Fibre Optic Towed Array: The High Tech Compact Solution for Naval Warfare

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ABSTRACT

High performance lightweight towed arrays can offer significant defence capability benefits when applied to future defence programs. A thin lightweight Fibre Optic Towed Array (FOTA) system was developed by applying the electro-optic (EO) hydrophone technology successfully developed for previous sea bed array demonstrator systems. In early 2013, a FOTA prototype was built and demonstrated in a meaningful environment showing comparable performance with existing towed array systems. The target FOTA product configuration would be similar to existing submarine towed array systems, but thinner and more compact, easing the overall submarine design challenge. The development of FOTA also serves to strengthen the Priority Industry Capability (PIC) of "Acoustic Technologies & Systems", identified by Defence as a capability to be nurtured in the Australian industry context. This paper outlines the advantages of this specific fibre optic towed array technology and identify key actions required to nurture this PIC for the continued self-reliance of the ADF operational capability.

INTRODUCTION

Fibre Laser Sensor (FLS) technology has been pioneered in Australia by the Defence Science and Technology Organisation (DSTO) (Foster , Tikhomirov, Milnes, Van Vetzen & Hardy 2005). Since 2003, Thales Australia (TA) has been engaged with DSTO in a series of collaborations in the field of FLS applications. As part of this collaboration, the FLS Capability and Technology Demonstrator (CTD) program was established in 2005, the output of which was a Rapidly Deployable Seabed (RDS) array using fibre laser sensors. The FLS CTD created the opportunity to develop a revolutionary totally fibre-optic based sensor, the Electro-Optic (EO) hydrophone (Bedwell & Jones 2010). The EO hydrophone was validated by using it as the acoustic sensor in the FLS CTD RDS array (Baker & Cain 2011) demonstrated in 2008 and later in an improved RDS array developed and demonstrated in 2012.

The key advantage of the EO hydrophone is that it is not a interferometric-based sensor (Lee, Kim, Park, Eom, Kim, Rho & Choi 2012) widely used in other fibre optic acoustic sensing applications. Its principal of operation is to convert acoustic pressure into a voltage (as a conventional piezo-electric actuator) then convert this voltage into a strain and finally to convert this strain into an optical wavelength shift within the FLS device. This wavelength shift is then transmitted to the inboard system via a standard optical fibre. Different FLS devices are built with different wavelengths. Thus this intrinsic optical telemetry principle dramatically simplifies multiple sensor channel arrangements, with the inherent benefits of good thermal and vibration immunity and the continual desire for high acoustic sensitivity and wide bandwidth. This is all done without the use of any electronics and without the need of electrical power to be sent to the sensors. As a bonus from its construction, the EO hydrophone can be reconfigured to support non-acoustic sensors, crucial in towed array sonar systems.

The successful demonstration of a fully optical RDS array in 2008 and 2012 emphasised the potential of creating small lightweight sonar systems that could even be fitted to vessels of opportunity to turn them into sonar sensor platforms. This stimulated the motivation to apply EO hydrophone technology to a towed array.

The genesis of towed array sonars goes back to the early wartime experiments of 1916 (Lemon 2004). Even then, by moving the sensors away from the noisy platform, towed arrays demonstrated a significant contribution to Anti-Submarine Warfare (ASW) when applied to the defence of surface ships and submarines (Hackmann 1984), as well as their application in the geo-physical survey commercial market. Applying the EO hydrophone technology to towed arrays enables new solutions capable of increasing ASW performance and capabilities when compared with the existing conventional towed array systems.

In a Fibre Optic Towed Array (FOTA), the inboard system and the wet end sensors communicate through optical fibre only. When using the EO hydrophone as sensors, the array does not need to be powered by electricity, hence there are no copper wires from the array to the inboard through the Vibration Isolation Module (VIM) and associated tow cable. Noting this reduction in material, weight and volume, it is possible to target towed array products with thinner outboard sections, which reduce the infrastructure requirements on the towing platform in terms of size and weight and winch space.

The FOTA CTD program commenced in 2011 with conceptual studies and analysis of optimal performance versus different array topologies. This considered the array length, number of channels, frequency bands, group lengths, space between channels and construction constraints. Within this CTD, the FOTA demonstrator was engineered, constructed and demonstrated in March 2013 in Jervis Bay NSW, Australia.

