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75 Years of Scientific Air Accident Investigation Support at the Bend

L. Molent and N. Athiniotis

DST GROUP

Science and Technology for Safeguarding Australia

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Aerospace Division

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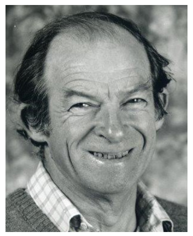

In memory of the late John Kepert, and in the words of his favourite investigator:

Arrange your facts. Arrange your ideas. And if some little fact will not fit in – do not reject it, but consider it closely. Though its significance escapes you, be sure that it is significant.

Hercule Poirot – The Murder on the Links (Agatha Christie, 1923)

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FOREWORD

The need for aeronautical science and technology in Australia was recognised by the 1938 Wimperis Report to the Australian Government which led to the establishment of the then Aeronautical Research Laboratory (ARL) in 1939 at Fishermans Bend, Port Melbourne, Victoria, a forerunner to the current Defence Science and Technology Group (DST Group). The ARL then provided the foundation to the conduct of independent and scientific aircraft accident investigations in support of Defence Aviation, and to the wider community, which is a staple of DST Group to the present day.

This manuscript updates the paper presented at the International Society of Air Safety Investigators Seminar in 2014 which gave a brief history of 75 years of systematic scientific support to aircraft accident investigation at DST primarily at Fishermans Bend. The paper has been updated and more recent contributions to the field by DST have been included.

During these 75 years DST not only made significant contributions to the investigation into the causal factors behind many significant air accidents but also made significant innovative contributions to improvements in aviation safety, including the in-flight data recorder and the Tee Visual Approach Slope Indicator System (T-VASIS) international landing system. DST has a proud history in the support and enhancement of aviation safety and is now even better enabled to continue in this important role.

Dr Alex Zelinsky
Chief Defence Scientist

ABSTRACT

Like other nations, early Australian attempts at powered flight fared poorly. The first recorded accident was when Colin Defries tried to coax a Wright Flyer into the air at Victoria Park Racecourse in Sydney on 4 December 1909. The attempt terminated abruptly when the aircraft struck logs hidden by long grass. Whilst early aircraft accident investigation causal findings such as "a lack of lift in the air"[1] were a useful meteorological observation, they provided little assistance for making the aviation system safer. As at the time, there was no formal system or infrastructure for the investigation of air accidents; these were often left to the discretion of the pilot or owner (or another generally non-expert body) to investigate. The net result was a wide variation in approach and little in the way of science.

The intervening years has seen the establishment of internationally agreed delegations for the conduct of air accident and incident investigation (see ICAO Annex 13), the establishment of professional investigation bodies (e.g. the Australian Transport Safety Board) and the science and technology base to assist in what is still a complex and demanding endeavour. The Defence Science and Technology (DST) Group has contributed to innovations in flight safety and support to both Defence and civilian air safety investigations since its establishment in 1939 at the Bend in Port Melbourne Victoria.

The evolution of aircraft design has resulted in safer aviation; however the technical complexity of aircraft (particularly military) and performance continue to increase under pinning the constant need for science and technology to assist in the unlikely advent of an accident.

This book presents a brief history of 75 years of systematic scientific support to aircraft accident and incident investigation at DST.

Authors

Mr Molent has worked in the fields of aircraft structural integrity, structural mechanics, structural and fatigue testing, advanced bonded repair, aircraft vulnerability and aircraft accident investigation. He has over 250 publications in these technical areas and is a qualified aircraft accident investigator. He has been attached to both the then Civil Aviation Department (1985) and the US Navy (NAVAIR, 1990-1991) in Washington D.C. as an airworthiness engineer. Mr Molent is currently the DST's Head of Emerging Aircraft Structural Integrity. In 2010 he was awarded with the Minister's Award for Achievements in Defence Science. Mr Molent was recognised with an AM in the 2016 Queen's Birthday honours.

Mr Athiniotis is Head of Aircraft Forensic Engineering and Accident Investigation. He commenced at DST in 1989 and has amassed extensive knowledge and experience in metallurgical investigations of aircraft structures, components and systems, and investigations of military accidents and incidents. In 2008, Mr Athiniotis was awarded a Chief of Defence Commendation for his investigation support into the Sea King accident in 2005, and a Chief of Air Force Commendation for his investigation support into the recovery of the Canberra aircraft that went missing in Vietnam in 1970.

[1]WW1 Royal Flying Corps Monthly Safety Report December 1917.

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INTRODUCTION

"In the 1920s, there was growing public disquiet at what was seen, likely, as officialdom's rather elementary approach to the investigation of aircraft accidents. Events came to a head in 1927 when two accidents occurred before large crowds and, more importantly in the eyes of the daily paper, before the Duke and Duchess of York. Their Royal Highnesses were visiting Australia to open the new Parliament House in Canberra with due Imperial pomp and ceremony. On 21 April 1927, during their official visit to Melbourne and just as the royal procession was turning from St Kilda Road into the grounds of Government House, two DH.9 aircraft of the Royal Australian Air Force (RAAF) flypast collided. The crowds of many thousands watched as A6-5 and A6-26 disintegrated and plummeted to earth in the vicinity of Sturt Street, South Melbourne. Fortunately, there were no casualties among the crowd but all four RAAF aircrew were killed making it the worst aircraft accident in Australia to that time. Three weeks later, their Royal Highnesses had the misfortune to witness the crash of SE-5a A2-24 during the opening ceremony in Canberra on 9 May 1927. The pilot F/O F.C. Ewen was killed. The following day, while returning from Canberra to Melbourne with photographs of the opening ceremony, SE-5a A2-11 suffered an engine failure and crashed in remote bushland near Whitfield, Victoria. The pilot, Sgt Orm Denny, walked 25 miles to secure assistance. This was too much for the newspapers. Bowing to pressure, Sir William Glasgow, Minister of Defence, signed a Statutory Rule on 25 May 1927 under the Air Navigation Act of 1920 appointing an Air Accidents Investigation Committee (AAIC). The committee was empowered to make an independent inquiry into aircraft accidents, to study probable cause and to suggest preventative measures. The committee made a flying start by holding its first meeting at Victoria Barracks Melbourne on the 25 May"[2].

The Aeronautical Research Laboratory (ARL) was established at a site on Fishermans Bend Victoria Australia [2] as a division of Council for Scientific and Industrial Research (CSIR) in 1939 following the recommendation of Mr. Wimperis, formerly Director of Scientific Research for the Air Ministry in Britain. Mr. Wimperis was commissioned to advise the Australian Government on the inauguration of aeronautical research in Australia. From its inception ARL provided a system of technology, science, facilities and tools to support the AAIC. The first part of the Laboratories to take shape was a structures and materials section and one of the first buildings on the ARL site was a Structural Test Laboratory, later to be referred to locally as the "Wing Bay", with a reinforced concrete floor for reacting the test loads applied to full-scale structures, largely to support investigations into in-flight structural failures. Subsequently came the wind-tunnel facilities, engine test cells, aircraft systems laboratories and human factor experts. In short a system was established in-part to support aircraft accident investigations.

The ARL[3] then provided the foundation to the conduct of independent and scientific aircraft accident investigations in support of Defence Aviation (in particular today the Directorate of Defence Aviation and Air Force Safety (DDAAFS)), and to the wider community, which is a staple to the present day. This paper presents a brief history of 75 years of systematic scientific support to aircraft accident investigation at the (then) Defence Science and Technology Organisation at the Bend, now Defence Science and Technology (DST) Group.

[2] From [1].
[3] ARL has experienced several changes of name (Aeronautical Research Laboratory, Aeronautical and Maritime Research Laboratory (AMRL), the Defence Science and Technology Organisation (DSTO Melbourne) and currently Defence Science and Technology Group (DST Melbourne).

