:

- NAOC contract revenue
- value of publications and citations
- human capital formation
- expanded scientific footprint (increased scientific and research exports)

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3 Hayman, D (2017), *CASS Project Review Board 128 – FAST Multibeam Receiver*, CSIRO, October

4 http://en.45stories.com/portfolio_page/li-di-and-george-hobbs/

5 CSIRO (2019), *CSIRO Australia Telescope National Facility Annual Report 2018–19*, p. 61, https://www.atnf.csiro.au/the_atnf/annual_reports/2018/2018_AnnualReport.pdf

- an enhancement of Australian cultural value, and
- learning by doing (table 1).

1 Summary of quantified impact value

Benefit	
	$million, PV
NAOC contract revenue	3.6
Value of publications and citations	8.4
Human capital	1.5
Expanded scientific footprint (increased scientific and research exports)	1.2
Cultural value	2.6
Learning by doing	2.0
Total	**19.4**

Note: 7 per cent discount rate and 20-year evaluation timeframe. All values are $2020.
Source: CIE.

Additional qualitative benefits include:

- soft international diplomacy
- more cost-effective science, and
- potential innovations taken up by industry to improve productivity.

NAOC contract revenue

CSIRO has executed numerous contracts with NAOC to provide FAST associated infrastructure and advice, with a total value of $4.3 million (nominal) (table 2).[6] [7]

2 NAOC contract revenue

Contract	Revenue
	$ nominal
Design, build and install FAST's Multibeam receiver	3.7
Searching for pulsars with FAST and the Parkes telescopes	0.2
Studying pulsars with FAST and the Parkes telescopes	0.1
Implementing a Fast-Folding Algorithm for FAST Pulsar Searching	0.1
Data Archiving: Pulsar Data Analysis with FAST	0.2
Total	**4.3**

Source: Hayman, D (2017), 'CASS Project Review Board 128 – FAST Multibeam Receiver', 27 October 2017; CSIRO personal communication.

6 CSIRO personal communication

7 Hayman, D (2017), CASS Project Review Board 128 – FAST Multibeam Receiver, CSIRO, October

Value of publications and citations

CSIRO’s FAST association has spurred extensive research and several associated publications and citations, which serve as one measure of the value of knowledge output.

We estimate:

- $775 264 in researcher time is dedicated to the use of CSIRO’s involvement with FAST each year based on papers associated with the 19-beam receiver and FAST team doing follow up research on CSIRO’s Parkes radio telescope, and
- an additional $98 000 in value is generated annually through papers associated with the 19-beam receiver and FAST team doing follow up research on CSIRO’s Parkes radio telescope associated citations.

Human capital formation

CSIRO advise an estimated 50 students are actively involved in FAST projects utilising the 19-beam receiver across 133 Principal Investigator programs from 21 institutions.[8] We estimate this will lead to $3.2 million (undiscounted) in additional human capital associated with CSIRO’s FAST collaboration, over an assumed 20-year period.

Expanded scientific footprint and international diplomacy

Expanded scientific footprint

Astronomy plays an ongoing and important role in the broader bilateral Australia-China relationship, as it provides avenues for engagement and shows how Australia and China can be global partners. CSIRO’s involvement with FAST is one part of the larger Australia-China radio astronomy relationship, spanning over 40 years and underpinned by a continuous cycle of:

- networking
- establishing professional relationships
- building mutual respect and trust, and
- joint scientific and engineering projects.

CSIRO was invited as part of an open tender process conducted by CAS to provide input on the FAST receiver during the initial design phase. The tender invitation came about due to CSIRO’s previous work building telescope receivers for the Parkes facility (amongst others), and previous collaborations on other Chinese projects. The FAST invitation subsequently led to the 19-beam receiver design and construct contracts, as well as the research MOU.

Australia exported an average $30.8 million per year of research and development and engineering services to China, over the period 2009 to 2016.[9] We assume that 1 per cent

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8 CSIRO personal communication.

9 Australian Government (2018), 'Australia’s Trade In Services With China: Attachment A Australia’s Service Exports To China By Type Of Activity (A$ million),' p. 13, Department of

of this revenue ($0.31 million) is attributed to the ongoing networking and associated activities between CSIRO and CAS. Using a demand-supply analysis, and the change to producer surplus, we estimate an annual benefit of $0.15 million per annum attributable to CSIRO's FAST collaboration.[10]

International diplomacy

CSIRO's collaboration with FAST is directly aligned to the Foreign Policy White Paper and the Global Innovation Strategy, which are part of the National Innovation and Science Agenda. The collaboration was recognised by the Australian Government as strengthening Australia-China diplomatic relations, as outlined in the 45 Years, 45 Stories initiative.

In this regard, CSIRO's collaboration with FAST (amongst other projects) has reinforced CSIRO's status as an attracted advisor to engage in soft diplomacy. This leads to the continued cross pollination of scientific thinking and collaborative behaviour through the power of common attraction and ideas.

Australia ranked seventh in 2019 on the Lowy Institute Asia Power Index, an analytical tool that ranks 25 countries and territories in terms of their power within the Asia-Pacific Region.[11] Australia's top 10 Asia-Pacific ranking is underpinned by strong results in the following categories relevant to CSIRO's collaboration with FAST:

- technology
  - the technological and scientific sophistication of countries
- regional trade relations
  - the ability to influence other countries through bilateral trade flows and relative dependencies
- information flows
  - the regional appeal of a country's media outlets and universities, and
- people exchange
  - the depth and influence of a country's people-to-people links in the region.

Cultural value

We estimate a per person annual cultural value of $0.02 for the 19-beam receiver and $0.80 for FAST by extrapolating the findings of Florio et. al. (2018),[12] and converting to 2020 Australian dollars. Applying these values to the Australian adult population results

Foreign Affairs and Trade, https://dfat.gov.au/about-us/publications/Documents/australias-trade-in-services-with-china.pdf

10 $0.5 \times \$0.31$ million = $0.15 million.

11 Lowy Institute (2019), 'Asia Power Index', https://power.lowyinstitute.org/about.html

12 Florio et. al. (2018), 'Should Governments Fund Basic Science? Evidence from a Willingness-to-pay Experiment in Five Universities,' *Departmental Working Papers 2018-10, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano,* as stated in Florio (2019), 'Investing in science: Social cost-benefit analysis of research infrastructures, chapter 9, Taxpayers: Science as a Global Public Good', p. 266, Cambridge, MA, *The MIT Press*

in an estimated an annual cultural value of $0.3 million for the 19-beam receiver and $15.7 million for FAST.

Learning by doing

Highly specialised components and techniques were used in the 19-beam receiver build, which are constantly evolving due to technical advances. The 19-beam receiver project provided an opportunity for CSIRO to enhance their knowledge and skills, which have been applied in subsequent projects. For instance, the Low Noise Amplifier bias cards and the control and monitor system formed the basis for the subsequent Parkes Ultra-Wideband Receiver.[13]

More cost-effective science

FAST is the largest single reflector telescope in the world, and has improved sensitivity by a factor of 2, increased survey speed by a factor of 5-10 and covers 2 to 3 times the sky area compared with pre-existing telescopes.[14] This improves astronomer's ability to survey the galaxy more precisely (less noise), with increased data/observations.[15]

The research benefits of more precise observations (less noise) include:

- a reduction in the amount of individual resources necessary to participate in research, with more time available for data analysis as opposed to simple collection
- improved ability of astronomers to distinguish common events from anomalies and build out a more comprehensive image of our skies, and
- higher probability of successful discoveries as a result.[16]

Innovations taken up by industry to improve productivity

FAST, utilising the 19-beam receiver, is the latest in a line of new telescopes to exponentially advance our astronomy observation capabilities. The speed of the exponential astronomy data acquisition has been likened to Moore's Law, and presents challenges to our current data ICT storage, analysis and transmission infrastructure.[17]

This ever-increasing growth in data has spawned demand for new innovations in big data collection, storage and manipulation. For example, FAST will produce an estimated

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13 CSIRO personal communication.

14 Smith, S.L et. al. (2016), 'Analysis of the Five-hundred-metre Aperture Spherical radio Telescope with a 19-element Multibeam Feed', *2016 IEEE International Symposium on Antennas and Propagation*, p. 383

15 Kanapathippillai, J et. al. (2017), 'The FAST Multi-beam Receiver Design with RF over Fiber Link', IEEE Asia Pacific Microwave Conference (APMC)

16 Andersen, R (2012), *How Big Data Is Changing Astronomy (Again),* The Atlantic, April, https://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy-again/255917/

17 Andersen, R (2012), *How Big Data Is Changing Astronomy (Again),* The Atlantic, April, https://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy-again/255917/

18.8 Peta Bytes of data per annum, requiring a throughput data rate capability of 150 tera bytes/day.[18] Given this, NOAC contracted CSIRO to prepare and deliver advice on the requirements for the data archiving of pulsar and spectral line data from FAST. CSIRO was requested to provide this advice due to their experience with the Parkes Pulsar Data Archive (PSRDA), and the CSIRO Australian Square Kilometre Array Pathfinder (ASKAP) Science Data Archive (CASDA).[19]

A summary of CSIRO's collaboration with FAST impact pathway is set out in chart 3.

