Sydney Air Traffic Services and Radar 1981

Analysis aiding the Search for missing aircraft VH-MDX

3rd Edition, November 2017

(1st Edition: May 2014)

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Document purpose

This document was drafted to support VH-MDX related search operations.

The contents of this document are purely intended to clarify accident events to the best of the author's ability to offer a solid base in determining the location of VH-MDX.

This document must not be used for any purpose other than to provide guidance in locating VH-MDX.

The information and data presented in this document must not be used for any legal purpose, as the content may be inaccurate or subject to interpretation errors of the author.

Executive Summary

This paper was drafted to provide base data and information of Sydney Air Traffic Services (ATS) and radar as it was in 1981 and the interaction of these ATS with the VH-MDX accident. As much data and information *as possible* was obtained to support current and future VH-MDX research.

The *Airways Operations Organisation* known today as ATS consisted of three Services two of which are of interest: Air Traffic Control (ATC) Service and the Flight Information Service (FIS).

The ATC Service provided *positive control* of aircraft and was the service that operated radar. The FIS provided *advice and information* to *assist* achievement of safe and efficient flight.

Sydney ATC was involved in the VH-MDX accident and was found to operate *two* radar heads in the accident area. These were 160NM, 12 second sweep Route Surveillance Radar's (RSR) located at *Sydney Airport* and *The Round Mountain*. Both RSR's featured both primary and secondary type radars at each location.

Geographical positions of the radar heads were confirmed whilst various technical aspects of the radar system and display system were defined. Tolerances for radar returns were determined which can now be applied in statistical or basic flight path analyses.

System accuracy values for the *primary* radar system were specified and will be assumed relevant for the *secondary* radar system until actual values are located.

Radio propagation software was used to analyse radar links from the two RSR heads to various positions of VH-MDX. It was found the *Sydney* RSR was *unlikely* able to interrogate VH-MDX during the accident but *The Round Mountain RSR* was able to do so. Propagation analysis software also offered corroborating evidence into the likely VH-MDX radar fade position.

It appears that although radar-recording equipment was installed, it was not operational by the time of the VH-MDX accident.

Radar observations made of VH-MDX by Sydney Air Traffic Control Officers (ATCO's) were discussed and analysed with various conclusions made.

Four *final* Sydney ATC radar positions were identified from various sources all having characteristics that result in uncertainty however, one position was much more defensible than the others (the ≈330˚M/45NM from Williamtown position).

Overall this document provides a solid basis for VH-MDX analysis but investigations are on going and more material will be added to this document with time.

This reference paper will be subject to change as new information and data is found or errors corrected; it is a 'living' document.

Amendments:

2nd Edition May 2015

- Many new additions
- Referencing system changed to superscript type
- SSR symbols and codes added
- SSR and PSR paint sizes added
- More ATCO suggested paint read-off tolerances
- Radar 'pro-forma': name changed to 'radar plot sheet'
- Many photos of Sydney radar displays added
- Sydney radar observations section *significantly* expanded with new additions
- Radar propagation analysis updated

3rd Edition November 2017

- A vast number of significant new findings and analysis results
- Section 3.10.3: Inverted 'Y' symbol for all non-emergency, non-allocated codes (not allocated a discreet symbol).
- Thompson CSF RSR and TAR model corrected from ER-610 to RT18.
- Section 3.8.8: Reports of aircraft paints jumping slightly when transiting between Tullamarine and Majura RSR heads on the Tullamarine Northern Mosaic. This was found due to an incorrect distance between these two RSR's as depicted on the Bright display map.
- Section 4.5: Timings of initial Sydney (36NM) fix, West Maitland present heading, 320˚M/45 Sydney fix, easterly heading observation and 150˚ heading *estimated*.
- Various images updated with better resolution
- SPI SSR symbol specified as being three times the size of a normal SSR symbol
- Many additional PSR and SSR specifications confirmed and added
- Section 3.8.6: addition of tangential fade velocity and blind velocity definition with values for the Thompson CSF RSR PSR
- Section 3.14.1 updated with Thompson CSF RSR PSR data. Coverage in elevation confirmed to be limited by terrain, Earth curvature and obstacles not boresight angle. Antenna gain values available. Minimum of 21dBi antenna gain between -1.5˚ and 5.5˚, 28dBi at 0˚. VH-MDX was at edge of RSR PSR coverage
- DoT policy: Radar headings to maintain track required correction for wind drift and 10˚ initial, and 5˚ final accuracy expected.

- Section 3.11 split into subsections. SSR electronic gating line added. VH-MDX was very close to the SSR electronic gate on The Round Mountain side. Bright display accuracy added.
- Addition of confirmed Sydney Bright display programs available c.1981 in section 3.8.5 and in Annex H.
- New section 3.24 added outlining basic RSR upgrade details.
- Sector 1 airspace was within 90NM Sydney; question raised if the ≈290NM Northern Mosaic was the standard setting. This could elude to no Sydney RSR coverage of VH-MDX thus backing propagation analysis.
- Slant error section 3.18.3 added. Slant error found to be minor for The Round Mountain RSR interrogating VH-MDX (10m).
- Section 4.7.7: Addition of reason for the 150˚ heading call at around 0936:50UTC. Likely due to repeating given heading to VH-MDX approximately 5 minutes previous. '*all over the place*' was likely stated as VH-MDX was tracking east but given heading was south-east (150˚M).
- Minor refinement of section 3.22.2 positions.
- Extra fix added in section 3.22.2
- Sections 3.11.2, 4.7.5.4, 4.7.5.6: Williamtown 0936:00UTC radar fix updated to 324˚M-325˚M at 47NM from Williamtown.
- Extra radar fix/ topographical/aeronautical chart graphics added.
- Addition of a statistical deviation plots based on predicted radar system accuracy and read-off errors for specific radar fixes.
- Section 3.9: Confirmation of electronic gating line gating all SSR and remote PSR returns to the respective source's sector and Sydney RSR PSR returns un-gated (visible throughout mosaic program).
- Sections 3.5.1 and 3.5.2: Newly located DoT documents suggest Sydney RSR tower height was 55' (16.8m) and The Round Mountain RSR was 25' (7.6m). This yields SSR antenna heights of 18.3m and 9.1m respectively.
- Section 3.4.2: The Round Mountain RSR head location confirmed.
- Addition of section 3.18. 5 Extraction accuracy and section 3.18.6 Registration accuracy.
- DoT The Round Mountain RSR PSR flight test results included
- Section 6 completely re-written
- Three Sydney ATC *final* radar fixes identified: Sydney deposition final fix, ≈330˚M/45NM from Williamtown, ≈6NM-7NM east of the Singleton NDB – Mount Sandon NDB/VOR track/ 40NM north of Singleton NDB.
- Innovative methods to reduce and define the 330˚M/45 from Williamtown final Sydney ATC radar fix. This perhaps has been the most important ever breakthrough in the VH-MDX conundrum
- Arial font.

Abbreviations

ASIB	Air Safety Investigation Branch
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATS	Air Traffic Services
CRT	Cathode Ray Tube
CTA	Control Area
DoT	Department of Transport
DME	Distance Measuring Equipment
FIA	Flight Information Area
FIS	Flight Information Service
fpm	feet per minute
FS	Flight Service
FSC	Flight Service Centre
FSU	Flight Service Unit
FSO	Flight Service Officer
GHz	Gigahertz
ICM	Inter Console Marker
IEEE	Institute for Electrical and Electronic Engineers
˚M	Degrees Magnetic
NDB	Non-Directional Beacon
MHz	Megahertz
NM	Nautical Mile
PPI	Plan Position Indicator
PPS	Pulses Per Second
PRF	Pulse Repetition Frequency
PSR	Primary Surveillance Radar
RAAF	Royal Australian Air Force

RCC	Rescue Coordination Centre
RCS	Radar Cross Section
RSR	Route Surveillance Radar
SAAC	Senior Area Approach Controller
SAR	Search and Rescue
SOC	Senior Operations Controller
SPI	Special Position Identification
SRC	Sector Radar Controller
SSR	Secondary Surveillance Radar
STAC	Senior Terminal Approach Controller
SYD	Sydney
˚T	Degrees True
TAR	Terminal Area Radar (In 1981 Sydney ATS context: In 1981 Williamtown context it is Terminal *Approach* Radar)
TAST	Terminal Area Severe Turbulence (display)
TRM	The Round Mountain
VHF	Very High Frequency
VOR	VHF Omni Directional Range
WGS	World Geodetic System
WLM	Williamtown

Table of Contents

1. Introduction

1.1. Purpose

Understanding Sydney Air Traffic Services (ATS) such as Air Traffic Control (ATC) and Flight Information Service (FIS) as it was during the VH-MDX accident in August 1981 is crucial to forming likely and defensible assumptions as to the location of the missing aircraft VH-MDX. Sydney ATS were importantly involved in a number of ways with VH-MDX:

- Sydney Flight Information Service 5 (FIS-5) was the *only* ATS agency to communicate with VH-MDX from Taree to loss of communications
- Sydney ATC identified and tracked VH-MDX on radar
- Sydney ATS liaised with RAAF Williamtown ATC to establish radar contact with VH-MDX
- Sydney ATC observed radar *fade* of VH-MDX.

The search for VH-MDX will likely continue for some time following the initial release of this reference paper. Without doubt, new opportunities for analysis and response will present themselves in the form of technology that does not currently exist or, is cost prohibitive today.

Accordingly, *as much detail as possible* will be recorded in Sydney ATS key interest areas and although possibly not of use immediately, could provide a solid base for future analysis. Analysis areas of the VH-MDX accident involve topics such as human factors, radio propagation and radar fix characteristics.

This document is drafted to support these tasks and satisfy the information requested by individuals involved in these areas whilst also offering a long-term reference to minimise iterative research thus, increasing economy of effort whilst also minimising 'witness fatigue'.

1.2. Methodology

Information and data will be sought from publications, reports, official correspondence and members of the ATS system such as Air Traffic Control Officers (ATCO's), Flight Service Officers (FSO's) and Radio Technical Officers.

The capture in particular of key personnel directly or closely involved with the VH-MDX accident or with Sydney ATS experience is a focal point.

1.3. Note on recent interviews and discussions

Interviewing key personnel over thirty years from an event can result in changed views compared to what was apparent at the time. The author has proceeded as carefully as possible to ensure capture of the most true-to form views of the event however, caution must be applied in using such information.

1.4. Legal Disclaimer

The information and data presented in this document must NOT be used for any legal purpose, as the content may be inaccurate or subject to interpretation errors of the author.

1.5. Acknowledgement

Hearty thanks are due to the key personnel involved in the VH-MDX accident and to the numerous Air Traffic Controllers, Radio Technical Officers and others who have assisted the author with research.

For many involved there has been over thirty years of repetitive discussion and questioning of this event and to go over events yet again can be a burden. Your efforts are truly appreciated.

Special thanks are in order for the National Archives of Australia and the Airways Museum and Civil Aviation Historical Society who have provided so much support to my research.

Thanks also go to the assistance provided by Airservices Australia.

2. Sydney Air Traffic Services (ATS)

2.1. Department in charge of ATS (Airways Operations Organisation)

The *Department of Transport*, New South Wales Region, was in charge of Sydney ATS between 8th February 1977 – 7th May 1982.

From the 7th May 1982 – 24th July 1987, Sydney ATS was overseen by the *Department of Aviation*, New South Wales Region.

The same departments were also in charge of the Air Safety Investigation Branch (ASIB) that was responsible for conducting aviation safety investigations in 1981. The ASIB was disbanded for the operationally *independent* Bureau of Air Safety (BASI) in 1982.

Later changes to the department names were:

- 24th July 1987 – 1st July 1988, Department of Transport and Communications, Aviation Group
- 1st July 1988 – 6th July 1995, Civil Aviation Authority.

2.2. The ATS structure

2.2.1. Overview

The Civil ATS and aviation emergency services structure was termed ‘the Airways Operations Organisation’ in the 1980’s[15]. It is known today as Air Traffic Services (ATS)[13]. The contemporary title will be used in this document.

Contemporary ATS is divided into three branches[13] and is assumed *similar* to the structure in the 1980’s:

- Air Traffic Control (ATC) Service
- Flight Information Service (FIS)
- The Alerting Service.

Of interest are the first two that provide very different services from each other.

2.2.2. ATC service
The ATC Service provides airspace *control* services to prevent collisions between aircraft whilst also expediting and maintaining an orderly flow of air traffic[13]. Specific services provided today are[13]:

- Aerodrome Control Service: Controlling aircraft on or close to the aerodrome
- Approach Control Service: Controlling aircraft arriving and departing the aerodrome
- Area Control Service: Controlling traffic away from the aerodrome (enroute between aerodromes).

These services would effectively be the same as those provided by 1981 ATC.

2.2.3. Flight Information Service (FIS)
FIS provides *advice* and *information* to assist the achievement of safe and efficient flight. This is done by providing[13]:

- ATC initiated FIS, providing weather, airspace and hazard information
- An on-request service providing the same information
- Automatic radio broadcasts with weather, hazards etc.

During the 1980's, FIS was provided by Flight Service (FS), a dedicated service with *separate* manpower and facilities.

The 1981 FS used *Flight Service Units* (FSU) at *regional* outstations and *Flight Service Centers* (FSC) at *capital city* airports[5]. These FSU's and FSC's would be responsible for providing FIS within certain boundaries of airspace called Flight Information Areas (FIA)[5]. FSU's and FSC's were manned by *Flight Service Officers* (FSO) and provided[5]:

- Pre-flight pilot briefing
- Operational information to/from aircraft
- Weather reports from observations
- Monitoring of ground-based radio navigation aids
- Search and Rescue (SAR) alerting.

As can be seen FIS is an *assistance* service rather than a *control* type service as ATC is.

2.3. Sydney airspace

2.3.1. Overview
Controlled airspace surrounding Sydney was broken down into manageable areas each with dedicated Air Traffic Controller Officers (ATCO's).

Within a 30NM circle of Sydney was the Terminal Area (TMA). Narrow bands of airspace along the extended centerline of the runways from the TMA out to about 80NM to 100NM were classed as Approach and Departures airspace.

The remaining Sydney airspace surrounding the TMA and approach and departures airspace were divided into Area Control Service *Sectors*.

Airspace portions (Approach/Departures, various Area Sectors) could be combined during times of low traffic to match manpower to workload[2].

From the memory of one Sydney ATCO present in 1981 multiple Sectors at Sydney were normally (but not always) combined into single Sectors around 2100 local time dependent on actual and expected traffic movement numbers[2]. Sydney ATC Sectors and FIS-5 FIA boundaries are shown below.

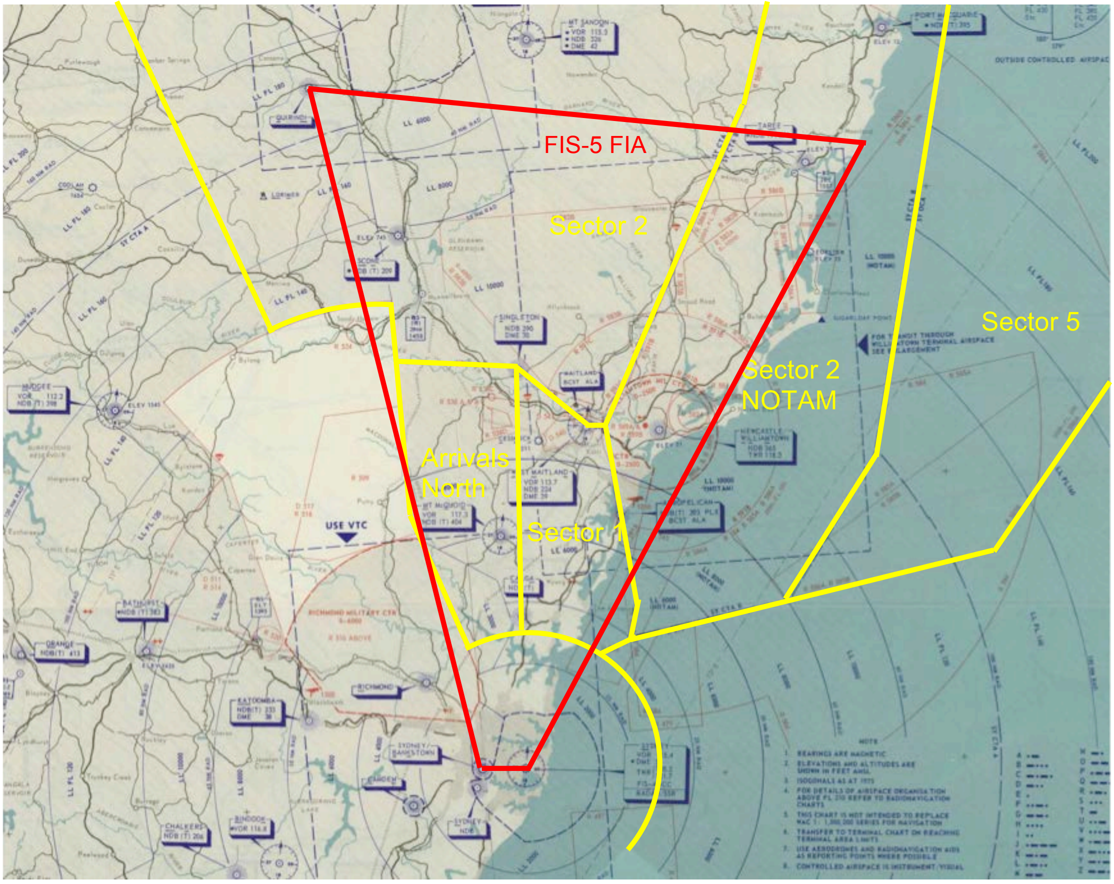


Figure 1: Relevant Sydney northern airspace. VH-MDX was operating at or below around 8500'AMSL between Taree and north of Singleton. This was *below* Sector 2 airspace (10000'AMSL and above). Sector 1's vertical airspace commenced from the controlled airspace lower limits (4000', 6000', 8000') up to 10000'AMSL. As VH-MDX was tracking southbound for Bankstown, Sector 1 was likely to receive VH-MDX from OCTA. Accordingly, Sector 1 was the logical choice of radar information and assistance to FIS-5 and VH-MDX. FIS-5 *generally* encompassed the Sector 1 and 2 areas (Base chart: Australian Government (Department of Transport Australia) 1980, additions: Glenn Strkalj 2014).

Housing most of the Sydney ATC functions was the *Area Approach Control Centre* (AACC). The *Senior Area Approach Controller* (SAAC) was in charge of the AACC[5]. A *Senior Terminal Area Controller* (STAC) supervised the Terminal Control Cell that included Departures, Approach, Arrivals and Flow Control[5]. The floor plan of the AACC is shown in Annex A whilst Annex B contains photos of the AACC during the 1970's and early 1980's.

On a different floor within the same building was the Sydney FSC containing the individual FIS FSO's and the *Supervisor Flight Service* (SFS) in charge of the FSC. A photo of the Sydney FSC is contained in Annex C.

2.3.2. Sydney Sector 1 and Sector 2

Sydney Sector 1 was responsible for lower altitude airspace (*below* 10000'AMSL) outside of 30NM Sydney with a northern limit roughly bounded by Calga, Singleton, West Maitland and Aeropelican[2]. This was shown in figure 1 on the previous page.

Sydney Sector 2 was responsible for airspace north of Sydney at *higher* altitudes (flight levels) whilst also encompassing a much *broader area* than Sector 1 including airspace much further up the coast[2]. Sector 2 airspace included an area north of Sector 1 up to Scone, Narrabri, Moree to Armidale and Coffs Harbour then including the coast back down to approximately the Sydney TMA again[2].

Readily obvious from figure 1 is that VH-MDX was just north of Sydney Sector 1's airspace and beneath Sydney Sector 2 airspace (VH-MDX operated at around 8500'AMSL and below).

As VH-MDX intended to track south to Bankstown, Sector 1 would likely have received the aircraft after it's navigational difficulties were sorted. Accordingly Sector 1 was a logical choice of radar information and assistance to FIS-5 and VH-MDX.

As Annex A shows, Sectors 1 and 2 had their respective consoles next to each other in the Sydney AACC. Because of this and the airspace coverage close to VH-MDX, Sydney Sectors 1 and 2 are of high interest to the VH-MDX accident.

2.3.3. Sydney Arrivals North

Sydney Arrivals North airspace abutted Sector 1 to the west and terminated to the north at Singleton, approximately 85NM from of Sydney. Accordingly, the Sydney Arrivals North position is also of potential interest although as will be explained in this report, shorter-range terminal type radar was likely used for this ATS position with a range probably unable to interrogate VH-MDX.

2.3.4. Sydney FIS-5

The Sydney FIS-5 Flight Service Officer (FSO) was responsible for an area *generally* encompassing ATC Sector 1 and Sector 2[2]. The FIS-5 position may have also had an FSO acting as an assistant if required. This appears to be the case during the VH-MDX accident as transcripts do show a 'FIS-5 ASST' position[9].

The Sydney FSO's reported to the Sydney Supervisor Flight Service (SFS) who was in charge of the Sydney FSC.

The area defined for Sydney FIS-5 in 1972 was bounded by straight lines between Sydney- Bankstown – Quirindi – Crowdy Head (near Taree) – Sydney[29] as shown in figure 1 on page 16.

2.4. Sydney Rescue Coordination Centre (RCC)

The applicable *Search and Rescue Region* (SRR) for the VH-MDX accident was Sydney SRR. As a result Sydney RCC was the allocated RCC.

Reportedly, the RCC was normally an uninhabited room that was populated during an emergency phase[23]. The RCC was normally near the *Operations Control* room that carried out pilot briefing, checks of flight plans and other liaison duties[23].

A *Searchmaster* would coordinate search activities with *emergency services*. The Searchmasters in VH-MDX's case were located near or within the Barrington Tops area for many days[1]. The Searchmaster was the interface between the RCC operated by the Department of Transport and the emergency services conducting the land and air search.

The Sydney RCC was managed by the NSW Regional branch of the Department of Transport (DoT)[1]. The RCC was located at the Sydney Kingsford-Smith Domestic Terminal in or near one of the old control towers currently (2014) occupied by Qantas aircraft movements at the western end of the present Domestic Terminal[1].

The RCC was supplemented by DoT ATCO's and other staff sourced locally and/or flown in from around the nation to overview information and data relating to the crashed aircraft to develop effective search plans for various emergency services and private organisations[23].

Supplemental staff was transferred from Brisbane and Adelaide Operations Control centres to Sydney RCC to assist in the search for VH-MDX[42].

ATC and FS were responsible to declare formal emergency phases when aircraft ran into difficulties. The specific phase declared was appropriate to the level of difficulty the aircraft was in (note: only the *major* definition of each is included)[35]. The emergency phases in 1981 were[35]:

- INCERFA (Uncertainty phase): *Doubt* exists to the safety of an aircraft and its occupants
- ALERFA (Alert phase): *Apprehension* exists as to the safety of an aircraft and its occupants
- DETRESFA (Distress phase): There is reasonable certainty that an aircraft and its occupants are threatened by grave and imminent danger and *require immediate assistance*.

2.5. Conclusions: Sydney ATS

Relevant ATS positions of interest to the VH-MDX accident are:

- ATCOs controlling Sydney's *northern* radar Sectors; Sector 1 and Sector 2
- ATCO controlling Sydney Approach airspace (Arrivals North)
- FSO operating Sydney's FIS-5 FIA in the Gloucester area
- SAAC and STAC

3. Sydney ATC radar

3.1. Overview

Radar coverage *north* of Sydney is of interest as VH-MDX was approximately 110NM-120NM north of Sydney during the final 15 minutes of recorded flight.

Sydney ATC utilised *three* radar units contributing to airspace coverage to the *north* of Sydney at the time of the VH-MDX accident with:

- *Two* being located at Sydney Airport in close proximity to each other[1][2]
- The third located on *The Round Mountain* near Point Lookout on the northern NSW coast[2][3].

The Round Mountain radar provided 'fill in' radar coverage between Brisbane and Sydney airports thus, providing radar coverage at *higher* levels (above FL200)[26] between the two busy airports[3][4].

The two Sydney Airport located radars each performed different roles: one *shorter*-range radar was used for terminal/approach airspace closer to the airport the other, for *longer*-range coverage away from the airport of the same radar type as The Round Mountain radar.

3.2. Types of radar used by Sydney AACC

Radar background theory is discussed briefly in *RAAF Williamtown Air Traffic Control and radar 1981*[16]. To gain a basic understanding of radar this document or another source should be read.

All air surveillance radars at Sydney and The Round Mountain during 1981 incorporated both Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) as specified in the ensuing sections.

Sydney ATC radars of 1981 were defined in what *role* they performed in airspace management:

- *Terminal Area Radar (TAR):* providing coverage in areas close to the terminal and approach areas with high target refresh rates
- *Route Surveillance Radar (RSR):* providing coverage at long distances from the terminal area and between major airports enroute.

Annex D contains photos of the Sydney TAR and RSR.

Figure 2 shows the extent of Australian *high-level primary* radar coverage in 1981. *Secondary* radar was also installed to the Sydney and The Round Mountain primary radar sites by 1981 and would have had a range generally better than that shown in figure 2.

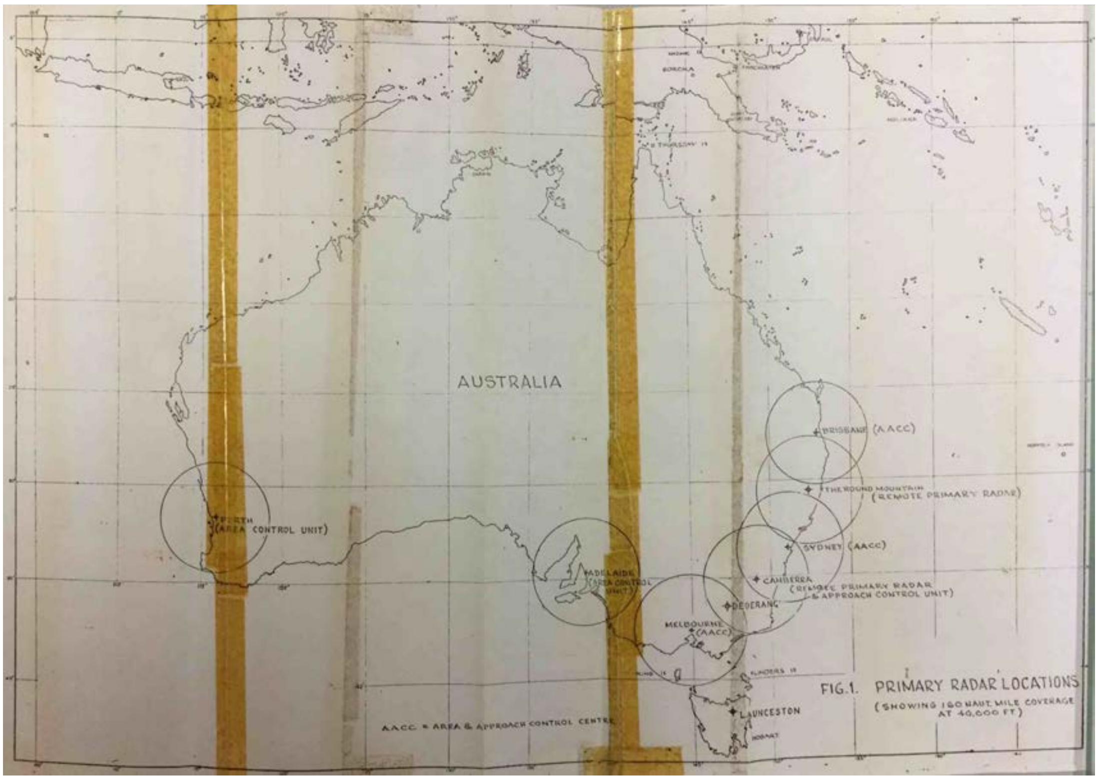


Figure 2: Primary ATC radar sites by 1981. *Secondary* radar was also installed at Sydney and The Round Mountain by 1981 with superior range to primary radar (Image: National Archives of Australia (Department of Transport) 1981[40]).

3.2.1. Route Surveillance Radar (RSR)

RSR is *slower* sweeping radar used for monitoring and control of airspace *beyond* the terminal and approach areas[2][5].

Sydney ATC received information from The Round Mountain RSR and Sydney RSR heads to provide radar coverage of airspace north of Sydney[2][3]. The Round Mountain RSR was known as the *remote northern* RSR to Sydney.

The *primary* RSR units were manufactured by the French company Compagnie Générale de Télégraphie Sans Fil (CSF) and were progressively installed from the early 1960's[5]. The Round Mountain *primary* radar completed final flight tests in late 1972[38]. The model was the RT18[28] /ER410[40] and incorporated dual channel Ultra High Frequency (UHF)[14] L-Band (IEEE) transceivers[28].

All RSR's by the time of the VH-MDX accident featured both a *Primary* Surveillance Radar (PSR) (big 'dish' antenna) and a *Secondary* Surveillance Radar (SSR)[5][43], with the antenna of the latter 'piggybacked' on top of and co-axial to the PSR antenna[5]. Figure 3 overleaf presents the different antennas.

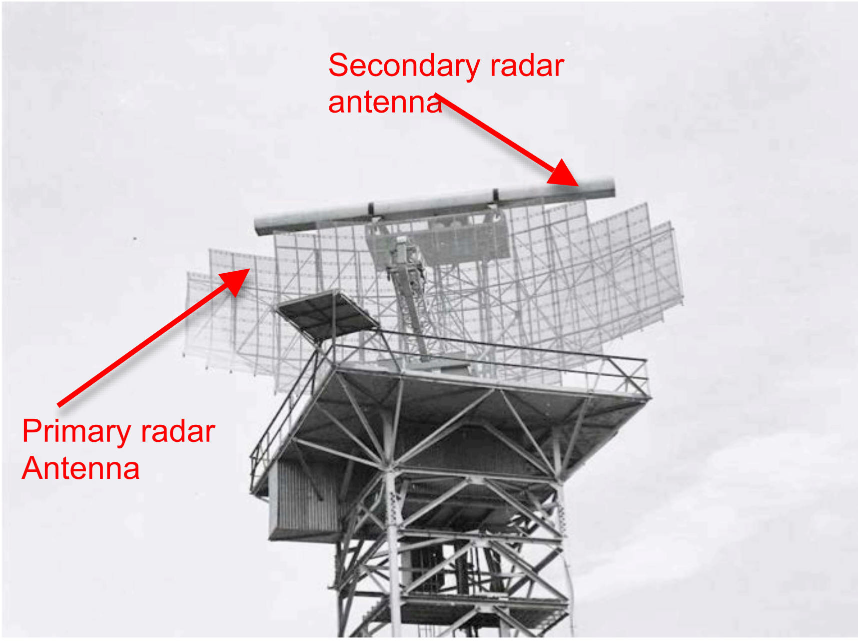


Figure 3: Sydney RSR head. The main 'dish' is the PSR reflector whilst the 'bar' on top of the 'dish' is the SSR antenna. By 1981 both the Sydney and The Round Mountain RSR heads featured both PSR and SSR (Photo: M. Price c.1983).

SSR was introduced to the RSR's from the early 1970's[5]. The SSR model was the British made Cossor SSR700[4]. Specifically, Sydney RSR SSR went through initial flight tests in November 1972 while The Round Mountain RSR SSR went through a follow up flight test in August 1977[43]. *Operational* SSR would have existed within a year of these tests.

3.2.2. Terminal Area Radar (TAR)

Terminal Area Radar (TAR) offers a *faster* sweep rate and accordingly more frequent display updates to facilitate closer range approach, departures and terminal airspace control within about 30-40NM of the airport with reduced aircraft separation distances[2][4][5].

PSR and SSR[28] TAR existed at Sydney Airport during 1981[2][4][5][28] having been installed during the 1970's. Note that TAR in this case refers to Terminal *Area* Radar rather than Terminal *Approach* Radar in the Williamtown case reflecting the different approved role.

The TAR reportedly used the same model transceiver as the RSR (the RT18/ER410) but incorporated different settings to facilitate closer range operations[5][28]. Model number ER720L5 has also been specified for the TAR[40].

A different antenna compared to the RSR was used for the TAR PSR[28] that allowed much better coverage at *high* elevation angles to reduce the 'cone of silence' overhead the radar head. This was important for terminal area coverage.

A photo of the RSR and TAR heads circa 1983 is shown in figure 4 overleaf.

Figure 4: Sydney radar heads. A Sydney radar head is located either side of the 747's tail; RSR is at left and TAR is at right. The RSR had a broader primary reflector and was perched on a shorter tower than the TAR (Photo: M. Price c.1983).

3.3. Magnetic variation

3.3.1. Chart derived

Based on interpolation of the:

- Isogonals dated 1975[11] from the c.1981 En-Route Chart from the NSW Regional Office VH-MDX Accident Investigation folio, and;
- Isogonals dated 1980[12] from the Visual En-Route Chart (VEC) dated 5 August 1982;

The following approximate magnetic variation figures to *true north* are found:

- Sydney RSR: 12.3˚ East
- The Round Mountain RSR: 11.6˚ East.

3.3.2. Australia Geomagnetic Reference Field derived

Research of the likely magnetic deviation values present in the VH-MDX geographical areas of interest during 1981 was carried out by Glenn Horrocks[8]. This research was based on extrapolation of the Australia Geomagnetic Reference Field (AGRF)[8].

The following values of magnetic deviation to *true north* in WGS84 datum charts were calculated[8]:

- Sydney RSR: 12.198˚ East
- The Round Mountain RSR: 11.503˚ East.

3.3.3. Conclusion: Magnetic variation

AGRF values are likely to be more representative of the magnetic variation during 1981 and are recommended for use in calculations.

3.4. Radar head locations

3.4.1. Sydney RSR and TAR

Both the Sydney Airport RSR and TAR radar heads were located within approximately 100 meters of each other, south-east of the runway intersection, approaching the edge of Botany Bay[2][4] as shown in figures 5 and 6. The RSR is the east-most (right) radar head highlighted by the green circle whilst the TAR is marked with a red circle.

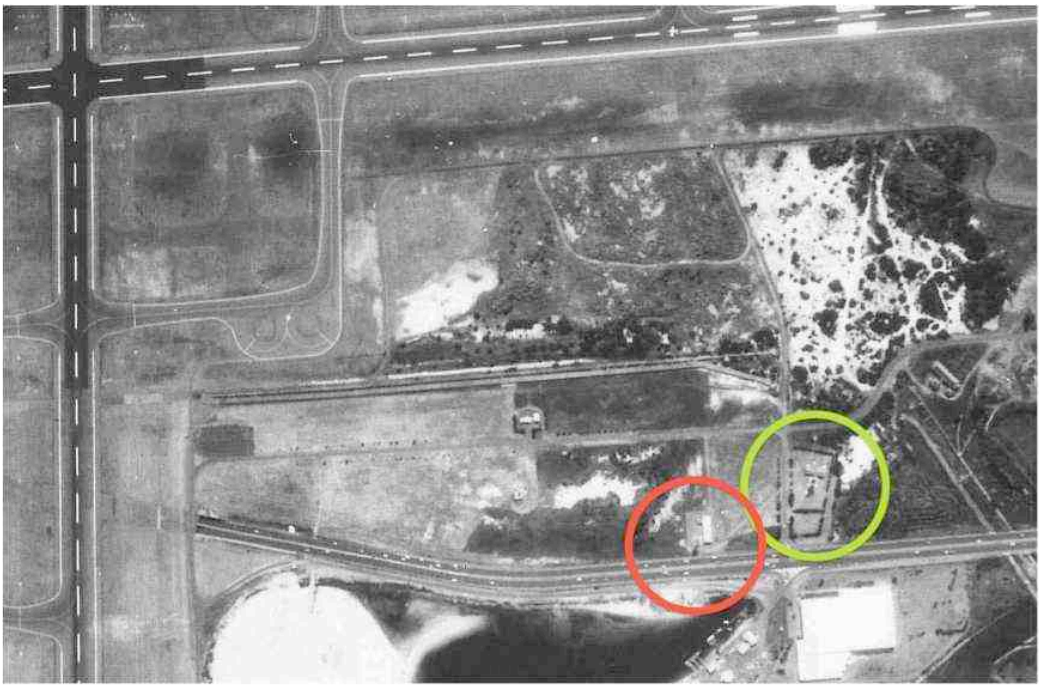


Figure 5: Sydney radar head positions 1977. Close up of TAR (red circle) and RSR (green circle) radar head positions during 1977. The main TAR building has been transformed into a McDonalds restaurant (Photo: Sydney Airport Corporation Limited 2014: additions: Glenn Strkalj 2014).

Figure 6: Former Sydney TAR and RSR radar head positions 2014. The yellow pin at right is the position of the RSR head; arrow at left the TAR (Image: Europa Technologies 2014, Google Earth 2014, Sinclair, Knight, Merz, 2014: additions: Glenn Strkalj 2014).

Annex E contains a larger image of the Sydney Airport during 1977 with the TAR and RSR head locations circled.

The *exact* positions of the Sydney Airport radar heads during the VH-MDX accident were (WGS84): [7]:

<u>Sydney RSR</u>:
-33.944110°, 151.185969°
S33˚56'38.78", E151˚11'09.49"
56H 3 32357.89 m E, 62 42558.77 m S

<u>Sydney TAR</u>:
-33.944972°, 151.184661°
S33°56'41.90", E151°11'4.78"
56H 3 32238.72 m E, 62 42461.05 m S

3.4.2. The Round Mountain RSR

During 1981, The Round Mountain RSR was positioned very close (within meters) to the current Round Mountain radar head on the NSW north coast at a position approximately 297˚T/ 7NM from Point Lookout (PLO) VOR beacon (Very High Frequency (VHF) Omni Directional Range)[3]. Figure 7 refers.

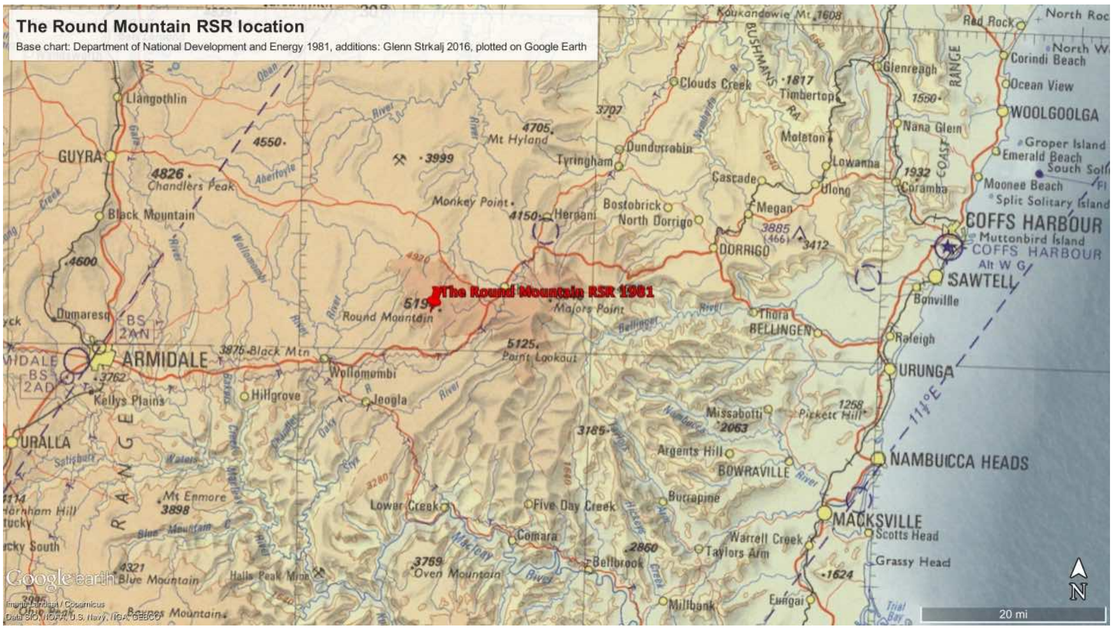


Figure 7: The Round Mountain RSR head location 1981 (red pin). This radar head was located atop a 5200' AMSL peak that offered exceptional line-of-sight ability. The head was approximately 46NM west south west of Coffs Harbour NSW (Base chart: Department of National Development and Energy 1981, additions: Glenn Strkalj 2016, plotted on Google Earth).

The head was perched upon 5150'AMSL terrain offering exceptional line-of-sight ability. Such a high perch would also offer improved detection of aircraft at lower altitudes; i.e. an aircraft that may otherwise be masked by terrain from a radar head positioned at sea level may be detected by a higher perched radar head. The following images show where The Round Mountain RSR head was located.

Figure 8: The Round Mountain radar facility 1985. The RSR in 1985 used the same head as in 1981. The distinct shadow of the radar head can be seen at the north-east corner of the facility (Image: Land and Property Information NSW 2015 (1985)).

Figure 9: The Round Mountain RSR head location 2013 and 1981. The 1981 RSR head was within meters of the 2013 head. Elevation of the radar site is almost 5200'AMSL. The higher the radar head elevation the longer the potential range. Additionally, aircraft can potentially be interrogated at lower altitudes for the same distance from the radar head (Google Earth 2014, Land and Property Information NSW 2013).

Annex F contains topographic maps of The Round Mountain site from 1976 and c.1990's clearing showing the radar facility. The position of The Round Mountain RSR head during the VH-MDX accident was close to (WGS84):

-30.437757°, 152.240359°
30°26'15.93"S, 152°14'25.29"E
56 J 427057.00 m E, 6632461.00 m S

3.5. Antenna height

Antenna height is a key parameter in radio propagation analysis. Knowledge of actual radar head tower heights and height of the antenna feed horns during 1981 are important for accurate radio propagation analysis.

3.5.1. Sydney RSR

The height from ground to the Sydney RSR work platform at the top of the *tower structure* was *estimated* at 50ft (15.2m)[4]. It was mentioned in DoT correspondence that RSR platforms were normally 55' (16.8m) or 70' (21.3m) above ground[38]. It is accepted that the Sydney RSR platform height was 55'/16.8m.

The PSR feed horn was reported as being close in height to the work platform[4]. Estimated at a *further* 1.5m above this platform was the SSR antenna (18.3m above ground level)4].

3.5.2. The Round Mountain RSR

The Round Mountain RSR tower height above ground level was less than the Sydney RSR installation. A height of 25' (7.6m) was specified[38], giving heights above ground level of 7.6m for the PSR horn and 9.1m for the SSR antenna.

3.5.3. Sydney TAR

Sydney TAR platform height was estimated at 60ft (18.3m) above ground level[4].

3.6. Range

3.6.1. RSR

The Round Mountain and Sydney RSR's reportedly had a maximum *certified* range of 160NM[2][4][5]. PSR and SSR were stated by a Radio Technical Officer to have been classed as having the same range as defined by the *certified* range limit of 160NM of the system[4] despite SSR's inherently longer range.

It was specified by the DoT that the limit to RSR range was due to the range limit of the Bright display rather than any limitations from the radar transceiver itself[28]. Indeed *primary* paints (radar returns) of aircraft 200NM away were observed by one Radio Technical Officer[33].

The Sydney 'Northern Mosaic' radar plot sheet used by Sydney ATC to record VH-MDX's radar positions for the Coronial inquest is presented in figure 10 on the next page[6].

Green and pink arcs in figure 10 on the next page marks the 160NM range of both the Sydney and The Round Mountain RSR's respectively.

The dark shaded areas to the west and east represent areas of no *certified* radar coverage but aircraft paints were still displayed and indeed observed in these areas.

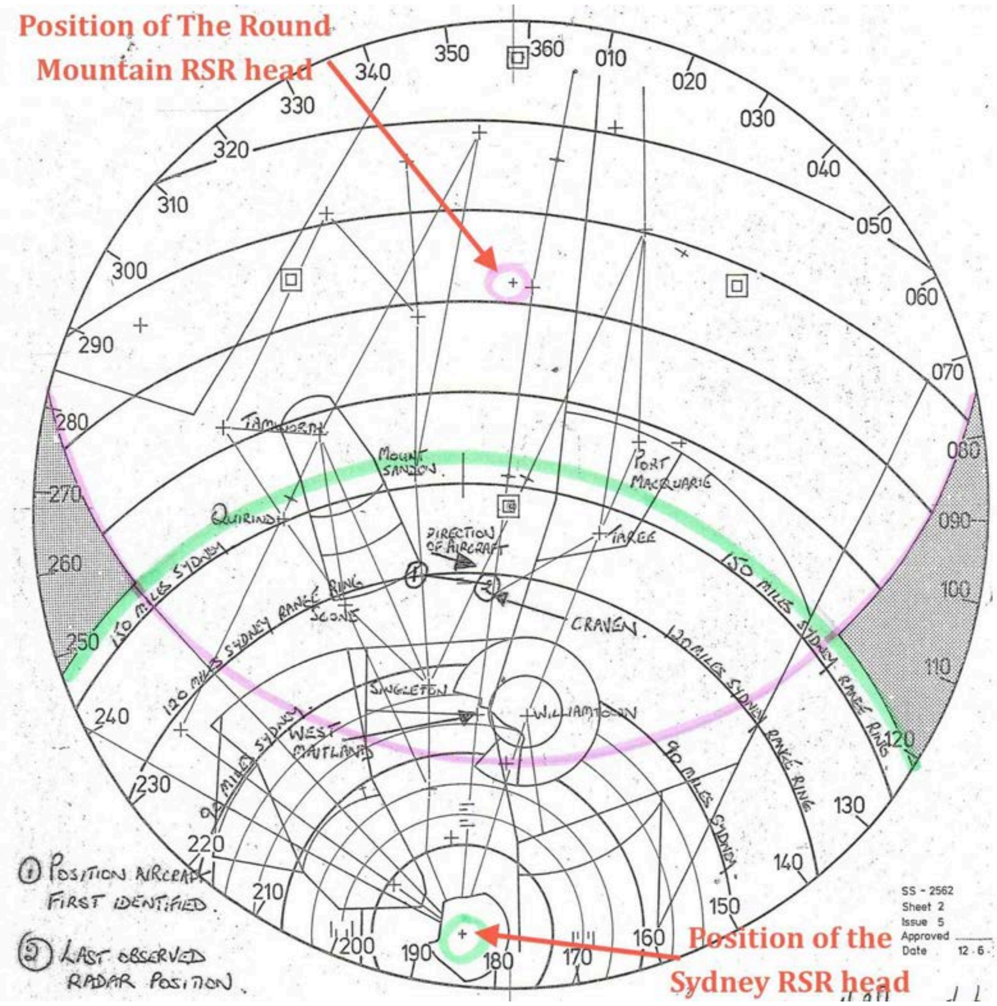


Figure 10: Sydney Northern Mosaic radar plot sheet. This radar plot represents what one ATCO deposed having observed at the Sydney Sector 1 position during the VH-MDX accident. Information from two radars was combined and presented for this *particular* display 'program'. The position of both radar heads are highlighted. The Round Mountain RSR certified radar range is highlighted in pink, Sydney RSR in green, both being 160NM. Obviously, terrain masking yields a practical range at lower altitudes much less than this (Image: Australian Government 1981: additions: Glenn Strkalj).

VH-MDX was positioned almost half way between these two radars (a little closer to The Round Mountain RSR) during the accident [7]. Detection ability was of course subject to line-of sight limitations from terrain and aircraft altitude.

The Round Mountain RSR perched on a 5150' AMSL mountain offered superior coverage of the accident area compared to the sea-level located Sydney RSR.

A photo of the Sydney RSR is presented on the following page as figure 11. Note that this photo was pre-SSR installation.

Figure 11: Sydney RSR radar head c.1960's. This photo was taken not long after the Sydney RSR was installed. Note a more conventional parabolic shape compared to the Williamtown SURAD reflector and also the feed horn angled up. There was still a deformity in the lower sections of the reflector upwards to minimise the blind cone overhead[4]. No Secondary Surveillance Radar is fitted in this photo: this came in the early 1970's in the form of a bar type 'hog trough' antenna fitted atop the primary reflector (Photo and information: Airways Museum and Civil Aviation Historical Society 2014).

3.6.2. TAR

A Sydney Airport Radio Technical Officer suggested the TAR had a maximum range of 80NM[4], a Sydney ATCO 90NM-100NM[2] whilst the Australian Airways Museum reports a range of 120NM[5]. The Department of Transport's *Air Traffic Control Radar Training Manual* specifies 95 'miles'.

It is the author's opinion that the 120NM range suggested by the Australian Airways Museum is actually referring to the *initial* range of some RSR's before being enabled for 160NM (120NM was the initial certified range of some RSR's)[5].

The TAR could be 'tweaked' to obtain an increased maximum range to provide enlarged coverage when the RSR was taken out of service[4]. No value was given.

Despite the maximum radar range, the normal *display* range for the TAR was 20NM, 40NM, 50NM, 90NM or 100NM to facilitate arrivals and departures[33][34].

A 90NM-100NM normal *maximum* range is accepted for the TAR. It is acknowledged that the range could be increased beyond these values to some degree to make up for an inoperative RSR.

3.7. Radar sweep speed

Sweep speed refers to the time taken for one complete 360˚ rotation of the radar head in azimuth. Sweep speed affects outcomes such as:

- Maximum range of the radar
- Refresh rate of aircraft paints on the radar display
- Accuracy of the radar (coupled with other factors such as Pulse Repetition Frequency (PRF) and beam-width).

3.7.1. RSR Sweep speed

Both The Round Mountain and Sydney RSRs rotated at a relatively (to TAR) slow 5RPM[2][5] giving a sweep time of 12 seconds. This enabled 5NM separation between aircraft and 160NM maximum range (slower speed allows longer time to 'listen' for returns hence longer range)[5].

An ATCO best describes the pragmatic effects of a slow-sweeping Thompson CSF RSR in the following comment: '*They* <RSR> *turned @ 5RPM giving an update/refresh time of 12 seconds so there was a bit of waiting to see where the next paint would appear*'[22].

3.7.2. TAR Sweep speed

The Sydney TAR was mainly used for *terminal* (airspace close to the airfield) and arrivals and departure operations within about 20NM-100NM of the radar head. The radar antenna rotated at a faster 15RPM[2][5] compared to the RSR.

Accordingly, a 360˚ sweep of the antenna in azimuth took 4 seconds and this faster refresh rate enabled a closer 3NM separation between aircraft but resulted in a shorter maximum range than the RSR[5].

3.8. Radar displays

3.8.1. Introduction

Sydney ATC radar displays were known as 'Bright' radar displays and offered reduced operator fatigue and longer paint persistence times compared to basic Plan Position Indicators (PPI). The displays were monochrome green Cathode Ray Tube (CRT) screens with a Television type scan. Bright displays were provided for each ATC position with a radar controller.

3.8.2. Differences to a PPI

Traditional PPI's illuminated targets rather *brightly* during the sweep but paints fade *quickly* post sweep[28]. This resulted in challenges for the ATCO to determine aircraft track. Viewing of the PPI in a dark room or beneath a shield was required to determine track[28] but this obviously caused eyestrain and fatigue.

Additionally, map features on a PPI were presented as *brilliant* lines using the same illumination method, colour and similar intensity as aircraft paints. This also resulted in eyestrain and difficulties in discerning aircraft paints amongst the map features[28].

The Bright display resolved these problems by projecting a map composed of low brilliance *black* lines on the display[4][5][28] whilst also offering a much *longer* paint persistence so that paint history could easily be seen in a normally lit room[28]. As the ATCO looked predominately at black map lines and a dim background, eyestrain and fatigue was reduced[28].

The PPI used a *radial scan* (outward from origin along the sweep (bearing line) whereas the Bright display used a *television* scan (raster or rectangular).

Information for the map overlay and radar returns were sourced using two separate methods. These will be described in the next two sections.

3.8.3. Map overlay

Map information for the Bright display was sourced from video cameras 'staring' at physical maps in dark boxes. This video camera output was fed into the Bright display separately from the radar paint (scan converter) information. Figure 12 shows the map cabinet and camera set up used in the Bright display.

Figure 12: Map box and camera. Map overlay for the Bright display was generated by a camera staring into a box at a paper 'plate' of the applicable airspace map. The camera image was then sent to a TV mixing and distribution unit that combined this with radar information. The result was a display of radar paints over an airspace map (Photo: Glenn Strkalj 2015, access to equipment courtesy of the Civil Aviation Historical Society and Airways Museum).

At Sydney, approximately ten video cameras were positioned to 'stare' over different maps representative of the airspace being presented on radar[4].

The image from the appropriate camera was then presented on the Bright display with radar information from appropriate scan converters superimposed giving the controller a map view with 'live' radar tracks overlaid[4][5].

At Tullamarine at least one SAAC (Senior Area Approach Controller) at times liaising with a senior Technical Officer, was responsible for *drawing* the maps[27]. Corrections could be made of inconsistencies using white out and a pen[27]. An example of this is if ATCO's *continually* observed aircraft offset from a positive fix on the map such as a navaid when reporting overhead the fix would be whited out and re-drawn in the correct position[27].

3.8.4. Radar returns

Radars generate rotating type *polar* scan (bearing/distance) information whilst the Bright display uses a television type *rectangular* scan. A conversion process is necessary to interface the *polar* output radar head with the *Cartesian co-ordinate* driven Bright display.

A device known as a *scan converter* changed rotating type radar data into horizontal line data allowing radar information to be fed into the Bright display[28]. The scan converter did this through projection of polar information on a phosphorous screen not unlike a TV picture tube and electrically rescanning this image into a rectangular scan as shown below in figure 13.

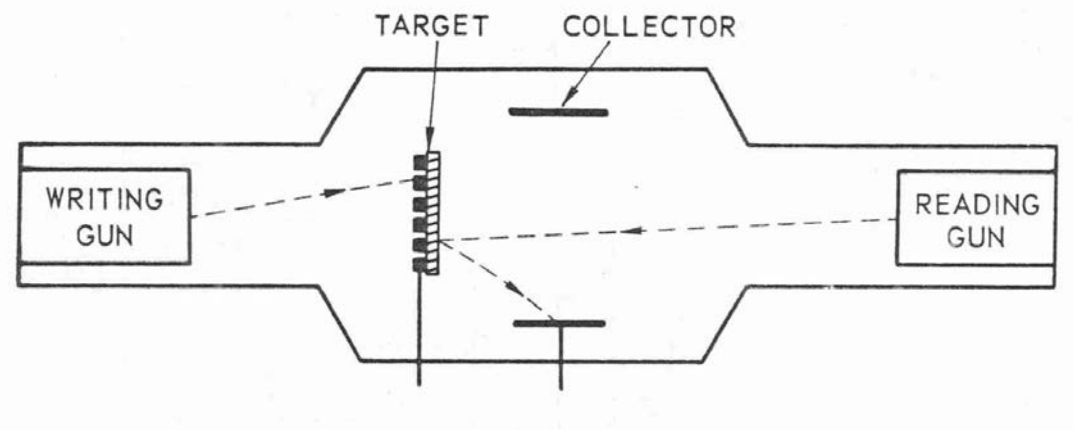


Fig. 68. Scan Conversion Tube.

Figure 13: Scan converter tube. (Australian Government (Department of Transport) 1977[28]).

The scan converter tube also offered a *delay* in the images presented following initial paint and it is this feature that allows *significant* persistence of displayed paints[28]. Paint persistence in excess of *one minute* was normal for the Bright display, this being much longer than the sub *ten seconds* for a PPI.

Scan converters also combined information from different radar sources: PSR, SSR and in some cases PSR and SSR from both local and remote heads.

3.8.5. Program selections

Bright displays had *preset* selections that chose 'programs' of specific radar information (scan converter) and map (camera) *paired* sources[4].

The ATCO would select a particular airspace of interest by button and the 'program' would default to the required radar heads and video camera map to service that area[4].

Figure 14 shows the Sydney 160NM program. On the left side of the display is the scan converter (radar) source labeled 'SC' and the camera (map) source labeled 'CA'. In this case scan converter 6 and camera 5 are being used in this selected display program.

