Radio Science: an Australian perspective

Ross McPhedran, Member, National Committee for Space and Radio Science,
Australian Academy of Science

June 7, 2021

Abstract

A survey of Radio Science organised according to the Commissions of URSI, stressing Australian achievements and impact. The main focus is on the areas of early history of radio, radio astronomy, and optics/ photonics.

1 Introduction

This article is a combined brief history of the field of Radio Science, particularly emphasised as it affected Australia, and a discussion of some notable current day activities within or affecting this country. The presentation is my own account, but has benefited from the cooperation and advice of a number of experts, who are listed in the Acknowledgements section. Given space requirements, the article cannot be comprehensive, but it attempts to present in a lively fashion a field with a long and significant history in this country, once widely considered to be important, but today perhaps regarded as [1]:

> A topic in a permanent state of decline, rather like Viennese music or English cricket.

The field of Radio Science suffers perhaps from its name, in that today this seems to cover a narrow scope, but when the field began it described the science and technology of a new and very important method of communication, which was bringing far flung nations closer together, and raising for solution new questions about the generation and propagation of electromagnetic waves, their use for the transmission and acquisition of information. As a member of the British Commonwealth located on the other side of the world from what was described as the Mother Country, it was natural that Australia would benefit early form this new field, and contribute significantly to it.

The scope of Radio Science can be gathered from the list of the Commissions of the Union Radio-Scientifique Internationale, the international organisation devoted to the field:
Electromagnetic Metrology; Fields and waves; Radiocommunication Systems and Signal Processing; Electronics and Photonics; Electromagnetic Environment and Interference; Wave Propagation and Remote Sensing; Ionospheric Radio and Propagation; Waves in Plasmas; Radio Astronomy and Electromagnetics in Biology and Medicine.
Other organisations cover part of this scope (OSA, SPIE, IEEE, IAU, IGU, AOS, etc) but URSI seems to be the one with the largest umbrella. From the list of topics, we see that related research activity will be found in organisations carrying a range of descriptions. In Australia, for example, that list would include university departments (Physics, Mathematics, Engineering, etc), and various branches of CSIRO.

2 Early History of Radio Science

The early history of Radio Science is an example of a quote from Maxwell himself:

There is nothing more practical than a good theory.

The following account of it is based on the excellent book of David Park [2], recommended as good reading or as the basis of a "Physics for poets" course.

The birth year of Radio Science may be confidently stated as being 1865, and its paternity as Scottish. James Clerk Maxwell was then Professor at King's College London, and was seeking to place the empirical deductions of the self-taught genius Michael Faraday on a firm theoretical basis. The difficulties were not only physical but mathematical: the differential operators now used to express Maxwell's equations were not yet developed, and so Maxwell used Hamilton's quaternions to fill this gap. The new arrival was announced in a paper entitled *A Dynamical Theory of the Electromagnetic Field*. One of its most important conclusions is expressed in the simple equation

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}, \tag{1}$$

Here the quantities appearing on the right are the force constants for the electrostatic and magnetostatic fields, and the quantity on the left is dimensionally a speed. The force constants being known, and the speed of light having being measured, Maxwell could compare the two sides, and infer that the speed so expressed is that of light in vacuo, and make the interpretation that light is in fact an electromagnetic wave. The electric and magnetic fields of this wave oscillated in time, and were at right angles to each other and to the direction to wave propagation. This triumph of intuition and reasoning was enough[3] to earn Maxwell's picture a place of honour in Einstein's office but not on a Scottish banknote!

Heinrich Hertz in 1887 conducted decisive experiments demonstrating the generation and properties of the electromagnetic waves predicted by Maxwell. The waves were generated using a spark gap powered by a high voltage induction coil, and had a frequency of roughly 50 MHz. They were detected by observing tiny sparks in micrometer spark gaps in loops of wire [4]. Hertz performed a range of experiments demonstrating standing waves, refraction, diffraction, polarisation and interference of the waves.

Hertz inspired a number of other investigators, who performed related experiments at different frequencies- for example Jagadish Chandra Bose produced waves of wavelength around 5 mm. Due to the high frequency of operation, Hertz's waves could not travel beyond the horizon. This was believed by many to be a fundamental limit on the propagation of Hertzian waves, as it was thought that they necessarily propagated along straight lines like light. Oliver Lodge in 1894 speculated that their maximum transmission distance was only around 600 m. Thus, they were not at first considered as opening up new possibilities for long-distance communication.

3 I've Gotta Get a Message to You

Guglielmo Marconi commenced research in Italy in 1894 with the idea of overcoming the distance barriers which prevented Hertzian waves from being regarded as offering a new and flexible approach to long distance communication, rivalling or even supplanting the telegraphic method. His innovations were evolutionary rather than revolutionary, with transmitters still based on spark gaps, but with circuit refinements and elevated antennas (see Fig. 1). He soon surpassed Lodge's postulated transmission limit of 600 m. At the age of 21 he went to England, and was quickly successful in gaining interest and support from the British Post Office. By 1898, the British lightship service had authorised the linking by wireless of Dover and the East Goodwin lightship, separated by a distance of 19 km. On 17 March 1899 the East Godwin lightship transmitted an SOS message to Dover on behalf of a merchant vessel grounded on Godwin Sands [5].

Marconi then commenced work on achieving transatlantic communication. With increased transmission power from his station at Poldhu in Cornwall, he was able to demonstrate by 1902 shipborne reception at over 3000 km. That same year a successful transmission of a message took place between the Marconi station in Nova Scotia and the United Kingdom.

Marconi had established his eponymous company in 1897, and followed this with Canadian Marconi and American Marconi. These companies at first dominated ship to shore communication, and refused communication with non-Marconi equipped ships. Unfortunately, the Marconi Company name ceased to exist in 2006, a victim of the Tech Wreck.

In 1904, the Marconi Company in Australia established two temporary wireless stations in Australia, one in coastal Victoria and the other in northern Tasmania. Round 1910, the Australian Government planned a network of coastal stations ringing the continent. Each was to have a spark gap transmitter, a tall tower aerial and a simple crystal set receiver. Interestingly enough, given events shortly to occur, the two largest stations in Sydney and Perth were designed and installed by the German company, Telefunken [6]. They had a 25 kW spar gap transmitter, which delivered 8 kW into the transmitter system. Other coastal radio stations were set up around the Australian coast and throughout the islands of the South Pacific. One interesting development was made by Mawson for his 1911 expedition to Antarctica. He established a manned relay station on Macquarie Island to link his base in Commonwealth Bay with Hobart.

The role of wireless in the sinking of the Titanic in 1912 is well known. The Titanic was equipped with a 5 kW transmitter, and had two operators, both employed by the Marconi Company, and not by the White Star Line. Their primary responsibility was to send messages for the passengers, and not to gather weather information for the ship's captain. Consequently, not all the reports warning of icebergs sent by other ships close by were forwarded to the captain. When the severity of the ice strike became apparent, SOS messages were sent out. These enabled the ship Carpathia to arrive around 90 minutes after the sinking, and rescue over 700 passengers. This incident greatly increased public understanding of the vital role the new technology could play.

The Nobel Prize for Physics in 1909 was awarded jointly to Marconi and Karl Ferdinand Braun "in recognition of their contributions to the development of wireless telegraphy." Some later contributions in Radio Science receiving a Nobel Prize will be mentioned subsequently.

Figure 1: Marconi with the equipment used for long-distance transmission in the 1890's. The transmitter is at right, with the receiver and paper tape printer at left. (LIFE Photo Archive: 4a204d82f07524bd.)

4 The War to End All Wars

At the beginning of the First World War, Winston Churchill was a member of the Liberal Government, and First Lord of the Admiralty. As a result of prior agreements in relation to the eventuality of war, this made him Head of the newly formed Australian Navy. His first order is interesting, as it indicates the importance of good communications, and in particular wireless networks, to the war effort [7]:

> If your Ministers desire and feel themselves able to seize German wireless stations at Yap, the Marshall Islands, Nauru or Pleasant Island and New Guinea, we should feel that this is a great and urgent Imperial service.

A second instance of this is the destruction in battle of the German cruiser Emden by HMAS Sydney in November 1914. Sydney caught the Emden at Direction Island in the Cocos group, where the German raider had a landing party engaged in destroying the cable and wireless communication station. The station personnel had already communicated the Emden's arrival to an escorted convoy passing nearby. Sir Henry Newbolt, self-declared poet laureate of the Royal Navy, saluted the work of the Australian gunners in enthusiastic, if not erudite, lines [7]:

> Their hearts were hot, and as they shot,
> They sang like kangaroos."

While the First World War began as a rapid advance by German forces, it settled down to a bloody stalemate on the Western Front, with virtually static lines of trenches facing each other. However, technology was increasing in sophistication and in importance to military operations. Some examples are obvious: the rapid growth of military aviation, tanks, chemical weapons etc., but less obvious while still important was communication technology [8]. To the obvious telegraphy was added the telephone, wireless telegraphy and later wireless telephony. Increasing use of these was made in applications such as radio direction finding. Triangulation was used to locate enemy wireless transmitters, and particular transmitters were often associated with particular divisions, leading to knowledge about troop positioning. This technique was also employed by the Royal Navy to locate torpedo ships, mine layers and submarines. Wireless transmitters were increasingly lighter and more portable, able to be used in observation balloons and tanks, and finally in areoplanes. Attempts were also begun to use radio detection of lightning over the Atlantic to predict the arrival of fronts, aiding in planning of major attacks.Robert Watson-Watt commenced work on this project in 1915. Such applications of radio direction finding set the stage for the development of radar prior to the Second World War.

5 The Radio Science Community Post Bellum

After the Great War, a significant world political reordering occurred, with territory of the losing powers redistributed among the winners. For example, German New Guinea was placed by the newly formed League of Nations under Australian control as a mandate. Around the same time, a significant reorganisation of world science was occurring, with the setting up of specialist organisations representing practitioners and researchers in various sub-fields of importance.

Among the new bodies in Radio Science, the American Institute of Electrical Engineers had been in existence since 1884, but was joined by the Institute of Radio Engineers, founded in 1912. The two merged in 1963, to form the IEEE, which claims to be the world's largest association of technical professionals. The American Geophysical Union (AGU) was established in 1919 by the US National Research Council to be its representative in the newly-formed International Union of Geodesy and Geophysics.

These were soon followed by URSI, the International Union of Radio Science, whose first General Assembly took place in 1922 in Brussels. This initially had four Commissions:
Measurements, methods and standardisation; Radio propagation (with two parts: electromagnetic fields and radio goniometry); Atmospheric disturbances; Liaison with operators, practitioners and amateurs (abolished in 1948).
A comparison of this list of topics with that in the Introduction illustrates the diversification and enrichment of Radio Science since 1922.

The major industrial entity in Radio Science in Australia in the 20th century was AWA (Amalgamated Wireless Australasia Ltd.). This commenced operations in 1909 as a Telefunken agent, but the English Marconi Company disputed the patent rights on which they relied. The issue was resolved by their becoming the representative of both Telefunken and Marconi. AWA engaged broadly in supporting the nascent field of Radio Science, being engaged in both manufacture of receivers and transmitters, as well as training personnel. In 1918 the first radio broadcast (an address by the Prime Minister Billy Hughes) from the UK to Australia was received by AWA. In 1922 the Australian Government commissioned AWA to create a direct radio service with the

Figure 2: The AWA factory in Burwood, Sydney in 1935. (Royal Australian Historical Society - 19268794499/.)

UK. It also operated the Coastal Radio Service for the Government. In the 1930's it established an Aviation Department servicing airports throughout Australia and Papua New Guinea. Its building in York St. Sydney was topped by a radio tower, which made it the tallest building in Australia until 1958. During the First World War, the government of Prime Minister Billy Hughes established an Advisory Council of Science and Industry to coordinate the contributions of these two sectors to the war effort. An Act of Parliament in 1926 established the Council for Scientific and Industrial Research (CSIR) [10], which initially focused its research on primary and secondary industry. After the Depression in the early 1930's, it extended its research into supporting manufacturing industries. It changed its name in 1949 to the Commonwealth Scientific and Industrial Research Organisation.

6 Ground Waves and Skywaves

The early transmissions of Marconi and other pioneers used spark gap transmitters, which radiated at low frequencies and with poorly controlled bandwidth, and whose signal could only be modulated at low speeds consistent with Morse code transmissions. The fact that they could propagate much further than line of sight ideas would permit stimulated much early theoretical research. It was quickly realised that they were surface waves, of the same type as those associated with the emerging field of seismology. The term *ground wave* was used to describe them, and their characteristics include frequencies below 3 MHz, electric field oriented perpendicular or near perpendicular to the Earth's surface, and a propagation distance increasing with the surface conductivity. Most long distance low frequency radio communication (30 kHz- 300 kHz) uses ground wave transmission.

There are a wide range of wave types associated with electromagnetic waves propagating along or close to a surface. Depending on the nature of the surface and the medium of propagation, types of surface waves identified and studied include Zenneck-Sommerfeld waves, trapped surface waves, gliding waves and Dyakonov surface waves [11].