SOME TECHNICAL BREAKTHROUGHS

DST has pioneered several significant technologies related to the investigation or prevention of aircraft accidents. These include the development of:

1. The "Black Box" flight data recorder[4].
2. The Tee Visual Approach Slope Indicator System (T-VASIS) landing system that was adopted as the international standard in 1971.
3. Global Positioning Satellite (GPS) based wreckage mapping.
4. Human factors and visual optics.

Flight data recorders

The idea of a crash and fire protected device that records both the voices and sounds in the cockpit and some instrument readings before an accident was conceived by Dr David Warren at ARL circa 1954 [3].

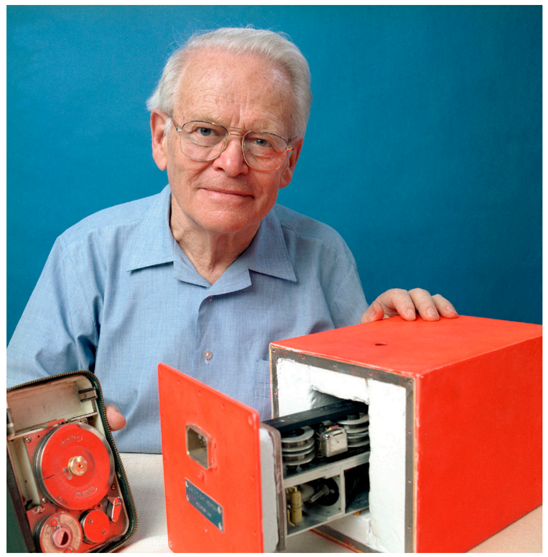

Figure 1: David Warren with the prototype "black box" circa 2000 (Source DST)

A demonstrator unit was produced in 1957, and successfully tested in an Australian F27. The device was compact and light, weighing about one half of a kilogram, and its recording tape was a fine stainless steel wire, as fine as a human hair. The wire tape could survive being heated to red-hot. As well as cockpit noise, it recorded eight channels of flight data such as aircraft speed, height, pitch and roll and had sufficient capacity to record these for four hours. The box was orange in colour. Despite what now appears to be undeniable virtues of such a device, it was not favourably received by the Australian Aviation Authorities at the time. The then Department of Civil Aviation (DCA) stated "Dr Warren's instrument has little immediate use in civil aircraft". The RAAF stated that "Such a device is not required. Opinion is that in fact the recorder would yield more expletives than explanations. To the RAAF, the loss of aircraft is an acceptable risk". How things change!

The British however received the concept with more enthusiasm and further developed the device. On 10 June 1960, an accident occurred in which 29 people died in a Fokker F27 aircraft landing at Mackay in Queensland. The subsequent Board of Inquiry (BoI) was unable to come to any definite conclusions as to the factors underlying the accident and recommended that all airliners be fitted with flight recorders. The Federal Government implemented this recommendation the following year. The decision was made that the Warren device was unsuitable and the US firm United Delta Corporation was approached to develop a device. They chose to use scratch foil recorders for flight data and plastic tape for speech.

[4] Throughout the years DST has received a number of commendations for its work in this area. Some include: a. Diplome d'Honneur of the Federation Aeronautique Internationale (FAI) for the invention and development of T-VASIS. b. 2008 Chief of the Defence Force Commendation: Accident Investigation of the Sea King Helicopter accident in Nias, Indonesia. c. 2009 Chief of Air Force Commendation, into the disappearance of Royal Australian Air Force Canberra aircraft A84-231.

Accordingly, they struck problems of protecting the tape from the heat and damage of the crash. In 1967, the DCA were forced to admit: "The future prospect of recorders based on the use of magnetic wire is brighter now than they have ever been".

Australia was one of the first countries to introduce this requirement and today, all aircraft on the Australian register with a maximum take-off weight greater than 5,700 kg are required to carry both a cockpit voice recorder (CVR) and a flight data recorder (FDR). This is now also required for aircraft operating in or between International Civil Aviation Organization (ICAO) member nations.

T-VASIS

Another notable aircraft safety system developed by ARL also took a considerable time to be accepted. The Human Engineering Division invented the "Tee" aircraft visual approach slope indicator system (VASIS), a method by which the pilots can judge whether they are on the correct glide path for landing (Figure 2) [4]. The "T" shaped pattern of lights on the runway approach became the international standard after some resistance from competing UK systems in 1972. The possibility of developing glide path guidance by visual means arose from a study of landing accidents initiated by ARL in 1956 supported by the Department of Civil Aviation (DCA). The concept was quite simple; a series of lights was positioned to each side of the approach to the runway. When the aircraft was on the incorrect guide slope a figure T was visible to each side of the runway. ARL set up a T-VASIS along with its UK competitor the red and white VASIS at Avalon Airfield near Melbourne for evaluation trials. ARL staff would be bussed to the top of You Yangs hills after work to partake in the evaluation, from which the T-VASIS was clearly visible. In 1973, the DCA and ARL shared receipt of the Diplome d'Honneur of the Federation Aeronautique Internationale (FAI) for the invention and development of T-VASIS. The patent for an "Improved glide path guidance means for aircraft" credited the inventors as John Baxter and Ronald Cumming (from ARL), and Bruce Fraser and Dr John Lane (DCA).

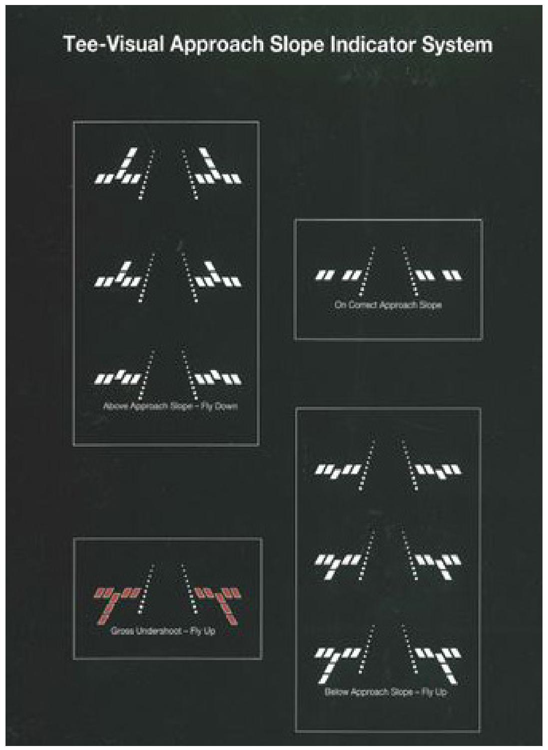

Figure 2: The Tee Visual Approach Slope Indicator System runway light scheme

GPS Wreckage Mapping

During the investigation of aircraft mishaps, identification and mapping of wreckage is usually required prior to its collection (and, if necessary, detailed examination). This recording phase can be time-consuming and very expensive in resources, particularly when the wreckage is spread widely. Traditionally apart from the required surveyors, a team conversant with the aircraft's structure, a photographer, and one of the investigators may be necessary to produce useful data. This could take considerable time depending on the accuracy required and the number of parts to be mapped. Accurate mapping by conventional methods may restrict mapping to 50 or less points a day, followed by data plotting and map generation away from the accident site. The time consumed, and expense, were well illustrated during DST's involvement in the accident investigation of two Australian Army Black hawk aircraft at High Range near Townsville during June 1996. In this case, a group of four surveyors was used along with two personnel familiar with the aircraft structure, a photographer and one of the investigation team. The process in the field was very slow and considerable time elapsed between the initiation of the wreckage survey, and the production of useable maps and the collection of the parts of interest. Indeed parts were collected and analysed, and reports were written well before wreckage maps were generated and made available to the investigators. As a direct result of the difficulties encountered with the Black Hawk investigation, DST began the development of a rapid wreckage mapping system. This had become possible as a result of the GPS being assembled by the US Department of Defense, and the development of mapping equipment using GPS signals, by commercial surveying instrument manufacturers. Other developments include the introduction of reasonably priced medium-resolution digital cameras, and the rapid rise in portable computing power and Geographic Information Systems (GIS) software, which are geographic coded (spatial) databases. Although the use of GPS at accident scenes was not new, when fully developed and refined, the system developed provided considerably greater, almost instantaneous readouts of wreckage maps in any format desired. The accuracy is sub-metre and may be considerably better than this in a relative sense (relative position of points at a site) [5]. An example of such a map is shown in Figure 3.