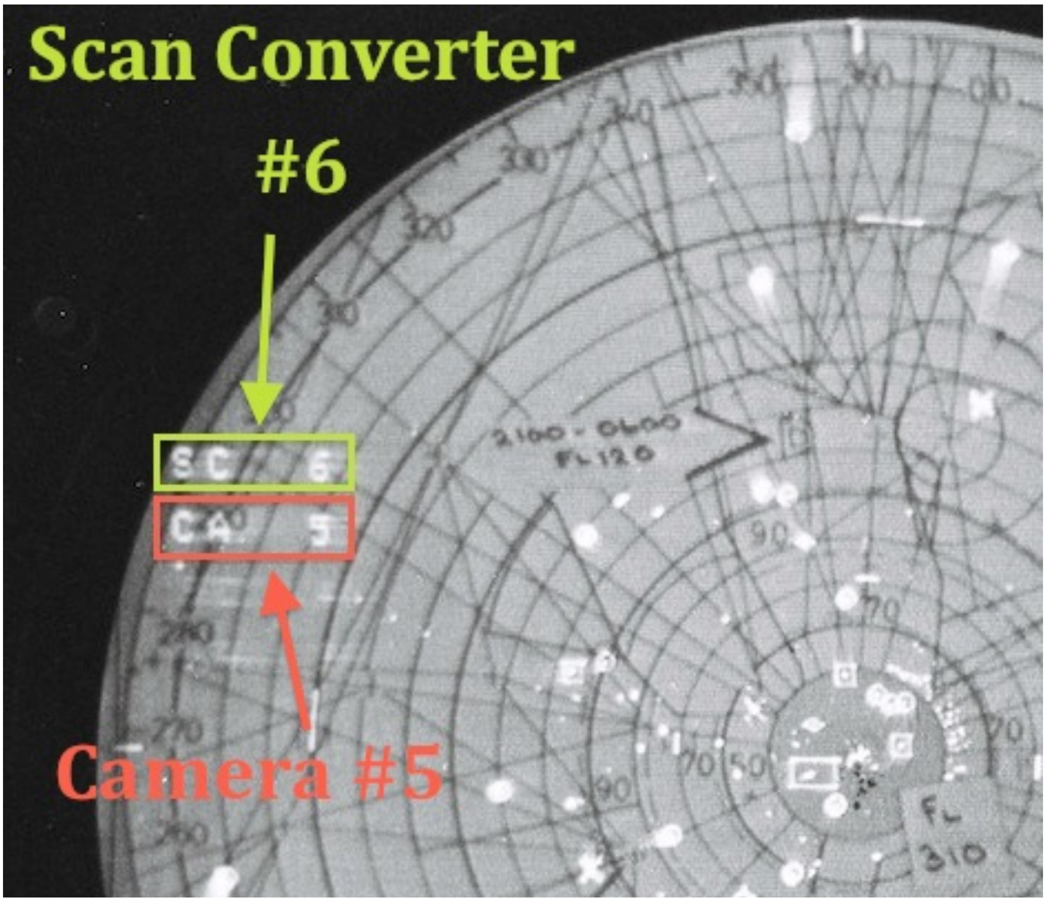


Figure 14: Scan converter and camera source. Sydney 160NM program (Photo: M. Price c.1983; additions: Glenn Strkalj).

A single scan converter could be set up to combine the information from two radar heads and this program was called a 'Mosaic' program. When using a Mosaic program, the *specific* radar *heads* were not *directly* ATCO selectable (i.e. one could not *solely* select The Round Mountain RSR on a Mosaic program)[2][4]. Rather, the mosaic program would be a pre-selection of appropriate radar heads.

It appears there was no program that *solely* displayed The Round Mountain RSR at the Sydney ATCO operated Bright Displays: only the combined Sydney and The Round Mountain RSR information could be displayed.

If the ATCO had the Northern Mosaic program selected and desired to only see Sydney RSR information, the ATCO would have to select the Sydney 160NM RSR program and the display would change from Mosaic to a Sydney Airport centered display. So, the ATCO would lose the ≈290NM Mosaic display for a 160NM display.

Display programs with associated radar sources at Sydney so far have been identified as:

- Northern Mosaic 290NM (Sydney and The Round Mountain RSR's) (Sector 2)[34]
- Southern Mosaic 240NM (Sydney and Majura RSR's)[34]
- 160NM Sector display Sydney (Sydney RSR) (Sector 3, Sector 4) [34]
- 100NM Sector (Sydney TAR) (Sector 6)[40]
- 100NM Arrival (Sydney TAR or RSR, (Selectable)) (Sector 1)[34]
- 50NM Sydney Approach/Departures (Sydney TAR)[34]
- 50NM Sydney Offset, Richmond Military (Sydney TAR)[34]
- 20NM Tower display (Sydney TAR) [34],
- 20NM Departures North and South, Approach South (Sydney TAR)[40]

Figure 15 presents a block diagram of the Bright display system.

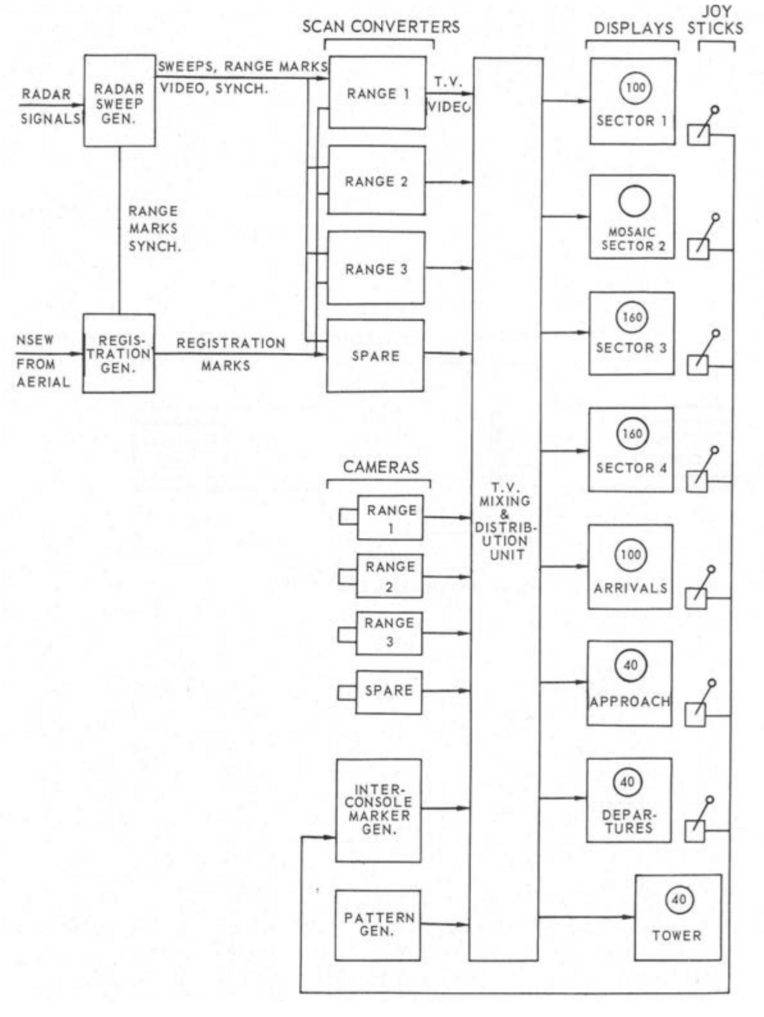


Figure 15: Bright Display system. Radar data is fed into scan converters that provide the 'illuminated' or 'painted' information to the Bright display. Other than inter console symbols and calibration markers, radar paints are the only 'illuminated' returns on the display. The map information is sourced from cameras staring over paper maps in dark boxes. Maps are presented in black to prevent eyestrain and offer good contrast from radar paints (Image: National Archives of Australian (Department of Transport) 1977).

3.8.6. Display in use during the VH-MDX accident

Figure 10 on page 27 presented the radar plot sheet used to record VH-MDX's radar positions and is indicative of what program the Sector 1 ATCO's Bright display was set to during the VH-MDX accident.

This particular display program was known as the *Northern Mosaic*[4]. The Northern Mosaic combined information from both Sydney RSR and The Round Mountain RSR[2][4]. It has been confirmed the Northern Mosaic program was selected during the VH-MDX accident[2]. Figure 16 is a photo of the Sydney Northern Mosaic display program.

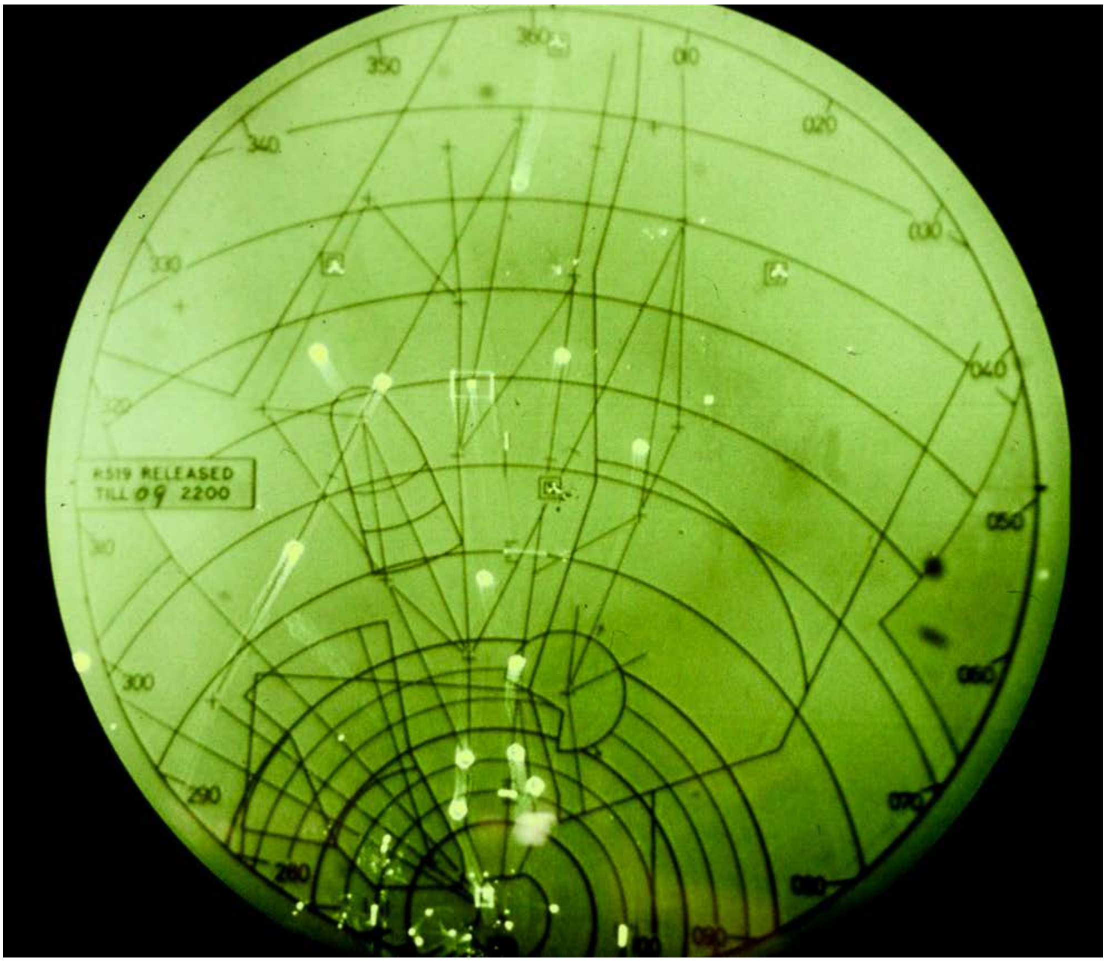


Figure 16: Sydney Northern Mosaic program photo. Both the Sydney RSR and The Round Mountain RSR were 'fed' into this particular program. Airways, beacons and range rings displayed were sourced from a video camera 'staring' at a map.

A legend of map markings on the Sydney Northern Mosaic display program is presented in figure 17 on the next page whilst Annex G contains more images of the Sydney Northern Mosaic display.

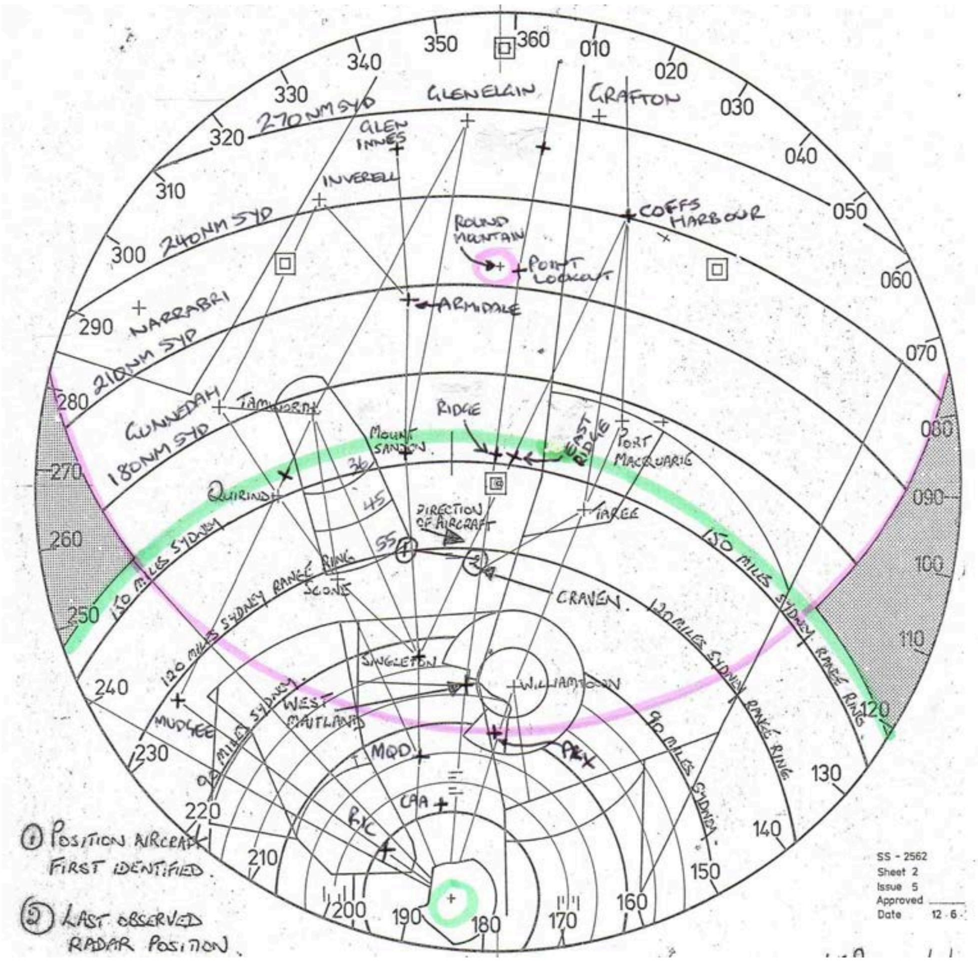


Figure 17: Northern Mosaic program legend. (Base image: Australian Government (Image: Department of Transport) 1981, additions: Glenn Strkalj 2014).

Of interest, Sydney Sector 1 airspace was contained within 90NM of Sydney so a 100NM or 160NM display program would be more appropriate for normal use rather than the ≈290NM Northern Mosaic used during the VH-MDX accident.

Indeed figure 15 on page 33 appears to be a block diagram *specifically* of the initial Sydney AACC radar setup with Sector 1 represented with a 100NM display. So why was the Northern Mosaic used to locate VH-MDX?

Making the likely assumption that the Sydney 160NM RSR program was available at the Sector 1 workstation, and considering:

- FIS-5 advised Sector 1 that VH-MDX was tracking Craven to Singleton[9]
- Craven and Singleton are within 120NM of Sydney
- The 160NM program is a smaller, more useable scale than the Mosaic;

The Sydney 160NM program was a more logical choice to radar observe VH-MDX that the Northern Mosaic. However, in later sections it will be shown that the Sydney RSR was highly *unlikely* able to interrogate VH-MDX as a result of terrain obstruction. As the Sydney 160NM program used the Sydney RSR, if it could not successfully interrogate VH-MDX then no returns from VH-MDX would be displayed when using the 160NM program. Annex H contains the 160NM and other Sydney display programs.

It is not known if the Sector 1 ATCO attempted to identify VH-MDX on the Sydney 160NM program first or if the ATCO simply knew Sydney RSR coverage for aircraft in VH-MDX's area below 10000'AMSL was unreliable before selecting the Northern Mosaic program. If this question could be answered, this would offer confirmation of lacking *Sydney* RSR coverage of VH-MDX thus;

- Confirming the radar of interest is The Round Mountain RSR and;
- Supporting radar propagation analysis findings.

3.9. PSR returns

3.9.1. Airport RSR PSR returns

Airport RSR (Sydney RSR) PSR paints were characterized by arcs in azimuth or 'blobs' the size of which was dependent on aircraft size, shape and type of construction materials used in the airframe (Radar Cross Section (RCS)) and target aspect: the track of the aircraft relative to the radar beam.

The larger the RCS the larger the *primary* return. Raw returns could be many nautical miles in size but could also be so small they appeared more as a dot.

These arcs were commonly referred to as 'raw' returns or 'slashes'. The latter name is attributed to the shape of primary returns that are normally displayed on a PPI. Resolution of the Bright display rarely presented arcs/slashes but tended to display 'blobs' for primary returns from the Airport located RSR[32]. A connectivity overview of the primary radar system is given below in figure 18.

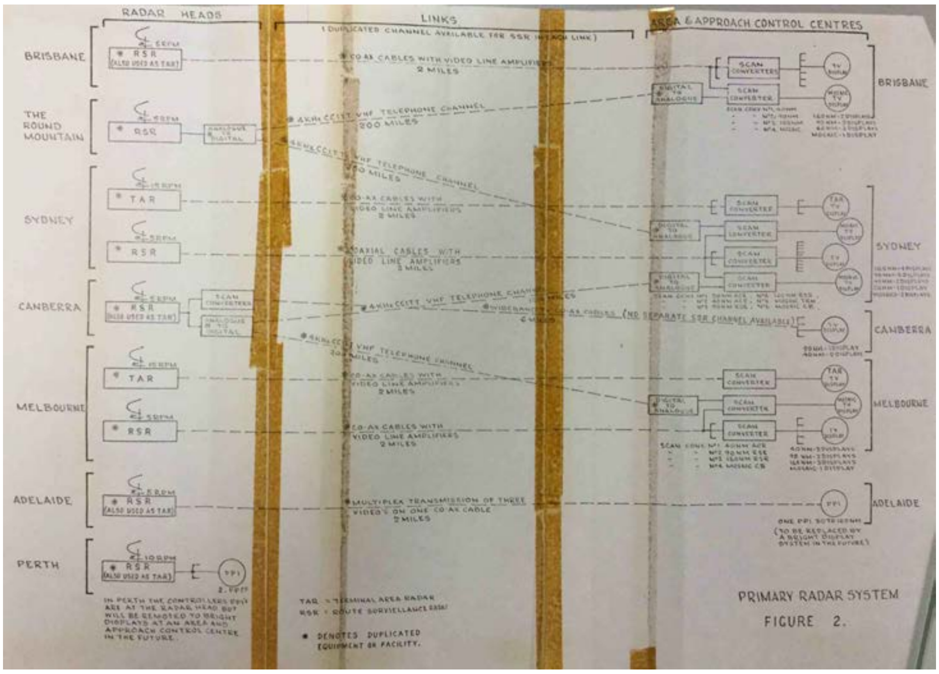


Figure 18: Primary radar system. Raw *primary* radar data was fed from the *Airport* radar heads via coax *directly* into the scan converters. This resulted in the Airport head *primary* radar returns being displayed across the *entire* Mosaic display program. *Remote* primary radar data (e.g. The Round Mountain) was converted to digital, transmitted to the AACC via VHF radio links then converted back to analogue format before being fed to the scan converters. As the Remote radar information was in digital format, unlike the Airport RSR it was gated so that it would only be displayed in a certain sector of the Mosaic display (Image: National Archives of Australia (Department of Transport) 1981[40]).

Airport PSR information was fed as an *analogue* signal along *coaxial cable* directly into the scan converter[27][33][39][40]. This resulted in the *Airport RSR* raw slashes being visible throughout the *entire* Mosaic display area (i.e. un-gated)[27][33][39][32].

Examples of raw PSR returns are shown in figure 19 below.

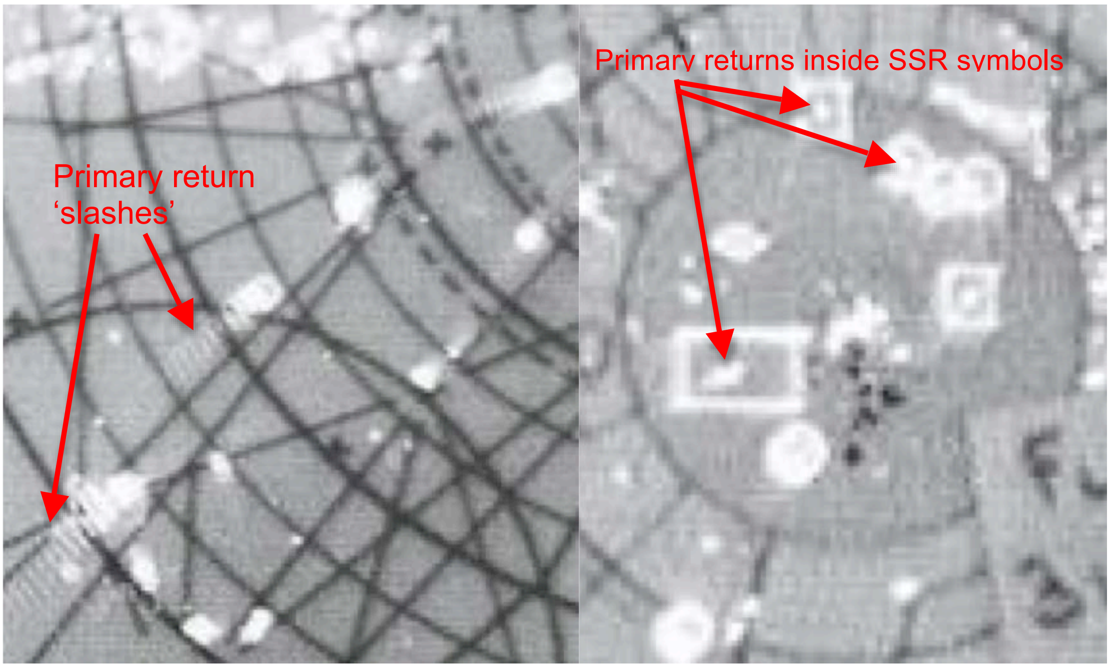


Figure 19: Primary surveillance radar paints. Slashes/raw returns are immediately obvious in the left photo although they do consolidate into a blob in the current aircraft position perhaps when mingling with the SSR return. Examples of small primary returns almost displayed as dots are shown in the right photo. Left photo is the Sydney 'Southern Mosaic' program, right photo is the 'Sydney 160NM' program. The slashes in the left photo are from the Sydney RSR (Photos: M. Price c.1983).

3.9.2. Remote RSR PSR returns

Rather than raw slashes/blobs, the *primary* returns from the *remote* RSR's were a *synthetically generated symbol* in the form of small solid squares[22][23][27][32].

The reason for having synthetic PSR paint symbols for the *remote* heads was said to be a result of the inability to transmit the *raw* (analogue) primary radar data from the remote heads to the Area Approach Control Centre (AACC)[27][33][39] as raw returns required excessive bandwidth for transmission.

As shown in figure 18 on page 36, radar information was transmitted from The Round Mountain RSR to the Sydney AACC on a 4kHz CCITT carrier telephone channel via a VHF link[40].

Accordingly, *raw* returns from remote PSR's were converted into a digital format allowing low bandwidth transmission along radio telemetry to the AACC[27]. When arriving at the AACC, this information was fed into the symbol generator section (where the SSR symbols were also synthesized) *prior* to the scan converter. The symbol generator produced a small solid square to represent the position and fed it to the scan converter.

As a result of being synthesised by a symbol generator, these synthetic PSR paints did not vary in *size* with changing signal characteristics as raw returns did other than fading when radar returns were below a certain signal threshold.

Size-wise, the remote *primary* return squares were much *smaller* in size than the mode A code 2000 SSR square and were *solid* rather than outline as the mode A 2000 symbol was (SSR Symbols will be discussed in the following section)[22][27].

One ATCO estimated the size of these remote head PSR squares as 1NM – 2NM[23]. From a photo of the Sydney Southern Mosaic display, the author has estimated these solid squares were approximately 2NM in size.

Remote head primary returns are shown below in figure 20 and figure 21.

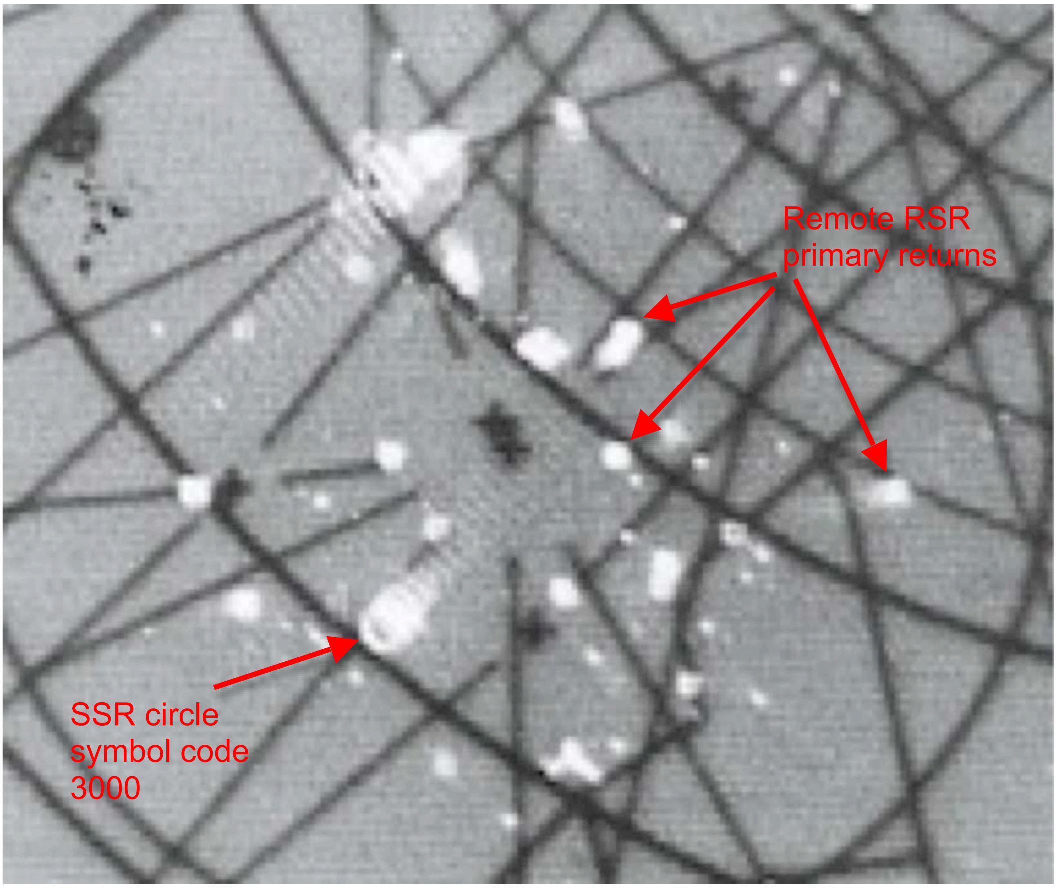


Figure 20: Remote RSR primary returns. This image is a cropped section of the Sydney 'Southern Mosaic' program that incorporated the Sydney RSR and Majura RSR located in Canberra of the Canberra Terminal Area. The small solid squares are remote head (Majura RSR) *primary* radar returns. Compare these to the much larger SSR circle to the southwest of Canberra. The squares allocated to SSR mode A code 2000 were much larger and not *solid* as the remote head PSR squares were. The more traditional 'slashes' that can be seen to the southwest and northwest of Canberra are probably high-flying aircraft being interrogated by Sydney RSR. Sydney RSR primary returns were *not* gated and could be seen across the entire mosaic unlike *remote primary* paints that were gated past a certain line (Photo: M. Price c.1983).

As the *remote* PSR returns were processed along the same electronic path as all SSR information, **the remote PSR returns were *gated* in the same way as SSR information** (unlike *airport* PSR information). More of this will be discussed in section 3.11.

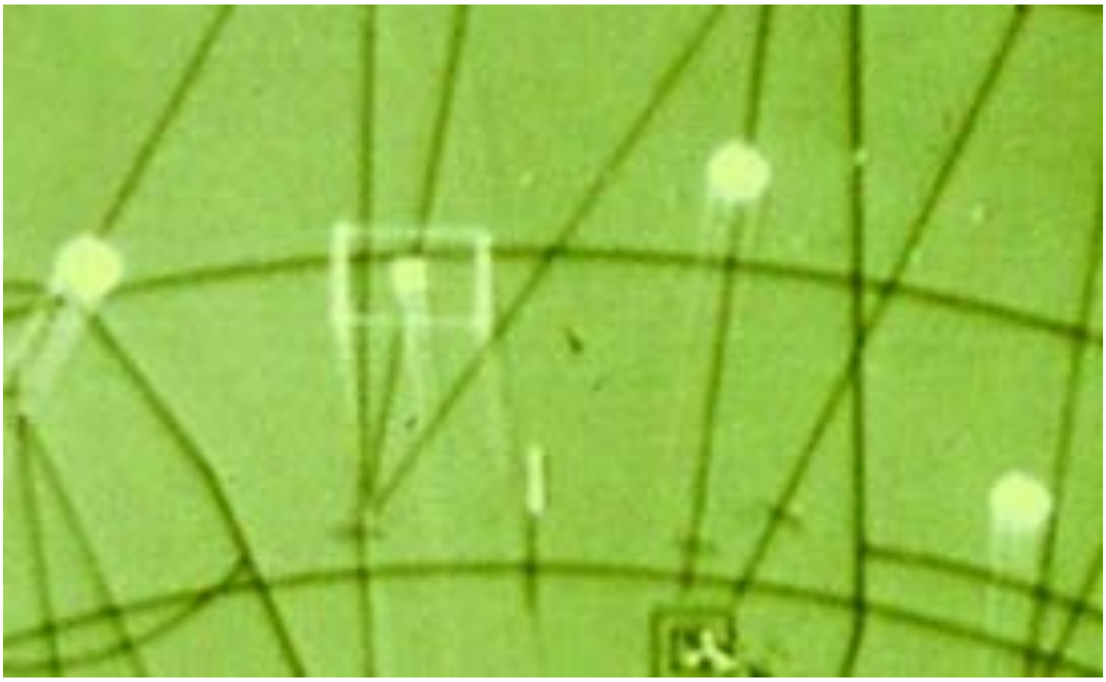


Figure 21: Remote PSR symbol. Located within the 'heavy' jet SSR symbol (oblong) is an example of a primary paint solid square from The Round Mountain RSR.

Additionally, if *remote* primary *and* secondary paints had similar azimuth and range values (same target), the plot extractor would combine these paints into a single 'message' to be transmitted to the AACC[32]. This would still result in both the primary and secondary paints being displayed on the Bright display at the AACC and was known as a '*SSR reinforced with primary*' message[32].

In summary, the *remote* PSR paint was a synthetic box symbol, approximately 2NM in size and was only displayed on the remote RSR side of the electronic gating line on the Mosaic display (to be covered in section 3.11).

3.9.3. Aircraft aspect vs. PSR returns

As a general rule, a target tracking roughly tangentially to the radar beam should present a larger RCS than a target tracking straight to the radar head, radially. This is because in many cases aircraft present larger surface area structures when flying *tangential* to the radar such as the fin and fuselage sides. These surfaces normally *increase* primary radar reflections.

Accordingly, an aircraft on close to a tangential track to the radar beam should normally present a larger PSR slash/blob return in azimuth than if it were tracking head on into the radar beam.

This does not always hold true as light aircraft can make up for lost *airframe* RCS when head on to the radar by propellers that spin to generate a large radar reflector.

Additionally, there was a technical limitation of the type of radar being discussed that caused radar fade when aircraft travelled tangentially to the radar head. This will be described in the following section.

3.9.4. PSR tangential fade velocity

The PSR filtered out any returning signals that were close to or in phase with the outgoing signal. Little to no phase shift indicated the reflecting object was not moving relative to the radar head thus, was in *most* cases representing reflections from terrain and weather.

Radar returns from terrain and weather is obviously best suppressed from presentation rather than cluttering the radar display. Terrain does not move and many clouds are not moving or are moving relatively slowly to/from the radar resulting in 'slow' to zero radial speeds.

It can be seen filtering out targets with a low or zero *radial* speed will suppress many unwanted returns. This is known as MTI (Moving Target Indicator) filtering.

It must be remembered that this signal processing technique considers *radial* velocity between the target and radar head. An aircraft may be travelling at high *forward* speed but if positioned tangentially to the radar head may have zero to little *radial* velocity. Accordingly the aircraft is likely to be filtered out from being displayed.

This is a limitation of the radar system and a threshold speed is set for MTI filtering to enable effective permanent clutter suppression but allow reliable aircraft tracking.

The Thompson CSF PSR RSR had a tangential fade speed of 15 knots radial velocity. This means any target with a radial velocity of less than 15 knots to or from the radar head would be filtered out.

Tangential fade affected all PSR returns regardless if sourced from the remote or airport heads. Tangential fade did *not* affect SSR paints as these were not reliant on radar *reflections*.

MTI filtering was suggested to be applied to maximum range of the Sydney RSR but was set (initially at least) inside 78NM of The Round Mountain RSR[38]. This means that the Barrington Tops and Gloucester Tops amongst other areas of the main range would likely have *generated* and *displayed* terrain clutter and weather clutter from the orographic cloud associated with these areas.

3.9.5. PSR Blind velocity

At particular radial speeds well away from zero, the interaction of the outgoing and returning signal can result in effectively zero phase shift. This occurs at speeds where the phase change between successive pulses is 360˚ or multiples of 360˚.

The result is that aircraft flying at speeds resulting in a radial velocity on or very close to these ‘blind speeds’ will be filtered out by the MTI circuitry and not displayed.

Blind speed is a function of factors such as Pulse Repetition Frequency (PRF), wavelength and radial speed and can be readily predicted. Blind speed can either be eliminated or the effects minimised through staggering the PRF’s through a set range. This PRF staggering known as *wobbulation*, results in differing blind speeds that when combined eliminate or reduce the adverse effects of blind speed overall[28].

The Thompson CSF RSR PSR effectively eliminates blind speeds except the first and second order speeds. The first order blind speed was reduced in extent whilst the second order blind speed had a significant reduction in response[28]. Figure 22 below graphically presents the blind and tangential fade speed characteristic and the effects of wobbulation on the Thompson CSF PSR.

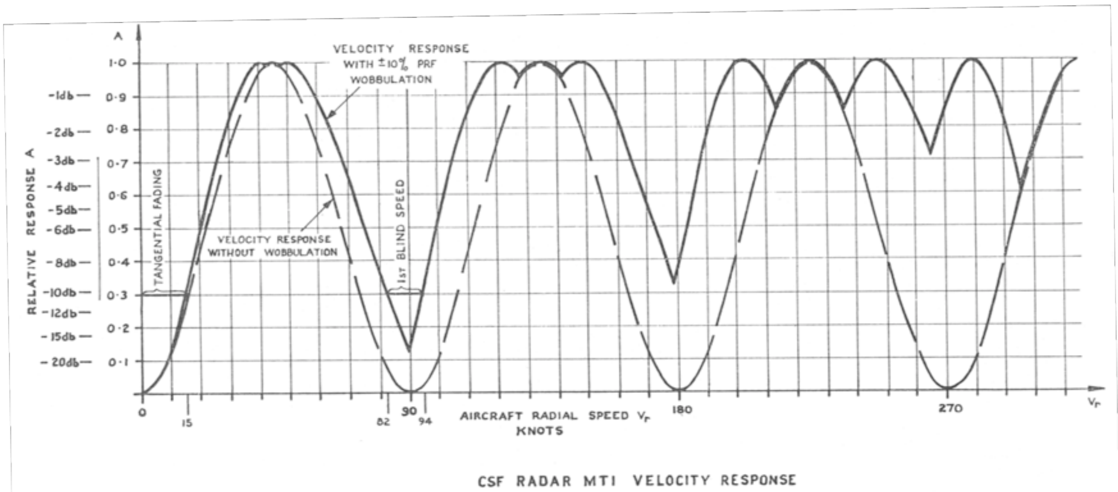


Fig. 51. Route Surveillance Radar—Near Zone Visibility—CSF Radar—MTI Velocity Response.

Figure 22: RSR PSR Blind speed and tangential fade speed. This graph shows the effects of MTI on target detection at certain *radial* speeds. The first and second order blind speeds are of significance as is the tangential fade speed of 15 knots (Image: Department of Transport 1977[28]).

The Thompson CSF RSR had the flowing blind speeds (at 400PPS)[28]:

- 1st order: 90 knots (82-94 knots) *radial* velocity, decreasing response by ≈75% to below the visibility threshold
- 2nd order: 180 knots *radial* velocity, decreasing response by ≈40%

Blind velocity affected all PSR returns regardless if sourced from the remote or airport heads. There was *no* blind velocity for SSR returns as SSR does not rely on radar reflections.

3.9.6. Summary of primary paints

Figure 23 on the following page presents the findings in terms of size and shape of primary returns on the Mosaic display program.

RSR head	Symbol type	Paint example	Approximate Size	Photo Derived
Airport	Slashes[23]or 'blobs'[32]	⬮)	3-5NM[23]	1-8NM
Remote	Small solid square [23][27][33][39][40]	■	1NM[23]	2NM

Figure 23: PSR returns on Mosaic display program.

3.10. SSR returns

3.10.1. Overview

SSR systems allow easier identification and tracking of aircraft compared to primary radar. This is because SSR:

- Does not rely on *reflected* energy: a transceiver exists at both ends
- Does not generate weather or terrain *clutter*
- Is not affected by tangential fade or blind speed
- Generates a synthetic, easily discernable symbol to represent the aircraft
- Allows different symbols to be allocated to different pilot selectable codes

A synthetic SSR symbol is presented over the primary return of the target aircraft (if a primary interrogation also exists).

No display of weather or terrain clutter *originates* from an SSR system. SSR relies on an ATC transponder unit on the aircraft to receive a UHF signal from the ground radar station which it then responds to with encoded information such as a pilot selected code and barometric altitude.

Effectively, aircraft and ground station 'talk' to each other. Accordingly SSR is *not* affected by tangential fade or blind velocity.

In order to gain an understanding of how SSR symbology affected the accuracy of operator position *readings*, the question arises of the *size* and *shapes* of the SSR symbology that was presented on the Bright display.

All SSR symbol sizes for the Sydney AACC Bright displays were preset relative to the mode A 2000 *square* symbol[43]. The Sydney ATCO appears not to have had any control over symbol size like the Williamtown ATCO of the same period did[16]. Sydney technicians did not regularly change symbol size: sizes were specified for optimum performance[43] and then left set.

SSR symbols on the Bright display always appeared in the same orientation in reference to the display; i.e. an oblong always had its longest axis east-west, an inverted 'Y' always had the singe stem running north-south and a square always had its sides oriented with the cardinal points.

3.10.2. Allocated SSR symbols

Only a handful of SSR *symbols* could be *allocated* to specific codes with the Bright display system[5]. All other codes dubbed '*non-allocated*' were displayed with a single symbol type[43], the inverted 'Y'. The SSR system was able to interrogate and display *every* SSR mode A code possible[4].

It was suggested by a former Sydney radar technician that 'heavy' aircraft codes displayed an oblong and 'non-heavy' aircraft codes displayed a hexagon[4].

As stated in section 3.10.1, SSR symbols were fixed in size for a particular display program[25][26][43]. For instance, in 1973 the length of the square symbol at the Sydney AACC was set to[43]:

- 4NM for 160NM and Mosaic display programs
- 2.5NM for 90NM and 100NM display programs
- 1.5NM for 50NM, 50NM Offset and 40NM display programs.

During 1972, the symbols were 0.5NM (for 40NM, 50NM, Offset, 90NM, 100NM) to 1NM (for Mosaic and 160NM) larger than that specified above[43).

Both SPI ident (to be covered in section 3.10.4) and *emergency codes* were displayed *three* times the size of the code 2000 square[43].

Figure 24 on the next page presents SSR symbology as suggested by various sources. A column also shows results from the author's overview of Sydney Northern Mosaic photos circa 1983.

Symbol [22][23][26][32]	Mode A Code	Allocation	Specified or derived size	Photo derived
×	1700[22][26][27]	Military[22][23][26][27][30]	3-5NM[23]	7NM
□	2000[22][26][30][43]	International Non-Heavy[26][27][30][32]	3-5NM[23] 5NM (Nov 72)[43] 4NM (Jun 73)[43]	5NM
▭	2400[22][23][27][30]	Civil/Military (on ATC request) heavy jet [23][27][30][32]	≈10NM[23]	10NM
○	3000[22][23][26][27][30]	Domestic RPT[23][26][30][32]	3-5NM[23]	5NM
◇	4000[22][23][26][27][30]	General Aviation[23][26]/ Special domestic civil operations[22][30]Training flights, aerial work, OCTA surveillance etc.[30] Normally only upon ATC request[30]	3-5NM[23] Within confines of SSR circle[27]	5NM sides 6NM-7NM across horizontally
⅄	Any code not pre-assigned to a symbol (Non-allocated codes)	Non-allocated codes	5NM	5NM
△	SPI (Ident) [22][23][26][27]	Identification[22][23]	3x the size of normal SSR symbols[28] 3x size of code 2000 square symbol[43] >5NM[23]	No example
M		Emergency[23][26][30]	>5NM[23] 3x size of code 2000 square symbol[43]	No example
R		Radio Failure[23][26][30]	>5NM[23] 3x size of code 2000 square symbol[43]	No example
H		Hijack[23][26][30]	>5NM[23] 3x size of code 2000 square symbol[43]	No example

Figure 24: Mosaic SSR returns symbology. The symbol sizes refer to symbols on the Mosaic display. Symbol sizes were specified relative to the code 2000 square symbol size.

Figure 25 on this page and figure 26 on the following page present photos of RSR paints, the first from the Sydney 160NM program and the second figure from the Sydney Northern Mosaic program.

Examples of all ‘normal’ SSR mode A code symbols are present in figure 25 below.

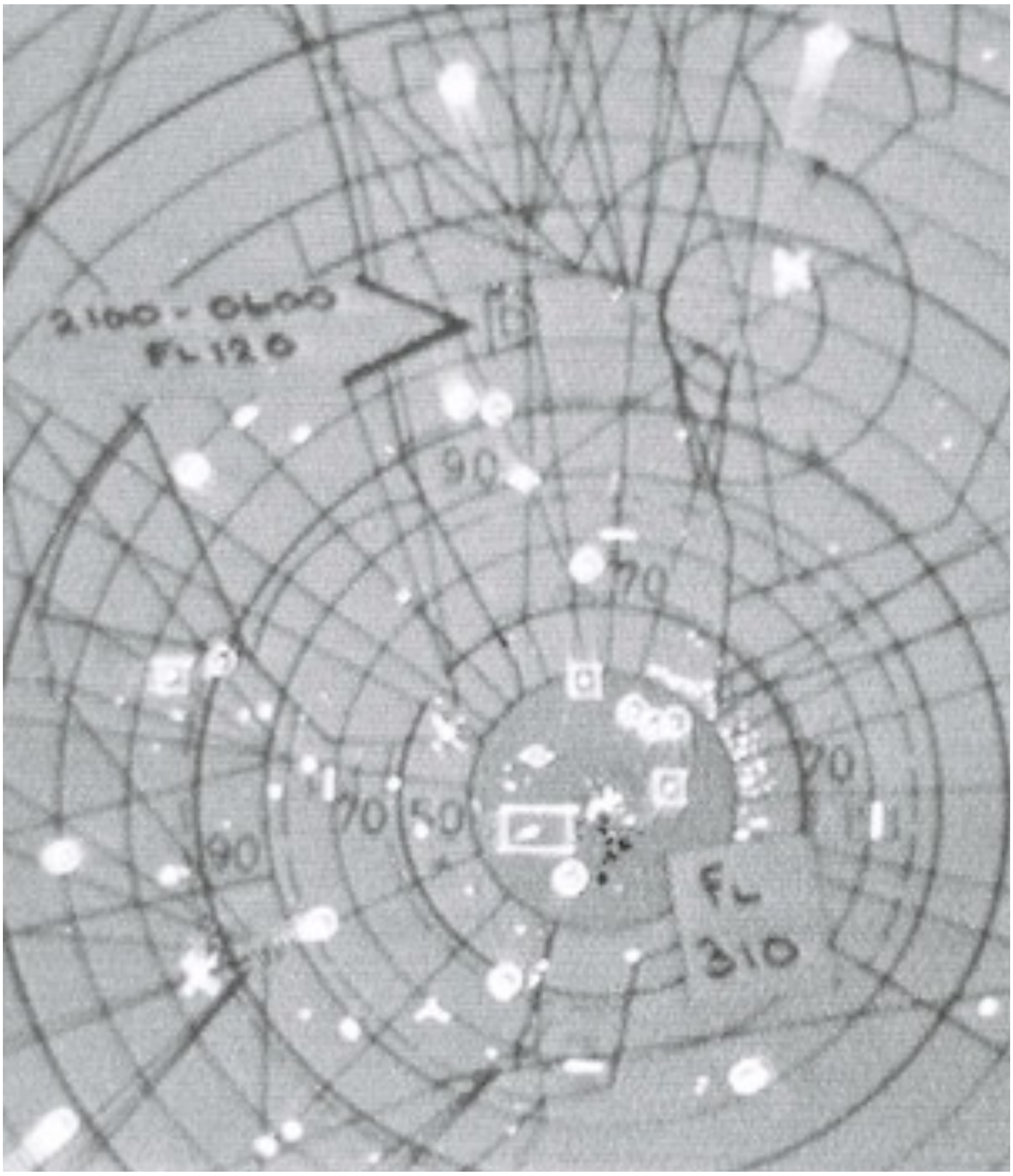


Figure 25: RSR paints. All symbols allocated to ‘normal’ SSR codes are displayed in this photo of the ‘Sydney 160NM’ program (Sydney RSR). Examples of square, oblong, circle, diamond and cross are readily evident. There are also good examples of primary returns surrounded by SSR symbols within 20NM of Sydney (first ring). (Photo: M. Price c.1983).

Figure 26 is a zoomed photo of the Sydney Northern Mosaic display program revealing SSR paint sizes relative to range rings. Photos such as that in figure 26 were used to determine SSR paint sizes and populate the last column of figure 24.

Figure 26: Northern Mosaic paints. Darker range arcs represent 30NM divisions whilst the thinner, lighter arcs represent 10NM divisions. It can be seen in this photo that SSR *circles* and *squares* fit about half way between a 10NM arc alluding to a paint size of around 5NM. The SSR *diamond* (top left) is also about 5NM along the faces and about 6NM-7NM across horizontally. The *oblong* symbol almost over Sydney airport to the bottom of the image is much larger in the order of 10NM whilst the *cross* just to the northwest of the oblong is around 7NM (Photo: M. Price c.1983).

3.10.3. Non-allocated codes

As touched on in the previous sub-section, any code that was not subject to a specific symbol allocation would display an inverted ‘Y’. The important point to highlight is that the system would display any SSR code received; it was just the symbol type that varied.

3.10.4. Special Position Identification (SPI) symbol

A SPI transmission is sent by the pilot pressing the ident button on the aircraft’s transponder that temporarily displays a special symbol (large triangle)[23] on the ATCO’s radar display to allow positive identification.

The SPI triangle was specified for the Bright display to be about *three times* larger than a ‘normal’[28] SSR symbol or code 2000 square[43] SSR symbol. One ATCO described the SPI triangle as encompassing the whole mode A SSR symbol[26] and this is also stated by the Airways Museum website[5].

An example of the SPI triangle on a Melbourne Approach display is shown in figure 27.

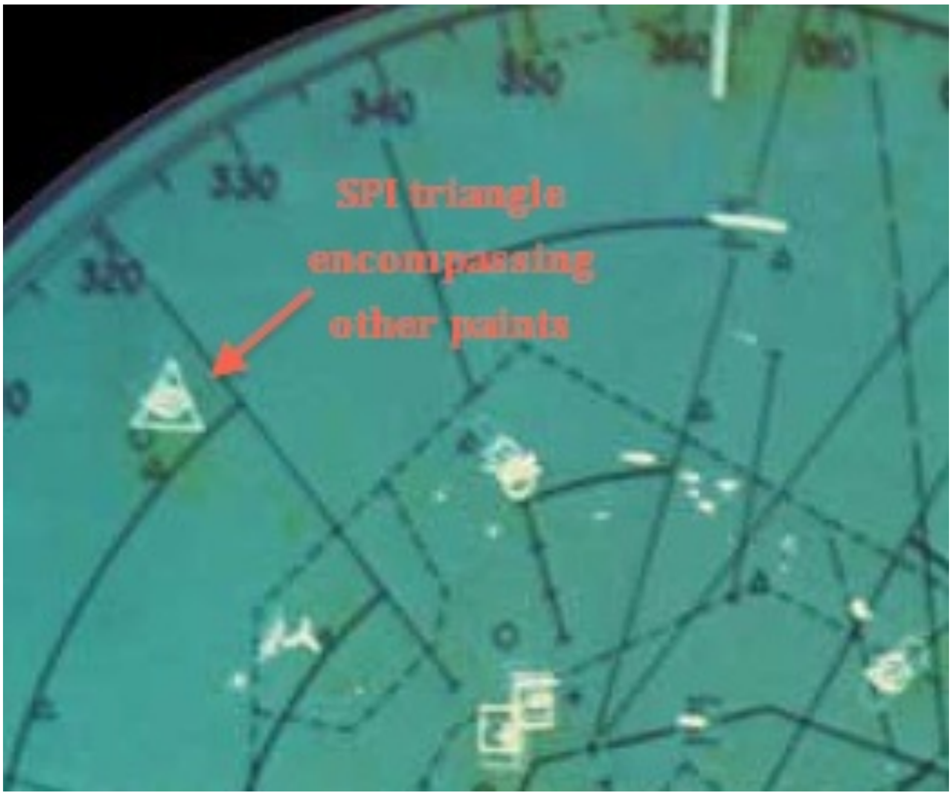


Figure 27: SPI (ident) triangle. Readily evident is the large size of the SPI triangle. The SPI triangle was specified as being three times the size of a normal SSR paint. This photo is of the Melbourne Tullamarine Approach display (Image: Airways Museum and Civil Aviation Historical Society, 2014).

3.11. Combining returns by Mosaic

3.11.1. Overview

As the Sydney Northern Mosaic display program was fed with information from both the Sydney and The Round Mountain RSR's simultaneously, the following questions arise:

- Were both the Sydney RSR PSR slashes and The Round Mountain RSR PSR squares simultaneously presented for the same target?
- If so was the target then subject to position dilution, non-coincidence or excessive enlargement of the PSR or SSR returns?

Additionally, alignment between the two RSR's and to the map is another area that may lead to displayed paints being offset from true geographical position so this characteristic must be known.

3.11.2. Secondary radar source selection

SSR returns were gated on *Mosaic* Bright display programs to ensure only *one* SSR symbol would be displayed at a time even if the aircraft was successfully interrogated by both SSR RSR's[22][23][28] [31][32].

An *electronic gating line* in the RSR coverage overlap area performed this action[28] and was not visible on the display; it was defined electronically[28].

Whilst the *exact* position of the electronic gating line on the Sydney Northern Mosaic has not been verified in publications, the usual position was a straight-line joining the intersection of the 160NM arcs from both RSR's as depicted below in figure 28[28].

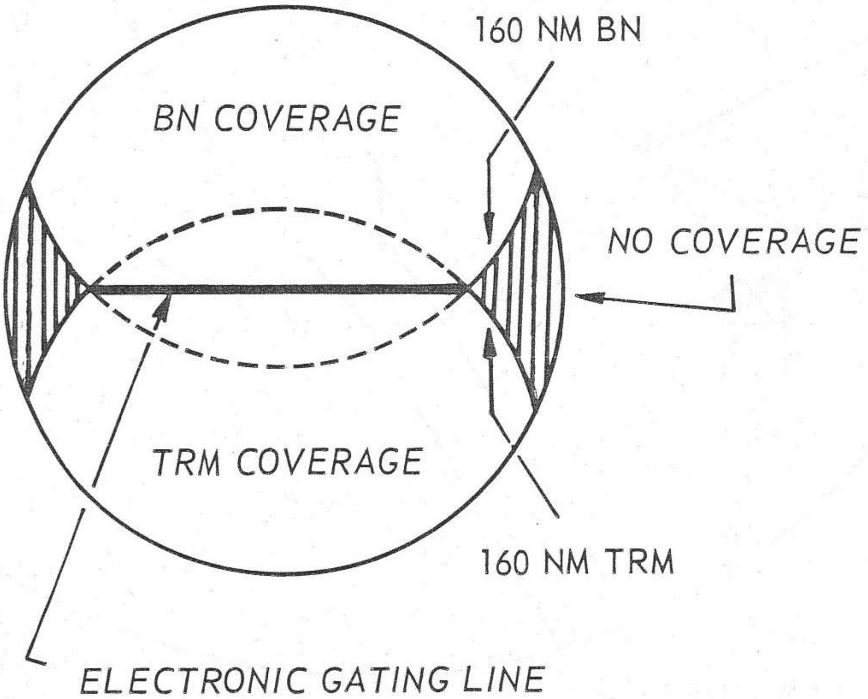


Figure 28: Electronic Gating Line. This line was not visible on the display. The 'normal' position was the common chord between the intersection of the 160NM range arcs of both RSR's. This figure depicts Brisbane and The Round Mountain RSR's on a Mosaic program (Image: Australian Government (Department of Transport) 1977).

A Bright display Radar Engineer believes that the Sydney Northern Mosaic display SSR gating line was located midway between the RSR's as described in the previous paragraph and similar to what is shown in figure 28 above[32].

The gating logic was simple. On the Sydney Northern Mosaic only The Round Mountain *secondary* RSR information would be displayed *north* of the gating line and only Sydney *secondary* RSR information would be displayed *south* of the line[27][31][33][32][39].

The gating line was described as having a very *sharp* response[33][39]. Indeed radio technicians are confident of a thickness not more than ¼ NM but suggested the line was much, much thinner[33][39]. Despite this, the *actual position* the gating line could be at when within tolerance could possibly have been displaced by +/-2NM. This is a prediction by the author based on the 100NM SSR emergency code alarm gate tolerance of +/-2NM[43].

3.11.3. Primary radar source selection

As touched on in section 3.9.2, the electronic gating line also gated The Round Mountain (*remote*) RSR *primary* returns. This is because this radar's primary information was transmitted back to the AACC in a low-bandwidth digital format requiring symbol generation at the AACC to display the information[32][33][39].

The same symbol generator was used for The Round Mountain PSR returns as SSR thus, the same gating process was applied to The Round Mountain RSR *primary* returns as the *secondary* returns[33][39].

Sydney (*Airport*) RSR primary return information on the other hand was fed directly into the scan converter as an *analogue* signal[33][39][40]. This information was displayed as raw slashes or blobs and were *not* gated on the Mosaic display[27][32][33][39]. This meant that Sydney RSR *primary* returns were visible throughout the *entire* Mosaic display. The photo in figure 20 on page 38 gives a good example of primary slashes from the Airport RSR (Sydney) visible above the remote RSR (Majura) head with remote primary squares around Majura.

3.11.4. Conclusions: Electronic gating line logic

The radar source display logic in place for the Sydney Northern Mosaic was:

- **Sydney (airport) RSR *primary* returns:** un-gated, visible throughout *entire* Sydney Northern Mosaic
- **The Round Mountain (remote) RSR *primary* returns:** gated, only displayed on the north side of the gating line
- **SSR RSR returns from both Sydney and The Round Mountain RSR's:** gated and displayed only on their respective sides of the gating line.