FIBRE OPTIC TOWED ARRAY DEMONSTRATOR

The main sections of the FOTA demonstrator are shown in Figure 1. The outboard consists of the array section, VIM, tow cable and tail rope. The inboard system comprises a deployment and recovery system, a deck cable, an inboard electro-optic transceiver box, the acoustic signal processor and display computer.

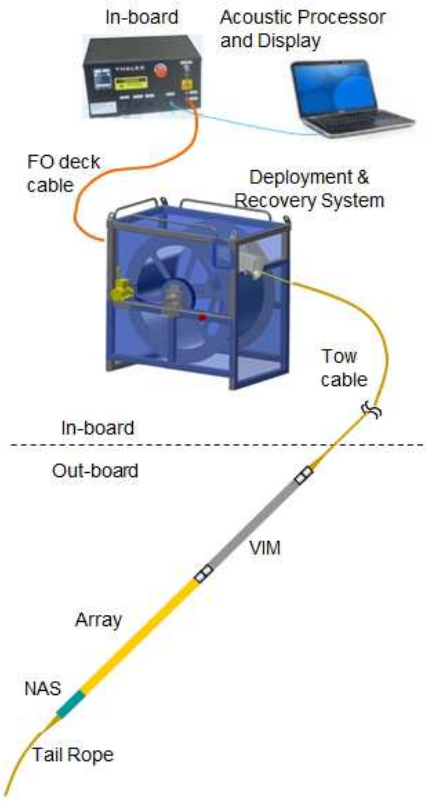

Figure 1. FOTA Demonstrator Sections

Acoustic Array

The acoustic array section (Figure 2) consists of a neutrally buoyant thin line array of 25mm diameter, 50m length with 32 EO hydrophone channels installed. Although the array length is short when compared to existing conventional towed array systems, this trial array is constructed effectively as a subsection of fielded towed arrays, with High Frequency (HF), Medium Frequency (MF) and Low Frequency (LF) acoustic sections built in a nested arrangement to gather acoustic data on critical areas of towed array design.

Figure 2. FOTA Array section wound on calibration drum

Vibration Isolation Module (VIM)

The VIM has the same length and diameter as the acoustic array section. Its purpose is to reduce the axial vibration from the tow cable. Once deployed, the VIM is neutrally buoyant maintaining an horizontal position and subsequently minimising the cross flow.

The VIM is constructed such that potential damage to its internal optical fibres is minimised by limiting the fibre stretch and the bend radius is limited to minimise optical losses. Fibre migration was also addressed in the design as the VIM stretches and relaxes during towing operations.

Tow Cable

The FOTA is seen as being particularly suited to submarine operation where the array is generally streamed behind the submarine with some depression angle below the submarine. The density of the tow cable used in the trial is representative of a submarine tow cable with a density close to that of sea water, taking into account the need to depress the array away from the surface and the tow vessel wake.

The FOTA tow cable is fully optical with multiple individual fibres, an external diameter of 9.6mm and 300m in length.

Tail Rope

The tail rope consists of a compliant rope that provides the necessary drag at the tail end of the array to stop the AFT (after or rearmost) end from “wagging” from vortex shedding, causing vibration induced noise and some deformation of the acoustic array aperture. The tail rope also provides stability of the entire towed system by reducing tail induced vibration.

Underwater Fibre Optic (UW FO) Connector

The UW FO connector was specially designed to connect multiple optical fibres from the array to the VIM (first set) and from the VIM to the Tow Cable (second set). This UW FO connector provides very low optical losses during towed operation, combined with the required ruggedness and reliability demonstrated by several disconnection/reconnection cycles.

Deployment & Recovery System

The automated FOTA CTD streamer deployment and recovery system (Figure 3), provides uniform stowage of cable (no crossed turns) with limited and controlled tension regulated at the drum and variable drum speed. This section is powered by an hydraulic system and affords safety protection to the operator and generally shields the outboard system from the elements.

The deployment and recovery system is competed by a fairlead that consists of a fender, a PTFE sheet, straps and guards.