18 Dempsey, J et. al. (2017), 'Data Archiving – Pulsar Data Analysis with the FAST Telescope: Review copy', p. 26, CSIRO

19 Dempsey, J et. al. (2017), 'Data Archiving – Pulsar Data Analysis with the FAST Telescope: Review copy', p. v, CSIRO

3 Impact pathway

Inputs

- $5.4 million to design, build and install FAST's primary multi-beam receiver
- An unknown amount to operate FAST's primary multi-beam receiver
- Hypothecated funds to CSIRO for follow up research/analysis
- 2 000 hours of observing time over three years on the Parkes facility

Activities

- Design, manufacture and installation of the 19-beam receiver
- Supporting/follow-up observations of FAST discoveries
- International scientific networking

Outputs

- FAST's primary receiver, the 19-beam receiver
- CSIRO and NAOC MOU
- An established database of observations/discoveries
- Relationships with international research facilities/firms

Outcomes

- Ability to test/enhance scientific theories
- Strengthened international relations and reputation
- Opportunities for collaboration with scientists

Impacts

- NAOC contract revenue
- Value of publications and citations
- Human capital formation
- Expanded scientific footprint and international diplomacy
- Cultural value
- Learning by doing benefits
- More cost-effective science
- Potential industrial innovations to improve productivity

Data source: CIE and CSIRO.

1 FAST and its association with CSIRO

FAST in Guizhou Province China, is the largest single dish radio telescope in the world and helps enhance our understanding of the interstellar medium (ISM) life cycle, cosmology, galaxy evolution, star formation and exoplanets.

CSIRO has expanded Australia's scientific capabilities and international networks via a formal collaboration with NAOC, operators of FAST, resulting in:

- **exports of Australia's scientific knowledge**
  - **FAST's primary multi-beam receiver (known as the 19-beam receiver) was built by CSIRO, with most activities conducted within Australian facilities. The 19-beam receiver is the largest multibeam receiver of its kind, resulting in FAST being the most sensitive single dish survey instrument at this frequency, and**
- **leveraging Australia's scientific assets and expanding networks**
  - **The Parkes radio telescope has found more than half of known pulsars and remains active in finding and timing pulsars. FAST has recently found several new pulsars, confirmed by the Parkes telescope and a team of CSIRO astronomers working with their Chinese colleagues.**
  - **FAST makes many discoveries but does not have sufficient time available to carry out follow-up studies of these objects. Under the NAOC memorandum of understanding (MOU), the Parkes radio telescope analyses the data collected by FAST for scientific research into new phenomena. This includes postdoctoral research and establishing formal links for two-way international student collaboration.**

FAST objectives and policy context

FAST in Guizhou Province China, is the largest single dish radio telescope in the world following its completion in 2016. Prior to this, the Arecibo Observatory in Puerto Rico was the world's largest single-aperture telescope. The fundamental scientific motivation for building the largest radio telescope is to survey the radio universe by utilizing FAST's unparalleled sensitivity, high surveying speed and sky coverage. Broadly speaking, FAST will help to enhance our understanding of the interstellar medium (ISM) life cycle, cosmology, galaxy evolution, star formation and exoplanets.[20]

[20] Nan, R et. al. (2011), 'The Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) Project', p. 1, *International Journal of Modern Physics*

The key science goals of FAST are:[21]

1 survey the Galactic ISM, including the 21 cm neutral hydrogen gas cloud (HI) hyperfine structure line[22]
2 discover approximately 4 000 new Galactic pulsars and search for the first extragalactic pulsars
3 spectroscopic survey of the radio spectra of rich Galactic sources with continuous coverage between 70 MHz and 3 GHz, and
4 detect tens of thousands of HI galaxies and detect individual massive galaxies (box 1.1).

FAST is also uniquely placed to discover new and unanticipated phenomena, commonly referred to as unknown unknowns. This is achieved in part by FAST providing researchers with operational flexibility in the form of direct access to FAST data without imposed limitations on its theoretical application. Wilkinson, P (2016) refers to this as maximising the ‘human bandwidth’.[23]

CSIRO and FAST association

CSIRO has expanded Australia’s scientific capabilities and international networks via a formal collaboration with NAOC, operators of FAST. The benefits of this collaboration can be summarised into two themes:

1 exporting Australia’s scientific knowledge, and
2 leveraging Australia’s scientific assets and expanding networks.

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21 Li, D. (2016), ‘Summary of the FAST Project’, *Frontiers in Radio Astronomy 2015 Astronomical Society of the Pacific Conference Series*, Vol. 502, http://aspbooks.org/a/volumes/table_of_contents/502

22 Refers to the electromagnetic radiation spectral line that is created by a change in the energy state of neutral hydrogen atoms.

23 Wilkinson, P (2016), ‘Discovery with FAST’, *Frontiers in Radio Astronomy 2015 Astronomical Society of the Pacific Conference Series*, Vol. 502, http://aspbooks.org/a/volumes/table_of_contents/502

1.1 Scientific themes advanced using FAST

21 cm HI hyperfine structure line – The majority of the normal matter in the universe is in the form of HI gas. A key goal for Galactic ISM study will be a systematic study of very cold atomic gas through measuring HI Narrow Self-Absorption features[24] which will be analysed together with CO surveys (survey of interstellar carbon monoxide) to reveal the conversion of atoms to molecules in our Milky Way. Compared with Arecibo, FAST has three times the scan speed at L-band (the range of frequencies in the radio spectrum from 1 to 2 gigahertz) and twice the sky coverage.

For the local universe, FAST will conduct surveys to measure the gas mass especially in dark galaxies that contain no visible stars, and are not visible using optical telescopes. Such census of gas will help explain the discrepancy between the amount of estimated dark matter[25] using established scientific methods and the actual observable universe: "the missing baryon problem".

Discover and search for new Galactic pulsars – Using the 19-beam receiver, FAST aims to discover over 4 000 new pulsars, about 300 of which should be millisecond pulsars. The contribution of FAST-discovered pulsars and their subsequent timing will improve the overall pulsar timing array (PTA) sensitivity by a factor of approximately 3 for detecting gravitational waves[26].

This provides new insights into the cosmos, such as detecting events that would otherwise leave little to no observable light, i.e. black hole collisions and neutron stars.

Molecular spectroscopy – FAST will enhance molecular spectroscopy[27] by undertaking targeted galaxy surveys and increasing the sample of currently known extragalactic hydroxyl (OH) megamasers[28] by a factor of 10, with a total of about 1 000 detections as far as z=2. This will provide more details of the structural and compositional information of atoms or molecules, or to study physical processes.

Detect HI galaxies and individual massive galaxies – FAST will undertake spectral scans of constellations, such as the Orion nebula with the goal of detecting new molecules, particularly long-chain carbons. Researches are also looking into an extension of the Herschel HEXOS source model of Orion to clarify the potential for FAST discoveries of new lines and new interstellar molecules.

Source: Li, D (2016), 'Summary of the FAST Project', *Frontiers in Radio Astronomy 2015 Astronomical Society of the Pacific Conference Series*, Vol. 502, available at (http://aspbooks.org/a/volumes/table_of_contents/502)

24 Occurs when cold foreground gas absorbs HI emission from warmer background gas at the same velocity. Source: https://www.atnf.csiro.au/pasa/18_1/mccluregriffiths/paper/node3.html

25 Dark matter refers to the mass of the universe which cannot be directly observed as it does not emit light or energy. Source: https://www.space.com/20930-dark-matter.html

26 Colloquially known as ripples in the otherwise tough, stiff fabric of spacetime produced by the most violent phenomena the cosmos can offer- exploding stars, neutron star collisions, or merging black holes. Source: https://www.nationalgeographic.com/news/2017/10/what-are-gravitational-waves-ligo-astronomy-science/

Exporting Australia's scientific knowledge

Motivated by the desire to maximise FAST's observing efficiency, NAOC commissioned CSIRO to develop and build FAST's primary multi-beam receiver, known as the 19-beam receiver.[29] The 19-beam receiver was developed from previous Australian technology developed to upgrade the Parkes telescope from a single beam, to multi-beam receiver. This in turn improved the speed, by a factor of 10, at which the Parkes radio telescope can map the sky and is directly linked to the CSIRO's discovery of fast radio bursts and hundreds of new galaxies hidden behind the Milky Way.[30]

The 19-beam receiver is the largest multibeam receiver of its kind, weighing over 1.2 tonnes and approximately 2 metres high and 1.6 metres in diameter. Several bespoke design elements were incorporated into the final product to achieve low noise, high dynamic range, adequate gain and system stability.[31] This results in FAST being the most sensitive single dish survey instrument at this frequency.[32] These elements were designed, built and tested using CSIRO/Australian facilities.

Leveraging Australia's scientific assets and expanding networks

CSIRO have a long history of active involvement in galactic research and associated discoveries. For example, the Parkes radio telescope has found more than half of the known pulsars since 1968 and remains active in finding and timing pulsars today.[33] In response to Australia's astronomical knowledge and capability, NAOC signed a memorandum of understanding (MOU) with CSIRO to use the Parkes radio telescope to follow-up FAST pulsar candidates and projects, to share expertise and resources with the goal of further pulsar discoveries.[34]

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27 The interaction of electromagnetic radiation with materials in order to produce an absorption pattern from which structural or compositional information can be deduced. Source: Goodman, B.A. (1994) 'Molecular spectroscopy: introduction and general principles' In: Wilson M.J. (eds) Clay Mineralogy: Spectroscopic and Chemical Determinative Methods. Springer, Dordrecht

28 Astrophysical Microwave Amplification by Stimulated Emission of Radiation (maser) is a naturally occurring source of stimulated spectral line emission. Megamasers are 100 million times brighter than masers in the Milky Way, hence the prefix mega.