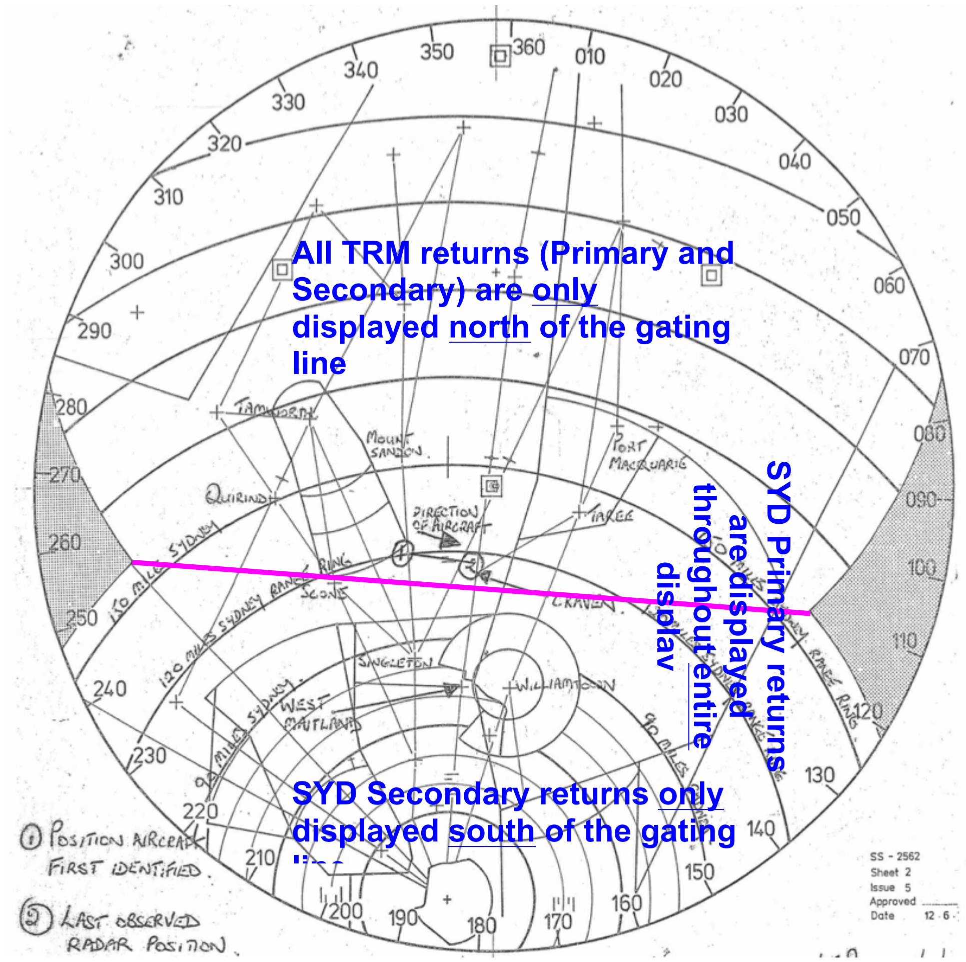


Figure 29: Gating line position (pink) and gating logic: Sydney Northern Mosaic (Base image: Australian Government (Image: Department of Transport) 1981, additions: Glenn Strkalj 2014).

The gating line and associated gating logic are important findings that can be used in flight path analysis to determine or exclude VH-MDX geographical areas of interest and refine radar fixes.

3.11.5. Calibration and alignment of radar sources

There were a number of *registration* markers that were monitored by ATCO's and Technical Officers to ensure alignment between both RSR's and the map.

The map (camera) and scan converter (radar) information were aligned together via known references in range and azimuth. It was also important to align the two radar sources on the common mosaic display.

For the remote RSR (The Round Mountain) this was done by aligning scan converter markers with double boxes on the map[4][23]. The double boxes are shown below in figure 30 and such alignment was reportedly checked by technicians *multiple times daily*[4].

Figure 30: Mosaic registration markers. The ATCO would check if the illuminated inverted 'Y' was located within inner and outer boxes. This was only one of many calibration checks performed. Equipment was reportedly calibrated to very tight tolerances at least three times daily. Indeed many ATCO's stating that aircraft were almost always radar observed over navaids or specific points demonstrates this. Despite this, it would be prudent to confirm calibration if applicable information ever presents (Drawing: Glenn Strkalj, 2015)

Accuracy calibrations were specified to be carried out three times a day[28]. In addition, ATCO's monitored the markers whilst on duty[23][28].

One ATCO stated that alignment was normally maintained although there were occasions where alignment required adjusting[26]. Ultimately, alignment was always monitored and adjusted[26].

If the display marker was *within* the inner map box the system was 'in tolerance', if outside the *inner* box even partially but inside the *outer* box the system was 'out of tolerance but useable'[23]. Should the display marker be located outside the outer box the system was 'out of tolerance'[23].

The position of the boxes on the Sydney Northern Mosaic display program are shown in figure 31 on the next page and a zoom of the alignment markers are presented in figure 32.

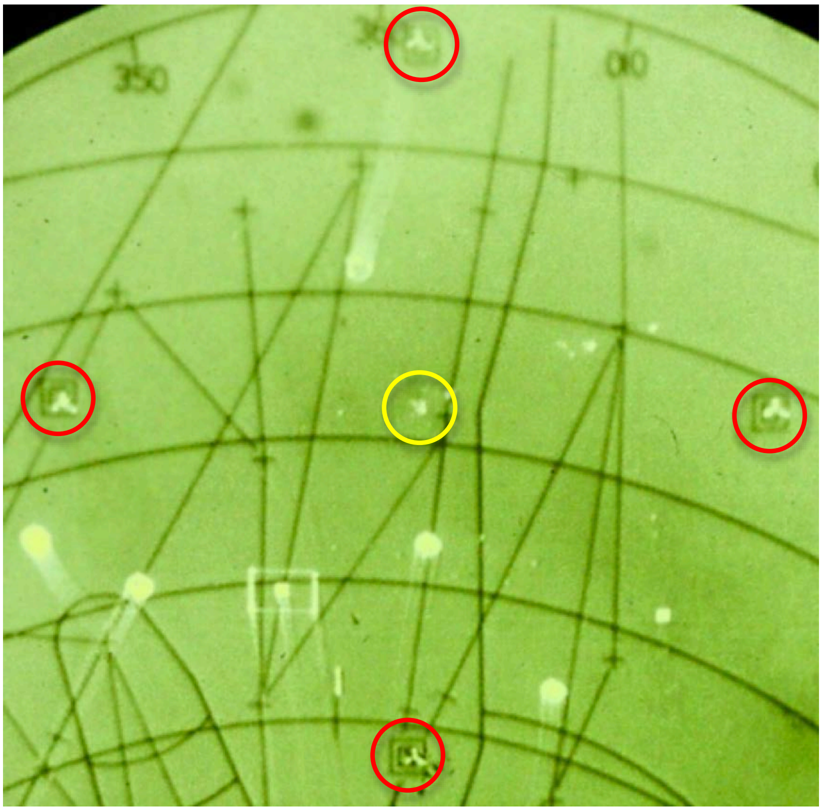


Figure 31: Sydney Northern Mosaic alignment. Red circles highlight the map boxes and scan converter (bright inverted 'Y') markers. The yellow circle highlights The Round Mountain radar head location. The double boxes were used to ensure The Round Mountain radar returns were correctly aligned to the map to give an accurate position display[4]. In this example, the alignment was slightly out but useable. Alignment was reportedly within tolerance the vast majority of time (additions: Glenn Strkalj).

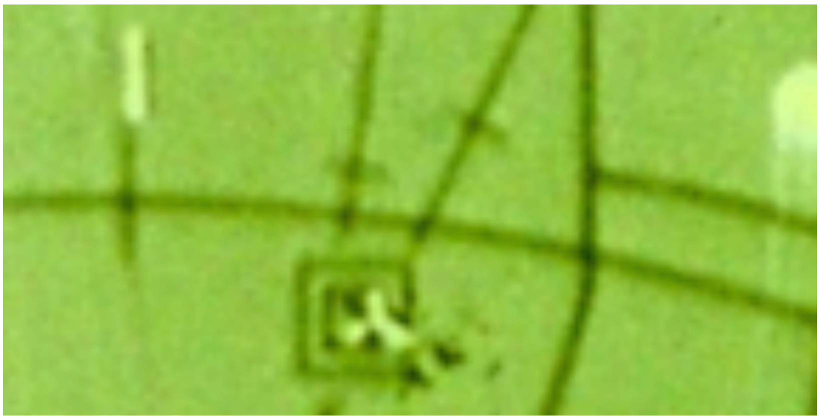


Figure 32: The Round Mountain RSR display alignment marker. Sydney RSR/map azimuth alignment markers are also apparent to the left.

Scan converter generated registration markers in *range* and *azimuth* had to be aligned on the display with equivalent markers also marked on the map. Such markers are shown in figure 33 below.

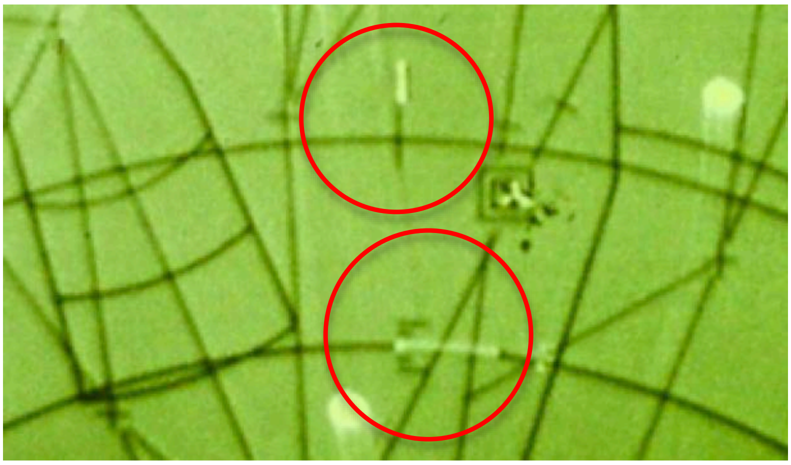


Figure 33: Azimuth and range alignment. The red circles highlight examples of azimuth (top) and range (bottom) registration markers.

Many ATCO's have stated that to radar observe aircraft displaced from a reporting point was the exception. It was stated by one DoT officer involved in the VH-MDX investigation that aircraft were radar observed co-incident with reporting points on the night of the VH-MDX accident[1].

3.11.6. Paint transitions between sources

Mosaic displays were subject to distortion as a result of combining and using two geographically dispersed radar sources. This was sometimes indicated by a 'jump' in the aircraft paints when crossing over from one radar source to another over the gating line.

Despite this, transition of aircraft paints from one radar source to the next was reportedly *very smooth* and unnoticeable by most ATCO's[26]. Many ATCO's stated that they did not recall paints 'jumping' when changing radar sources nor during every sweep; displayed paints were presented in a highly stable fashion[26].

Despite this another ATCO did describe how aircraft paints jumped a little (around 0.3NM - 0.5NM) when transitioning from the Tullamarine RSR to the remote Majura RSR on the Melbourne Northern Mosaic display[27].

This was later linked to a slightly incorrect distance set on the Mosaic map as a result of not precisely accounting for factors such as Earth spheroid irregularities and/or Earth curvature[27].

Another Melbourne Tullamarine Technical Officer stated that there were initial teething problems with alignment of paints from both RSR's on the Melbourne Northern Mosaic display[33].

Association of paints from the two heads and with map features was problematic[33]. The reason was found to be map distortion and magnetic variation compensation at the two RSR head locations[33].

The former is more prominent if the radar heads were displaced more east-west rather than north-south[33]. Accordingly, the 'jump' effect was more pronounced with significantly *east-west* displaced radar heads[33].

Figure 34 shows how the Melbourne Northern Mosaic had significant east-west displacement between Melbourne RSR and Majura RSR. This reportedly resulted in noticeable jumps of paints when transitioning between radar sources.

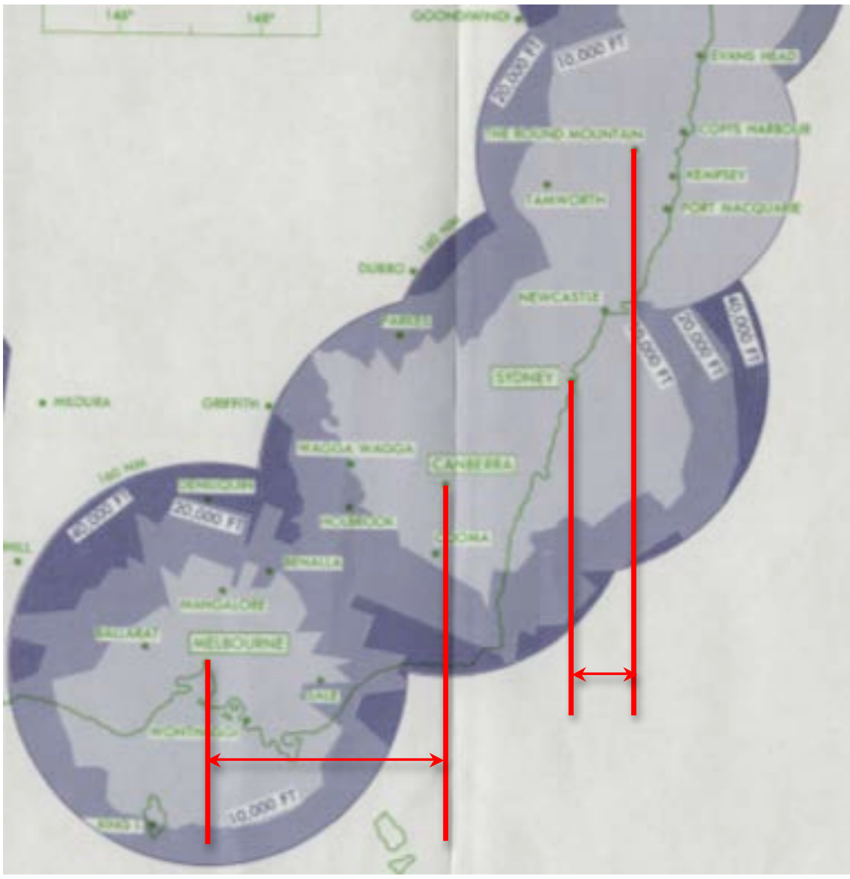


Figure 34: Displacement of RSR ‘s east-west. Paints were reported to jump east-west when crossing the gating line on the Melbourne Northern Mosaic. This was attributable mainly to the significant east-west displacement of the radar heads used. The east-west displacement between Sydney and The Round Mountain RSR was much less so; a less pronounced jump would be expected (Image: Department of Transport c.1980’s, Additions: Glenn Strkalj 2015).

3.11.7. Conclusions: Combining returns by Mosaic

The electronic gating line is an important finding that will be used to confirm or quash VH-MDX radar positions.

Dilution of radar position by presentation of multiple paints is not classed as a significant factor except perhaps if Sydney primary returns were overlaid on top of The Round Mountain SSR and PSR paints. This is unlikely in VH-MDX’s case.

It is clear the mosaic Bright display and radar heads were calibrated and checked for accuracy regularly and to high standards so accurate equipment during the accident can confidently be assumed.

3.12. Range determination

Range was determined mainly by *visual judgment* of the distance although sometimes a pen would be used to measure the distance between two points of interest followed by comparison of the pen distance to range rings[20][26].

Other methods included marking the distance between a paint and reference point on a piece of paper then measuring off the paper distance along range rings[26]. Rulers were also used[26].

Range rings at *varying* intervals, generally representative of ATS airspace, were displayed on the Bright display to allow assessment of target range from the airport of interest.

Referring to the Northern Mosaic radar plot sheet in figure 17 on page 35, it can be seen that varying ring distances are used dependent on airspace. The Sydney radar head position in this case is offset to the bottom of the display whilst The Round Mountain RSR radar head position is represented by a small cross almost due north of the Sydney RSR head at approximately 217NM.

Most range rings are referenced to the Sydney airport located radar heads as Sydney is where the AACC is located. The Round Mountain RSR provides 'fill in' radar returns to enhance Sydney and Brisbane's control ability. RAAF Williamtown and RAAF Richmond airspace was also marked on the Sydney Northern Mosaic.

A *read-off* tolerance of +/-5NM for the Northern Mosaic program was suggested by one ATCO who utilised the Bright display system in Sydney c.1980[20].

Another ATCO who utilised the same system in Tullamarine and who was also involved in technical development of the system strongly suggested a read-off tolerance of +/- 1NM-2NM but no more than 2NM would be likely achievable by most ATCO's[23].

The reasoning behind the reduced tolerance was that ATCO's had to ensure a minimum of 5NM spacing between aircraft in enroute airspace thus were highly proficient at judging 5NM of distance[23]. Accordingly, this ATCO was rather confident that a maximum error of 2NM could easily be achieved if the distance measured was small (≈10NM or less) *from a reference point* on the map.

A Tullamarine ATCO suggests read off errors of up to around +/-3NM were possible on the Mosaic display program[27].

Another ATCO who was on duty the night of the VH-MDX accident suggests +/-2NM read-off tolerance was *easily* achievable on the Northern Mosaic[2]. It was also highlighted that ranges could be determined more accurately than bearings given the features of the display system[26].

From the previous paragraphs, it can be concluded that:

- Judging distances *more than* 10NM from a map feature resulted in larger errors of up to +/5NM
- Judging distances less than 10NM from a map feature resulted in smaller read off-errors of up to +/-2NM.

These conclusions are equally applicable to determining range in an azimuth/range position or simply the distance from a map feature point.

3.13. Bearing determination

A compass rose was situated on the outside of the screen to allow controllers to determine target magnetic bearing by placing a straight edge from the *centre* of the screen over the centroid of the target and then reading off the bearing on the compass rose.

If the display program had an offset origin from the radar head as the Northern Mosaic had, then the bearing had to be *paralleled* to the display centre position before reading off.

Despite this, *visual judgment* was reportedly the normal method of determining bearings[20]. Another method used with the Bright Display was to simply reference the radar returns in NM from a position marked on the map such as a track, waypoint, beacon or airspace boundary so, avoiding the need to determine a bearing[2].

It was important to determine the centroid of the returns to take a bearing and range measurement through regardless if a PSR or SSR return, in order to achieve a *precise* bearing.

The compass rose was marked with 10˚ intervals in degrees and given the large size of the display, fine bearing resolution was *possible.* It was confirmed the compass rose was referenced to degrees magnetic[2][20].

A read-off tolerance of +/-10˚ for the Northern Mosaic program was suggested by one ATCO who utilised the Bright display system in Sydney[20]. Another ATCO stated that +/-5˚ read-off tolerance was *easily* achievable on the Northern Mosaic[2].

+/-10˚ was also suggested by a Tullamarine ATCO[26] whilst an ATCO on duty during the VH-MDX accident stated +/-5˚ was easily achievable on the Northern Mosaic display[2].

What can be concluded is that a *bearing read-off* error of +/-5˚ could *normally* be expected on the Northern Mosaic program along with a *maximum* read-off error of +/-10˚.

3.14. Aircraft identification

There were no identification/information tags generated electronically by the display and the ATCO had to maintain identification through the use of pieces of Perspex stuck on the screen with water next to the radar return[5].

These pieces of Perspex were called ‘shrimp boats’[5]. The ATCO would chinagraph the aircraft’s details on the Perspex and manually slide the shrimp boat along with the moving radar return[5].

Initial identification of aircraft was performed by one or more of these methods[26]:

- Requesting the aircraft to ‘squawk ident’ and observe the SPI triangle symbol on the radar display,
- Requesting the aircraft to turn certain directions and observe the maneuver on the radar display

- Observing the aircraft in a particular position on a marked track
- Correlating position with aircraft DME distance
- Aircraft reports overhead a navaid.

3.15. Persistence

During each radar sweep, paints would be brightened if the associated aircraft, weather or terrain were still reflecting PSR energy or if an aircraft was responding to an SSR interrogation.

As the radar antenna rotated away, the return intensity on the radar display would gradually fade until reenergized by the next passing sweep; provided the target was still reflecting energy or responding to a secondary interrogation.

When a target no longer responds to a radar interrogation, the radar paints would fade in intensity at some rate until being indiscernible. This time of fade is dubbed *persistence*. Persistence allows the ATCO to assess the tracking trend of an aircraft.

Secondary and primary paints were 'written' on the scan converter based on the characteristics of the individual inputs from each radar system. So, one could have a well illuminated SSR symbol displayed on the Bright display as a result of continued transponder interrogations but, at the same time, a fading primary blip as a result of being beyond PSR range. The *individual* display *returns* were dependent on the *individual radar sources*.

One ATCO suggested that paints would fade in around 5 sweeps but the ATCO did state that most of his memories are more of the faster sweeping TAR used in Approach Control and may be thinking of this[26]. This ATCO also mentioned that technicians could possibly adjust persistence times[26].

Another ATCO from Tullamarine stated 5-6 sweeps was normal on the Mosaic display and that technicians could adjust the persistence a little each way of 5 sweeps to ATCO's requests[27].

Adjusting the number of sweeps for persistence reportedly affected *all* users of the same radar head (i.e. if Sector 1 requested a change of persistence on the Northern Mosaic, another ATCO using the 160NM Sydney program would also receive the same sweep persistence on another display)[27].

A 1977 DoT radar training manual specifies persistence for long range Bright displays of 6-7 sweeps[28]. This coarsely aligns with the ATCO suggestions above and the DoT manual values are viewed as the values apparent in 1981 for the Sydney Northern Mosaic Bright display.

6-7 sweeps of the RSR would equal 72-84 seconds worth of track history. This was stated as being the optimum persistence time regarding track history to clutter integration[28]. A Tullamarine ATCO suggested persistence was quite *reasonable* on the Bright display to determine aircraft track[26].

3.16. Track determination

Photos of Sydney RSR Bright displays can clarify how ATCO's determined aircraft tracks using the Bright display.

In figure 35, there are aircraft that give significant history trails and these may simply be high and fast flying aircraft thereby stretching the returns out in distance. Aircraft located close to the Sydney Terminal Area generally have minimal 'trails' and again this could be a function of aircraft speed.

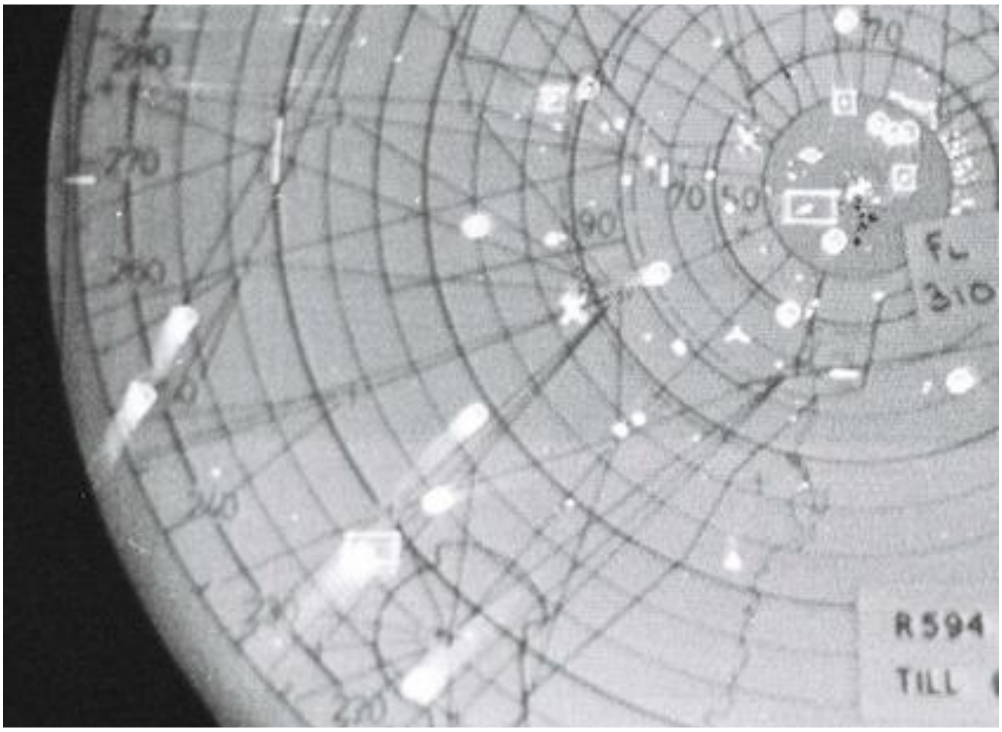


Figure 35: Radar track persistence/history: 'Sydney 160NM' program. Many returns to the left appear as 'comets' indicating high speed. The track direction of these aircraft can be determined from this return history. The aircraft close to the Sydney Terminal Area at top right have minimal history trails and are likely flying much slower. VH-MDX flying relatively slowly would likely have offered minimal track history, particularly when tracking into wind from the initial Sydney radar position. This coupled with possible intermittent radar coverage would have made track determination of VH-MDX challenging for the Sector 1 ATCO (Photo: M. Price c.1983).

Accepting that track history on the RSR's was rather sensitive to aircraft speed it can be seen a relatively slow aircraft such as VH-MDX would have a minimal trail for the ATCO to determine track. An ATCO's explanation of how the slow sweep speed of the RSR resulted in a relatively long wait for the next paint from Section 3.7.1 highlights this point.

Going against the argument of aircraft speed affecting ability to judge track, one ATCO stated that aircraft speed did not matter when it came to determining aircraft track on the Mosaic program and that the process was not too difficult[26].

It must be clarified here that pure *persistence time* is the *same* when considering *radar fade* regardless of aircraft type or speed.

It can be seen that determining the precise tracking of a slow speed aircraft with RSR information on a large display program such as the Sydney Northern Mosaic may have been challenging for an ATCO.

In the VH-MDX case it is readily apparent that track determination was initially difficult: just after the initial Sydney radar fix FIS-5 asks Sector 1 for '*…..present heading by radar?*' and Sector 1 responds: '*Oh…it's a bit hard to tell*' and '*I'll let you know in about two or three*'[9].

VH-MDX would have been squawking the assigned 4000 code for less than around 45 seconds by this time. With a sweep rate of 12 seconds around 4 closely spaced paints could have been expected. All this coupled with VH-MDX possibly turning south at this stage would have made track determination difficult.

This particular situation could also have been aggravated by intermittent paints given the altitudes VH-MDX was at combined with the distance of the aircraft to radar heads resulting in terrain obstruction in the propagation path.

The Department of Transport did specify that drift correction for wind was required for headings issued to aircraft to maintain a particular track. 5˚ of accuracy was specified although 10˚ was deemed acceptable in the '*early stages of vectoring at medium ranges*'[28].

3.17. Inter Console Marker (ICM)

An Inter Console Marker (ICM) was located at each Bright display control station[5]. The ICM was a joystick that could control a symbol on another Bright Display to facilitate identification and handover of aircraft to that display position[5].

ICM symbols included diamond, square and possibly an inverted triangle.

3.18. Radar accuracy/errors

A highly experienced Thompson CSF/Bright Display ATCO did confirm that aircraft were *almost always* observed by radar to be overhead navaids depicted on the Bright display map when pilots reported overhead[23].

A Williamtown ATCO also stated that radar positions given by Sydney ATC to Williamtown during aircraft handover were '*generally accurate*'[24].

Another ATCO's comments align with those in this section whilst also confidently stating that the RSR information displayed on the Mosaic program was '*deadly accurate*' and '*spot on*' when compared to reported aircraft positions[26]. This is further supported by a Tullamarine ATCO who described how aircraft paints were generally observed over reported fixes[27].

It is obvious the Thompson CSF/Bright display normally provided rather *precise and accurate* information. The following sections will briefly overview the errors associated with the individual types of radar system.

Errors will be broken down into three groups depending on their origin:

- **Radar system errors:** Relate to the characteristics of the radar emission. i.e. *from* the target to the extraction of radar positional data.
- **Display system errors:** Originating from the process of displaying radar data. i.e. errors originating from *after* the position extraction process to the Bright display.
- **Read-off errors:** Originating from the process of the ATCO determining the target position on the Bright display. i.e. *after* the Bright display.

3.18.1. Radar system errors

3.18.1.1. SSR system errors

Cossor SSR system errors have not been confirmed. ICAO SSR standards of 2004 give typical standard deviations of SSR systems being 250 meters in range and 0.15˚ azimuth[21]. 0.15˚ at 120NM results in approximately 0.30NM or 556 meters of displacement.

This document also states the importance of carefully aligning radar north to geographical north when overlapping multiple radar sites (such as in the Northern Mosaic) suggesting such alignment should be within 0.1˚[21].

Although not completely relating to SSR in 1981, this standard does give an *insight* into SSR errors possible of the time. It is reasonable to assume that technical/calibration errors for the 1981 Sydney ATC SSR units were minimal and were more than but not too far off the values stated in this subsection.

The Cossor SSR system being around one decade younger than the PSR system would be expected to be somewhat more accurate than the Thompson CSF PSR.

3.18.1.2. PSR system errors

The following accuracy values for the primary RSR with paints being viewed on a PPI were specified[28]. Relevant deviation values in NM at 100NM and 110NM respectively from the radar head are given in brackets:

- +/-1% of range (1.0NM/ 1.1NM)
- +/-1.5˚ in azimuth (2.6NM/ 2.9NM)

As the Bright display had a specified deviation for map to scan converter alignment (discussed in section 3.11.5), it is viewed that this deviation combined with the values above will represent actual deviations well enough in the Bright display/ PSR combination. This will be discussed in section 3.18.2.

3.18.1.3. Registration accuracy

The difference between the position of a PSR and *related* SSR return is termed *registration*. Discussions with various ATCO's of civilian and defence experience have all suggested that PSR and SSR returns were *rarely* observed displaced from each other, if ever. One ATCO stated he cannot recall a time when the PSR and SSR paints were not co-incident[26].

Despite this, one former Sydney Thomson CSF/Bright display Technical Officer did mention that PSR and SSR paints were observed to not always be perfectly aligned[25].

Although presently not located, there would have been standards specifying maximum PSR and SSR position *registration*. During pre-operational tests of the Sydney RSR SSR system in November 1972, registration accuracy was better than 2NM[43].

It was suggested in 1973 that if the registration between the centre of a primary paint and the centre of the associated secondary paint exceeds 1NM, reporting action should be taken[43]. Additionally as section 3.9.2 discussed, if the secondary and primary paints at The Round Mountain RSR had similar azimuth and range values then the paints would be combined into a single message known as '*SSR reinforced with primary'* for transmission to the AACC[32].

Given this and ATCO reports, a fair assumption can be made that PSR paints were coincident with SSR paints for the vast majority of time.

Consequently, notwithstanding anomalous propagation characteristics, it is reasonable to assume that PSR accuracy is representative of *worst case* SSR accuracy.

3.18.1.4. Extraction accuracy

The accuracy of the extracted position from raw radar positions is termed *extraction accuracy.* Regarding the SSR system, extraction registration accuracy '*in general*' was found to be within 1/8NM (232m) of the raw SSR return during a 1972 test of the Sydney RSR SSR[43].

3.18.1.5. Slant error

Slant error is the deviation resulting from the difference between:

- The direct, straight line distance between radar head and aircraft (Slant range)
- The distance, following the curvature of the Earth, between the radar head and the aircraft's projected position on the ground (True range or down range).

Radar distance is *slant* range whilst *map* (geographic) distances are the *true* or *down* range. Figure 36 on the following page pictorially presents slant error.

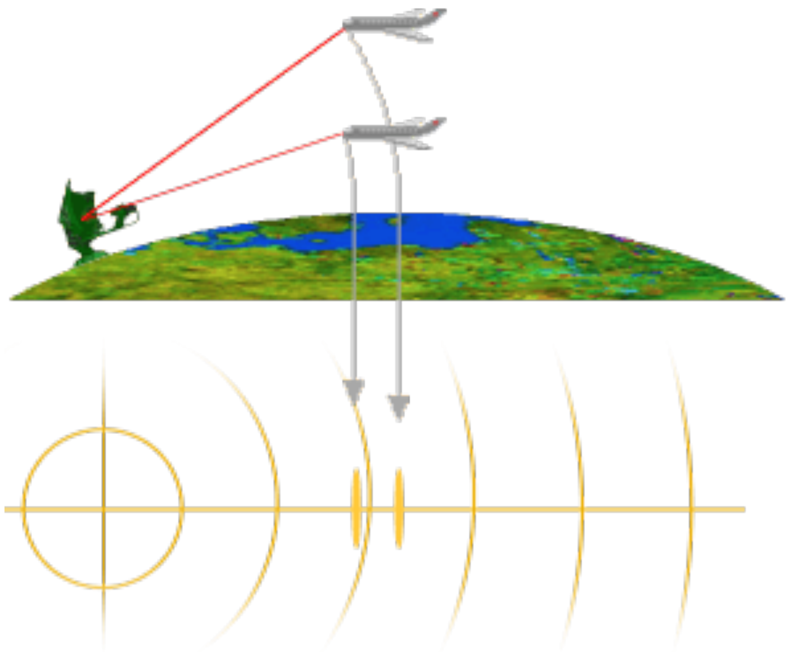


Figure 36: Slant error. Aircraft at *higher* altitudes for the *same* true range have a longer slant distance thus increased slant error. Increased slant error also results from aircraft being *closer* to the radar head for the *same* altitude (Image: Christian Wolff, obtained 2015).

The *greater* the *angle* of the aircraft to the radar head, the *greater* the slant error. A greater angle is apparent when:

- Aircraft are at *higher altitudes*
- For the same altitude, aircraft are located *closer* to the radar head (closer down ranges).

It is obvious then that aircraft at the same position over the Earth but at differing altitudes will be detected at different radar ranges. Modern radars with powerful processing ability can carry out the complex corrections to correct displayed radar data for slant error however, the Thompson CSF RSR of 1981 could not.

Information for slant error using two Thomson CSF RSR's combined by mosaic is shown in figure 37.

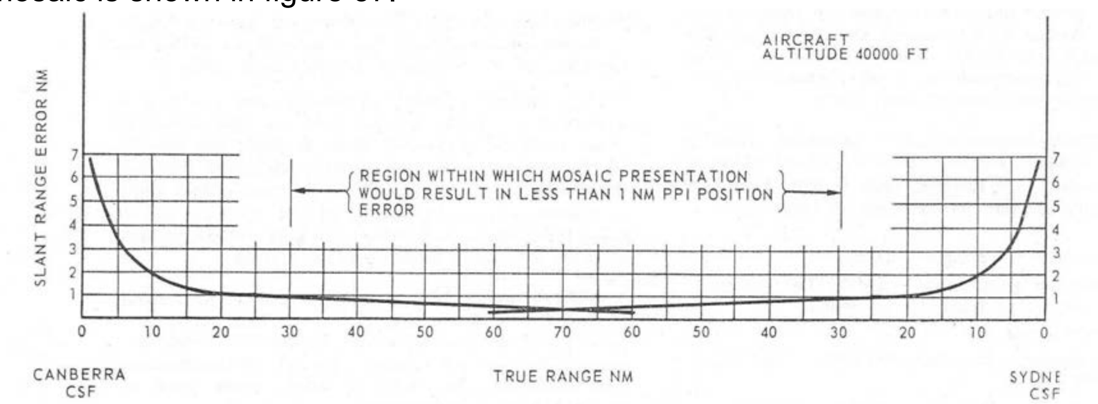


Figure 37: Thompson CSF slant error. This graph shows the effects of combining the Majura RSR and Sydney RSR slant errors (Graph: Australian Government (Department of Transport) 1977).

What can be extracted from this graph is that a *single* RSR would not have a slant error in excess of about 0.25NM (463m) for an aircraft at 40000’ above the radar head and beyond 60NM true range.

For aircraft at lower altitudes as VH-MDX was at, the slant range error would be much lower than 0.25NM. Coarsely extrapolating the curve in figure 37 reveals that slant error would be approaching 0NM for an aircraft at 40000’ above the radar head at around 100NM true range.

Slant error for The Round Mountain RSR interrogating VH-MDX at 8500’AMSL at the initial Sydney radar position at a range of 102NM is calculated to be 18 meters. A slant error of 10 meters is calculated for VH-MDX at 105NM at 6500’AMSL. Considering:

- Other Sydney ATC radar fixes of VH-MDX were at *greater* distances than 102NM (therefore less slant error)
- Other Sydney ATC radar fixes of VH-MDX were at *lower* VH-MDX altitudes (therefore less slant error)
- Slant error *decreases* with *increased* distance between radar head and aircraft or with *lower* aircraft altitude
- Other radar deviations are significantly larger than slant error;

Slant error is not considered a significant factor in VH-MDX flight path analysis.

3.18.2. Display system accuracy

These are the errors accumulated during the course of processing the extracted radar positional data in order to display the data on the Bright display.

The Bright display was specified as having a radar signal to video map accuracy of +/-0.5% of the display diameter[28]. There are at least two known Bright display diameters, 20”/ 508mm[28] and 22”/559mm[40]. It appears Sydney Sector workstations used the CSF MI470C Bright displays that were 22” diameter[40].

Using relative measurement of the pixels between range rings and of the display diameter on two Sydney Northern Mosaic photos it was determined the applicable accuracy was 1.79NM and 1.76NM.

Following tests in 1972 of the Sydney RSR SSR system, it was concluded that ‘*overall system accuracy*’ should be capable of being maintained to the following tolerance square sizes centred on the raw return[43]:

- 50NM program: 1NM square
- 100NM program: 1.25NM square
- 160NM and Mosaic: 1.75NM square.

The 1.75NM value for the Mosaic agrees with photo derived values. It appears the comment of ‘*overall system*’ in context was referring to the *display* errors accumulated between the extraction circuitry and the Bright display but not inclusive of the radar system errors.

This is the *maximum* error of Bright display alignment so it is expected that provided alignment was sound (as would be expected), actual deviations would be much less.

The linearity of the digital to analogue converter was found to offer the most variations in position (error)[43].

3.18.3. Read off errors

These were discussed in sections 3.12 and 3.13 and are summarised here.

It appears likely that tolerances of +/-5˚ and +/-2NM could be achieved on the Northern Mosaic when care was taken in assessing paint positions and a suitable map reference was available within 10NM of the paint.

+/-10˚ and +/-5NM would be the expected *maximum* paint read-off tolerance.

It seems obtaining accurate *ranges* was easier than obtaining accurate *bearings*.

3.18.4. Discussion: Radar accuracy/errors

It can be seen that radar technical errors relating to system design, alignment and calibration when considered for statistical deviation, amount to values in the order of hundreds of meters to a few nautical miles.

Given the reported and specified co-incidence (registration) of SSR and PSR paints it can be confidently assumed both systems had *similar* accuracy. Accordingly, in lieu of SSR system accuracy specifications, PSR specifications can be used and would be slightly conservative.

Read-off errors on the other hand can be highly variable and significant as they are *operator* and *situation* dependent.

Slant error was shown to be negligible to VH-MDX radar fixes.

Additionally, a DoT Officer involved in the VH-MDX accident investigation does recall that the radar system at Sydney for the Sector 1 position was verified as being *well within* tolerance and that aircraft during the night of the accident were radar observed over positions they were advising over the radio[1].

3.18.5. Conclusions: Radar accuracy/errors

The Sydney and The Round Mountain RSR's were subject to the following errors of significance:

- **Read-off error:** with care: +/-5˚ and +/-2NM, Max: +/-10˚ and +/-5NM
- **Target position error:** +/-1% of range, +/-1.5˚ in azimuth
- **Display system accuracy:** 1.75NM square centred on the centroid of the radar paint.

Read-off error accounts for the bulk of radar related position deviations.

PSR target position accuracy values can confidently be used in lieu of SSR accuracy values.

3.19. PSR filtering

Primary radar normally used different filtering techniques to reduce clutter on the display. These filtering techniques have been discussed in more detail in *RAAF Williamtown Air Traffic Control and radar 1981*[16]. The filtering techniques discussed in this section only relate to *primary* radar returns; they do not apply to secondary returns.

Bright displays were weather suppressed to the point of requiring another stand alone display to present areas of significant weather[5]. This stand-alone weather display was known as TAST; Terminal Area Severe Turbulence advice and is shown below in figure 38[5]. Hand drawn (electronically) areas of likely severe turbulence were drawn on TAST based on Bureau of Meteorology weather radar information[5].

Figure 38: Bright display workstation with TAST. The TAST display is the small display on top of the Bright display (Image: Department of Transport c.1970's courtesy of the Airways Museum).

Despite this, significant weather was still displayed as clutter on the Bright display[26]. It was reported that very bad weather would need to be 'tweaked out' by Technical Officers at the radar head through adjustment of Circular Polarisation (CP) filtering[4][26].

The problem with technicians filtering out weather was that weak or distant primary paints were at risk of being filtered out themselves resulting in a fine line between clutter suppression and displaying aircraft[26].

Moving Target Indicator (MTI) filtering was reportedly apparent *throughout* the *entire* display area for Sydney RSR[4][25] whilst it has been found The Round Mountain RSR had MTI limited to within 78NM of the radar head.[38]. MTI was reported as functioning very well with *terrain* reportedly not visible to the north of Sydney on the Bright display[4].

Weather on the other hand was said to be visible regularly enough on the Bright display[26]. Observation of aircraft paints within weather related clutter was very difficult[26][28] with SSR symbols assisting significantly[26]. PSR aircraft returns were viewed as being impossible to track in weather related clutter[26].

It will be shown in ensuing sections that The Round Mountain RSR was the only Sydney ATC operated radar likely able to interrogate VH-MDX. Given the orographic cloud formation on the Barrington ranges and 78NM MTI, it is likely there was weather induced radar clutter in the Barrington ranges area during the accident. These would appear as small solid squares (remote head primary returns).

3.20. Recording ability

3.20.1. Radar tracks

An ATCO[2], a Radio Technical Officer[4] and a DoT Searchmaster/ ASIB Inspector[1] have reported that no ability to record radar track information was available of the Bright display in 1981 at Sydney AACC.

Contrary to these suggestions, the author has located what appears to be a Department of Transport radar related recording unit with the appearance of 1960-1970's styling. The unit is labeled 'Australian Department of Transport, Air Transport Group', 'Radar Recorder'. The *exact* function of the equipment in DoT ATC use is unconfirmed.

The organisational sub branch 'Air Transport Group' appears to have been used exclusively between November 1973 – February 1977. This suggests the recorder was around from at least the 1970's. The model is an SE7000 manufactured by EMI.

In September 1968 a DoT document was written outlining the systems proposals and implementation program for SSR installation around Australia. In this document, one requirement for the *display processors* was to: '*Provide a target report output for connection to the Department's magnetic tape recorders*'[40].

A study into an '*....economic method of recording Bright display programs*' was initiated during the beginning of 1973 with tenders called for the provision of such a capability during April to June 1973[41].

Equipment for the *continual* recording of primary and secondary *digitized* radar data at Melbourne, Brisbane and Sydney AACC's was being procured by December 1978[45]. The only radars with *digitized* primary data in 1978 were the Canberra and The Round Mountain RSR's with more radars to be digitized over '*the next few years*'[45].

It was said that the '*equipment will be available in the second half of 1979*'[45]. By 4th March 1981 '*all major equipment items including module spares have now been delivered*' and considering the minute was from the Central Office to the NSW Region, it appears this equipment was delivered to the Sydney AACC[45].

Duplicated SE labs model SE7000A/14 recorders were procured for each AACC with 4 record and 2 replay channels planned for Sydney AACC (the recorders have a capacity of 12 record and 12 replay channels)[45]. Photos of the recorder are shown on the next page in figure 39.

The recording setup would allow the '*out of* service' recorder to replay radar information onto standby display equipment while the in-service recorder could still record radar information[45].

Only one recorder would be active at a time with automatic changeover between units occurring at the end of tape[45]. Data could be stored for a 48 hour period during which, if an accident or incident occurred the appropriate tape would be removed and forwarded to DoT Central Office for analysis[45].

Recorded tapes had to be kept for a period of time in a lockable cabinet with access only allowed to radar maintenance staff[45].

Recorded tapes were only available for release for processing after a written request being signed as approved by the Chief Engineer, Surveillance Section[45].

Other information regarding the planned radar recorded setup[45]:

- Tape: 1" width, 4600' long, thickness 0.001"
- Spool size: 10.5" spools
- Record period: 16 hours at 15/16ips
- Input signals: up tot 12 modem channels (data and clock signals), 1x time code direct record, 1x tape servo channel (14 channels total).

In October 1980, a white powdery deposit of highly toxic cadmium salt was detected on radar recording equipment at Sydney[45]. Discussions with Technical Officers reveal this may have delayed the *acceptance* of the recording equipment *into service*.

Given the analogue nature of *airport* radar head PSR radar data in 1981, it is unlikely that Airport PSR returns were recorded. SSR and digitized remote PSR data on the other hand could readily be fed into a recording device.

Overall it appears *unlikely* that there are *radar* track recordings of VH-MDX even though radar recording equipment was installed at Sydney AACC and capable of recording Sydney RSR SSR and The Round Mountain SSR and PSR radar data.

Figure 39: SE7000A/14 radar recorder and ID plate. It is believed two such recorders were installed in the Sydney AACC by the time of the VH-MDX accident however, the system appears not to have been commissioned (photos: Glenn Strkalj 2015 access courtesy of the Airways Museum and Civil Aviation Historical Society).

3.20.2. Communications

ATCO radio, intercom and intercom/ landline based telecommunications were recorded as evidenced by the ASIB (Air Safety Investigation Branch) transcripts. Recordings were made by a multi-channel reel-to-reel recorder. It is believed either a Magnasync or Electrodata multi channel, 1” reel recorder was installed during the accident.

During accident investigations, the 1” audio recordings were normally transferred to a ¼” reel tape for further analysis and record keeping. The ¼” reel tape is normally kept indefinitely with the accident investigation folio but in the case of VH-MDX is missing.

Other aircraft accident investigation folios of the era have been overviewed in 2014-2016 by the author and ¼” tape reels have been found in those folios.

It has been confirmed a ¼” reel tape version of the ATS recordings was made for VH-MDX and was analysed at the RCC. Copies to compact audio cassette were made from the ¼” reel version.

3.21. Sydney ATC radar workstations

3.21.1. Area Approach Control Centre (AACC)

The AACC, alternately known as the ‘A squared, C squared’ was a room that contained Bright displays and ATCO’s to perform the following tasks:

- Area Control Service (Sector)
- Terminal Control Service (Arrivals, Approach, Departures)
- Flow control
- RAAF Richmond Air Traffic Control (Sydney AACC only).

The Sydney AACC was located in the building adjoining the old control tower near the mouth of the Cooks River as it still is in 2014. A photo inside the Sydney AACC as it was in the 1970’s is shown below in figure 40.

Figure 40: Sydney AACC. The Sector 1 workstation and the SAAC were located to the far end of this photo (Image: Australian Government (Department of Transport) c.1970’s, courtesy of Airways Museum and Civil Aviation Historical Society).

A Senior Area Approach Controller (SAAC) was the overall AACC supervisor[20] whilst a Senior Terminal Area Controller (STAC) supervised the *Terminal Cell* (arrivals/ approach/ departures) and sat next to the SAAC. A floor plan of the Sydney AACC is located in Annex A.

3.21.2. Area Control Service (Sector) workstations

For each Sector, normally two ATCO's were allocated: a *Procedural* Controller and a *Radar* Controller[2][5]. The latter was positioned in front of a Bright radar display whilst the former was positioned immediately next to the Radar Controller (within around arm's length) at a procedural workstation[2].

The *Procedural* Controller was the ATCO in charge of the Sector, coordinating aircraft separation and tracking[20]. This was done both through the use of the procedural workstation and observation of the radar display in front of the Radar Controller[20].

The Radar Controller's duty was to monitor the radar display and advise the Procedural Controller on the information presented[20]. During quiet times, a single ATCO could man the sector. The Bright display console was mounted on wheels and could be maneuvered to enable the procedural ATCO a better view of the display during single controller operations. Annex I contains workstation photos.

Sydney Sector 2 was located next to Sector 1 both with identical workstations approximately 3 meters apart[2]. An example of a sector workstation is shown in figure 41. The photo is of Melbourne Tullamarine AACC.

In this photo there is both a procedural and radar ATCO with two other ATCO's supervising possibly for the purposes of training or simply wanting to be in the photo. During a SAR phase declaration, the SAAC would likely physically overview the sector control workstation.

Figure 41: Melbourne Tullamarine Area Approach Control Centre (AACC) 1979. Normal manpower included a Procedural Sector Controller and Radar Sector Controller. The former was in charge of the sector. At times of low traffic, both positions could be consolidated into a single controller. A Senior Area Approach Controller (SAAC) provided oversight of a number of sectors (Photo and information: Airways Museum and Civil Aviation Historical Society 2014).

3.21.3. Manning during the VH-MDX accident

Sector 1 was manned by at least one ATCO. Next to the Sector 1 workstation was the Sector 2 workstation[2]. Sector 2 was manned during the accident and was responsible for higher-level airspace well north of Sydney and overhead VH-MDX during the last 15 minutes of flight[2][20].

3.22. Location of VH-MDX to Sydney northern radar heads

Figures 42 and 43 give bearing and distance of VH-MDX at key radar positions *from* the Sydney RSR and The Round Mountain RSR heads.

All positions were plotted on Google Earth (2014)[7]. The determination of the exact radar positions will be discussed in ensuing sections. Note that in these tables, the accepted centre point of the radar fix is used for ease of reference. Pragmatically the radar positions are much more diluted and broader.

3.22.1. Location from Sydney RSR

VH-MDX was at the following approximate distances from the *Sydney* RSR radar head at various radar fixes:

Position	Bearing/ range from Sydney RSR Radar Head
Initial Sydney radar position (as defined in 6.1.5)	002.9˚T/ 121NM
Pure 320˚/45NM (0936:00UTC Williamtown radar fix)	006.1˚T/ 109NM
ASIB/RCC Final Williamtown radar position (325.23˚M/46.98NM WLM)	007.4˚T/ 113NM
324˚M/47NM from Williamtown	007.2˚T/ 111NM
330˚M/45NM from Williamtown	009.5˚T/113NM
Sydney deposition final fix centroid (as defined in section 6.11.1.5)	014.4˚T/ 117NM

Figure 42: Bearing/range of VH-MDX at various positions from Sydney RSR head.

3.22.2. Location from The Round Mountain RSR

VH-MDX was at the following approximate distances from *The Round Mountain* RSR radar head at various radar fixes:

Position	Bearing/ range from The Round Mountain RSR Radar Head
Initial Sydney radar position (as defined in 6.1.5)	207.9˚T/ 101NM
Pure 320˚/45NM (0936:00UTC Williamtown radar fix)	202.4˚T/ 110NM
ASIB/RCC Final Williamtown radar position (325.23˚M/46.98NM WLM)	201.7˚T/ 106NM
324˚M/47NM from Williamtown	201.7T/107NM
330˚M/45NM from Williamtown	199.4˚T/105NM
Sydney deposition final fix centroid (as defined in section 6.11.1.5)	194.2˚T/99NM

Figure 43: Bearing/range of VH-MDX at various positions from The Round Mountain RSR head.

3.23. RSR coverage in elevation

3.23.1. Coverage in elevation: PSR

The Thompson CSF RSR PSR antenna was a modified cosecant squared type with an upward 'kick' at the bottom to maximise high elevation angle coverage (minimising the 'cone of silence')[4][28].

This antenna had a *deep* radiation pattern in *elevation* from well *below* horizontal to approximately 35˚ up[28]. This was not as deep as the Williamtown TAR as the RSR was optimised for *longer-range* work and the lack of coverage over the top of the radar head (≈110˚ total) was the compromise for longer range[28].

The Sydney RSR PSR antenna boresight was reportedly tilted *upwards* from the horizontal 3˚[4][28]. This was to minimise the strength of *ground reflections* that caused lobing and other adverse effects and to maximize power at the angles where it was needed[16][28].

Tilting up of aviation surveillance radar antennas was explained in *RAAF Williamtown Air Traffic Control and radar 1981*[16] as a means to control the projection of *radiated power* rather than simply generating a no-coverage area beneath the set elevation angle.

Figure 44 shows the vertical pattern of the Thompson CSF RSR in service at Sydney and The Round Mountain sites during the VH-MDX accident.

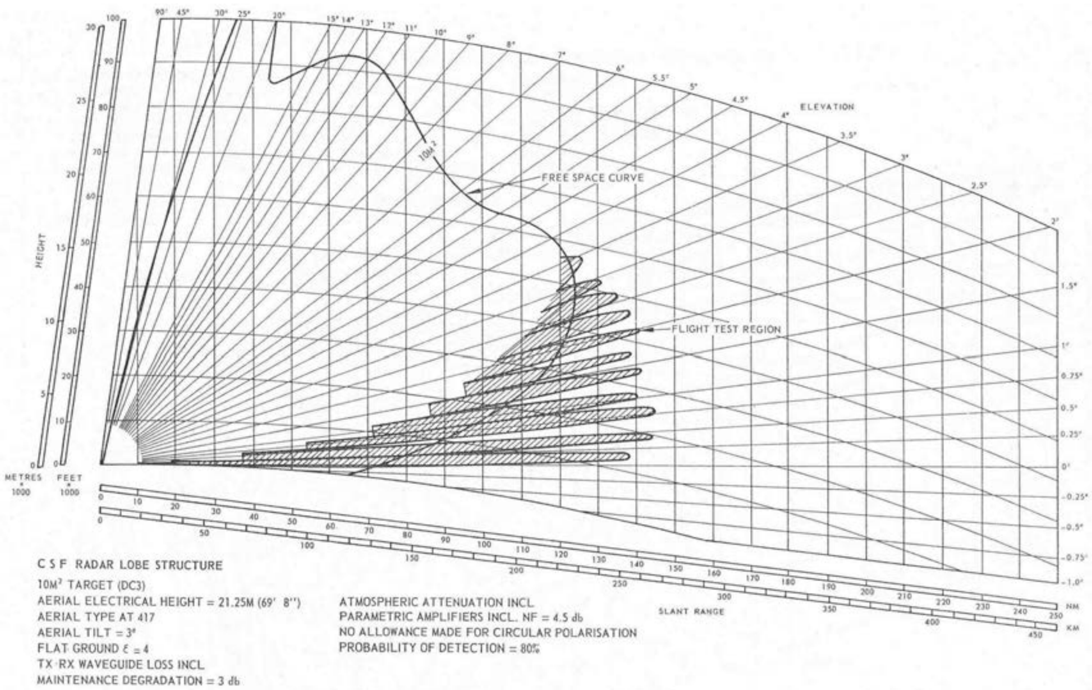


Figure 44: Vertical coverage of Thompson CSF primary RSR. Obvious is that Earth curvature (bottom of graph) is the major factor limiting low-angle coverage. The reduced range at some angles is the effect of 'lobing': combinations of ground reflected and direct radiation generating 'stacked lobes' in coverage below angles of approximately 3.5˚. It is incorrect to assume a blind sector below mechanical and electrical tilt angles as has been suggested in one VH-MDX paper[17]. Also obvious is that VH-MDX was at the limit of PSR coverage at and below 8000'AMSL at approximately 100NM-110NM (Graph: Australian Government (Department of Transport) 1977).

Even with 3˚ upwards tilt, figure 44 shows that the Thompson CSF PSR had significant low-angle coverage.

It must be remembered the *vertical* beam is purposely broad like a ping-pong bat and only the *horizontal* portion of the beam is highly narrow. The RSR in particular required low angle emissions down to the *horizon* to ensure long range coverage[28].

The low-beam *vertical* radiation pattern graph for the Thomson CSF RSR PSR antenna in figure 45 below shows that a *minimum* of 21dbi antenna gain is apparent between -1.5˚ and 5.5˚ elevation angles[28]. At 0˚ elevation 28dBi antenna gain is evident. These are reasonable gain values and quash the suggestion of hard blind angles below tilt angle.