One interesting type of surface wave in nano-optics with several applications is the surface plasmon. Its dispersion relation is driven by the fact that for metals in the visible and at longer wavelengths the dielectric permittivity is negative. This can give rise to interesting colour effects due to wavelength dispersion absorption, exploited in the magnificent stained glass windows of medieval cathedrals, or in relics of the Roman Empire, such as the Lycurgus cup[12]. It has been exploited in design of high-performance photovoltaic cells, where metal particles can scatter in such a way as to enhance absorption of light in a thin layers. Another application is in Surface Enhanced Raman Spectroscopy [13]. This is a technique where for example molecules to be sensed are placed close to a rough metallic surface, where sharp corners give rise to strong field concentrations. The consequent enhancement of the Raman effect may be by a factor of 10^{10} or 10^{11}, enabling single-molecule detection.

As transmitters became more sophisticated than those relying on spark gaps, higher frequency transmission was investigated. It was discovered that a second mechanism for long distance propagation came into play, based on wave-guiding. This mechanism requires two reflectors, with the wave bouncing from one to the other as it propagates. The lower reflector is of course the Earth's surface, while the upper reflector came to be known as the *ionosphere*. The idea of the such a reflecting layer goes back to Gauss (like many things), but came into the radio science literature in 1902 [14], when Oliver Heaviside and Arthur Kennelly suggested that such a layer might explain Marconi's success in transmitting signals across the Atlantic.

R. V. Appleton put this idea on a firm footing in studies in the 1920's, for which he was awarded the Nobel Prize in Physics in 1947. He combined two types of measurements to achieve a measurement of the height of the reflecting layer. The first was to study the frequency at which the wave coming directly from the transmitter reinforced (was in phase with) that coming by reflection off the ionosphere, as a function of receiver position. This was combined with a measurement of the angle of the incoming reflected beam at the receiver. Putting these together, Appleton found that the reflecting layer was at a height of about 90 km.

Radio waves propagating over long distances using ionospheric reflectance are known as *skywaves*. The mechanism works better at night than during the day since an absorbing lower layer called the D layer thins nocturnally. An interesting skywave phenomenon is called the *Luxembourg effect*. In this, one radio transmitter's signal can modulate the ionosphere locally, and so affect the signal from another transmitter at a slightly different frequency. Early observations of this cross modulation were between the BBC and Radio Luxembourg.

7 Needs Must When the War Drives

As the Second World War loomed, radios were an essential element in well to do Australian homes, providing entertainment and information. The British Commonwealth and Empire were linked by wireless and telegraphy, and aviation was playing an increasing role in transportation. Science had played an important role in the First World War, and it was clear this would be even more the case in the approaching conflict. We will briefly describe some of the contributions made in two areas: development of optical munitions and radar.

The work on optical munitions has been well described in an article by H. C. Bolton [15]. It was organised from June 1940 on by the Optical Munitions Panel, chaired by Professor T.H. Laby of the University of Melbourne, and having representatives from five of the six Australian Universities, three government laboratories and the armed services. One of their first tasks was seemingly prosaic, but vitally important: the development of manufacturing capacity for the range of optical glasses needed for such things as lenses for range finders for anti-tank guns, telescopes, binoculars and for aerial reconnaissance. The effort on glass was organised by the Professor of Chemistry at Melbourne, E.J. Hartnung. When Laby asked Hartnung whether it was going to be possible to make optical glass in Australia, Hartnung replied:

> I don't see any reason why not. It is a very big place and we ought to get suffiiciently pure sand.

The effort commenced in August 1940, and by November 1940 the Australian Window Glass Company Sydney was able to deliver commercial quantities of crown and flint glass.

The entities using the optical glass to fabricate devices were numerous and disparate: twenty five establishments were used, including companies and physcis departments. Bolton reports that there were produced 43 different types of optical instruments and 26,237 individual instruments were manufactured. Personnel needed existed or more frequently to be up-skilled or trained on the job, and in one case a key individual was brought in from Adam Hilger in the United Kingdom. Some instruments were obtained by requisition on the public and refurbished. A considerable effort of an inter-disciplinary nature had to be made to proof instruments against tropical conditions prevailing in the New Guinea and later campaigns, with fungal penetration liable to render instruments quickly inoperative.

Many young people became involved in the work on optical instrumentation, although only a few of these built their post-war career around it. A notable case was that of W.H. (Beattie) Steel, who started with wartime work at AWA and then joined CSIR National Standards Laboratory. After the war, he did a PhD in France at the University of Besancon, where he learned about the use of Fourier analysis in optics from its pioneer, Professeur Duffieux. Returning to Australia, he became a world authority in interferometry, and later was President of the International Commission of Optics, and first President of the Australian Optical Society. Another interesting case is that of Hans Buchdahl, who was a German Jew who fled with his older brother to the UK to escape persecution in the 1930's. When the war broke out, the two were interned, and came to Australia on the HMT Dunera. He was interned in New South Wales, and then in Victoria, where his mathematical abilities were recognised. He was transferred to the Physics Department of the University of Tasmania, where he developed Gaussian optical methods into a sophisticated design tool. This was put to use in designs inter alia for aerial reconnaissance imaging cameras fabricated in Hobart. He went on to become Professor of Theoretical Physics in the Faculty of Science at the ANU. He made major research contributions in geometrical optics, thermodynamics and general relativity.

Returning to the pre-bellum years, work was going on in several countries on systems aimed at using emitted radio beams to estimate direction of travel and distance to incoming aeroplanes or ships. This had been thought about since the days of Marconi, but the rapid development of aviation and its use as an offensive weapon in the First World War and the Spanish Civil War gave increasing impetus to the development programs in the United Kingdom, United States, Germany, the USSR, the Netherlands, France and Japan [16].

Intensive work on the development of the British radar network to be called Chain Home commenced in 1935, and by early 1938 the RAF took control over it. The transmitters operated on frequencies between 20 and 55 MHz, and delivered a peak power of 200 kW; they were able to detect aircraft at a distance of about 130 km. The Chain Home network covered the southern coast of England, and the east coast all the way up to the Orkney and Shetland Islands (with the British Fleet being based at Scapa Flow in the Orkneys). The British Army and Navy also developed radar systems for their particular requirements.

An important development in the years 1939-40 had an Australian connection. Mark (later Sir Mark) Oliphant headed the Physics Department at Birmingham University. He was asked by the Admiralty in 1939 to investigate building a radar source at microwave frequencies. The Air Ministry were also interested in a 10 cm system capable of fitting into the nose of aircraft. Oliphant put John Randall and Harry Boot onto this task. They initially tried klystrons, but the power achievable (400 W) was insufficient. Boots and Randall then moved on to magnetrons, and made a breakthrough by combining the magnetron with multiple (six) resonant cavities. Their first test provided 400 W, and within a week they achieved 1 kW. An important contribution to achieving still higher powers was made by French researchers, and consisted in the use of oxide coated cathodes. With this implemented, the cavity magnetron reached 10 kW power by August 1940. This device was taken to the USA by the Tizard Mission in August- September 1940, with Dr. Edward (Taffy) Bowen being the radar expert. It so impressed the US experts that soon thereafter the MIT Radiation Laboratory was founded (with Nobel Prize Winner Julian Schwinger being among its four thousand employees). Another consequential secret shared with the US was the Frisch-Peierls concept for an atomic bomb. (Frisch and Peierls were also working in Oliphant's Department, and made the first correct calculation of the critical mass for an atomic bomb, capable of airborne delivery. Interestingly, Heisenberg got a value significantly too large, and concluded an airborne atomic bomb was impossible.)

In February 1939 the Commonwealth High Commissioners in London were informed by the Air Ministry of the radar program, and were offered a briefing to a well-qualified physicist drawn from each country. At the request of the Australian Prime Minister, Joesph Lyons, the Chairman of the CSIR chose David Martyn to go to London. He was briefed on the state of the radar program, and given technical information and important electrical components [18]. As a result of decisions based on the information Martyn brought back, a secret Cabinet meeting approved £80,000 for setting up a radar research establishment. It was domiciled in the National Standards Laboratory in the

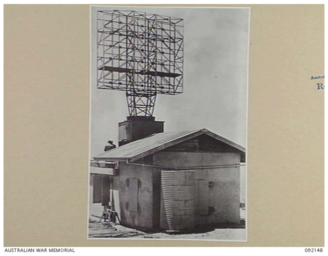


Figure 3: The shore-defence radar installation at Dover Heights Sydney around 1940. (Australian War memorial :AWM.092148.)

grounds of Sydney University. Of the sixty physicists recruited to develop radar, three were women (Joan Freeman, Rachael Makinson and Ruby Payne-Scott). Radar technology developed included ground-to-air and air-to-surface vessel capabilities. All-Australian manufacture of components was stressed, and this involved up-skilling companies previously limited to producing wireless sets. The work on air defence radar was prioritised when Japan became an active adversary after the Pearl Harbour attack. Unfortunately, the radar defences were not in place when the first and deadliest of the Japanese air attacks took place on 19 February 1942. This attack killed 235 people, and resulted in the abandonment of Darwin. However, the radar played a key role in the successful defences against the second air raid. There were at least 111 attacks by aircraft from the Imperial Navy and Army Air Forces on Australia during 1942 and 1943. Defence against them was provided by US, Australian and British fighter planes, by anti-aircraft artillery and by radar detection.

One of the leading radio scientists working on the development of the early radars in Australia was Jack Piddington [17], who had completed his PhD in England under Appleton in 1938. Returning to Australia, he helped build the first radar system in Australia. At the time of the Pearl Harbour Attack, it became a matter of the utmost priority for Australia to build its own radar systems for warning against air attacks. As Piddington recalled:

> We had foreseen that air warning was likely to be the major role of radar, but the RAAF had worked on the basis that they would get their air-warning sets from England. Pearl Harbour put a sudden end to that idea. On Pearl Harbour Day I designed an air-warning set in two hours, and with 14 others worked on it. Five days later we had the set completed, installed and tested at Dover Heights- and that rough set provided air warning for Sydney for the next nine months.

One interesting aspect of the Pacific Campaign was the Japanese use of radar. Their development of radar had been built on their own pre-war development, but was aided by German technology, and by British and US radar sets captured respectively in the fall of Singapore and of the Philippines. However, the Allies first discovered that the Japanese had radar when they captured a set on Guadalcanal in August 1942 [19]. Thereafter, Radar Countermeasures Groups (RCM's) were set up, to locate and neutralise Japanese radar installations. As well, the US developed electronic reconnaissance aeroplanes code-named Ferrets to locate and characterise enemy radar sites. Both sides of the use of radar: as a defensive and an offensive weapon were thus established before 1945.

Manufacture of radar components and systems in Australia commenced with a Shore Defence (ShD) radar tested at Dover Heights in Sydney in 1940. One design which was widely used was the Light Weight Air Warning radar (AW/LW), developed in September 1942 for the RAAF as an air-transportable radar, readily assembled in the field by the radar team [20]. The wide use of such systems in the Australian Army, Navy and Air Force of course depended on the rapid creation of a well-trained set of radar operators.

In order to train these personnel, courses were commenced in the Physics Department of the University of Sydney, under the supervision of Professor Victor Bailey (who already had an international reputation in Radio Science for his research into the Luxembourg Effect). The courses commenced in September 1941, with 38 students in the first intake. The extent of the demand may be gathered from a letter form the Department of Air to the Vice Chancellor, University of Sydney in June 1942 [21]:

> To meet the Department's requirements approximately 200 more officers must be obtained before August 1943. 50 trainees should enter university in July and October of 1943 and January 1943. There is a strong possibility of further courses in 1943.

Courses were run for each of the three services, and the graduates tended to be rather young in relation to their officer status. They were widely known as "Bailey Boys" for that reason. Four of the Bailey Boys died during the war period, with one (Stan Deacon) being the only one killed in action (February 1943). Among the many Bailey Boys who went on to have distinguished careers was the late Professor John Bennett, a pioneer of Computer Science in Australia. Another was the novelist, Hal Porter.

8 A New Window on the Universe

The classic definition of the concept of "noise" is:

> A noise annoys.

Yet there are many examples in the history of science (Brownian motion, Roentgen's accidental discovery of X rays, etc.) where annoying distractions when looked into closely yielded discoveries of the first magnitude. We will mention some of these as we go on.

Karl M. Jansky [22] was an early-career physicist at Bell Laboratories in the early 1930's who was given the task of learning as much as possible about "static", or radio noise, and how it could be mitigated. To work on this problem, he built a 30 m long antenna, steerable and with good directionality and stability, and started observing static and classifying it by probable origin. Much of the static could be identified with thunderstorm activity, but there was one component which was always present but not associated with atmospheric electrical events. He observed this component for a year, and ultimately assembled enough evidence to be confident it came from a direction fixed in space, and was not associated with the Sun, other planets or terrestrial causes. His boss suggested that this discovery was important, and, as Jansky described in a letter to his father [22]

> I presented my paper in Washington before URSI, an almost defunct organisation....The URSI meetings in Washington are attended by a mere handful of old college professors and a few Bureau of Standards engineers.