29 Dunning, A et. al. (2017), 'Design and Laboratory Testing of the Five hundred meter Aperture Spherical Telescope (FAST) 19 Beam L-band Receiver', *32nd URSI GASS*, Montreal, 19–26 August 2017, http://www.ursi.org/proceedings/procGA17/papers/Paper_J9-1(1385).pdf

30 Douglas, B (2016), 'How CSIRO is turbocharging the world's largest radio telescopes', https://theconversation.com/how-csiro-is-turbocharging-the-worlds-largest-radio-telescopes-60367

31 Kanapathippillai, J et. al. (2017), 'The FAST Multi-beam Receiver Design with RF over Fiber Link', *IEEE Asia Pacific Microwave Conference* (APMC)

32 CSIRO (2019), 'Multibeam receiver for FAST', Australia Telescope National Facility, https://www.atnf.csiro.au/technology/receivers/FAST_Multibeam.html

33 Hobbs, G et. al. (2017), 'Fifty years ago Jocelyn Bell discovered pulsars and changed our view of the universe', November, https://ecos.csiro.au/pulsar/

34 'Memorandum of understanding FAST Follow-up Observations with the Parkes radio telescope between National Astronomical Observatories, Chinese Academy of Sciences and CSIRO'

The Parkes telescope and a team of CSIRO astronomers working with their Chinese colleagues have confirmed 24 per cent (25/103) of the new pulsars originally discovered by FAST over the period 2017-2019.[35] This includes the first pulsar discovered by FAST as part of its commissioning and confirmed FAST's pulsar data acquisition and processing pipelines.[36] The collaboration has also led to joint research papers authored by NAOC and CSIRO staff describing the new findings.

Further, the on-going collaboration between CSIRO and NAOC facilitates the development of scientific networks between Australia and China, including postdoctoral research and opportunities for international student exchange (table 1.2).

1.2 FAST associated international student exchange projects

Name	University	Project title
Yi Feng	National Astronomical Observatory, CAS	Jitter noise and GWs
Renzhi Su	Shanghai Astronomical Observatory, CAS	Tracing fuelling and feedback in powerful radio galaxies with 21 cm HI absorption
Chao Zhang	National Astronomical Observatory, CAS	Pulsar search with interpretable machine learning
Lei Zhang	National Astronomical Observatory, CAS	Millisecond pulsars with FAST
Songbo Zhang	Purple Mountain Observatory, CAS	Searching for radio bursts in archival Parkes data

Source: CSIRO 2019, *CSIRO Australia Telescope National Facility Annual Report 2018–19*, p. 61, https://www.atnf.csiro.au/the_atnf/annual_reports/2018/2018_AnnualReport.pdf

Going forward, it is expected that the collaboration between Australia's and China's radio astronomers will grow and lead to significant enhancements in our ability to understand a broad range of scientific phenomena. Examples include searching for faint radio signals from planets beyond our solar system, to discovering pulsars and studying our galaxy in unprecedented detail.[37]

35 http://crafts.bao.ac.cn/pulsar/

36 Qian, L., Pan, Z., Li, D. (2019) et. al. 'The first pulsar discovered by FAST', *Sci. China Phys. Mech. Astron*. 62: 959508, https://doi.org/10.1007/s11433-018-9354-y

37 http://en.45stories.com/portfolio_page/li-di-and-george-hobbs/

2 *Impact pathway for CSIRO's collaboration with FAST*

The impact pathway for CSIRO's collaboration with FAST is summarised in chart 2.1.

2.1 Impact pathway

Inputs

- $5.4 million to design, build and install FAST's primary multi-beam receiver
- An unknown amount to operate FAST's primary multi-beam receiver
- Hypothecated funds to CSIRO for follow up research/analysis
- 2 000 hours of observing time over three years on the Parkes facility

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Activities

- Design, manufacture and installation of the 19-beam receiver
- Supporting/follow-up observations of FAST discoveries
- International scientific networking

↓

Outputs

- FAST's primary receiver, the 19-beam receiver
- CSIRO and NAOC MOU
- An established database of observations/discoveries
- Relationships with international research facilities/firms

↓

Outcomes

- Ability to test/enhance scientific theories
- Strengthened international relations and reputation
- Opportunities for collaboration with scientists

↓

Impacts

- NAOC contract revenue
- Value of publications and citations
- Human capital formation
- Expanded scientific footprint and international diplomacy
- Cultural value
- Learning by doing benefits
- More cost-effective science
- Potential industrial innovations to improve productivity

Data source: CIE and CSIRO.

Inputs

Design, construct and installation of the 19-beam array receiver for L-band

The CSIRO was commissioned by NAOC to design, build and install FAST's primary multi-beam receiver, known as the 19-beam array receiver for L-band (19-beam receiver). The total project cost was $5.4 million. This included 15.6 full-time staff equivalent (FTE) working an estimated combined total of 18.3 FTE years.[38] The 19-beam receiver's ongoing operation and maintenance costs are unknown.

Research using FAST data/observations

CSIRO receives hypothecated funding to undertake research and analysis of FAST related data/discoveries. This is mostly attributed to the MOU between CSIRO and NAOC.

Activities

Design, construct and installation of the 19-beam array receiver

CSIRO was exclusively responsible for the design and manufacture of the 19-beam receiver, with CSIRO and NAOC collaborating on the installation. This project commenced with design in 2014 and finished with installation in 2018 (table 2.2).

2.2 CSIRO 19-beam array receiver for L-band activities

Activity	Date
Preliminary design activities commence	2014
Preliminary design of feed array and engineering drawings completed	2015
Multibeam receiver interface meeting at CSIRO including discussion of draft receiver design. Testing and assessment of prototype feed and orthomode transducer	August 2015
Agreement on final receiver design to enable manufacture of receiver to commence	October 2015
Manufacture contract commences	March 2016
Feed array manufacture and testing completed	December 2016
Receiver construction completed. Multibeam Receiver tests completed at CSIRO (off–antenna).	
All tests complete	April 2017
NAOC site visit and test sign-off	May 2017
Deliver Multibeam Receiver to NAOC and CSIRO participate in on-antenna tests.	
Ready to deliver	June 2017
Delivered, unboxed on site and operating in lab	December 2017

38 Hayman, D (2017), *CASS Project Review Board 128 – FAST Multibeam Receiver*, CSIRO, October, and CSIRO excel file 'FASTProjCosts'.xls

Activity	Date
Installed and commissioned	May 2018

Source: Hayman, D (2018), 'FAST Multibeam receiver: Project Review and Closure', CSIRO, p.3.

Research using FAST data (NAOC MOU)

FAST has purchased approximately 2 000 hours of observing time, over three years on the Parkes facility, as part of CSIRO's on-going collaboration with NAOC. This is in the order of 10 per cent of observing time in that period and makes NAOC CSIRO's second biggest customer in terms of sale of telescope time over that period.[39]

Bespoke NOAC contracts

CSIRO has also executed several bespoke contracts with NAOC to provide additional research and specialist advice associated with FAST. For example, data archiving and implementing search algorithms.

International scientific networking

CSIRO and NAOC staff have spent numerous hours networking with scientists at their respective partner facilities. This includes:

- initial site visit to FAST by 3 CSIRO staff for approximately 1 week to unpack and undertake laboratory testing of the 19-beam array receiver
- two CSIRO scientists to install the 19-beam receiver at FAST and participate in on-antenna tests for approximately 4 weeks[40]
- numerous visits by Di Li to the Australia Telescope National Facility Marsfield site in Sydney as part of the 19-beam array program
- George Hobbs from CSIRO and Di Li from NAOC running the Parkes facility remotely from Guizhou to confirm FAST pulsar candidates over several days,[41] and
- five international PhD exchange students to date analysing FAST data/observations at the Parkes facility.[42]

Outputs and outcomes

The key outputs of CSIRO's interaction with FAST include:

- FAST's primary receiver, the 19-beam receiver
- Progressing CSIRO's capability in radio telescope receiver design
- CSIRO and NAOC MOU

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39 CSIRO personal communication.

40 Hayman, D (2017), 'CASS Project Review Board 128 – FAST Multibeam Receiver', October

41 http://en.45stories.com/portfolio_page/li-di-and-george-hobbs/

42 CSIRO (2019), *CSIRO Australia Telescope National Facility Annual Report 2018–19*, p. 61, https://www.atnf.csiro.au/the_atnf/annual_reports/2018/2018_AnnualReport.pdf

- an established database of observations/discoveries, which:
  - provides database for scientists to test various theories in radio astronomy
  - provides international recognition to Australian scientists and programmers, and
  - links professionals together though common data, which is most prominently displayed in CSIRO's collaboration with NAOC
- educational benefits to scientists and programmers, such as through:
  - programming skills in storing, using and analysing FAST data/discoveries, and
  - scientific advances through analysis of FAST data/discoveries to confirm theoretical understanding or produce new theories, and
- increased profile of the Parkes facility and its scientists amongst the international community.

Thirty five published research or conference papers have been authored to date (March 2020), attributable to CSIRO's involvement with FAST, either via the 19-beam array receiver project, the analysis of FAST data/discoveries using the Parkes radio telescope, or FAST discoveries using the 19-beam receiver (table A.1 in Appendix A).

Impacts

The impacts of CSIRO's collaboration with FAST are complex, as is the case for all large-scale scientific research infrastructure and programs that facilitate such as wide range of research. Scientific understanding is of great value to the community, which in some cases may lead to industry applications that have market value. The impacts of CSIRO's involvement with FAST is the ability to enhance an understanding of the universe and improve Australia's reputation and connections with the international research community.

Impacts have been monetised or discussed qualitatively in the following chapter. Costs and benefits are calculated from an Australian perspective. CSIRO's collaboration with FAST has also been evaluated using CSIRO's National Benefit Scorecard, with results shown in Appendix B (table B.1).

