International Civil Aviation Organization
Automatic Dependent Surveillance – Broadcast (ADS-B)
Study and Implementation Task Force

Brisbane, Australia, 24-26 March 2003

Agenda Item 2: Review of ADS-B Activities

b) Review SASP ADS-B activity

ADS-B SEPARATION STANDARDS UNDER DEVELOPMENT IN THE ICAO SEPARATION AND AIRSPACE SAFETY PANEL (SASP)

SUMMARY

Attached is a paper presented to SASP at the Second Working Group meeting of the whole held in Montreal October 2002.

The paper proposes that ADS-B Separation Standards be developed using the comparative reference system methodology detailed in Doc 9689 Manual on Airspace Planning Methodology for the Determination of Separation Minima. The Reference system proposed is the four second update rate en enroute radar.

(Presented by Australia)

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SEPARATION AND AIRSPACE SAFETY PANEL (SASP)

SECONDFIRST MEETING OF THE WORKING GROUP OF THE WHOLE

Montreal, Canada, 28 October – 8 November 2002

Agenda Item 4c:
Separation minima for ADS-B

INITIAL COMPARATIVE ASSESSMENT BETWEEN ENROUTE RADAR SERVICES AND PROPOSEDPROPOSAL FOR DEVELOPMENT OF ENROUTE ADS-B SERVICES USING A 5NM SEPARATION MINIMA

(Presented by Mr R. Butcher)

(Prepared by R. Butcher, E. Williams and R. Powell and R. Powell)

SUMMARY

This paper expands on WP46 presented at SASP WG/WHL/1 held in Canberra in May 2002. It details an initial comparative assessment between enroute radar services and enroute ADS-B services undertaken by Australia in accordance with the requirements of the comparative reference system methodology detailed in Doc 9689 Manual on Airspace Planning Methodology for the Determination of Separation Minima.

1. INTRODUCTION

2.

2.1 The SASP has identified the development of separation minima for use where ADS-B is used as a surveillance system, as a specific project task for its current work program. The working group has recognised the importance of such a project given its allocation of a priority 2 status, and as such this reflects the high levels of development work being undertaken into ADS-B applications by a number of States in a number of different regions. The project team is reminded that at the last meeting of the working group of the whole in Canberra, the plenary supported the agreement reached by the members of the project team that a comparative assessment of ADS-B against a reference system such as radar was a valid methodology to use in the establishment of suitable separation minima for this surveillance system. In addition the meeting endorsed the need to develop a comprehensive set of requirements against which such a comparative assessment could be undertaken. To that end it is proposed that an in depth assessment between the reference system and the proposed system using the criteria defined in Doc 9689 *Manual on Airspace Planning Methodology for the Determination of Separation Minima*, Chapter 3 would be suitable. This paper details such an assessment based on a proposal for an ATC ADS-B service using ADS-B for aircraft surveillance as a replacement for a reference system of an ATC radar service using 12 second enroute radar. The project team has previously indicated that it would be beneficial to expand the use of the reference system methodology to include the ATC operating environment.

3. BACKGROUND

3.1 The project team may also recall that at previous working group meetings of both SASP and RGCSP, information was presented by one State concerning the implementation of radar like services using ADS-B which permitted a 5nm separation minimum to be utilised in the enroute environment. Our current understanding is that the United States Federal Aviation Administration has now approved the use of this minima using ADS-B for a specific geographic region. In addition to this particular application of ADS-B in air traffic services, other States, including Australia, have advised the project team that they will be undertaking trials using ADS-B surveillance to assess the applicability of ADS-B in providing radar-like services.

3.2 To ensure that the implementation of ADS-B can achieve worthwhile benefits to airspace users in an efficient and timely manner, the project team needs to continue its work on the development of suitable separation minima and ATC procedures with a view that these will be reflected in Doc 4444 PANS ATM . It is understood that the technical SARPS for ADS-B are being developed by other ICAO Panels. There may also be a need for pilot procedures to be developed and published but this is not being proposed at this time.work on the development of suitable separation minima needs to be undertaken in parallel with the development of system and technical SARPs being undertaken by other Panels. For example the technical SARPs for Mode S are being developed by SCRSP; VDL4 by AMCP; and the ADS-B functionality SARPs by OPLINKP. The meeting should note that the technical SARPs for at least one ADS-B datalink have been available in Annex 10 for some years, and there are extensive trials in a number of States around the world utilising one or more of the ADS-B datalinks, and at least one datalink is already in operational use.

3.3 ADS-B is already being used in one State in airspace where previously radar services were not available, and ATC are using it to provide radar-like services (including vectoring), with published separation minima of 5nm en-route and 3nm in terminal environments. Australia is similarly intending to utilise ADS-B to provide radar-like services in airspace where currently such services are unavailable. Details on the proposed 'trial' in Australia were provided to the project team at the last meeting in Montreal, November 2001.

3.4 Research work undertaken by Australia into the capabilities of ADS-B systems (both airborne and ground systems) has indicated that in nearly all criteria, ADS-B capabilities exceed those of current radar systems used by ATC. This fact was similarly recognised by the FAA when implementing ADS-B systems as part of their Capstone Project (see SASP-WG/A/1-WP/11 of 7 May2001). Specifically that working paper stated that in the FAA's opinion the Capstone Project "*…had demonstrated that ADS-B performances are no worse than radar and that it can provide "radar-like" capabilities, therefore allowing ATC to use ADS-B in applying procedures for separation, sequencing, and other VFR and IFR radar-like services in a non-radar environment.*"

3.5 This paper aims to provide the project team with an initial comparative assessment between Route Surveillance Radar services and enroute services using ADS-B. proposes that the ADS-B project team of SASP should develop suitable ADS-B separation minima for eventual publication in PANS-ATM, based on a safety assessment that uses a comparison of ADS-B systems to a suitable reference system such as radar. ICAO Doc 9689 *Manual On Airspace Planning Methodology For The Determination of Separation Minima,* identifies that a comparison methodology is a valid form of safety assessment. The basis of comparison used in this paper is that both systems deliver positional data to air traffic control using various technologies and that it is expected that both systems will provide ATC radar like separation services in an enroute environment using a 5 nm or 3nm separation standard. ATC use of the proposed ADS-B system is envisaged to be comparable to the existing radar system.