Visual Optics

The visual environment and achieved visual performance of aircrew can determine mission success or failure, particular so for military aviation. DST pioneered much applied research into visual displays, optical radiation hazards, visibility, transparency scatter, vision enhancement, helicopter separation judgement and visual landing aids [4].

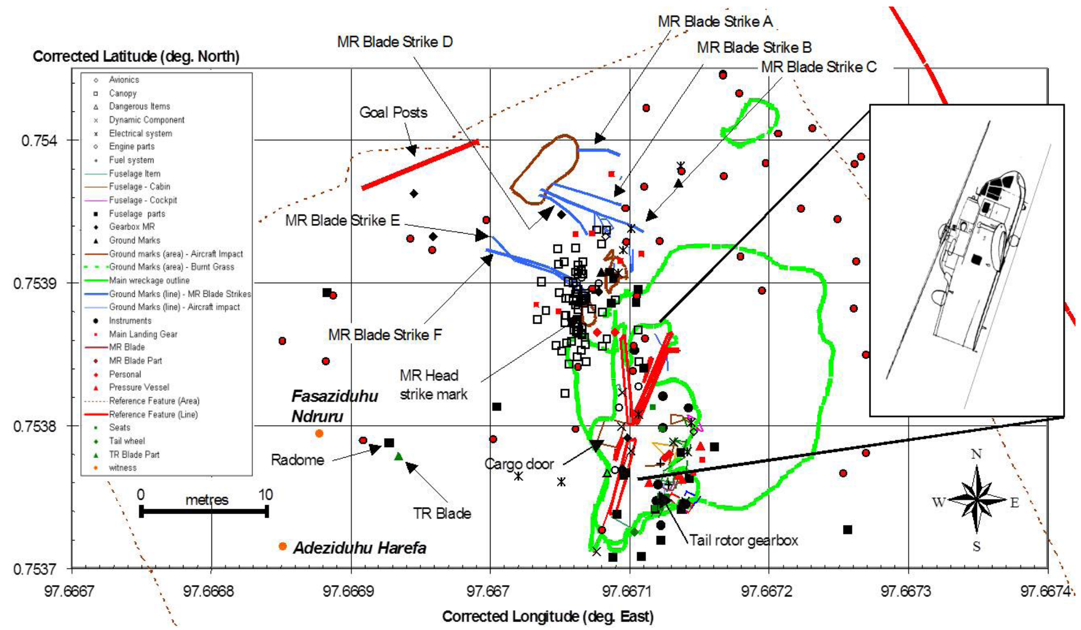

Figure 3: An example of a DST GPS/GIS generated wreckage map

Significantly this research culminated in the development of the Head Up Display (HUD) which has undoubtedly led to increases in safety as well as operational effectiveness [6][5].

The Pulfrich Effect is a visual localisation error arising from unequally illuminated eyes viewing objects moving across the field of view. Researching (see Figure 4) the practical consequences of this led to the realisation that helicopter aircrew views of their own and adjacent main rotors were devoid of most of the usual cues to distance. This research was pivotal in understanding accidents related to rotor-craft main rotor strikes [7].

Figure 4: Barry Clark and his Rotor Rig in the Vision Laboratory

[5]ARL's J. Baxter was seconded to transfer the DST technology, free, to the USA. The US Federal Aviation Agency provided a technical assistant but was adamant that Baxter be listed as second author of the resulting report (Workman and Baxter, 1962) [7].

SOME (FURTHER) INVESTIGATIONS OF NOTE

Early Australian and DST-specific investigations up to 1992 (i.e. the first 50 years) were well described in [1]. In Table 1 a summary of significant DST accident/incident investigation activities up to July 2014 (i.e. 75 years since the inception of DST) is presented. Below are a few examples where significant advances in technology were applied to the accident investigation, or the accident itself was the result of unusual circumstances.

Black Hawk Mid-air

A mid-air accident between two Australian Army Black Hawk (see Figure 5) S70-A-9 helicopters occurred near Townsville, Queensland, in northern Australia, on 12 June 1996. The Army was conducting operational training and the mission was flown at night using night vision goggles and a formation of six aircraft. Aircraft B1 was the flight lead and in close formation (one rotor spacing) with aircraft B2. These aircraft collided and impacted the ground.

In addition to wreckage mapping, considerable efforts were devoted to aircraft reconstruction. By matching blade impact marks with the orientation of the aircraft an estimate of the impact projection of the two aircraft was made. By conducting individual trajectory analyses of each of the various component groups identified (e.g. rotor blades, light materials, major components) and considering their measured spread on the ground (e.g. Figure 6), the overlapping common areas was considered the most probable area of aircraft contact (see Figure 7). These two technical aspects were critical in postulating a credible scenario to explain the collision.

Figure 5: Black Hawk

Macchi Trainer

On 22 November 1990 RAAF Macchi aircraft A7-076 was observed by other pilots in the vicinity to suffer a wing failure during an air combat manoeuvre. Examination of the wreckage recovered from the sea disclosed that the port wing had failed when the aluminium alloy 7075-T6 lower spar boom broke as the result of a large fatigue crack [8,9]. The cracking was found to have initiated from a machining detail in the base of a flange fastener hole, Figure 8. This defect had the effect of introducing a severe notch into the fastener hole. Examination of the recovered starboard wing revealed further fastener hole cracking. All spars in the RAAF fleet had been replaced in a life extension program however a fatigue test of the new configuration had not been conducted. Examination of the Deutsch™ fastener hole from which the fatigue crack initiated revealed that the hole had been drilled though the flange to a depth where the drill tip had just penetrated the rear surface of the flange. This penetration had occurred in the central region of the hole and corresponded to the centre of the tapered end of the drill used to machine the hole. The cracking had initiated at the resultant tapered base of the hole between where the hole penetrated the back face of the flange, and the main bore of the hole. Cracking had occurred