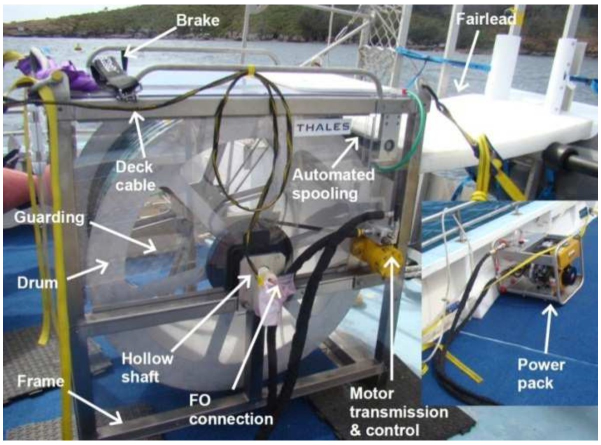

Figure 3. FOTA Deployment & Recovery system

Inboard Electro-Optic Transceiver Box

The inboard Electro Optic (EO) Transceiver box is connected to the fibre carrying the multiplexed optical signals from all the array channels. The EO transceiver box comprises a pump laser source to energise the array, an interferometer, front end photo-detection electronics and a Field Programmable Gate Array (FPGA) board that performs the demodulation, filtering and output of hydrophone data over ethernet.

The 32 channel digital hydrophone data generated by the EO transceiver box is then sent to the acoustic signal processing computer via the ethernet connection.

Acoustic Signal Processor and Display

The standard sonar acoustic signal processing and display function is carried out by a laptop computer with the following additional features:

- Records data from the FOTA acoustic array;
- Displays selected individual channel spectrum;
- Provide analysis displays such as Frequency-Azimuth (FRAZ), Frequency Wavenumber Analysis (FWAN), Low Frequency Acquisition and Ranging (LOFAR), Performance Monitoring Fault Location (PMFL), Waterfall, Time Series and Audio Control.

FIBRE OPTIC TOWED ARRAY PERFORMANCE

The FOTA demonstration was carried out at sea outside Jervis Bay-NSW on 6th March 2013. This trial successfully demonstrated the anticipated FOTA system functionality and performance against the relevant CTD target requirements.

Figure 4. Support vessel towing the FO Array

The FOTA array was towed 400m behind a 18m long support vessel (Figure 4). The acoustic signal captured by each of the array optical channels was translated into fibre laser wavelength variations and transmitted via two (2) single mode optical fibres to the inboard system inside the support vessel. Without need for any copper or electrical connections, these light signal travelled from the array to the inboard through a fully optical Vibration Isolation Module (VIM) and tow cable. Inside the support vessel the inboard system captured the acoustic signal, processed and recorded the data. A live display tool on a single laptop computer showed the detections of reference sound sources (as part of the trial) and vessels of opportunity.

The first section of the demonstration sea trial assessed the towed array detection performance at its broadside (perpendicular direction to the axis of the array) and endfire (direction along the axis of the array) using a known sound source.

The second part of the demonstration focussed on detection and tracking of designated trials surface vessels as well as vessels of opportunity such as small runabouts, commercial cargo ships and trawlers.

FOTA Performance Assessment

The FOTA system performance assessment verified and confirmed the towed array sonar detection range at different bearings and speeds by using a sound source producing multiple tones (300Hz, 600Hz and 1200Hz) with an adjustable level ranging from 170 down to 130dB re 1μPa at 1m.

Once the outboard sections were fully deployed, the towing vessel performed a broadside run (#1) with 2km distance from the sound source followed by a more distant broadside run (#2) at 4km distance. The towing vessel next performed a Forward (FWD) endfire run followed by an AFT endfire run as illustrated in Figure 5.