4. VALIDITY OF REFERENCE SYSTEM

4.1 ICAO Doc 9689 allows comparison between reference systems (such as SSR only radar) and new systems (such as ADS-B). In particular the ICAO document details the minimum requirements for a reference system to be considered sufficiently similar to a proposed system. These requirements are detailed in the table below and compared against the proposed ADS-B system. as:

ICAO Doc 9689 (assuming a route surveillance radar environment)	Proposed ADS-B system
Separation minima must not be less in the proposed system than in the reference system	Separation minima will be no less than that currently in use in the reference system airspace
Proposed means of communication and surveillance must be no worse in terms of accuracy, reliability, integrity and availability than those of the reference system	Air-ground voice communications provided in the airspace where ADS-B separation services are planned, are equal to those provided in airspace where radar services are provided and hence the communication component is no less that that for the radar standard
Frequency and duration of the application of minimum separation between aircraft must not be greater in the proposed system than in the reference system	The frequency of application of ADS-B minimum separation will be no different to airspace in which radar separation is used.
Navigation performance (typical and non typical) of the population of aircraft in the proposed system should not be worse in its effect on collision risk, in any dimension, than that of aircraft in the reference system	Navigation performance of aircraft in airspace where ADS-B is implemented is no different than that of aircraft currently operating in the reference system radar airspace. (Since aircraft navigation data is an input to ADS-B, the aircraft navigation performance will be reflected in the ADS-B surveillance performance and it will be dealt with in the actual comparison)

5. REFERENCE SYSTEM CHOSEN

5.1 This paper compares the Mode S Extended Squitter ADS-B (the New System) against en-route SSR only radar (the Reference System).

6. OPERATIONAL USE OF AUTOMATIC AIRCRAFT POSITION DATA

6.1 Automatic aircraft position data supports a number of ATC purposes. These include Plan View presentation of aircraft position to Controllers in support of:

a. Aircraft Separation Service
b. Aircraft Advisory Service

5.2 Ancillary ATC purposes also supported include:

a. Search & Rescue
b. Emergency alerting
c. Emergency navigation service (vectors)

5.3 In modern computer based ATC automation systems, automatic aircraft position data can also be used to support automatic updated of electronic Flight Plan information as part of flight following of each aircraft.

5.4 Automatic aircraft position data is also used to support automated Safety monitoring facilities such as:

- Short Term Conflict Alert
- Clear Level Adherence Monitoring
- Route Adherence Monitoring
- Danger Area Infringement Warning
- Missed Way Point Report Warning

- Pilot Estimated Time Over

5.5 To date, extracted and digitised Radar data is the only widely used source of automatic aircraft positional data.

separation minima must not be less in the proposed system than in the reference system;

proposed means of communication and surveillance must be no worse in terms of accuracy, reliability, integrity and availability than those of the reference system;

frequency and duration of the application of minimum separation between aircraft must not be greater in the proposed system than in the reference system; and

navigation performance (typical and non typical) of the population of aircraft in the proposed system should not be worse in its effect on collision risk, in any dimension, than that of aircraft in the reference system.

6.2 This paper contends that the above requirements can be satisfied using ADS-B and as a result ADS-B could be used in any airspace to provide radar-like services. In brief, the requirements in 1.6 above can be met as follows:

a) separation minima of 5nm and 3nm are proposed (this is no less than that used in radar airspace);

b) it is expected that air-ground voice communications provided in the airspace where ADS-B separation services are planned, are equal to those provided in airspace where radar services are provided and hence the communication component is no less that that for the radar standard;

c) the frequency of application of ADS-B minimum separation should be no different to airspace in which radar separation is used today and therefore does not need to be considered in this comparison. Initial application of ADS-B is anticipated in enroute environments which is less demanding than terminal environments which is adequately supported by radar; and

d) the navigation performance of aircraft in airspace where ADS-B is implemented should be no less than that of an aircraft in radar airspace. (Since aircraft navigation data is an input to ADS-B, the aircraft navigation performance will be reflected in the ADS-B surveillance performance and it will be dealt with in the actual comparison).

1.8 For the purposes of this paper, the comparison will be made between radar and ADS-B (Mode S squitter).

7. COMPARISON OF SURVEILLANCE SYSTEMS

7.1 Radar provides data for a number of ATC purposes. These include the presentation of information for situational awareness, for formally maintaining separation between aircraft, and a number of ancillary purposes such as Search & Rescue, Emergency alerting , aircraft identification. Air Traffic Controllers assess and utilise presented radar positional data in the context of the complete traffic management picture. ATC is not based on the presentation of a single positional data report (measurement). Rather, the history of the track together with the most recent data is used to predict where the aircraft will be in the future. Controllers also use other information such as knowledge about aircraft intent and the commands that have been issued to modify their perception of the data presented. No tool is perfect, and controllers use radar as a significant tool, but take account of its strengths and weaknesses.