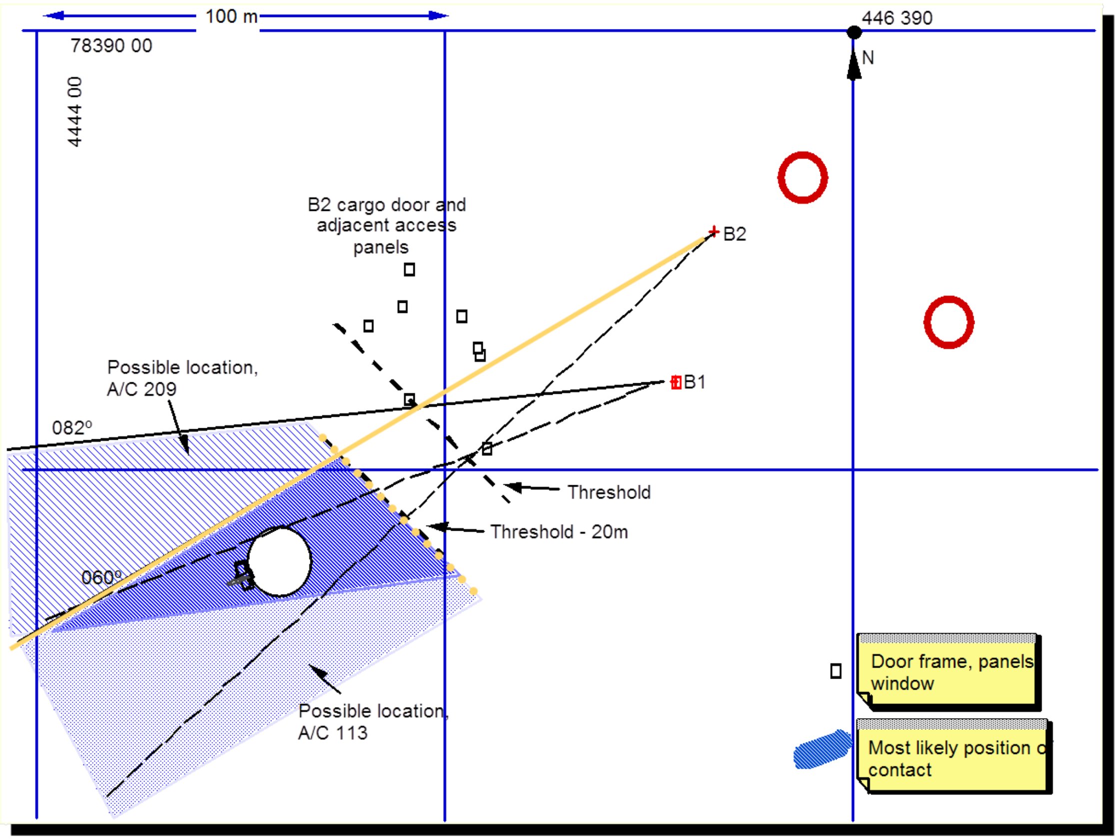

Figure 6: Debris trajectory analysis of cargo door parts from B1 and B2, indicating most likely location of impact.

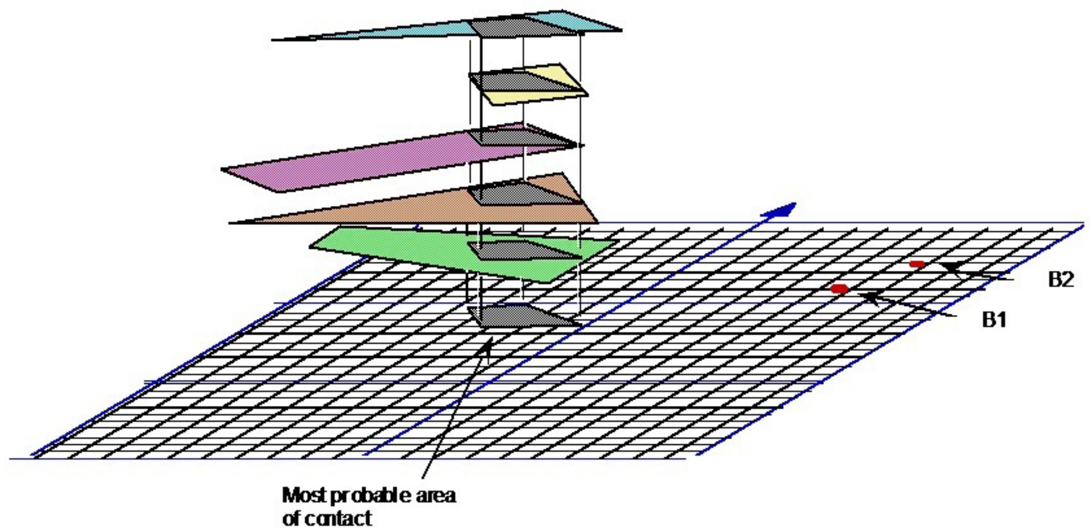

Figure 7: Most likely location of impact (grey shaded area). Each other colour represents the estimated projection of a component group (separated in height dimension for illustration purposes).

on either side of the penetration, roughly in the plane perpendicular to the length of the spar boom with the cracking on either side being slightly offset. Providence dictated that the step produced by the fastener hole drilling was aligned at the worse possible orientation, namely approximately perpendicular to the principal loading direction. The depth of the notch-step produced was estimated to be approximately 0.22 mm (i.e. a large flaw, see [10]). It was postulated that the stress concentration effect of this notch, coupled with that of the hole and low interference of the fastener, contributed to the rapid crack growth rate. Further,

Figure 8: Fracture surface of A7-076 lower spar cap after recovery from the ocean. Note the fatigue progression marks propagating from the upper (nominally) blind fastener hole (upper left hand side)

teardown inspection of the recovered starboard wing revealed the presence of other fatigue cracks, including at the mirror location to the port wing failure site; generally these cracks could also be attributed to poor hole machining quality. With the aid of the load history from the aircraft's Nz meter, the growth pattern on the fatigue fracture surfaces of two holes was determined via quantitative fractography. The largest of the cracks were investigated to establish their growth rates which, coupled with assistance of the non-destructive inspectors, enabled the RAAF to conduct a safety-by-inspection program which helped to recover their training capability.

Royal Australian Navy Sea King Accident, 2005 Nias Indonesia

On 2 April 2005, RAN Sea King (see Figure 9) helicopter N16-100 (call sign "Shark 02"), deployed to Indonesia as part of the Australian humanitarian support operation "Sumatra Assist II", crashed on approach to the village of Tuindrao, on the Indonesian island of Nias. DST support for the investigation of the crash of RAN N16-100 began with the on-site investigation support with specialist materials and structural assessments of the wreckage and its mapping, followed by laboratory analysis by a larger DST specialist team, and presentation of evidence at the BoI [11,12,13].

The rotating machinery on a helicopter makes sounds at various frequencies. DST has developed techniques to analyse the frequency of the ambient noise which can identify and isolate the noise generated by rotating machinery such as engines, gearboxes, and pumps. The Sea King Crash Data Recorder signal analysis of the microphone channels confirmed that the main rotor gearbox and engines were working correctly, and did not show any evidence to indicate a failure in the rest of the aircraft rotating propulsion system components. This supported the accident site and laboratory assessment and analysis.

Figure 9: Sea King

The most significant evidence found suggested that a flight control system failure occurred due to disconnection of the fore/aft bellcrank from the flight control's Mixing Unit (see Figure 10). The physical evidence indicated that an unsecured castellated nut detached from the end of a bolt holding the fore/aft bellcrank onto the Mixing Unit lugs. The bolt then slid out of the lugs, permitting the bellcrank to separate from the Mixing Unit. The Sea King flight modelling developed at DST indicated that the forward motion of the bellcrank and its detachment from the fore/aft lugs of the Mixing Unit would, in less than a second, cause the aircraft to pitch forward rapidly, leading to a nose-dive towards the ground. Any fore/aft inputs made by the pilot with the cyclic stick would have been ineffective because the disconnection of the fore/aft bellcrank from the Mixing Unit prevented fore/aft cyclic stick motions from being transmitted to the swashplate. There was no possibility of recovering the aircraft.

Figure 10: Sea King Accident Site, and disconnected fore/aft bellcrank (below)

The last known maintenance activity on the fore/aft bellcrank occurred on HMAS KANIMBLA, 40 flight hours before the accident, by Sea King detachment personnel on 4 February 2005. The fore/aft bellcrank was removed due to suspected lateral play in the pivot point of the Mixing Unit.

Due to the difficulty in re-installing the item, the maintenance activity carried out by the early watch handed over the task to the late watch with the fore/aft bellcrank loosely secured at the pivot point, with the castellated nut not torqued and with no split-pin fitted. Whilst those undertaking the maintenance were aware of the activity, no aircraft maintenance documentation existed that recorded the removal, serviceability assessment, reinstallation or final inspections of the fore/aft bellcrank. This meant that there was no documented record of a critical maintenance operation task to act as a prompt for the necessary associated maintenance and inspections. It was considered that this lack of documentation and therefore prompt to inspect the critical item which may have noticed the missing split pin, that ultimately led to the unwinding of the castellated nut, extraction of the bolt and separation of the fore/aft bellcrank from the Mixing Unit pivot point.

Australian Army S-70A-9 Black Hawk Accident, 2006

On 29 November 2006, an Australian Army S-70A-9 Black Hawk helicopter carrying four crew and six soldiers crashed into the deck of HMAS Kanimbla and sank into 3000 m water while conducting routine training operations in international waters southwest of Suva, Fiji. Two persons died as a result of the accident.