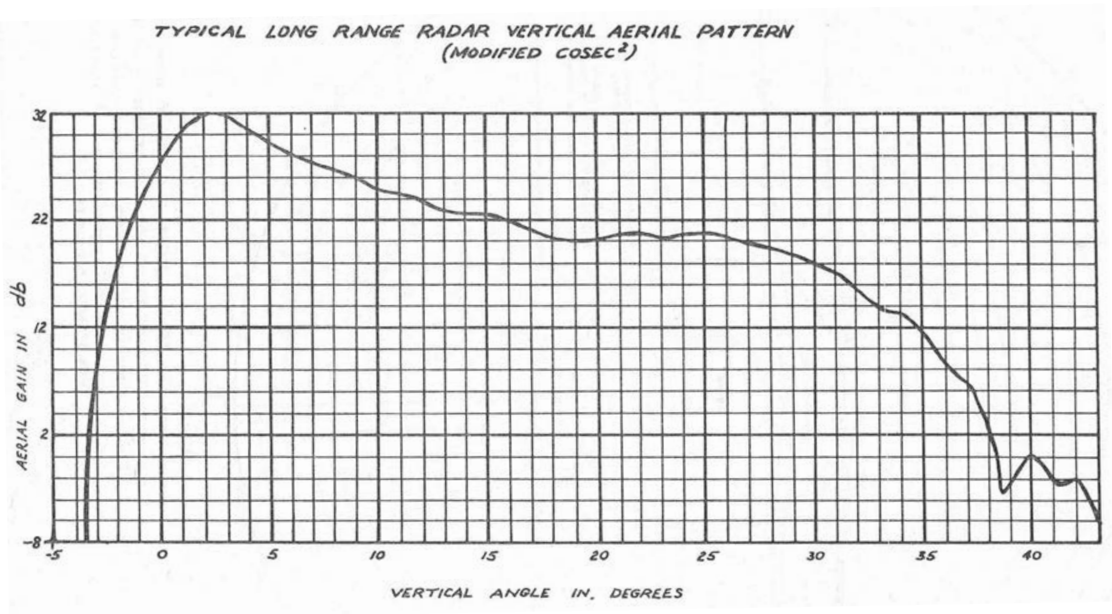


Figure 45: Thompson CSF RSR PSR vertical radiation pattern (low beam only). This graph only considers the *low beam* of the RSR but it was the low beam that determined antenna performance at elevation angles below 5.5˚ on the Thomson CSF PSR RSR. Reasonable gain at low elevation angles existed (Graph: Australian Government (Department of Transport) 1977).

A Melbourne Tullamarine ATCO described how trains and trucks were detected by the Tullamarine radar units[26]. These were predictable as they appeared in the same or similar position all the time[26]. Although anomalous, this does elude to low-angle radar *propagation* with the Thomson CSF radars.

August 1972 flight tests of The Round Mountain primary RSR reveal detection of a Fokker F-27 aircraft at 6500'AMSL at 110NM from the radar head with 3˚ up-tilt of the antenna[38]. The test results for this one test condition are shown in figure 46 on the following page.

The *pure difference* in height above mean sea level between the radar head and the F-27 in this case is approximately +1300'. Earth curvature would have resulted in a pragmatic difference less than 1300'. This is a relatively low height above the radar at a significant distance. In fact this distance and height difference was very similar as The Round Mountain RSR was to VH-MDX.

This result point is only one of many others but does prove that coverage at low elevation angles for the Thomson CSF PSR could be good despite antenna up-tilt.

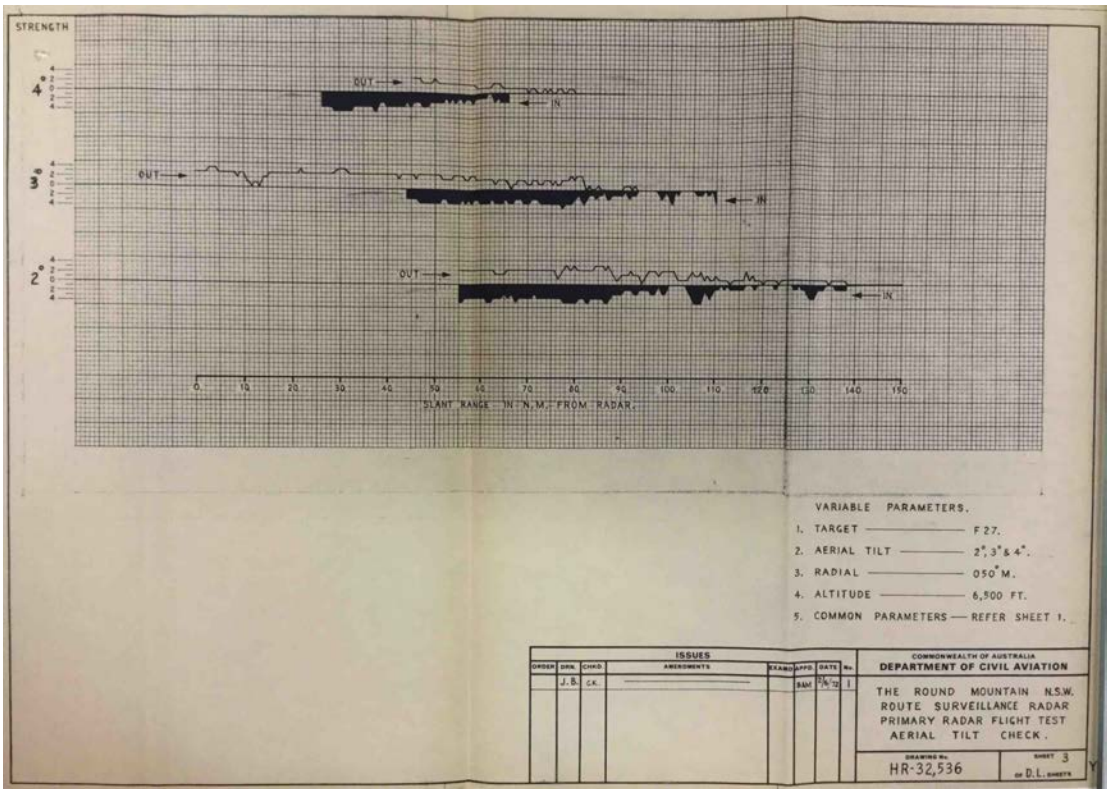


Figure 46: The Round Mountain PSR flight test 1972. The Round Mountain PSR was shown to be able to detect an F-27 flying at 6500'AMSL at 110NM using 3˚ up-tilt (which became the final tilt setting). The received signal was at a 'good' (3 out of a max of 4) strength. The difference in *relative* height between the radar and aircraft was less than +1300'. The position of the F-27 at 110NM along the 050˚M bearing would have put the aircraft about 38NM offshore abeam the Yamba/Grafton area. This resulted in minimal terrain blockage. Results for other radials were not as good and this was due to blocking terrain (National Archives of Australia (Department of Transport) 1972)[38].

The flight test report also found that The Round Mountain PSR identified the test aircraft climbing through 3000'ASML near Coffs Harbour[38]. This means the radar successfully detected an aircraft that was around 2200' lower than the radar head. Aiding this outcome is a radar path relatively free of blocking intermediate terrain and a reasonable sized aircraft to reflect radar off.

These results provide strong evidence of primary radar coverage below antenna tilt angle.

Sydney and The Round Mountain PSR's can confidently be assumed to have low-angle coverage *mainly* determined by terrain, obstacles and received signal strength, rather than *purely* the angular elevation of beam boresight.

This means line-of sight analysis can solidly reveal low-angle *primary* radar coverage.

3.23.2. Coverage in elevation: SSR

The RSR SSR antenna was a 'hog trough type'[4]. These antennas have a characteristically *deep* radiation pattern in elevation. In fact on most occasions with such an antenna in an SSR application, mechanical tilting upwards and a minimum elevation above ground level is *required* to minimise the amount of radiated power being pointed at the ground[21].

High power being radiated into the ground greatly increases the chances of false positions being displayed as a result of a non-direct, reflected (off the ground) propagation path to the aircraft transponder[21].

Accordingly ICAO specifies that *adequate power* should be transmitted between 0.5˚ and 40˚ from the horizontal and that antenna height and tilt should be used to minimise power radiated towards the surface[21].

Figure 47 shows the signal strength/loss at various elevation angles of a SSR hog trough antenna. The curve is rather flat from around 0˚ to 15˚ indicating minimal power gain/loss. Approximately 2dBi reduction in gain is apparent between the maximum gain angle of around 10˚ and -5˚.

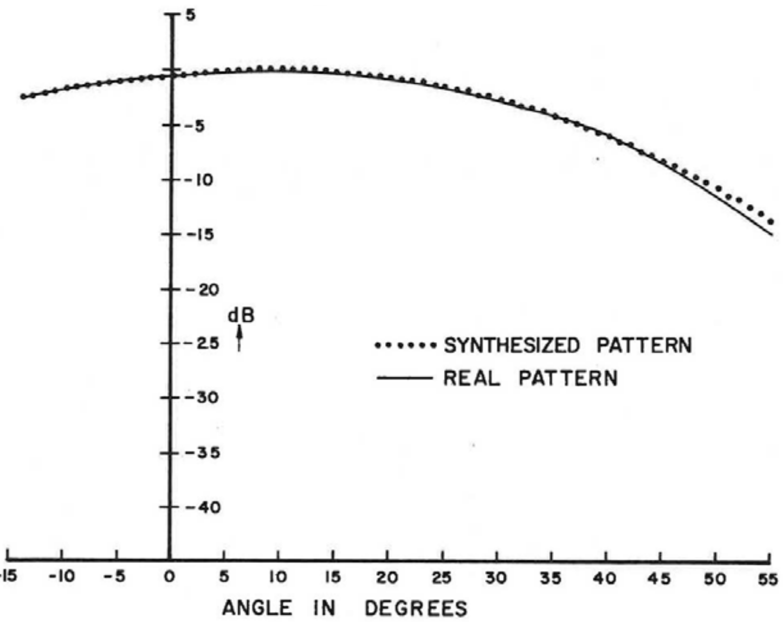


FIG. 11: Normalized free space elevation plane pattern of the existing "hog-trough" antenna.

Figure 47: Hog Trough SSR antenna elevation radiation characteristics. This graph shows the amount of projected power/ antenna gain change at different points in elevation angle. Immediately obvious is that significant power is still radiated /received down to 10˚ below the horizontal. Even with electronic and/or mechanical tilt of a few degrees up applied to the antenna, coverage still exists down to the horizontal and below. Most power is radiated around +10˚ in this case (Graph: J. Zatkalik, Sengupta. D.L, Tai. C, 1975).

November 1972 tests of the Sydney RSR SSR concluded: '*The SSR system coverage, using the ICAO minimum transponder tolerances, was virtually line of site*'[43].

Additionally: '*the improvement in coverage over the RSR* (primary radar) *radar was significant (depending of course on the size of the aircraft in the case of RSR coverage) and varied from 10% to 40%*'[43].

Re-considering the low-angle coverage found of The Round Mountain PSR in section 3.23.1 and applying these SSR findings to them, it is obvious that low angle coverage with SSR would be superior to primary radar. This would be expected as SSR is not reliant on aircraft size, shape or aspect.

Sydney and The Round Mountain SSR RSR's can confidently be assumed to have low-angle coverage *mainly* determined by terrain, obstacles and received signal strength, rather than *purely* the angular elevation of beam boresight. Aircraft size is no factor in this matter and aircraft aspect is only a consideration with respect to antenna blanking.

This means line-of sight analysis can *confidently* reveal low-angle SSR coverage probability.

3.23.3. Conclusions: RSR coverage in elevation

It has been shown in the preceding sections that vertical coverage of both the PSR and SSR of the 1981 RSR was broad with good low-angle coverage.

Coverage was primarily determined by terrain, Earth curvature and obstructions rather than antenna boresight angles alone.

Other factors such as power output, receiver sensitivity, aircraft aspect (PSR only) and aircraft size and shape (PSR only) were also significant factors.

Line of sight analysis is a confident method of determining propagation of PSR and SSR.

3.24. RSR Upgrades

The Round Mountain RSR was subject to the following upgrades:

- By mid 1982: '*Extensive refurbishment program*' all stages of the program completed[36].
- The Sydney PSR was digitized and this was thought to have occurred around 1983.

Digitization potentially affects how Airport PSR returns were gated in the Northern Mosaic display. It does appear digitization occurred well after the VH-MDX accident.

3.25. Radar specifications

The following sub sections will summarise the TAR and RSR specifications discussed or determined in section 3 for both PSR and SSR, Bright display system and aircraft transponder.

3.25.1. Terminal Area Radar (TAR) specifications

3.25.1.1. TAR *Primary* radar specifications

Item	Value
Model	Thomson CSF[28] ER720L5[40]
Transmitters	2 transmitters, 2 beam, frequency diverse ('A' and 'B' Tx)[28]
Peak output power	2.0MW each[28][40]
Frequency	L Band, 1305Mhz and 1350MHz (diverse)[2]
Wavelength	23cm[28]
Horizontal beam width	2.2˚[28][40]
Vertical beam depth	NOT CONFIRMED
Relative vertical beam angles between feed horns[28]	'Low' beam and 'High' can be varied between 4.0˚-5.5˚ from each other
Pulse Repetition Frequency (PRF)	900PPS, wobbulated (varied)+/-10%[28] 800pps[40]
Pulse width (duration)	1.5 micro sec[4][5][28][40]
Antenna type	Thompson-Houston THD284, Modified cosecant squared for high angle reinforcement[4][28] THD284B[40]
Antenna gain[28]	30dB[4]
Nominal antenna tilt[28]	4.5˚ (low beam can be varied between 2.0˚ and 7.0˚ with high beam following with differential set)
Sweep rate	4 seconds/ 15RPM[4][5][28][40]
Receiver sensitivity (approx)	≤ -80dBm[4]
Antenna height	Estimated: 60'/18.3m[4] Specified: tower 60'/18.3m above ground level[28]
Maximum certified range	≈100NM[2], 95NM[28] but can be tweaked to operate as an RSR
Resolution[28]	Range: +/- 0.12 to 1NM depending on range used
Accuracy (including Bright display)[28]	Range: +/-1% of range scale in use Azimuth: +/-1.5˚

Figure 48: Thompson CSF PSR TAR Specifications.

3.25.1.2. TAR *Secondary* radar specifications

Item	Value
Model	Cossor SSR700[43]
Interrogator power output (EIRP)	15.8kW[21] (estimated based on ICAO requirement (EIRP 72dBm) for 160NM nominal range)
Frequency	1030MHz (Tx) / 1090Mhz (Rx)
Horizontal beam width	≈2.5˚[28]
Vertical beam depth	NOT CONFIRMED but likely at least -5˚ to 45˚ with max 10dbi loss
Receiver sensitivity	≤ -85dBm[21][4][40]
Antenna type	Slotted Waveguide (Hog Trough)[4]
Antenna gain	Not less than 23dBi @ 1030MHz[40]
Sweep rate	4 seconds/ 15RPM[4][5]
Antenna height	≈19.8m above ground level[4]
Maximum nominal range	100NM[2][28]

Figure 49: Cossor 700 SSR TAR Specifications.

3.25.2. Route Surveillance Radar (RSR) specifications

3.25.2.1. RSR *Primary* radar Specifications

Item	Value
Model	Thomson CSF RT18[28] ER410[40]
Transmitters	2 transmitters, 2 beam, frequency diverse (‘A’ and ‘B’ Tx)[28]
Peak output power	2.0MW each[28][40]
Frequency	L Band, 1275Mhz and 1320MHz (diverse)[28] 1300/1340MHz[40]
Wavelength	23cm[28]
Horizontal beam width	1.3˚ +/-0.2˚[28][40]
Vertical beam depth	At least -1.5˚ to 26˚ with 12dbi max loss (min 20dbi antenna gain)
Relative vertical beam angles between feed horns[28]	‘Low’ and ‘High’ beam permanently set 3˚ from each other
High/low beam switch over point	TRM: Variable[38]: 8 miles ideal, 15 miles max (after which low beam only)[28]
Pulse Repetition Frequency (PRF)	400PPS, wobbulated (varied)+/-10% of 50Hz[28][38][40] (confirmed for TRM)
Pulse width (duration)	2.5 micro sec[4][28][38][40] (confirmed for TRM)
Antenna type	AT417[4][28][40], Modified cosecant squared for high angle reinforcement[4][28]
Antenna vertical cutoff	≈ 35˚ from horizontal
Antenna gain[28]	0˚ 27.5dBi 1˚ 30.0dBi 2˚ 32.0dBi 3˚ 32.0dBi 4˚ 30.5dBi 5˚ 29.0dBi
Nominal antenna tilt[28]	3.0˚ (can be permanently set between 2.0˚ and 6.5˚) (TRM confirmed 3˚ for 1972 final test and 1977)[38]
Sweep rate	12 seconds/ 5RPM[4][5][28] +/-5%[28][40]
Tangential fade velocity	< ≈15knots tangential speed[28]
Blind velocity	≈82-94 knots radial velocity (higher order blind velocities eliminated with wobbulation)[28]
Receiver sensitivity (approx)	≤ -80dBm[4]
Antenna Height	Sydney: Estimated: Tower height 50’/15.2m above ground level[4] Specified: Tower 70’/21.3m above ground level[28] (RSR’s normally had 70’ or 55’ tower heights[38]). Likely: 55’/16.8m TRM: tower height of 25’/7.6m only parallel sections of tower used[38]
Maximum certified range	160NM[2][4][5][6]
Slant range error beyond 30NM and at 20000’ above radar head	< 0.17NM in range[28]
Resolution (using PPI display)[28]	Range: 0.2 to 1NM depending on range scale used Azimuth: ≈ 1.3˚

Accuracy (using PPI display)[28]	Range: +/-1% of range Azimuth: +/-1.5˚
Sub Clutter Visibility Factor (fixed pwr : moving pwr component)[28]	≈ 1:100 (measured as part of routine maintenance)
Sub Clutter Visibility ∆ gain (SCV)[28]	≈ 22dB in low beam area (≈ >8-15miles) ≈ 50dB in two beam area (≈ <8-15 miles)
Moving Target Indicator (MTI) boundary	TRM: 78NM in 1977[38]

Figure 50: Thompson CSF RT18 PSR RSR Specifications.

3.25.2.2. RSR *Secondary* radar specifications

Item	Value
Model	Cossor SSR700[43]
Interrogator power output (EIRP)	- 125.9kW EIRP with 23dBi antenna gain based on specified 28dBW (631W/ 58dBm) at antenna input[43][44] (this was for TRM during 1977 test and SYD in 1971). - Power at antenna to be limited to 52.5dBW for 200NM nominal range[40]. - (15.8kW previously estimated on ICAO requirement (EIRP 72dBm) for 160NM nominal range)[21] - At transceiver cabinet (able to be reduced by 9dbW +/-9dB): [44] P1 33.5dbW +/-0.5dbW (Main 800110/6) P1 34dbW +/-0.5dbW (Aux 800110/7)
Frequency	1030MHz (Tx) / 1090Mhz (Rx)
Horizontal beam width	Interrogation beam: 1.8˚-2.3˚ at 3dB levels[44] Otherwise specified (possibly for Rx 3dB points) as ≈2.5°[28]
Vertical beam depth	3db pure (not to horizontal) depth: 44˚ +/-4°[44] Estimated at least -5˚ to 45˚ to horizontal at 10dbi points
Receiver sensitivity	≤ -85dBm[21][4][40] Tangential sensitivity at input to receiver cabinet:[44] ≤ -86.5dmW (Main 800110/6) ≤ -86.8dmW (Aux 800110/7)
Antenna type	Slotted Waveguide (Hog Trough)[4]
Antenna gain	Not less than 23dBi @ 1030MHz [40]
Sweep Rate	12 seconds/ 5RPM[4][5]
Antenna Height	SYD: ≈16.8m above ground level TRM: ≈9.1m above ground level
Maximum Range	160NM[2][4][5][6][28]

Figure 51: Cossor 700 SSR RSR Specifications.

3.25.3. Northern Mosaic Bright display specifications

Item	Value
Model (SYD AACC)	MI470C (high speed deflection circuitry for ICM)[40]
Persistence	6-7 RSR sweeps (72-84 seconds)[28]
Azimuth (bearing) read-off tolerance	Subjective: +/- 5˚ normal +/-10˚ maximum expected
Range read-off tolerance	Subjective: +/-2NM if a map reference was within 10NM of the aircraft paints, or; +/-5NM if no map feature was within 10NM of the aircraft paints
Linearity and accuracy of radar signals to video map	+/- 0.5% of display diameter (20”)[28] therefore approx 1.75NM
Scan Converter sources (SYD AACC)	10[4]
Map sources (SYD AACC)	10[4]

Figure 52: Bright display Specifications.

3.25.4. Aircraft transponder specifications

Item	Value
Transmitter power	DoT test standard: 21dBW at the antenna[43][44] ICAO standard: 18.5dBW to 27dBW (71W to 500W) (*peak* transmission power) VH-MDX: 125W peak (=21.0dBW)(23.0dBW with 2dB antenna)
Receiver sensitivity	DoT test standard: -69dBm[43][44] ICAO standard: -69dBm to -77dBm, nominal -71dBm
Antenna gain	<2.0db
Nominal line loss	3.0db
Link reliability	90%

Figure 53: Aircraft transponder specifications.

4. Sydney ATS VH-MDX positional information

4.1. Introduction

Section 3.20.1 identified that *radar track* recordings of VH-MDX at Sydney ATC are unlikely to exist so, the following information sources must be used to determine VH-MDX positional information:

- Communications transcripts
- Formal records
- Discussions with staff directly involved
- Discussions with staff indirectly involved

4.2. ASIB Communications transcripts

4.2.1. Sydney Sector 1 radar observations

Communications transcripts[9] reveal the following information (figure 54) with respect to Sydney Sector 1 radar observed tracking of VH-MDX[9]. Note, a '-' is appended to times where the call was made just *before* the stated time whilst a '+' appended on a time indicates that the call was made just *after* the stated time.

Time (UTC)	Sector 1 radar observation
0928:28	'*He's identified four zero miles North of Singleton on the Mt Sandon-Singleton track*'
0928:45	'*Oh hang on I'll do it accurately seeing he's……...he's probably about three-six*'
0929:53-	'*to West Maitland remain on his present heading*'
0931:16	'Ah, *Mike Delta X-ray, he looks like he's turned southbound now. Um, just ask him his present heading and stay on the line please*'
0931:47	'Um, *if he wants to go to West Maitland-heading of about 150 from his present position*'
0934:00+	'*Roger bearing 320 Willy at 45NM Mike Delta X-ray squawking code 4000, you got anything there?*'
0934:20+	'*He's just turned onto an easterly heading looks like about 120*'
0934:30 to (?) 0934:50	'*Just a moment I'll try and get – as a – little bit……………46 miles according to me*' '*Heading straight towards you now*'
0935:10	'*….and he's just about in an area of suspect radar coverage and I'd like …….if you could pick him up and keep track on him*'
0936:50	'*Well he's on a heading of 150 mate he's all over the place*'
0939:00	'*…..we've lost him….*'

Figure 54: Sector 1 radar observations.

There is a question of the exact time of the 0934:30UTC and 0934:50UTC calls. Both calls in this period may have been made *together* or *separately*. The following will be accepted as the most likely timings of calls:

0934:30UTC: '*Just a moment I'll try and get – as a – little bit…………..46 miles according to me'*

0934:50UTC: *'Heading straight towards you now*'

The final point in the table (*'….we've lost him*') is important as this suggests fade of VH-MDX from Sydney ATC operated radar *by* 0939:00UTC.

4.2.2. Sydney FSC derived position information

Sydney FIS-5 in the Sydney FSC had no radar display but was the only agency after Taree to communicate with VH-MDX[9]. Accordingly although not radar derived, information with respect to VH-MDX's position can be gained from overviewing communications with the aircraft.

Figure 55 lists the findings from communications transcripts[9].

Time (UTC)	Sydney FSC derived positional information
0929:10	'*I'm struggling to get to eight-five* <8500 feet altitude>'
0931:28	When questioned of present heading: '*Mike Delta X-ray its averaging somewhere around two-two-zero*'
0934:20	'*We've picked up a fair amount of ice and ah, I can just make out a few towns on the coast.*'
0934:40	'*It's a single……and we'll try to continue our flight plan*'
0937:40	'*Seven and a half* <7500' feet altitude>'
0938:33	'*We're down to six and a half* <6500 feet altitude>'
0939:26	'*Five thousand* <5000 feet altitude>'

Figure 55: Sydney FSC positional information.

Most of the information from pilot reports relates to VH-MDX altitude.

4.3. Sydney ATC radar plot sheet and deposition

4.3.1. Radar plot sheet

VH-MDX radar track information was recorded on a radar plot sheet by a Sydney ATCO[6]. The plot sheet was based on a map of the Sydney Northern Mosaic program used by Sector 1 and the observed radar paints of VH-MDX[6].

This plot sheet has been displayed numerous times in previous sections and is included again overleaf in figure 56.

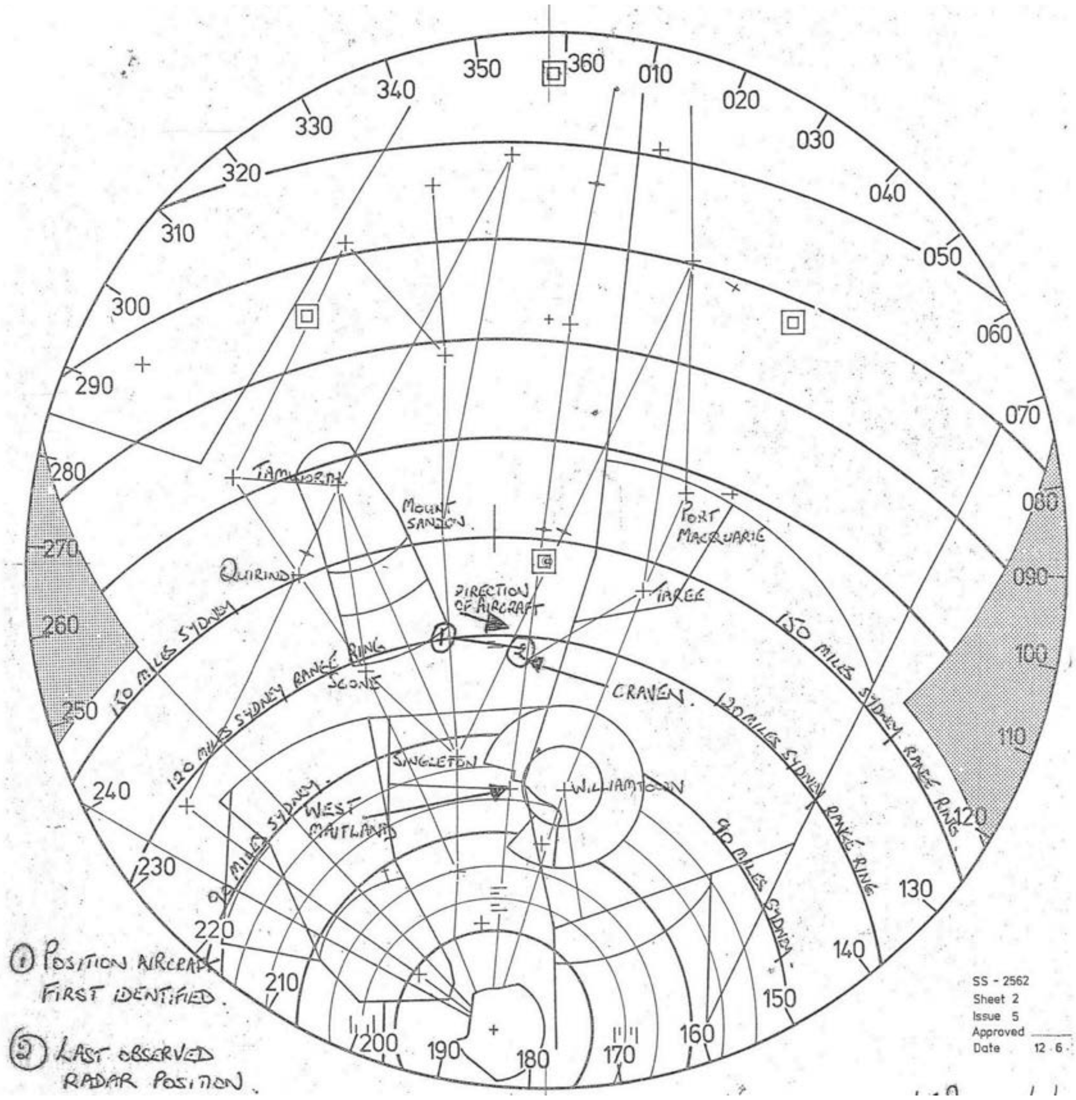


Figure 56: Sydney radar plot sheet. (Image: Australian Government (Department of Transport) 1981).

The initial and final radar observed positions of VH-MDX are identified. This plot sheet was drafted approximately four months after the accident date.[6]

4.3.2. Deposition by Sydney ATCO

A deposition was made of the observed radar paints and *general* observed tracking of VH-MDX then signed the same day as the plot sheet and by the same ATCO[10]. Figure 57 on the following page shows this deposition.

Deposition.

I'm employed as an Air Traffic Controller by the Department of Transport Australia. I commenced duty at 2 p.m. as a Sector Radar Controller and my duties are to provide a radar service to and to communicate with aircraft flying in controlled airspace within my area of responsibility.

At 7.50 p.m, I observed Mike Delta X-Ray, Squawk Identification, the position being 120 miles from Sydney, just west of the Mount Sandon, Singleton track. I observed the aircraft then tracking on an easterly heading of approximately 100 degrees. After observing the aircraft travel about 20 miles, the aircraft faded from radar. Position was approximately 5 miles west of Craven.

Figure 57: Deposition made by one of the Sydney Sector 1 Air Traffic Controllers. (Image: Australian Government (Department of Transport) 1981).

Although distances are written as 'miles' it is accepted that Nautical Miles (NM) was the actual measurement. Also, track bearings from the Bright display were in degrees magnetic so the track specified in degrees is accepted to be magnetic.

The initial identification of VH-MDX was said to be at 1950EST (00950UTC) at 120NM from Sydney, '*just west of the Mount Sandon, Singleton track*'[10].

The deposition specifies VH-MDX having been radar observed to travel '*about*' 20NM along a track of 'approximately' 100˚M from initial identification to radar fade[10].

Radar fade position was specified as *approximately* 5NM west of Craven waypoint.

4.4. Other records of Sydney radar fade

4.4.1. Approximately 330˚M/45NM from Williamtown

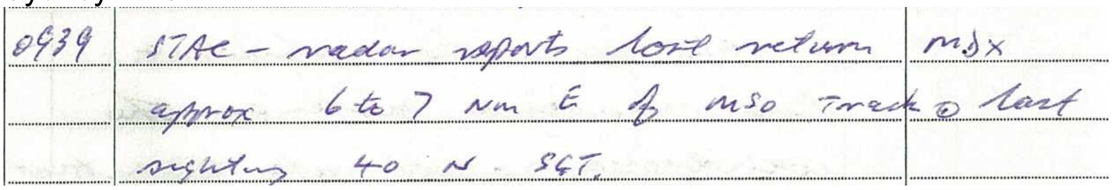
On the day after the VH-MDX accident, the Department of Transport was reviewing the final radar positions of VH-MDX from Williamtown and Sydney ATC. By evening, a Sydney radar fade position of *approximately* 330˚M/45NM from Williamtown at 0939UTC was recorded as shown in figure 58. The *exact* source (person(s)) of the positional information was not specified.

SYDNEY RADAR PLOT WAS LOST @ APPROX @ APPROX 330 NM 45
@ 0939

Figure 58: Reported Sydney radar fade. This position was recorded in writing during the day after the accident (Image: Australian Government (Department of Transport) 1981).

4.4.2. Approximately 6-7NM east of the ‘Mount-Sandon track’/40NM north of Singleton NDB

At 0939EST during the accident (the time of transcribed radar fade at Sydney ATC), the following report was made as to the VH-MDX final radar position at Sydney ATC:



0939	STAC – radar reports lost return	MDX
	approx 6 to 7 NM E of MSO Track @ last	
	sighting 40 N SGT.	

Figure 59: Sydney ATC ‘lost return MDX’ approx 6 to 7 NM east of SGT-MSO track.

A comment stating ‘last sighting’ of VH-MDX at 40NM north of SGT (Singleton) NDB is also included.

4.5. Discussions with Sydney ATCO’s

4.5.1. Introduction

Figure 60:

4.5.2. ATCO A

No significant persistence trails of VH-MDX returns sufficient to *confidently* indicate a track trend were observed by this ATCO. This may be due to:

- The ATCO conducting important co-ordination tasks and possibly intercom communications
- The relatively slow scan rate of the Round Mountain RSR
- Slow relative speed of VH-MDX along the large scale display
- Possible intermittent radar propagation between The Round Mountain RSR and VH-MDX
- Weather clutter over the Barrington ranges ‘washing out’ VH-MDX paints
- Attempting to remember details after more than 30 years.

4.5.3. ATCO B

4.5.4. Department of Transport (DoT) Officer A

This Officer was an active Sydney ATCO that would be seconded to the ASIB for the purpose of co-coordinating Search and Rescue duties when required[1].

With respect to the final Sydney observed radar position, this Officer recalls that the ATCO’s at Sector 1 observed the VH-MDX radar paint fade in the *approximate* position as reported in the deposition discussed in section 4.3[1]. The paint fade on the Bright display from best memories was *distinct* and relatively *slow*[1].

The slow suggested paint fade is supported by the Bright display persistence values of 72-84 seconds found in section 3.15.

Also of significance to this Officer’s memory was that reportedly the radar paints of VH-MDX slowed down (in terms of speed) rather quickly in approximately the final minute[1].

When questioned of which final radar position he viewed as the most likely to represent VH-MDX's final radar position, the Upper Williams Valley ASIB/RCC final position or the Sydney ATCO's position, the latter was suggested[1].

The primary reasons why were effectively the same as the author's in that although Williamtown radar was much closer to VH-MDX, thereby potentially offering more accurate positions, the Williamtown ATCO was alone conducting procedural duties in addition to providing advice on VH-MDX.

Sydney ATCO's on the other hand were focused on VH-MDX almost continually and observed a radar fade. It was revealed by the author that the Williamtown ATCO stated that he did *not* observe radar *fade* of VH-MDX[3] and this is significant in determining the final position of VH-MDX.

4.6. Mode C altitude reporting

There was no mention of Mode C transponder altitude interrogations of VH-MDX by deposition or through discussion with the Sydney ATCO's[2][20]. Also, the flight plan for VH-MDX indicated only Mode A transponder capability[9].

A Sydney Thompson CSF/Bright display Technical Officer did state 'full mode C' was available by the *late* 1980's but was not sure about 1981[4].

Further expansion is offered by an ATCO who was at Melbourne/Tullamarine during the early 1980's suggesting Mode C could be interrogated by the Cossor system but not displayed on the *ATCO's* screen however, mode C was available on the *technicians* display[22].

It appears Sydney ATC may have had the ability to interrogate mode C in a cumbersome way not directly available to the ATCO's. Regardless, it appears that VH-MDX's transponder did not have mode C altitude encoding meaning no transponder derived altitude readouts are available of VH-MDX.

4.7. Conclusions: Sydney ATC positional information

An *initial* Sydney ATC radar fix of VH-MDX was found.

Multiple Sydney ATC *final* radar fixes of VH-MDX were found (shown on the following page as figure 61 and 62):

- **Sydney ATC radar plot sheet and deposition:** Approximately 5NM west to north-west of Craven waypoint recorded approximately 4 months after the accident
- **Approximately 330˚M/45NM from Williamtown at 0939:00UTC:** recorded the evening after the accident
- **Approximately 6-7NM east of the 'Mount-Sandon track' (from Singleton NDB) /40NM north of Singleton NDB:** 'last sighting 40NM north of SGT', recorded during the accident.

Communications transcripts reveal an *intermediate* radar fix whilst also providing clues as to radar observed *tracks* at various times.

Pilot reported *altitudes* and a *heading* were found from communication transcripts.

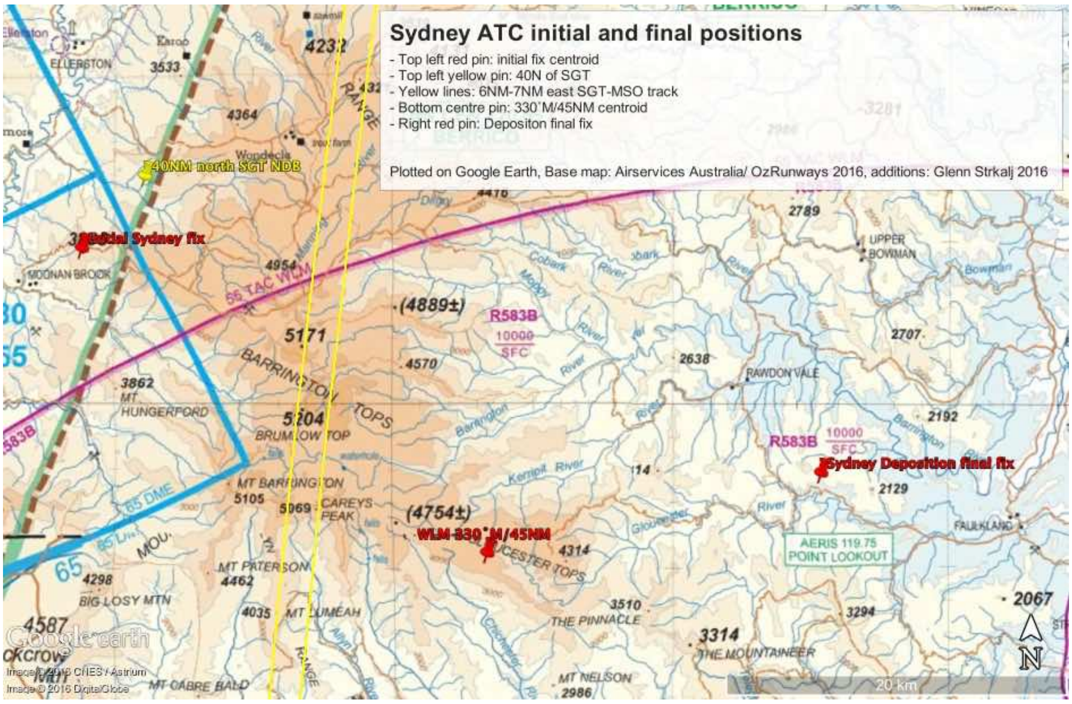


Figure 61: Initial and *final* Sydney ATC radar positions of VH-MDX. All suggest an easterly track direction from initial fix (red pin top left). The actual positions are much broader: point sources are shown for initial reference. (Topographical chart: Airservices Australia 2015/OzRunways 2015, additions: Glenn Strkalj 2016, plotted on Google Earth).

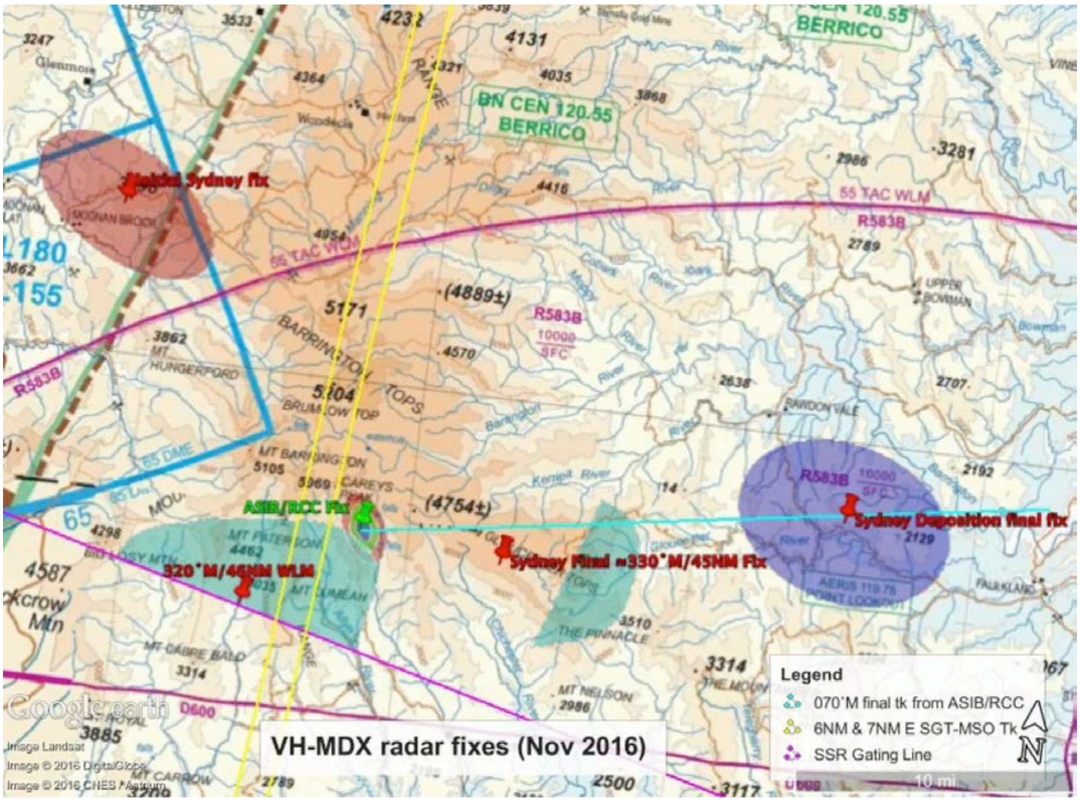


Figure 62: All radar fixes (SYD and WLM) with deviations applied: This image shows the effects of considering read-off, display and system errors to the point fix that will be applied in future sections. VH-MDX may have been anywhere within these areas at the applicable time (Topographical chart: Airservices Australia 2015/OzRunways 2015, additions: Glenn Strkalj & Glenn Horrocks 2016, plotted on Google Earth).

5. Radar Propagation

5.1. Introduction

Determining which radar heads could interrogate VH-MDX at specific times and at what minimum aircraft altitudes offers the possibility to filter out likely radar positions whilst also offering understanding as to what the ATCO's were seeing on their displays.

Some Department of Transport *flight test* and clutter data relating to Sydney and The Round Mountain *primary* RSR's of 1981 has been located and will be discussed. The most flexible and relevant source of propagation information however is by radio propagation analysis *software*.

Radio propagation analysis software involves using software to simulate radio wave paths over a terrain database of the Earth. Such a simulation can graphically depict the radio propagation path across terrain and also yield predictions on received signal strength. Minimum radar interrogation altitudes of VH-MDX can be determined then the analysis can be cross-referenced to pilot reported VH-MDX altitudes to geographically 'fix' the aircraft's position.

Section 3.23 revealed that the Sydney ATC operated radar units offered effectively *line of sight* coverage so, *line of sight* propagation paths can be analysed at particular geographic locations and at different VH-MDX altitudes. When the line of sight path is obscured by terrain or Earth curvature, this yields the radar mask angle for the analysed geographic point. Figure 63 presents an example of a radio propagation software result.

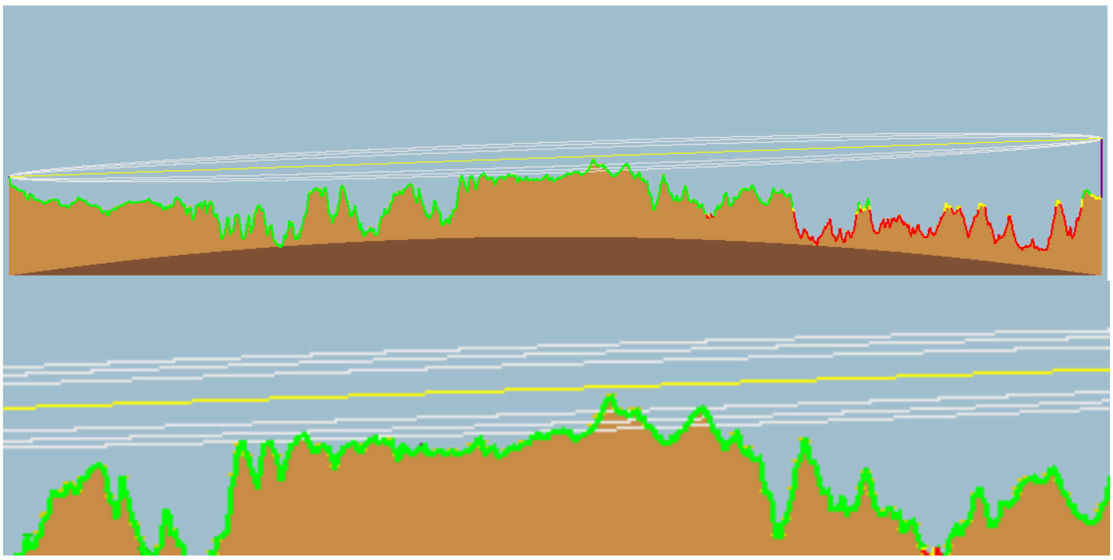


Figure 63: Radar mask angle. The radar head location is the point where the 'rays' are originating from at left. The *geographical position* of VH-MDX is at the *bottom* of the black line at right whilst the *physical position* (altitude) of VH-MDX is at the *top* of the black line. VH-MDX altitude can be lowered until the main line of sight line (yellow in this case) just clears terrain (light brown areas) and Earth curvature (dark brown area). When this is achieved the minimum interrogation altitude of VH-MDX is then known. (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

5.2. Department of Transport information

5.2.1. Clutter diagram: The Round Mountain PSR

Figure 64 presents the *unfiltered* terrain clutter (permanent echoes) from The Round Mountain PSR in 1972 out to 80NM. Immediately obvious is the lack of terrain clutter along the 050˚M bearing from the radar head where the detection of a F-27 aircraft occurred at 110NM, 2200' lower than the radar head as discussed in section 3.23.1.

Significant clutter exists to the west and south. VH-MDX was located generally south to south-south-west of The Round Mountain RSR.

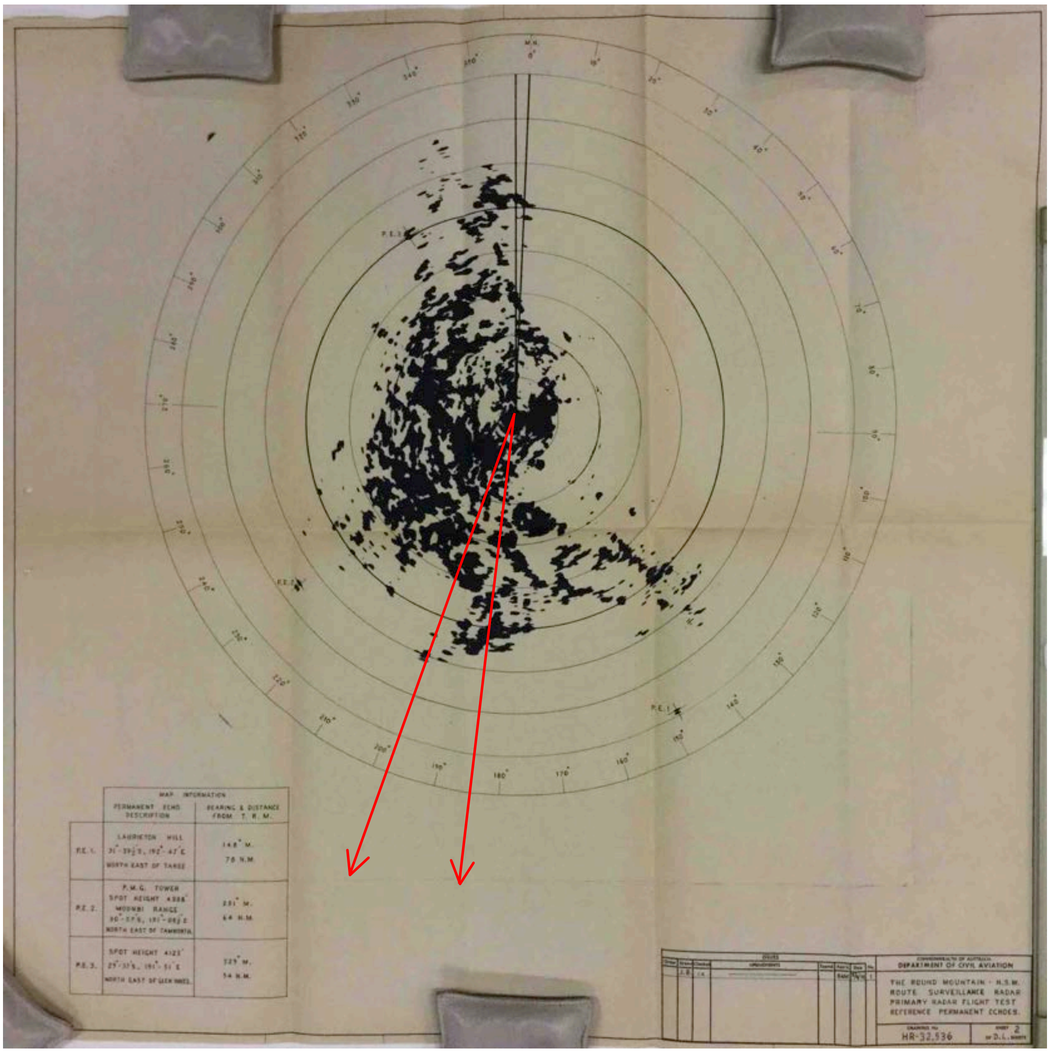


Figure 64: Terrain clutter/permanent echo's of The Round Mountain RSR to 80NM. Insight is given into terrain shielding *towards* the Barrington ranges (approximately 184˚M-198˚M, red arrows). Significant clutter exists suggesting higher minimum detection altitudes of aircraft in the Barrington ranges area than eastwards. Radio propagation software can offer precise insight into where the radar masking occurred (Image: National Archives of Australia (Department of Transport) 1972, additions: Glenn Strkalj 2016)[38].

VH-MDX was located approximately between 184˚M to 198˚M from The Round Mountain RSR. Figure 64 shows significant terrain clutter existed in this sector that would have *increased* the minimum detection altitude of aircraft.

The main obstructions are 35NM-42NM and 50NM-57NM from the radar head. This is the terrain north and south of the Oxley Highway between 'Tia' and 'Yarrowitch'.

5.2.2. Flight test results: The Round Mountain PSR

Additional coverage insight is given by a FL110 flight test radar coverage map of The Round Mountain PSR in 1972 contained in Annex J. An extract of this map covering the area VH-MDX was operating in is shown below in figure 65.

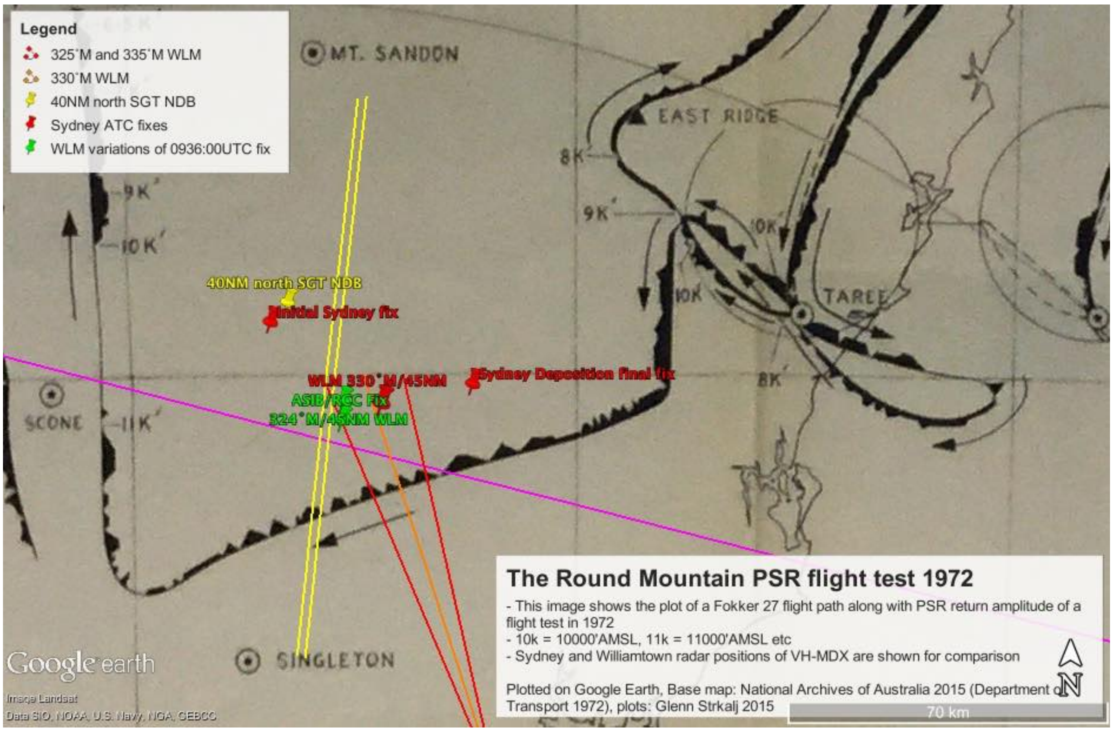


Figure 65: The Round Mountain PSR test flight FL110 and VH-MDX radar positions. VH-MDX was 8-9NM *north* of the test flight leg. The magenta line is the electronic gating line. As this was a test flight, raw un-gated data was being analysed. From Taree to 30NM SGT, coverage was 'reasonable to good'. 30NM SGT is where the test track intersects the gating line. Accordingly, reasonable to good PSR coverage at FL110 of the accident area was likely. (Image: National Archives of Australia (Department of Transport[38]) 1972, additions Glenn Strkalj 2016, plotted on Google Earth).

The leg from Taree then south-west at FL110 gives an idea of the coverage in the southern sections of the Barrington ranges. This portion of the test was flown about 8-9NM *south* of VH-MDX's likely track meaning the test track was somewhat more *critical* in coverage than coverage in the accident area.

Test narrative stated that coverage on this test leg between Taree and approximately 30NM north-east of Singleton was '*reasonable to good*'. 30NM from Singleton is at the point of intersection between the gating line and test track from Taree.

As can be seen, the final five or so minutes of VH-MDX's flight was north of this line so, reasonable to good *primary* radar coverage at FL110 could have been expected in the *accident area*.

Between 30NM north-east and 15NM north-east of Singleton (NDB), coverage was *intermittent* with many *good* and *weak* points but also 'misses'[38].

From 15NM north-east of Singleton coverage was *poor* until 7NM north-west of Singleton[38]. The F-27 was again lost at 45NM south-south-east of Tamworth at 10000'AMSL[38].

As these areas were further away from the radar head than the accident area, it can be concluded that radar coverage in the *accident area* was possible below FL110. Also, as the test involved *primary* radar it can confidently be stated that *secondary* coverage would have been at least *equal to* but probably *superior* to the primary results discussed.

The test aircraft entered *Sydney* RSR coverage 20NM north-east of Singleton (100NM Sydney/ 117NM TRM) then faded from *Sydney* RSR at 22NM north-west of Singleton (102NM from Sydney) which is approximately near Muswellbrook[38]. A couple of radar paints were displayed by Sydney again at 104NM from Sydney[38].

These results suggest that Sydney RSR probably could not cover the accident area as well as The Round Mountain RSR particularly at altitudes below FL110.

5.2.3. Low angle PSR coverage: The Round Mountain RSR

Section 3.9.3 identified that *primary* radar is reliant on target *aspect* to the radar head. The extract below in figure 66 shows the signal strength of The Round Mountain RSR *primary* radar returns from a Fokker 27 aircraft flying both inbound and outbound along the 050˚M radial to/from the radar head.

Four different altitudes were flown with the focus of discussion being the results at the bottom of the graph where the aircraft was at 6500'AMSL.