7.2 ADS-B provides similar capabilities which permits a controller to use the system as a situational awareness tool and as a separation tool. A comparison of these capabilities is detailed below:

DATA	RADAR (SSR)	ADS-B
Position	Radar itself measures range and azimuth	Down-linked from aircraft
Altitude	Down-linked from aircraft (Mode C)	Down-linked from aircraft
Identity	Down-linked from aircraft (Mode 3/A and use of Special Purpose Ident)	Down-linked from aircraft (Unique 24-bit address and flight identity)
Velocity Vector	Computed from successive position determinations	Down-linked from aircraft (more responsive)
Emergency Alerting	Down-linked from aircraft (Reserved Mode A codes)	Down-linked from aircraft (Contained in status field)

7.3 **Data link.** ADS-B technology using Mode S squitter is part of the Mode S SSR system and hence has the same basic characteristics. It should be noted from the table above that in both radar and ADS-B information is data linked form the aircraft to the ground. It is useful to compare the properties of the data links. The Mode A and C data is sent as a frame comprising 12 bits of information. The data is not protected by any parity, cyclic redundancy check (CRC) or any other inherent error detection mechanism. Ground stations attempt to eliminate errors by comparing multiple messages of the same data for consistency. Error in the received identity (Mode A) could mislead either the controller or the automation system as to the aircraft's identity. Error in the received Mode C code could mislead the controller on aircraft altitude and lead to error in slant range correction and hence the aircraft position is incorrectly displayed. These errors are often seen in an operational environment. The Mode S transmission of data (including ADS-B squitter messages) is very secure as the data-link uses a very robust 24-bit error detection algorithm for protection.

7.4 **Position.** The aircraft position is determined by range and bearing. Range is measured by the radar by accurate measurement of elapsed time from transmission of the interrogation to the aircraft to the reception of the reply from the aircraft. The azimuth (bearing) of the aircraft is determined by the radar by the direction the very narrow beam-width antenna. In modern monopulse radars the azimuth within the beam is also determined to deduce an accurate bearing with the aircraft. The radar measures range very accurately but the azimuth is measured in angle and hence at long range is not very accurate. In the ADS-B system, positional data is determined by the navigation system on the aircraft and broadcast to the ground station. Hence the accuracy is a property of the aircraft's navigation system or capability.

7.5 **Altitude**. In the case of both radar and ADS-B the aircraft pressure altitude is measured by an encoder on the aircraft and the data is transmitted to the radar or ADS-B ground station. Therefore the performance is identical.

7.6 **Identity**. In the case of SSR the aircraft identity is contained in the Mode A code which is input by the pilot on each flight and hence subject to human error. Ground equipment translates the Mode A code to the flight ID. Special Purpose Ident allows a pilot on the request of a controller to highlight the aircraft symbol on the display screen. All Mode S ADS-B messages inherently contain the aircraft's unique 24-bit address. Also one of the ADS-B messages contains the aircraft's flight ID. There is no direct equivalent of SPI nor is one required as each message contains the aircraft's unique identifier.

7.7 **Velocity Vector**. This element is determined by radar through successive position measurements. This leads to a slow detection of turn nor is it very accurate. Modern aircraft navigation systems provide a responsive and accurate vector that is down-linked by ADS-B.

7.8 **Emergency alerting**. SSR has reserved Mode A codes to indicate three types of emergency (EMG, RAD, HIJ). ADS-B in its status field contains the same information.

7.9 **System Monitoring**. The end to end performance of a radar is continually monitored through the deployment of SSR site monitors. If the positional data of the site monitor is in error or the sight monitor is not received, alerts are provided to a controller and the individual radar maybe removed from service. In the case of ADS-B site monitors can also be deployed. The reception of the site monitor at the correct location indicates that the ADS-B ground station can 'hear'. If the ADS-B position data that comes from the site monitor uses GPS, the position check verifies the correct function of GPS. The navigation system that provides positional data to ADS-B also provides figure of merit for the positional information which is also down-linked to the ground.

7.10 **Loss of Service**. If a planned or unexpected loss of radar data occurs, the most ATC systems "coast" the radar track and update the flight plan processing system using the last detected position. The system then displays the best estimate of aircraft position, based on the available FDP data. If an unexpected loss of ADS-B data occurs, the ground system should be able to "coast" the ADS-B track in a similar way to the radar system, update the flight plan processing system using the last detected position, and then display the best estimate of aircraft position, based on the available FDP data.

8. COMPARISON OF KEY PERFORMANCE ELEMENTS

8.1 The key performance elements of ADS-B and radar are compared as follows:

Accuracy

8.1.1 **Radar.** Radars measure position in range and azimuth. The range noise errors are 0.125 Nm (1 σ) and the noise errors in azimuth are 0.08 degrees (1 σ). Since GPS (ADS-B) errors are expressed with respect to a 95% confidence, this paper will use 1.65 σ (95% assuming Gaussian distribution of errors) - namely a 0.132 degree error. In addition to these errors one must consider systematic errors of alignment. Radars are typically maintained with an alignment accurate to +-0.044 degrees in azimuth.

8.1.2 Azimuth errors are clearly the dominant error, and can be translated into positional errors as follows:

Taking into account the random noise errors only:

At 50 Nm the 0.132 degree error results in a position error of 0.115Nm
At 200 Nm this error has risen to 0.46Nm and to 0.576Nm at 250 Nm

Systematic errors of +/- 0.2Nm at 250Nm from the radar also need to be considered.

8.1.3 In a monopulse SSR system such as that used in Australia, azimuth errors are a function of the received signal strength. Strong signals allow monopulse azimuth determination to work very well whereas at very low signal strength, signal noise causes a significant deterioration. For low signal strength SSR detection's, the positional error could exceed the above values.

8.1.4 No "real time" measurement of accuracy over the total coverage area is maintained. Real time monitoring of a single pseudo aircraft (site monitor) gives a degree of comfort that the measurement accuracy is within normal bounds. It is assumed that a commissioned radar continues to deliver accurate positional data within the total coverage area independent of environmental constraints. The reality is that radar is affected by a large range of phenomena which corrupt the positional data to some extent. These corruptions are typically the result of multipath reflection of radar signals and the "bending" of the beam around obstacles. Transient positional errors are experienced as aircraft fly through regions subject to the phenomena. These errors can result in moderately large position errors up to 0.5 Nm.