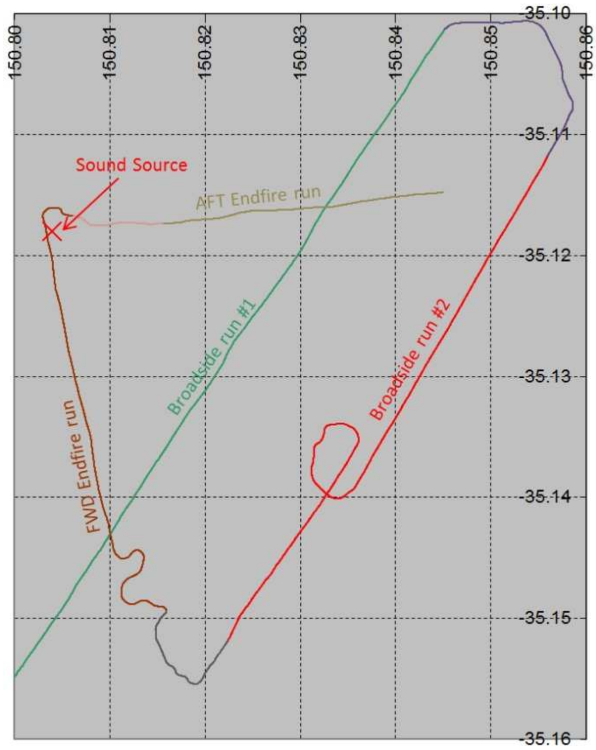

Figure 5. FOTA travel during its performance assessment

The highest level from the source was used at the start of each run and gradually reduced until the source was no longer detected. This data has been used to test the ability of the array to provide an accurate bearing on the source. Consequently there was insufficient energy to form strong tracks on the live analysis tool but the source tones could be used to obtain the exact bearing of the source and calculate the array gain.

The target bearings were estimated from the export of the FRAZ data and measuring the bearing at the three frequencies of the sound track. The bearing error is given in Figure 6 and indicates that generally the bearing error is less than about 3 degrees, unless the towing vessel is in a turn. The array appears to give a good representation of the true bearing. Some of the error comes from the fact that the array is always estimated to be 400m behind and on the heading of the towing vessel. There appears to be a slight tow off due to cross currents but this is only about 2 degrees.

During the FWD endfire the towing vessel ran a snaking course towards the source to allow the sound source to be more clearly identified. This occurred at the time 9:17 (Figure 6) and although there was some increase in bearing error the source was tracked continuously.

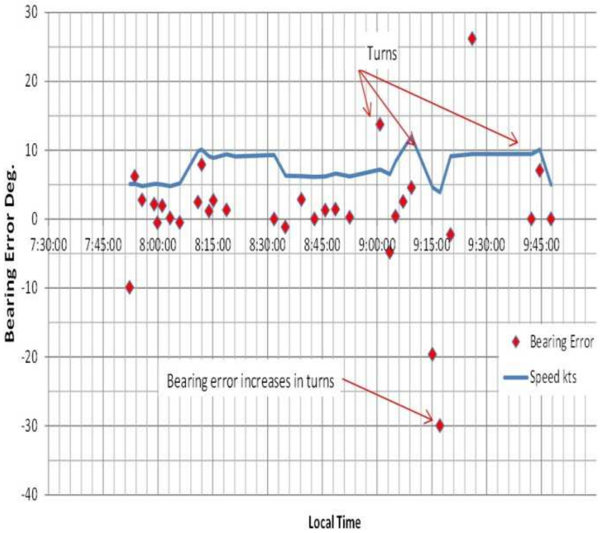

Figure 6. Bearing errors during performance assessment

The result of the detection performance assessment showed a signal excess (amount by which the signal to noise ratio (SNR) exceeds the detection threshold) of 30dB for ranges up to 4 km as illustrated in Figure 7.

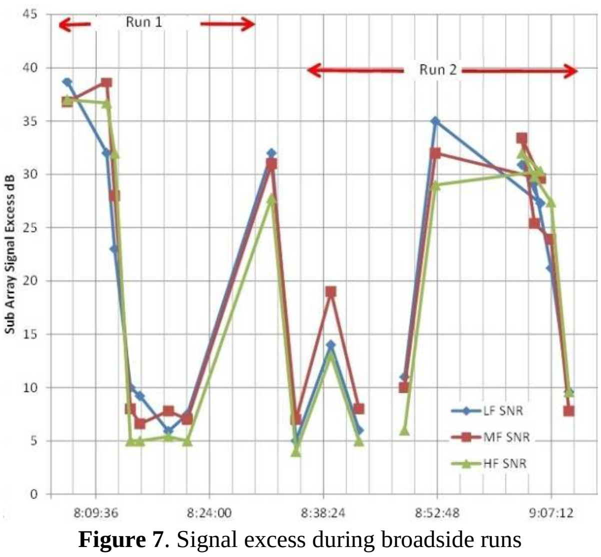

Figure 7. Signal excess during broadside runs

Detection and Tracking of Surface Vessels

On the demonstration of detection and tracking of surface vessels, the towing or support vessel first performed a S-SW run while a Rigid Hull Inflatable Boat (RHIB) approached from starboard closing range down to 200m proximity before then opening range as shown in Figure 8.