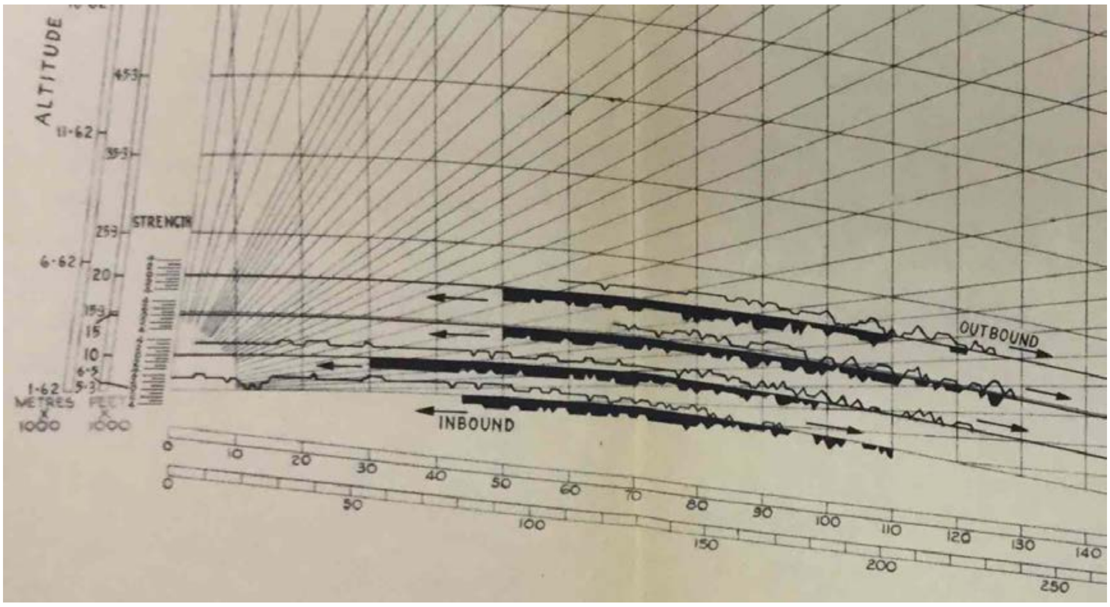


Figure 66: The Round Mountain PSR flight test: low beam vertical pattern (Image: National Archives of Australia (Department of Transport[38]) 1972, additions Glenn Strkalj 2016).

The radar antenna was set to a tilt angle of 3˚ up. Signal strength of returns is shown by vertical displacement from the 6500' horizontal line: increasing strength depicted upwards for the outbound leg, downwards for the inbound leg.

These results show that the F-27 faded from radar at just over 90NM from the radar head when travelling *outbound* but came back into coverage at 110NM when travelling *inbound*. This is a great example of target aspect affecting *primary* radar coverage. *Secondary* radar would *not* be subject to this characteristic *at all*.

These results do prove that *primary* radar coverage was possible from The Round Mountain RSR out to 90NM-110NM. Section 3.22.2 identified that VH-MDX was between 99NM and 110NM from The Round Mountain RSR head. Although VH-MDX was in a totally different sector azimuth-wise than these test results, it can be seen *primary* radar coverage of VH-MDX was possible provided line of sight was apparent.

5.3. Sydney and The Round Mountain RSR propagation analysis

5.3.1. Analysis approach

Radio Mobile Online is a radio propagation tool that can predict radio propagation between two points on the Earth based on a number of transceiver variables. This software will be used for the propagation analysis. Radar transceiver variables for the Sydney ATC operated RSR's are sourced from section 3.25 and expanded on in Annex K.

A terrain database in Radio Mobile Online provides reasonably accurate terrain and Earth curvature data but vegetation is not accounted for. The propagation analysis conducted will consider achievement of line-of-sight and minimum specified signal strength.

Except for confirmation of The Round Mountain PSR flight test results of 1972, only SSR links will be analysed with only the most critical link, the *uplink* from the RSR head to the aircraft, being analysed.

VH-MDX did not likely exceed 8500'AMSL altitude in the last 15 minutes of flight and was almost *certainly* below 10000'AMSL. Accordingly, altitudes above 10000'AMSL will not be considered. The lowest altitudes VH-MDX could be interrogated at in various key geographical positions will be presented.

A graphic depicting the position of the radar head and VH-MDX with the radio propagation path and terrain is presented for each case considered. A zoom of the area where the *main* obstruction to propagation path occurs is also provided.

5.3.2. Analysis results

Radio propagation analysis results for:

- Sydney SSR RSR to key VH-MDX positions are presented in Annex L
- The Round Mountain SSR RSR to key VH-MDX positions are presented in Annex M
- The Round Mountain SSR RSR for the final track of VH-MDX in Annex N
- For The Round Mountain PSR RSR Flight Test in Annex O.

5.3.2.1. Sydney RSR results

It was found the Sydney RSR was *unlikely* able to interrogate VH-MDX below 10000' AMSL at the following locations:

- Initial Sydney fix
- ASIB/RCC fix
- 324˚M/47NM from Williamtown fix
- 323˚M/46.9NM from Williamtown fix (MPP 11 Aug 81)
- 330˚M/45NM from Williamtown fix
- Sydney Deposition final fix.

These locations are representative of the greater accident area. Terrain close to Sydney and Earth curvature are the main obstructions to the Sydney RSR's radar path to VH-MDX in the accident area.

Based on radio propagation analysis, the Sydney RSR was *unlikely* able to interrogate VH-MDX at any time during the accident.

These results may explain the reason why the more appropriately-scaled Sydney 160NM bright display program was not used during the VH-MDX accident as discussed in section 3.8.6.

5.3.2.2. The Round Mountain RSR results

It was found that The Round Mountain RSR *was* able to interrogate VH-MDX at all the same locations specified in the previous sub-section. Figure 67 below presents the *minimum interrogation altitudes* at the analysed locations.

It should be emphasised these results are only valid for the *point* specified and that movement of the analysis point slightly in any direction could change the result. Despite this, it is viewed that the results are representative of the *immediately* surrounding area around the point.

Position	Minimum VH-MDX interrogation altitude (feet AMSL)
Initial Sydney fix	7200
ASIB/RCC	8200
324˚M/47NM	8400
MPP 11 Aug 81 (323˚M/46.9NM)	8100
330˚M/45NM	7000
Sydney deposition final fix	6000

Figure 67: Minimum interrogation altitudes of VH-MDX by The Round Mountain RSR.

A solid finding from these results is that minimum VH-MDX interrogation altitudes generally *increase* when moving *west* from the Sydney Deposition final fix. Such a finding can be used to confidently determine areas where VH-MDX could *not* have faded from radar in accordance with communications transcript timings and altitudes.

5.3.2.3. VH-MDX final track results

Given the results of The Round Mountain RSR propagation analysis in section 5.3.2.2, it was decided to analyse the final track of VH-MDX to achieve more *resolution* and *understanding*. The most likely *final* track VH-MDX was radar observed on was close to 070˚M.

A track of 070˚M *from* the 324˚M/47NM fix and the ASIB/RCC fix was analysed as well as a track of 074˚M from the 324˚M/46NM position. Additionally, analysis was performed along the 187˚M bearing from The Round Mountain RSR in the Gloucester River area. This selection of tracks was used to give a wider geographical spread of results.

The Round Mountain RSR was used in the analysis as this was the radar that most likely was interrogating VH-MDX. Annex N presents the results.

Results indicate a clear radar screen altitude gradient with values in the order of 8000' near the ASIB/RCC fix tapering down to around 6000' east of the Gloucester Tops. Also, screen altitudes reduce by about 500' when moving 9.3km along the *axis from the radar head* in the Gloucester River area.

5.3.2.4. The Round Mountain PSR flight test 1972 comparison

Section 5.2.2 described The Round Mountain PSR coverage flight test of 1972. Observations of Sydney RSR returns during the same flight test were also noted.

It cannot be confirmed if the Sydney RSR primary or secondary system was used for these observations. *Primary* radar will be used for the radio propagation analysis of both The Round Mountain and Sydney RSR's in this section.

From the findings of the flight test described in section 5.2, the following have been selected to compare with radio propagation software results:

- Sydney RSR detecting the F-27 at 20NM north-east of Singleton NDB at FL110[38]
- Sydney RSR losing the F-27 at 22NM north-west of Singleton NDB at FL110[38]
- The Round Mountain PSR having poor returns of the F-27 from 15NM north-east of Singleton NDB at FL110[38]
- The Round Mountain PSR losing the F-27 at 45NM south-south-east of Tamworth at 10000'AMSL[38].

The four examples selected above are *approximate* points where radar coverage increased or decreased *significantly*. These positions and associated altitudes are inputted into the *radio propagation software.* The resultant bore sight paths of the analysis are expected to be very close to touching terrain. The level of displacement of the bore sight paths from terrain (mask angle) suggest the level of disparity between the 1972 test and the radio propagation software results.

Raw software propagation results are included in Annex O whilst summarized results are presented in figure 68 on the next page.

Position on flight test track	Propagation analysis supports flight test results:
20NM north-east of Singleton NDB at FL110	*very strongly*
22NM north-west of Singleton NDB at FL110	*very strongly*
15NM north-east of Singleton NDB at FL110	*moderately*
45NM south-south-east of Tamworth at 10000'AMSL	*moderately*

Figure 68: Results for The Round Mountain flight-test comparison.

Software results for the first two cases showed that the resultant bore sight angles from Sydney PSR were right on the radar *mask angle*. These are examples of results *exactly* matching what was expected: *minimum interrogation altitudes* in the geographical positions analysed.

The last two comparisons were classed as 'moderately' supporting because resultant bore sight angles were somewhat (but not hugely) above the mask angle. Reasons for this may include:

- Aircraft *aspect* to the radar head
- Tangential fade
- Blind velocity
- Accuracy of the reported point (moving analysis point changes result).

But, these two results still correlate to a large extent with the 1972 flight test results. *Overall*, the four results from radio propagation software analysis correlate with the flight test findings of 1972.

5.3.2.5. Conclusions: Radar propagation

- Sydney SSR RSR was *unlikely* able to interrogate VH-MDX in the key positions analysed below 10000'AMSL, indicating Sydney RSR was *unlikely* to have contributed to VH-MDX radar positions
- The Round Mountain SSR RSR was shown *able* to interrogate VH-MDX at all three key positions analysed below 10000'AMSL.
- Specifically The Round Mountain SSR RSR could interrogate VH-MDX at:
    - 7200'AMSL at the initial Sydney radar fix
    - 8200'AMSL at the ASIB/RCC position
    - 8400'AMSL at the 324˚M/47NM position
    - 6000'AMSL at the Sydney deposition final fix
    - 7000'AMSL at 330˚M/45NM from Williamtown
    - Between 6200' to 8300'AMSL along the final track between 325˚M and 335˚M from Williamtown.
- Propagation analysis results correlate with flight test results of 1972.

The radio propagation analysis conducted offers an excellent insight into where and if VH-MDX could be interrogated by radar in addition to identifying that The Round Mountain RSR was likely to be the only Sydney ATC operated radar that interrogated VH-MDX. Despite this, these results are not *completely* conclusive.

6. Analysis of Sydney ATC VH-MDX radar observations

6.1. Initial Sydney radar fix: ≈0928:45UTC

6.1.1. Timing

The time of *initial* Sydney ATC radar identification of 1950EST made in the *deposition* in figure 57 on page 85 does not line up with communications transcripts (≈1928:45EST)[9] and is to be ignored. The four-month gap between the accident and deposition dates is viewed as a major factor leading to the incorrect identification time.

Communications transcripts reveal this position was obtained between 0928:24UTC and 0928:57UTC[9]: an interval of 33 seconds.

The spacing of the above two calls was 31 seconds when timing an available compact cassette *audio recording*. This validates:

- The communications transcript used, and;
- To *some extent* the audio recording in possession.

Timing the compact cassette *audio recording* suggests the 36NM position assessment occurs around 0928:45UTC so this time will be used as initial Sydney radar fix time.

6.1.2. Position

Taking the deposition and radar plot of section 4.3, communications transcripts extracts of section 4.2 and the timing of section 6.1.1 into account, it is clear that VH-MDX was identified by SSR SPI approximately 36NM north and slightly west of the Singleton NDB-Mount Sandon VOR track at around 0928:45UTC.

The *initial* Sydney radar fix was defined as having been located[2]:

- Just north of the Sydney 120NM arc
- Just west of the Singleton NDB – Mount Sandon NDB track (NDB: Non-Directional Beacon)
- Just to the south of the south-eastern side of the 55DME Tamworth Control Area (CTA) step (DME: Distance Measuring Equipment).

These points provide excellent boundaries to contain the paint within a tight, easily defined position. This makes for a read-off ability that was very good for the large scale Northern Mosaic display. Figure 69 on the next page shows this pictorially.

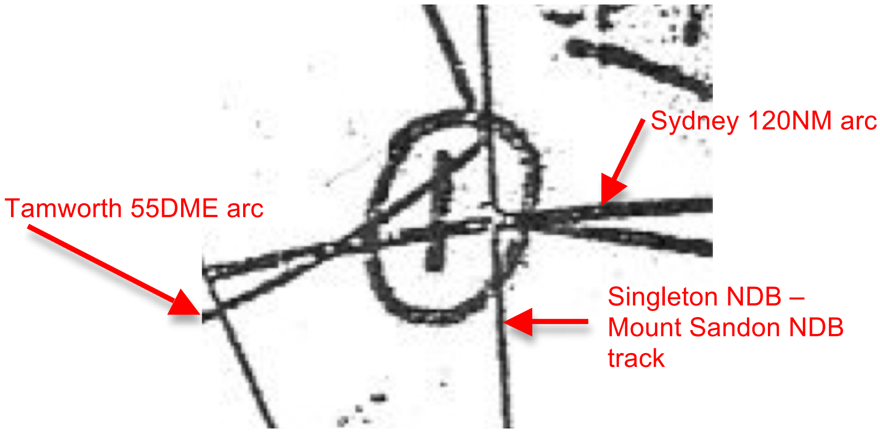


Figure 69: Initial Sydney radar fix. The position was defined by how the paint centre was bracketed by the Tamworth 55DME arc, Sydney 120NM arc and Singleton NDB-Mount Sandon VOR track. This provides a confident definition of this position (Image: Australian Government (Department of Transport) 1981; additions Glenn Strkalj 2014).

This initial fix lies in the Moonan Brook area around 9NM north-west of Mount Barrington and is 37.5NM from Singleton NDB: a difference of 1.5NM from the 36NM reported in *communications transcripts*. This difference in radar terms is inconsequential so, strongly corroborating *ATCO suggestions* with *communication transcripts* regarding the initial radar fix position.

6.1.3. SSR symbol sizes

VH-MDX was initially allocated a mode A code of 4000 by Sector 1[9]. From section 3.10.2 this code was normally allocated to *General Aviation* and *special domestic civil* flights and was likely a *diamond* symbol approximately 6NM-7NM across the *corners* and 5NM along *faces* in size. An SPI triangle encompassing this diamond would also have displayed during initial identification for around 20 seconds. Figure 70 compares the deposition radar plot and to-scale symbol sizes.

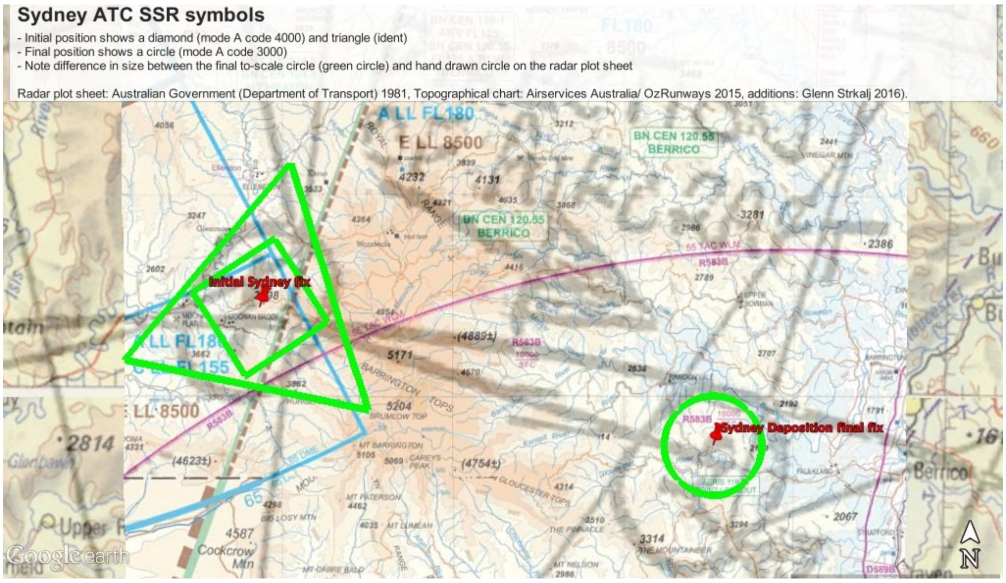


Figure 70: Sydney ATC SSR paints of VH-MDX: Actual and plot sheet sizes. The green triangle, diamond and circle are the shapes and relative sizes of the SSR symbols the Sydney ATCO's would have observed. Note the significant difference in size of paint '2'. (Topographical chart: Airservices Australia 2015/ OzRunways 2015, radar plot: Department of Transport 1981, additions: Glenn Strkalj 2016, plotted on Google Earth).

It can be seen the hand drawn radar plot initial position circle (circle ‘1’) roughly represents the actual diamond symbol size.

6.1.4. Positive identification

As:

- The deposition specified VH-MDX was identified by *SPI ident* at the position in figure 69[10], and;
- Communication transcripts show SPI was requested of VH-MDX and;
- Communications transcripts show Sector 1 ATCO verbalising ‘identified’;

It is highly likely that VH-MDX was positively identified.

Additionally, given that the progress of VH-MDX was generally followed by *multiple* Sydney ATCO’s, the ATCO’s would have seen (but has not been confirmed by the author) VH-MDX track from the initial fix in figure 69 to a position *near* 324˚M-325˚M/47NM from Williamtown where a *second* SPI ident triangle would have appeared around 0936:00UTC. (VH-MDX was instructed to squawk ident again around this time).

Transcripts suggest this second SPI triangle was seen by Williamtown ATC around 0936:00UTC and coupled with the position given by Sydney to Williamtown just prior to this Williamtown ATC identification (near co-incident paints between two separate ATC units), this strongly suggests the aircraft to be VH-MDX and backs to a large extent VH-MDX being at the initial fix shown in figure 69.

6.1.5. Accepted centroid of initial Sydney radar fix

The *position* of the *diamond* symbol in figure 70 was both adjusted to fit within the deposition *drawn* initial paint circle and centred as best as possible within the boxing features discussed in 6.1.2. The following position was determined and will be used to *represent* the accepted *centroid* of the initial Sydney radar fix (WGS84) at 0928:45UTC:

-31.926916°, 151.308142°

31°55'36.90"S, 151°18'29.31"E

56J 340058.00 m E, 6466416.00 m S

6.1.6. Radio propagation analysis

Radio propagation analysis results from section 5.3.2.2 found that the minimum interrogation altitude of VH-MDX by The Round Mountain RSR at the initial Sydney radar fix position specified in the previous sub-section was 7200’AMSL.

VH-MDX *should* have been at 8000’AMSL when first entering cloud around 0923:52UTC then not long after the initial radar identification reported ‘*I’m struggling to get eight-five* (8500’ AMSL)’[9].

This *suggests* VH-MDX was between 8000’AMSL and 8500’AMSL. Accordingly, The Round Mountain RSR was *likely* able to generate the initial Sydney radar fix discussed in the previous sub-section.

6.1.7. Statistical representation of the initial Sydney radar fix

Radar positions are not simple *points*; deviations dilute the position to a broad area. Even if an ATCO reads off a radar position with perfect precision, radar and display errors inherent in the radar system result in inaccuracies of *displayed* paints to some extent. This subsection will determine the likely geographical area that VH-MDX may have been within during the initial Sydney ATC radar fix.

6.1.7.1. Read-off error

Given the strong boxing in effect of the map features (figure 69) and considering the distance between these features whilst also bearing in mind communications transcripts suggesting an accurate position assessment was taken by the ATCO, the following *read-off* tolerance (better than 'standard' from section 3.18.3) is deemed appropriate:

- +/-1NM north-south and;
- +/- 1.5NM east-west.

The respective planes of these tolerances are *coincident* and *normal* to a line from The Round Mountain RSR head to the initial Sydney radar fix centroid.

6.1.7.2. Radar & display system errors

The initial Sydney radar fix is located 101.2NM from The Round Mountain RSR head. This results in the following *radar system* errors:

- Azimuth error (+/-1.5˚): +/- 2.65NM
- Range error (+/-1%): +/- 1.01NM

Display system error was found in section 3.18.2 to be a 1.75NM box.

6.1.7.3. Resultant representation of Initial Sydney radar fix

Statistically combining the errors (deviations) from sections 6.1.7.1 and 6.1.7.2 results in the area shown in figure 71. The method viewed most appropriate was to use the *square root of the sum of squared errors*. VH-MDX's geographical position during initial radar identification by Sydney ATC at 0928:45UTC was likely to be anywhere *within* or *close to* this area.

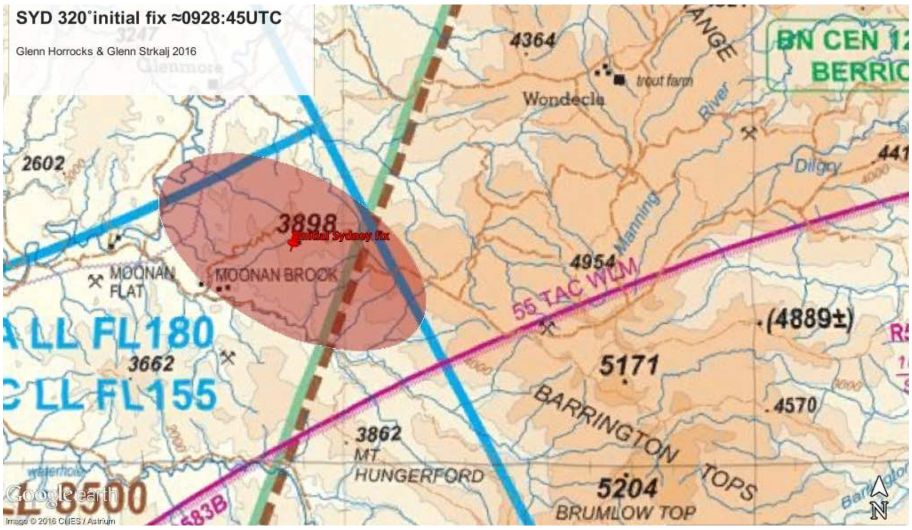


Figure 71: Statistical representation of the initial Sydney radar fix (red ellipsoid) (Base Map: Airservices Australia/ OzRunways 2015, ellipsoid: Glenn Horrocks 2016, plotted on Google Earth).

6.1.8. Conclusion: Initial Sydney radar fix

The *initial* Sydney radar fix is of *high reliability* in terms of geographic location and positive identification of VH-MDX.

6.2. West Maitland present heading: ≈0929:53UTC

At 0929:32UTC the pilot of VH-MDX requests a heading to track to West Maitland. At just before 0929:53UTC the Sydney Sector 1 ATCO advises the FIS-5 FSO that '*to West Maitland remain on his present heading*[9]'.

This response could suggest any of the following:

- VH-MDX was radar observed tracking in a generally south-east direction
- The ATCO required more paints to determine track trend
- The ATCO did not want to give heading instructions initially as it was known that VH-MDX had suffered failure of the primary attitude and directional instruments (prevent loss of control).

As discussed in section 3.16, a little after 0928:30UTC, FIS-5 asks Sector 1 for a present heading of VH-MDX to which Sector 1 responds: '*Oh*… its *a bit hard to tell*' and: '*I'll let you know in about two or three*'[9].

This can hint at difficultly in determining VH-MDX's track approximately 1 minute prior to the first West Maitland vector request. This was expected as the vector request was probably only seconds after the first paint(s) of VH-MDX appeared on the Bright display.

It is expected that VH-MDX would have turned somewhere towards the south after the initial radar fix was given (to head towards intended plan and/or destination (Bankstown)). Given the relatively short time frame (about 1 minute) of the vector request after the initial radar fix, it would be reasonable to assume VH-MDX was likely changing track (turning) leading up to the request for a West Maitland vector.

The combination of minimal VH-MDX paints, slow sweeping RSR, large-scale display, possible weather clutter and a turn being carried out result in potential difficulties for the ATCO to determine radar track.

Additionally, VH-MDX was likely at climb speed and experiencing a significant headwind component with the result being a *slow* ground speed. Such a slow groundspeed on the large-scale mosaic display would result in closely clustered aircraft paints making track determination more challenging.

But VH-MDX may have indeed been heading south-east or the ATCO could simply have been cautious in overloading the pilot.

It cannot be concluded that VH-MDX was tracking to West Maitland at this stage however considering the radar limitations and intentions of VH-MDX to turn south, it is probable VH-MDX commenced a turn towards or was already established, on a *generally* southbound track.

6.3. Turning southbound: 0931:16UTC

Just after 0931:16UTC, the Sydney Sector 1 ATCO states to FIS-5: '*Mike Delta X-ray looks like he's turned southbound just ask him his present heading and stay on the line please*'[9].

This observation ties in *generally* well in order for VH-MDX to achieve the later 0936:00UTC Williamtown radar fix: i.e. VH-MDX had to turn south-east from its probable south-westerly course (possibly around 245˚M if tracking the Scone NDB) at the initial radar fix described in section 6.1. It must be remembered 'southbound' may indicate any course in the southern cardinal *hemisphere*.

The pilot of VH-MDX does report his heading to Sydney ATS at 0931:28UTC: '*Mike Delta X-ray is averaging somewhere around 220*', alluding to a south-west heading that given the ARFOR winds would result in a *track* of around 200°M: very roughly southbound.

Given the reported moderate to severe turbulence, the direct reading compass would have been bouncing around and very difficult to read. As a vacuum system failure was reported, the pilot of VH-MDX had no gyro stabilised heading reference to offer a more accurate heading.

Given the prevailing conditions, it is difficult to accept 220˚M as the *actual* heading VH-MDX was on at this stage. Despite this, the average 220˚M heading advice given by the pilot offers some evidence that VH-MDX was tracking *generally* southbound by this stage.

6.4. Heading 150° to West Maitland: 0931:47UTC

At around 0931:47UTC (determined by timing available audio and comparing with communications transcript references) the Sydney Sector 1 ATCO advises FIS-5 that a heading of 150°M is applicable to steer VH-MDX towards West Maitland. This suggests a position of VH-MDX from West Maitland navaids on the reciprocal bearing, 330°M.

This suggestion was also made in *Operation Wittenoom VH-MDX Research*[17]. Further information is required of this heading to coarsely determine the aircraft's position namely:

- If the heading was corrected for wind, and;
- If the heading was a pluck.

Discussions with various ATCO's of the era reveal a trend of *not* adjusting heading for wind that currently is normal practice[19].

Additionally, given the situation the heading was likely a rough pluck to get VH-MDX tracking roughly towards West Maitland with refinement being done later. This is normal procedure applied by ATCO's now and in the past.

Section 3.16 found Department of Transport procedures specified up to 10˚ of accuracy was acceptable in the *initial* stages of radar vectoring at *medium ranges*. VH-MDX at the Sydney initial radar fix was approximately 335˚M from West Maitland so, was within this +/-10˚ radar vector tolerance.

As VH-MDX *initially* tracked generally south to south-south-westerly from this position, with time VH-MDX would have only tracked *closer* to the 330˚M from West Maitland. This can be seen in figure 72 below.

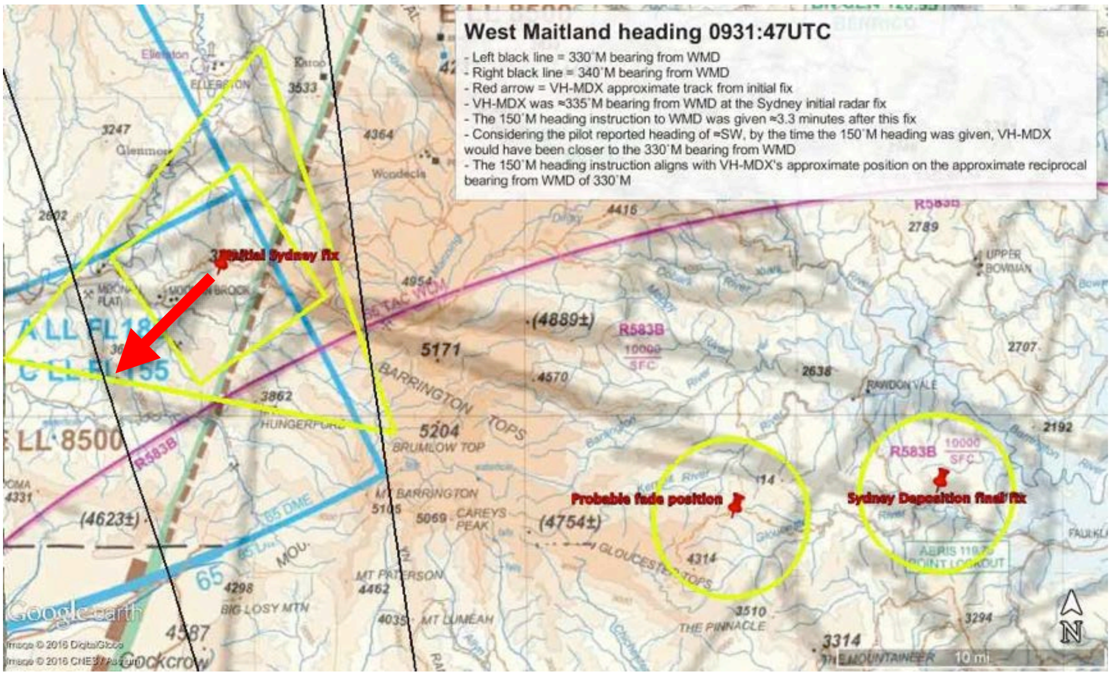


Figure 72: West Maitland (WMD) heading instruction 0931:47UTC. VH-MDX was shown to be located within expected deviations of the 330˚M WMD bearing (reciprocal to 150˚M heading to WMD) at the time of the 150˚M heading instruction to WMD at 0931:47UTC. Black lines indicate the 330˚M and 340˚M bearings from WMD, red arrow is initial VH-MDX pilot reported *average heading* (Topographical chart: Airservices Australia 2015/ OzRunways 2015, additions: Glenn Strkalj 2016).

Accordingly, it is concluded the 150˚M heading advice at 0931:47UTC suggests VH-MDX was at least on a bearing within +/- 10° of the actual 150°M bearing *to* (330˚M from) West Maitland navaids but, more likely between 330˚M to 335˚M from West Maitland given the initial radar fix *location* and *initial* tracking direction after the initial Sydney fix.

6.5. ≈320°M/46NM from WLM fix: 0934:00UTC to 0934:40UTC

6.5.1. Position briefing to Williamtown

Just after 0934:00UTC, the Sydney Sector 1 ATCO asked the Williamtown ATCO: '*Roger bearing 320 Willy at 45NM Mike Delta X-ray squawking code 4000, you got anything there?*'[9]. The Williamtown ATCO states that he does not observe any SSR paints (in vicinity of the specified position) but does observe a '…*primary paint about 45 miles*'[9].

The Williamtown ATCO has clarified with the author that this was not referring to a PSR paint likely of an aircraft but was referring to the Permanent Echoes (PE's) of the Barrington Tops in vicinity of the 320˚M/45NM position[3].

Accordingly, Williamtown had *not* yet *identified* VH-MDX on radar.

Just after 0934:30UTC, possibly around 0934:40UTC considering position assessment and transcript position, Sydney Sector 1 determines a *refined* range of VH-MDX from Williamtown being 46NM however the Williamtown ATCO still does not *identify* SSR returns[9].

The lack of detection has been found to be the result of one of the following[16]:

- VH-MDX being just *outside* the ≈49NM-50NM visible area of the 48NM maximum range scale set on the Williamtown radar display, and/or;
- Clutter from the Barrington ranges and associated weather 'washing out' *portions* of the SSR symbol 'hanging into' the display from outside 49-50NM or;
- Clutter from the Barrington ranges and associated weather 'washing out' *the entire* SSR symbol if wholly inside the display (noting that the larger SPI triangle was not displayed during the period discussed).

6.5.2. Read-off deviations: 320˚M/46NM fix

Section 3.12 described how a 2NM read-off resolution could be achieved when referencing the returns from map features *within about 10NM of the return and* 5NM otherwise. Figure 73 shows that VH-MDX was over 20NM from the nearest Williamtown range ring (25NM) presented on the Northern Mosaic display when this fix was taken.

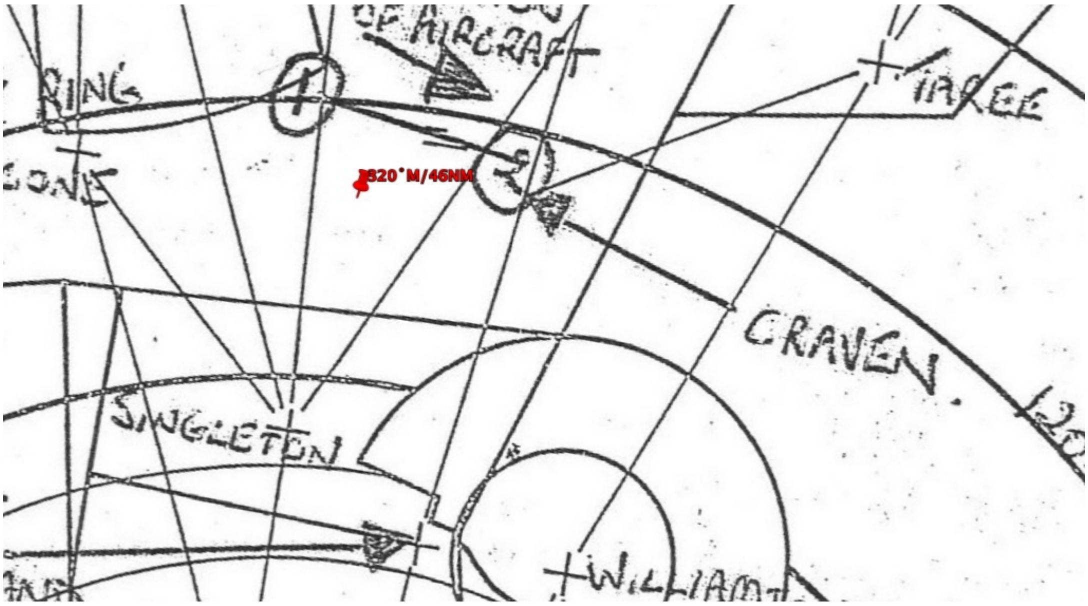


Figure 73: Reference points for the 320˚M/46NM fix. There were no Williamtown range rings in the vicinity (within 10NM) of the fix whilst the bearing would have to be 'paralleled' to the origin or other known map track. Williamtown 12NM and 25NM rings could be extrapolated. Time pressure could have also diluted precision although transcripts reveal the ATCO taking an exacting process of position determination (Image: Australian Government (Department of Transport) 1981; additions Glenn Strkalj 2016).

Although there were no range rings from Williamtown in the *immediate* vicinity of the paints, the ATCO could extrapolate using the 12NM and 25NM Williamtown range rings.

Determining an accurate range could have involved doubling the Williamtown 25NM ring and then working back using either the ATCO's good judgment of 5NM distances (from section 3.12) or using the known size of the diamond symbol VH-MDX would have displayed at this time to judge proportionally.

The latter would have been a ready reference as the SSR symbol orientation would have been such that two of the 5NM faces were roughly aligned in the same axis as the bearing line to Williamtown.

Figure 74 shows the diamond symbol at the 320˚M/46NM position in the orientation that would have been apparent.

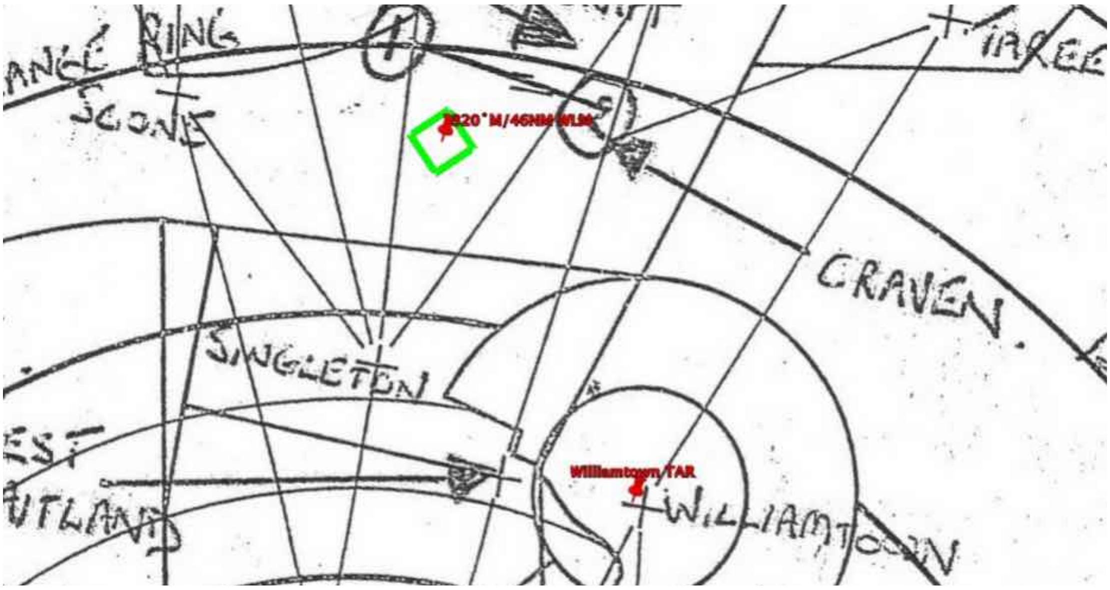


Figure 74: Diamond SSR symbol orientation at the 320˚M/46NM fix. Two of the 5NM faces would have been roughly aligned with the bearing axis from Williamtown. This would have provided a reasonable 5NM reference length that the ATCO could use working back from the extrapolated 50NM from Williamtown position (2x 25NM WIlliamtown rings). Half the SSR diamond symbol face (2.5NM) could also be used. (Image: Australian Government (Department of Transport) 1981, additions Glenn Strkalj 2016, plotted on Google Earth).

So, the 25NM Williamtown range ring could be doubled, a corner of the diamond symbol would be close to the 50NM point, and then the ATCO could slide back along the diamond face to estimate the distance.

Bearing read-off deviation was found in section 3.13 to normally be +/-5˚ and at worst +/-10˚. To obtain an accurate *bearing* the position would have to be 'paralleled' to a known track or to the *origin* and compass *rose*. The *bearing* assessment for this fix occurred just after 0934:00UTC and was not updated when the *revised range* assessment occurred around 0934:30UTC to 0934:40UTC.

It must be remembered that this position was *dynamic*: the aircraft was moving along the radar display every 12 seconds. This coupled with high workload and likely weather clutter would result in obtaining the fix under some pressure.

As stated in sections 3.12 and 3.13, ATCO's became good at eyeballing bearings and range but the 320˚M/46NM fix can be seen to present a challenging fix.

Notwithstanding the clutter and dynamic nature of the fix, transcripts show the ATCO appears to have taken an exacting process for this fix whilst the methods available to the ATCO also suggest a reasonably accurate fix was possible.

It is accepted that an exacting approach was taken for the 320˚M/46NM fix although it must be remembered that the *bearing* and *range* assessments were taken around 30 to 40 seconds apart. Depending on VH-MDX's ground speed at the time the aircraft could have travelled around 1NM in this period that could result in about *one degree* of displacement. Read-off tolerances of +/-5˚ and +/-2NM apply to the 320˚M/46NM position although a liberal approach must be taken for this read-off tolerance because of the bearing/range time split.

Deviations will be applied to the *pure* 320˚M/46NM location rather than to the split location for simplification. Future iterations of deviation application may account for the split.

6.5.3. Radar and display system deviations: 320˚M/46NM fix

Applying RSR *system* errors specified in section 3.18.5 to this position that is 109.6NM from The Round Mountain RSR head, the following values of deviation are found:

Azimuth (bearing) error: (+/-1.5˚) = +/-2.87NM
Range error: (+/-1%) = +/-1.10NM
Display system accuracy: 1.75NM square

6.5.4. Accepted centroid of the Sydney 320˚M/46NM fix

The 320˚M/46NM from Williamtown position was plotted on Google Earth using predicted 1981 magnetic variation as described in section 3.3.2.

The accepted centroid for the Sydney 320˚M/46NM fix is:
-32.121828°, 151.403105°

32° 7'18.58"S, 151°24'11.18"E

56H 349356.00 m E, 6444944.00 m S

6.5.5. Electronic gating line

Section 3.11.4 concluded that:

- The Round Mountain RSR *primary and secondary* paints were suppressed from display *south* of the electronic gating line
- Sydney RSR *secondary* paints were suppressed *north* of the gating line
- Sydney RSR *primary* paints were un-gated.

Section 5.3.2.1 found that Sydney RSR was *highly unlikely* to have contributed to any VH-MDX radar fixes given blocking terrain and Earth curvature.

This suggests the Sydney ATC fix between 0934:00UTC and 0934:40UTC was likely in a geographical position *above* the electronic gating line (so that returns from The Round Mountain RSR could be displayed).

Figure 75 shows the position of the electronic gating line and both the 320˚M/45NM and 320˚M/46NM positions.

Figure 75: Electronic gating line and Sydney ATC 0934:00UTC - 0934:40UTC fix. The 320˚M/46NM position is just above the gating line whilst the 320˚M/45 position is well below and would likely have been gated from display (Image: Department of Transport) 1981, additions: Glenn Strkalj 2014).

Obvious from figure 75 is that the Sydney Sector 1 ATCO's preliminary fix of 320˚M/45NM from Williamtown was unlikely to be precise given that this position was just *below* the gating line (by about 1.2km/0.66NM) meaning the paints were unlikely to have been displayed.

The 320˚M/46NM from Williamtown refined position is just *above* the gating line so was likely to be displayed. In fact, it is believed that VH-MDX was further north of the *pure* 320˚M/46NM location as the secondary paints were not detected on the Williamtown radar display.

The electronic gating line is useful in:

- Refining the 0934:00UTC-0934:40UTC position by supporting the 320˚M/46NM from Williamtown *refined* position
- Offering solid evidence that VH-MDX was unlikely at 320˚M/45NM from Williamtown or further south at *any time*.

The gating line also supports the finding[16] that VH-MDX was likely to be around 324˚M-325˚M/47NM from Williamtown at 0936:00UTC rather than the commonly accepted 320˚M/45NM.

6.5.6. Statistical representation of the Sydney 320˚M/46NM fix

Statistically combining (square root of the sum of squares) the read-off deviations of section 6.5.2 with system deviations of section 6.5.3, centered on the centroid position found in section 6.5.4 followed by clipping of any area south of the electronic gating line results in the area shown in figure 76 on the following page.

VH-MDX's *actual* geographical position from 0934:00TC to 0934:40UTC may have been anywhere within or closely outside this area. Read-*off* deviations form the bulk of the position dilution.

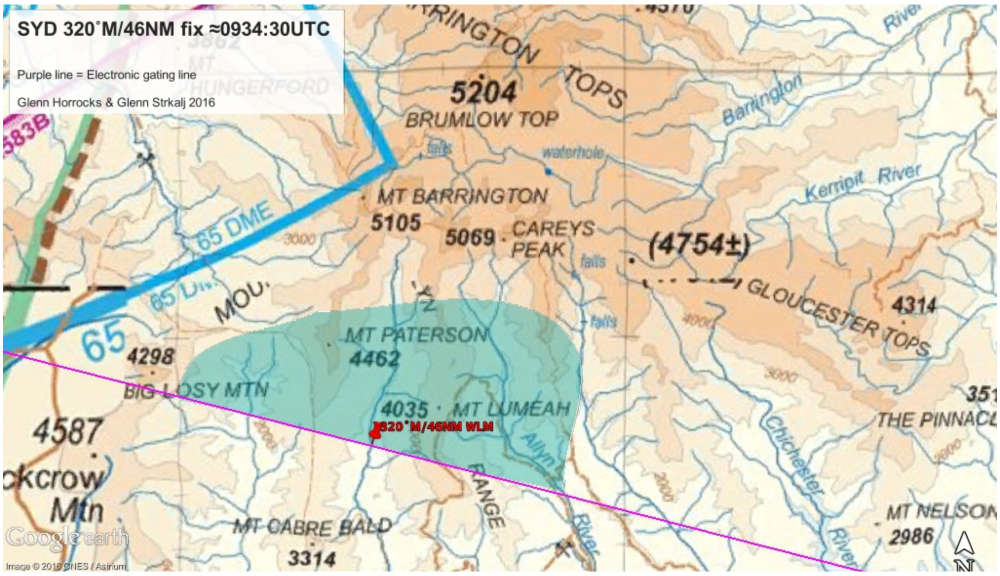


Figure 76: 320˚M/46NM position. Probable maximum positional variation of this radar fix is represented by the aqua blob. VH-MDX was likely located somewhere in or close to, this blob from 0934:00UTC to 0934:40UTC. The area is reduced by the electronic gating line (purple line) that suppressed The Round Mountain RSR paints south of this line (Base map: Airservices Australia/OzRunways 2016, plots: Glenn Horrocks & Glenn Strkalj 2016).

Applying tracks from the *initial* Sydney radar fix to 0934:00UTC to 0934:40UTC using known winds and predicted speed profiles suggests VH-MDX was located in the northern sections of the statistical area in figure 76 during these times. This suggests the actual position of the fix was a bearing somewhat more than 320˚M and a range more than 46NM.

Section 6.6 will discuss how Sydney Sector 1 called a radar observed track of VH-MDX of about 120˚M at 0934:20UTC. It must be emphasised that this track was historical: i.e. a number of paints would have been observed and an average track taken. This track can be used to suggest how VH-MDX tracked into the area shown in figure 76 and then on to the 0936:00UTC Williamtown fix (324˚M-325˚M/47NM).

If VH-MDX actually tracked to the 324˚M-325˚M/47NM position, dead reckoned tracks suggest that between 0934:00UTC and 0934:40UTC VH-MDX was:

- Likely *around* 48NM from Williamtown *if* VH-MDX was established on a 070˚M track by 0934:30UTC
- Likely between 48NM and around 50NM from Williamtown *if* on a track of ≈120˚M at 0934:20UTC followed by a turn to towards 070˚M dependent on turn rate.

The *statistical representation* of the 0934:00UTC-0934:40UTC fix supports the first option above more than the second. Despite this, if the statistical area was better synthesised to reflect the split bearing/range nature of the fix, such a statistical area may support the second option.

Referring to the *read-off tolerances* of section 6.5.2, these suggest the first option as more likely although read-off tolerances for this fix were shown to be subjective.

It can be seen three ‘methods’ suggest VH-MDX was likely around 48NM from Williamtown at some time between 0934:00UTC and 0934:40UTC.

It must be emphasised if a track more *northerly* than 070˚M was apparent at 0934:30UTC then VH-MDX would highly likely be inside 48NM from Williamtown. This is not viewed likely given VH-MDX’s progress along a gradual turn to the east then around 120˚M just before 0934:20UTC.

The overview conducted in this sub-section suggests that between 0934:00UTC and 0934:40UTC VH-MDX was likely to be located:

- Around 48NM to 50NM from Williamtown but most probably around 48NM and;
- A little more than the 320˚M bearing from Williamtown (somewhere around the 321˚M to 324˚M bearings).

The next sub-section will discuss why the paints were not detected by the Williamtown ATCO if they were hanging inside the display at 0934:30UTC.

6.5.7. VH-MDX not observed by Williamtown

The Williamtown ATCO attempted to locate VH-MDX on the Williamtown radar display at various times between around 0934:00UTC and 0935:20UTC to no avail.

The previous sub-section found that VH-MDX was likely located between 48NM and 50NM but most probably 48NM from Williamtown between 0934:00UTC to 0934:40UTC.

This would result in VH-MDX’s radar paints having been either *partially* inside or outside the Williamtown maximum set radar display range of 48NM-50NM. This would result in the SSR symbol either being clipped by the outer edge of the radar display or hanging into the edge of the display from around 0934:00UTC to 0934:40UTC.

It is viewed likely that parts of or the entire hard to distinguish inverted ‘Y’ SSR symbol (likely associated with Mode A code 4000)[16] was ‘washed out’ by the significant terrain and weather clutter of the Barrington Tops.

Note that the SPI triangle was not displayed at this time (SPI was selected closer to 0936:00UTC by the pilot) and without this triangle, discerning the inverted ‘Y’ symbol in significant terrain and weather clutter would have been challenging.

There was also a change of mode A code from 4000 to 3000[9] just before the Williamtown radar fix at 0936:00UTC. It has been found likely that the SSR symbol associated with Mode A code 3000 was a 1NM radius circle on the Williamtown radar display[16]. To some extent the circle would have been easier to detect than the inverted ‘Y’ although detection would still be challenging in clutter.

Contrary to one suggestion[17] regardless of the mode A SSR code VH-MDX was squawking, the Sydney RSR, The Round Mountain RSR and Williamtown TAR could interrogate and display *any received* transponder code almost simultaneously (contingent on the exact interrogation times)[16]. At around

8000’AMSL, VH-MDX was within line of sight of the Williamtown TAR around 0934:30UTC[16].

Accordingly, VH-MDX would have presented an SSR symbol (or part thereof) on the Williamtown radar display if the aircraft were within 48NM-50NM of Williamtown (Williamtown radar display *selected* maximum range); it was just the symbol *shape* that varied.

Note also that the Williamtown ATCO had to side step from his procedural workstation to view the radar display and that he likely viewed the display from a *longer* rather than shorter distance. The ergonomics of the 1970’s Williamtown ATC tower set-up would have made symbol detection more challenging.

It can be seen there are a number of factors working against VH-MDX being detected on Williamtown ATC radar.

Figure 77 shows the limited ‘stand out’ geometry of the inverted ‘Y’ symbol in the clutter on the Williamtown radar display.

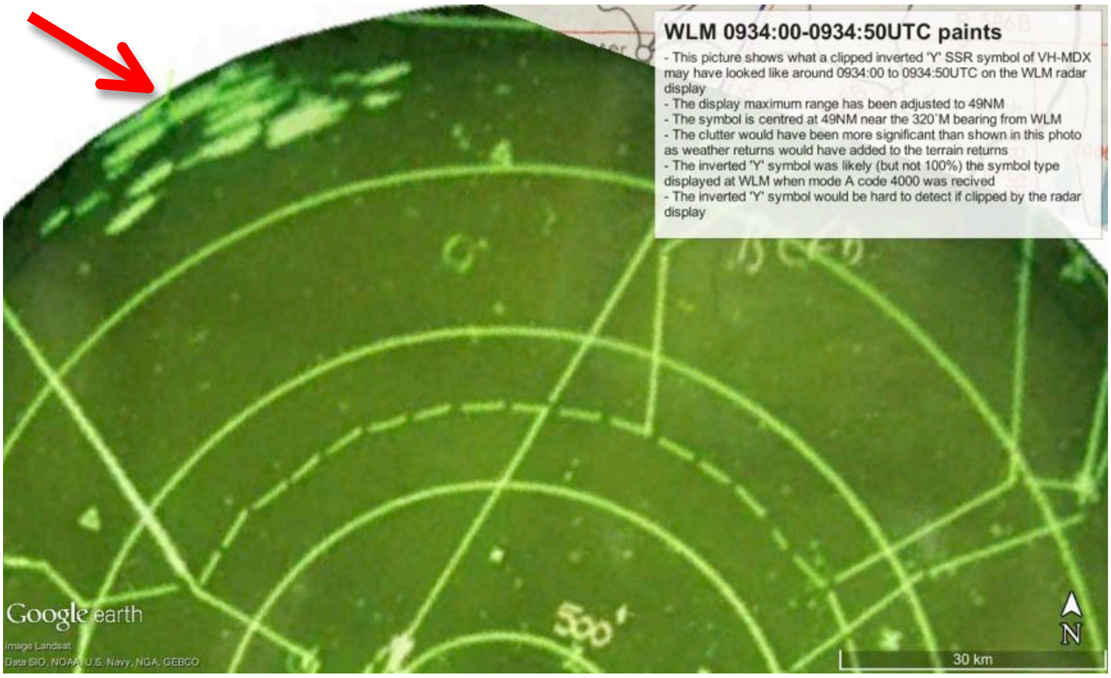


Figure 77: Inverted ‘Y’ symbol on Williamtown display. In this image the symbol was placed at 320˚M/49NM with maximum display range adjusted to 49NM. This particular symbol shape hanging into the display is difficult to detect in the Barrington terrain clutter. Weather clutter would also have been apparent (Photo: H. Howard c.1983, additions: Glenn Strkalj 2016).

This section has shown that VH-MDX was either just inside or outside the Williamtown radar display between 0934:00UTC to 0934:40UTC. If just *outside*, it is quite possible a portion of the SSR symbol may have been hanging *inside* the display. If just inside the SSR symbol would be clipped. Discerning part of or even the complete inverted ‘Y’ SSR symbol amongst significant weather and terrain clutter would have been very challenging.

6.5.8. 'Heading right towards you now'

After the 46NM refined range call, Sydney Sector 1 advises to Williamtown ATC at around 0934:50UTC: '…….*heading right towards you now*'. This could suggest either:

- Latest radar observed track or;
- General overview of VH-MDX tracking from the initial Sydney radar fix.

The latter is viewed more likely as the ATCO is attempting to perform a position and situation handover to Williamtown and as figure 78 shows, the *overall* progress of VH-MDX had been towards Williamtown.

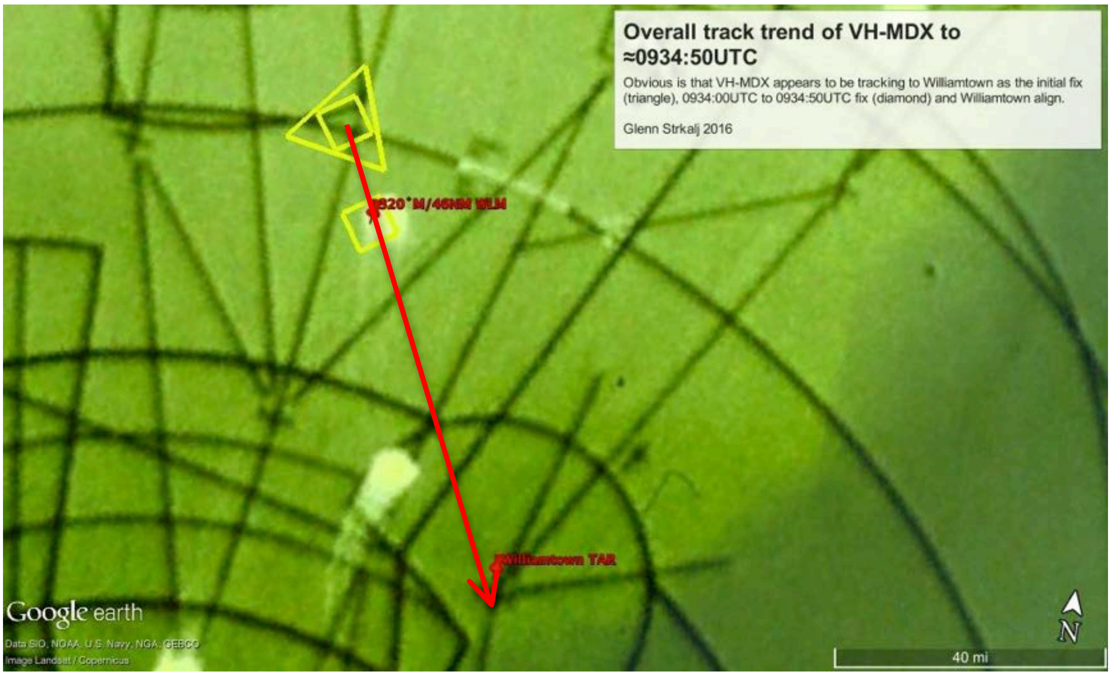


Figure 78: Overall track trend of VH-MDX up to 0934:30-0934:50UTC (red arrow). The *overall* progress up until this time was clearly towards Williamtown. (Image: Plotted on Google Earth, additions Glenn Strkalj 2016).

With either option the track is *historical*: i.e. it has already occurred and may not be indicative of where the aircraft is tracking presently.

It must also be remembered that the large scale of the Sydney Northern Mosaic display coupled with weather clutter from the Barrington Ranges, would have made accurate track determination of a relatively slow moving aircraft such as VH-MDX challenging.