8.1.5 The positional accuracy of ADS-B is determined by the navigation system in the aircraft. For high-end aircraft this is typically FMS/IRS/GPS. These navigation have a knowledge of the accuracy of the aircraft position report and this is passed as figure of merit to the ground system which can exclude reports of insufficient accuracy. Similarly GPS based navigation systems can determine figure of merit based on satellite geometry.

8.1.6 The accuracy of the ADS-B positional data is not a function of the distance between the aircraft and the ground station. Where the aircraft is very close to a radar site the radar accuracy may exceed the ADS-B accuracy. ATC procedures and separation standards are developed to allow for on worst case conditions. Therefore the separation standards allow for the low accuracy of radars at longer ranges.

8.1.7 **Mapping to the display plane**. In the radar environment, position is adjusted based upon the height of the aircraft. Radar data is provided as a "slant range" measurement from the radar. In cases where the aircraft altitude is unknown (no Mode C), a default altitude or other approximation must be used. This can lead to considerable position error close to the radar. This issue does not exist with ADS-B.

Update Rate

8.1.8 **Radar**. Typical enroute radar sensors rotate between 16.4 RPM (3.6 seconds/scan) and 5 rpm (12 seconds). Thus at any moment the data displayed to an enroute controller can be as much as 12 seconds old. Typical terminal radar sensors rotate between 16.4 RPM (3.6 seconds/scan) and 12 rpm (5 seconds). Thus at any moment the data displayed to a TMA controller can be as much as 5 seconds old.

8.1.9 **ADS-B**. Most implementations of ADS-B utilise a high update rate of positional data, typically in the order of every second. Thus potentially the data presented to a controller is no more than 1 second old.

8.1.10 Resolution

8.1.11 A limitation of Mode A/C SSR is encounted when two aircraft are at similar slant range and azimuth but adequately separated by altitude. In this case the replies from the two aircraft overlap when received by the radar and the radar may not be able to distinguish that there are two replies present. Thus only one aircraft is displayed. Radar sensors have an ability to resolve two aircraft provided they are separated by least 1.0 degree This 1 degree is equivalent to more than 4 Nm at 250 Nm range from the radar.

8.1.12 ADS-B does not have a limited resolution capability. Two aircraft at exactly the same position will be fully resolved.

Continuity

8.1.13 Continuity is the probability of a system to perform its required function without unscheduled interruptions during the intended period of operation. The consequence of unscheduled interruption would be the transition back to procedural control for either a single aircraft (avionics failure) or for all aircraft (system failure). Reversion to procedural control for a single aircraft is identical to an aircraft transponder failure. Similarly, system failure in ADS-B is equivalent to a radar failure.

8.1.14 Continuity is a function of the system design (eg: duplication) and the reliability of the various equipment deployed. Continuity needs to be considered in conjunction with the backup systems and alternative methods of achieving the operational objectives.

8.1.15 To examine the comparison between radar and ADS-B environments, the reliability can be considered as a number of series elements namely:

a) Space segment : The availability of the GPS signals (in the ADS-B case)
b) Avionics segment : The reliability of the avionics and aircraft power systems
c) The surveillance ground system : The radar ground station or the ADS-B ground station

d) The link between the ATC system and the ground sensor

8.1.16 Each of the various elements of systems would need to be reviewed in detail by the project team in its deliberations during development work of separation minima using ADS-B, however such detail will not be described in this paper. Of interest though to this meeting may be some information concerning the reliability of the space segment, which is detailed in the following paragraphs.

Availability

8.1.17 Availability is the ability of a system to perform its required function at the initiation of the intended operation. Unexpected failure of a system has a direct safety consequence. The time it takes to repair a system, in the environment of radar or ADS-B has no safety consequence. Failure itself triggers transition into procedural separation rules. Once that transition is complete, there is no safety impact of continuing the procedural separation rules for an extended time. In the radar environment, on failure, ATC will transition to procedural rules and, if in many cases the ground system would display flight plan tracks for aircraft with flight plans. Exactly the same is true in the ADS-B environment.

8.1.18 Given a particular reliability of a system, normally through design, the availability of a system is almost solely determined by the logistic support arrangements in place. These logistic support arrangements determine the time it takes to replace failed system elements - and restore service. It is unclear to what extent this will impact on the development of the separation minima but it is likely that this is more an issue for implementation of ADS-B as a technology.

Coverage

8.1.19 When radar is used as a tool for ATC, it is used knowing that coverage limitations apply. The terrain and buildings around a radar site significantly affect the coverage achieved. This limitation is documented during commissioning tests and controllers use the tool within the limits of "coverage". The same is true for ADS-B.

8.1.20 When ADS-B is used as a tool for ATC, the same coverage limitations will apply since both technologies employ line-of-sight data-link between aircraft and ground station.

Integrity

8.1.21 Integrity is the probability that errors will be mis-detected.

8.1.22 **Radar.** The current integrity monitoring for SSR radar is a site monitor. A site monitor is a SSR transponder installed at a fixed site. The radar measures the position of the site monitor transponder unit and reports it to the ground system in the same manner as the transponder on any aircraft. The reported position is compared to the known location of the fixed site. A significant difference between the two positions typically results in the radar being declared non-operational.

8.1.23 **Radar Positional data integrity.** In the case of radar there are other errors that fall outside the above integrity tests and thus lead to undetected errors. These errors include multipath corruption of position, SSR reflections, diffraction, “beam bending”, data-link error, incorrect time delay in the transponder and incorrect reply mode from the transponder.

8.1.24 **Altitude data integrity**. The integrity of the mode C altitude data is not assured. The data is passed on the data link without error detection capabilities nor is there any check for aircraft encoder/altimetry error.

8.1.25 **ADS-B Site monitor.** One method of integrity monitoring for ADS-B is a site monitor. This works in the same manner as a radar site monitor. The source of positional data in the aircraft outputs in the ADS-B message an indicator of the integrity of the navigation solution. The ground station uses this indicator to determine whether to display the report.