3 Measuring the impact of CSIRO's collaboration with FAST

A Cost Benefit Analysis framework has been used to estimate the net benefits of CSIRO's association with FAST, via the 19-beam receiver, and ongoing scientific collaboration under the research MOU between CSIRO and NAOC. A 7 per cent discount rate has been chosen consistent with the Office of Best Practice Regulation Cost-Benefit Analysis Guidance.[43] Costs and benefits are calculated from an Australian perspective.

The *net* present value of CSIRO's collaboration with FAST via the 19-beam receiver and MOU is estimated to be $13.2 million over 20 years (2014-2034), with a benefit-cost ratio of 3.1. This considers capital expenditure costs and estimated operational (employee) costs. Unknown maintenance costs are not considered.

Costs

19-beam receiver

The total project cost for the 19-beam receiver was $5.4 million. This included:

- 15.6 full-time staff equivalent (FTE) working an estimated combined total of 18.3 FTE years
- electronics
- facilities
- mechanical
- travel, and
- software licences.[44]

We have assumed an equal annual cost attribution over 5 years (2014-2018). This is $4.7 million in present value terms.

43 Australian Government (2016), *Cost-Benefit Analysis; Guidance Note*, Department of the Prime Minister and Cabinet – Office of Best Practice Regulation, https://www.pmc.gov.au/sites/default/files/publications/006-Cost-benefit-analysis.pdf

44 Hayman, D (2017), *CASS Project Review Board 128 – FAST Multibeam Receiver*, CSIRO, October, and CSIRO excel file 'FASTProjCosts'.xls

Operational costs of CSIRO and NAOC collaboration

We estimate annual operating expenditure of $184 000. This is $1.5 million in present value terms.

CSIRO incur costs associated with the ongoing management and execution of the NAOC collaboration, as well as subsequent research. For example, the research MOU allows NAOC access to Parkes radio telescope to provide a specific amount of observing service, including staff support, software support and data archiving for FAST.[45]

CSIRO advise that NAOC used approximately 10 per cent of observing time at the Parkes facility over recent years.[46] Twenty staff are employed at the Parkes facility.[47] We assume that two FTE equivalent staff are associated with NAOC activities,[48] at an annual cost of $91 867 per FTE.[49]

Benefits

The greatest impact for Australia of CSIRO's involvement with FAST is the ability to enhance an understanding of the universe and improve Australia's reputation and connections with the international research community. We estimate a total impact value of $19.4 million (present value) associated with:

- NAOC contract revenue
- value of publications and citations
- human capital formation
- expanded scientific footprint (increased scientific and research exports)
- an enhancement of Australian cultural value, and
- learning by doing benefits (table 3.1).

Qualitative benefits include:

- soft international diplomacy
- more cost-effective science, and
- potential innovations taken up by industry to improve productivity.

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45 'Memorandum of understanding FAST Follow-up Observations with the Parkes radio telescope between National Astronomical Observatories, Chinese Academy of Sciences and CSIRO'

46 CSIRO personal communication.

47 CSIRO (2019), CSIRO Australia Telescope National Facility Annual Report 2018–19, p. 8, https://www.atnf.csiro.au/the_atnf/annual_reports/2018/2018_AnnualReport.pdf

48 Applying the 10 per cent attribution.

49 We estimate the cost per FTE based on the average annual salary of a person employed in the 'Scientific Research Services' industry where that worker has a masters degree level qualification. This subset of the workforce has an average income of $1 767 per week, or $91 867 per year inflated to $2020 using the wage price index.

3.1 Summary of quantified impact value

Benefit	
	$million, PV
NAOC contract revenue	3.6
Value of publications and citations	8.4
Human capital	1.5
Expanded scientific footprint (increased scientific and research exports)	1.2
Cultural value	2.6
Learning by doing	2.0
Total	**19.4**

Note: 7 per cent discount rate and 20-year evaluation timeframe. All values are $2020.

Source: CIE.

NAOC contract revenue

CSIRO has executed numerous contracts with NAOC to provide FAST associated infrastructure and advice, with a total value of $4.3 million (nominal) (table 3.2).[50] [51] This is $3.6 million in present value terms.

3.2 NAOC contract revenue

Contract	Revenue
	$ nominal
Design, build and install FAST's Multibeam receiver	3.7
Searching for pulsars with FAST and the Parkes telescopes	0.2
Studying pulsars with FAST and the Parkes telescopes	0.1
Implementing a Fast-Folding Algorithm for FAST Pulsar Searching	0.1
Data Archiving: Pulsar Data Analysis with FAST	0.2
Total	**4.3**

Source: Hayman, D (2017), 'CASS Project Review Board 128 – FAST Multibeam Receiver', 27 October 2017; CSIRO personal communication.

Value of publications and citations

An estimated $8.4 million (present value) is attributed to the value of publications and citations. This assumes all the researcher time is attributable to CSIRO FAST collaboration projects and researches would otherwise not undertake any such research.

Value of publications

CSIRO's FAST association has spurred extensive research and several associated publications and citations, which serve as one measure of the value of knowledge output.

50 CSIRO personal communication

51 Hayman, D (2017), CASS Project Review Board 128 – FAST Multibeam Receiver, CSIRO, October

In line with the approach adopted by Florio et. al. (2015),[52] the value of publications can be deemed equivalent to the time taken to produce publications and the cost of researcher time. While not a measure of 'net benefit' of the CSIRO's involvement with FAST per se, this approach does show that an estimated $775 000 in researcher time is dedicated to the use of CSIRO's involvement with FAST each year (table 3.3).

3.3 Value of publications associated with CSIRO's FAST collaboration

Measure	Value	Unit	Source
Quantity of publications			
Number of refereed papers (2016 to March 2020)	35	publications	ATNF website, CSIRO and Google Scholar search
Number of refereed papers per year [a]	18	publications	Assumption
Average work required to produce a paper	0.4	FTE	Assumption[b]
Cost of academic work			
Weekly cost per FTE [c]	2 071	$/week	ABS
Annual cost per FTE	107 676	$/year	CIE calculation
Total value of publications			
Undiscounted value of 35 papers [d]	1 507 458	$	CIE calculation
Undiscounted value of 18 papers per year	775 264	$/year	CIE calculation

[a] We assume that 2019 is a representative year in which 18 papers were produced.

[b] The quoted average work required to produce a paper used in the evaluation of the Murchison Widefield Array, as stated in The CIE 2019, 'Pawsey: making Big things happen', Final Report prepared for the CSIRO on behalf of the Pawsey Supercomputing Centre, April 2019, unpublished,

[c] We estimate the cost per FTE based on the average annual salary of a 'Design, Engineering, Science and Transport Professional' working in the 'Scientific Research Services' industry where that worker has a Postgraduate Degree Level qualification. This subset of the workforce has an average income of $2 071 per week, or $107 676 per year inflated to $2020 using the wage price index.

[d] The value of papers produced is the product of the number of papers over the period (i.e. 35), the workload (0.4 FTE) and the value per FTE.

Source: Australian Telescope National Facility (ATNF) https://www.atnf.csiro.au/technology/receivers/FAST_Multibeam.html; CSIRO; CIE.

Value of citations

The value of citations is similarly estimated based on the value of researcher time and the time taken to read citations. Assuming it takes a researcher one hour to read and cite a paper,[53] and 1 900 citations per year, an additional $98 000 in value is generated annually through CSIRO FAST associated citations.

52 Florio, M., Forte, S. and Sirtori, E., (2015), 'Cost-benefit analysis of the Large Hadron Collider to 2025 and beyond', *arXiv:1507.05638v1,* https://arxiv.org/abs/1507.05638

53 Consistent with the assumption in Florio et al. (2015), as discussed by: Schopper, H (2016), 'Some remarks concerning the cost/benefit analysis applied to LHC at CERN', *Technological Forecasting and Social Change*, http://isidl.com/wp-content/uploads/2017/08/E4668-ISIDL.pdf

3.4 Value of citations associated with CSIRO FAST publications

Measure	Value	Unit	Source
Quantity of publications			
Rate of citations	1 900	citations/year	Assumption
Average time required to read and cite a paper	1	hour	Florio et. al. (2015)
Cost of academic work			
Weekly cost per FTE	2 071	$/week	ABS
Hourly cost per FTE [a]	52	$/hour	CIE calculation
Total value of citations			
Value of citations per year	98 358	$/year	CIE calculation

[a] We assume a working week of 40 hours.

Source: CIE.

Human capital benefits

An estimated $1.5 million (present value) is attributed to the uplift in human capital.

CSIRO advise an estimated 50 students are actively involved in FAST projects utilising the 19-beam receiver across 133 Principal Investigator programs from 21 institutions.[54] This is potentially an overestimation as it likely includes overseas institutions.

One way of measuring human capital benefits is to examine the increase in income of those who obtain a PhD qualification that would otherwise not have were it not for access to FAST data/research. While there are many factors that influence the attractiveness of higher education, the research opportunity presented by access to FAST data/observations is unique, without which arguably higher education in radio astronomy might be less attractive.

Even if CSIRO's collaboration with FAST did encourage a higher degree of academic research, it remains important to separate higher incomes that result from more (or better) education vis-à-vis higher incomes that result from an individuals' ability.

Leigh (2010)[55] uses robust econometric techniques to estimate, after controlling for 10 per cent upwards ability bias,[56] returns to Bachelor and higher degrees relative to no post-school qualifications as follows:

- Certificate level - 17 per cent higher annual earnings
- Bachelor degree - 45 per cent higher annual earnings, and
- Masters or Doctorate - 66 per cent higher annual earnings.