6.6. Turned easterly: ≈0934:20UTC

During the process of passing VH-MDX's position to Williamtown, the Sydney Sector 1 ATCO advises just after 0934:20UTC: '*He's just turned onto an easterly heading looks like about 120*'[1]. The immediacy of the 120˚ turn as recorded in the communications transcripts can insinuate a turn was 'just made' to a 120˚M track at a fast rate.

But, considering the situation at a big picture level, one can see how VH-MDX may have been radar observed at a *certain instant* of a *continuous* turn towards the east. I.e., VH-MDX may have been observed for the last number of radar paints to be turning to a track of 120˚M and this may have simply been *one portion* of a slow turn to the east.

What must also be considered is that a number of paints would be required to develop a tracking trend. With the slow sweeping RSR, two paints would take 12 seconds and three paints 24 seconds. Consequently, VH-MDX may have been on an approximate 120˚M track around half a minute prior to the Sector 1 ATCO verbalizing the radar track.

Additionally, just after 0934:20UTC, the pilot of VH-MDX informs FIS-5: '*……..I can just make out a few towns on the coast'*[1]*.* This does suggest the pilot may have made the decision to track *eastwards* towards the coast away from the danger of the mountains.

A 120˚M track from VH-MDX's approximate position at 0934:20UTC would take the aircraft roughly to Nelson Bay however, as will be explained it appears VH-MDX kept turning east to east-north-east. Indeed, two of the *final* Sydney ATC radar positions lie east of the 0936:00UTC Williamtown radar position.

To have turned from approximately south at around 0932:00UTC to a track of 120˚M at around 0934:20UTC suggests a slow turn rate: 60˚ in 2 minutes 20 seconds = 0.4˚/sec which is a relatively slow turn rate).

It is reasonably clear when comparing all information that VH-MDX was heading generally easterly just after 0934:20UTC and that the '*about'* 120˚M radar observed track fits in well with the expected aircraft tracking.

6.7. VH-MDX identified by Williamtown 0936:00UTC

It was found that VH-MDX was positively identified on Williamtown TAR around 0936:00UTC most probably at 324˚M-325˚M/47NM (based on two position definitions) from Williamtown with the following observations[16]:

- SSR mode A 3000 SSR symbol (likely to be a circle)
- SSR Ident (SPI) triangle;

superimposed on each other with the centroid of the symbols easily determined. All SSR symbols were reportedly *unclipped* (not extending beyond approximately 48NM-50NM Williamtown) and not hanging below the 44NM clutter (MTI) boundary. This suggests the symbols were centred between approximately 46NM to 47NM from Williamtown.

This finding of the author (324˚M-325˚M and 47NM from Williamtown) is viewed as fitting the *transcribed* position given by the Williamtown ATCO of '*…just about*' 320˚M/45NM from Williamtown at 0936:00UTC considering workload and likely read-off errors[16].

The ASIB/RCC determined position just south of Mount William at approximately 325˚M/47NM is shown in figure 79 below. The author suggests this to be the 0936:00UTC Williamtown *intermediate* fix rather than a radar *fade* position as described by the Department of Transport. This position is one of the two that are accepted as valid definitions of the 0936:00UTC Williamtown fix.

As discussed in section 6.5.6, the distances from the 320˚M/46NM fix statistical area at 0934:00UTC to 0934:40UTC to the 324˚M-325˚M/47NM fix at 0936:00UTC could be flown at probable speeds of VH-MDX. This to some extent supports validity of the 324˚M-325˚M/47NM fix position.

Figure 79: Mt William position (ASIB/RCC fix). This radar position was determined post accident on 18 Aug 81 by radar vectoring a helicopter to where the Williamtown ATCO observed VH-MDX. It is viewed by the author that this fix is the Williamtown 0936:00UTC fix rather than a radar *fade* position as suggested by the DoT (Image: National Archives of Australia (Department of Transport 1981))[46].

6.8. Heading of 150 all over the place: 0936:50UTC

At 0936:50UTC Sector 1 responds to Williamtown who asked if VH-MDX is heading for '…..*here is he*' with: '*Well he's on a heading of 150 mate he's all over the place*'[9].

This radar observed track does not fit in with the concept of a slow turn to the east as the previous observed radar track approximately 2.5 minutes prior was 120˚ (opposite direction to that expected).

No hard conclusions can be made but valid options include:

- VH-MDX poor heading control, temporary errors
- VH-MDX loss of control
- Radar system limitations making track assessment difficult (slow sweeping RSR, relatively large paints for speed, minimal track history through persistence, paints 'jumping' with each sweep, scale excessively large, position near the gating line etc.)
- ATCO's attempting to observe track trends in weather clutter
- Sector 1 ATCO was simply repeating the 150˚M *heading* that VH-MDX was *advised* to fly at around 0931UTC to track to West Maitland.

The last option is viewed as the most probable.

At around 0934:20UTC, Sector 1 states: '*He's just turned onto an easterly heading looks like about 120*'[9]. It is clear that this call relates to a *radar observed* track and track trend. A *final* radar track of 060˚M to 070˚M was also observed at Sydney[47]. For VH-MDX to have been tracking 150˚M between these two observations is unlikely given that communications transcripts suggest substantial control of the aircraft appeared to be maintained in this period.

The pilot of VH-MDX may indeed have been attempting to hold a *heading* close to 150˚M but with prevailing westerly winds could have resulted in *tracking* around 120˚M at around 0934:20UTC. But as will be discussed VH-MDX was radar observed continuing a turn towards the east to a final track of around 060˚M to 070˚M.

It can be seen that VH-MDX was radar observed to have made a gradual turn to the east through at least 120˚M by 0934:20UTC despite previously having been *advised* a 150˚M heading from Sector 1 via FIS-5 to track to West Maitland.

A statement of '*he's all over the place*' can be seen appropriate in this circumstance as the Sector 1 ATCO was *expecting* a radar observed track of around 150˚M (modified by wind) yet VH-MDX was tracking more easterly.

The context of the Sector 1 call at 0936:50UTC is accepted as a *general brief* to the Williamtown ATCO rather than a *specific* exchange of information: i.e. '*heading of 150*' relates to the *heading* previously *advised* to VH-MDX to track rather than the radar *observed* track of the aircraft.

6.9. We've lost him: 0939:00UTC

6.9.1. Overview

Around 0939:00UTC Sector 1 states to Williamtown: '*You got a present heading, we've lost him- to track him towards yours*'[9]. Williamtown advises '*…about 150 would be good*'[9].

This signifies Sydney Sector 1 had lost radar contact with VH-MDX. The final received transmission *from* VH-MDX was approximately one half of a minute after this report of radar fade (0939:26UTC)[9].

6.9.2. Reported time of Sydney ATC radar fade

The *deposition* by a Sydney ATCO does *not* include a time for the final observed Sydney radar position but a fade time of 0939UTC was written down for the '*approx 330WLM45' position*' of section 4.4.1.

Accident Investigation Summary Reports suggest communications and radar contact were lost with VH-MDX *simultaneously*: 0939:30UTC in one report and 0939UTC in the other[9].

The *communications transcript* time of 0939:00UTC is viewed as the most accurate time of reporting VH-MDX *radar fade* at Sydney ATC. This is because communications transcripts are a *base* source of information whilst reports are an interpretation of base information.

6.9.3. Actual time of Sydney ATC radar fade

For the ATCO to report radar fade, the fade must have occurred *before* or *at* the time the ATCO reported the fade at 0939:00UTC. The Sector 1 ATCO would have to observe a *number* of sweeps without VH-MDX paints to conclude the aircraft has indeed faded.

Input from experienced Bright display ATCO's suggest *one* to *two* missed paints with most suggesting two were required in the VH-MDX case before declaring that the aircraft had faded[1][22][23][26][27].

Other considerations include:

- VH-MDX being in an area of poor radar coverage and likely not 'painting' during each sweep (this was confirmed by one ATCO)
- Sector 1 ATCOs hearing (via intercom from FIS-5) the pilot-reported reducing altitude of VH-MDX (anticipation of radar fade).

If considering a *single* sweep before declaring radar fade, then the actual fade time would be closer to 0939:00UTC.

If considering the RSR sweep rate of 12 seconds found in section 3.7.1 with two sweeps before declaring fade, it can be seen the actual time of radar fade could be from *around* 0938:48UTC (two sweeps) to 0939:00UTC (one sweep).

If allowing for half a sweep (6 seconds) of recognition and reaction time, VH-MDX would have faded from 0938:42UTC (2.5 sweeps). If considering 3 sweeps to allow for recognition time and hearing the '..*loosing a hell of a lot* <of altitude>' call (fade anticipation rather than accepting intermittent paints), fade would have occurred at 0938:36UTC.

Despite these suggestions, radar fade from Sydney ATC may have occurred *well before*. The period between 0936:00UTC and 0939:26UTC was rather busy for both Sector 1 and Williamtown ATC with transcripts showing significant intercom use.

Radar fade may have occurred as far back as 0936:00UTC and the ATCO's may not have declared fade as they could hear VH-MDX transmissions over the intercom and were aware that although in trouble, the aircraft was substantially in control.

Indeed at 0935:10UTC a Sydney Sector 1 ATCO informed Williamtown ATC that '*he's just about in an area of suspect radar coverage and I'd like…………….if you could pick him up and keep track on him*'[9].

Without further information, radar fade at Sydney ATC is accepted to likely have occurred between 0938:36UTC and 0939:00UTC with a time just before or at 0938:48UTC viewed as most probable because:

- Most ATCO's suggested two missed sweeps to declaration of fade
- The Sydney ATCO's knew VH-MDX was descending rapidly by this stage (monitoring situation carefully).

6.9.4. Position at fade

This will be discussed in a later section dedicated to analysing the radar fade location from Sydney ATC.

6.9.5. Pop-up

Despite the reported radar fade at around 0939:00UTC, VH-MDX may have 'popped up' at a later time to re-present on radar.

This may have occurred due to the aircraft moving beyond a radar terrain obstruction or a change in altitude (climb).

Considering pilot altitude calls show VH-MDX was descending rapidly with significant ice accumulation, it seems unlikely that VH-MDX regained any lost altitude. Also, the rapid altitude loss likely negated any chance of terrain opening up a propagation path as radio propagation analysis has shown no further *significant* 'dips' in minimum interrogation altitudes in the area east of Gloucester Tops and west of Maudville.

Accordingly it is viewed that although completely possible, VH-MDX was *unlikely* to re-appear on the Sydney operated radar after fading at around 0939:00UTC.

6.9.6. Conclusion

VH-MDX faded from the Sydney ATC Northern Mosaic display:

- Likely between 0938:36UTC to 0939:00UTC
- Most probably just before or at 0938:48UTC
- And was *unlikely* to have re-appeared on Sydney ATC radar after these times.

There is still a possibility that VH-MDX faded from Sydney ATC operated radars much earlier.

6.10. Final radar observed track

6.10.1. Observations

Two different sources suggest the *final* observed radar track at Sydney ATC was between 060˚M-070˚M. The Williamtown ATCO did *not* observe a final radar track as he was busy with a significant procedural control and communications workload[16]. Despite this, the ATCO did state (in the 2014-2015 period) that he *felt* VH-MDX was tracking *easterly* but that he could not determine exactly why he felt this[16].

This observation would have been apparent at the *only* time the Williamtown ATCO has confirmed observing VH-MDX paints: at 0936:00UTC, being around two minutes prior to transcribed radar fade at Sydney ATC.

6.10.2. Determining the final radar track

To make an assessment of the accuracy of the final radar observed track, the methodologies available to the ATCO need to be known. A number of options existed and will briefly be discussed.

The Craven to Taree track was labeled as 059˚M in July 1981[49], which is effectively 060˚M. This track was located close to where VH-MDX was last observed on radar and could have been used by the Sydney Sector 1 ATCO's as a reference to determine VH-MDX's final radar observed track. Figure 80 shows this track on the Sydney Northern Mosaic display.

Figure 80: 060˚M track reference: Aqua line is the 070˚M track from ASIB/RCC fix. The Sector 1 ATCO had a 060˚M track reference in proximity to VH-MDX radar paints. This could be used to obtain a reasonably accurate assessment of final track (Plots: Glenn Strkalj 2016, plotted on Google Earth).

A straight edge such as a pen or ruler could be placed over the VH-MDX paints then paralleled to the Craven-Taree track. Visual proportions could then be used to dissect the track: e.g. guessing 10˚ and adding this to the Craven-Taree track value. Alternatively the ATCO's could *visually* transpose VH-MDX's paint trend against the Craven-Taree track.

Also, the Sydney ATCO's could have placed a straight edge (ruler/pen etc.) along the radar paints then paralleled the straight edge between the compass rose *origin* (Sydney Airport) and the *compass rose* to read off the final track.

If either of these methods were used it can be seen that quite an accurate track could be determined.

6.11. Radar fade time and Propagation

6.11.1. Overview

Section 6.9 identified that *Sydney* radar fade of VH-MDX highly likely occurred between 0938:36UTC and 0939:00UTC. Pilot reported altitudes and average rates of descent could be used to predict VH-MDX *altitudes* at particular times within this period.

These altitude predictions could then be compared with radio propagation analysis determined *minimum radar interrogation altitudes* of section 5.3 at different geographic locations. This way it can be confirmed if radar fade was actually possible at particular times and locations along VH-MDX's flight profile.

This process can both *eliminate* and *confirm* geographic areas where radar fade was possible.

6.11.2. Known VH-MDX altitudes and descent rates

Communications transcripts show that the pilot of VH-MDX reported altitudes of:

- 7500'AMSL at 0937:40UTC
- 6500'AMSL at 0938:33UTC and;
- 5000'AMSL at 0939:26UTC [9].

An ASIB specialist report analysing communications recordings of VH-MDX determined that the approximate *average* rates of descent of VH-MDX within two altitude blocks were:

- Between the pilot report of 7500' and 6500' was 1100 feet per minute (fpm)
- Between the pilot report of 6500' and 5000' was 1700fpm[9].

6.11.3. Predicted altitudes at various rates

Predicting altitude and rate of descent values within the likely radar fade time range of 0938:36UTC and 0939:00UTC and at the most probable time of 0938:48UTC can greatly assist in suggesting or eliminating geographical areas where VH-MDX was located at during radar fade.

This is possible by comparing predicted *VH-MDX altitudes* with radio propagation analysis *minimum interrogation altitudes*.

Assuming the downward rate once commenced would not reduce, rates of descent would be *lower* than average *closer* to the *first* altitude in a block and *higher* than average closer to the *second* altitude in a block. As we do not know *initial* or *final* rates of descent for the blocks there can be a great number of combination possibilities.

Assuming a *linear* change of rate of descent within the blocks and using the average rates of descent for each block, the following *initial* and *final* rates of descent result:

- 7500' = 900fpm
- 6500' = 1300fpm
- 5000 = 2100fpm

These values are plotted in figure 81 below. The resulting curve is extrapolated from the original *form*: i.e. in the shape the curve was trending. The extrapolated values may not necessarily be indicative of VH-MDX's rates of descent or altitude but are offered as an indication of trend.

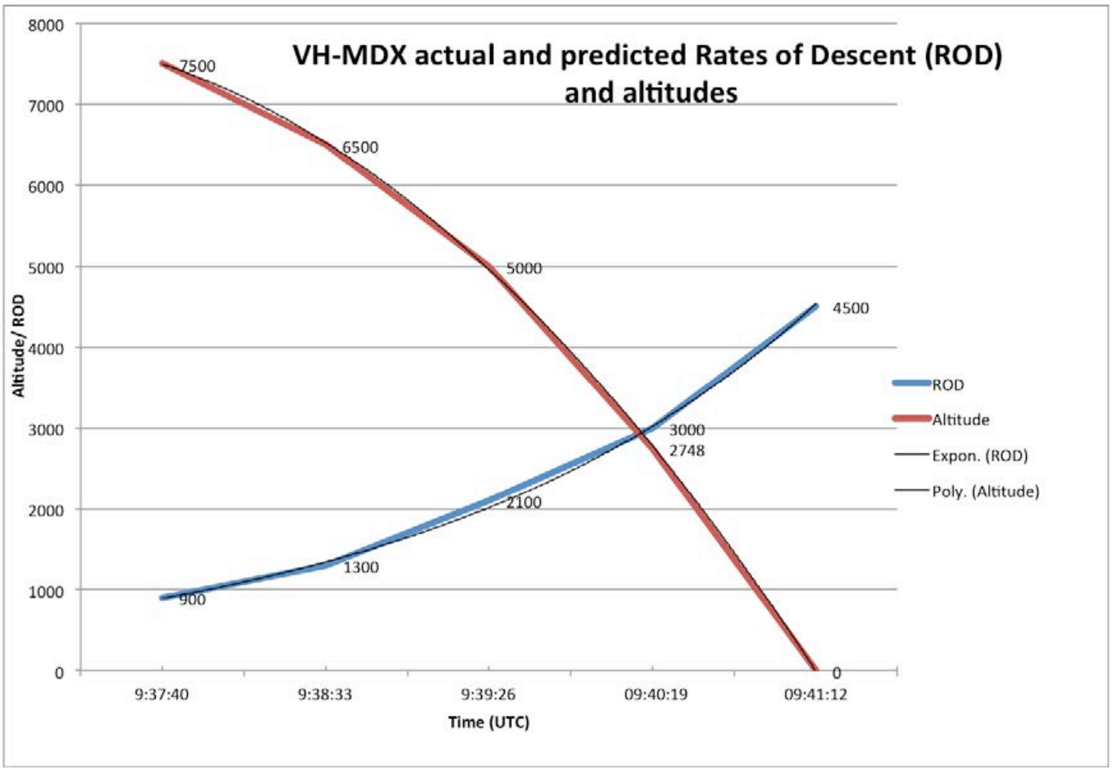


Figure 81: Actual and predicted VH-MDX rates of descent and altitude. Values after 0939:26UTC are predicted and are simply based on continuing the apparent mathematical relationship trend. Black lines represent the curve trends. (Graph: Glenn Strkalj 2016).

From the graph in figure 81, the predicted rate of descent at 6000' is around 1500fpm.

From the information in this section, it is accepted that VH-MDX was descending at a rate *between* 1300fpm and 2100fpm from 6500'AMSL to around 6000'AMSL.

But given the time between the 2100fpm value at 5000' and where 6000' would be passed, it is more likely VH-MDX was descending at some value much closer to 1300fpm. Accordingly, the 1700fpm *average* value for this block will be used as the maximum considered rate of descent *to 6000'*.

Rates of descent of 1300fpm, 1500fpm and 1700fpm will be used to determine likely VH-MDX altitudes in the radar fade time range. These values can then be compared to radio propagation analysis results.

Figure 82 presents predicted altitudes at even 10-second intervals following the 6500' call based on rates of descent of 1300fpm, 1500fpm and 1700fpm. The specific times of 0938:36UTC, 0938:42UTC and 0938:48UTC are also included to yield data for the:

- Two sweeps to fade with half sweep ATCO recognition and reaction time (2.5 sweeps to fade)
- Two sweeps to fade (Most probable fade time)
- Three sweeps to fade.

Time (UTC)	Rate of descent (fpm)(bold)/ Predicted altitude (ft)		
	1300	**1500**	**1700**
0938:33	6500	6500	6500
0938:36	6435	6425	6415
0938:40	6348	6325	6302
0938:42	6305	6275	6245
0938:48	6175	6125	6075
0938:50	6132	6075	6018
0939:00	5915	5825	5735

Figure 82: Predicted uncompensated altitudes at times just after the 6500' call. VH-MDX highly likely faded from Sydney ATC radar between 0938:36UTC and 0939:00UTC but most probably just before or at 0938:48UTC.

Many radar fade altitude ranges can be specified from the above data based on different considerations so a number of key ranges will now be determined and briefly discussed.

From this information VH-MDX was expected to fade from Sydney ATC radar between:

- 6435'AMSL (0938:36UTC) and 5735'AMSL (0939:00UTC) (1300fpm data for first fade time and 1700fpm data for the second fade time) (*extreme* range)
- 6305'AMSL (0938:42UTC) and 6125'AMSL (0938:48UTC) (1300fpm data for first fade time and 1500fpm data for the second fade time) (*probable* range).

It was found that VH-MDX could have experienced total altimeter *over-read* deviations of 130' (normal static source used) to 280' (alternate static source used at maximum cruise speeds) and that *approximately* 240' (alternate static source used at 115KIAS) was likely at 115KIAS[48].

Accordingly, when comparing the altitudes found in this sub-section to radio propagation minimum interrogation altitudes, *subtraction* of a value between 130' to 240' is recommended to closer represent VH-MDX's true altitude at the time.

Applying 130’ over-read error to *highest* fade altitude and 240’ over-read to the *lowest* fade altitude yields the following adjusted *extreme* range:

- 6305’AMSL (0938:36UTC) and 5495’AMSL (0939:00UTC) (adjusted *extreme* range)

Assuming the pilot used alternate static air, the following is the adjusted *probable* range:

- 6065’AMSL (0938:42UTC) and 5885’AMSL (0938:48UTC) (adjusted *probable* range).

Many different ranges of altitude at fade can be derived from the data in this section. There were significant amounts of communications on the ATC intercom involving Sector 1 from around 0937:32UTC to around 0939:10UTC. This coupled with intermittent paints leading into this time frame may have resulted in a *delay* in reporting the fade.

As stated, Sector 1 or the STAC or SAAC overhearing the pilot’s report of loosing a ‘*hell of a lot of* <altitude>’ on the intercom could have triggered the decision to declare fade around 30 seconds later at 0939:00UTC even thought the fade occurred earlier.

Radar fade may have occurred at 6500’ or even higher. Debriefs of Sydney staff suggest there were intermittent paints leading up to a reasonable number of paints prior to fade. This information is sketchy but should be considered to some extent in radio propagation analysis.

6.12. Analysis of the four Sydney ATC final radar fixes

Four Sydney radar fixes have in various ways been described as ‘final’ or ‘last’ radar positions of VH-MDX. These are shown in figure 83 on the next page. These positions are significantly displaced from each other so they are not likely to be representative of the same position. This means only one can be correct.

Taking records of interactions between individuals and/or sections during dynamic times will almost always result in errors. It must be remembered different individuals hear and see different information or interpret the same information in a different way.

Records tend to reflect a running commentary rather than presenting a conclusion: it is up to investigators to analyse such records to determine conclusions. This is one reason why so many options exist to the Sydney final radar fix.

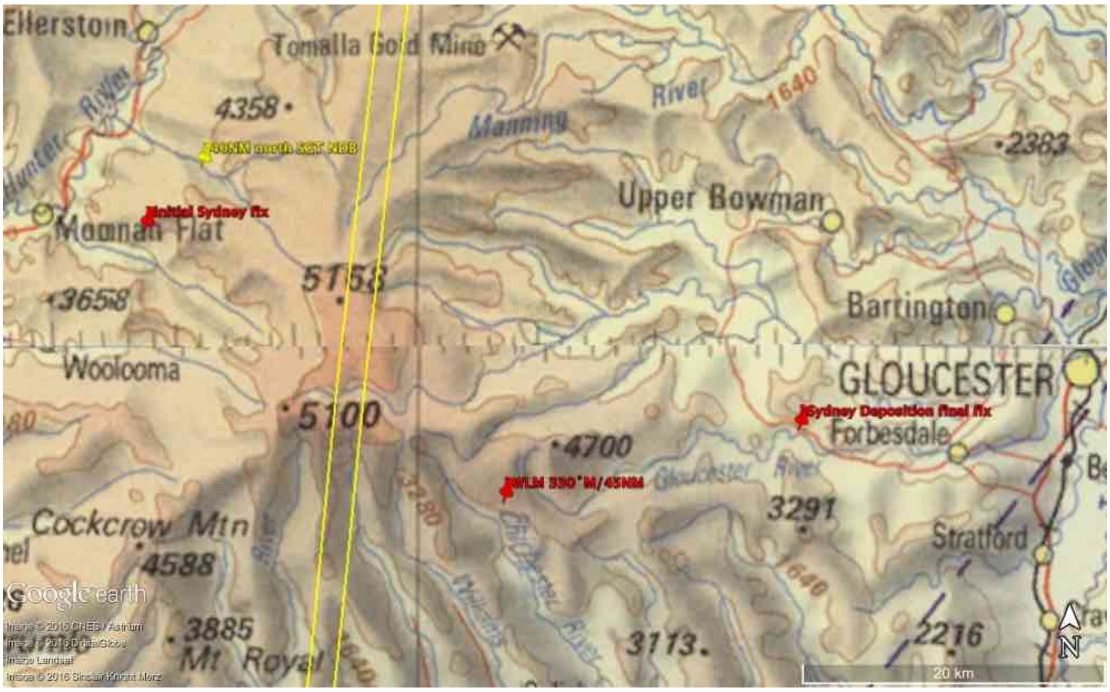


Figure 83: The four Sydney ATC final radar fixes. The yellow lines are the 6NM and 7NM displacements east of the SGT-MSO track , yellow pin 40NM north of SGT. The Sydney initial fix is also shown for reference (Base chart: Department of National Development and Energy 1981, additions: Glenn Strkalj 2016, plotted on Google Earth).

The four *final* Sydney ATC radar fixes are:

- Sydney deposition final radar fix (Approximately 5NM west of Craven waypoint)
- Sydney final radar fix approximately 330˚M/45NM Williamtown
- Approximately 6NM-7NM east of Mount Sandon Track
- 40NM north of Singleton.

The following sections will analyse these four positions.

6.12.1. Sydney *Deposition* final radar fix (plot sheet)

6.12.1.1. Overview

From section 4.3, this position was specified by a deposition and radar plot sheet approximately four months after the accident date. There is no time stated for this *final* radar position.

The *deposition* itself describes the final radar position as being 5NM *west* of Craven waypoint whilst the radar plot sheet graphically shows the centroid of the last radar return positioned 3NM-4NM *northwest* of Craven waypoint[6].

An ATCO involved in SAR co-ordination of the VH-MDX accident recalls that he was informed that only *primary* paints were observed at the final position but is not completely sure[1].

Radio propagation results from section 5.3.2.2 suggest a minimum interrogation VH-MDX altitude of 6000'AMSL at the center point (that will be defined in the following sections) of this position.

Section 6.11.3 identified that VH-MDX *most probably* faded between 6205'AMSL to 5920'AMSL. Therefore, propagation analysis supports that VH-MDX could have faded from Sydney ATC radar at the *centre point* of this position.

6.12.1.2. 100˚M track line

A straight line was drawn on the radar plot sheet by the ATCO to join the initial fix and the final fix to represent the 'observed track' of VH-MDX. This track was specified in the deposition as being 100˚(M)[10].

Such a straight track is not likely given that VH-MDX was observed by Sydney and Williamtown ATCO's *around* 324˚M-325˚M/47NM from Williamtown at around 0936:00UTC, this fix being further south of the track line deposed as seen below in figure 84.

Figure 84: 100˚M track. Most radar fix centroids are significantly below the 100˚M track line. Accordingly, it is unlikely that VH-MDX flew along the 100˚M track. It appears that the 100˚M track line simply defines the *overall* track of VH-MDX from *initial* to *final* radar fix rather than representing observed aircraft track. Another possibility is SSR symbols could have touched the 100˚M track line even though centered further south given the large display (Image: Australian Government (Department of Transport) 1981; additions Glenn Strkalj 2014, plotted on Google Earth).

The 100˚M track line is viewed as simply and approximately joining the initial and final deposition radar fixes.

It was also deposed that VH-MDX was observed to track for about 20 miles (NM) from the initial to the final radar fix. As shown in figure 85 on the following page, the 20NM point lies just on the western edge of the *drawn* final position circle.

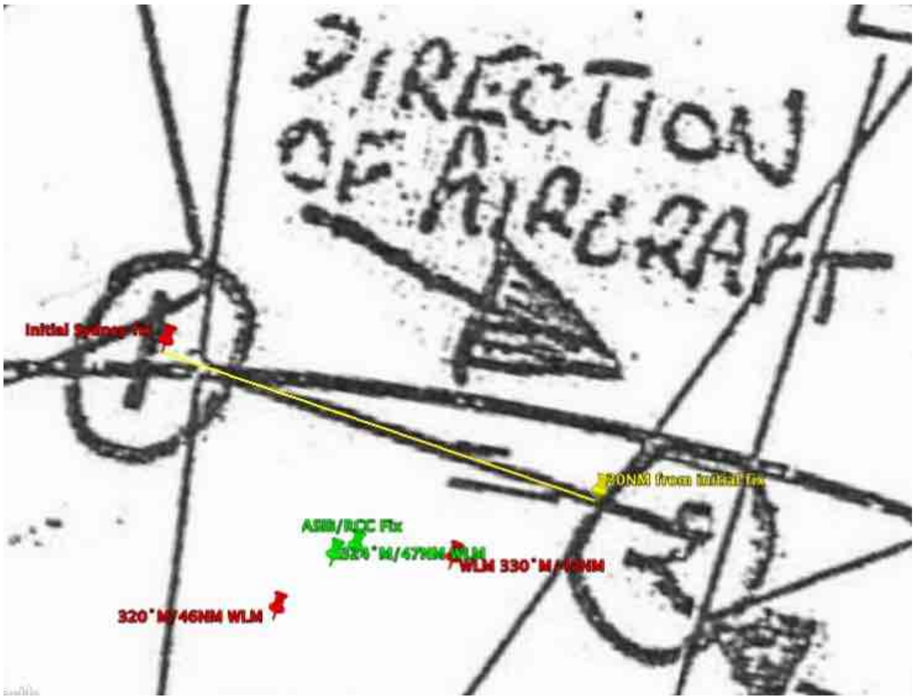


Figure 85: It was deposed by the ATCO that VH-MDX tracked 'about 20 miles (NM)' from the initial fix along the 100˚M bearing. 20NM from the initial radar fix is just on the western edge of the final position circle (Image: Australian Government (Department of Transport) 1981, additions Glenn Strkalj 2016, plotted on Google Earth).

6.12.1.3.

6.12.1.4. Radar paint sizes

As stated previously, it is likely that a *diamond* symbol was allocated to code 4000 and a *circle* symbol was allocated to code 3000. From section 3.10.3 the total size of these symbols (horizontally) was estimated at being approximately 6NM-7NM for the diamond and 5NM for the circle.

VH-MDX initially squawked mode A code 4000 followed by a change to mode A code 3000 from around 0935:41UTC. As a result, the SSR *circle* symbol would have been displayed *from around* 0935:41UTC to radar fade on the Sydney Bright display.

Section 3.9.6 found that primary paints from The Round Mountain RSR (Remote RSR) were a small solid square around 2NM in size.

The *drawn* circle associated with the Sydney deposition *final* fix is around 8NM in east-west diameter and around 10NM in north-south diameter. This is significantly greater than the actual SSR code 3000 circle size (5NM) or remote PSR symbol (2NM square).

Immediately obvious in figure 86 below is the difference between the drawn radar plot (black) and the to-scale (green) SSR symbol sizes of the final deposition paint.

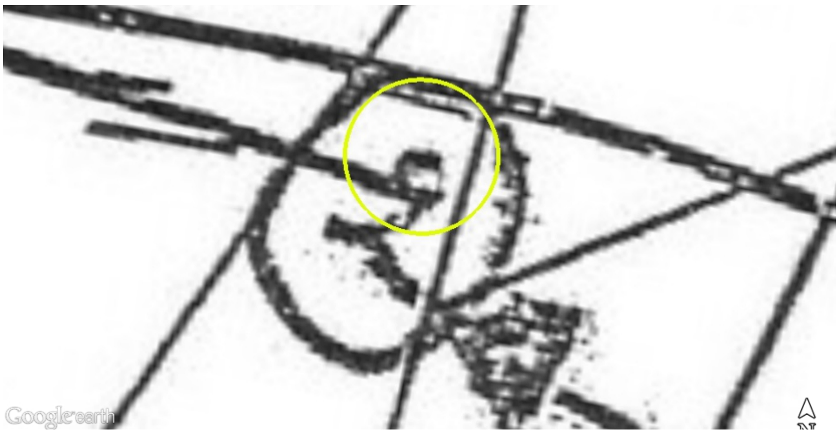


Figure 86: Comparison of final radar plot ‘symbol’ (black) and to-scale SSR symbol (green) (Plot sheet: Australian Government 1981, additions: Glenn Strkalj 2015, plotted on Google Earth).

This opens the question as to the centroid position of the deposition final fix. Figure 86 positions the green 5NM diameter circle so that the western and northern edges touch the Singleton NDB – East Ridge track and 120NM

Sydney arc as this appears to have been what the deposition ATCO attempted to do. Figure 87 expands on explanation.

Note: the radar plot sheet has much distortion and the circle was positioned relative to accurately plotted Google Earth track and arc positions rather than the plot sheet features.

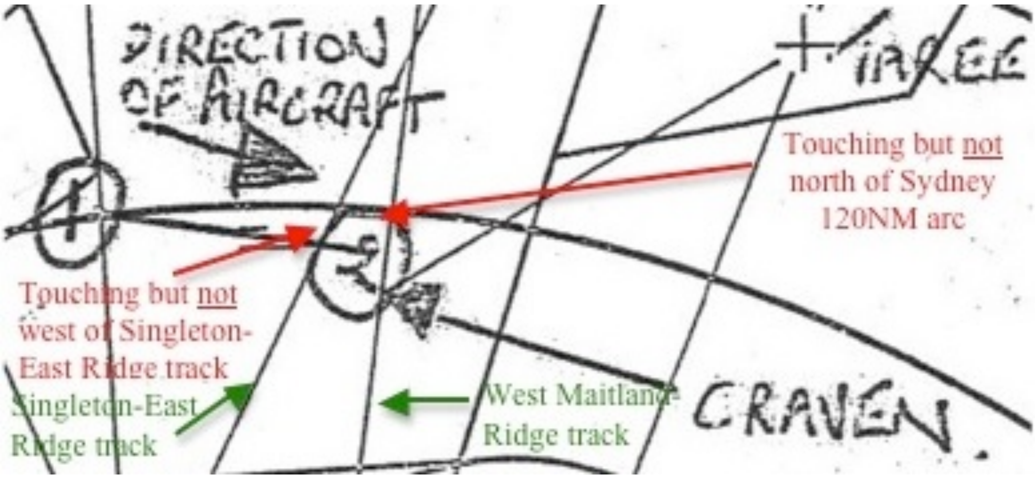


Figure 87: Boundaries of the Sydney deposition final radar fix. ATCO's used reference points on the map display to record radar positions. The Sydney *final* radar fix is not as well 'boxed in' as the *initial* fix but there are still convenient references (Image: Australian Government (Department of Transport) 1981, additions Glenn Strkalj 2014, plotted on Google Earth).

6.12.1.5. Final paint position

As stated, there appears to have been an effort to depict the Sydney deposition final position (marked as '2' in figure 86) to butt up *against* but not beyond;

- The Sydney RSR 120NM range ring to the north
- The Singleton - East Ridge track to the west.

The *drawn* position *shape* appears to be modified so as not to extend over the Singleton-East Ridge track and 120NM arc. This is obvious in figure 88 below.

Figure 88: Zoom of Sydney deposition final radar fix. Obvious is an emphasis to contain the paint inside the Singleton-East Ridge track and 120NM Sydney RSR arc resulting in circle distortion to do so (Image: Australian Government (Department of Transport) 1981).

Such hard boundaries provide limits to the extent of the paint to the north and west. There are no ‘hard’ boundaries for the final paint to the south and east.

The final paint extends beyond the West Maitland VOR-Ridge track to the east whilst extending slightly south and below of Craven waypoint.

Section 6.12.1.4 identified that the *drawn* circle representing the final deposition fix is significantly larger than the expected size of a Northern Mosaic SSR circle symbol.

The centroid of the *drawn* circle may be used to define the centre point of this position however, it is viewed more relevant to find the centroid of the:

- 5NM SSR circle positioned to touch the 120NM Sydney arc and Singleton-East Ridge track, or;
- Centroid of the end of the 100˚M track line.

As the SSR symbol (if displayed) appears to have been used as a reference in the drawing of the radar plot sheet, the first option will be used. Regardless, the end of the 100˚M track line is actually in close proximity to this centroid.

When considering the actual 5NM size of the SSR circle and placing the circle to touch the 120NM Sydney arc and Singleton-East Ridge track to reflect the emphasis of the ATCO in positioning the final circle in this position, the following centroid position is found (WGS84):

-32.043615°, 151.759409°

32° 2'37.01"S, 151°45'33.87"E

56H 382871.02 m E, 6454057.04 m S

Figure 89 on the next page shows the position of the 5NM SSR circle as described.

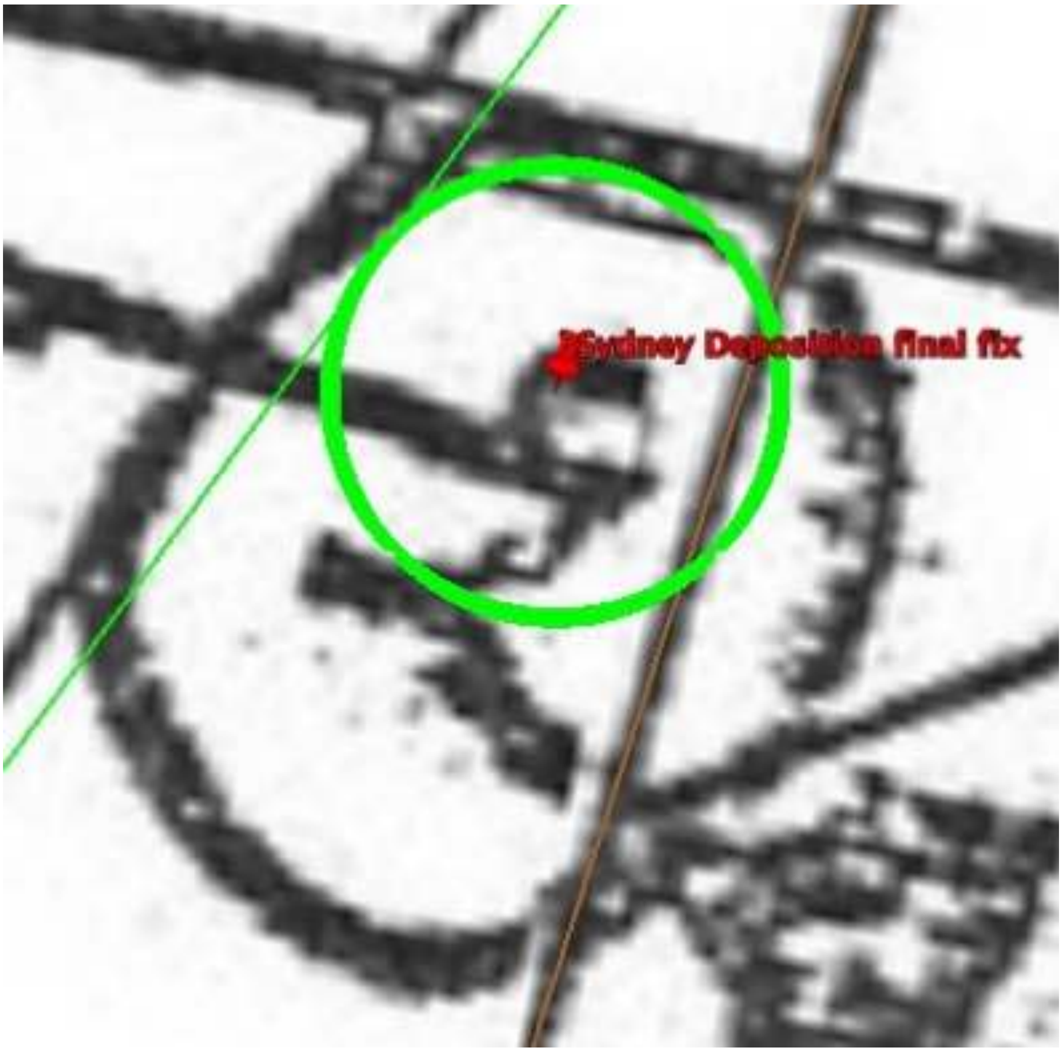


Figure 89: 5NM SSR circle in north-west corner. Accurately plotted tracks were used for positioning the circle. Note that the SGT-East Ridge track (green line) is displaced from the distorted plot sheet track (Plot sheet: Australian Government (Department of Transport) 1981, additions: Glenn Strkalj 2016, plotted on Google Earth).

6.12.1.6. Deviations to the Sydney deposition final radar fix

Radar *system* deviations are based on a VH-MDX position 99NM in range from The Round Mountain RSR with the following values resulting:

- Azimuth deviation (+/-1.5˚): +/-2.59NM
- Range deviation (+/-1%): +/-0.99NM

Display accuracy was found in section 3.25.3 to be not more than a 1.75NM box.

Given the proximity of the position to and, the effort to contain the depicted paint on the deposition within the confines of particular radar map features as discussed, a +/-2NM read-off deviation in azimuth and range is considered applicable to azimuth and range. This equates to a 4NM diameter circle.

Combining these deviations statistically as the square root of the sum of squared errors results in the area shown in figure 90 (next page) to represent the Sydney deposition final radar fix.

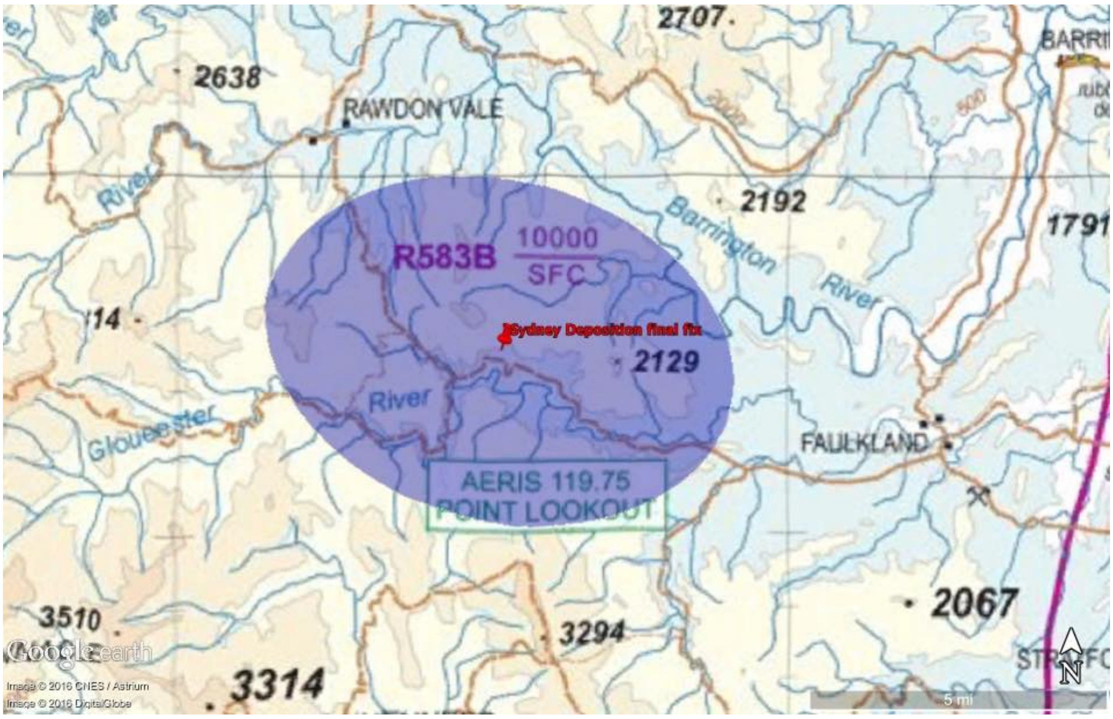


Figure 90: Sydney deposition final radar fix statistical area (Base map: Airservices Australia/OzRunways 2016, additions: Glenn Horrocks & Glenn Strkalj 2016, plotted on Google Earth).

6.12.1.7. Possibility of achieving the deposition final fix

VH-MDX was *radar observed* as having travelled generally easterly by Sydney ATC whilst the Williamtown ATCO had the *impression* that VH-MDX was tracking easterly[16].

The fix previous to the deposition final was at 0936:00UTC between 324˚M-325˚M/47NM from Williamtown. As the deposition radar plot final position is in the range of 336˚M-347˚M/ 40-48NM from Williamtown, it is east of the previous position thus supporting the suggestion of an easterly track.

It was found that a *maximum* expected IAS of 130KIAS was likely given the two known bouts of icing VH-MDX accumulated and that *actual* IAS was probably even *lower* than this figure.

Applying 130KIAS with a 45 knot tail wind with 2.8 minute legs from both the ASIB/RCC fix and 324˚M/47NM from Williamtown definitions of the Williamtown 0936:00UTC fix, shows in figure 91 (next page) that VH-MDX could at best only achieve positions west of the number ‘2’ final position drawn circle.

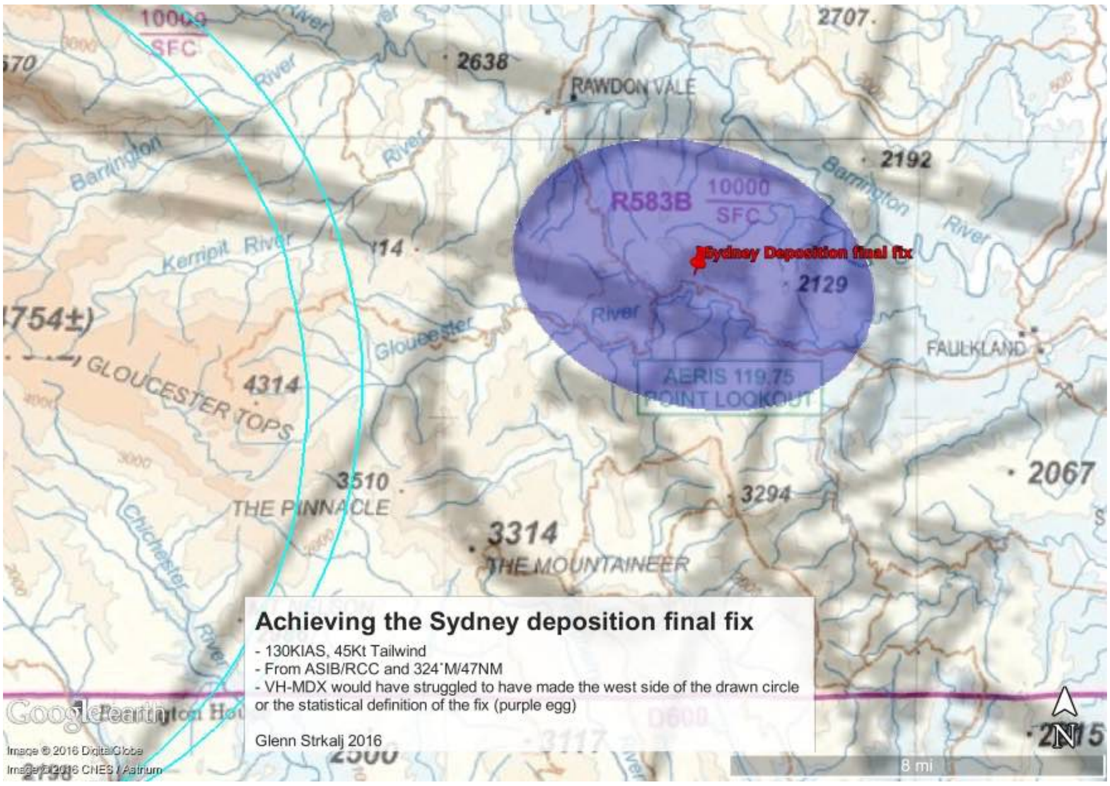


Figure 91: Achieving the deposition final fix. The two aqua arcs represent the positions of VH-MDX travelling at *fastest* probable speeds from both the ASIB/RCC and 324˚M/47NM WLM locations. It is unlikely that VH-MDX achieved the deposition final fix (Base map: Airservices Australia/OzRunways 2016, radar plot: Australian Government 1981, additions: Glenn Horrocks & Glenn Strkalj 2016, plotted on Google Earth).

Section 6.9.5 described how a ‘pop up’ back onto radar after fade was unlikely considering the ever-decreasing pilot reported altitudes and blocking terrain to radar line of sight. Accordingly, it is viewed unlikely that VH-MDX could

6.12.1.8. Discussion: Sydney deposition final fix

The findings in the previous sections demonstrate that there are a number of questionable traits of the Sydney deposition final fix. Both the deposition and associated radar plot sheet specify slightly different final radar positions.

VH-MDX was shown not able to make the *drawn* final position circle on the plot sheet. Defining the actual centroid of this position was also found to be challenging given the drawn circle was larger than the SSR symbol size.

Given the position is a radar fade position then minimal read-off deviations would be expected. Radio propagation supports that VH-MDX could have faded at the centroid point at the expected altitude but movement away from this point may yield a variety of different results.

Without confirmation of observed SSR paints at this final position, a question arises if the deposed final radar position may have been weather clutter. Going against this suggestion is:

- Other ATCO's that would have observed the paints as well
- SSR's proven superior coverage over PSR (10%-40% better) as discussed in section 3.23.2 meaning the SSR symbol would more than likely fade *last*
- Detection of code 3000 and SPI by Williamtown around 2.5 to 3 minutes prior to likely Sydney radar fade time confirms the transponder on VH-MDX was functioning correctly.

Overall, this fix is viewed more as a *guide* to the final resting place of VH-MDX rather than an *observed* radar fade position. Specifically, this fix can be used to confirm if final track direction is valid; i.e. the extended final track should intersect this fix area.

6.12.1.9. Conclusions: Sydney deposition final radar fix

The Sydney deposition final radar fix is classed as a position that offers a gross error check to VH-MDX's final track rather than being a radar fade position.

6.12.2. Sydney final radar fix ≈330˚M/45NM from WLM

6.12.2.1. Overview

Section 4.4.1 identified that this position was recorded the evening after the accident as 'approximately' 330˚M/45NM at 0939UTC. The *exact* source (specific ATCO) for this position is unknown.

The previous radar position to this was at 0936:00UTC between 324˚M-325˚M/47NM from Williamtown[16]. Accordingly, a generally eastwards track is indicated between the 0936:00UTC position and 'approximately' 330˚M/45NM at 0939UTC. This agrees with findings from section 4 that indicated VH-MDX travelled generally easterly.

6.12.2.2. Read-off deviations

As the position was recorded as 'approximately' 330˚M/45NM from Williamtown[2] coupled with the inability to discuss this position with ATCO's involved, resulting deviations could be broad.

Nevertheless, unlike the intermediate 320˚M/46NM Sydney position at around 0934:00 to 0934:40UTC, this fix was 'static' as it was an observed radar *fade* position; i.e. the paints were *not* moving.

Considering the significant persistence of Bright display systems (72-84 seconds)[1] and even with weather clutter reducing contrast of the fading paint, it can be seen there would have be sufficient time to assess the paint position to realise a *precise* read-off.

Because of this and that ATCO's knew VH-MDX was in trouble and descending, the fade position was likely assessed to the best expected Mosaic read-off tolerance suggested: +/-5˚ and +/-2NM[1]. Furthermore, considering that a change in azimuth must have been observed to conclude 330˚M *after* observing ≈320˚M minutes before, a +/-5˚ read-off deviation is further supported[1] (+/-10˚ would have been excessive). Figure 92 presents the area of the ≈330˚M/45NM fix with read-off tolerance of +/-5˚ and +/-2NM.

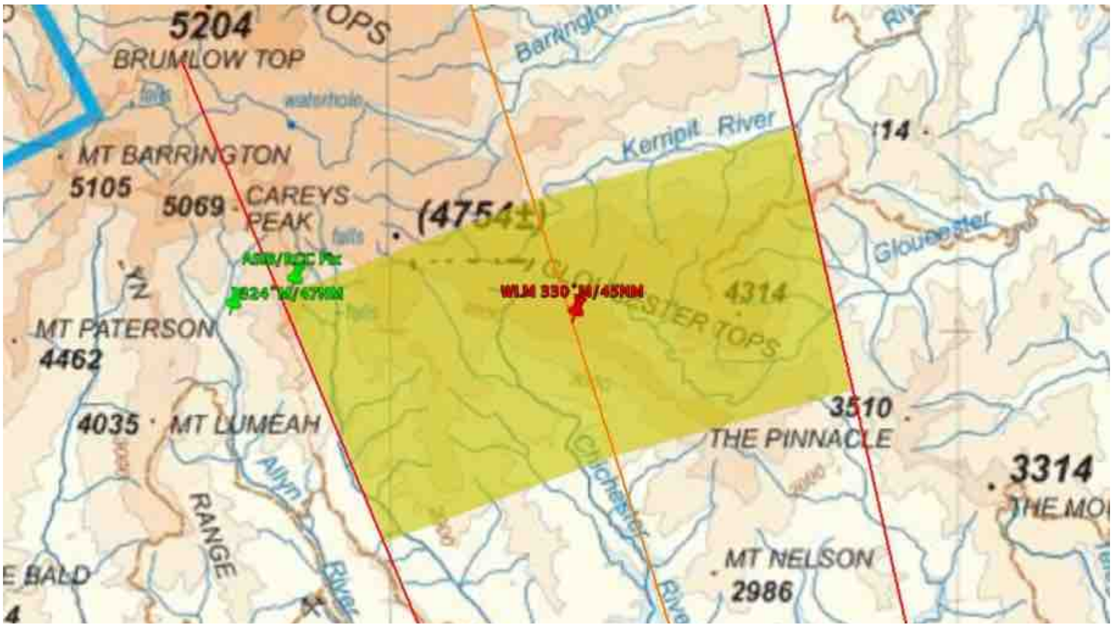


Figure 92: *Read-off* deviations to ≈330˚M/45NM Sydney radar fade (yellow area). Note the position of the Williamtown 0936:00UTC fix (ASIB/RCC & 324˚M/47NM). The Sydney deposition final fix is well east of the yellow area (Image: Airservices Australia/ OzRunways 2016, plotted on Google Earth, Additions: Glenn Strkalj 2016).

6.12.2.3. Radar and display system deviations

The following deviation values apply to the *pure* 330˚M/45NM fix (105NM in range from The Round Mountain RSR):

- Azimuth deviation (+/-1.5˚): +/- 2.75NM
- Range deviation (+/-1%): +/- 1.05NM
- Display accuracy deviations: not more than 1.75NM.

6.12.2.4. Statistically combined deviations Sydney ≈330˚M/45NM WLM fix

Statistically combining the read-off error of section 6.12.2.2 with the system deviations from section 6.12.2.3, results in the following graphical representation of the Sydney ≈330˚M/45NM from Williamtown radar fade position.

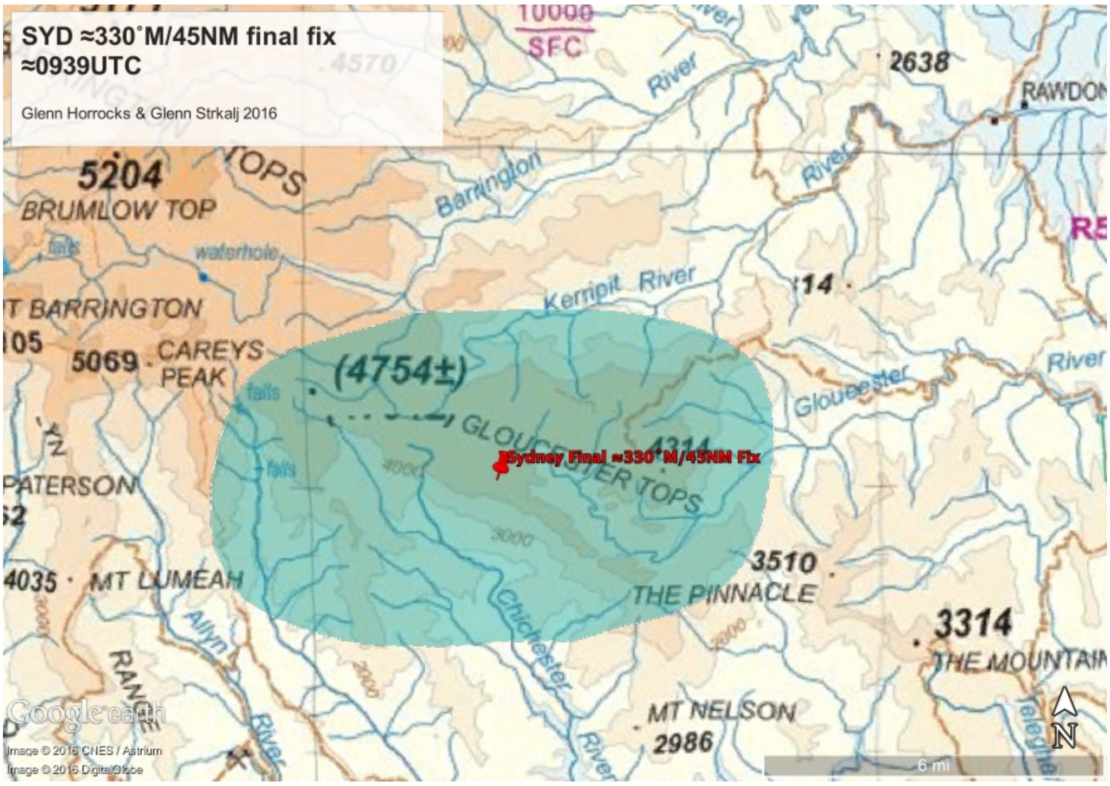


Figure 93: Statistically *combined* deviations: Sydney ≈330˚M/45NM WLM fade position. This is a representation of all deviations (Base map: Airservices Australia/OzRunways 2016, deviation plots: Glenn Horrocks 2016, plotted on Google Earth).