Anomalies

8.1.26 It should be recognised that for any given implementation, be it radar or ADS-B, there may be specific circumstances that generate anomalies. These need to be considered by authorities certifying implementation.

9. **Conclusion**

9.1 The comparison between radar and ADS-B systems detailed in this paper shows that on initial assessment ADS-B is equal to or better than radar for a number of technical elements and criteria. The comparison was not intended to be exhaustive but was provided to show that the development of separation minima utilising ADS-B as the surveillance medium would more than likely be possible using the ‘comparison with a reference system’ methodology identified in Chapter 6 of ICAO Doc 9689.

10. **Conclusion**

10.1 The comparison between radar and ADS-B systems detailed in this paper shows that on initial assessment ADS-B is equal to or better than radar for a number of technical elements and criteria. The comparison was not intended to be exhaustive but was provided to show that the use of existing separation minima (such as those used for enroute radar) utilising ADS-B as the surveillance medium would more than likely be possible using the ‘comparison with a reference system’ methodology identified in Chapter 6 of ICAO Doc 9689.

10.2 Importantly, use of the comparative methodology should permit widespread implementation of ADS-B systems in the short-term given that the need for the development of detailed collision risk methodologies for the determination of the separation minima is removed. Importantly also, is the fact that use of the comparative methodology may make implementation more cost effective for those States that do not have a capability to undertake exhaustive collision risk assessments. However, use of such a methodology will not remove the need for a State intending to implement ADS-B systems for the provision of radar-like services, to comply with the provisions of to the need to undertake a safety assessment as part of the implementation process.

10.3 Importantly, use of the comparative methodology should permit widespread implementation of ADS-B systems in the short-term given that the need for the development of detailed collision risk methodologies for the determination of the separation minima is removed. Importantly also, is the fact that use of the comparative methodology may make implementation more cost effective for those States that do not have a capability to undertake exhaustive collision risk assessments. However, use of such a methodology will not remove the need for a State intending to implement ADS-B systems for the provision of radar-like services, to comply with the provisions of PANS-ATM in relation to the need to undertake a safety assessment as part of the implementation process.

11. ACTION BY THE PROJECT TEAM

11.1 This paper intended to provide a starting point for the project team's work in developing separation minima using ADS-B as the surveillance medium. The team is invited to review the information presented in this paper, and to:

a) Endorse the use of the comparative methodology to demonstrate that ADS-B technology can support at least the same level of safety as currently found in a radar environment; and

b) Undertake the development of radar-like separation minima for use with ADS-B noting the three available data-links.

12. ACTION BY THE PROJECT TEAM

12.1 This paper intended to provide a starting point for the project team's work in developing separation minima using ADS-B as the surveillance medium. The team is invited to review the information presented in this paper, and to:

a) Review the comparison between Radar and ADS-B detailed above;

b) Identify any additional detail or characteristics of radar and ADS-B which need to be included in the comparison; and

c) Progress the development of radar-like separation minima for use with ADS-B, initially for Mode S Extended Squitter and subsequently for other ICAO recognised ADS-B data-links.

APPENDIX AATTACHMENT TO WP/

DESCRIPTION OF THE CURRENT AIRSPACE AND THE CNS/ATM SYSTEMS – BASED ON ALMA AND KEPPLE RADAR SECTORS IN FRASER GROUP, BRISBANE CENTRE, BRISBANE FIR, AUSTRALIA

ELEMENT			**CURRENT AIRSPACE & SYSTEMS**	**PROPOSED AIRSPACE & SYSTEMS**
Airspace structure	Route structure		Enroute radar airspace on east coast of Australia. The airspace vertical dimensions are from F125 to FL600 over land and FL245 to FL460 over international waters. The airspace is approximately 360 nm north/south and 120 nm east/west. Route structure consists of published bi-directional and omni-directional	Enroute ADS-B airspace on east coast of Australia. All other airspace structural elements remain the same as for the reference system.

			ATS routes using ground navigation aids as delineation points.	
	Separation minima and how often values close to the minima are used		5 nautical miles. Values close to the minima are used less than 5%.	5 nautical miles with no variation to the percentage application of values close to the minima
	Complexity	Traffic demand pattern	Traffic demand is high density during the morning and early evening periods. The relative demand outside these periods is medium to low density. During high density periods a single controller may have 12 or more aircraft under his/her jurisdiction at any one time. In	Same as for reference system.

			medium to low density the number of aircraft is 5 or less.	
		Numbers & location of crossing tracks	The route structure in the airspace permits significant use of a 'race-track' pattern along the length of the airspace. However there are a significant number of crossing tracks with 12 main intersection points distributed throughout the airspace. The actual number of crossing tracks is not considered a significant factor in this comparison as the airspace and route structure remains the same for both the current and	Same as for reference system.

			proposed system.	
		Amount of traffic on opposite tracks	Less than 15% of the total traffic would present as opposite direction traffic pairs.	Same as for reference system.
		Amount of climbing or descending traffic	Approximately 40% of traffic will climb or descend within the airspace.	Same as for reference system.
		Nature of aircraft population	In a typical 24 hour period the aircraft population is made up of: International jet: 10% High capacity domestic jet: 45% Low capacity turbo-prop scheduled aircraft: 30% General aviation (piston engined): 10% Military: 5%	Same as for reference system.
		Peak average traffic demands versus system capacity	The current peak average traffic demand is approximately 60% of system capacity	Same as for reference system.
		Runway capacities	**Not applicable to this**	**Not applicable to this**