This implies a total return of:

54 CSIRO personal communication.

55 Leigh, A (2010), 'Returns to Education in Australia', Table 4, p.18, https://pdfs.semanticscholar.org/2ce4/58633ceceeac4b9cd48b612129bb2304d978.pdf

56 This is where people who complete post-graduate qualifications have higher ability that is independent of their decision to study. Estimates not accounting for upward ability bias are likely to overestimate the returns from education.

- 24 per cent (1+0.45)/(1+0.17) for a persons' Bachelor Degree compared to a person with a Certificate qualification, and
- 14 per cent (1+0.66)/(1+0.45) for a persons' Masters or Doctorate qualification compared to a person with a Bachelor Degree.

We assume that all the researchers that use the FAST data/observations would not have pursued their additional qualifications without the prospect of CSIRO's FAST collaboration.

Applying the Leigh (2010) premiums to 2016 ABS wage data of a 'Design, Engineering, Science and Transport Professional' working in the 'Scientific Research Services'[57] results in the following annual earnings improvements:[58]

- $10 587 per annum where that worker previously held a Certificate Level qualification and now holds a Bachelor Degree, and
- $12 258 per annum where that worker previously held a Bachelor Degree Level qualification and now holds a Postgraduate Degree.

Considering the number of estimated annual Doctorate students per year (table 3.5), and calculating income differentials from 2017, the un-discounted value of additional human capital associated with CSIRO's FAST collaboration is estimated at $3.2 million over a 20 year evaluation period.

3.5 CSIRO FAST supported tertiary qualifications

Qualification	Theses/degrees (on-going)	Average per year[a]
	Number	Number
Postgraduate Degree Level	50	14.3

[a] We assume that the 50 students are all completing a PhD qualification over a 3.5-year time period.

Source: CSIRO personal communication, CIE.

Expanded scientific footprint and international diplomacy

Expanded scientific footprint

An estimated $1.2 million (present value) is attributed to expanded scientific footprint (increased scientific and research exports). Astronomy plays an ongoing and important role in the broader bilateral Australia-China relationship, as it provides avenues for engagement and shows how Australia and China can be global partners. CSIRO's involvement with FAST is one part of the larger Australia China radio astronomy relationship, spanning over 40 years and underpinned by a continuous cycle of (chart 3.6):

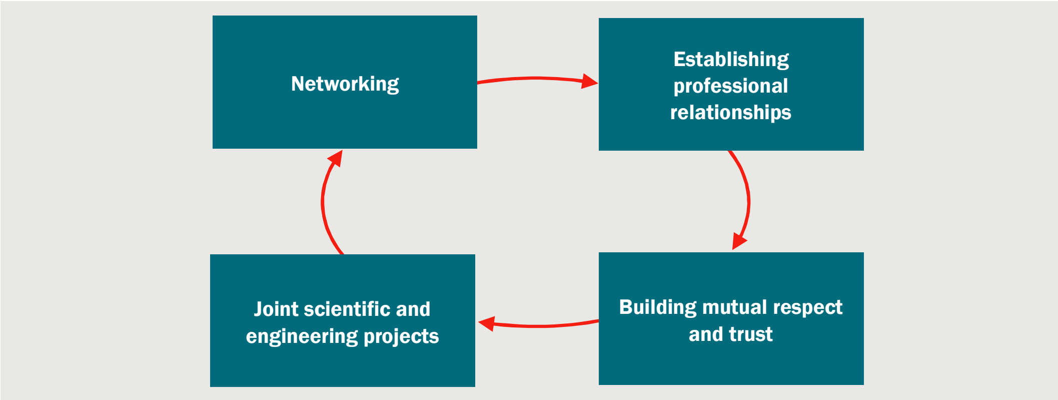
- networking
- establishing professional relationships

57 ABS 2016 Census - Counting Employed Persons, Place of Work (POW) Total Personal Income (weekly), converted to annual figures assuming 52 weeks per year.

58 Figures inflated to $2020 using the ABS Wage Price Index

- building mutual respect and trust, and
- joint scientific and engineering projects.

3.6 Australia China radio astronomy relationship dynamics



Data source: CIE.

The Australia China radio astronomy relationship commenced with ad-hoc networking and one-off project collaboration in the 1960's between Australian universities and Chinese radio astronomy organisations. The relationship became increasingly formalised from the early-1970s. For example:

- Australia established diplomatic relations with the People's Republic of China in 1972[59]
- Australia established an embassy in Beijing in 1973[60]
- a delegation from Beijing's Academia Sinica (now Chinese Academy of Sciences) visited Australia, including CSIRO in 1975[61], and
- The Vice President of Chinese Academy of Sciences visited CSIRO and senior CSIRO executives visited the Chinese Academy of Sciences during the 1970s[62]

Cooperation was then an emerging framework, formalised in the 1980's with the:

- 'Agreement between the Government of Australia and the Government of the People's Republic of China on Cooperation in Science and Technology'[63], and
- signing of a 'Research Cooperation Agreement between CSIRO and Chinese Academy of Sciences'.[64]

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59 Australian Government, 'China country brief: Bilateral relations', Department of Foreign Affairs and Trade, https://dfat.gov.au/geo/china/Pages/china-country-brief.aspx

60 Ibid

61 CSIRO (2015), 'Celebrating 40 years of collaboration with China 1975 — 2015', https://www.csiro.au/china/

62 Ibid

63 Australian Government (1980), 'Agreement between the Government of Australia and the Government of the People's Republic of China on Cooperation in Science and Technology,' http://www.austlii.edu.au/au/other/dfat/treaties/1980/14.html

64 CSIRO (2015), 'Celebrating 40 years of collaboration with China 1975 — 2015', https://www.csiro.au/china/

These agreements led the way for specific project collaborations between CSIRO and the Chinese Academy of Sciences, such as Very Long Baseline Interferometry (VLBI) joint telescope activities (box 3.7).[65]

3.7 Very Long Baseline Interferometry (VLBI)

Very Long Baseline Interferometry (VLBI), links together widely separated radio telescopes to allow astronomers to see the universe in more detail. A signal from an astronomical radio source is collected at multiple radio telescopes on Earth. This allows observations of an object that are made simultaneously by many radio telescopes to be combined, emulating a telescope with a size equal to the maximum separation between the telescopes.

Australian telescopes at Tidbinbilla, Parkes, Narrabri, Hobart, Alice Springs and Molonglo have been used for VLBI observations directly with China, as well as part of multi-nation telescope observations as part of the formation Australia-Pacific Telescope.[66]

Australian and Chinese radio astronomy collaborations continue with a vast number of specific projects, including: FAST, SKA Regional Centre Coordination Group and Antarctic Collaboration. Typically, each telescope facility has its own oversight committee to advise on engineering inputs for new and proposed facilities, and operational considerations for established ones.

In the FAST context, CSIRO was invited as part of an open tender process conducted by CAS to provide input on the telescope receiver during the initial design phase. The tender invitation came about due to CSIRO's previous work building telescope receivers for the Parkes facility (amongst others), and previous collaborations on other Chinese projects. The FAST invitation subsequently led to the 19-beam array receiver design and construct contracts, as well as the MOU.[67]

In 2013 the umbrella advisory panel, the Australia-ChinA ConsortiuM for Astrophysical Research (ACAMAR), was founded as an outcome of a formal high-level meeting held under the auspice of the 1980 Cooperation in Science and Technology Agreement. ACAMAR's goal is to collaborate on areas of common interest within astronomy, astrophysics and cosmology.[68] Broadly speaking, ACAMAR provides:

- a forum to discuss progress on current projects, and
- an opportunity for additional informal scientific networking, exchange of ideas and potential collaboration on future research and engineering projects.

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65 CSIRO communication.