Jansky's work however achieved much publicity as a result of a subsequent Bell Labs press release, and on May 5 1933 was featured on the front page of the New York Times with the headline "New Radio Waves traced to the Centre of the Milky Way". No doubt it contributed post-war to an enlivening of the Washington URSI Meetings! Jansky's career in radio astronomy was relatively brief, as he was redirected onto other work in Bell Labs, and undertook war work into radiolocation of U boats. He died in 1950 at age 44.

One of those inspired by Jansky's work, and the sole researcher able to concentrate upon extending it in the decade after 1935 was Grote Reber. In the summer of 1937 Reber built his own radio telescope in his backyard in Wheaton Illinois [23]. This was the first of the big dishes in radioastronomy, 9 meters in diameter, focused to a receiver 8 metres above the dish. Its first successful operation was at 160 MHz in 1938. Reber made a major contribution to radiastronomy by making the first radiofrequency sky map over a period of five years. His maps revealed the existence of particular sources such as Cygnus A and Cassiopeia A for the first time. His observations at low frequency pointed out for the first time the need for a new source, subsequently identified as synchroton radiation. In 1954 Reber moved to Tasmania, where he

Figure 4: Some participants at the URSI General Assembly, Sydney, 1952. Some figures of note: front row, from left: Wilbur Christiansen, Graham Smith, Bernie Mills, Steve Smerd, Charles Shain, Robert Hanbury Brown, Ruby Payne-Scott, Alec Little, ?, Bruce Slee and John Bolton. Paul Wild is between Smith and Mills, while Jack Piddington is at the back left.

cooperated with Professor Bill Ellis, and had a dipole array set up near Bothwell. He died in 2002, just short of 91 years of age.

What is regarded as the founding event in radio astronomy in Australia took place 75 years ago, October 3 1945, at Collaroy Plateau in Sydney. The experiment took place at a radar station used for detecting approaching ships and aviation, and which was adapted to look for radiation coming from the Sun at a frequency of 200 MHz. The research was reported in a Nature paper by Joe Pawsey, Ruby Payne-Scott and Lindsay McCready [24]. One of the interesting discoveries reported in the paper is the very high effective temperature of the solar corona (in the range $10^6 - 10^7$ K, much higher than that of the photosphere- around 6000 K).

The radar programs in the United Kingdom and Australia had created a generation of experienced and confident young scientists, forged in the high tempo and demanding war years. Many did not have PhD's- indeed, until the creation of the Australian National University, local universities did not have PhD programs, with aspiring young researchers like Mark Oliphant going off to the U.K. to start their higher education. This pattern was repeated with some of the war generation, like Ron Bracewell in radio astronomy and Beattie Steel in optics, while for others like Ruby Payne-Scott this was not possible. However, with the new field of radio astronomy waiting to be explored under southern skies, and their confidence in their own abilities coming from the war time challenges surmounted, they took their opportunity with both hands.

One feature in common between researchers like Ron Bracewell and Beattie Steel was their grounding in the emerging technique of Fourier analysis. While Fourier series had long been used in analysis, Fourier transforms had not been long exploited in pre-war science. However, this changed rapidly post-war, and scientists learned to think in reciprocal space rather than direct space, with advantages in imaging system design and image interpretation. This was reinforced when more powerful computers began to be available widely, and particularly when the Fast Fourier Transform algorithm became available in the 1960's. Around this time, Ron Bracewell's book [25] became the standard reference on the subject in radio astronomy, while applied mathematicians were more likely to use Lighthill's masterly condensation [26]. Both these books cover Fourier analysis and generalised functions, the latter being the Dirac delta function and related functions needed for the calculus of discrete systems.

A very elegant addition to the story of the Collaroy sunspot observations is contained in a subsequent paper by McCready, Pawsey and Payne-Scott [27]. This was the *sea interferometer*, the radio frequency implementation of a device known in optics as Lloyd's mirror. They were using it to supply the required angular resolution to determine source position of 200 MHz radiation coming from the Sun. The measurements worked best when carried out at dawn, with the Sun rising above the sea at Dover Heights. The interference arises between the rays directly coming from the Sun, and those reflected off the sea surface. The latter may be thought of as arising from a mirror Sun, placed symmetrically with respect to the flat sea surface: interference between rays coming from two source points. Alternatively, the view may be taken that one has two symmetrically placed receivers rather than one, and their recordings are superposed. Either way, one has interference traces, complicated by variations in sea height due to waves of varying surface profile. Resolution of a few minutes of arc was possible, sufficient to correlate the emissions with observed sun spots.

Another remarkable instrument at Dover Heights was a "hole-in-the-ground" 72 ft diameter parabolic reflector, built surreptitiously by Bruce Slee and John Bolton, helped by John Stanley and Kevin Westfold. As Bolton describes in his article reprinted in [22],

> the construction was carried out in our own time and in secrecy.... Only Taffy Bowen was taken to see it when it was sufficiently advanced that its purpose was obvious. He both approved of it unofficially and agreed to say nothing about it until it was operational.

The instrument was inspired by one at Jodrell Bank, and was used in a survey of galactic radiation at 160 MHz. The results were sufficiently good to warrant an official enlargement and improvement of the "hole-in-the-ground" reflector. The improved instrument was used in a survey at 400 MHz by Bolton and Dick McGee [28]. This resulted in an identification of a source Sagittarius-A, unresolved by their 2° beam, and which they concluded was the nucleus of our galaxy. This view was ratified by the IAU, when it adopted Sagittarius-A as the "Greenwich equivalent", the zero of longitude in a new system of galactic coordinates.

An instrument rather too big to be accommodated at Dover Heights was the Mills Cross, the brainchild of Bernie Mills, who had joined the CSIR Radio Astronomy Group in 1948. The Cross was constructed at Fleurs in the west of Sydney, near where the second Sydney International Airport is now under construction. It consisted of North-South and East-West arrays of dipoles about 450 m long, with the dipoles backed by a wire mesh reflector, and was only steerable to a limited extent. It relied largely on the movement across the sky of sources to transit them into the radio telescope field of view. The cross operated at a frequency of 85.5 MHz, and its 49 arc minute beam gave it an angular resolution remarkable for the time. It was used between 1954 and 1957 to conduct a survey of 2000 discrete sources, many extra-galactic. When the results of this survey were compared with those of the second Cambridge survey (C2) made contemporaneously there was significant disaccord, which gave rise to a controversy. This was ultimately resolved when the instrumental flaw in the Cambridge data was unearthed.

There were other telescopes at Fleurs, including the Chris Cross, designed by Wilbur Christiansen. This was used to give high resolution images of the radio emission from the Sun.

By the end of the 1950's, Australia was one of the leading countries in research in Radio Astronomy, vying with the United Kingdom. Universities were increasingly interested in research on the topic, and were producing their own PhD graduates. Some of them found jobs in the CSIRO, and some of their supervisors had been recruited from the CSIRO, like Bernie Mills. Other research leaders like John Bolton and Ron Bracewell had faculty positions in leading US universities, as the field became stronger in that country. The decade of the 1960's was to see continuing strong growth, some associated with NASA, and the international infrastructure necessary to make a Moon landing possible.

A recent paper [29] reviews the considerable international impact of Australian radio astronomy during the post-war period until 1969.

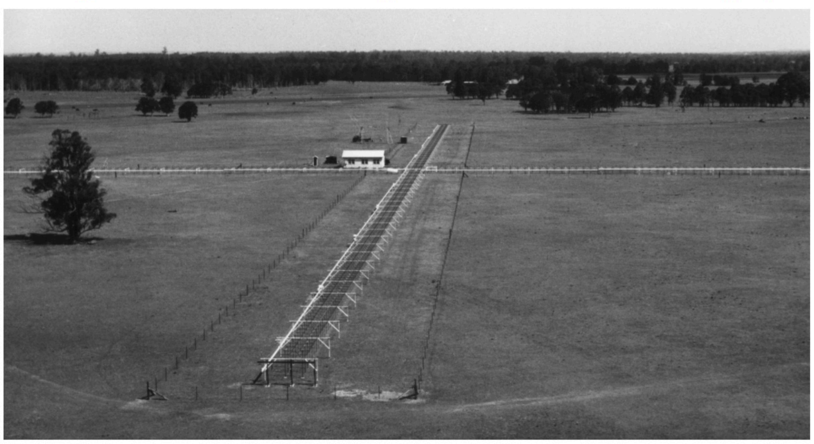


Figure 2: View looking south showing the N-S arm and most of the E-W arm of the Mills Cross, with the receiver hut at the centre of the array (ATNF Historic Photographic Archive: 3476-3).

Figure 5: View looking south showing the N-S arm and most of the E-W arm of the Mills Cross, with the receiver hut at the centre of the array.(ATNF Historic Photographic Archive: 3476-3) .

9 Cosmic Cannibals

The interaction of light with matter has been a topic which has fascinated humans over several millennia. The laws of reflection were known to the Ancient Greeks, while the law of refraction was established at the end of the sixteenth century. The two were brought together in Fermat's Principle, that light rays followed the path requiring least propagation time. Light being trapped by water flowing from illuminated fountains leads to the concept of light guides, while the extreme property is that of light being trapped and unable to escape due to the gravitational field of a massive object. That idea was put forward and investigated surprisingly early by Michell and Laplace [30]. However, their ideas were based on light as a stream of corpuscles effected by gravitation, and those ideas lost currency with the rise of the wave theory of light and the later framing of Maxwell's equations.

Einstein's special theory of relativity had as a central feature the constancy of the free space velocity of light, while in his general theory the path of light was controlled by the space-time metric influenced by the gravitational effect of massive bodies. Even before the general theory received its first confirmation in the 1919 observations of the perihelion of Mercury, Karl Schwarzschild had in two papers established exact solutions of the Einstein field equations round a non-rotating, uncharged massive body. Remarkably, Schwarzschild found his solutions while serving in the German Army on the Russian Front, a short time before his death in 1916.

The work of Schwarzschild did not predict the formation of a black hole, but rather provided a framework in which subsequent workers could clarify whether and at what mass a collapsing star would continue to contract until it arrived at a point of trapping light within it [31]. Important steps along this path were taken by Eddington, Lemaître and Oppenheimer. In 1958, Finkelstein identified the surface where Schwarzschild had connected interior and exterior solutions as the *event horizon*, essentially the surface of no-return (Hotel California) for infalling objects. Roger Penrose, working with Stephen Hawking, proved that the singularities associated with black holes were generic, and not peculiar features of particular solutions. For this achievement Penrose was awarded half of the 2020 Nobel Prize for Physics.

In the remainder of this section and the next, we will mention some of the observational results which have led physicists and astronomers to the conclusion that black holes not only exist, but play an important role in the structure of galaxies, being associated with the notion of the galactic nucleus mentioned in the previous section in the discussion of John Bolton's work.

We start this discussion with Bolton's return to Australia from the U.S.A., where he had been Professor of Radio Astronomy at Caltech. He came back to help with the exciting project of the construction and utilisation of the Parkes Radio Telescope, now an icon of Australian science. This 64 m diameter dish has been in operation since 1961, and one of its most exciting discoveries under Bolton's direction was made by the guest astronomer Cyril Hazard just a year later. Quasars had been identified as compact radio sources with difficult-to-locate optical counterparts. By 1960 hundreds of these objects had been listed in the Third Cambridge Catalogue of radio sources, with optical astronomers busily searching for them in the visible spectral region. Hazard, with two co-authors from the CSIRO Division of Radiophysics, gathered detailed records of three passes of the Moon (occultations) in front of the compact source 3C 273 [32]. What is important from these observations is the plot of signal versus time during the occultations. The position of the Moon being known, the time interval between the source going behind the Moon and re-emerging give a more precise angular position for it. Furthermore, modelling of the profile of the interference fringes evident in the signal trace give information about the source angular diameter and even shape (it being in this case a double source). The technique in this particular case gave angular position and diameter to a second of arc.

With this more accurate position data, Maarten Schmidt [22] was able to find 3C 273 using the Mt. Palomar optical telescope. He notes the importance of the radio astronomical position data: 3C 273 may be among the brightest sources at radio wavelengths in the 3C catalogue, but there are as many as three million stars brighter than it at optical wavelengths. Schmidt identified 3C 273 by what seemed to be peculiar emission lines in its optical spectrum, similar to what had been found for the other source with an identified optical counterpart, 3C 48. The resolution of the

Figure 6: The Parkes radiotelescope at night. (Credit: CSIRO) .

spectral puzzle was made by Schmidt when he noticed that the spectral lines he saw for 3C 273 bore a ratio of 1.16 to the wavelengths of the Balmer lines of hydrogen. This redshift identification of 0.16 led Schmidt and Jesse Greenstein to look again at the spectrum of 3C 48, and derive a redshift of 0.37 for it.

This solution held also for other objects of this class as they were subsequently identified. Like many a good solution, however, it raised another puzzle. Given their substantial redshifts, these sources were at great distances, but yet they were compact objects, not collections of stars. On the other hand, their distances and their high radio brightness indicated they were radiating enormous quantities of energy on a continuing basis. So what was the source of this energy? A solution was put forward in 1964 by the University of Sydney graduate Edwin Salpeter, and Yakov Zel'dovich: accretion of material into super-massive black holes in the nuclei of distant galaxies, cannibalising neighbouring stars.. However, in 1964 black holes were viewed as a speculative theoretical concept, with no solid observational evidence, and astronomers were reluctant to embrace the Salpeter-Zel'dovich idea. They gradually came round to acceptance, in part because of the related exotic physics needed to explain the next new and exciting class of astronomical objects: pulsars.