			analysis	**analysis**
		Adjoining special-use airspace, usage and types of activity	There is a large military training area in the north of the airspace. The area is active for high density military activity approximately once or twice a year. The activity comprises air-to-air and air-to-ground tasking. There is a small gunnery area located in the south of the airspace which is active regularly.	Same as for reference system.
		Regional met conditions	The majority of operations are conducted in visual met conditions.	Same as for reference system.
Communication capability	Direct controller/pilot voice communication (VHF/HF/SATCOM)		VHF	VHF
	Indirect controller/pilot		Not available as	Not available as

	voice communication (HF)		primary communication means	primary communication means
	Controller/pilot data link communication (CPDLC)		Not available	Not available
	Controller/controller voice and automated data link communication, both inter and intra ATS unit		Both voice and automated datalink available for controller /controller communication	Same as reference system
	Data link between ground ATC automation systems and aircraft flight management computers		See section 1.2.12 below	See section 1.2.12 below
	System availability, reliability and capacity		See section 1.2.7 below	See section 1.2.7 below
Surveillance capability	Procedural dependent surveillance	Content of pilot position reports	Not required in radar environment	Not required in proposed ADS-B environment
		Reporting intervals	When requested by ATC	When requested by ATC
	ADS	Basic update rate	ADS not used.	ADS not used.
		Display accuracy	N/A	N/A
		ADS contract (eg events triggering increased reporting rate)	N/A	N/A
		Sensor accuracy	N/A	N/A
		System reliability	N/A	N/A
		End-to-end	N/A	N/A

		communications time capabilities		
	Independent /dependent surveillance	Type of sensor (primary/secondary)	Secondary surveillance Enroute radar,	ADS-B receiver
		Coverage area	Line of sight	Line of sight
		Processing and associated delays	The importance of processing and associated delays is the latency it imposes upon the detection of aircraft manoeuvres. Latency comprises both the processing delay and the delay between positional data updates. Radar processing is usually subject some processing delay between the radar antenna sweeping the target and the data being presented to	ADS_B, with high updates therefore usually has better latency performance than radar. ADS-B suffers some processing delays between the derivation of positional information and the transmittal of that information to ground systems. In addition, some

			ATC. Delays of the order of 200mS are commonly accepted. Processing in some areas (eg very close to a radar) can exceed this and can be as large as 1 second.	systems can buffer information on the ground for periods as long as 1 second. Processing and display can be considered equivalent for ADS-B and radar, although ADS-B is likely to have superior manoeuvre detection capability.
		Accuracy of measured position after processing	See section 1.1.1 below	See section 1.1.7 below
		Update rate	Typical enroute radar sensors	A high update rate of positional data, typically in the order of every

			rotate between 16.4 RPM (3.6 seconds/scan) and 5 rpm (12 seconds). Thus at any moment the data displayed to an enroute controller can be as much as 12 seconds old.	second. Thus potentially the data presented to a controller is no more than 1 second old.
		Display accuracy	Controller air situation display	Controller air situation display
		System reliability	See section 1.2.7 below	See section 1.2.7 below
Aircraft navigation performance	RNP		No specified RNP requirement for the airspace.	Same as for reference system.
	Typical and non-typical performance		Typical performance determined by GNEs in the system.	Same as for reference system.
	Time-keeping accuracy		FMC based - GPS or other reference	Same as for reference system.
Flow management capability	Strategic air traffic flow management		Nil	Same as for reference system.

	Tactical air traffic flow management		Traffic in-bound to Brisbane are flow managed by Brisbane Flow.	Same as for reference system.
	Ad hoc ATC 'in trail' restrictions or enhancements		Nil	Same as for reference system.
	Procedural restrictions (local operating procedures)		Aircraft leaving holding for Brisbane require to be three minutes separated at outer holding points and two minutes at inner holding points.	Same as for reference system.
ATM tools to reduce controller workload or improve controller intervention capability	Automated controller planning tools, including conflict prediction and resolution		The following tools are available to the sector controllers: Short term conflict alert; time of passing tool; short route probe; bearing and range line	Same as for reference system.

	Controller displays		An advance technology air situation display is available to the controller which is fully integrated with flight data processing and depicts radar, flight plan and ADS-C (out side radar coverage) symbols.	Same as for reference system except that greater aircraft intent data will be provided to the controller as a result of intent data available from ADS-B.
	Out-of-conformance alerts		Short Term Conflict Alert; Dangerous Area Infringement Warning; Route Adherence Monitoring; Cleared Level Adherence Monitoring; Pilot Estimate Time Over	Same as for reference system.

1. TECHNICAL COMPARISON OF RADAR & ES-ADS-B

Principle Characteristics. The key pieces of data provided by an ATC Radar to a Controller and there origin for both Radar and ES-ADS-B is summarised in the table below:

DATA	RADAR (SSR)	ADS-B
Position	Radar itself measures range and azimuth	Down-linked from aircraft
Altitude	Down-linked from aircraft (Mode C)	Down-linked from aircraft
Identity	Down-linked from aircraft (Mode 3/A and use of Special Purpose Ident)	Down-linked from aircraft (Unique 24-bit address and flight identity)
Velocity Vector	Computed from successive position determinations	Down-linked from aircraft (more responsive)
Emergency Alerting	Down-linked from aircraft (Reserved Mode A codes)	Down-linked from aircraft (Contained in status field)

1.1.1 **Position**. Radar measures an aircraft's position in range and bearing. Range is measured by accurate measurement of elapsed time from transmission of an interrogation to the time of reception of the reply from the aircraft. The azimuth (bearing) of the aircraft is determined by the direction the very narrow beam-width antenna. In modern monopulse radar the azimuth within the beam is also determined to increase bearing accuracy. Radars measure accurately the range but azimuth is measured in angle and hence at long range has lower linear accuracy than range.
In an ADS-B system, positional data is determined by the aircraft's navigation system and broadcast to the ground station. Hence the accuracy of the positional data is a property of the aircraft's navigation system.