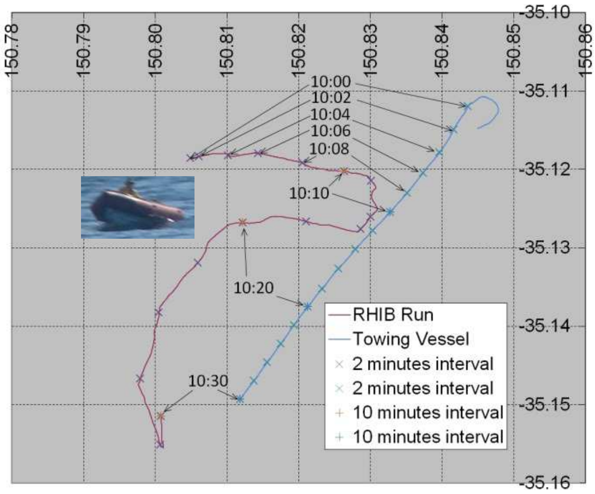

Figure 8. Detection of a RHIB track

The RHIB used as a source between 10:00am and 10:30am was tracked. This tracking is illustrated in Figure 9 by observing two sonar displays side-by-side: the Sub-band Peak Energy Detection (SPED) display, which shows the sonar Bearing versus Time Rate (BTR) and the FRAZ display showing the frequency versus sonar bearing. At the start of the run the towing vessel was completing a turn and it was positioned at about 45 degrees to the array head with the RHIB in the stern port side at about 45 degrees to the array tail.

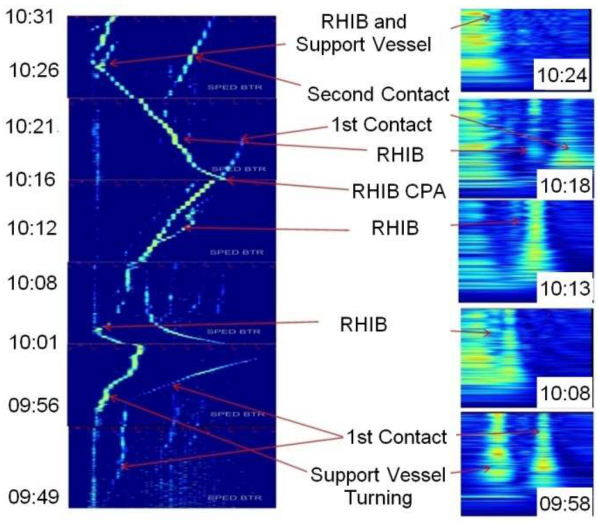

Figure 9. RHIB tracking summary

The track bearings were compared to the GPS bearing and the sonar bearing from the sonar waterfall display. There is generally good agreement in the bearings unless the array is in a turn. Degradation of towed array bearing estimation in a turn is a well-known effect and is the subject of many scientific studies. The FOTA appears to give a clean track during these manoeuvres. The RHIB tended to have a spectral energy above 1600Hz which was outside of the normal band of operating frequencies.

The next target (within the Trials Manager's control) was a diver support vessel, which overran the towing vessel in a N-NE track as shown in Figure 10. During this period, a new contact was identified close to the AFT end bearing, subsequently identified as a trawler heading towards the entrance of Jervis Bay from the South.