10 The Pulsar Hunters

The story of pulsars [22] begins with what must have been a fairly common activity in the 1960's and before: a group of post-graduate students aided by technical staff setting up wooden poles and connecting them with wires and embedding dipole antennas (the writer had friends engaged in similar activity at the University of Tasmania round the same time). Among the students was Jocelyn Bell, whose supervisor Tony Hewish had designed the radio telescope to operate at 81.5 MHz, and to search for quasar sources, which, being point like sources, should show scintillation (signal strength fluctuations) in a more pronounced fashion than extended sources. Jocelyn was to help build the telescope, carry out its commissioning tests and use it to find quasars as her PhD project. The telescope covered an area round 18200 square metres and had 2000 dipoles, so it took two years and considerable sweat to build! The output was onto a chart recorder, and the data was analysed initially by eye.

When examining data collected during a six months observation run, Jocelyn noticed three types of source signal, low scintillation, high scintillation, and a third type unlike the other two which she designated "scruff". Jocelyn began to notice particular features of the scruff: it seemed to be fixed in the sky, was sporadic, and very importantly when it was on had a periodic nature, with a period round 1.27 seconds. Tony Hewish analysed the positional data on the "scruffy" source, and found that over an observation period of three or four months it had kept a constant right ascension to within ten seconds. Its existence was verified on another Cambridge radio telescope, and terrestrial sources of interference were ruled out. The initial designation of the source was LGM 1 (for Little Green Men, first type).A second one was subsequently found with a period of round about a quarter of a second, approaching the time resolution of the chart recorder. Shortly before the Nature paper [33] was submitted, Tony Hewish gave a talk at Cambridge on the data, and Fred Hoyle suggested supernova remnants as the possible source. Hewish was to share the Nobel prize for Physics in 1974 with Sir Martin Ryle. Even though Hewish was cited for the discovery of pulsars, somewhat controversially Bell was not recognised in the 1974 award. She has of course gained notable recognition since: in 2018, she was awarded the Special Breakthrough Prize in Fundamental Physics. Following the announcement of the award, she decided to give the whole of the £2.3 million prize money to help female, minority, and refugee students seeking to become physics researchers, the funds to be administered by the Institute of Physics U.K. .

Australian observations of pulsars commenced at Parkes less than two weeks after the Hewish-Bell Nature paper was published- see the Appendix, which contains a chronology of some of the key Australian pulsar papers, supplied by Dr. R.N. Manchester. Key radio observations were made with both the Parkes telescope and the new Mills Cross radio telescope located at Molonglo near Canberra, built with the support of U.S. funding, and operated by the University of Sydney. The impact of this Australian research can be judged from the Appendix, and from the figure 7. For many years, over half of known pulsars have been identified first within this country: a circumstance which can be attributed to a number of factors: the favourable geographical location, the activity of the local pulsar hunting community and the excellence of the telescopes and their instrumentation. The last mentioned factor has been one of the strengths of Australian astronomy, both optical and radio, and has enabled important discoveries to be made locally, even when facilities otherwhere may have been larger or more sensitive.

We now comment on a few of the entries in the chronology of the Appendix. It has been established that the train of pulses from a pulsar can be fantastically regular: around one part in 10^{18}. After many years of development, atomic clocks are now approaching that level of accuracy. One of the early questions was of course the mechanism for this train of pulses, with separations ranging from seconds to milliseconds. As mentioned above, Fred Hoyle immediately reacted to the news of pulsars by suggesting that they could be supernova remnants. These on the basis of theory were known to be either white dwarf stars, or neutron stars. The first possibility was quickly ruled out, leaving the second, resulting from the collapse of more massive stars, the residue being a compact body, with a radius of about 10 km and a mass of about 1.4 solar masses. This body is typically rotating rapidly at its birth, and has a very strong magnetic field (between 10^8 and 10^{15} times that of the Earth). The strong magnetic field can direct a beam of radiation, like that of a lighthouse, and those pulsars we see have their radiation cones pointing towards us.

Pulsars provided the first observational evidence of neutron stars, and continue to inform us as to the rich details of their physics. The knowledge of the polarisation of pulsar radiation gave direct evidence for the "lighthouse" model of emission, while glitches in the regularity of pulsar may be due to "starquakes", akin to earthquakes occurring as the pulsar loses energy by radiation

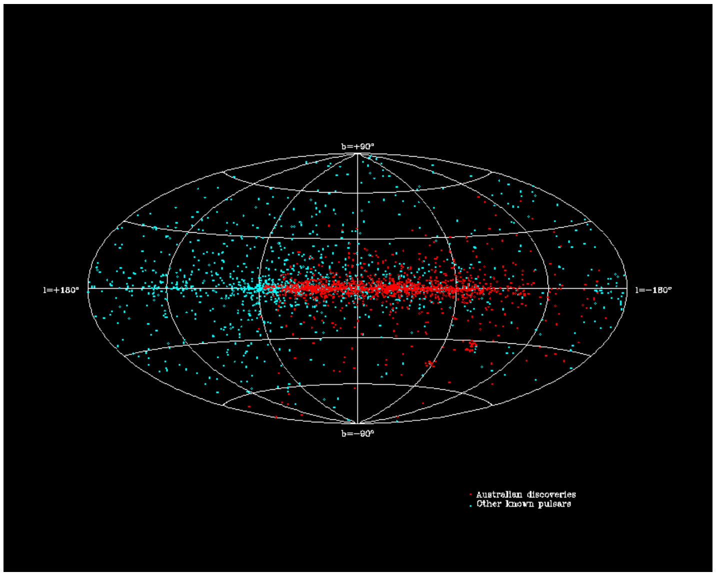


Figure 7: Plot of Australian pulsar discoveries and non-Australian pulsar discoveries, based on the current version of the ATNF Pulsar Catalogue. This plot has 1395 Australian pulsars and 1476 non-Australian (Figure copyright: Dr. R.N. Manchester. Used with permission).

and its spin slows, causing surface reshaping. Between glitches, the pulsar acts like a rigid body rotating with low frictional drag, explaining the regularity of its pulses. The pulsar is surrounded by a plasma of particles, and its very strong magnetic field can lead to electron-positron pair creation, the modelling of which requires the exotic new field of quantum plasmadynamics. As well, the neutron star can lose energy by the radiation of gravitational waves, and observations of decay of pulsar period with time can be used to check general relativity. Taylor and Hulse were awarded the Nobel Prize for Physics in 1993 for the 1974 discovery of a pair of neutron stars (one of which was a pulsar) which permitted a stringent test of general relativity. The 2003 discovery of a linked pair of pulsars by Burgay et al is notable for enabling five different tests of general relativity, some with unprecedented precision.

11 HBT

In this section, we will discuss what the renowned French physicist Alain Aspect has described as the foundational experiment in quantum optics [34]. It was carried out in the mid 1950's by Robert Hanbury Brown [35] and his long-term theoretical collaborator Richard Twiss, first at Jodrell Bank and was subsequently developed on a larger scale at Narrabri in Australia. Aspect ascribes the reason for this transfer of activities to the scepticism in the U.K. from quantum specialists as to the validity of the technique, and the consequent lack of funding there for it. He then goes on to wonder why it was funded in Australia: was quantum mechanics as yet unknown there, or did Australians simply know better? Of course, any true-blooded Australian can answer that question.

Hanbury (as he was invariably called by colleagues) had had a distinguished role in the development of radar in the period leading up to the Second World War, and during it, both in the U.K. and in the United States. In 1949 he decided he needed a PhD if he were to pursue a research or academic career, and joined Bernard Lovell's group at Jodrell Bank as a PhD student, with immediate impact. He joined with Cyril Hazard, a graduate student already referred to, and succeeded in detecting the first radio signals from an extra-galactic source, the Andromeda nebula M31.

Hanbury in collaboration with others at Jodrell Bank began to investigate techniques based on interferometry, and in particular intensity interferometry, where it was not necessary (or indeed possible) to combine beams having a precise phase relationship. He eventually decided to pursue this problem at optical wavelengths, and was advised to establish a collaboration with Richard Twiss, then in the Services Electronic Research Laboratory, who had a more mathematical orientation [35]. The two devised and carried out the foundational experiment [36] to which Aspect referred [34]. It was in essence simple , but there were critical details which had to be correct. The light source used was a bright mercury vapour lamp, which passed through a small aperture (spatial filter), so producing partial coherence from an incoherent source. After spectral filtering to isolate the 453.8 nm line, the violet light encountered a beam splitter, which produced two beams, each going on to a photon detector (photomultiplier), with one being able to be shifted perpendicular to the arriving beam to vary the degree of partial coherence with the other. The outputs from the two multipliers were amplified over a band 3-27 MHz and multiplied together in a linear mixer. The average value of the product gave a measure of the correlation of the fluctuations in the two beams. The results of the experiment showed that the correlation existed, could be varied with spatial separation of the two photocathodes, and could be predicted by electromagnetic wave theory for beam intensities which were not too small (in line with the Correspondence Principle of quantum mechanics).

The Hanbury Brown- Twiss paper was initially controversial, with quantum mechanical theorists suspecting errors in the measurements. Two attempts to replicate the results failed, due to essential requirements of the HBT experiment not being met. However, there were soon comments from supporters, who pointed out that indeed what HBT showed was indeed only to be expected from established results in other fields. One of these fields is statistical physics, in relation to fluctuation statistics of bosons and fermions [37]. The relative fluctuations pertaining to Bose-Einstein (+) and Fermi-Dirac statistics (−) are given by

$$\frac{\overline{(\delta n_i)^2}}{\overline{n_i}^2} = 1 \pm \frac{1}{\overline{n_i}}. \tag{2}$$

For bosons, we have the possibility of interference, with relative fluctuations heading towards unity as the mean population $\overline{n_i}$ increases. Thus, like buses on a wet day, bosons can bunch. On the other hand, for fermions the fluctuations tend to zero as $\overline{n_i}$ tends to its extreme values 0 and 1: fermions anti-bunch, due to the operation of the exclusion principle. As Aspect [34] stresses, the essence of the HBT experiment is the bunching of photons.

A second view of HBT is provided by the van Cittert-Zernike Theorem [38], which provides a Fourier transform formula for the degree of partial coherence as a function of position in a region illuminated by a quasi-monochromatic, incoherent source. What is then measured in an HBT experiment is proportional to the square of the degree of coherence, determined by classical arguments.

As one of their responses to the criticism of their initial experiment, Hanbury Brown and Twiss [39] made a measurement at Jodrell Bank using their technique of the angular diameter of Sirius. The mirrors used were two borrowed Army searchlights. The success of this measurement encouraged a more sustained observational program, which was carried out in Australia, where Twiss had just moved, initially into a position with CSIRO Radiophysics, and subsequently with the School of Physics at the University of Sydney. He chose the site at Narrabri for the future facility in conjunction with the Head of the School, Professor Harry Messel, before leaving Australia. Perhaps his reason for leaving was linked with an evaluation he conveyed to a colleague who later served at Narrabri:

> Bill, don't go to Australia. They eat peas out of tin cans there!

Professor Messel was able to persuade Hanbury Brown to accept a Chair at Sydney University, in order to carry out the Narrabri Intensity Interferometer project.

Despite Alain Aspect's comment on funding , the Narrabri project began as a cooperative effort between the U.K. Department of Scientific and Industrial Research and the Universities of Sydney and Manchester [35], with manufacture of components being shared between the U.K. and

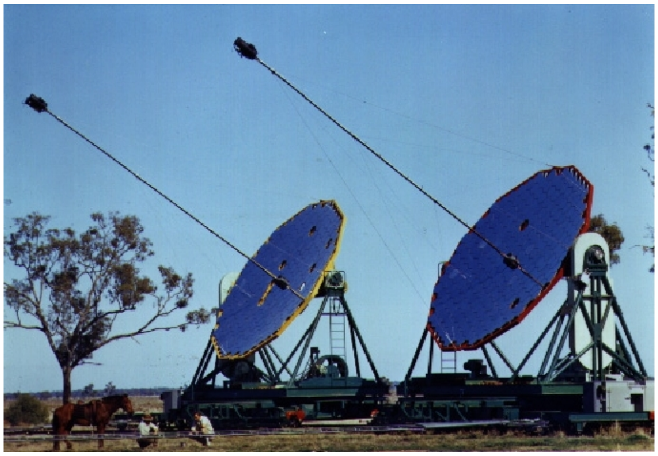


Figure 8: The mosaic mirrors on their carriages at the Narrabri stellar interferometer.(Figure copyright: University of Sydney).