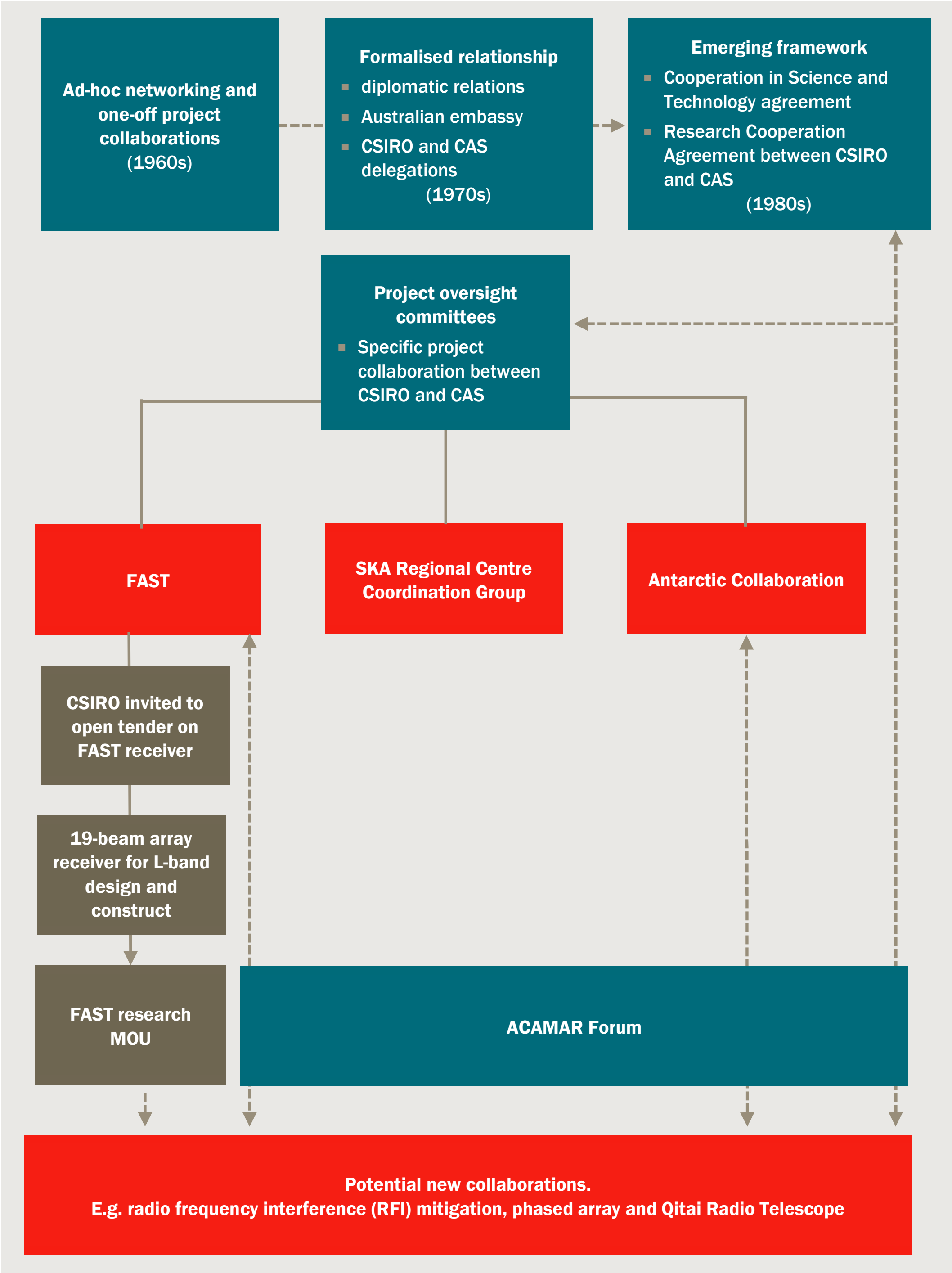
66 Jauncey, D.L (1991), 'VLBI in Australia A review', *Australian Journal of Physics 44(6)*, pp. 785 -804, https://www.publish.csiro.au/ph/pdf/PH910785

67 CSIRO personal communication.

68 https://acamar.org.au/

Current ACAMAR identified collaboration projects are FAST, Square Kilometre Array (SKA) Regional Centre Coordination Group,[69] and Antarctic Collaboration.[70]

3.8 Australia China radio astronomy relationship overview



Notes: Blue boxes are relationships, red boxes are projects, grey boxes are outputs, unbroken lines indicate a formal link, dashed lines indicate an informal link. CAS (Chinese Academy of Sciences). ACAMAR does not have any formal oversight of the SKA project.
Data source: CSIRO communication; CIE.

69 ACAMAR does not have any formal oversight of the SKA project.

70 https://acamar.org.au/projects/

Going forward, CSIRO and CAS are engaged in ongoing discussions about collaborations on new projects on the back of specific project successes (including FAST), and the ACAMAR forum. Examples include, radio frequency interference (RFI) mitigation, phased array feeds and the Qitai Radio Telescope.[71]

Framework for estimating the benefits of export promotion

The ongoing networking and associated activities between CSIRO and CAS (and more broadly between Australia and China) are akin to marketing of Australia's export research and engineering capabilities. A supply-and-demand model is a useful framework for illustrating the benefits of export promotion. This framework considers the benefits from export promotion that increases the volume of exports.[72]

Suppose that before any marketing activities Australian research and development and engineering services are exported at price P_0 and quantity Q_0 (chart 3.9).

If, following marketing activities, there is an increase in the quantity of Australian research and development and engineering services demanded by China (shift from Q_0 to Q_1) there will be a subsequent increase in the price of Australian research and engineering services for supply and demand to remain in equilibrium (price shifts upward from P_0 to the new higher price of P_1). This change in price may occur with a time lag.

The economic benefits to Australian research and engineering service suppliers associated with this higher price and quantity is referred to as producer surplus. Producer surplus is the difference between the amount the producer is willing to supply goods for and the actual amount received once traded. Producer surplus is roughly equal to profit.

Producer surplus is calculated using the following equation:

$$Producer\ surplus = \frac{1}{2} \times \Delta Q \times \Delta P$$

where

- ΔQ is the total change in exports of Australian research and development and engineering services, and
- ΔP is the price change of research and engineering services export markets.

Initially, producer surplus is represented by the blue shaded area in chart 3.9. That is:

$$Producer\ surplus = \frac{1}{2} \times (Q_0 - 0) \times (P_0 - 0)$$

Following the increase in price, producer surplus is now represented by the blue shaded area plus the red shaded area. That is:

$$Producer\ surplus = \frac{1}{2} \times (Q_1 - 0) \times (P_1 - 0)$$

The increase in producer surplus attributable to the scientific marketing activities is the difference between the initial producer surplus and the new producer surplus associated

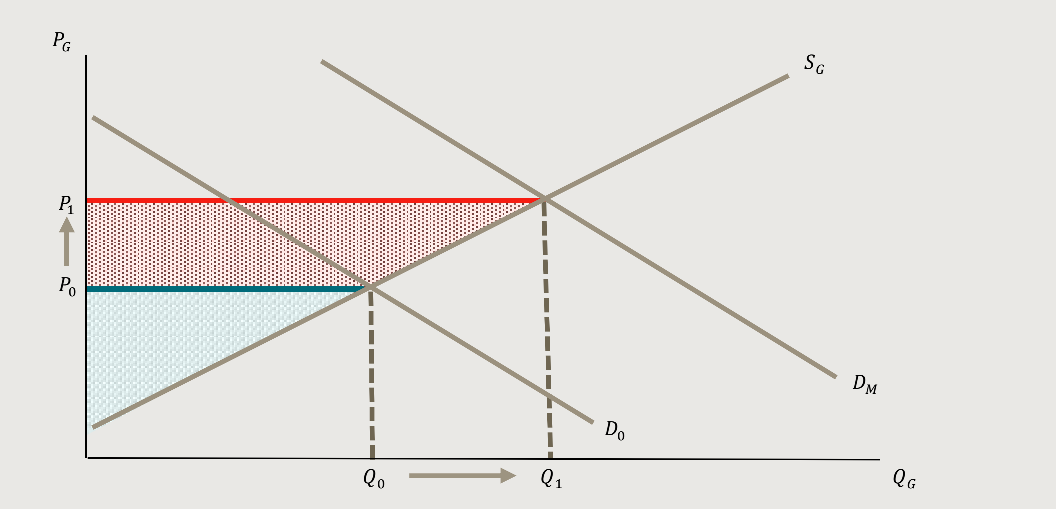
71 CSIRO communication.

72 That is such a change in export volumes involves a movement along the supply curve, and therefore an increase in price and total value of exports.

with the price increase. Hence, the increase in producer surplus is represented by the red shaded area and can be calculated as follows:

$$Increase\ in\ producer\ surplus = ((P_1 - P_0) \times Q_0) + (\frac{1}{2} \times (Q_1 - Q_0) \times (P_1 - P_0))$$

3.9 Framework for estimating the benefits attributable to export promotion



Data source: The CIE.

Australia exported an average $30.8 million per year of research and development and engineering services to China, over the period 2009 to 2016 (table 3.10).[73] This represents the post demand shift project case revenue (area under the rectangle bounded by P_1 and Q_1), as it occurred after Australia China science marketing activities.

It is not possible to definitively determine the amount of annual research and development and engineering export service revenues to China associated with the base case (area under the rectangle bounded by P_0 and Q_0). That is, what would have occurred in the absence of CSIRO marketing activities. To derive an estimate of the base case, we assume that 1 per cent ($0.31 million)[74] of the total annual research and development and engineering services revenue to China are attributed to the CSIRO FAST collaboration. The change in producer surplus (red shaded area) attributable to CSIRO's FAST collaboration is then $0.15 million per annum.[75]

73 Australian Government (2018), 'Australia's Trade In Services With China: Attachment A Australia's Service Exports To China By Type Of Activity (A$ million),' p. 13, Department of Foreign Affairs and Trade, https://dfat.gov.au/about-us/publications/Documents/australias-trade-in-services-with-china.pdf

74 0.01 × $30.8 million = $0.31 million.

75 0.5 × $0.31 million = $0.15 million.

3.10 Australia's Trade in Research and Development and Engineering Services with China

Service - Type of activity	2009	2011	2013	2015	2016	Average
	$ million	$ million	$ million	$ million	$ million	$ million
Research and development	2.0	15.0	4.0	8.0	7.0	7.2
Engineering	32.0	39.0	24.0	19.0	4.0	23.6
Total	**34.0**	**54.0**	**28.0**	**27.0**	**11.0**	**30.8**

Source: Australian Government (2018), 'Australia's Trade In Services With China: Attachment A Australia's Service Exports To China By Type Of Activity (A$ million),' p. 13, Department of Foreign Affairs and Trade, https://dfat.gov.au/about-us/publications/Documents/australias-trade-in-services-with-china.pdf; CIE.

This analysis assumes that the cost of additional production increases at a constant rate, resulting in half of the increased export revenue associated to an increase in producer surplus. It may be the case that CSIRO has increasing costs to supply additional research and development and engineering services, due to a high proportion of fixed costs. This would imply a greater association between increased export revenue to the change in producer surplus, ranging from half (value of 0.5), to all the export revenue change (value of 1). Sensitivities are shown in table 3.11.

3.11 Change in trade revenue producer surplus sensitivity

Proportion of total revenue	Change to Producer surplus
Number	$ million
0.5	0.15
0.75	0.23
1	0.31

Source: CIE.