1.1.2 Air Traffic Controllers assess and utilise presented radar positional data in the context of the complete traffic management picture. ATC is not based on the presentation of a single positional data report (measurement). Rather, the history of the track together with the most recent data is used to predict where the aircraft will be in the future. Controllers also use other information such as knowledge about aircraft intent and the clearances issued to modify their perception of the data presented. No tool is perfect, and controllers use radar as a significant tool, but take account of its strengths and limitations. A similar approach would be applied to the use of ADS-B data.

1.1.3 **Radar.** Radars measure position in range and azimuth. The range noise errors are 0.125 Nm (1 σ) and the noise errors in azimuth are 0.08 degrees (1 σ). Since GPS (ADS-B) errors are expressed with respect to a 95% confidence, this paper will use 1.65 σ (95% assuming Gaussian distribution of errors) - namely a 0.132 degree error. In addition to these errors one must consider systematic errors of alignment. Radars are typically maintained with an alignment accurate to +-0.044 degrees in azimuth.

1.1.4 Azimuth errors are clearly the dominant error, and can be translated into positional errors as follows:

Taking into account the random noise errors only:

At 50 Nm the 0.132 degree error results in a position error of 0.115Nm
At 200 Nm this error has risen to 0.46Nm and to 0.576Nm at 250 Nm

Systematic errors of +/- 0.2Nm at 250Nm from the radar also need to be considered.

1.1.5 In a monopulse SSR system such as that used in Australia, azimuth errors are a function of the received signal strength. Strong signals allow monopulse azimuth determination to work very well whereas at very low signal strength, signal noise causes a significant deterioration. For low signal strength SSR detection's, the positional error could exceed the above values.

1.1.6 No "real time" measurement of accuracy over the total coverage area is maintained. Real time monitoring of a single pseudo aircraft (site monitor) gives a degree of comfort that the measurement accuracy is within normal bounds. It is assumed that a commissioned radar continues to deliver accurate positional data within the total coverage area independent of environmental constraints. The reality is that radar is affected by a large range of phenomena which corrupt the positional data to some extent. These corruptions are typically the result of multipath reflection of radar signals and the "bending" of the beam around obstacles. Transient positional errors are experienced as aircraft fly through regions subject to the phenomena. These errors can result in moderately large position errors up to 0.5 Nm.

1.1.7 **ADS-B**. The positional accuracy of ADS-B is determined by the navigation system in the aircraft. For high-end aircraft this is typically FMS/IRS/GPS. These navigation have a knowledge of the accuracy of the aircraft position report and this is passed as figure of merit to the ground system which can exclude reports of insufficient accuracy. Similarly GPS based navigation systems can determine figure of merit based on satellite geometry.

1.1.8 The accuracy of the ADS-B positional data is not a function of the distance between the aircraft and the ground station. Where the aircraft is very close to a radar site the radar accuracy may exceed the ADS-B accuracy. ATC procedures and separation standards are developed to allow for on worst case conditions. Therefore the separation standards allow for the low accuracy of radars at longer ranges.

1.1.9 **Altitude**. A SSR radar does not measured the aircraft's Altitude. Rather the radar interrogates the aircraft's transponder with a request for Flight Level. In response the Transponder replies with the Flight Level as measured by a Barometric Pressure Encoder. For a Modes A&C Transponder the unit of encoding is 100 feet, for a Mode S Transponder the unit is 25 feet.
In the ADS-B system, the ADS-B transponder spontaneously transmits the exact same information as for a Mode S Transponder. Thus, for Altitude information, there is no distinction between Radar and ADS-B.

1.1.10 **Identity**. SSR radar does no measure the aircraft's Identity. Rather the radar interrogates the aircraft's transponder with a request for Identity (Mode-A code). In response, the Transponder replies with the Mode-A code entered on the transponder control panel by the pilot. The Controller or the radar display system translates the Mode-A code to a Flight Identity. There is a limited number of Mode-A codes (4096 – some reserved). This may lead to ambiguity in aircraft identification. Special Purpose Ident (SPI) can be activated by the pilot upon controller request to aid in resolving such ambiguity.

1.1.11 In the ADS-B system, the pilot enters the Flight Identity into the control panel. The ADS-B transponder spontaneously transmits the Flight Identity. Provided Flight Identity is allocated uniquely, there can be no ambiguity. Also all Mode S ADS-B messages inherently contain the aircraft's unique 24-bit address. ATC automation systems can check for consistency between the Flight Identity and the airframe registration recorded in the Flight Plan.

1.1.12 **Velocity Vector**. SSR radar determines Velocity Vector as a derivative of successive position measurements. Velocity Vector determined in this manner is of limited accuracy. Whenever the aircraft manoeuvres, the vector calculated by the radar lags the true vector. This leads to a slow detection of an aircraft's turn.

1.1.13 In an ADS-B system, velocity vector is determined by the aircraft's navigation system and broadcast to the ground station. Hence the accuracy of the velocity vector is a property of the aircraft's navigation system and typically considerably more accurate and responsive than that calculated by radar.

1.1.14 **Emergency alerting**. SSR has three reserved Mode A codes to indicate three types of emergency (EMG, RAD, HIJ). In an ADS-B system equivalent data is transmitted in the status field.

1.2 Other Relevant Characteristics

1.2.1 **Update Rate**. SSR update rate is determined by the antenna rotation speed. For Enroute radars this typically in the range of once per 12 seconds to once per 4 seconds. In an ADS-B system, positional data is broadcast twice per second. Thus as many as 7 out of 8 broadcasts messages can be lost while maintaining the same update rate as high-update rate radar.

1.2.2 **Multiple Target Resolution**. A limitation of a Mode A &C SSR is encountered when two aircraft are at similar slant range and azimuth but adequately separated by altitude. In this case the transponder replies from the two aircraft overlap in time. When received by the radar and the radar may not be able to distinguish that there are two replies present. Thus only one aircraft is displayed. Radar sensors typically require at least 1.0 degree difference in azimuth to reliably resolve two aircraft. One degree at a range of 250 NM is more than 4 NM apart. Mode S radars, by use of selective interrogation, avoid this limitation.