Australia. The heart of the intensity interferometer was a pair of mirrors, approximately seven metres in diameter, composed of hexagonal pieces and mounted on a paraboloidal framework (see Fig. 8). The mirrors on their carriages could be moved on a 188 m diameter circular rail track in order to ensure the star under observation remained perpendicular to the line joining them (thus retaining correct phasing).The coaxial cables carrying the signal from the photomultipliers to the control building had to be made cockatoo impenetrable. The first operation of the interferometer occurred in January 1963, and the first angular diameter measured was that of the star Vega. At the end of the observational program in January 1972 the angular diameters of 32 stars had been measured [35]. These enabled the establishment of the effective temperature scale and bolometric corrections for early-type stars.

The Narrabri Intensity Interferometer established a new era of precision in astronomy, as well as consolidating the desk-top experiment of HBT as the birth of a reliable technique for incoherent information mining in wave science. As quantum mechanics is ultimately a wave theory, it opened new avenues in that field, and also found applications in particle and plasma physics, and in experiments such as those of Aspect demonstrating interference effects with atoms and molecules. The Interferometer was closed in 1973, and was succeeded by a modernised Michelson (amplitude) interferometer. Other projects since 1973 have built on the lessons of Narrabri.

It is the author's opinion that HBT was fully deserving of a Nobel prize. While nominated for that honour in the 1970's, it never achieved such a recognition, but its seminal impact is undeniable.

12 Tripping the Light Fantastic

In the early years after 1945, most attention in Australian radio science was concentrated around the rapid growth of the new field of radio astronomy. The field of optics seemed by comparison far less lively, and perhaps heading towards "a permanent state of decline". One remarkable achievement in optics and spectroscopy from the early 1950's warrants attention, as today it is less well remembered than it should be. It was made by Alan Walsh[40], recently attracted to the CSIRO Division of Chemical Physics Fishermen's Bend in Melbourne. Walsh had graduated from the Physics Department of the University of Manchester (then headed by the Adelaide-born Sir Lawrence Bragg) just before the Second World War, and had spent the war years working on spectroscopy and metallurgy, some of which was connected with the Tube Alloys Project (the British atomic bomb project). When he joined Chemical Physics, one of his first achievements was to develop a double-pass extension of a Perkin-Elmers infrared spectrometer, which greatly improved its resolution and stablility. The extension was patented in 1950 and commercialised by Perkin-Elmers, greatly extending the utility of its spectrometers for infrared spectroscopy of small molecules.

The following quote details the "Eureka" moment, which gave rise to the birth of atomic absorption spectrophotometry:

> On a Sunday morning in March 1952 Walsh was working in the vegetable garden of his home in the Melbourne bayside suburb of Brighton when he suddenly had a revealing flash of thought, something that stemmed from his earlier work in related fields. He hurried inside, dirt still on his shoes, and phoned his colleague, John Shelton. 'Look John!' he exulted. 'We've been measuring the wrong bloody thing! We should be measuring absorption, not emission!' John reminded him: 'We've been through that before you can't work out the concentration of a sample from the absorption because of the emitted light at the same wavelength'. Walsh replied: 'I've thought of that. We'll use a chopper on the source and a tuned amplifier, so the light emitted from the sample won't matter.'
>
> Early next morning Walsh set up a simple experiment, using the element sodium. By morning tea he had a successful result.

Previous workers had assumed from Kirchhoff's Law relating emission and absorption properties of systems that this meant that absorption spectroscopy could not be more effective than emission spectroscopy, while the latter was likely to be more convenient in implementation. Walsh showed this to be wrong, but for succcessful implementation he needed to find a suitable sharp-line source, for which he developed sealed-off hollow-cathode lamps over a period of several years. The final patent specification was filed in late 1954, and was followed by Walsh's foundational paper, which not only set out the principles and advantages of the technique, but looked towards the ways it could be further developed.

The commercial development of atomic absorption spectrophotometry was not a straightforward process. The original partner in the process was the well known British firm Hilger and Watts. However, their efforts were hampered by a lack of sufficient finance and faith in the size of the market which could be developed. Walsh and colleagues developed their own framework for a do-it-yourself kit, and was then lucky enough to find the right local firm to make it a commercial reality:Geoffrey Frew, Chairman of Techtron Appliances Pty Ltd, undertook to facilitate the manufacture a 'complete' atomic absorption spectrophotometer. By early 1964, Techtron produced the first all-Australian atomic absorption instrument, the Model AA-3. The prism spectrometer of earlier systems now incorporated a 'Sirospec' grating monochromator designed by John McNeill CSIRO, with diffraction gratings ruled on a ruling engine designed and constructed by Dai Davies and Geoffrey Stiff at CSIRO. At this time, such ruling engines were regarded as one of the finest examples of precision mechanical engineering, and their were only a handful worldwide. The author used a Techtron replica grating in his early unsuccessful efforts at an experimental component for his PhD, but they found better usage in the many absorption spectrophotometers sold by Techtron, and in spectrographs for astronomy and other fields. Soon thereafter Techtron merged with Varian Associates, a, US company, but the manufacturing activity continued in Melbourne, driven in part by the substantial technical support from CSIRO Chemical Physics, which had moved from Fishermen's Bend to Clayton, close to Monash University. We will return later to the work on diffraction gratings in Chemical Physics and another important application. Varian Australia had 630 employees in 1972, and continues to be a large employer, currently having 400 employees.

We now turn to the development of two devices based on the concept of stimulated emission, one of Einstein's many brilliant contributions to physics [42]. Einstein recognised that detailed balance between absorption of light and emission required the existence of a process of stimulated emission, wherein the presence of photons in the vicinity of an atom or molecule could cause it to radiate "copies" of the stimulating photons. The two devices referred to are masers and lasers, in which a population inversion is created, with a higher energy level having a higher population than a lower level. In either case, we can have an "avalanche" of photons created if the radiating system is placed in a resonant cavity, which causes photons to bounce back and forth, stimulating the creation of further photons. Of course, energy must be continually supplied to sustain the process.

The maser was the first of the two devices to be created. The first maser was built by Charles H. Townes, James P. Gordon, and Herbert J. Zeiger at Columbia University in 1953. Townes, Nikolay Basov and Alexander Prokhorov were awarded the 1964 Nobel Prize in Physics for theoretical work leading inter alia to the maser. Interestingly enough, Prokhorov was born in Butcher's Creek, Queensland, his parents being revolutionaries fleeing the Imperial Government of Tsarist Russia. The family returned to Russia after Lenin's accession to power. It is also interesting that naturally-occurring masers or astrophysical masers have been observed. One mechanism which has been discussed for them [44] pertains to charges spiralling around magnetic field lines, which can bunch together near north and south poles of planets or stars, creating a resonator. Charges can be precipitated out of the trap, creating the population inversion necessary for maser emission.

The second device of the two was of course the laser, created on the basis of theoretical work by Townes and Arthur Schawlow. The first operating laser (in 1960) was a solid state laser developed by Theodore H. Maiman at Hughes Research Laboratories. It used a flash-lamp pumped synthetic ruby crystal, and was pulsed. Later that year, the first gas laser, the now common helium-neon red light continuous laser, was developed. There followed a period of rapid expansion of laser types and scientific applications. A humorous description of the laser as a "solution seeking a problem" was current for around twenty years thereafter, but while it may have been true for widespread commercial success it certainly wasn't true in terms of scientific impact. (The commercial breakthrough for lasers came with the humdrum but widespread application in supermarket laser scanners. One remarkable testament to the early public awareness of lasers came in the use of one in the 1964 James Bond film "Goldfinger').

One of the early developments made possible by the laser was the field of nonlinear optics [45]. The laser possesses both spatial and temporal coherence. The former permits inter alia the focussing of the laser beam down to a small spot, in which there are very high power densities. This can be used for dismembering James Bond, but more significantly the high local electric field strength in the spot can also give rise to substantial second and third order effects in the wave equation. This gives the possibility of a whole range of interesting and significant effects for applications. The first of these was frequency doubling [46], where two laser photons can interact in an appropriate nonlinear crystal to provide an output photon of twice the frequency. More generally, two photons of different frequencies can be caused to interact and give rise to sum and difference frequencies, and amplification of a signal input in the presence of a higher frequency pump wave (a process called optical parametric amplification).

Lasers soon became widespread in universities and research laboratories, and in the former permitted a revolution in the teaching of optics. Hitherto, phenomena like interference and diffraction had been difficult to demonstrate in large lectures, and ripple tanks were preferred. Now, the high coherence of the laser beam made it ideal for such demonstrations (in the same way that around 30 years later the discovery of high temperature superconductivity made possible the lecture hall showing of the Meissner effect, with it gravitating another twenty years later to cooking shows).

My own introduction to high power lasers came through a vacation studentship at the then Weapons Research Establishment in South Australia. I was attached to a group developing argon ion lasers for use in what became known as the Laser Depth Sounder (LADS) [47]. I can still remember entering a lab illuminated by the blue green light of an argon ion laser operating on the 488 nm line. This project took over twenty years to come to fruition, with initial flights being in a Fokker F27 aircraft. The laser system was capable of recording depths of up to 80 meters in pristine waters, and heights up to 50 metres above sea level. By the time of the last flight in November 2019 over 3,000 sorties had been flown, covering an area of more than 50,000 square kilometres- see Fig. 9. The data enabled the production of more accurate nautical charts, which was of great value since much of Australia's northern coastline had not been mapped since the circumnavigation of Matthew Flinders.

Parallel activity occurred in the CSIRO Division of Mineral Resources in the use of airborne lasers and satellite monitoring for the measuring and mapping of mineral information [48]. For example, a CO_2 laser flying at around 400 m was used to scan around 100 wavelengths between 9.2 and 11.2 μm (in the thermal infrared region) looking for silicate, carbonate, garnet and feldspar spectral signatures. The technologies used in this project continue to evolve.

We mentioned above the successful manufacture of diffraction gratings by ruling engines: large and sophisticated mechanical devices, which incorporated interferometric control of the positioning of the diamond which created approximately triangular grooves in an aluminium layer on top of a glass blank. In the second half of the 1960's another process was developed to create interference gratings [49]. The principle of this was very simple: the interference of two plane waves was used to create an interference pattern in a photoresist layer, which was then developed and overcoated with metal to create a diffraction grating. One feature of interference gratings was soon evident: their stray light levels were well below those of ruled gratings. A remaining issue of importance for applications related to that of "blazing": the ability of a grating to concentrate a high proportion of incident light in a single diffracted order, in order to efficiently deliver the spectrum. This seemed to be a problem, since the surface profile of interference gratings was near sinusoidal, whereas the elementary theory of blazing seemed to indicate a near-triangular profile was necessary. Computer calculations by the author and colleagues [50] showed in fact that sinusoids could match the blazing from triangular profiles.

M.C. Hutley obtained surprising results when he measured efficiencies of various diffracted orders of his interference gratings as a function of polarisation and angle of incidence. He found the presence of strong absorption peaks for one polarisation and not for the orthogonal polarisation, with the peak absorption being much larger than that of the metal without the grating. This phenomenon could only be explained with a new diffraction formulation due to D, Maystre, which took into account the actual complex permittivity of the metal coating the grating. In fact Maystre's theory gave remarkably good agreement between theory and the measurements [51]. Mayste and Hutley went on [52] to show that a metallic diffraction grating could absorb 100 % of incident light in one polarisation, that for which surface plasmons could be excited. This was extended in 1980 to 100 % of unpolarised light, using a doubly periodic grating capable of exciting surface plasmons along orthogonal directions- work which was only published in 2008 [53]. This early work on surface plasmons on textured surfaces as a means of enhancing optical absorption stimulated much work in later years when systems were intensively studied for the harvesting of solar energy, either photothermal or photovoltaic.

One development relating to the applications of gratings turned out to be noteworthy, in the exact sense of the word. In the 1970's, it was becoming that the development of computers, scanners and printers was going to threaten the integrity of currency notes unless techniques were developed to enhance their security. Work commenced in CSIRO on both the materials used for the notes (resulting in the development of polymer banknotes by the Division of Applied Organic Chemistry) and in the development of Optical Variable Devices (OVD's) immune to simple copying or photographic emulation. The basic theory behind OVD's was developed by R.A. Lee in a series of papers published in Optica Acta, dealing with the physical optics analysis of curvilinear diffraction gratings and the caustics they developed in analogy with the elementary catastrophes of the French mathematician RenéThom (see the excellent book by J.F. Nye [54]). The first banknote produced and circulated using an OVD was the ephemeral 1988 Bicentennial $10 note shown in Fig.10.

The 1988 OVD design was soon superseded by later generations of OVD's as a type of arms race was developed between note designers and increasingly sophisticated teams of counterfeiters. A description of this evolution is given in the CSIROpedia entry [55]. It is interesting to remember in this context that Isaac Newton's final years were spent in the same struggle, as Master of the Mint. His methods were sometimes drastic, but the results were successful.