International diplomacy

The CSIRO collaboration with FAST was recognised by the Australian Government as strengthening Australia-China diplomatic relations, as outlined in the *45 Years, 45 Stories* initiative.[76] The 45 years, 45 stories is a recognition of the 45th anniversary of Australia-China diplomatic relations in 2017. CSIRO's collaboration with FAST was chosen as one story told from Australian and Chinese perspectives that speak to the breadth and depth of the friendship between Australian and Chinese peoples.

Further, CSIRO's collaboration with FAST is directly aligned to:

- **The Foreign Policy White Paper**

  "Australia's institutions and expertise are themselves important sources of influence internationally … [The Australian Government] will continue to promote Australia's excellence in education, science and research and the creative industries…

76 http://en.45stories.com/about/

Many Australian researchers are experts in their field and hold influential positions in international organisations. Our science diplomacy, such as our joint research initiatives with China and India, strengthens bilateral relationships."[77]

- **The Global Innovation Strategy, which is part of the National Innovation and Science Agenda**

  "The government will continue to support Australia's position as a global leader in education and research. A strong focus on international partnerships will help increase researcher mobility and collaboration. By capitalising on our existing research strengths [the Government] will leverage our capacity to deliver solutions to national, regional and global challenges."[78]

In this regard, CSIRO's collaboration with FAST (amongst other projects) has facilitated CSIRO to maintain its status as a sought after advisor and engage in soft diplomacy. For example, both the 19-beam receiver contracts and research MOU provided for mutually beneficial future scientific research collaboration. This will lead to the continued cross pollination of scientific thinking and behaviour through the power of common attraction and ideas.

Framework to estimate improvements in soft diplomacy

The Lowy Institute Asia Power Index is an analytical tool that ranks 25 countries and territories in terms of a country's power and influence, using eight key measures:

1. economic resources
2. military capability
3. resilience
4. future resources
5. diplomatic influence
6. economic relationships
7. defence networks, and
8. cultural influence.[79]

These key measures are underpinned by various distinct sub-measures. The sub-measures of relevance to CSIRO's collaboration with FAST are:

- technology
  - the technological and scientific sophistication of countries
- regional trade relations
  - the ability to influence other countries through bilateral trade flows and relative dependencies.
- information flows

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77 Australian Government (2017), 'Foreign Policy White Paper', pp. 8, 13, https://www.fpwhitepaper.gov.au/foreign-policy-white-paper

78 Australian Government (2016), 'Global Innovation Strategy: A strategy to advance Australia's international industry, science and research collaboration', p. 13, https://publications.industry.gov.au/publications/globalinnovationstrategy/assets/Global-Innovation-Strategy.pdf

79 https://power.lowyinstitute.org/methodology

  - the regional appeal of a country's media outlets and universities.
- people exchange
  - the depth and influence of a country's people-to-people links in the region.[80]

Australia ranked seventh in 2019 on the Lowy Institute Asia Power Index, underpinned by strong results in these categories.

Cultural value

An estimated $2.6 million (present value) is attributed to the uplift in cultural value.

CSIRO has benefited from an uplift in cultural interest, via its association with NAOC and subsequent interest in CSIRO research. For example, media articles[81] and social media hits.[82]

Florio et. al. (2015) in their cost-benefit analysis of the Large Hadron Collider suggest the uplift in cultural value attributable to scientific research institutions can be measured via willingness to pay studies (amongst other methods).[83] Florio et. al. (2018)[84] estimate an annual per person willingness to pay of 13.5 Euros for investment in particle physics research using the Large Hydron Collider. We have extrapolated this value (after converting to $2020 Australian dollars) to estimate a per person annual cultural value of $0.02 for the 19-beam receiver and $0.80 for FAST. This assumes a linear relationship between infrastructure spend and per person cultural value. An exponential relationship would result in much lower per person cultural values (chart 3.12).

Applying these values to the adult Australian population results in a per annum cultural value of $0.3 million for the 19-beam receiver and $15.7 million for FAST (table 3.13).

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80 https://power.lowyinstitute.org/methodology

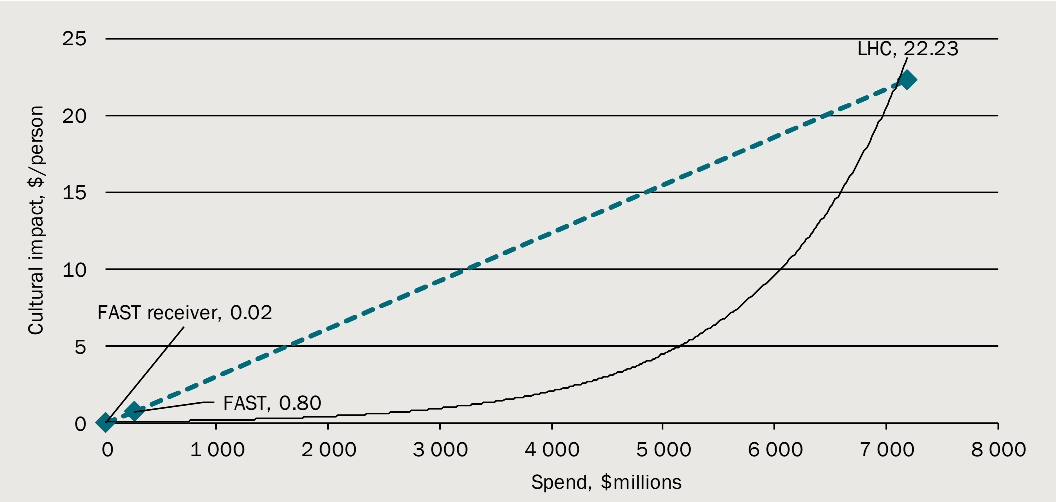
81 Birtles, B (2017), ‘Aperture Spherical Telescope: Vital Australian link about to be installed on world's biggest telescope’, Australian Broadcasting Corporation, https://www.abc.net.au/news/2017-12-17/csiro-made-device-for-aperture-spherical-telescope-in-china/9265692

82 For example, https://twitter.com/search?q=CSIRO%20FAST%20radio%20telescopeandsrc=typed_query

83 Florio et. al. (2015), *Cost-Benefit Analysis of the Large Hadron Collider to 2025 and beyond*, https://www.researchgate.net/publication/280330461_Cost-Benefit_Analysis_of_the_Large_Hadron_Collider_to_2025_and_beyond

84 Florio et. al. (2018), ‘Should Governments Fund Basic Science? Evidence from a Willingness-to-pay Experiment in Five Universities,’ *Departmental Working Papers 2018-10, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano,* as stated in Florio (2019), ‘Investing in science: Social cost-benefit analysis of research infrastructures, chapter 9, Taxpayers: Science as a Global Public Good’, p. 266, Cambridge, MA, *The MIT Press*

3.12 Relationship between science infrastructure spend and cultural impact



Note: A US/AUD exchange rate of 1.51 has been used to convert FAST capital costs, and a Euro/AUD exchange rate 1.62 has been used to convert Large Hydron Collider capital costs to Australian dollars.

Data sources: Florio et. al. (2018), 'Should Governments Fund Basic Science? Evidence from a Willingness-to-pay Experiment in Five Universities,' *Departmental Working Papers 2018-10, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano;* https://www.sciencealert.com/china-s-huge-500-meter-fast-radio-telescope-is-finally-up-and-running; https://www.forbes.com/sites/alexknapp/2012/07/05/how-much-does-it-cost-to-find-a-higgs-boson/#34d275833948; CIE

3.13 FAST cultural value to Australia

	Per person benefit	Australian adult population	Annual benefit
	$/person	Millions	Millions
19-beam receiver	0.02	19.8	0.3
FAST	0.80	19.8	15.7

Source: ABS (2019), '31010DO002_201906 Australian Demographic Statistics', June 2019, https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3101.0Jun%202019?OpenDocument; CIE

Learning by doing

We estimate an associated productivity enhancement of $2.0 million (present value).[85]

Highly specialised components and techniques were used in the 19-beam receiver build, which are constantly evolving due to technical advances. The 19-beam receiver project provided an opportunity for CSIRO to enhance their knowledge and skills, which have been applied in subsequent projects. For instance, the Low Noise Amplifier bias cards and the control and monitor system formed the basis for the subsequent Parkes Ultra-Wideband Receiver. CSIRO advise the knowledge and know how acquired in the 19-beam receiver project has an approximate value of in labour 2 FTE years that were saved on subsequent projects.[86]

85 Applying an annual salary of $125 102 per FTE, as per ABS 2016 Census - Counting Employed Persons, Place of Work Total Personal Income for Engineering Design and engineering consulting services, for the period 2018 to 2034, discounted using a 7 per cent discount rate.

86 CSIRO personal communication.

More cost-effective science

The 19-beam receiver is the largest multibeam receiver of its kind. Several bespoke design elements were incorporated into the final product to achieve low noise, high dynamic range, adequate gain and system stability.[87] As noted earlier, FAST is the largest single reflector telescope in the world, and has improved sensitivity by a factor of 2, increased survey speed by a factor of 5-10 and covers 2 to 3 times the sky area compared with pre-existing telescopes.[88] This improves astronomers' ability to survey the galaxy more precisely (less noise), with increased data/observations.[89]

The research benefit of more precise observations (less noise) is a reduction in the amount of individual resources necessary to participate in research, with more time available for data analysis as opposed to simple collection.