6.12.2.5. Radio propagation results

It was found in 6.11.3 that VH-MDX most probably faded from radar between 6175'AMSL and 5885'AMSL.

Section 5.3.2.2 showed that the minimum interrogation altitude of VH-MDX by The Round Mountain RSR was 7000'AMSL at the *exact* 330˚M/45NM position. This is *above* the expected fade altitude range derived from communications transcripts and *could* suggest radar fade occurred much earlier.

Section 5.3.2.3 produced radio propagation results along the final track from the various definitions of the 0936:00UTC position and along the normal axis from the radar head to the Gloucester River area to further expand on minimum interrogation altitudes. It was found that *west* of the pure 330˚M/45NM position, minimum interrogation altitudes *generally increased* from 7000'AMSL to 8300'AMSL although there was a slight dip in the middle of the Gloucester Tops plateau, whilst *east* of the position, minimum interrogation altitudes *reduced* from 7000'AMSL to around 6000'AMSL.

These *current* results when combined by dead-reckoned *straight* tracks and communications transcript timings suggest that VH-MDX was more likely to have faded somewhere in the *eastern* section of the 330˚M/45NM radar fade statistical area although there may be a part of the western section that was also possible. Further research is required.

Given software tolerances and lack of allowance for vegetation, any propagation-derived altitudes within *at least* 100’ of expected altitudes from communications transcripts should be considered.

Comparing the *highest adjusted extreme* interrogation altitude of 6305’AMSL with results from section 5.3.2.3 / Annex N, it can be seen VH-MDX could possibly stay within radar coverage then fade from radar as predicted if the fade point was approximately between RPP37 and RPP38 or east (6300’AMSL or lower minimum interrogation altitudes).

This finding can be used to cut-off and discard a vast area of the statistically defined 330˚M/45NM fix of figure 92 to indicate the *present* most likely radar fade area. Note that this will be subject to change as more analysis is conducted and a patch in the middle of the 330˚M/45NM +/-5˚ and +/-2NM area is appearing likely as an additional likely fade area.

The bearing from The Round Mountain RSR to halfway between RPP37 and RPP38 is 198.31˚T. The remaining area in figure 92 to the east of this bearing line now becomes the refined area for this position. This results in an area of interest approximately between 330˚M to 336˚M and 42NM to 47NM from Williamtown. This area is shown below in figure 94 and is 26.7sqkm in area.

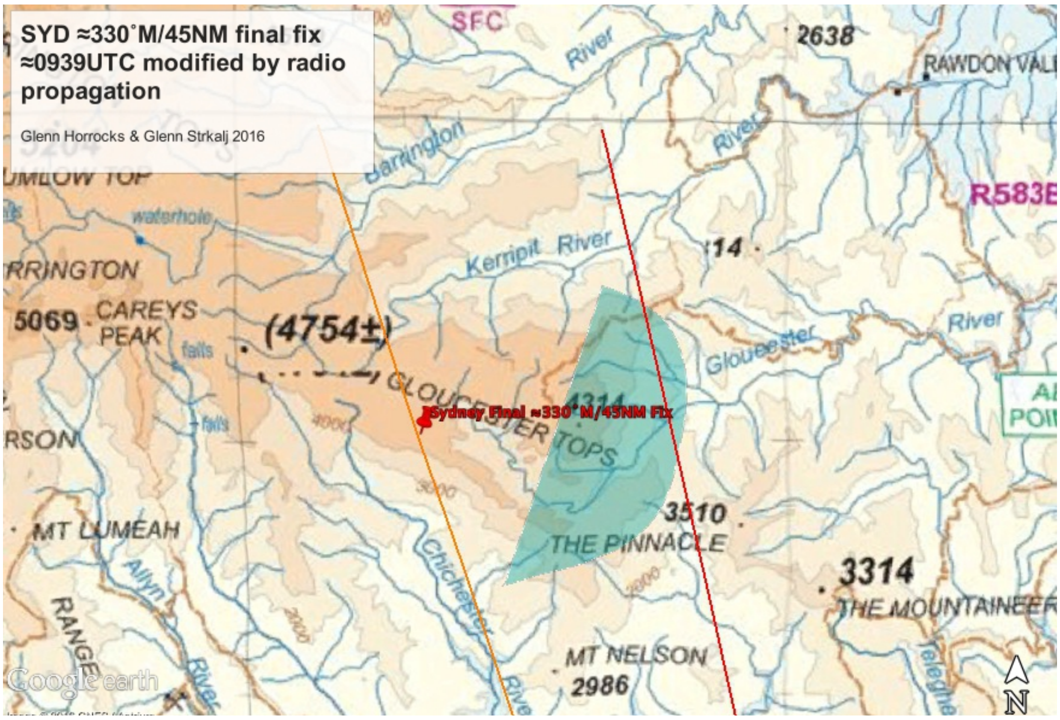


Figure 94: Resultant 330˚M/45NM fix at ≈0938:36UTC to 0939:00UTC. Orange line is the WLM 330˚M bearing, red line is the 335˚M WLM. The eastern section of the original area in figure 92 is of interest (Image: Airservices Australia/ OzRunways 2016, additions: Glenn Strkalj & Glenn Horrocks 2016, plotted on Google Earth).

6.12.2.6. Possibility of achieving the ≈330˚M/45NM fix

Straight dead reckoned tracks from both variants of the 0936:00UTC Williamtown position were plotted to verify if the ≈330˚M/45NM from Williamtown position as defined in the previous sub-section could be achieved by VH-MDX.

Two cases were considered: a slowest speed case of 110KIAS with 25 knot tailwind and a fastest speed case of 125KIAS with 45 knot tailwind that was previously used in section 6.11.1.7. The results are shown below in figure 95.

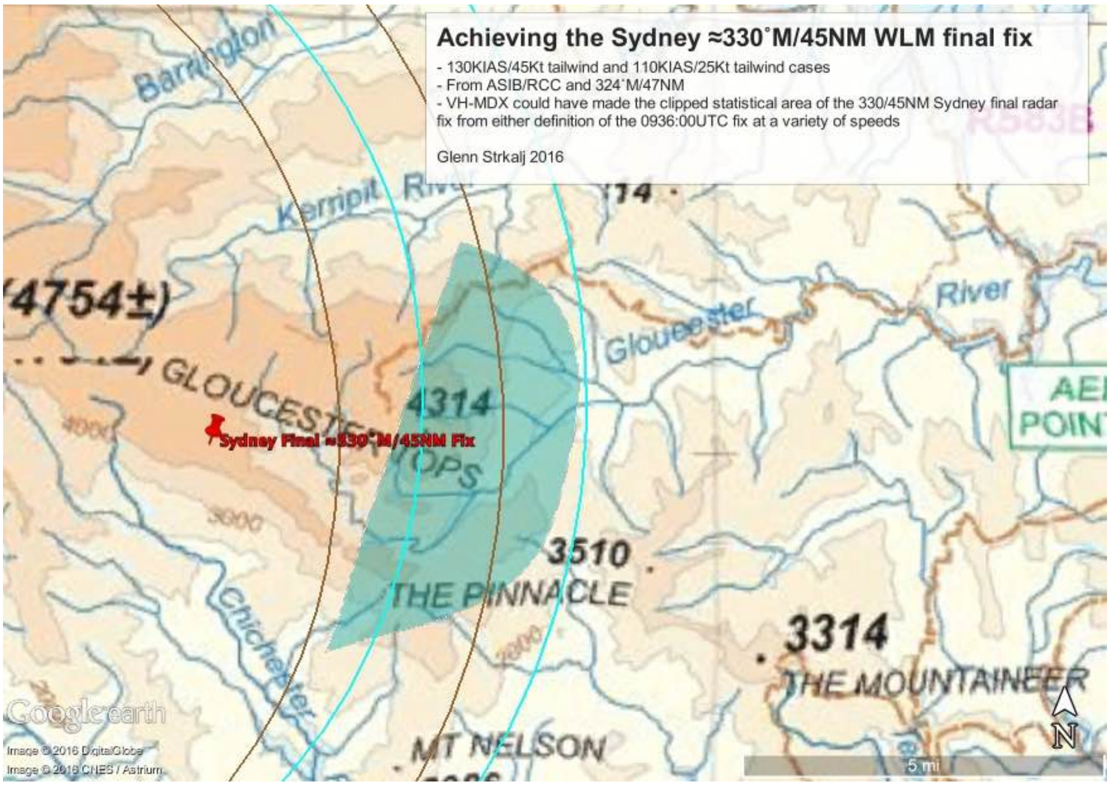


Figure 95: Achieving the ≈330˚M/45NM from WLM final fix. Brown arcs are slowest and fastest from 324˚M/47NM, aqua arcs same from ASIB/RCC fix. VH-MDX could have achieved the ≈330˚M/45NM fix area from either position at a variety of speeds (Base maps: Airservices Australia/OzRunways 2016, additions: Glenn Strkalj 2016, plotted on Google Earth).

Dead reckoned tracks at the probable speed extremes of VH-MDX show that VH-MDX could have fallen within the radar fade area as defined in section 6.12.2.5.

These results support the validity of an '*approximately*' 330˚M/45NM from Williamtown radar fade position at Sydney ATC.

6.12.2.7. Communications transcripts: the '330˚M' call

Also of interest is that communications transcripts show an agency reported VH-MDX was at 330˚M from Williamtown at 0938:30 UTC[9]. These transcripts attribute *Williamtown* ATC as reporting this position. The Williamtown ATCO was found by the author to not recall taking the 330˚M position or making the call[16].

Section 6.9 identified that VH-MDX likely faded from Sydney ATC radar between 0938:36UTC and 0939:00UTC whilst section 6.12.2.5 identified that fade probably occurred between the 330˚M and 336˚M bearings from Williamtown. This connects the 330˚M call with radar fade position as:

- VH-MDX was heading eastwards
- If close to the 330˚M bearing at 0938:30UTC, VH-MDX would have likely flown into the radar fade area further east determined in section 6.12.2.5 (only 12-18 seconds away)
- 330˚M really means 325˚M – 335˚M.

It has been shown that although attributed to Williamtown in communications transcripts, the call may have originated from Sydney and regardless of the origin is likely to represent VH-MDX's position[16]. Accordingly, the 330˚M call can be seen to offer further support to the timing and position of VH-MDX's radar fade at Sydney ATC at approximately 330˚M/45NM.

6.12.2.8. Discussion

The Sydney 'approximately' 330˚M/45NM from Williamtown final position at 0939UTC has been shown to be defensible from the following points:

- *Time* of transcribing position was close to the accident date (evening after accident)
- Aligns with transcribed 330˚ call *position* and *time* wise
- Aligns with communications transcribed report of *radar fade* time wise
- Radio propagation analysis *strongly* suggests radar fade occurred in the eastern sector of the statistical representation of this fix shown in figure 92
- Dead reckoned tracks from the 0936:00UTC fix align *strongly* time and position wise
- Final observed *radar track* at Sydney ATC connects the 0936:00UTC and this position very well.

This position can also be suggested to correlate and/or represent either or both the ASIB/RCC position and/or the '6-7NM east of the Mount Sandon track' final position from a Sydney ATC perspective based purely on near-overlap with these positions. However, the following points work against this proposition:

- Radio propagation analysis suggests *significantly* higher minimum radar interrogation altitudes in the area of the ASIB/RCC and 6NM-7NM east positions than what is expected from transcript derived VH-MDX altitudes at radar fade
- Final observed *radar track* does not align with these final positions
- VH-MDX would have to have lost significant control rather *early* in the accident timeline to achieve these positions and this is currently viewed as *unlikely*.

6.12.2.9. Conclusions: Sydney final radar fix ≈330˚M/45NM from Williamtown

The Sydney final radar fix at 'approximately' 330˚M/45NM from Williamtown:

- Occurred between 0938:36UTC to 0939:00UTC but most probably just prior to or at 0938:48UTC
- Is currently classed as a *separate* fix to the ASIB/RCC, 'approximately' 6-7NM east of Mount Sandon track and Sydney deposition final fixes

- Could be classed as a similar position to ASIB/RCC, 'approximately' 6-7NM east of Mount Sandon track
- Is highly defensible in many different respects.

6.12.3. Approximately 6-7NM east of the 'Mount-Sandon track'/ 40NM north of Singleton NDB

6.12.3.1. Overview

These positions were recorded on the night of the accident at 0939UTC[47]: the same time as Sydney ATC reporting radar fade in communications transcripts.

Effectively *two* areas are specified by this reported final position (see figure 96 below):

- '*lost return*': approximately 6NM-7NM east of the Singleton NDB – Mount-Sandon NDB/VOR track
- '*last sighting*' at 40NM north of Singleton NDB.

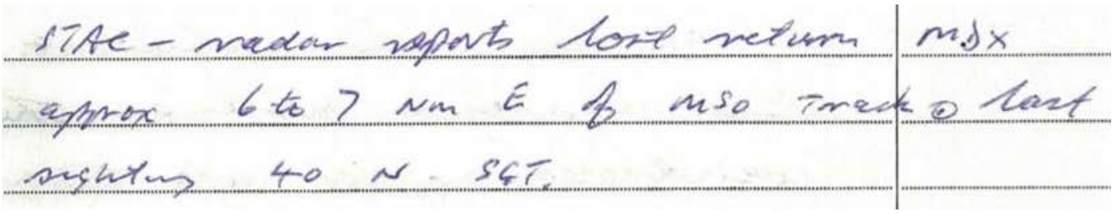

STAC – radar reports lost return | MDX
approx 6 to 7 NM E of MSO Track @ last
sighting 40 N - SGT.

Figure 96: Report of 'lost return' and 'last sighting' by Sydney ATC at 0939UTC (Australian Government (Department of Transport) 1981).

6.12.3.2. 40NM north of Singleton NDB

The '*last sighting*' of VH-MDX at 40NM north of Singleton NDB on Sydney ATC radar does *not* make sense with respect to being a final radar position. This is because VH-MDX was:

- First identified at 36NM north of Singleton NDB near the Singleton NDB- Mount Sandon NDB/VOR track (close to 40NM north of Singleton NDB)
- Observed to conduct a turn from the above position southwards followed by a slow turn to the east
- Radar fixed by Sector 1 near 320˚M/46NM from Williamtown (well away from 40NM north of Singleton NDB) some 6 minutes after the initial fix above
- SPI identified by Williamtown ATC at 324˚M-325˚M/47NM from Williamtown at 0936:00UTC (well away from 40NM north of Singleton NDB).

Accordingly, 40NM north of Singleton NDB is highly *unlikely* to be the final radar position of VH-MDX at Sydney ATC.

Interestingly, search aircraft tasked within minutes of VH-MDX's final radio call were tasked to search the area 40NM north of Singleton NDB and generally within 10NM west and 20NM east of the Singleton NDB-Mount Sandon NDB/VOR track[47].

6.12.3.3. Approximately 6NM-7NM east of Mount Sandon Track

The ‘radar’ report of a ‘lost return’ at approximately 6NM-7NM east of Mount Sandon Track position could possibly be valid and will be considered as a final radar position in this section.

This position can justify the Williamtown 0936:00UTC ASIB/RCC fix as a radar fade position (as it is labeled) given the close proximity between the two. The two variations of the 0936:00UTC position (324˚M/47NM and 325˚M/47NM) are all either within 6NM-7NM east of the Singleton NDB - Mount Sandon track or 1NM outside this area (a minimal excursion in radar terms). This is shown in figure 97 below.

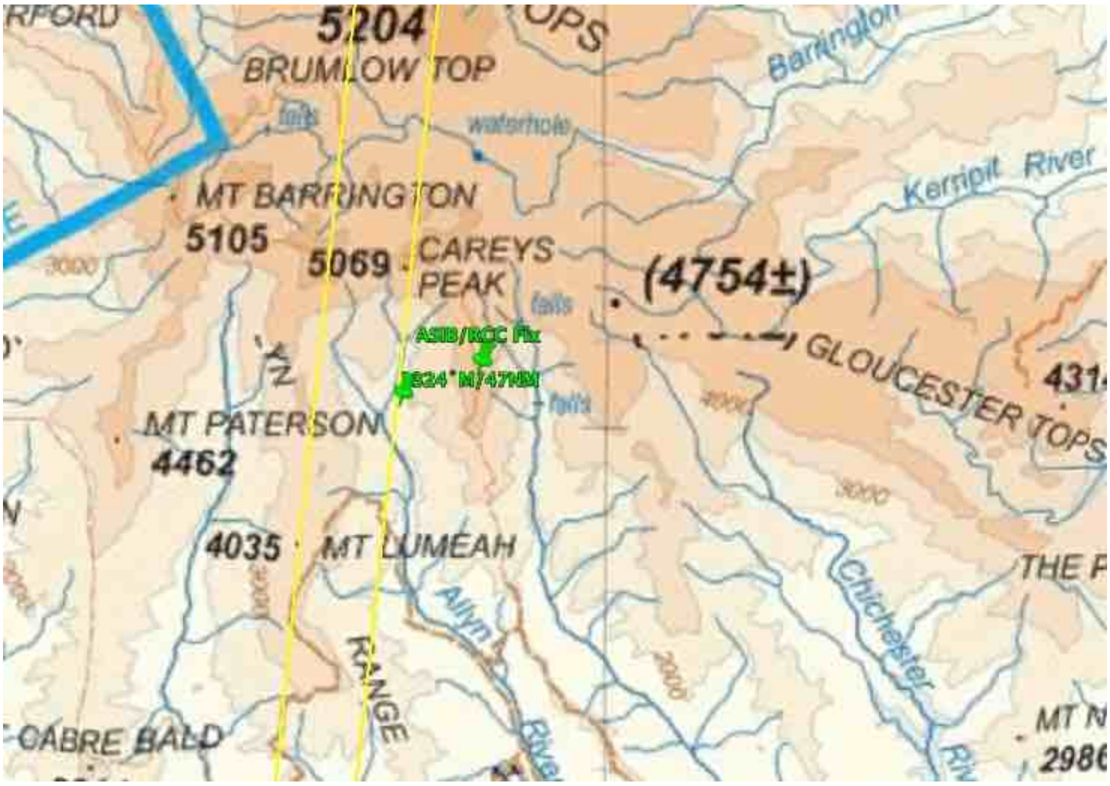


Figure 97: Close proximity of ASIB/RCC fix to 6NM-7NM east of SGT-MSO track (yellow lines) (Base maps: Airservices Australia/OzRunways 2016, additions: Glenn Strkalj 2016, plotted on Google Earth).

This 6NM-7NM position could also be referring to the 320˚M/46NM from Williamtown position achieved by *Sydney* Sector 1 at around 0934:00UTC to 0934:40UTC as the 6NM to 7NM east position cuts through the 320˚M/46NM fix statistical area determined in section 6.5.6. This is shown in figure 98 on the next page.

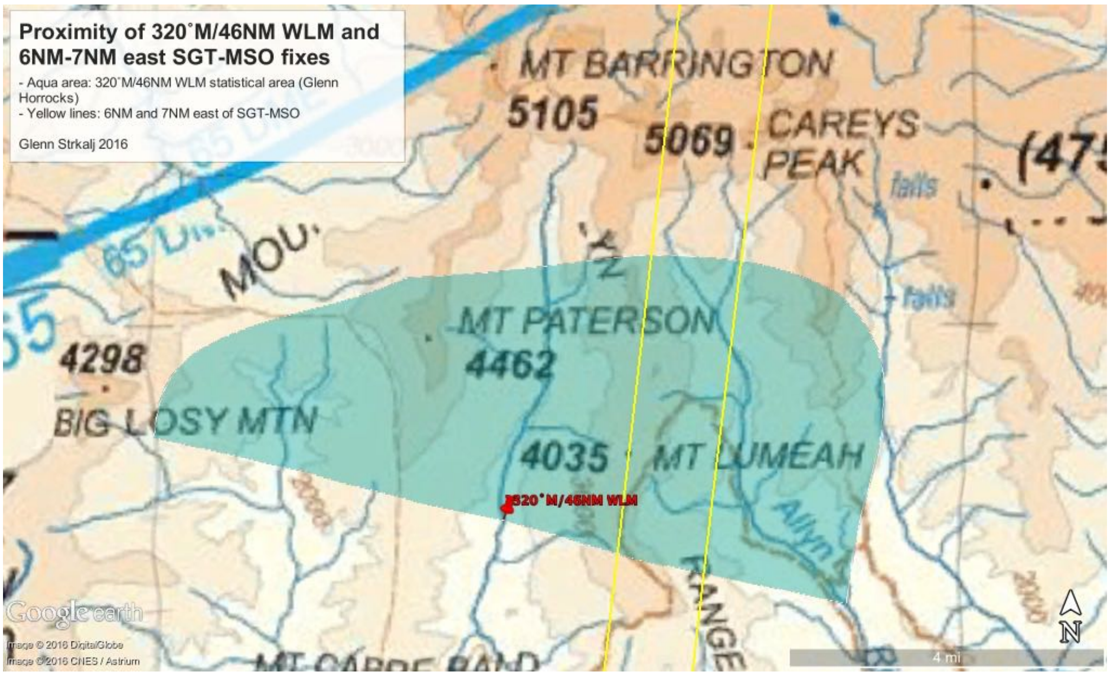


Figure 98: Close proximity of Sydney 320˚M/46NM WLM fix at 0934:30UTC to 6NM-7NM east of SGT-MSO track (yellow lines) (Base maps: Airservices Australia/OzRunways 2016, additions: Glenn Strkalj 2016, plotted on Google Earth).

Given the overlaying of the two fixes, it can be seen how the 6NM-7NM east position may be referring to the 0934:00UTC to 0934:40UTC Sector 1 fix.

Despite the close proximity, radio propagation results from sections 5.3.2.2 and 5.3.2.3 suggest that fade from Sydney ATC radar displays was unlikely to occur in the geographical position of the ASIB/RCC fix or by extrapolation, the 320˚M/46NM position from Williamtown. This is because the minimum radar interrogation altitudes found in proximity to these positions yield values well above the range expected from communication transcripts derived pilot altitude reports as specified in section 6.11.3.

The ≈6NM-7NM east position can support a *slow* turn to the east as suggested by communications transcripts and ATCO's if one uses these position lines near the ASIB/RCC or Sector1 320˚M/45NM fixes. But away from the two areas above, the ≈6NM-7NM east position does not support the radar observed slow turn to the east as there would have been many more minutes of flight time prior to radar fade (circling to stay in a similar area). This suggests a turning flight path for a significant period that does not align with radar observations.

6.12.3.4. Radar fade or intermediate fix?

Although recorded as a radar *fade* position, the 6NM-7NM east position may very well be referring to perhaps the *only* fix by Sector 1 after the *initial* fix at 0928:45UTC that was positively verbalized as a bearing/ range and recorded on communications tapes: The 320˚M/46NM from Williamtown fix between around 0934:00UTC to 0934:40UTC.

Communications transcripts show no further complete radar fixes by Sector 1 after the 320˚M/46NM fix.

The previous sub-section identified that the ≈6NM-7NM east position does lie in the statistical area of the Sector 1 320˚M/46NM fix. The ≈6NM-7NM east position may very well be another definition of the 320˚M/46NM fix by Sydney ATC. If so and given that coarse control of VH-MDX appears to have been maintained for a few minutes after 0934:00UTC, it appears more likely that the ≈6NM-7NM east position was the last *fully defined* radar position at Sydney ATC rather than a radar *fade* position.

Despite the previous, it is possible this position may indeed have been a radar *fade* position. If so, the ≈6NM-7NM east position could support the ASIB/RCC fix as a Williamtown radar fade position.

6.12.3.5. Discussion

The points raised show that it is difficult to develop a case for the 40NM north of Singleton NDB position being a radar fade position.

The approximately 6NM-7NM east of the Singleton NDB – Mont Sandon NDB/VOR track position can corroborate either the Sydney 0934:30UTC (320˚M/46NM WLM) fix or the 0936:00UTC Williamtown position (that includes the ASIB/RCC fix).

The former is more likely given radio propagation results from sections 5.3.2.2 and 5.3.2.3 coupled with *expected* radar fade times strongly suggest that radar fade at Sydney ATC was *unlikely* to have occurred at the ASIB/RCC or 320˚M/46NM fix locations.

Additionally, considering that *substantial* control of VH-MDX appears to have been maintained for a few minutes after the 320˚M/46NM fix, this also somewhat suggests that the ≈6NM-7NM east position correlating to the 320˚M/46NM fix area is more likely an *intermediate* position rather than a radar *fade* position.

It can then be seen that the 6NM-7NM east position is *unlikely* to be a radar *fade* position based on current understanding.

6.12.3.6. Conclusions

The 40NM north of Singleton NDB position is *not* classed as a valid radar *fade* position.

The 6NM-7NM east of the Singleton NDB – Mount Sandon NDB/VOR track position could weakly support a radar fade at the ASIB/RCC fix but much more likely be referring to the Sector 1 0934:30UTC (320˚M/46NM WLM) *intermediate* fix.

6.12.4. Conclusions: Three final Sydney radar fixes

The *Sydney deposition final fix* is *unlikely* representative of the radar *fade* position of VH-MDX at Sydney ATC but can be used to offer a gross error check in final *track direction*.

The *40NM north of Singleton* '*last sighting*' position is *highly unlikely* to be a VH-MDX radar fade position.

The *6NM-7NM east of the Singleton NDB – Mount Sandon NDB/VOR track* could *weakly* back a radar *fade* at either the 320˚M/46NM or ASIB/RCC positions but is more likely referring to the only fully defined Sydney ATC radar *intermediate* position after initial identification recorded on communications tapes: the Sydney Sector 1 0934:00 to 0934:40UTC 320˚M/46NM from Williamtown fix.

The *≈330˚M/45NM from Williamtown fix* at 0939UTC is currently viewed as the *most defensible* radar fade position available of VH-MDX.

7. Conclusions

An overview of 1981 Sydney ATS and radar was carried out.

Many useful findings have been and will be used in the future to shed light on the VH-MDX accident.

This document provides a robust background into 1981 Sydney ATS and radar to support VH-MDX research.

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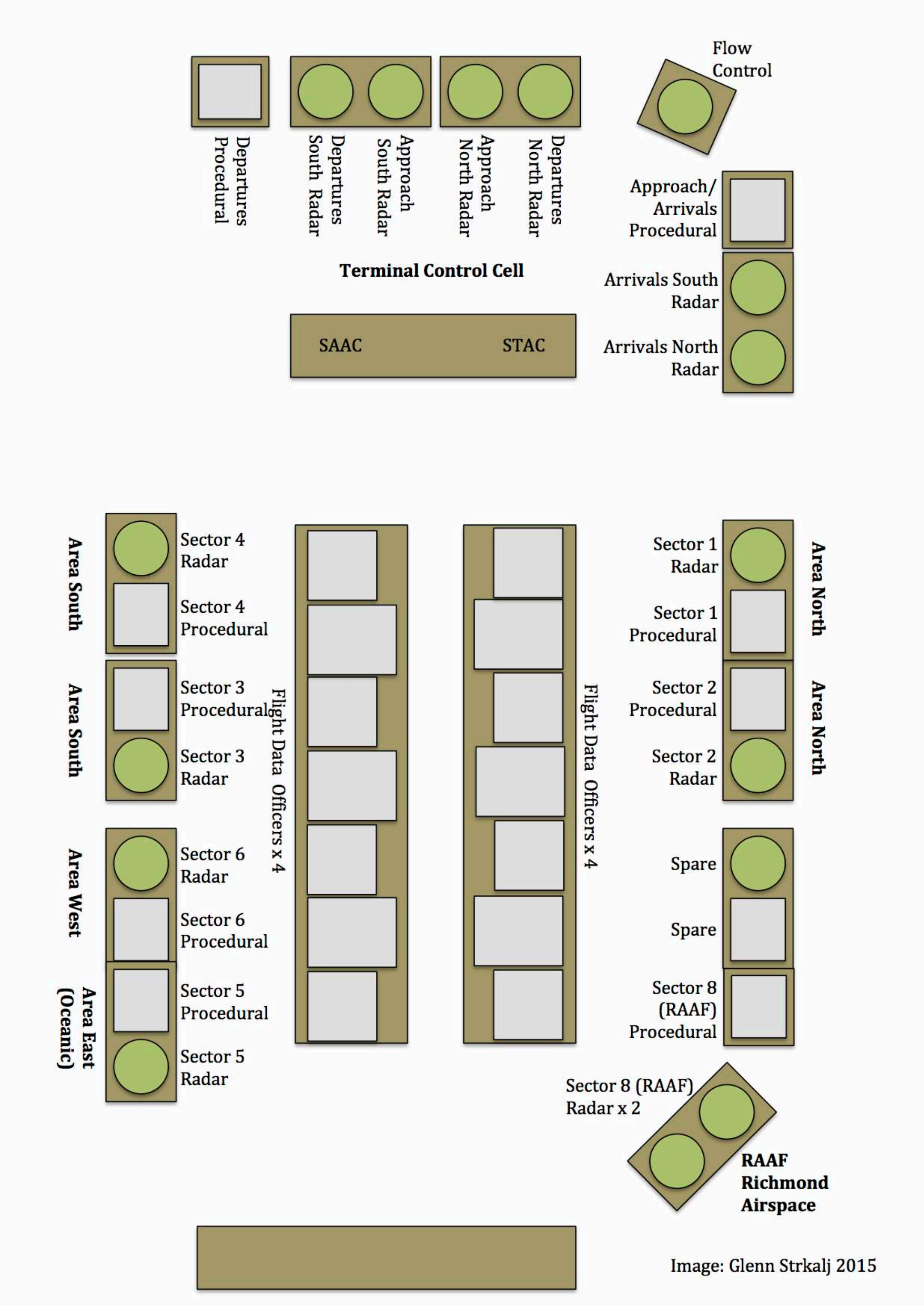
Annex A: Sydney Area Approach Control Centre (AACC) floor plan



Annex B: Sydney AACC photos 1970's-early 1980's

Figure 99: Sydney AACC. The flight data officers occupied the centre tables, Sector ATCO's the workstations at either side, terminal ATCO's at the very rear whilst the SAAC and STAC sat at the tables at the far end of the flight data officer tables (Photo: Australian Government (Department of Transport) c.1970's, courtesy of the Airways Museum).

Figure 100: Sydney AACC manned (Photo: Australian Government (Department of Transport) c.1980, courtesy of the Airways Museum).

Figure 101: Terminal control cell. This part of the AACC focused on arrivals, departures and flow control into Sydney Kingsford Smith airport. The table in the immediate foreground is where the SAAC and STAC sat (Photo: Australian Government (Department of Transport) c.1970's, courtesy of the Airways Museum).

Figure 102: View from the STAC/SAAC desk across the AACC. STAC sat at left position, the SAAC at the right. The terminal control cell was located behind the STAC and SAAC (Photo: Australian Government (Department of Transport) c.1970's, courtesy of the Airways Museum).

Annex C: Sydney Flight Service Centre (FSC) photos

Figure 103: Sydney FSC circa 1970's. The Supervisor Flight Service (SFS) desk is in the foreground (Photo: Australian Government (Department of Transport) c.1970's, courtesy of the Airways Museum).

Annex D: Sydney TAR and RSR photos

Figure 104: Sydney RSR (left) and TAR (right). This photo was taken pre-SSR installation (Photo: Australian Government c.1970's courtesy of the Airways Museum and Civil Aviation Historical Society).

Figure 105: Sydney TAR (left) and RSR (right). This photo was taken pre-SSR installation (Photo: Australian Government c.1970's courtesy of the Airways Museum and Civil Aviation Historical Society).


Figure 106: Sydney RSR antenna. SSR is installed (Photo: M. Price c.1983).

Annex E: Sydney TAR and RSR head locations

Figure 107: Sydney airport plan view 1977. The Sydney TAR head is centered within the red circle whilst the longer range Sydney RSR is centered within the green circle (Photo: Sydney Airport Corporation Limited 2014: additions: Glenn Strkalj 2014).

Annex F: Topographic maps: The Round Mountain

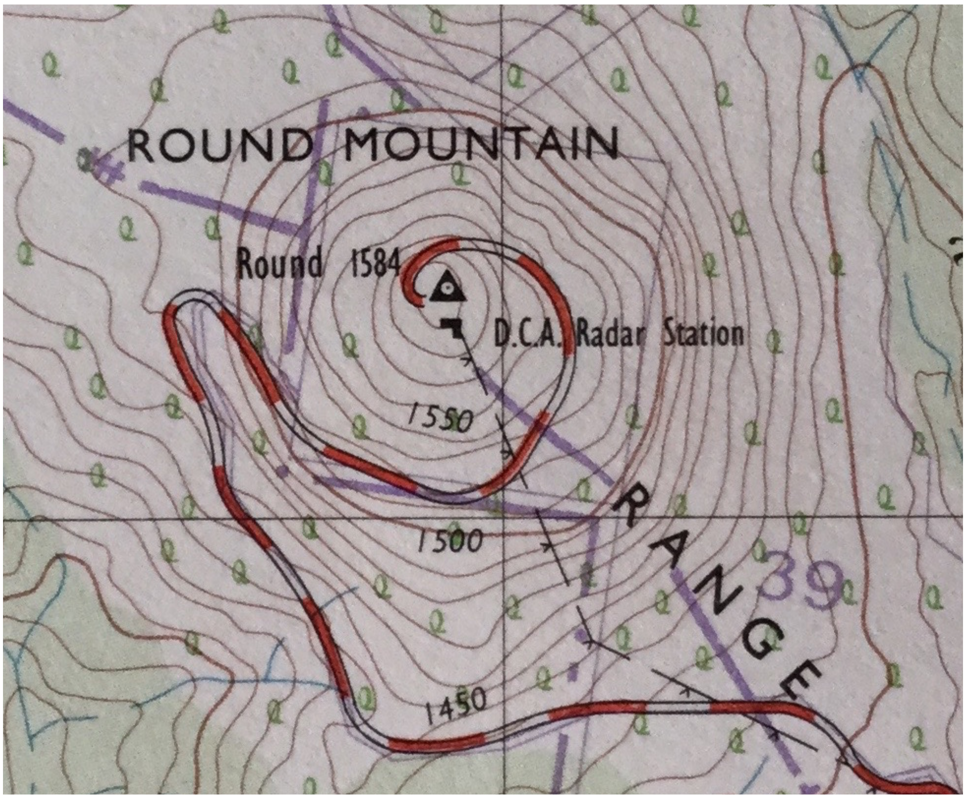


Figure 108: Topographical map 1976. The Round Mountain RSR was installed only a few years prior to the publication of this map. Clearly marked is the position of the Radar Station. Radar heads generally need to be located close to the radar transceiver to minimise attenuation. The head was located at the north-east corner of the building depicted (NSW Government (Central Mapping Authority) 1976).

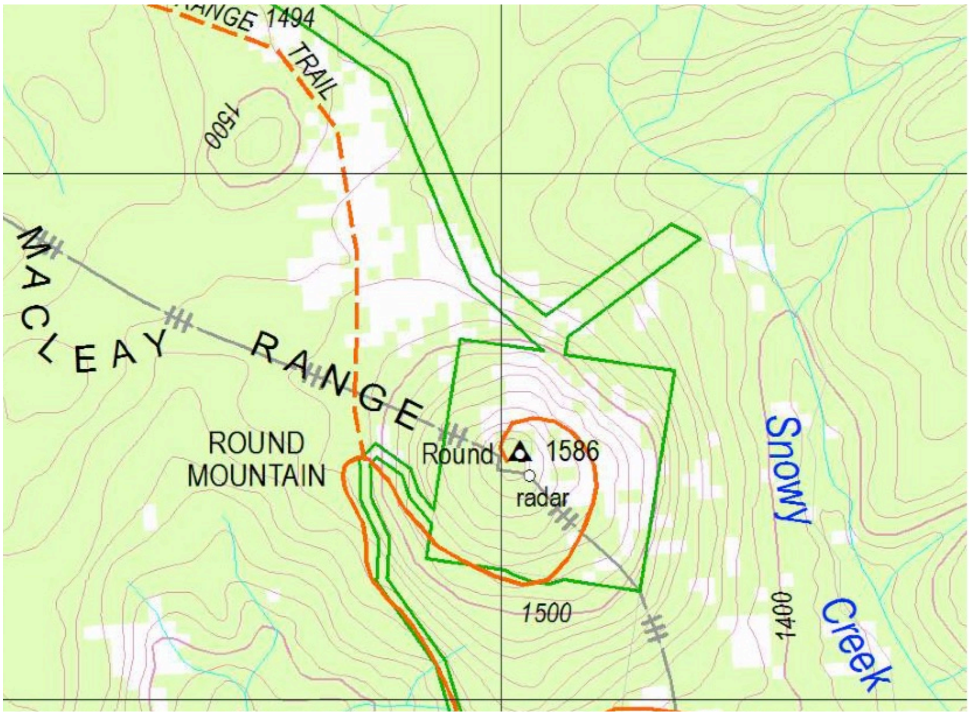


Figure 109: The Round Mountain RSR location. Clearly marked on this topographic map is the position of The Round Mountain RSR head at the white circle (Land and Property Information NSW c.1990's).

Annex G: Sydney Northern Mosaic display photos

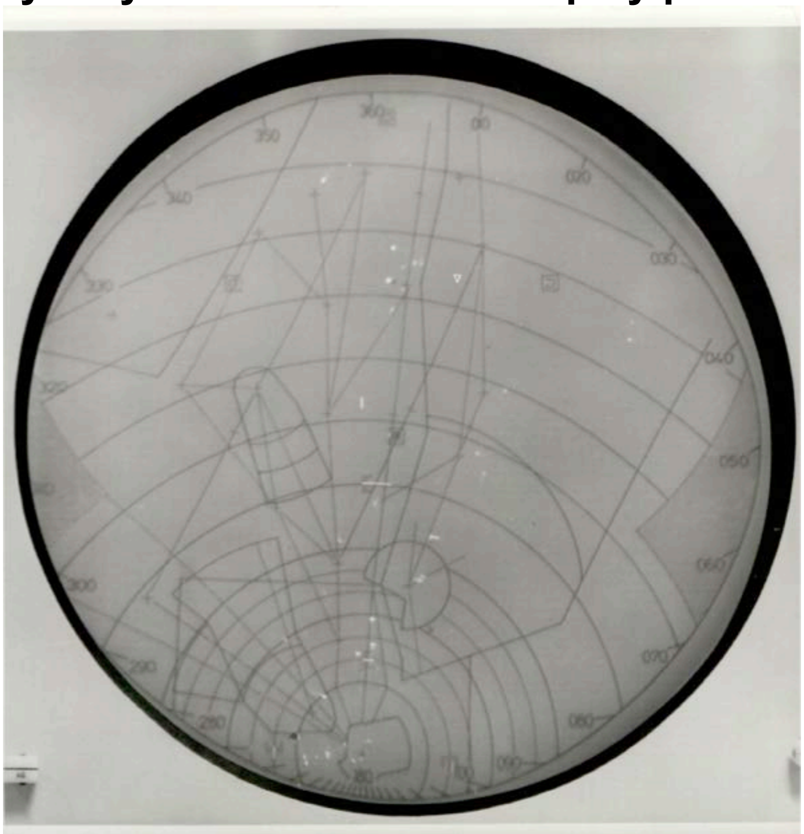


Figure 110: Sydney Northern Mosaic Bright display (Photo: M. Price c.1983).

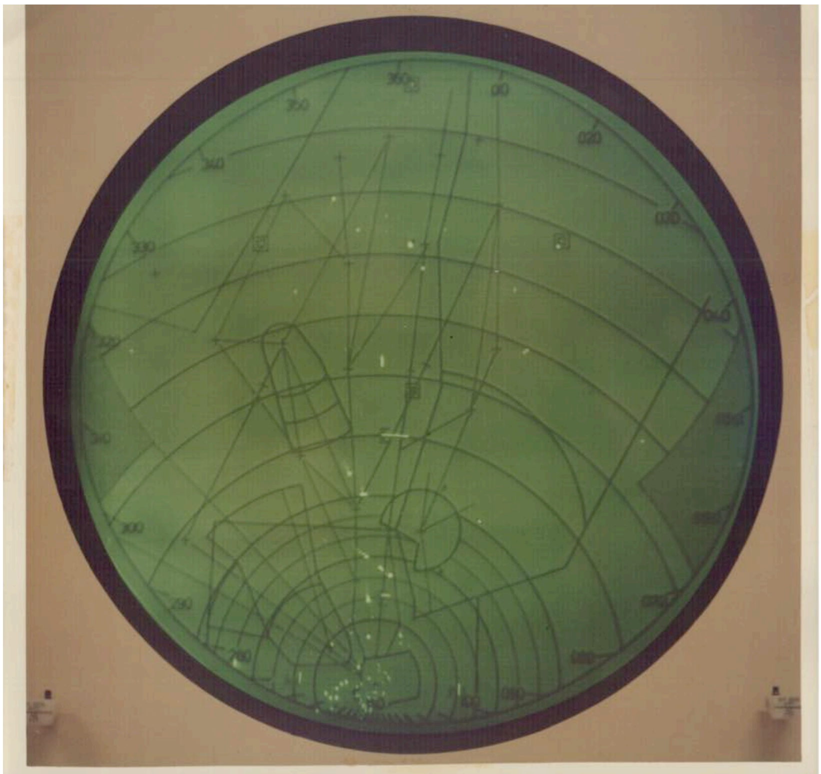


Figure 111: Sydney Northern Mosaic Bright display (Photo: Australian Government (Department of Transport) c.1908's, courtesy of the Airways Museum).

Figure 112: Sydney Northern Mosaic Bright display c.1983.

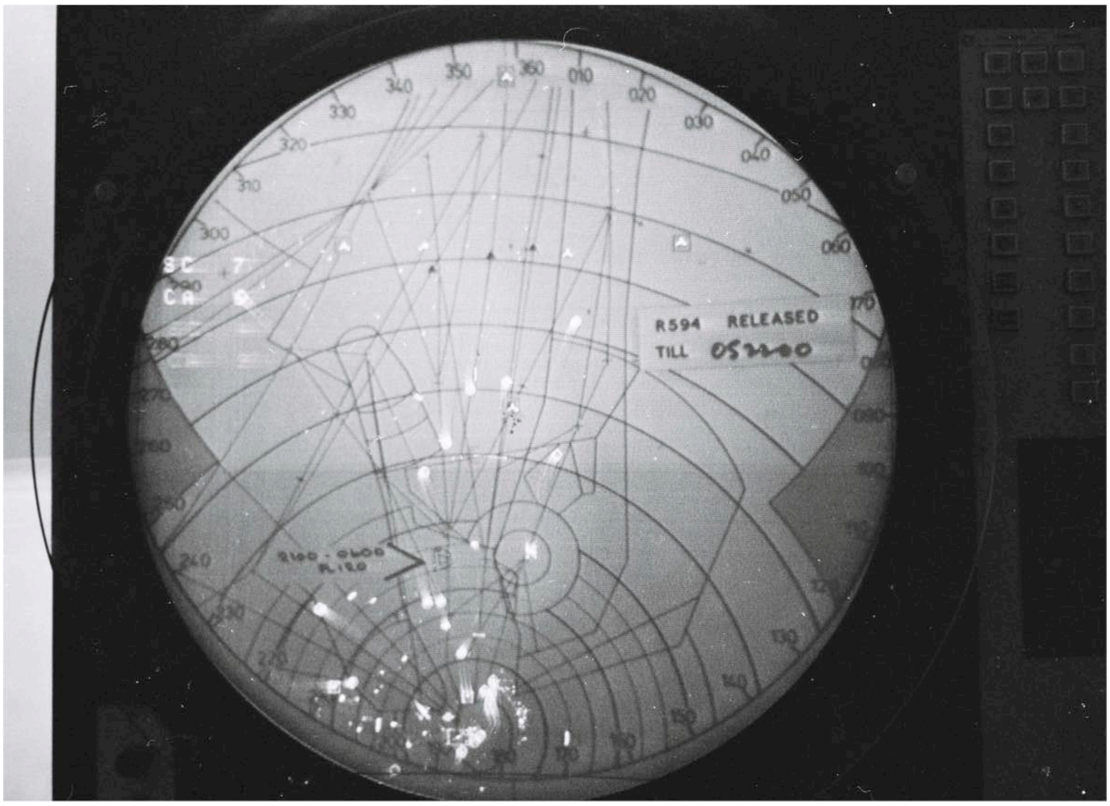


Figure 113: Sydney Northern Mosaic Bright display (Photo: M. Price c.1983).

Annex H: Other Sydney display programs

Sydney 20NM

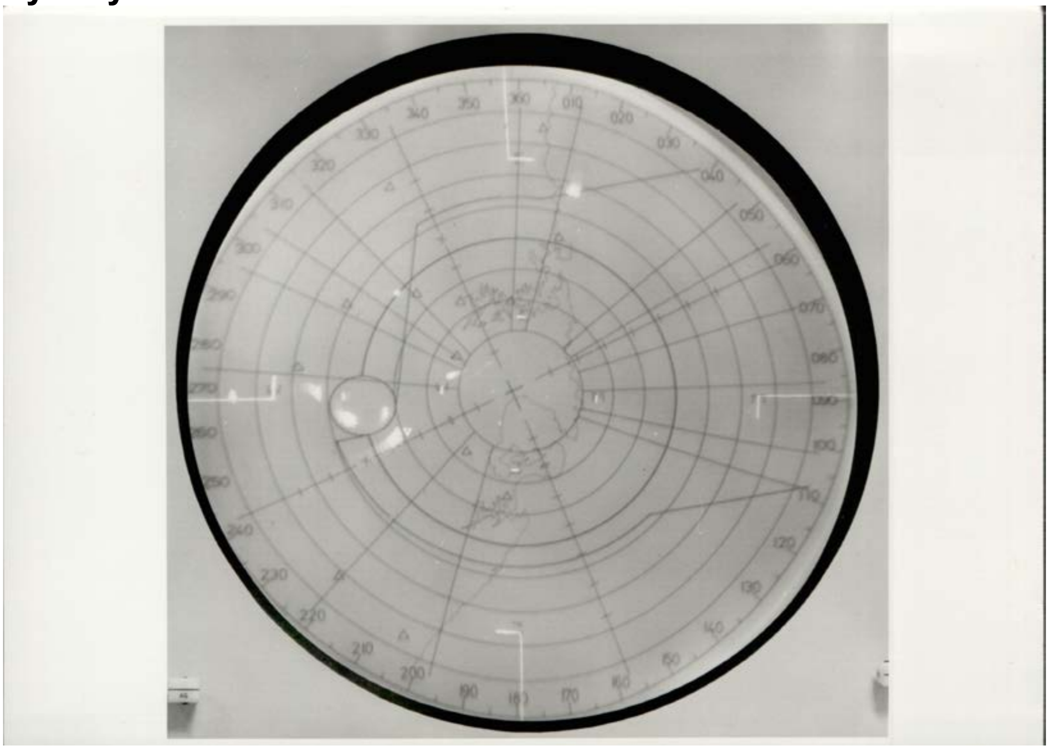


Figure 114: Sydney 20NM program c.1970’s (Photo courtesy of Airways Museum).

Sydney 50NM

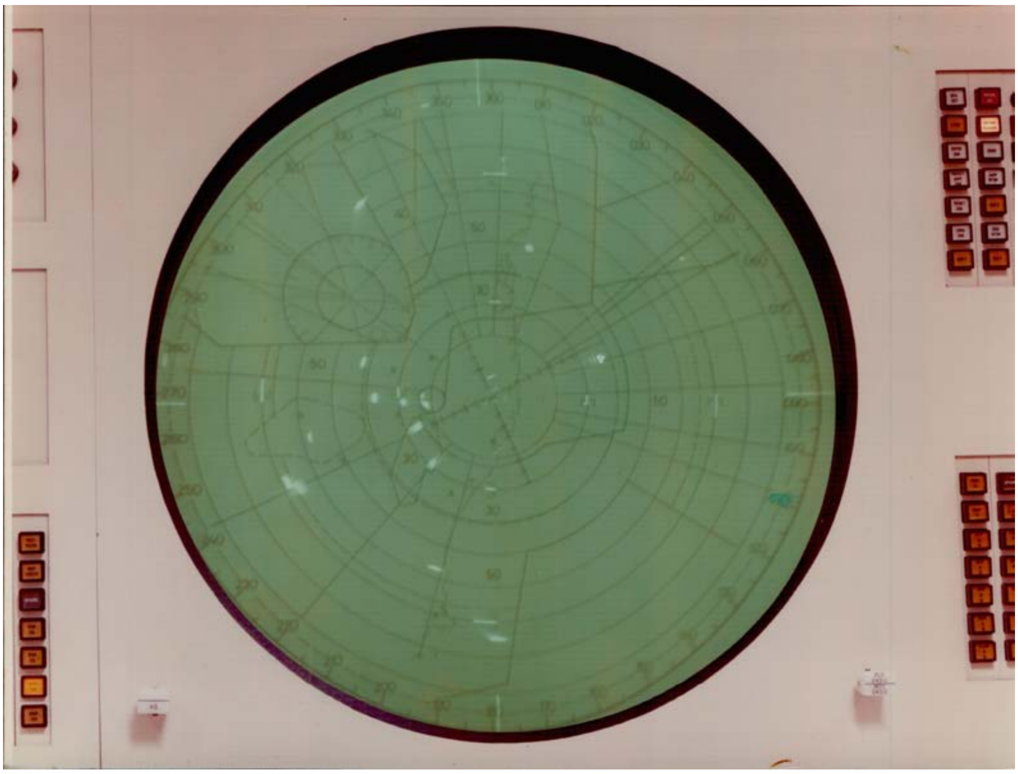


Figure 115: Sydney 50NM Bright display c.1980’s (Photo courtesy of Airways Museum).

Sydney 100NM

Figure 116: Sydney 100NM Bright display (Photo courtesy of Airways Museum).

Sydney 160NM

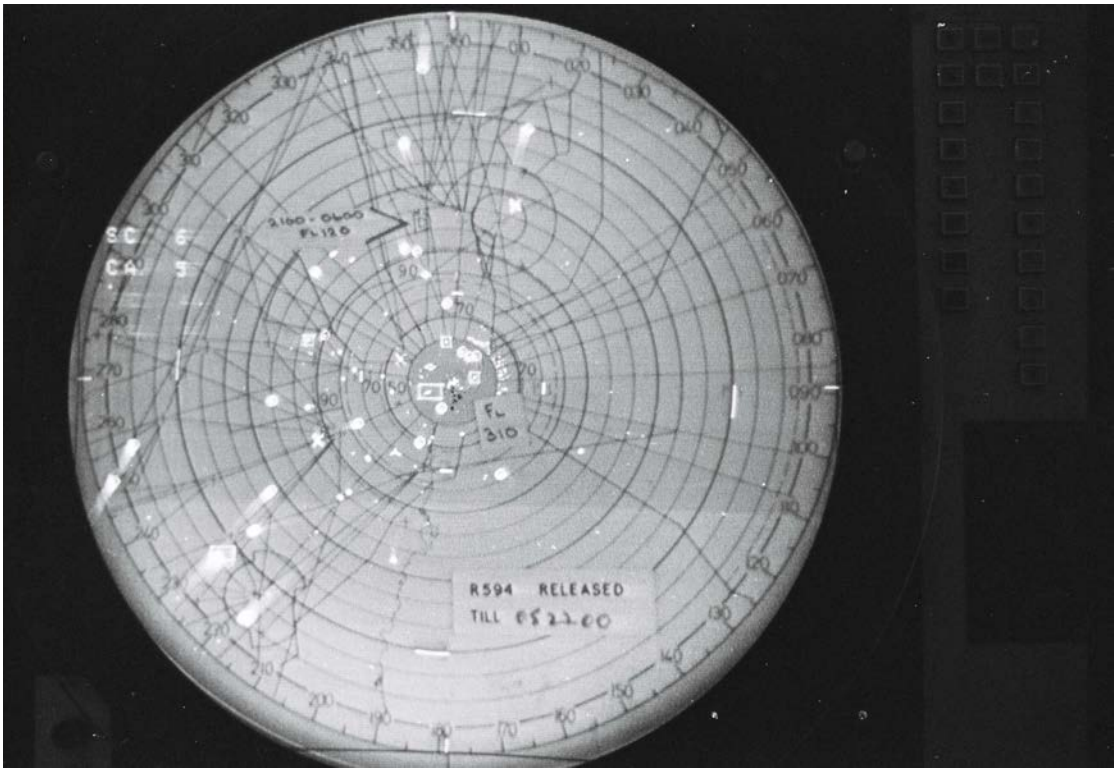


Figure 117: Sydney 160NM Bright display (Photo: M. Price c.1983).

Sydney Southern Mosaic

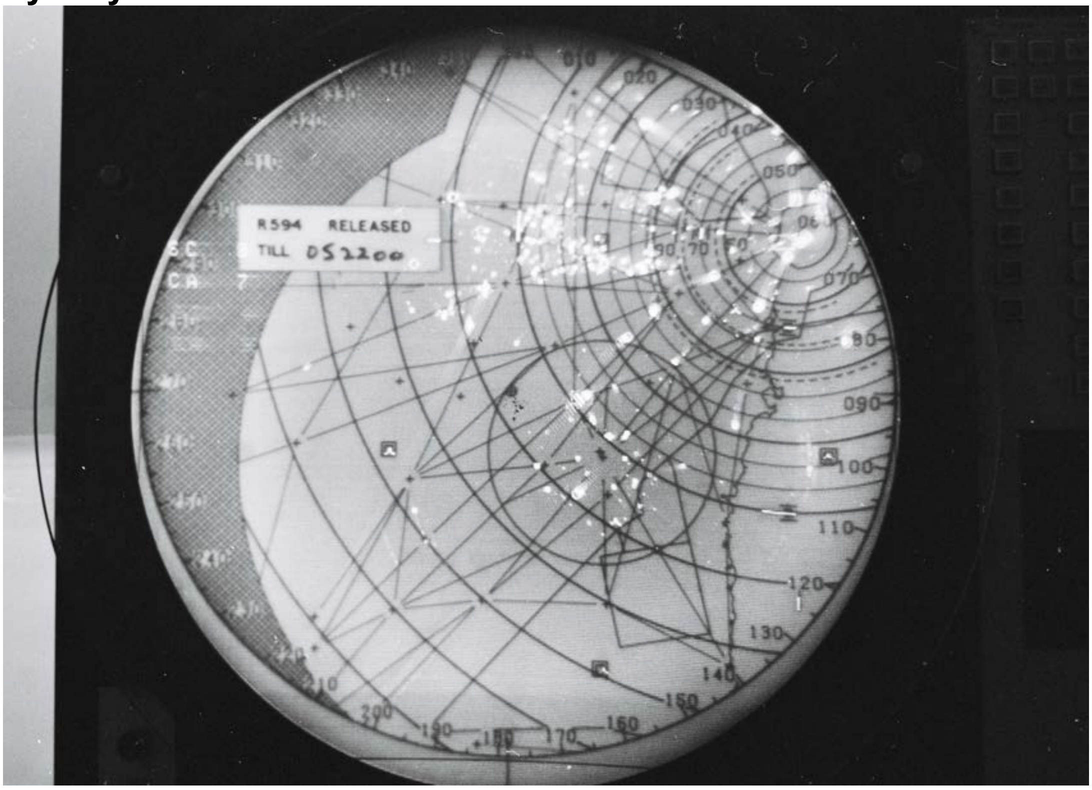


Figure 118: Sydney Southern Mosaic Bright display program (Photo: M. Price c.1983).