DST investigations commenced in parallel to the deep sea operation to recover the aircraft, deceased and the Flight Data Recorder (FDR). Using the recovered (and water damaged) video from an on-board hand-held camera along with the ship's video of the flight deck impact, DST photogrammetry was used to reconstruct the flight path and estimate the approach speed of the aircraft. This information was then used to develop a flight model and reconstruction of the accident, which was used in the DST Air Operations Simulation Centre (see Figure 11), to assist pilot instructors to fly a series of manoeuvres that started with defined initial conditions and ended in a manner similar to that recorded by the video imagery of the actual accident. This allowed an understanding of the phases of the approach that led to impact with the flight deck.

DST forensically examined the aircraft wreckage following its recovery, however did not identify anything that may have contributed to the accident. DST also examined Life Support Equipment to determine the sequence of events leading to the death of the pilot. The reconstruction of the recovered FDR data matched closely to the initial DST flight reconstruction, and confirmed that the combination of low speed, large aircraft attitudes and high yaw rate caused a large angle of side slip and placed the aircraft in an unrecoverable state leading to the impact on the ship's flight deck and subsequent ditching.

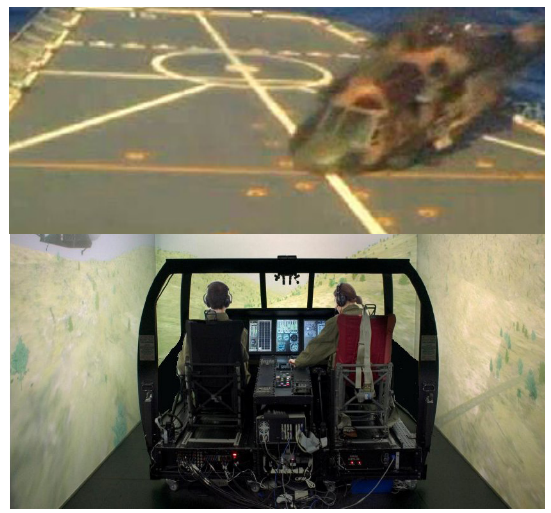

Figure 11: Black Hawk impact on HMAS Kanimbla, and DST Simulator with 'roll-in' Black Hawk cockpit

DST presented its evidence alongside DDAAFS at the subsequent BoI. The BoI determined that "The principal and overarching finding of the BoI was that the cause of the crash was pilot error by the aircraft captain," and "this accident was the regrettable result of a number of factors coming together which culminated in this tragic incident. There was a gradual adoption of approach profiles which, on occasions, exceeded the limits of the aircraft. Other factors included a 'can do' culture in the Squadron, inadequate supervision, the pressures of preparing for operations, the relocation of the Squadron and a high operational tempo".

Locating Missing RAAF Canberra Aircraft from Vietnam, 1970

On the night of 3 November 1970, a RAAF Canberra aircraft (see Figure 12), call sign "Magpie 91", went missing following a routine bombing mission in Vietnam. The aircraft had flown from Phan Rang where it made contact with the ground controller and was directed to the target without incident. Shortly afterwards the aircraft disappeared from radar. A three-day intensive aerial search failed to locate the crew or aircraft. A Court-of-Inquiry held in late November 1970 in Phan Rang, Vietnam, considered all available evidence but was not able to determine the cause of the disappearance.

Figure 12: Canberra bomber

What happened to Canberra A84-231 and her crew remained a mystery for almost 39 years until renewed investigation in 2008 to locate the missing aircraft and recover the two missing pilots was launched, in what was called "Operation Magpies Return". DST's forensics and flight reconstruction capabilities were utilised to estimate the flight path of the Canberra aircraft with the purpose of providing possible locations of aircraft wreckage or debris.

DST have been developing methods, tools and software to reconstruct the flight-paths of aircraft involved in incidents and accidents since early 1990. All Australian Defence Force (ADF) aircraft incidents and accidents have been reconstructed by DST since this date; as well a few foreign military aircraft incidents and accidents. This includes both fixed wing aircraft and rotary wing aircraft. The DST reconstruction of the Canberra flight path utilised audio tape recordings of the pilot and the ground controller which provided airspeed, heading changes/corrections, and included weather at the time, aircraft weight, trajectory calculations, mission briefings and normal pilot actions.

The DST reconstruction provided a refined area of interest for the Principal Investigator (see Figure 13), which assisted in discovery of an aircraft. DST forensic examination of items recovered from the wreckage site confirmed that this aircraft was the missing RAAF Canberra and its crew.

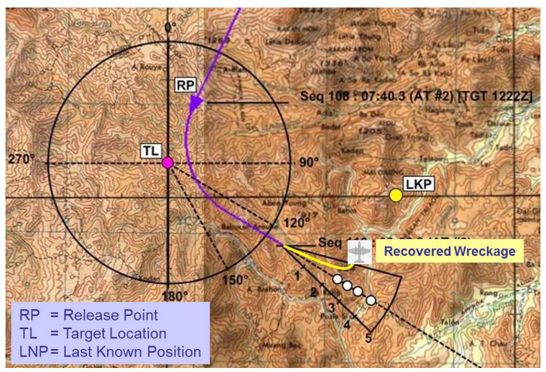

Figure 13: Reconstructed flight path showing approximate location of recovered aircraft. RP =Release Point, TL=Target Location, LKP= Last Known Position based on radar 1970. DST predicted quadrants including possible in-flight breakup (debris field based on fragmentation size).

Chinook

On May 30 2011 an Australian CH-47D Chinook (see Figure 14) was involved in an accident, which occurred in Afghanistan while assisting with the recovery of a downed US Army Blackhawk. The accident resulted in the loss of the aircraft and the death of one passenger (see Figure 15 and 16). Immediately prior to the accident the aircraft crossed a sharp ridgeline at around 1500ft above ground level (AGL). A sharp nose up pitch excursion was experienced followed by a series of pitch oscillations. Pitch attitudes were reported to have reached 60-80° nose up and 120° nose down (inverted) in the fourth oscillation. During the fourth oscillation the pilot applied large longitudinal cyclic inputs and the aircraft was returned to a level attitude at around 10ft AGL but with insufficient rotor energy to maintain a hover. Subsequently, the aircraft contacted the ground, rolled over and caught fire. The aircraft was later destroyed for tactical reasons before the FDR could be recovered. Three further incidents of pitch oscillations were encountered by Australian CH-47D aircraft during operations in Afghanistan over a three month period following the accident, and flight and operational data was recovered for each of these.


Figure 14: Chinook

DST examined the FDR data from each of the incidents, and developed a flight control simulation model to estimate the performance of the Advanced Flight Control System (AFCS) during the oscillations. This indicated that saturation of the longitudinal AFCS was likely to have been the primary cause for the oscillations experienced during the incidents as well as the accident [18]. Subsequently, verification work was undertaken by a combined DST, DDAAFS and Aircraft Research and Development Unit (ARDU) team at the Boeing Helicopters Simulator (BHSIM) in Philadelphia, in which the conditions of the accident were able to be reproduced. This allowed a comprehensive set of recovery procedures to be developed, which were subsequently incorporated into the ADF CH-47D Flight Manual. Following the simulation work undertaken in the Boeing simulator, Boeing released a service note to all CH-47D operators worldwide informing them of the issue.

DST presented its evidence at the subsequent Commission of Inquiry (CoI), covering CH-47D flight characteristics/flight control system analysis identifying the cause of the oscillations experienced in the accident, forensic analysis of life support equipment worn by the deceased passenger, and details of meteorological hindcasts of weather conditions in Afghanistan at the time of the accident. The CoI determined that the method utilised by aircrew "for controlling pitch oscillations on CH-47D aircraft was incorrect and a causal factor in the CH-47D aircraft A15-102 call sign "Brahman 12" crashing in Afghanistan on 30 May 2011. As a consequence of following such method the Aircraft Captain did not take control of the aircraft prior to the aircraft exceeding its flight limits". DST subsequently collaborated with the Australian Army to provide aircrew with detailed explanations of the flight characteristics associated with AFCS saturation, and produced a comprehensive training document to improve pilots' awareness of the more advanced concepts associated with tandem rotorcraft operation.