Survey Data.pdf

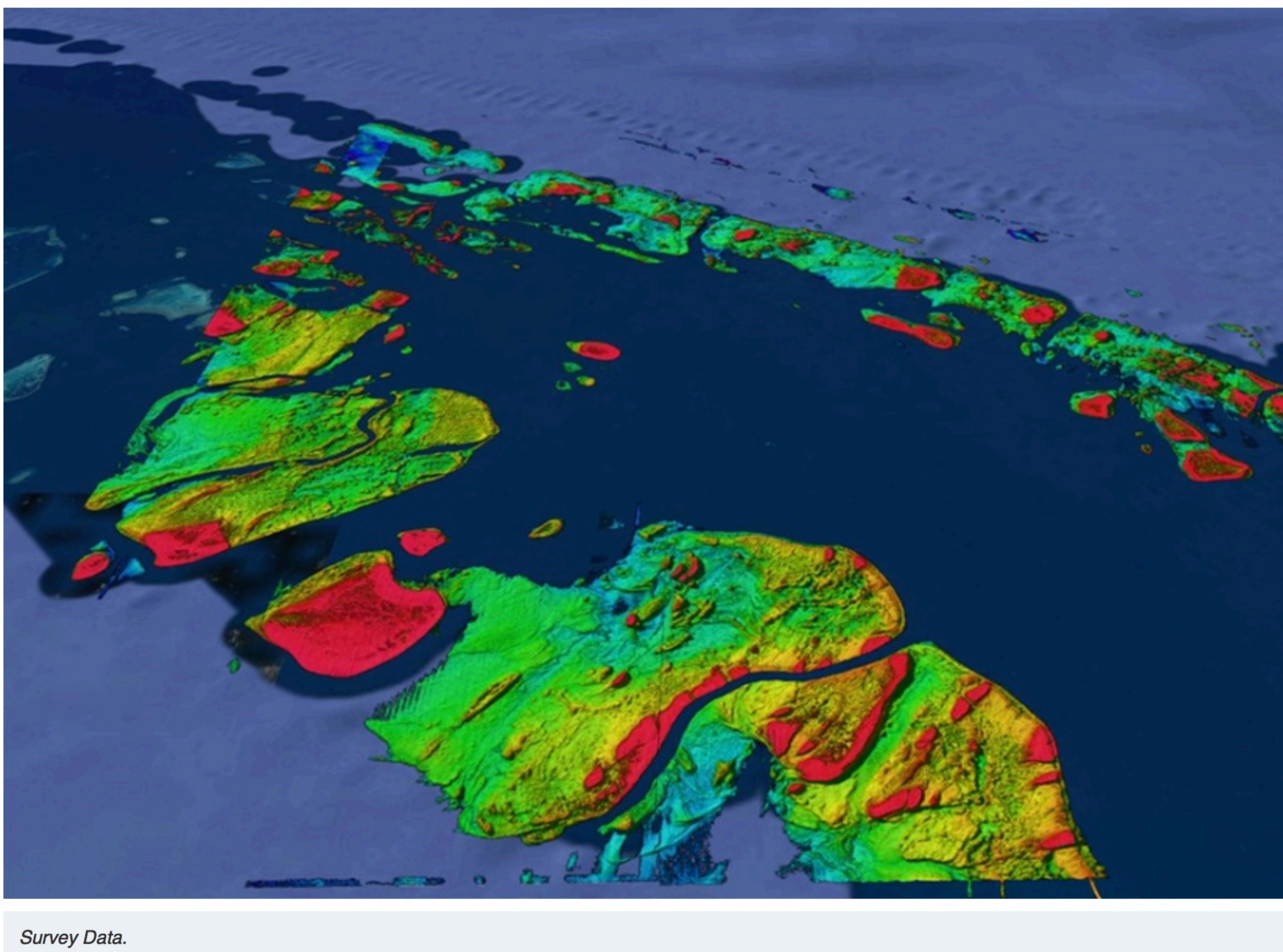


Figure 9: An airborne image of part of the Australian coastline generated by the LADS program. The depth data pertains to part of the coastline taken to be near Cape Melville, Queensland. Copyright: Department of Defence, Australian Government.

Figure 10: One side of the Bicentennial bank note, with the OVD incorporated in the image of Captain Cook

13 Through a Glass Longitudinally

The principle of trapping light in a higher refractive index material surrounded by a lower index one goes back to the 1840's, with the two media being water and air: the light fountain or light pipe [56]. By 1953 the technique had found an application: a bundle of several thousand glass fibres was constructed at Imperial College by Hopkins and Kapany, and shown to be able to transmit an image over 75 cm. This system was quickly adopted in medicine for endoscopy . The idea of achieving transmission over kilometre lengths was investigated by Charles Kao and George Hockham at Standard Telephone and Cables U.K. in 1965. They predicted that by using silica glass of high purity, fibres could be made with transmission losses below 20 decibels/km. This work earned Kao the Nobel Prize for Physics in 2009.

The figure of 20 dB/km was first achieved at Corning Glass Works in 1970, and then substantially reduced using germanium oxide as a core dopant in a silica fibre. This opened the way for implementation on a city scale: this was demonstrated in Turin in 1977. For long distance fibre communication, repeaters were used with separations of 70-150 kilometres. Ideas of nonlinear optics and light emitting diode pumping were combined in systems using erbium-doped fibre amplifiers, developed first by the team of David Payne at the University of Southampton. (The 1986 paper by the Payne team included as an author Simon Poole, who moved to Australia and played an essential role in the development of fibre-associated technologies in Sydney.) Fibre optic cable systems were laid world wide, and were ready for the rapid growth in traffic consequent upon the arrival of the World Wide Web, ecommerce and social media around the period of transition between the 20th and 21st centuries.

The growth of research into and development of optical fibre technologies in Australia was assisted by the arrival here of Professor Antoni Karbowiak [57], who had supervised Charles Kao at STC. He took up a Chair in communications at the University of New South Wales in 1964. In 1976, as a member of the Radio Research Board, he obtained funding to run the first Australian conference on optical fibre technology, which developed into the Australian Conference on Optical Fibre Technology in 1984 [58]. The attendance and presentations at the early meetings was dominated by three groups: that from UNSW, the group of Prof. Allan Snyder at the Australian National University, and members of the Telecom Research Laboratory in Melbourne.

The work of Allan Snyder's group was well known world wide, and played an important role in the growth of research into optical fibres. The seminal book "Optical Waveguide Theory" that Snyder wrote with Dr. John Love has currently around 7,500 citations. John Love played a key role in the ongoing success of the ACOFT conferences, which have continued to this day, and constitute the second oldest conference series on optical fibres. The Snyder group formed a nucleus for the growth of optics as a major research and specialised teaching area within the ANU.

The Australian Optical Society was founded in 1983, and commenced yearly conferences which were often combined with ACOFT. The existence of the AOS contributed to the growth of optics in university departments, CSIRO and industry. Its principal membership groups are in laser physics and photonics, particularly in connection with optical fibre communication and signal processing. It has strong overlaps with the optical astronomy and electrical engineering communities. For example, the successful Australian research record in astronomy owes much to the sophistication of the instrumentation which is employed at (by world standards) relatively small telescopes. One case of this is the development of the simultaneous imaging and spectroscopy on multiple stars within an observational field, achieved using many optical fibres precisely placed in position to capture the light at focus from the chosen stars and convey it to the spectrograph entrance slit.

While the School of Physics at the University of Sydney had long had a strong group in optical astronomy led by Professor Hanbury Brown, activity in other areas of optics ramped up in the mid 1970's with the founding of a strong group researching the development of photothermal solar collectors, paralleling work at the University of New South Wales led by Professor Martin Green. The experimental work at Sydney centred round the development of materials capable of showing high absorptance across the visible spectrum, switching to high reflectance in the near infrared. Among the theoretical work in support of experiment was the development of a multipole method [59] based on a paper of Lord Rayleigh [60] capable of accurately modeling the optical properties of metal-dielectric composites. The outcome of the program of work by the Sydney group was a successful design and implementation of high performing evacuated tubular photothermal collectors. Unfortunately, efforts to commercialise them in Australia failed to come to fruition, but commercialisation ultimately took place in China, where the collectors have found a mass usage, and are exported world-wide.

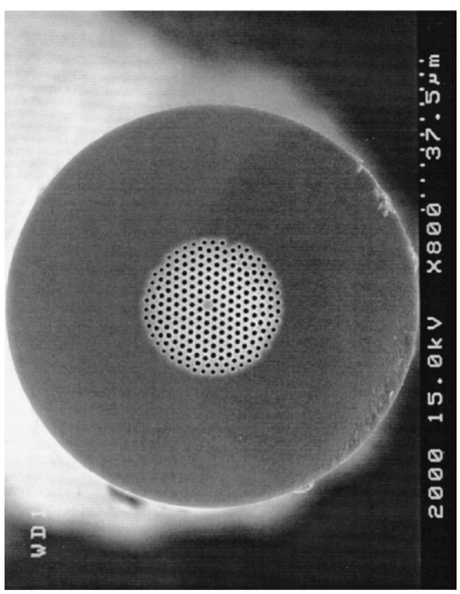
The multipole method continued to find application over the years, and was further developed to deal with the emerging topics of photonic crystals, phtotonic crystal fibres and metamaterials. These will be discussed shortly.

Photonics research at the University of Sydney was broadened considerably in the early 1990's with the establishment of the Optical Fibre Technology Centre [61]. Founded with the support of the Overseas Telecommunications Commission, among its early personnel was Dr. Simon Poole, recruited from the United Kingdom. The OFTC's founding departments within the University were Physics, Chemistry and Electrical Engineering. The OFTC achieved international success in research on optical fibres and fibre gratings. It was on this success that a successful case was built for the establishment of the Australian Photonics Cooperative Research Centre. This had as participants the Australian National University, the CSIRO Division of Applied Physics, RMIT University and the Universities of Melbourne, New South Wales and Sydney, and ran from 1992 until 2006. Its research areas included photonics, optical fibre and planar waveguide materials characterisation and precision networking, while its spin-off companies included the members of the Redfern group of photonics enterprises.

The research field of photonic crystals commenced with two seminal papers by Eli Yablonovitch [62] and Sajeev John [63], who discussed the new physics which would arise if one could create optical materials which behaved for light as semiconductors behaved for electrons. This necessitated the creation of dielectric structures with high enough contrast and the correct geometry to create optical band gaps- frequency ranges in which propagating waves were not allowed. It was desirable that the band gaps be total, with propagating waves travelling in any direction not allowed, and for some applications independently of the polarisation of light. Such total band gaps could be achieved by structures consisting of high refractive index elements (typically with refractive index greater than 3) in air, or the inverse structures (air holes in a high index matrix) [64]. The new research field of photonic crystals quickly became a hot topic internationally, with the first Australian papers coming from a Sydney University- University of Technology Sydney collaboration [65]. The first papers from this group were based on the generalisation of the multipole method to the Helmholtz equation from the Laplace equation, and were connected with two dimensional lattices of cylinders. While much effort was put into the achievement of full 3D band gaps, in fact most photonic crystal applications have been associated with slabs of high index material perforated by air cylinders, structures easily and accurately fabricated with technologies devised for the production of integrated circuits.

A very important extension of photonic crystal concepts was made by the group of Professor Philip Russell at the University of Bath. They realised the possibility of guiding light in cylindical structures consisting solely of silica and air, with air holes distributed in rings around a central region or core, which could be either air or silica. The refractive index contrast between silica and air is small (around 1.4:1) but sufficient to guide electromagnetic waves propagating almost parallel to the axes of the air-silica cylindrical boundaries. There were controversies arising from early numerical modelling of such structures related to degeneracy of the modes in them, and also difficulties in determining how many layers of holes were necessary to furnish guided modes propagating over long distances. These were resolved when a Sydney University/ University of Technology Sydney/Marseille collaboration adapted the multipole method to the study of microstructured fibres in some influential papers [67]. Fig. 11 shows a micrograph of a microstructured optical fibre and multipole results for the confinement loss as a function of the number of rings of air holes. With 4 or more layers of holes, microstructured fibre modes can propagate over kilometer lengths.

It soon became apparent that microstructured optical fibres (MOFs) that, in addition to good confinement of light, provided novel possibilities in the control of mode dispersion. This came about through a quite unexpected experimental result: Ranka *et al* showed that [68] high power laser pulses at a wavelength of 770 nm when injected into a 20 m length of MOF created a



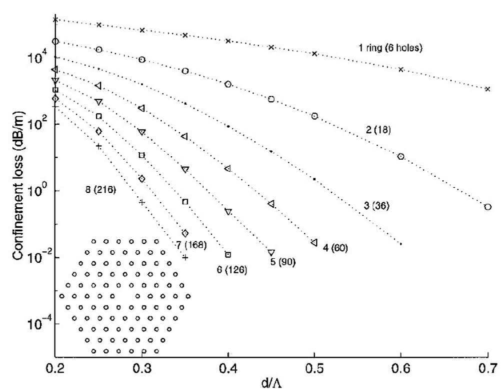


Figure 11: Left: the structure of a microstructured fibre (figure courtesy of H. Kubota). Right: confinement loss in a microstructured fibre of air holes with diameter to spacing ratio d/Λ in silica as a function of the number of rings in the hexagonal structure.