1.2.3 ADS-B does not have a limited resolution capability. Multiple aircraft at exactly the same position will be fully resolved.

1.2.4 **Coverage**. SSR coverage is limited by the terrain and buildings around a radar site. The limitations are documented during radar commissioning tests Controllers use radar with knowledge of its coverage limitations.

1.2.5 ADS-B is also subject to coverage limitations. The limitations will be documented during testing and Controllers will use ADS-B with knowledge of its coverage limitations.

1.2.6 Given that SSR and ADS-B use the same data-link, the coverage restrictions will be identical.

1.2.7 **Continuity of Service**. Continuity is the probability of a system continuing to perform its function without unscheduled interruptions during the intended period of operation. Continuity is a function of the system design and the reliability of the various elements forming the system. The elements of the ADS-B system are essentially the same as a radar system plus the source of positional data on board the aircraft.

1.2.8 SSR failure initiates a transition to procedural control for either a single aircraft (radar transponder failure) or for all aircraft (radar system failure).

1.2.9 ADS-B failure would also initiate a transition to procedural control for either a single aircraft (ADS-B transponder failure) or for all aircraft (ADS-B system failure).

1.2.10 Continuity needs to be considered in conjunction with the backup systems and alternative methods of achieving the operational objectives.

1.2.11 **Integrity**. The integrity of data is the probability that the data, when not indicated to be in error, is in fact correct.

1.2.12 **Data-Link Integrity**. It can be seen from the discussion above that in both SSR and ADS-B information is data linked form the aircraft to the ground. Mode S ADS-B is an inherent part of the Mode S SSR system and hence has the same data-link characteristics as Mode S radar. Many of today's radars, which provide satisfactory service, use only Modes A & C. It is useful to compare the integrity of the Modes A&C and Mode S data-links. The Mode A (identity) and Mode C (pressure altitude) data is sent as a frame comprising 12 bits of information. The data is not protected by any parity, cyclic redundancy check (CRC) or any other inherent error detection mechanism. Radars attempt to detect transmission errors by checking for consistency of Replies from multiple interrogations. Error in the received identity (Mode A) could mislead either the controller or the automation system as to the aircraft's identity. Error in the received Mode C code could mislead the controller on aircraft altitude and lead to error in slant range correction and hence the aircraft position is incorrectly displayed. These errors are often seen in an operational environment. The Mode S transmission of data (including ADS-B squitter messages) uses a very robust 24-bit error detection algorithm for integrity check.

1.2.13 **Radar Positional Data Integrity**. SSR end to end performance is continually monitored through the deployment of SSR site monitors. If the radar measured position of the site monitor is in error or the sight monitor is not received, alerts are provided to a controller and the individual radar may be removed from service. Position data errors not detected by this check include multipath corruption of position, SSR reflections, diffraction, "beam bending", Mode C data-link error into Slant Range Correction, incorrect time delay in the transponder and incorrect reply mode from the transponder.

1.2.14 In an ADS-B system, ADS-B site monitors can also be deployed. The reception of the site monitor broadcast indicates that the ADS-B ground station can 'hear'. If the site monitor ADS-B position data that comes from a GPS receiver, GPS performance can also be verified. The integrity of the positional information from the aircraft navigation system must be sufficiently high.

1.2.15 **Altitude data integrity**. The integrity of the mode C altitude data is not assured. The data is passed on the data link without error detection capabilities nor is there any check for aircraft encoder/altimetry error.

1.3 ATC Automation System Implications

1.3.1 **Slant Range Correction**. SSR inherently measures Slant Range of aircraft. In order to determine the True range of the aircraft, an adjusted is made based upon the height of the aircraft. In cases where the aircraft altitude is unknown (no Mode C), a default altitude or other approximation must be used. Significant error in Mode C data (pressure encoder error, data-link error or Mode A reply to Mode C interrogation) leads to an incorrect adjustment. These can lead to significant position errors close to the radar.

1.3.2 ADS-B does not have an equivalent mechanism and hence is not subject to such errors.

2. Emergency Navigation Service

2.1 Radar may be used to provide emergency navigation to an aircraft when the pilot is unable to navigate by normal means. This service may be required in the event of failure of various items of equipment (navigation sensors or display) or pilot performance limitations (ie VFR pilot in IMC).

2.2 Assuming that ADS-B uses positional information from the aircraft's Navigation Sensors, a Controller using ADS-B could provide emergency navigation (vectors) to an aircraft provided at least one navigation sensor was functioning.

2.3 Aircraft navigation systems need to be designed with sufficient redundancy to make ensure that the probability of total loss of navigation is suitably low. The required level of probability should be determined by type of Operation (GA, Aerial Works, Air Carrier) and category of Airspace.

2.4 In the event of total loss of navigation, Separation can be assured using vertically separation, temporarily using half the usual vertical standard if normal vertical standard is not immediately available.

2.5 Thus the dependence of ADS-B on the aircraft's navigation system should not preclude the deployment of ADS-B. Suitable procedural means exists to manage this most infrequent event.

3. Emergency Altimeter Service

3.1 Radar may be used to provide emergency altitude/Flight Level information to an aircraft when the pilot is unable to determine altitude by the normal means. This service may be required in the event of failure of all altimeters available to the pilot. This service is only available if the Pressure Encoder associated with the Transponder is operating normally,

3.2 Assuming the pressure encoder associated with the Transponder is operating normally, a Controller using ADS-B, could also provide emergency altitude information to an aircraft.

4. Anomalies

4.1.1 It should be recognised that for any given implementation, be it radar or ADS-B, there may be specific circumstances that generate anomalies. These need to be considered by authorities certifying implementation.