Figure 15 - Graphic illustration of possible crash site


Figure 16: Remaining debris at crash site

DST Group support to the MH370 search

On 7 March 2014, flight MH370 (a Boeing 777 registration 9M-MRO) lost contact with Air Traffic Control during a transition between Malaysian and Vietnamese airspace. Subsequent analysis of radar data and satellite communication system signalling messages placed the aircraft in the Australian search and rescue zone on an arc in the southern part of the Indian Ocean. On 17 March 2014, the Australian Transport Safety Bureau (ATSB) took charge of the search and rescue operation and over the following six weeks an intensive aerial and surface search was conducted by an international team. The DST contribution was led by Neil Gordon of National Security and ISR Division.

At the start of the search there was a time critical requirement to search for floating debris and acoustic transmissions from the battery-powered underwater locator beacon (ULB) attached to the aircraft's "black box" flight recorder before the battery expired. The Australian Geospatial Intelligence Organisation (AGO) assisted with the debris search at this stage, scanning imagery of approximately 850,000 square kilometres of the ocean. The Australian Defence Vessel (ADV) Ocean Shield, with the aid of the United States Navy (USN), deployed a towed pinger locator (TPL) in an effort to detect acoustic transmissions from the ULB and quickly produced a number of possible underwater acoustic detections. However, overnight analysis by DST Group very quickly revealed these to be spurious detections. At the same time the RAAF dropped in excess of 1,400 sonobuoys in the TPL search area in an effort to detect the ULB before its battery expired. Subsequent analysis by DST quickly showed that, due to the depth of the ocean, there was minimal probability of any of the 1,400 sonobuoys being able to detect underwater locator beacon acoustic transmissions. DST were also asked by the Australian Transport Safety Bureau (ATSB) to independently analyse potential underwater acoustic detections of the 9M-MRO impact with the ocean by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) undersea acoustic array located at Cape Leeuwin, south of Perth, and were again able to rapidly determine that the signals were extremely unlikely to have originated from 9M-MRO.

With the debris and ULB searches being unsuccessful, attention turned to information from Inmarsat related to the satellite communication system on-board 9M-MRO. Satellite communication systems rely on transmissions between a ground station (Inmarsat ground station located in Perth, WA), a satellite (Inmarsat Indian Ocean Region) and a mobile terminal (in this case 9M-MRO). It was noticed that for the last approximately 6 hours of flight, the satellite communication system on 9M-MRO had been automatically responding to hourly ground station initiated log-on confirmation messages (or handshakes). No explicit information relating to the aircraft location is contained in the messaging. The data available with each handshake message is limited to a measure of the range between the satellite and the aircraft and a frequency offset. The frequency offset gives a broad indication of allowable values of aircraft speed and heading at the time of the handshake. In addition to the hourly handshake measurements there are also frequency measurements associated with two unanswered satellite telephone calls initiated by Air Traffic Control to 9M-MRO. The first of these turned out to be critical in determining that 9M-MRO turned south after the final military radar detection.

ATSB convened a search strategy working group bringing together experts in satellite communication systems and statistical data processing from the following organisations: Air Accident Investigation Branch (UK), Boeing (US), Inmarsat (UK), National Transport Safety Board (US) and Thales (UK). DST was invited to join the working group and contribute expert analysis and advice in satellite communication systems, target tracking and sensor data fusion for trajectory prediction. The task for predicting the 9M-MRO flight path was to re-process and calibrate the communication system transmissions in such a way as to infer plausible aircraft locations at the time of the final satellite handshake. The DST team analysed and calibrated the Inmarsat satellite communications data, generated statistical trajectory models and developed novel Bayesian numerical procedures to calculate a probability distribution for the final location of the aircraft. This probability distribution define the search zone in the Southern Ocean and is shown in Figure 15. This work has been reported in a series of ATSB public reports which appeared in June 2014, October 2014 and October 2015 [15,16,17].

The novel Bayesian numerical procedures developed by DST [18] to more accurately define the final search zone are summarised below (see Figure 17). The Bayesian prediction method developed by DST has been validated against a number of earlier flights of the accident aircraft 9M-MRO. Inmarsat data logs and accurate measurements of the actual aircraft location are available for these validation flights from the aircraft's logging system and give good agreement with the predicted probability distribution in each case.

On 29 July 2015 a wing control surface known as a flaperon was recovered from Reunion Island which was later confirmed as being debris from 9M-MRO. CSIRO used data from un-drogued Global Drifter Program [19] drifting buoys (drifters) to generate a probability distribution of the crash site based on the debris find, which was incorporated into the search distribution by DST. The result of the DST and CSIRO analysis is that this one piece of debris could not significantly refine the search zone derived from the Inmarsat data. However it does increase our confidence that the flight path analysis underpinning the search zone area is not wrong.

At the time of writing, the search had covered an area of about 67,000 km^2 which contained approximately 50% of the probability content of the search probability distribution. The search is on-going.

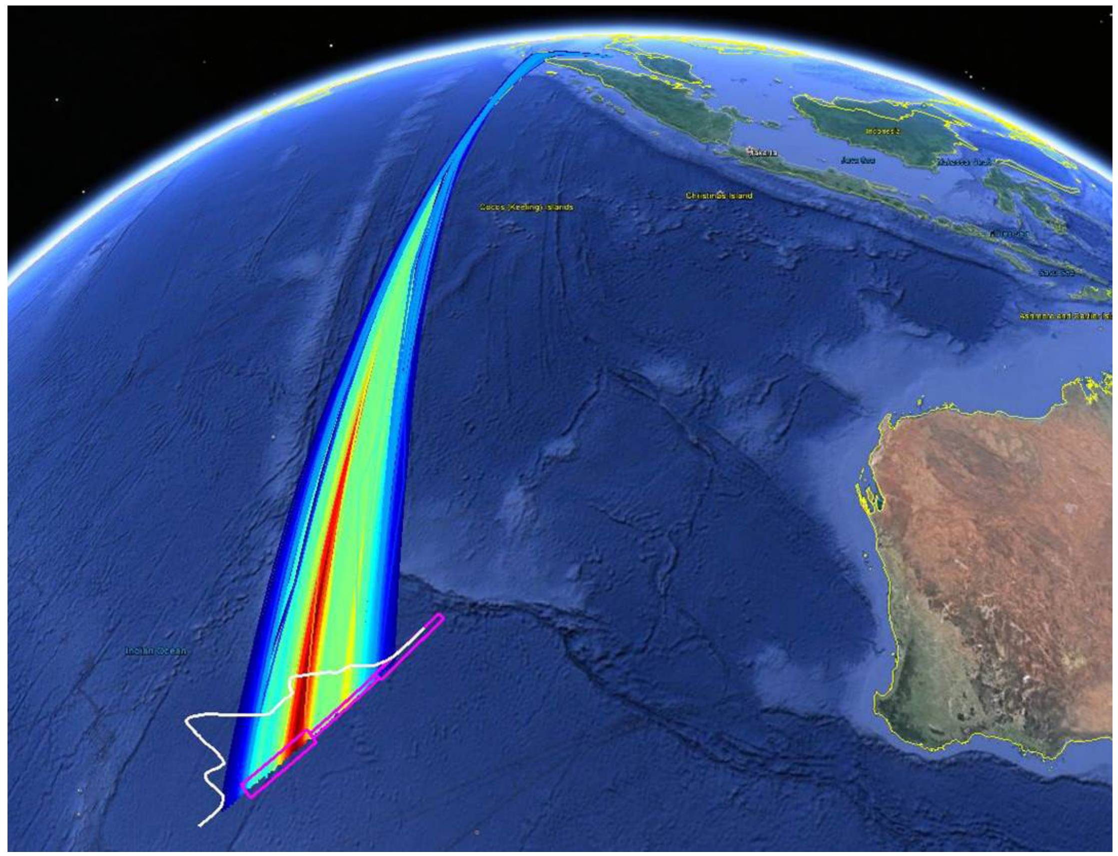

Figure 17: Probability distribution of MH370 trajectories and search zone. Red trajectories are higher probability than blue. White line represents the probability distribution at the time of the final satellite handshake. Magenta shows the searched area as of July 2015.