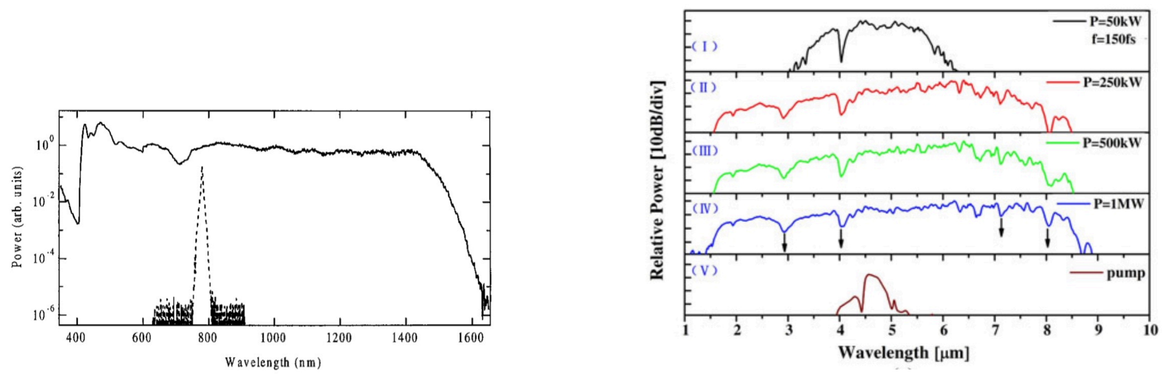


Figure 12: Left: spectrum of the input 770 nm 100 fs, 1.6 kW input pulse (dashed) and the output power from a MOF [68]. Copyright OSA. Right: Experimental SC spectra with different pump peak powers from a As_2Se_3 $-As_2S_3$ chalcogenide glass fibre in the mid infrared (from [70]). Copyright IEEE.

supercontinuum output extending from the ultraviolet to the infrared (see Fig. 12). Such sources of electromagnetic radiation containing over a factor of two in frequency range are valuable in creating frequency combs for applications in metrology. Half of the 2005 Nobel Prize in Physics was shared by John Hall and Theodor Hänsch for their work on frequency combs.

Two of the early research leaders internationally in the field of microstructured optical fibres were Tanya Monro at the University of Southampton and Ben Eggleton at Lucent Technologies. Both were attracted back to Australia, with Tanya Monro joining the University of Adelaide and Ben Eggleton returning to the University of Sydney. The latter was the Director of the Australian Research Council Centre of Excellence, which ran from 2003-2017. With the research participation of seven universities and fifteen partner investigators, it played an important role in the development of Australia's international reputation in optics and photonics. Among its main research strengths were photonic crystals, photonic crystal fibres, metamaterials, optical communications technology and new optical materials.

Cudos became particularly well known for innovations in chalcogenide photonics [69]. Chalcogenides are non-stoichiometric compounds containing one or more of the group V elements such as sulphur or arsenic. They have interesting properties such as good non-linearity and photosensitivity which have made them candidates for a range of applications [69]. For example, if optical fibres are constructed using chalcogenides to give strong non-linearity, they can give super continuum spectra extending well into the infrared region- see Fig. 12. Such emission spectra can for example be used in fiber evanescent wave spectroscopy, permitting detection of the mid-IR signatures of most biomolecules.

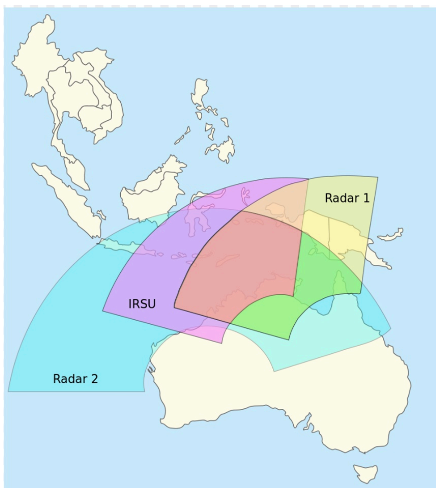
14 Over the Hills and Far Away

In Section 6 we discussed two mechanisms for long distance electromagnetic wave propagation: ground waves and sky waves. These are exemplified in two major defence installations in Australia. The first of these is the Naval Communication Station Harold E. Holt, named after the late Australian Prime Minister, who disappeared whilst swimming around the the time the facility was commissioned [71]. The station provides very low frequency (VLF) radio transmission (19.8 kHz) to ships and submarines of both the U.S. and Australian Navies operating in the western Pacific and Indian Ocean. The station has thirteen radio towers and a transmission power of 1 MW. It also incorporates a Space Surveillance Telescope, an optical telescope with 3.5 m mirror (due to operate from 2022) and a Space Surveillance Radar, both of which can monitor space satellites and debris. It is located near the town of Exmouth in Western Australia, in an area which had accommodated a US navy submarine base in World War II, and near to the RAAF Learmonth airfield, as well as a Solar Observatory operated by the Australian Ionospheric Prediction Service.

The second installation operates at far higher frequencies (5-30 MHz) and relies on radar signals reflected off the ionosphere (see Fig. 13). The installation is referred to as JORN (the Jindalee Operational Radar Network) [72], and dates back to cooperative work between the U.S.A. and Australia in the immediate aftermath of World War II. The Australian arm of the development project was carried out within the Defence Science and Technology Organisation, with the main part of the initial design effort being Project Jindalee. This aimed at proving feasibility and giving an estimated costing for the over the horizon radar (OTHR) network. Jindalee ran until 1985, and successfully demonstrated OTHR capability using an initial and then a more sophisticated radar. A first attempt to construct JORN by a Telstra-GEC Marconi collaboration was unsuccessful, and terminated in 1996. The second attempt was made by Lockheed Martin and Tenix, which delivered an operational system in April 2003. This was upgraded in a further stage finished around 2014, and provided radars at Alice Springs, Laverton and Longreach with similar and updated electronics. A ten year upgrade of JORN is now underway, being carried out by BAE Systems Australia. The project up to the present has cost around $ 1.8 Australian billion, with the upgrade project estimated as costing $ 1.8 Australian billion. The system comprises the three active radar stations mentioned, a control centre at the RAAF Base Edinburgh near Adelaide, seven transponders and twelve vertical ionosondes.

JORN monitors air and sea movements over the region shown in Fig. 13, with a normal operating range of 1000 to 3000 km. However, it is reported that the prototype system was able to detect missile launches by China over 5500 kilometres away. The range depends on ionospheric conditions to some extent, but it is evident from Fig. 13 that JORN is able to provide extremely valuable coverage guiding the coastal defence activities of the Australian Navy and Air Force. It is claimed that JORN is even able to detect stealth aircraft, typically not designed to avoid detection at JORN's frequency range.

Intensive computational work is necessary to JORN's operation, and theoretical analysis can help greatly in the development of algorithms for more effective information retrieval. For example, to infer from the detected return signal as much information as possible about sea conditions in the target area is a difficult inverse problem in back-scattering by a random rough surface. The solution of the inverse problem requires empirical knowledge from measurements in a wide range of situations, as well as sophisticated analysis.



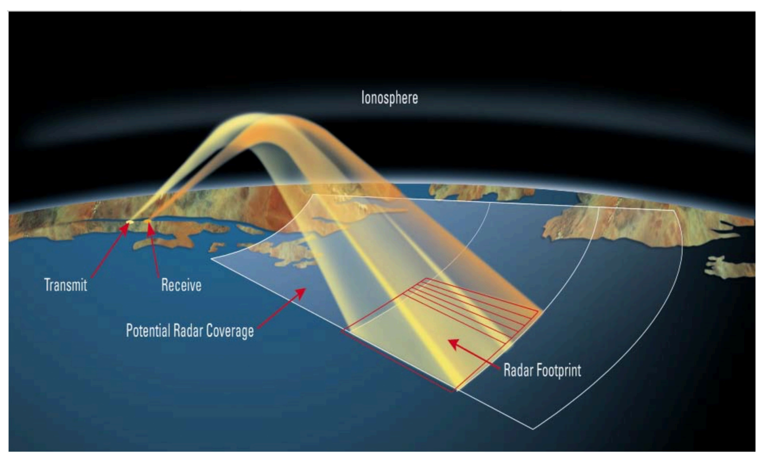


Figure 13: Left: Geographic coverage of the JORN network (copyright Wikimedia Commons: CC BY-SA 3.0). Right: operating principle of JORN (copyright JORN OTHR Operating Principles.RAAF.

15 Conclusion and Acknowledgements

This historical account has covered progress over the more than one hundred and fifty years since Maxwell's groundbreaking papers. My aim has been to highlight, particularly in an Australian context, the combination of achievements in research of both a pure and an applied nature and their effects in improving quality of life. What I hope to have shown is that Radio Science is not in a permanent state of decline, but rather continues to be challenging, important and relevant.

I acknowledge the valuable support and advice provided by many people to this work: Dick Manchester, Don Melrose, Dave Jauncy, Simon Fleming, Judith Dawers, Fred Menk and Jirana Boontanjai. Of course, I have also drawn on what I have learned from many others during my research career, and to them I have always been grateful. I apologise to those whose work I might have referred to appropriately in this work, but the inevitable constraints of space and time have limited my coverage.

Appendix: A Chronology of Major Australian Pulsar Research

This Appendix was kindly supplied by Dr. Richard N. Manchester.

- 1968 Feb 24: Discovery of first-known pulsar CP 1919. (Hewish, Bell et al., Nature, 217, 709)
- First pulsar observations at Parkes, March 8 - 28, 1968.
- 1968 April: Correction of Cambridge published period for CP 1919 (Radhakrishnan, Komesaroff and Cooke, Nature, 218, 229)
- 1968 June: Spectrum and pulse shape of CP 1919. Contained pulse train that later featured on first Australian $ 50 note. (By the way, I had started as a Post-doc at Parkes just a few weeks before this and saw the pulses come in as the telescope arrived on source.) (Robinson et al., Nature, 218, 1143)
- 1968 Nov : Discovery of seven pulsars at Molonglo (Large, Vaughan, Wielebinski, Nature, 220, 753). At this time, Molonglo had discovered more than half of the known pulsars.
- 1968 Nov: Discovery of short-period (89ms) Vela pulsar at Molonglo and association with Vela SNR (Large, Vaughan and Mills, Nature 220, 340)
- 1968 Dec: Discovery of Crab pulsar NP 0532 at Green Bank (and the nearby unassociated pulsar NP 0527). Pulse period unknown. (Staelin and Reifenstein, Science, 162, 1481)
- 1969 Feb: Period of Crab pulsar determined (33ms). (Comella et al., Nature, 221, 453)
- 1969 February: Observation at Parkes of high linear polarisation in Vela pulsar pulses and interpretation in terms of emission from the pulsar magnetic pole the now famous Rotating Vector Model for pulsar emission. (Radhakrishnan et al., Nature, 221, 443)
- 1969 April: Detection of first-known pulsar glitch, in the Vela pulsar , in these same Parkes observations. (Radhakrishnan & Manchester, Nature, 222, 228)
- 1969 May: Rapid spin-down of Crab pulsar measured. (Richards & Comella, Nature, 222, 551). With optical detection of pulses from central star in Crab Nebula (Cocke, Disney & Taylor, Nature, 221, 525, 1969), led to rotating neutron-star model for pulsars (Gold, Nature, 218, 731, 1968; Nature 219, Nature, 221, 25, 1969). Note: powering of the Crab Nebula by a rapidly spinning neutron star had already been proposed by Pacini (Nature, 216, 567, 1967).