Further, observing predetermined areas of the sky at consistent intervals and varied wavelengths helps astronomers distinguish common events from anomalies, and build out a more comprehensive image of our skies.[90]

Directly quantifying this productivity gain is difficult. The 19-beam receiver has facilitated a productivity improvement in radio astronomy, with more data collection and targeted research outcomes now possible per given dollar spent on building new telescopes. The benefits of this new data and research are likely to be widespread and diffuse worldwide,[91] however its underlying "use value" is currently unknown. An indirect lower bound measurement of the 19-beam receiver's productivity value is the $3.7 million paid by NAOC for its construction and installation on FAST.

Industry innovation

Productivity enhancing industry innovations can be spurred by access to FAST data/observations, particularly for industry sectors that are impacted by data analytics. The industries that are most related to the FAST and related research include:

- data processing and web hosting services
- scientific research services
- scientific testing and analysis services, and
- computer system design and related services.

FAST, utilising the 19-beam receiver, is the latest in a line of new telescopes to exponentially advance our astronomy observation capabilities. The speed of the

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87 CSIRO (2019), 'Multibeam receiver for FAST', Australia Telescope National Facility, https://www.atnf.csiro.au/technology/receivers/FAST_Multibeam.html

88 Smith, S.L et. al. (2016), 'Analysis of the Five-hundred-metre Aperture Spherical radio Telescope with a 19-element Multibeam Feed', *2016 IEEE International Symposium on Antennas and Propagation*, p. 383

89 Kanapathippillai, J et. al. (2017), 'The FAST Multi-beam Receiver Design with RF over Fiber Link', *IEEE Asia Pacific Microwave Conference* (APMC)

90 Andersen, R (2012), *How Big Data Is Changing Astronomy (Again),* The Atlantic, April, https://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy-again/255917/

91 Referred to as a public good due to it being non rivalrous and non-excludable.

exponential astronomy data acquisition has been likened to Moore's Law, and presents challenges to our current data ICT storage, analysis and transmission infrastructure.[92]

This ever-increasing growth in data has spawned demand for new innovations in big data collection, storage and manipulation. For example, FAST will produce an estimated 18.8 Peta Bytes of data per annum, requiring a throughput data rate capability of 150 tera bytes/day.[93] Given this, NOAC contracted CSIRO to prepare and deliver advice on the requirements for the data archiving of pulsar and spectral line data from FAST. CSIRO was requested for this advice due to their experience with the Parkes Pulsar Data Archive (PSRDA), and the CSIRO ASKAP Science Data Archive (CASDA) (box 3.14).[94]

3.14 Parkes Pulsar Data Archive and CSIRO ASKAP Science Data Archive

Parkes Pulsar Data Archive (PSRDA)

In 2011, the Parkes Pulsar Data Archive (PSRDA) was implemented as one of the first two components of CSIRO's data management strategy. In the initial implementation, data at the ATNF's Marsfield site was made available for discovery and download. This provided a significant improvement in the ability for scientists who were not onsite at Marsfield to access Parkes pulsar observations. Later enhancements improved the storage, so data was stored in read-only file-systems in multiple locations, ensuring the data was resilient to media failures and site issues.

CSIRO ASKAP Science Data Archive (CASDA)

Starting in 2014, CSIRO developed an archive for the Australia Square Kilometre Array Pathfinder (ASKAP) telescope called the CSIRO ASKAP Science Data Archive (CASDA). A key requirement for CASDA is the need for automatic, unattended deposit of processed ASKAP data. The aim has been for CASDA to operate on the same pseudo-real time timescale as the ASKAP soft processing pipeline. ASKAP generates around 20TB per day of data products that are to be archived, however CASDA has achieved deposit rates consistent with depositing 50TB/day, thus allowing significant catch-up capacity in the event of a backlog. The CASDA system is focused on imaging data, including continuum, spectral line and polarisation data cubes and catalogues of the data, including source catalogues generated from the image cubes. However, the system was designed to be readily extensible to new types of data, such as pulsar observations or fast radio bursts (FRB).

Source: Dempsey, J et. al. (2017), 'Data Archiving – Pulsar Data Analysis with the FAST Telescope: Review copy', pp. 9-10, CSIRO

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92 Andersen, R (2012), *How Big Data Is Changing Astronomy (Again),* The Atlantic, April, https://www.theatlantic.com/technology/archive/2012/04/how-big-data-is-changing-astronomy-again/255917/

93 Dempsey, J et. al. (2017), 'Data Archiving – Pulsar Data Analysis with the FAST Telescope: Review copy', p. 26, CSIRO

94 Ibid

A CSIRO FAST associated published research or conference papers

A.1 CSIRO FAST associated published research or conference papers

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Note: Identified papers produced over the period 2016 to March 2020.

Source: Australia Telescope National Facility 2019, *Multibeam receiver for FAST,* CSIRO, https://www.atnf.csiro.au/technology/receivers/FAST_Multibeam.html; CSIRO communication; Google Scholar search “FAST 19-beam receiver.”

B Evaluation of CSIRO's collaboration with FAST using the National Benefit Scorecard

An assessment of CSIRO's collaboration with FAST against CSIRO's National Benefit Scorecard (test phase) is presented in table B.1. A traffic light system has been used where:

- 🔴 = No alignment with benefit type
- 🟡 = Somewhat aligned with benefit type, and
- 🟢 = Strong alignment with benefit type.

B.1 Assessing FAST collaboration against CSIRO's National Benefit Scorecard (test phase)

Benefit type	Score	Rationale for score
Support Government foreign policy agenda		
Direct alignment to a priority sector of Government/National Challenge	🟢	CSIRO's collaboration with FAST is directly aligned to: ▪ the Foreign Policy White Paper, and ▪ the Global Innovation Strategy, which is part of the National Innovation and Science Agenda.
Enhances Australia's reputation as a significant global contributor to complex problems	🟢	CSIRO's 19-beam receiver project demonstrated Australia's scientific research and manufacturing capabilities.
Attract (or potential to) investment into Australia	🟢	CSIRO's collaboration with NAOC resulted in a direct export contract to build the 19-beam receiver, as well purchased telescope time at the Parkes facility for follow up scientific analysis of FAST data.
Contributes to foreign policy development/specific agenda in a region/country	🟡	Foreign policy development was not a core objective of the project. However, CSIRO's ongoing collaboration with NAOC has facilitated soft diplomacy. For example, the use of the Parkes facility to verify FAST discovered new pulsars and the signed MOU provides for mutually beneficial future scientific research collaboration.
Contributes to a secure Australia (health, defence, security, biosecurity)	🟡	Increasing collaboration with NAOC indirectly improves Australia's diplomatic relationship with China and associated regional standing, via the ability to influence the behaviour and thinking of others through the power of attraction and ideas.
Enhance our scientific standing, access to capability and talent		

Benefit type	Score	Rationale for score
Partnership with World class institutes to enhance global standings		Collaboration between CSIRO and NAOC has further strengthened the relationship with CAS.
Provides access to infrastructure and/or capability not otherwise available in Australia		CSIROs collaboration with NAOC and associated access to FAST data/observations, directly improved Australian access to scientific infrastructure not available in Australia.
Conduct of collaborative world-leading research to solve a global problem		CSIRO's collaboration with NAOC demonstrates world-class research and CSIRO's ability in radio astronomy, and not necessarily global "problems".
Promotion of CSIRO's research capability in global markets		CSIRO's ongoing collaboration with NAOC and supplementary research utilising FAST data/observations promotes CSIRO's capabilities as a world class scientific research organisation.
Increase (or potential to) CSIROs capacity to deliver impacts domestically		CSIROs collaboration with FAST developed CSIRO staff members skills in design, testing and installation of scientific infrastructure. These skills have been transferred to domestic projects as well as other international work.
Capture the value of CSIRO's innovations and services		
Financial ROI (potential) to CSIRO is evident		CSIRO achieved an uplift in financial revenue. However, it is not clear if a definitive ROI was achieved, due to incomplete labour cost records. Improved labour time recording was identified as a lesson learned in the 19-beam receiver project post completion review.
Market opportunity is greater than domestic opportunity		The international market for radio astronomy is greater than the domestic market opportunity. Engaging with an international agency has provided additional research and development opportunities for CSIRO staff.
Creation of industry - research linkages		A key part of the CSIRO's collaboration with NAOC is fostering research industry links via formal collaboration, underpinned by the signed MOU.
Promotion of CSIRO's innovation and capacity in global markets		The 19-beam receiver contract showcased CSIRO as a world-renowned scientific infrastructure manufacturer.
Leverage of existing investment for greater impact		All project funds generated are associated with government agencies or education facilities.
Create pathways to global markets for Australian innovation		
Develop strategic partnership with an SME and/or Domestic University		CSIRO's MOU with NAOC is an example of developing strategic partnerships.

Benefit type	Score	Rationale for score
CSIRO's value-add to the partner is evident- through a number of benefits – technology innovation, access to capability, access to global investment funding		The 19-beam receiver project and subsequent MOU with NAOC has demonstrated CSIRO's value add in the radio astronomy research and development sector. This includes advancement in radio telescope sensitivity, as well as NAOC's access to CSIRO staff/resources to test FAST and confirm its discovered PTAs.
Attract (or potential to) investment back into Australia		The 19-beam receiver resulted in $3.74 million in revenue from NAOC to CSIRO, with the subsequent MOU providing additional international investment.
New market is accessed where opportunity is greatest		China is a known leader in radio astronomy infrastructure building. The 19-beam receiver project and established relationship with NAOC has positioned CSIRO to capture these new market opportunities.
Promotion of Australia's innovation and research capability globally		The 19-beam receiver contract showcased CSIRO as a world-renowned scientific infrastructure manufacturer.

Note: = No alignment; = Somewhat aligned = Strong alignment.

Source: CSIRO, 'National Benefit Scorecard – Test phase'; CIE.

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