Assisting the Australian Federal Police in investigating the MH17 disaster

DST contributed to a whole-of-government response supporting the investigation and recovery operations following the destruction of Malaysian Airlines aircraft flight MH17 in a conflict zone over Ukraine on 17 July 2014.

The passenger list released by Malaysian Airlines on 20 July identified 38 Australian citizens and residents on board the plane. It is suspected that the plane was brought down by a surface-to-air missile.

The Australian Government dispatched a team of Australian Federal Police (AFP) investigators and forensics experts to help identify and repatriate the remains of the passengers and to conduct an investigation into what was responsible for bringing down the aircraft. DST scientists were included in the team that remained in Australia to assist the AFP in its accident investigation.

In support of the resulting international investigation, led by the Netherlands authorities, the AFP sought further input from DST {19].

Figure 18: Some recovered wreckage in a Dutch investigation facility

A work program was subsequently developed, and formed a component of Australia's contribution to the investigation. This ongoing effort includes the support of additional Defence scientists.

The AFP has commended the efforts of DST staff for demonstrating outstanding dedication and drive in the development of forensic and technical reports, and for their proactive and innovative contribution to the specialist reporting and mapping which ensured search and recovery opportunities were maximised and team members' safety maintained (see Figure 19).

Figure 19: L-R: Jennie Clothier (NS CTO), Michael Grant (AD), Jeremy Anderson (WCSD), Russell Connell (JOAD), Kelvin Bramley (JOAD), Dale Quinn (JOAD) and Simon Walsh (AFP).

CONCLUSIONS

The DST has a 75 year history of providing the system of technologies and know-how to support the investigations of air accidents. During this period significant technical advancements were made which have significantly contributed to safer aviation and more efficient investigations.

Over many years, the DST has developed a deep level of expertise and experience across a broad range of unique and world class sovereign capabilities, delivering science excellence and outcomes for Australia's defence and national security. It is these multi-disciplinary capabilities that are drawn upon to provide the high level scientific contribution necessary in order to fully understanding the causes of air accidents, and to preventing similar accidents in the future. Further details of some of the investigations highlighted in this book and the people involved can be obtained from the references cited.

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The authors would also wish to acknowledge the aircrew and passengers who have lost their lives serving their country and the international community.

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TABLE 1: SUMMARY OF DST ACCIDENT AND INCIDENT SUPPORT 1981 -2014

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
1981			
Bell UH-1B A2-380	30/10/1981	Tail rotor drive shaft coupling bolts	Tailrotor drive shaft coupling bolts appear to have failed in flight due to incorrect heat treatment
Bell UH-1B A2-380	Williamtown NSW 19/08/1981	Tail rotor drive shaft, 45 degree gearbox, pitch control cables, mast, warning lights, tail rotor pitch quadrant, fin	Pitch control cable pick up and tail rotor loss. Terminal mast bump
1983			
Wessex N7-215 [1]	Into sea Ninety Beach Vic 04/12/1983	Main gearbox components	Fatigue failure of input pinion
Pilatus Porter A14-702	Point Cook RAAF Base Vic 07 /12/1983	Pilots seat, warning lights	Controlled flight into terrain
1984			
Lockheed Orion P3B A9-300	Edinburgh SA 29/01/1984	Oxygen system components	Oxygen assisted fire
1985			
Macchi MB326H A7-085	Williamtown 19/08/1985	Control system components	Inflight fire
1986			
Macchi MB326H A7-085	Williamtown 19/08/1985	Control system components	Inflight fire
Bell 206	Into sea NT 14/04/1986	Main and auxiliary gearbox components, engine exhaust	Fuel Problem
Cessna 202 Air Ambulance	Essendon Airport 3/09/1986	Left propeller fine pitch lock, right fuel pump and connection to Air Throttle body	Power loss
Macchi MB326H A7-082	Pearce 12/11/1986	Fuel system components, warning panel lights and fuel filter	Fuel problem, inflight flame-out
1987			
General Dynamics F111 A8-128	Armadale NSW 2/04/1987	Instruments and warning lights	Controlled flight into terrain
Wessex helicopter RAN	Botany Bay NSW 26/05/1987	Compressor blades	Engine failure
Boeing F/A-18B A21-104	Great Palm Island Northern Qld 18/11/1987	Stand by instruments and the chest mounted oxygen regulator	Controlled flight into terrain

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
1988			
Macchi MB326H A7-033	Pearce WA 01/02/1988	STBD brake housing	Ran off runway
Winjeel A85-458	Mt Seaview NSW 24/02/1988	Instruments	Controlled flight into terrain
Macchi MB326H A7-049	Sale Vic 10/03/1988	Speed brake actuator	Mid-air collision
Macchi MB326H A7-054	Sale Vic 10/03/1988	Control rods	Mid-air collision
Winjeel A85-409	Williamtown NSW 05/04/1988	Instruments	Stall
Macchi MB326H A7-018	Pearce WA 05/04/1988	Fuel shut-off valve, instruments, warning lights, fuel filters	Fuel Problem
1989			
Macchi MB326H A7-021	Sale Vic 03/08/1989	Instruments	Engine fire
1990			
Boeing F/A-18 A21-29 [1]	Near Tindal NT 02/08/1990	Inspection of damage	Mid-air collision with A21-042
Boeing F/A-18 A21-42 [1]	Near Tindal NT 02/08/1990	Inspection of wreckage	Mid-air collision with A21-029
Augusta A109C M38-02 of the Malaysian Air Force	Kuala Lumpur Malaysia 19/09/1990	Flight controls, gear box mounts, wreckage examination	Mechanical failure
General Dynamics F111C A8-130	Amberley Qld 31/10/1990	P&W TF30-P3 Engine S/N P65-9064	Catastrophic in-flight engine failure caused by 4 1/2 bearing failure
Macchi MB326H A7-076 [1] [8]	Williamtown NSW 22/11/1990	Wings and centre section	Fatigue failure of lower port wing spar
1991			
Lockheed Orion P3C A9-754 [1], [20]	Cocos Islands 26/4/1991	Wreckage inspection, general wreckage analysis, elevators and leading edges. Failure analyses	Lost three leading edges to Separation of three leading edges
Boeing F/A-18B A21-41	Weipa QLD 05/06/1991	Instruments, actuators and oxygen diluter demand regulator	Hypoxia
Nomad N24A A18-403	Tindal NT 17/09/1991	Instruments, general wreckage reconstruction and analysis, controls, engines	Loss of control
Pilatus PC9A A23-035	Sale Vic 05/08/1991	Instruments, general wreckage analysis, canopy, ejection seats and actuators	Controlled flight into terrain
Boeing 707-388C A20-103	Into sea Sale Vic 29/10/1991	Instruments, general wreckage reconstruction and analysis, controls, engines	Loss of control