Figure 119: Sydney Southern Mosaic Bright display program (Photo courtesy of Airways Museum).

Figure 120: Sydney Southern Mosaic Bright display (Photo: Australian Government (Department of Transport) c.1970's, courtesy of Airways Museum).

Annex I: Sydney AACC Sector control workstations

Figure 121: Sydney AACC Sector workstation: This appears to be the spare Bright display and procedural area (left) and the RAAF Sector 8 Bright displays and procedural station (right) (Photo: Australian Government (Department of Transport) c. early 1980's or 1970's, courtesy of Airways Museum).

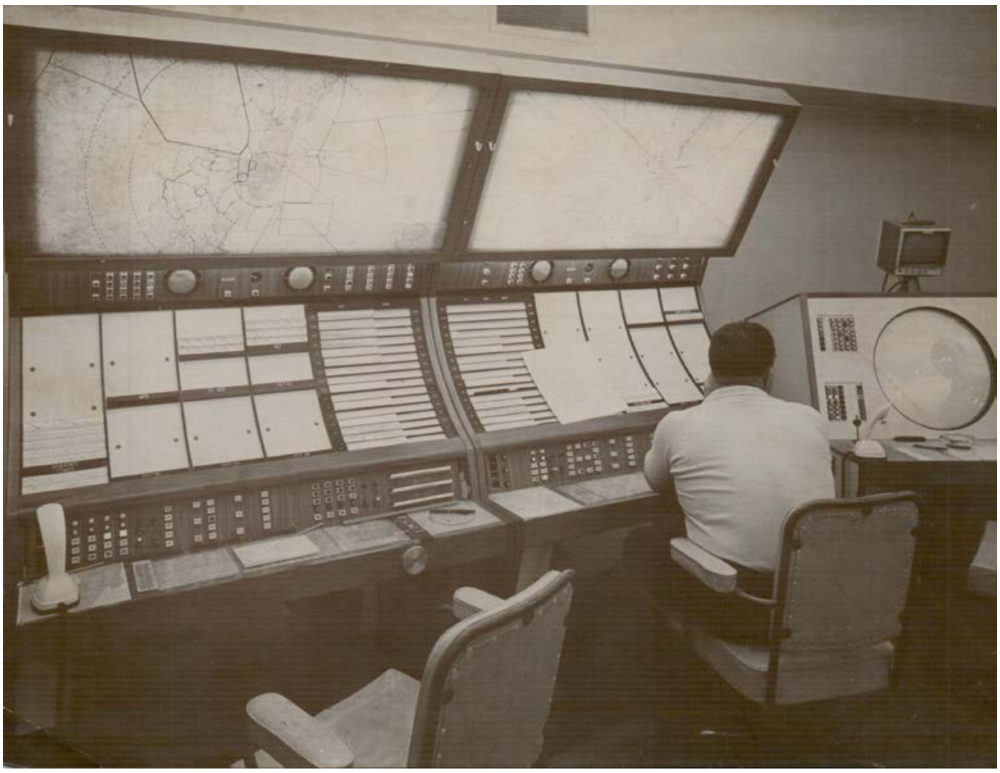


Figure 122: Sydney AACC workstation (Photo: Australian Government (Department of Transport) c.1970's, courtesy of Airways Museum).

Figure 123: Sydney Sector 4 Bright display console (Photo: Australian Government (Department of Transport) c.1970’s, courtesy of Airways Museum).

Annex J: Flight test of The Round Mountain PSR 1972

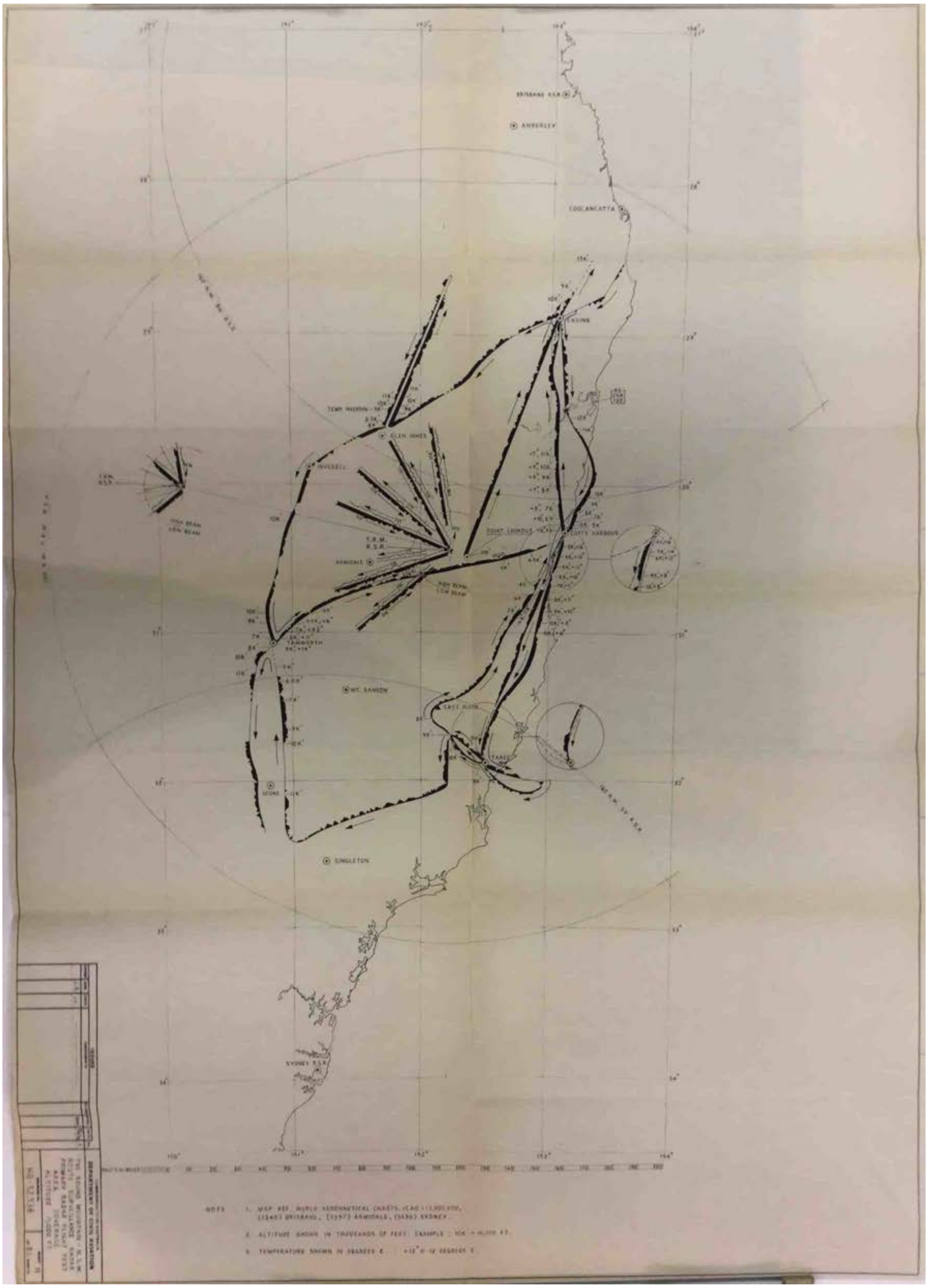


Figure 124: 11000'AMSL area coverage: The Round Mountain PSR 1972. The Taree to north of Singleton leg presented was around 8-9NM south of the VH-MDX accident area so gives good insight into PSR coverage near the accident area (National Archives of Australia (Department of Transport) 1972)[38].

Annex K: SSR Radio propagation analysis variables

Ground station power at the antenna: 125.9kW EIRP: (28dBW = 631W = 58dBm into antenna). This is the power output used during testing of the Sydney and The Round Mountain Cossor SSR700 RSR's.

Ground station antenna gain: 23dBi (Actual *minimum* antenna gain)

Ground station line loss: 0db (as power is at the antenna)

Transponder receiver sensitivity: based on the ICAO maximum sensitivity value of -77.0dBm + 0.5dBm buffer (-77.5dBm = 29.8 microvolts).

Transponder line loss: ICAO 3.0dB nominal

Transponder antenna gain: 2dB

Results require line of sight *and* received signal better than or equal to -77.5dBm (-77.0dBm (ICAO standard maximum sensitivity) with 0.5dBm buffer). -77.5dBm = 29.8 microvolts.

Transponder link reliability: 90%

Analysis frequency: 928MHz (nearest in software to 1030MHz (∆= -102MHz))

Variations of 30 meters can be present in STRM (Shuttle Terrain Radar Mission) data used in Google Earth and Radio Mobile On-Line: both being sources of data for this analysis.

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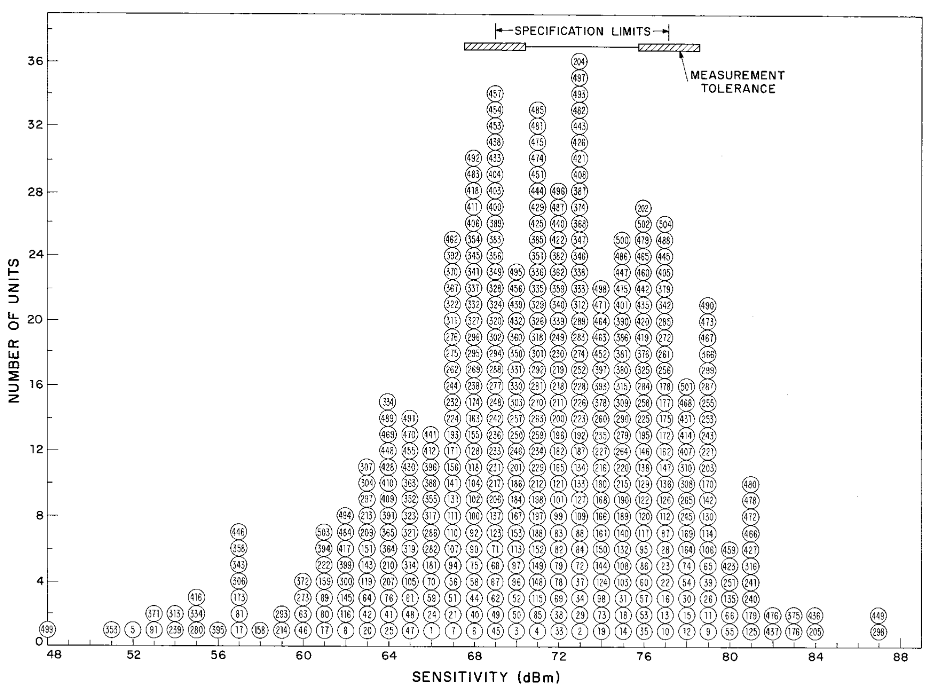


Fig. 17. Sensitivity – general aviation transponders.

Figure 125: Results of a study into Aircraft transponder sensitivity (Graph: G.V Colby & E.A Crocker, 1972, *Final Report: Transponder Test Program*, 12 April 1972, Lincoln Laboratory, Massachusetts Institute of Technology 1972).

Annex L: Sydney SSR RSR propagation results

L.1. Sydney RSR to initial Sydney radar fix

The accepted centroid of the initial Sydney radar fix determined in section 6.1.5 was used.

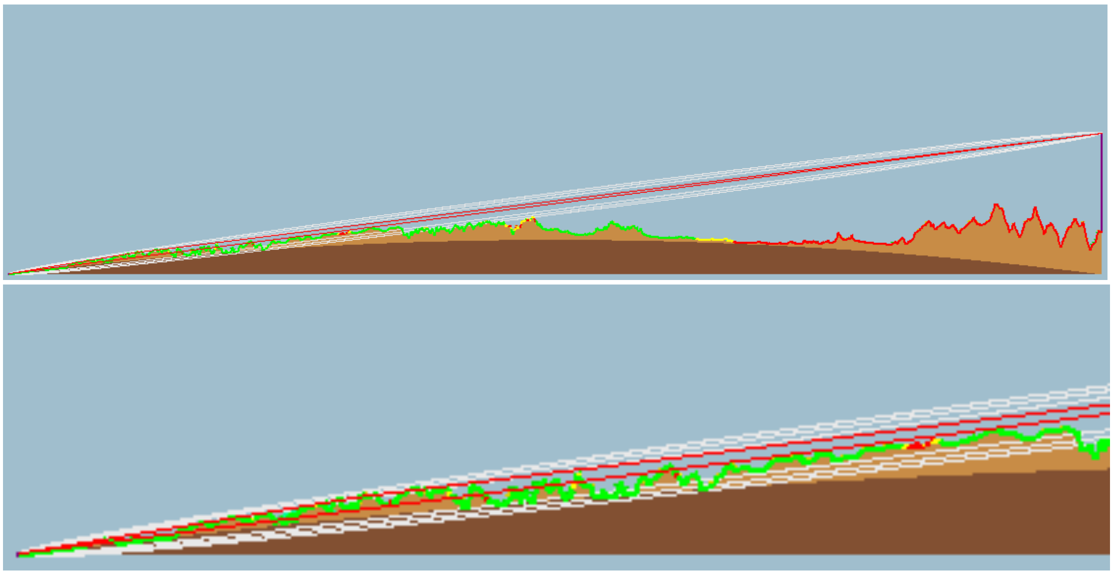


Figure 126: Sydney RSR to initial radar fix at 10000’AMSL: No line of sight, received signal: -101.53dBm, no link. Terrain obstruction is readily apparent (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

L.2. Sydney RSR to 324˚M/47NM fix

This position will be shown in upcoming sections to be one valid definition of the 0936:00UTC Williamtown fix.

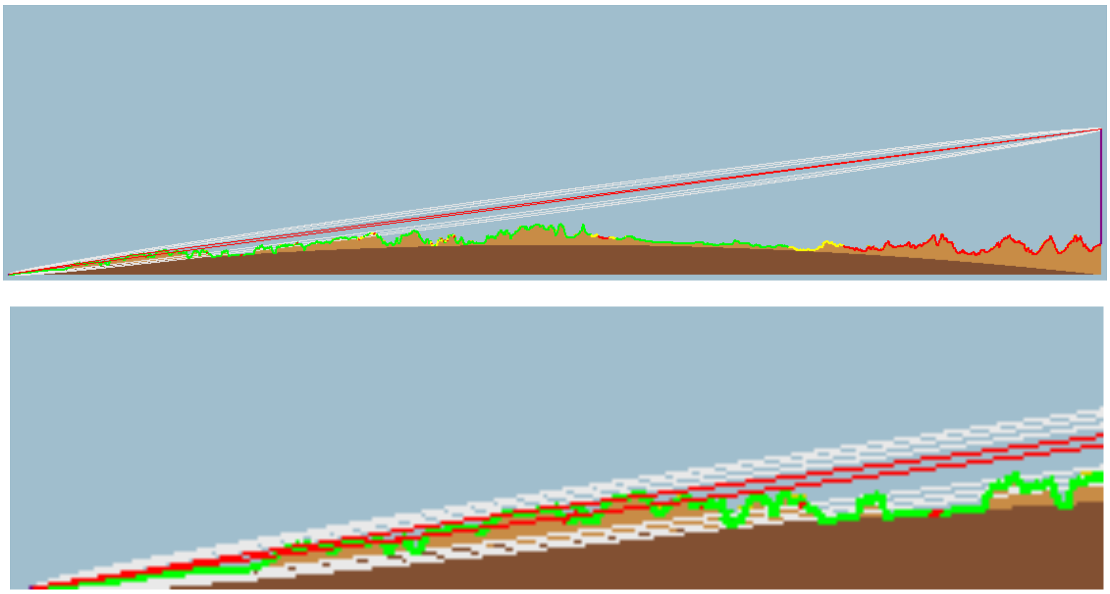


Figure 127: Sydney RSR to 324˚M/47NM WLM at 10000’AMSL: No line of sight, received signal: -99.45dBm, no link. Terrain obstruction is readily apparent (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

L.3. Sydney RSR to ASIB/RCC final fix

The centroid of the ASIB/RCC radar fix was determined by plotting 325.23˚M/47NM from Williamtown using 1981 magnetic variation. This fix is one valid definition of the 0936:00UTC Williamtown fix.

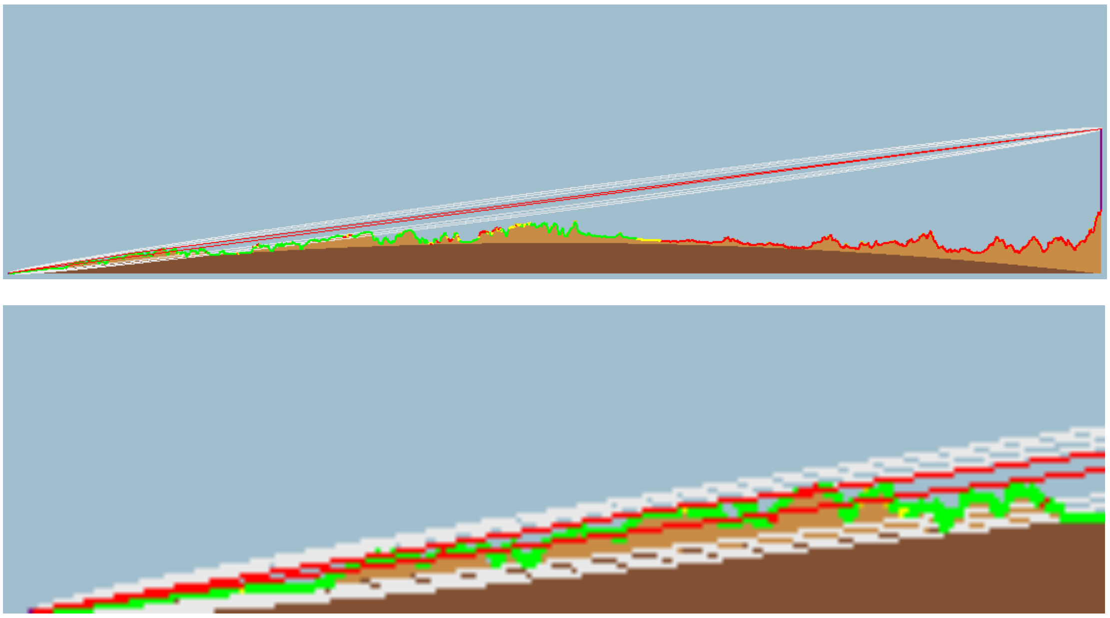


Figure 128: Sydney RSR to ASIB/RCC final radar fix at 10000'AMSL: No line of sight, received signal: -100.58dBm, no link. Terrain obstruction is readily apparent (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

L.4. Sydney RSR to 330˚M/45NM from Williamtown Sydney final fix

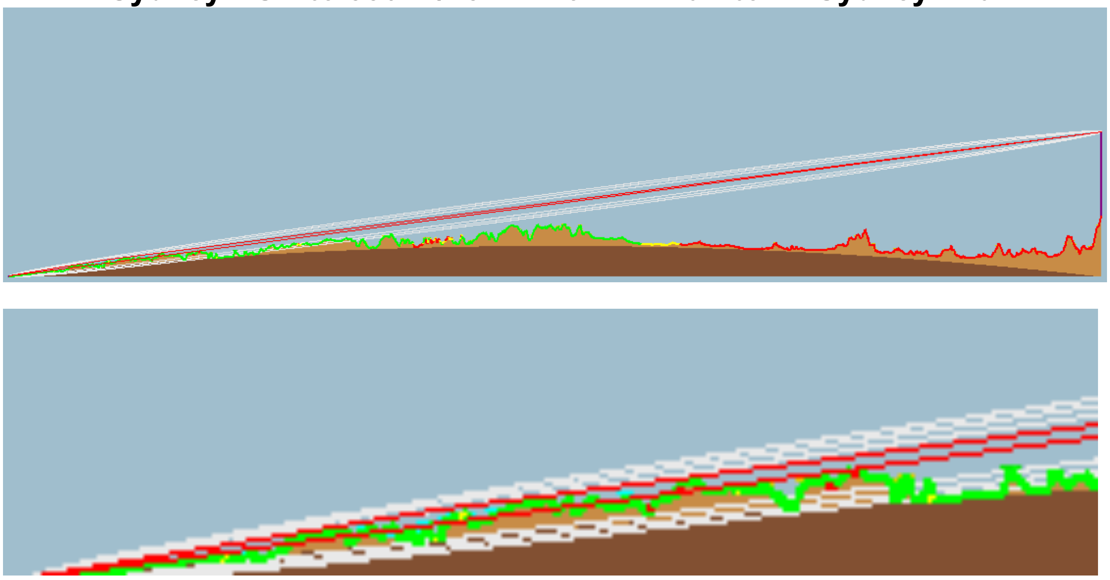


Figure 129: Sydney RSR to 330˚M/45NM from Williamtown at 10000'AMSL: No line of sight, received signal: -99.39dBm. VH-MDX could not be interrogated by Sydney RSR (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

L.5. Sydney RSR to Sydney deposition final radar fix

The accepted centroid of the Sydney deposition final radar fix determined in section 6.11.1.5 was used.

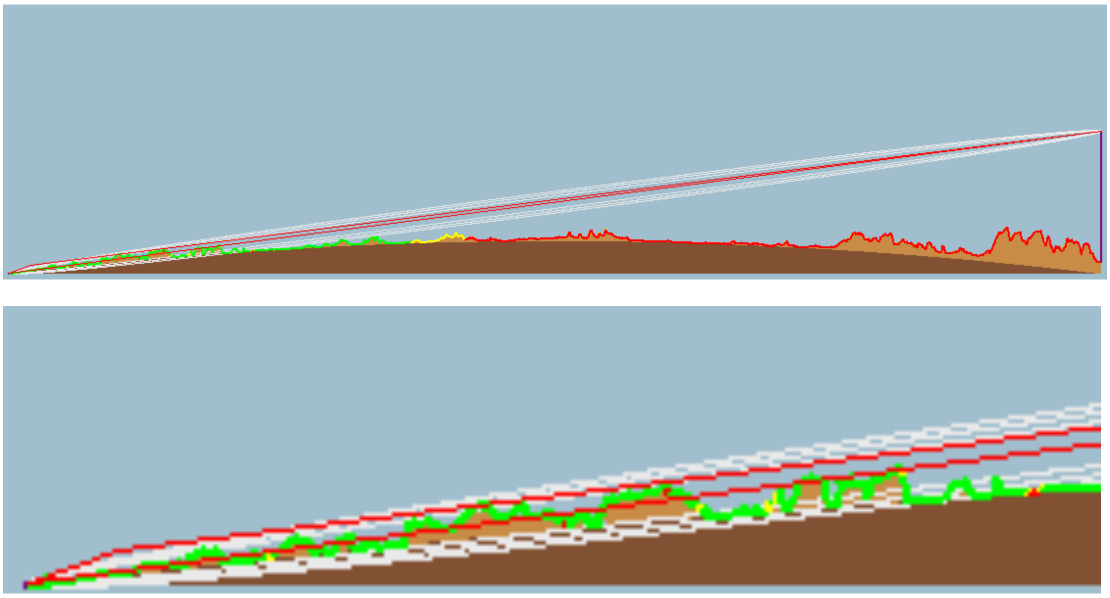


Figure 130: Sydney RSR to final deposition fix at 10000'AMSL: No line of sight, received signal: -118.02dBm, no link. Terrain obstruction is readily apparent (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

Annex M: The Round Mountain SSR RSR propagation results

M.1. General results

Generally, The Round Mountain RSR could interrogate VH-MDX below 10000’ AMSL.

High terrain in the area around Mt Sugarloaf to Mt Carrington being approximately half way between the radar head and VH-MDX is the main obstruction to radar propagation in the Barrington ranges area.

M.2. The Round Mountain RSR to initial Sydney radar fix

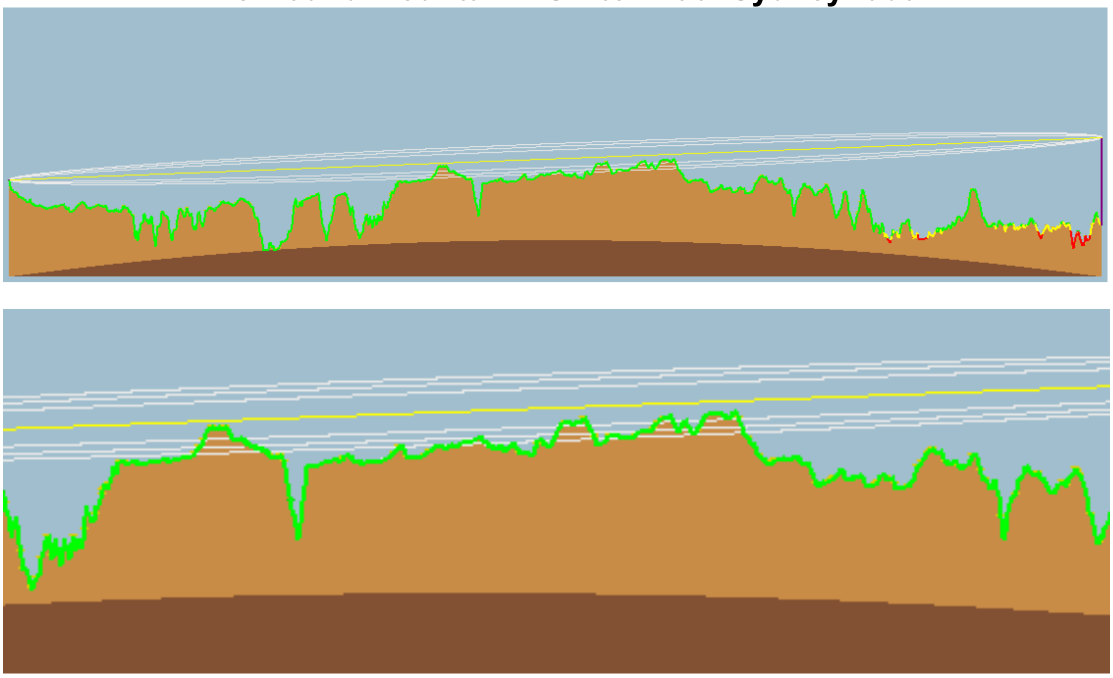


Figure 131: TRM RSR to initial Sydney radar fix at 7200’AMSL: Line of sight, received signal: -76.68dBm. VH-MDX could be interrogated by TRM at this position down to 7200’AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

M.3. The Round Mountain RSR to ASIB/RCC fix

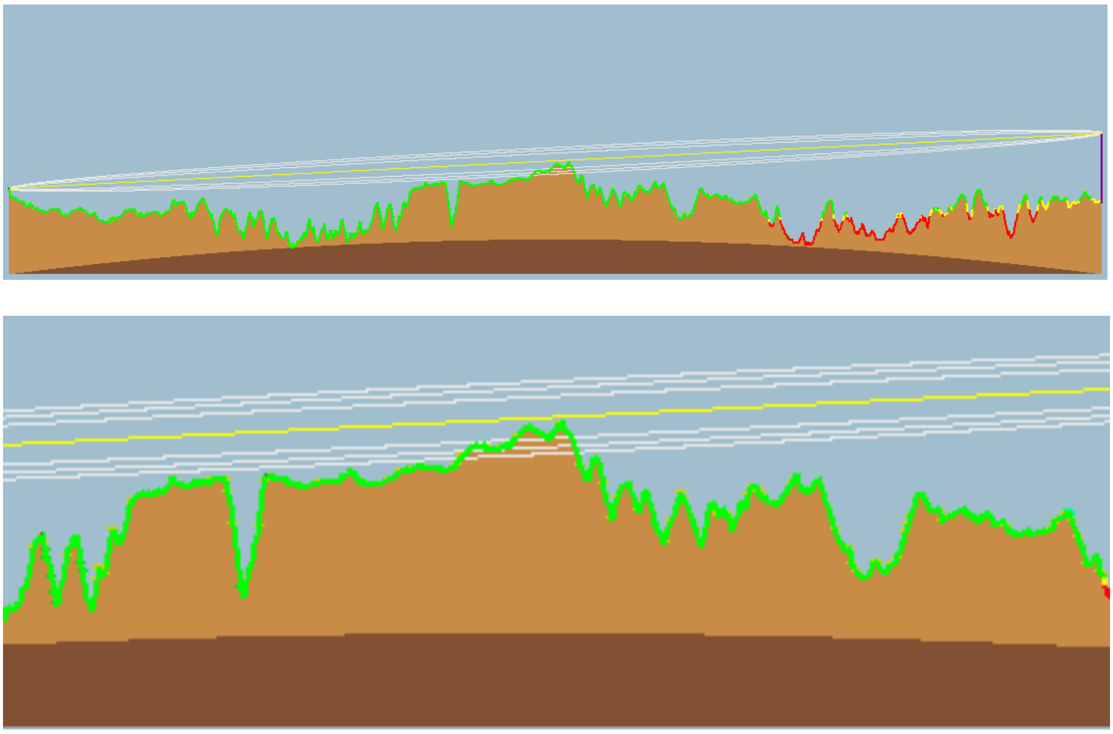


Figure 132: TRM RSR to ASIB/RCC fix at 8200'AMSL: Line of sight, received signal: -77.60dBm (accepted as link as a ≈ 10'-20' altitude increase would result in the -77.50dBm cutoff). VH-MDX could be interrogated by TRM at this position down to ≈8200'AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

M.4. The Round Mountain RSR to 324˚M/47NM WLM

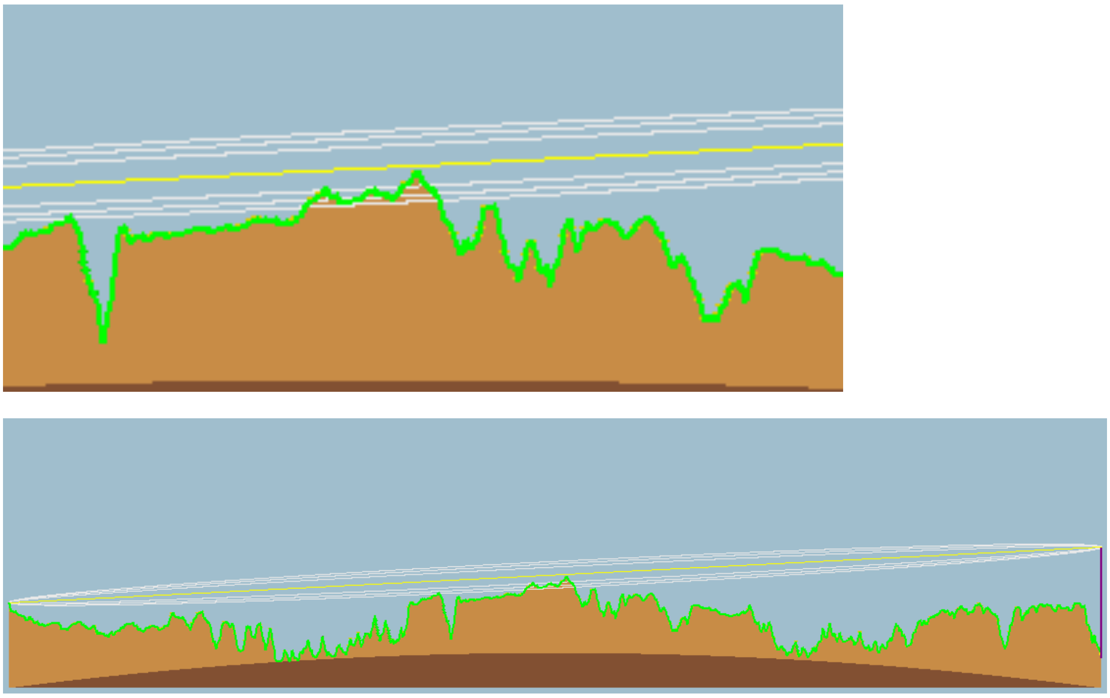
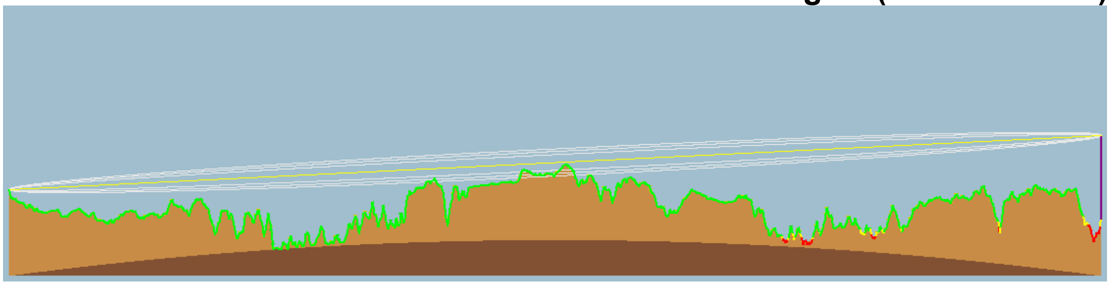


Figure 133: TRM RSR to 324˚M/47NM WLM at 8200'AMSL: Line of sight, received signal: -76.88dBm. VH-MDX could be interrogated by TRM at this position down to ≈8200'AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

M.5. The Round Mountain RSR to MPP 11 Aug 81 (323˚M/46.9NM)



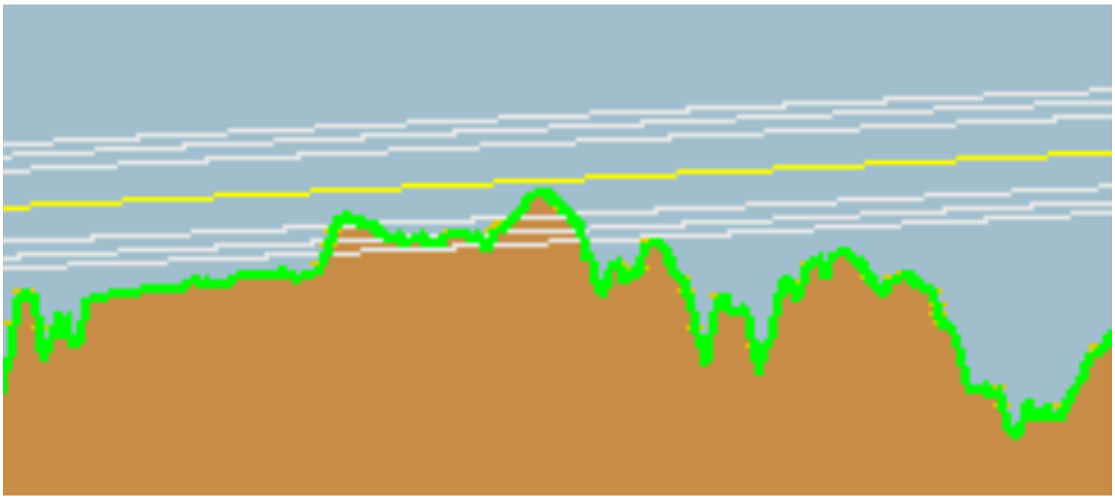
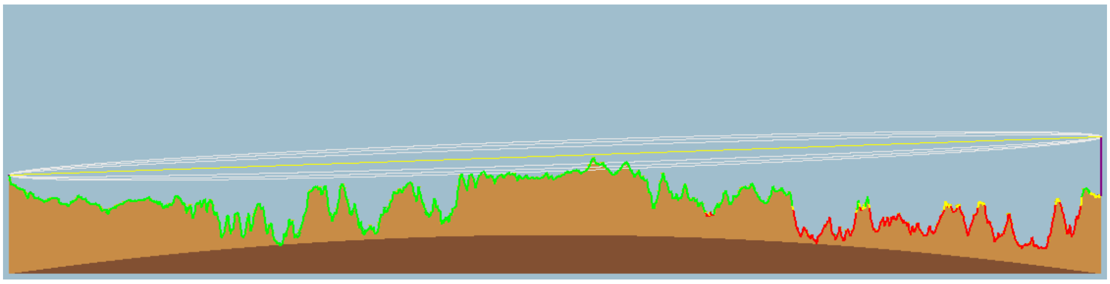


Figure 134: TRM RSR to 323˚M/46.9NM WLM at 8100’AMSL: Line of sight, received signal: -76.44dBm. VH-MDX could be interrogated by TRM at this position down to ≈8100’AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

M.6. The Round Mountain RSR to 330˚M/45NM WLM Sydney final fix



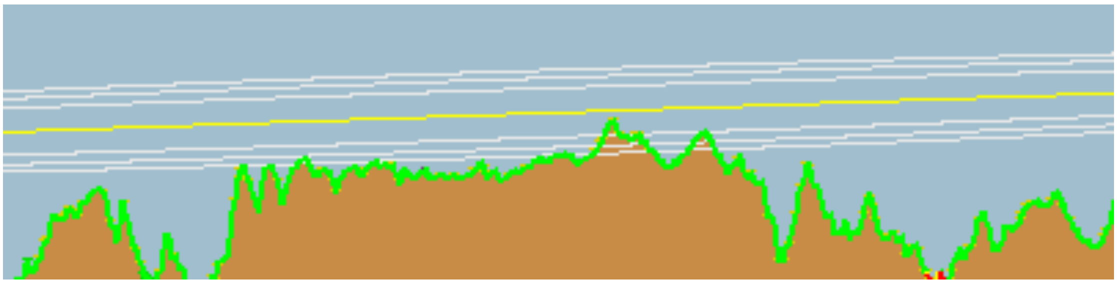


Figure 135: TRM RSR to 330˚M/45NM WLM at 7000’AMSL: Line of sight, received signal: -76.43dBm. VH-MDX could be interrogated by TRM at this position down to 7000’AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

M.7. The Round Mountain RSR to Sydney deposition final radar fix

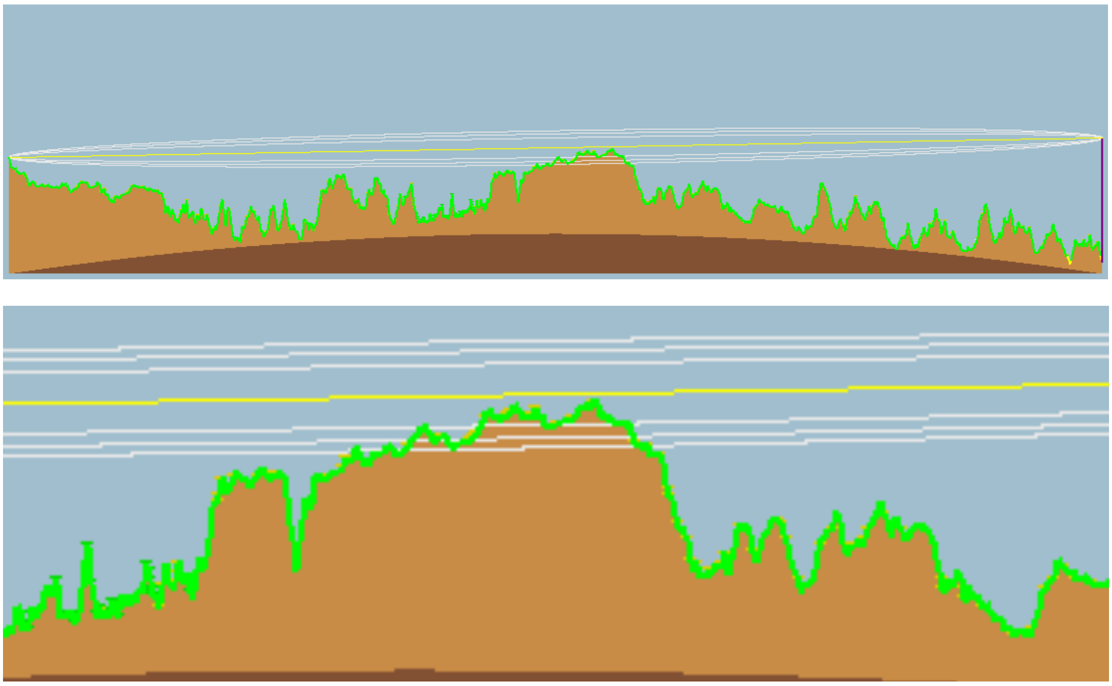
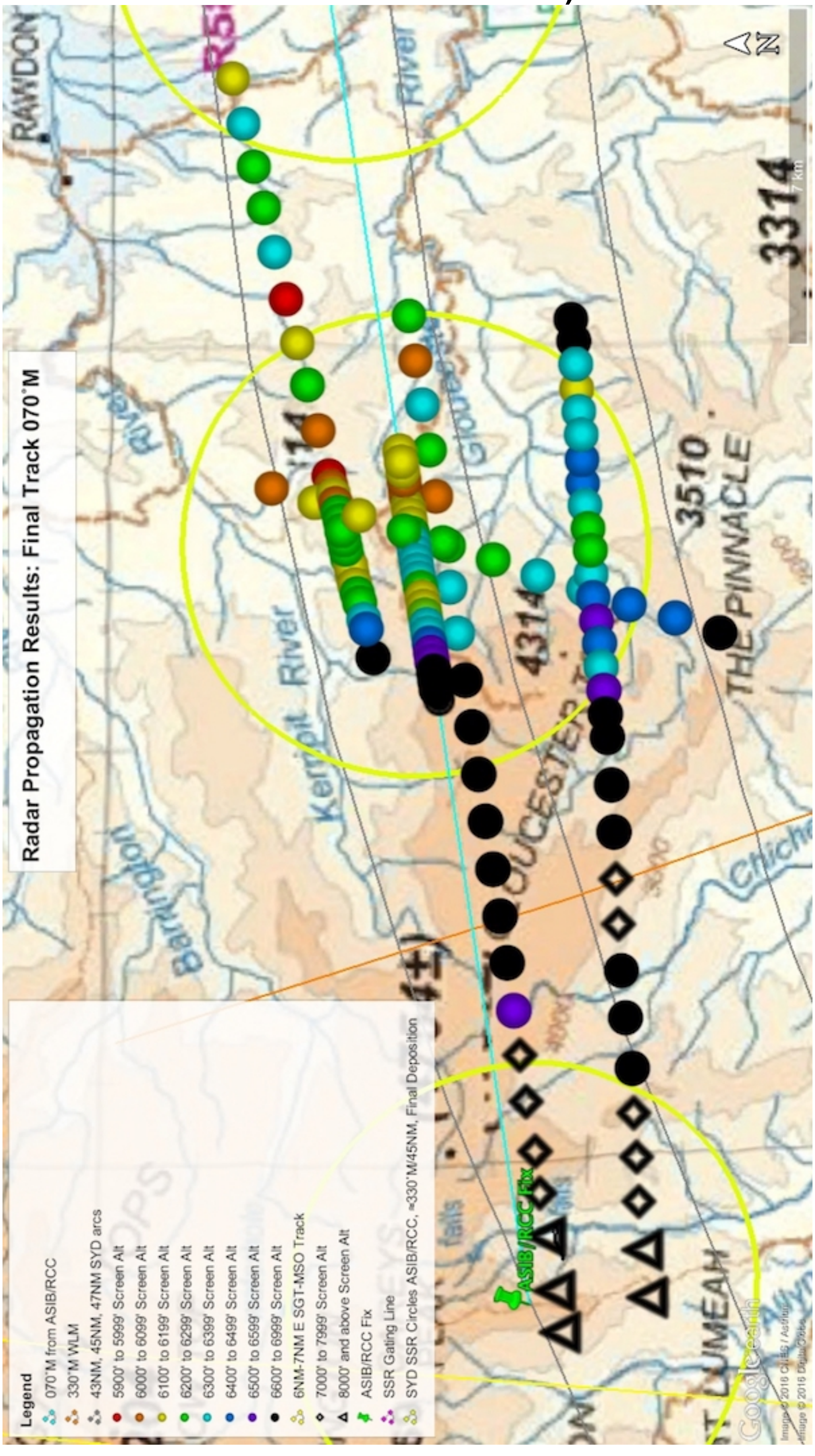
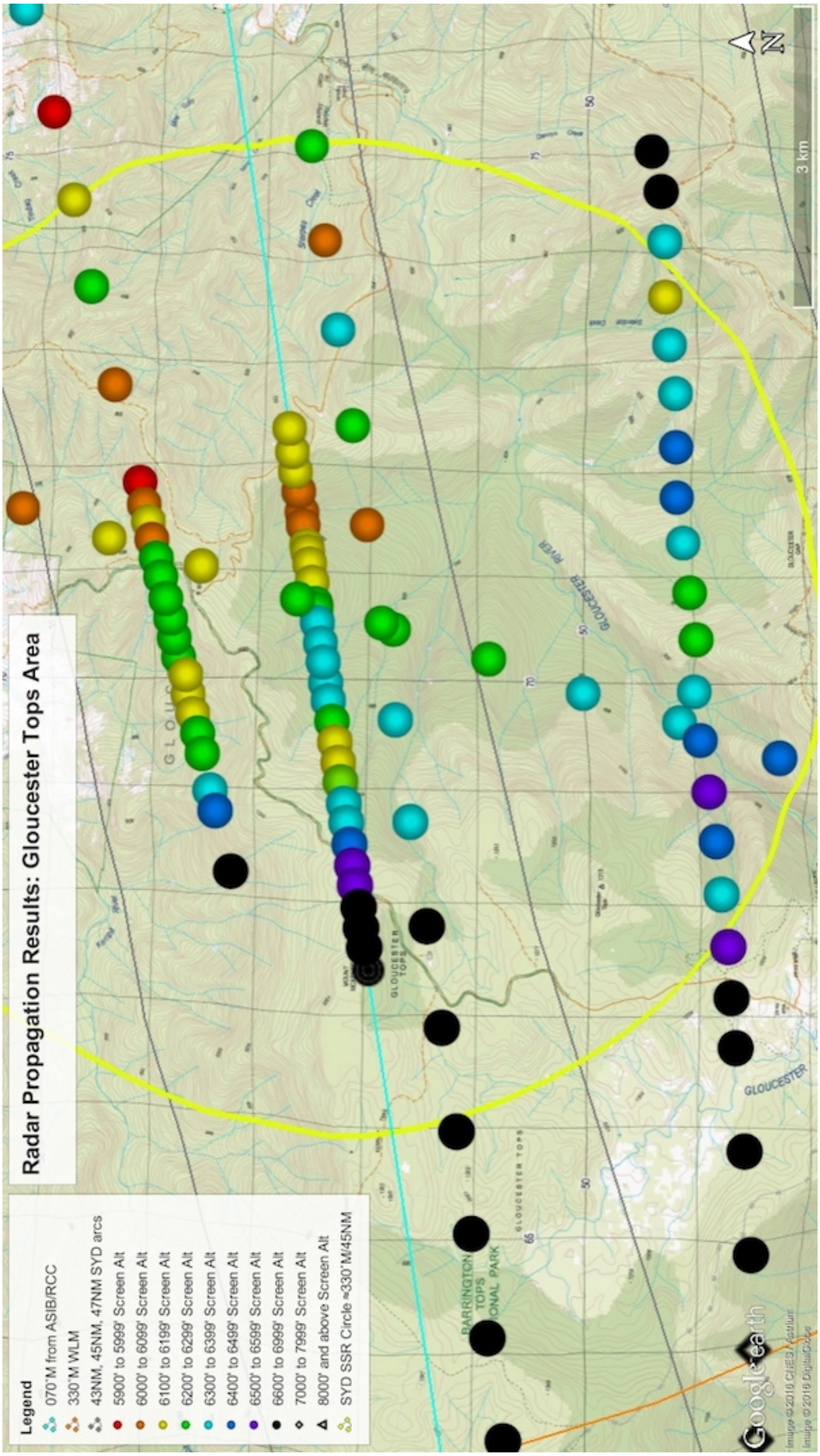


Figure 136: TRM RSR to Sydney deposition final radar fix at 6000’AMSL: Line of sight, received signal: -77.48dBm. VH-MDX could be interrogated by TRM at this position down to 6000’AMSL VH-MDX altitude (Image: Radio Mobile Online 2015, analysis: Glenn Strkalj 2016).

Annex N: VH-MDX final track propagation results (From The Round Mountain SSR RSR).




Radar Propagation Results: Gloucester Tops Area
Legend
070°M from ASIB/RCC
330°M WLM
43NM, 45NM, 47NM SYD arcs
5900' to 5999' Screen Alt
6000' to 6099' Screen Alt
6100' to 6199' Screen Alt
6200' to 6299' Screen Alt
6300' to 6399' Screen Alt
6400' to 6499' Screen Alt
6500' to 6599' Screen Alt
6600' to 6999' Screen Alt
7000' to 7999' Screen Alt
8000' and above Screen Alt
SYD SSR Circle =330°M/45NM
3 km
GLOUCESTER
BARRINGTON TOPS
Google earth

Annex O: The Round Mountain PSR RSR flight test 1972 comparison results

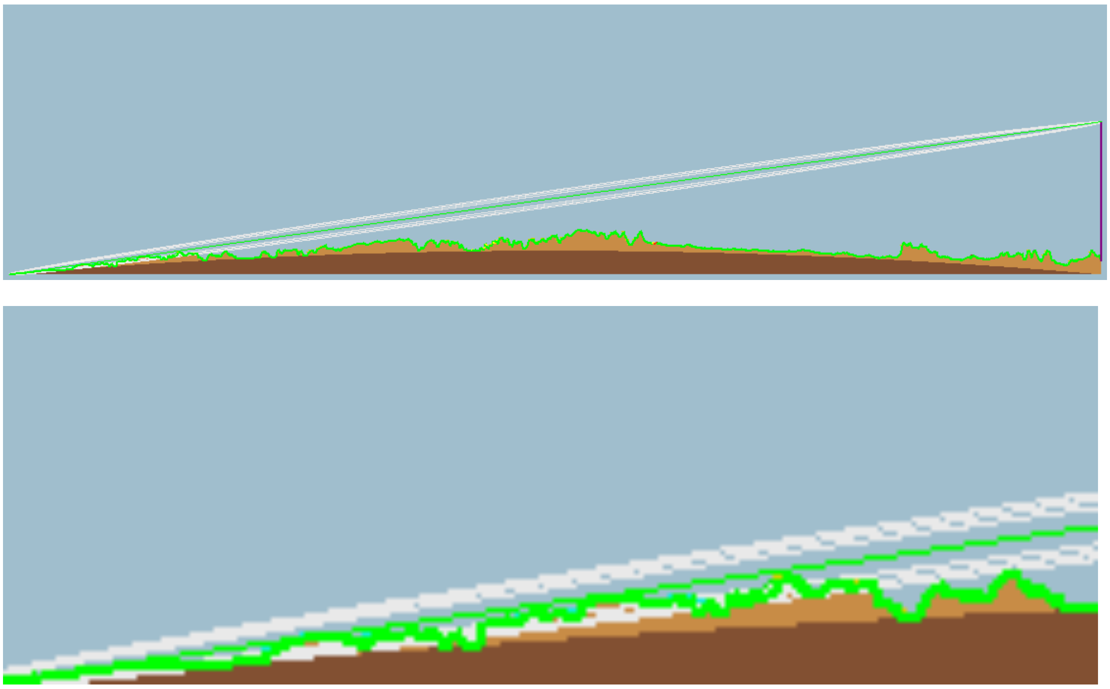


Figure 137: SYD RSR PSR to 20NM NE of SGT Fokker 27 at FL110. Received signal -70.0dBm

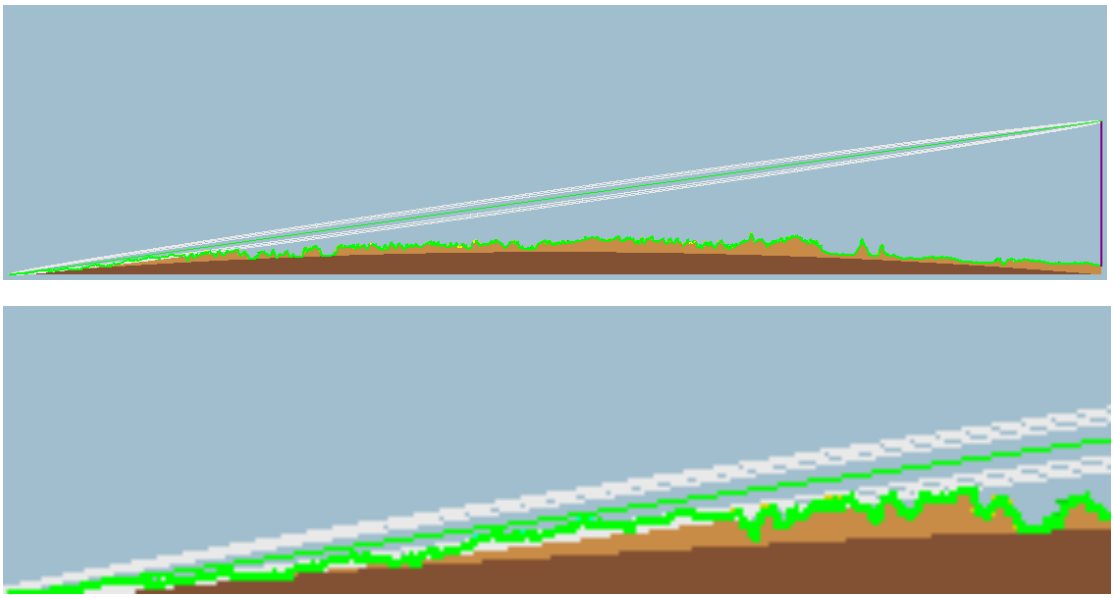


Figure 138: SYD RSR PSR to 22NM NW SGT FL110. -66.06dBm.

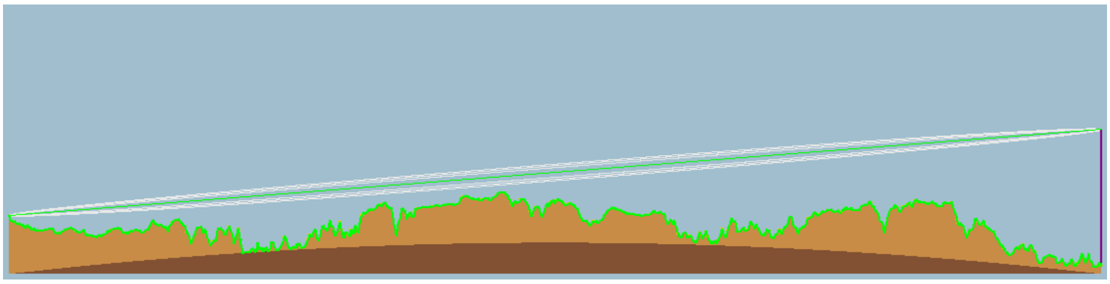


Figure 139: TRM RSR PSR to 15NM NE SGT FL110: -57.54dBm. Position: 202.31˚T/121.3NM from TRM, F-27 tracking ≈247˚T.

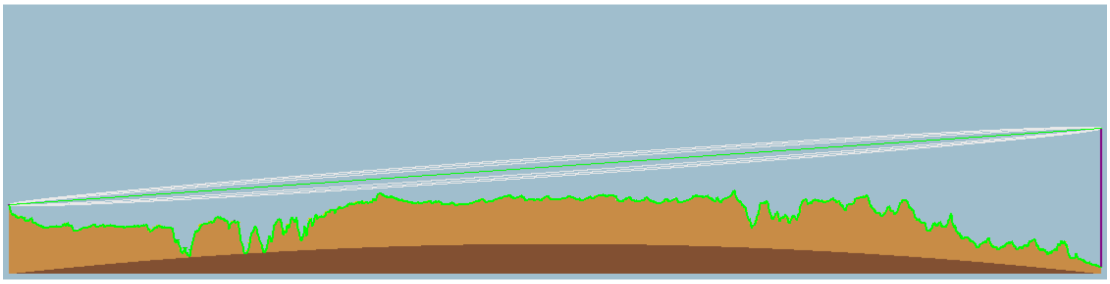


Figure 140: TRM RSR PSR to 45NM SSE TW 10000' AMSL -56.80dB