- 1973 November: First pulsar discoveries at Parkes. Use of novel 2D-FFT search method to discover eight pulsars (Komesaroff et al., Astrophys. Lett., 15, 169, 1973)
- 1977 April: First detection of optical pulses from Vela pulsar using AAT. (Wallace et al, Nature, 266, 992).
- 1978 November: The Second Molonglo Pulsar Survey discovery of 155 pulsars joint Molonglo-Parkes pulsar survey. Second time that Molonglo discoveries more than doubled the number of known pulsars. Survey observations commenced 1977 April. (Manchester et al., MNRAS, 185, 409)
- 1983 May: Discovery of the first known extra-Galactic pulsar, located in the Large Magellanic Cloud (McCulloch et al., Nature, 303, 307)
- 1985 April: Key paper on the Galactic pulsar population, based on all large-scale pulsar searches to 1982 over 490 citations to date. (Lyne, Manchester & Taylor, MNRAS, 213, 613).
- 1990, January: First precise measurement of the annual parallax, and hence modelindependent distance, of a pulsar observations with the Parkes-Tidbinbilla Interferometer. (Bailes et al., Nature, 343, 240).
- 1990 June: First Parkes detection of a pulsar in a globular cluster, 47 Tucanae. Subsequent searches have brought the number of known pulsars (all MSPs) in 47 Tuc to 25. (Manchester et al., Nature, 354, 598)
- 1992 April: Parkes high-frequency survey of the southern Galactic plane. Discovered 46 pulsars, including the unusual long-period binary system PSR B1259-63 (Johnston et al. 1992, ApJ, 387, L37). Survey commenced in 1988 May. (Johnston et al., MNRAS, 255, 401)
- 1993 February: Discovery of PSR J0437-4715, by far the brightest and one of the nearest millisecond pulsars (MSPs) known. (Johnston et al., Nature, 361, 613)
- 1993 August: First detection of the optical companion of PSR J0437-4715 and bowshock resulting from motion of the system through the ISM. (Bell et al., Nature, 364, 604)
- 1996 April: The Parkes Southern Pulsar Survey; covered the entire southern hemisphere and ultimately discovered 101 pulsars. Survey commenced 1991 July. (Manchester et al., MNRAS, 279, 1235)
- 1996 November: The Parkes Multibeam Receiver the most successful survey instrument on any radio telescope ever. Designed and constructed at ATNF for unbiased surveys for HI and pulsars, but also used for many other applications. (Staveley-Smith et al., PASA, 13, 243)
- 1998 March: Key paper on pulsar beaming mechanisms, largely based on Parkes observations over 600 citations to date. (Lyne & Manchester, MNRAS, 185, 409)
- 2001 July: New test of GR based on precise timing of PSR J0437-4715 that allowed determination of the three-dimensional structure of its orbit. (van Straten et al., Nature, 412, 158)
- 2001 September: The Swinburne intermediate-latitude pulsar survey covered latitudes $\pm 5 - 15^\circ$ adjacent to southern Galactic plane, optimised for MSP detection. 69 pulsars discovered, including 8 MSPs. Survey commenced 1998 August. (Edwards et al., MNRAS, 326,358)
- 2001 November: The Parkes Multibeam Pulsar Survey (PMPS) by far the most successful pulsar survey ever, with more than 830 pulsars discovered so far. The survey covered the southern Galactic plane ($|b| < 5^\circ$) and observations commenced 1997 August. (Manchester et al., 328, 17)

- 2003 December and 2004 February: Discovery of the first and still the only-known Double-Pulsar system, a highly relativistic binary system with orbital period of just 7.7 hours. Both papers each have over 600 citations so far. (Burgay et al., Nature, 426, 531, and Lyne et al. Science, 303, 1153)
- 2006 February: Discovery of rotating radio transients (RRATs) from re-analysis of PMPS data. (McLaughlin et al. Nature, 439, 817)
- 2006 September: First large-scale survey of the Magellanic Clouds for pulsars 14 Magellanic-Cloud pulsars discovered. (Manchester et al., ApJ, 649, 235)
- 2006 October: Highest precision test of general relativity in strong gravitational fields using the Double Pulsar based largely on Parkes and Green Bank pulse timing observations. Over 580 citations to date. (Kramer et al., Science, 314 97)
- 2007 November: Discovery at Parkes of the Lorimer Burst, the first-known fast radio burst (FRB), from a re-analysis of the Parkes Magellanic Cloud pulsar survey data. (Lorimer et al., Science, 318, 777)
- 2009 November: Pulse@Parkes outreach project where high-school students make and analyse pulsar observations. (Hobbs et al., PASA, 26, 468)
- 2013 January: Establishment of the Parkes Pulsar Timing Array (PPTA), the first purpose-designed MSP timing array internationally, for the detection of nanoHertz gravitational waves. PPTA observations commenced in 2004 January. (Manchester et al., PASA, 30, 17)
- 2015 September: PPTA observations used to set what is arguably still the most stringent upper limit on the amplitude of a stochastic background of gravitational waves. ((Shannon et al., Science, 349, 1522)
- 2020 March: Re-engineering of the Molonglo radio telescope signal processor as a fully digital instrument for pulsar surveys and timing. Observations commenced 2014 October. (Venkatraman Krishnan et al., MNRAS, 492, 4752)

References

[1] G. Contopoulos, Highlights of Astronomy, Volume 3, IAU, D.Reidel, 1974.

[2] D. Park, "The Fire within the Eye", Princeton U.P., 1997.

[3] For those not familiar with the choice of the figure to appear on the Scottish 10 £banknote, the voting competition placed Maxwell third behind Mary Somerville and Thomas Telford.

[4] Spark-gap transmitter, Wikipedia.

[5] Useful references in Wikipedia are: Guglielmo Marconi; History of Radio.

[6] The History of Short Wave Radio in Australia, bpadula.tripod.com.

[7] G. Freudenberg, "Churchill and Australia", Pan Macmillan Australia, 2009.

[8] P. Gannon, WW1: First World War communications and the Internet of Things, eandt.theiet.org, June 16, 2014.

[9] Wikipedia: Amalgamated Wireless (Australasia).

[10] Wikipedia: CSIRO.

[11] Wikipedia: Surface wave.

[12] Wikipedia: Lycurgus Cup.

[13] Wikipedia: Surface enhanced Raman spectroscopy.

[14] Wikipedia: Edward Victor Appleton

[15] H.C. Bolton, Australian Physicist, **27**, 31-43 (1990).

[16] Wikipedia: History of radar.

[17] D.B. Melrose and H.C. Minnett, Historical Records of Australian Science, **12**, 229-246 (1998).

[18] CSIROpedia:Radar, csiropedia.csiro.au.

[19] C. Bellamy, PhD Thesis, Charles Darwin University, espace.cdu.edu/cdu:56205.

[20] M. Keentok, The Dictionary of Sydney:Radar, dictionary of sydney.org.

[21] W. Fielder-Gill, Remarks (September 1994) on the occasion of the 50th anniversary of the Bailey Boys. Archives, School of Physics, University of Sydney.

[22] Serendipitous Discoveries in Radio Astronomy, Ed. K. Kellermann and B. Sheets, NRAO, Workshop No. 7, 1983.

[23] Wikipedia: Grote Reber.

[24] J.L Pawsey, R. Payne-Scott and L.L. McCready, Radio-frequency Energy from the Sun. Nature, **157**, 158-159 (1946).

[25] Ron Bracewell, "The Fourier Transform and its Applications", McGraw-Hill, New York 1965.

[26] M.J. Lighthill, "Introduction to Fourier Analysis and Generalised Functions", Cambridge U.P, 1964.

[27] L.L. McCready, J.L Pawsey and R. Payne-Scott,Solar radiation at radio frequencies and its relation to sunspots, Proc. Roy. Soc., **A 190**, 357- 375 (1947).

[28] R.X. McGee and J.G. Bolton, Probable observation of the galactic nucleus at 400 MHz, Nature, **173**, 985 (1954).

[29] A.W. Graham *et al*, History of Astronomy in Australia: Big-Impact Astronomy from World War II until the Lunar Landing (19451969), Galaxies , 9, 24,(2021) ,https://doi.org/10.3390/galaxies9020024.

[30] Montgomery, C., Orchiston, W., and Whittingham, I., Michell, Laplace and the origin of the black hole concept, Journal of Astronomical History and Heritage, **12**, 90 - 96 (2009).

[31] Wikipedia: Black hole.

[32] C. Hazard, M.B. Mackey and A.J. Shimmins, Investigation of the Radio Source 3C273 by the Method of Lunar Occultations, Nature, **197**, 1037-1039 (1963).

[33] Hewish, A.and Bell, S.J., Observation of a rapidly pulsating radio source, Nature, **217**, 709 (1968).

[34] Aspect, A., Hanbury Brown - Twiss, Hong - Ou - Mandel, and other landmarks in quantum optics, Institut des Hautes Etudes Scientifiques,October 6, 2018.

[35] Davis, J. and Lovell, B.,Robert Hanbury Brown 1916-2002, Historical Records of Australian Science, **14**, no.4, 2003.

[36] Hanbury Brown, R. and Twiss, R.Q., Correlation between Photons in two Coherent Beams of Light, Nature, **177**, pp. 27-32 (1956)

[37] Kittel, C., "Elementary Statistical Physics", John Wiley, New York (1958), Section 25.

[38] Born, M. and Wolf, E., "Principles of Optics", Pergamon Press, Oxford,1965 (3rd edn.), Chapter 10.

[39] Hanbury Brown, R. and Twiss, R.Q., A Test of a New Type of Stellar Interferometer on Sirius, Nature, **178**, pp. 1046-1053 (1956).

[40] Hannaford, P., "Alan Walsh 1916-1998", Biographical Memoirs, Australian Academy of Science.

[41] Walsh, A., The application of atomic absorption spectra to chemical analysis, Spectrochim. Acta, **7**, pp. 108-117,(1955); erratum, ibid., p. 252.

[42] Einstein, A (1917). Zur Quantentheorie der Strahlung, Physikalische Zeitschrift, **18**, 121128 (1917).

[43] Gordon, J. P., Zeiger, H. J. and Townes, C. H. The MaserNew Type of Microwave Amplifier, Frequency Standard, and Spectrometer. Phys. Rev. **99**, 1264 (1955).

[44] Melrose, D.B., Theoretical Problems Related to Stellar Radio Emission , in *Radio Stars*, R.M. Hjellming and D.M. Gibson (eds.), pp.351-358, (1985) D. Reidel, Dordrecht.

[45] Boyd, Robert (2008). Nonlinear Optics (3rd ed.). ISBN 978-0-12-369470-6. Academic Press, Cambridge, Mass..

[46] Franken, P.; Hill, A.; Peters, C.; Weinreich, G. Generation of Optical Harmonics. Physical Review Letters. 7 (4): 118119 (1961).

[47] Laser Airborne Depth Sounder (LADS), navy.gov.au

[48] Cudahy,T., Mineral Mapping for Exploration: An Australian Journey of Evolving Spectral Sensing Technologies and Industry Collaboration. Geosciences. 6 (4): 52 (2016); https://doi.org/10.3390/geosciences6040052.

[49] Hutley. M.C., "Diffraction Gratings", Academic press, London (1982).

[50] McPhedran, R.C., Wilson, I.J., and Waterworth, M.D., Blaze optimization for sinusoidal profile gratings, Optics Communications **7**, 331-334 (1973).

[51] McPhedran, R.C., and Maystre, D., A detailed theoretical study of the anomalies of a sinusoidal diffraction grating, Optica Acta, **21**, 413-421 (1974).

[52] Hutley, M.C. and Maystre, D., The total absorption of light by a diffraction grating, Optics Communications **19**, 431-436 (1976).

[53] Popov,E., Maystre,D., McPhedran,R.C., Nevière, M., Hutley, M.C. and Derrick, G.H., Total absorption of unpolarized light by crossed gratings, Optics Express, **16**, 6146-6155 (2008).

[54] Nye, J.F., "Natural Focusing and Fine Structure of Light", I.O.P. Publishing, Bristol, 1999.

[55] Ward, C., Optically Variable Devices (OVDs)- a revolution in anti-counterfeiting technology, csiropedia.csiro.au.

[56] Wikipedia: Optical fiber.

[57] Malcolm Brown, Pioneer of Optical Communications, Obituary, Sydney Morning Herald, August 11, 2011.

[58] Love,J., The Australian Conference on Optical Fibre Technology: ACOFT, AOS News 22 (2) 9-13 (2008). See also the interview of John by Simon Fleming on the ANZOS web site.

[59] McPhedran, R.C., and McKenzie, D.R. : The conductivity of lattices of spheres.I. The simple cubic lattice, Proceedings of the Royal Society of London,**A 359**, 45-63 (1978).

[60] , Rayleigh, J. W. S., On the influence of obstacles arranged in rectangular order upon the properties of a medium, Philos. Mag., **34**, 481-502 (1892).

[61] De Sterke, C.M., Optics and photonics research at the University of Sydney, CLEO Pacific Rim, cleo2020.org.

[62] E.Yablonovitch, Inhibited spontaneous emission in solid-state physics and optics, Phys. Rev. Lett., **58**, 2059 (1987).

[63] S. John, Strong localisation of photons in certain disordered dielectric superlattices, Phys. Rev. Lett., **58**, 2846 (1987).

[64] J.D. Joannopoulos, S.G Johnson, J.N.Winn and R.D. Meade,"Photonic Crystals: Molding the Flow of Light", Princeton U.P., Princeton, 2008.

[65] N.A. Nicorovici, R.C. McPhedran and L.C, Botten, Photonic band gaps for arrays of perfectly conducting cylinders Physical Review E **52**, 1135 (1995).

[66] P. StJ. Russell, Photonic Crystal Fibres, Sceince **299**, 358-362 (2003).

[67] White, T.P., Kuhlmey, B.T., McPhedran, R.C., Maystre, D., Renversez, G., de Sterke, C. M. and Botten, L.C.: *Multipole method for microstructured optical fibers I: formulation and II:implementation* , J. Opt. Soc. Am. B, **19**, 2322-2330 and 2331-2340 (2002).

[68] J. K. Ranka, R. S. Windeler, and A. J. Stentz, Visible continuum generation in airsilica microstructure optical fibers with anomalous dispersion at 800 nm, Opt. Lett., **25**, 25-27 (2000).

[69] B. J. Eggleton, B. Luther-Davies and K. Richardson, Chalcogenide Photonics, Nature Photonics, doi: 10.1038/nphoton.2011.309 (2011).

[70] B. Luo *et al*, Midinfrared Supercontinuum Generation in As_2Se_3 $-As_2S_3$ Chalcogenide Glass Fiber With High NA, J. Lightwave Tech., **35**, 2464-2469 (2017).

[71] Wikipedia: Naval Communication Station Harold E. Holt.

[72] Wikipedia: Jindalee Operational Radar Network.