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
1992			
Pilatus PC9A A23-055	Albany airfield WA 21/03/1992	Instruments for glass cockpit	Engine shut down in circuit
Boeing F/A-18B A21-106	Cape Clinton Queensland 19/05/1992	Site, Instruments, general wreckage analysis, controls, engines flight reconstruction	Controlled flight into terrain
1993			
Bell Kiowa (OH-58) A17-044	Oakey Qld 03/03/1993	Site. Structural and materials investigation of tail, tail boom and tail rotor drive shaft	Vertical stabilator hit ground
Boeing F/A-18B A21-009	Near Williamtown NSW 13/07/1993	Inspection of damage, trailing edge flap monoball bearing examination	Failure of outboard trailing edge flap hinge
GD F111C A8-127	Guyra NSW 13/09/1993	Reconstruction. Instruments, warning lights, fire damage, structural damage, windscreen and actuators	Controlled flight into terrain
Boeing F/A-18B A21-022	Tindal NT. 22/11/1993	Rear PTS bearing of AMAD gearbox	Bearing failed resulting in AMAD fire
1994			
Bell Iroquois A2-085	Cape Crawford NT 09/06/1994	Skids, struts	Skid collapse, heavy landing
Aerospatiale Squirrel AS350B A22-024	Canberra ACT	Tail damage structural and material investigation	Heavy landing (other aircraft with damage A22-020,010,008)
Ansett F50 (BASI)	Canberra ACT 01/03/1994	No. 3 bearing from P&W 125B engine	Bearing failed due to undersize ball
Boeing F/A-18B A21-53	Butterworth 13/10/1994	Stabilator bolt, composite material	Midair impact with RMAF F5E
Macchi MB326H A7-038	Bulahdelah NSW 24/10/1994	Wings and centre section	Midair impact with A7-088
Macchi MB326H A7-088	Bulahdelah NSW 24/10/1994	Wings and centre section	Midair impact with A7-038
1995			
Hughes 296C VH-PKK (Schweizer AIRCRAFT)	Near Moorabbin Airport 14/02/1995	Parts of failed tailboom support structure and rotor head	Fatigue failure of left tailboom support strut cluster fitting attachment lugs
Aerocommander 690A	Near Sydney Airport 14/01/1994	Tail structure, instruments	Controlled flight into terrain (water)
Macchi MB326H A7-079	Barrington Tops 60 Nm NW of Williamtown	Fuel system components, Instrument	Engine icing

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
1996			
Black Hawk A25-209	Townsville High Range fire station Barbera Qld 12/06/1996	Site inspection, tail and main rotor blades, engines, helmets, instruments etc.	Midair impact with A25-113
Black Hawk A25-113	Townsville High Range fire station Barbera Qld 12/06/1996	Site inspection, parts of failed tailboom support structure and tail and main rotor blades, engines, helmets, instruments etc.	Midair impact with A25-209
1997			
Bell 206L-3 VH-CKP	Tartus Qld 02/5/1997	Fixed and portable oxygen systems	Oxygen fire in fixed system
Lockheed Ventura VH-SFF	RAAF Richmond 11/1996	Ventura Engine Magneto Switch Vibration Test	Engines failed on takeoff
Re-investigation of Mirage A3-040	East of Williamtown over the sea	Structural integrity of wings	Lost at sea
Aerospatiale Squirrel AS350B A22-007	Canberra ACT	Main rotor star flex. Tail boom	Ground resonance
1998			
Aerospatiale Tiger	Townsville High Range	Site inspection and wreckage mapping	Controlled flight into terrain
Boeing F/A-18 USMC	Delamere range NT 20/08/1998	Site inspection and wreckage mapping	Controlled flight into terrain
1999			
F-111G A8-291	Palau Aur Malaysia 18/04/1999	Site inspection, wreckage mapping, detailed examination of wreckage	Controlled flight into terrain
2001			
Aerospatiale Squirrel AS350B N22-011	Wagga Wagga 05/2001	Site inspection, tail failure investigation	Tail strike
RNZAF Skyhawk NZ 6211	Nowra, NSW 17/02/2001	Laboratory examination of instruments, throttle quadrant, elevator booster package, fuel	Controlled flight into terrain, after attempting a plugged barrel roll
2002			
Kiowa A17-023	Clermont QLD 06/06/2002	Site inspection, detailed examination of wreckage, laboratory examination	Dynamic rollover
F-111C A08-112	Darwin 26/06/2002	Aircraft inspection, laboratory investigation	Arcing of the No. 3 fuel pump loom led to ignition of the fuel-rich air mixture in the F2 fuel tank
Army Kiowa A17-003	AAAC Oakey Qld 10/2002	Site inspection	Heavy landing
RAN Sea King N16-125	HMAS Manoora	Part Engine examination	Engine failure, due to salt build-up

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
2003			
Ilyushin 76TD Euro Asia Aviation RDPL-34141 [21]	Baucau East Timor 31/01/2003	Site inspection, wreckage mapping, detailed examination of wreckage	Controlled flight into terrain
Caribou A4-204	Yalumet PNG 08/02/2003	Laboratory examination	Failure of nose wheel steering components due to severe overload
2004			
RAN Kalkara	Jervis Bay NSW	Laboratory testing of parachute lanyards	Failure of “chinese fingers”
Black Hawk A25-216	Mt Walker Qld 21/02/2004	Site inspection and wreckage mapping	Controlled flight into terrain
USN F/A-18 VFMA-212	Tindal NT 14/09/2004	Site inspection and wreckage mapping	Hydraulic failure followed by double engine failure
2005			
PC9 A23-029	Sale Vic	Site inspection and wreckage mapping, wreckage reconstruction	Mid-air (with A23-039)
Sea King N16-100	Nias Indonesia	Site inspection, wreckage mapping, detailed examination of wreckage	Control system failure
RAN Kalkara	Jervis Bay	Examination of telemetry tapes	Unknown
USN F/A-18 bomb release	Delamere range NT 10/08/2005	Site inspection and wreckage mapping	Release of 500lb live bomb near Delamere control complex
2006			
Black Hawk A25-221	HMAS KANIMBLA Fiji	Wreckage, FDR, Simulation	Blade droop
2008			
Chinook A15-102	High Range Townsville 06/2008	Flight reconstruction, wreckage examination	Heavy landing
C130H A97-008	Dirt strip near RAAF Richmond	Failure investigation of nose landing gear Oleo	Fatigue failure from pre-existing flaw
Caribou A4-285	Efogi PNG 05/09/2008	Site Inspection, Wreckage examination	Heavy landing
Canberra A84-231 ‘Magpie 91’	Operation MAGPIES Return, Vietnam 03/11/1970	Flight reconstruction to predict debris field, wreckage examination to confirm aircraft	Possible engine failure
2009			
Black Hawk A25-204	E. Timor 09/02/2009	Flight Reconstruction	Heavy landing
Caribou A04-199	High Range training Area Townsville 25/09/2009	Site investigation	Missing HStab hinge bolts

Table 1: Summary of DST Accident and Incident Support 1981 -2014

AIRCRAFT TYPE, SNO.	PLACE AND DATE	DST INVESTIGATION	CAUSE
2010			
MRH-90 A40-011	Edinburgh	Forensic investigation of failed No. 1 Engine	Fatigue cracking of engine compressor blades
2011			
PC-9 A23-039	E. Sale 18/05/2011	Wreckage examination including engine, fuel system, flap actuator, propeller system and cockpit instruments	Failed Engine High Pressure Fuel Pump
CH-47D A15-102	MEAO	Modelling, Animation, Weather, Clothing, Forensic investigation to determine sequence of events. Air Warrior Aircrew Ensemble lanyard testing	Pitch Oscillation leading to loss of control
CH47D A15-103	MEAO	Forensic investigation of failed aft Longitudinal Cyclic Trim Actuator, and FDR simulation	Fatigue
2012			
Black Hawk A25-106	Kakoda, PNG	Engine Output Shaft	Failure of Engine Output Shaft flexible coupling
2013			
Hawk A27-023	Pearce WA	Low Pressure Turbine (LPT) Blades	Fatigue failure of LPT Blade
Kiowa A17-051	Brymaroo, QLD	Skids	Heavy landing leading to failure of skids
2014			
MH370	Indian Ocean	Defined search area	Ongoing
MH17	Ukraine	Support to government investigation	Likely surface to air missile

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