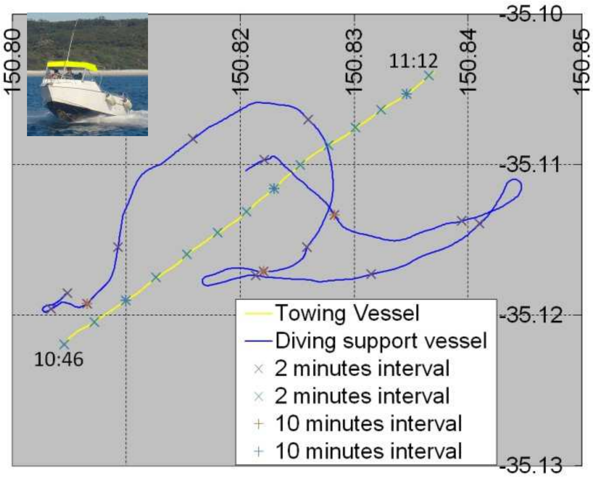

Figure 10. Detection of a diver support vessel track

A summary of the detection and tracking of the target (diving support vessel) is shown in Figure 11 by using the SPED BTR and FRAZ displays side-by-side. The comparison between the sonar and GPS bearings shows that the sonar bearing was consistent with the GPS bearing unless the towing vessel and hence the FOTA was in a turn. The array position has been estimated by assuming it tows directly behind the towing vessel on the same heading. During turns this is not the case as was noted immediately by looking at the real-time FWAN display.

These series of trials demonstrated the FOTA system's capability of protecting a naval surface vessel by detecting and classifying other vessels in littoral waters such as those found near Jervis Bay.

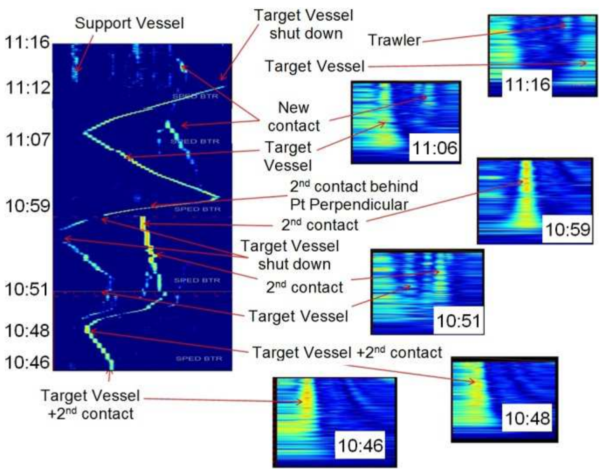

Figure 11. Diver Support Vessel tracking summary

There were some highlights during the trials that demonstrated the FOTA system exceeded its expected performance when it detected vessels of opportunity out at sea - such as a commercial ship at an estimated range of 13 km from the FOTA towed array (Figure 12). The array was able to track the ship in the frequency range of 250 to 4000 Hz using the HF array. There was also some indications of this ship in the lower frequencies and this performance would be improved by having a longer low frequency array baseline. This type of contact also indicates the benefits of having a large signal bandwidth such as that provided by FOTA.

Figure 12 shows the position of the RHIB and the commercial ship (utilising the AIS system) and the FRAZ display with the contacts.

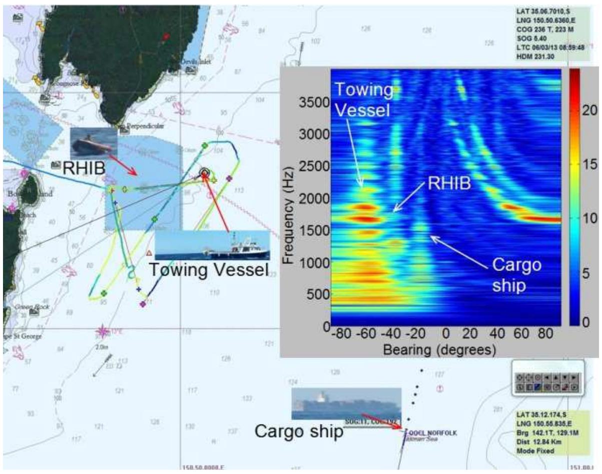

Figure 12. Detection of a commercial cargo ship and RHIB

CONCLUSIONS

The system built and demonstrated during the FOTA CTD confirmed that a lightweight, thinner diameter towed array, including a less complex inboard infrastructure was indeed feasible. The system also proved its reliability by keeping all its channels operational after deployment, operation and recovery processes carried out over several sea trials.

Overall the demonstration trial proved that the towed array technology developed in the FOTA CTD met its initial operational requirements through an operationally meaningful set of demonstration scenarios.

This demonstration emphasised the importance of the FOTA capability, confirming that a fibre optic based towed array is achievable and can thus provide a comparable scalable performance to existing technology with significantly less size and complexity.

The success of the FOTA trials and demonstrated performance forms the basis for further development to realise an industrial product capable of being used in strategic operational applications such as future naval surface ship and submarine towed arrays - conceived, designed, built and demonstrated in Australia.

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