



International Civil Aviation Organization

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- Agenda Item 6:** **Review:**
- a) **Strategy for the provision of Precision Approach and Landing Guidance Systems**
 - b) **GNSS strategy**
 - c) **GNSS implementation**
 - d) **GPS measurement campaign**

AUSTRALIAN GNSS OPERATIONAL ISSUES AND STUDY RESULTS

(Presented by Australia)

SUMMARY

This working paper a summary of various GNSS related work together with associated recommendations for consideration.

1. INTRODUCTION

1.1 Australia, through CASA has continued work on the operational use of GNSS for IFR. This has included participation in APANPIRG, AusAID projects in Papua New Guinea and consultancy studies. The outcomes of this work is summarised in this paper and, where appropriate, the study results attached.

2. DISCUSSION

2.1 The APANPIRG CNS/ATM I/C SG meeting was held in Bangkok in March 2002. A paper on the application of the new TSO C145/146 receiver design standard was presented that recommended states base their approvals on the C146 standard receiver rather than the C129 receiver. This recommendation was adopted by the SG and forwarded to APANPIRG for consideration.

2.2 The US DoT Volpe Centre carried out a study on the US of GNSS in Papua New Guinea. This study demonstrated that using the TSO C146 receiver standard, that GPS could meet the technical requirements to provide GPS based IFR operations in PNG.

2.3 CASA Australia funded an analysis of the performance of ground based and GNSS based navigation in the Australian FIR. The paper is at attachment A. The study indicated that the use of GPS with a TSO C146 receiver would provide a higher level of performance than the existing ground based aids.

3. RECOMMENDATIONS

3.1 The Meeting endorse the recommendations of the CAN/ATM/IC SG to base new approvals on the TSO C-146 standard receiver.

3.2 The Meeting note the material contained in this paper and utilize the findings and recommendations in its work.

Attachment: Fans Plans Study

FANS PLANS

ANALYSIS OF THE PERFORMANCE OF CURRENTLY USED AND PROPOSED NAVIGATION SYSTEMS INVOLVING GPS FOR GA IFR OPERATIONS IN AUSTRALIAN AIRSPACE

Final Report

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CIVIL AVIATION SAFETY AUTHORITY
AUSTRALIA**

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EXECUTIVE SUMMARY

Background

Since the introduction of satellite navigation using GPS for civil aviation commenced in the early 1990's, many developments in the satellite constellation and receivers have taken place. Improved performance has resulted from :-

- The increase in the satellite constellation from 18 to more than 24 satellites
- Selective Availability (SA) has been set to zero
- Receivers are available with Fault Detection and Exclusion (FDE)
- GPS has been integrated with the Inertial Reference System (IRS) in the larger aircraft

Further improvements in GNSS can be expected from Increased reliability of the GPS satellites, ranging signals from Geostationary satellites and from GPS at the L5 frequency, new satellite navigation systems such as Galileo, more augmentation systems and development of MicroElectronicMechanicalSystems (MEMS) integrated with GPS and suitable for GA.

It was therefore timely to review the performance and operation of the currently used and proposed navigation systems involving GPS for GA operations in Australian airspace. Accordingly, the Civil Aviation Safety Authority contracted FANS PLANS to undertake this study.

Aircraft navigation requires a navigation system to provide an acceptable level of accuracy, availability, integrity and continuity of function. The actual level of performance required varies according to the phase of flight eg en-route, terminal area, non-precision approach & departure and precision approach & landing. The basic satellite constellations such as GPS and GLONASS, of themselves, do not provide the levels of performance needed for the above phases of flight.

The only augmentation system which has been certificated and is in wide general use is the system of aircraft based integrity monitoring, where the GPS receiver incorporates Receiver Autonomous Integrity Monitoring (RAIM). RAIM or its equivalent is required for IFR operations (including NPA) in Australia. The basic type of RAIM detects a failure in the satellite system and is called Fault Detection (FD). Further development of RAIM into Fault Detection and Exclusion (FDE) allows the faulty satellite to be identified and excluded from the calculation of position, thus permitting the flight to continue.

RAIM has the big advantage of not requiring any additional space-based or ground-based infrastructure : it is all provided in the airborne GPS receiver.

To further improve availability and continuity of function, the satellite determined position can be integrated with other navigation sensors such as Inertial Reference Systems (IRS), altimetry, etc to form a multi-sensor system. The development of

MEMS opens the way to small lower cost GPS/IRS navigation systems for GA in this decade.

The focus of this study is on the determination of the levels of availability of high integrity navigation information from GPS receivers with augmentation from barometric altimetry and using RAIM for integrity monitoring. These determinations have been carried out for a wide variety of satellite constellations and receiver parameters under both normal and degraded conditions.

Assumptions

The study examined actual systems (both satellite constellations and receivers) which are in operation and on new systems which could reasonably be expected to be available in the next few years. No attempt has been made to design new systems, but some new operational procedures are proposed in Chapter 6. Many unknowns still exist for these new systems and so prudent assumptions have been made as to their performance. Some updating of this study in the light of detailed developments, such as updating of the GPS signal specification and receiver performance, may therefore be required in the future.

It would be impracticable to determine the performance of each possible combination of parameters of the satellite constellation and receivers. Rather, a range of likely combinations of parameters were selected for analysis and then a sensitivity analysis was carried out to discern trends.

The performance of GPS in the presence of interference was beyond the scope of this study. Although a study of GPS vulnerability has been done in the US, an analysis of the probability of harmful interference to GPS in Australia needs to be carried out. This needs to include the probability of harmful interference to conventional navigation systems eg NDB/ADF in Australia in order to make valid comparisons with GPS.

Methodology

The study was carried out in three main stages.

In the first stage, the performance was determined by simulation of a typical satellite constellation and receiver over the whole of the Australian airspace. This was done by dividing up the Australian airspace into a large number of pixels ($1^0 \times 1^0$) and determining the RAIM availability in each. The result shows that the “worst” areas over continental Australia are around Adelaide (SA) and Albany (WA). Adelaide was thus selected for the most detailed examination.

In the second stage, simulations were carried out for Adelaide over the GPS satellite constellation cycle using some 40 combinations of satellite constellation and receiver parameters to determine the of the most likely combinations and to show trends from the sensitivity analyses. This showed the performance at one of the “worst” locations. Better performance could then be expected at all other locations. A limited

examination of two “better” locations, Parkes and Toowoomba, was then carried out to show what the “average” performance was likely to be. The plotting of the RAIM performance against time over the whole of the GPS satellite constellation cycle proved to be a powerful tool in analysing performance in detail.

In the third stage, six operational scenarios were constructed for GA flights to a destination. As base-lines for comparison, the first two scenarios were constructed for a flight to a destination using NDB's. The next four scenarios were for flights using GPS with FD or FDE receivers and with or without a navaid at an alternate. The probabilities for RAIM availability over each phase of a 2 hr flight to the destination were determined.

In performance assessments in this study, the “risk” of RAIM not being available for an IFR flight was determined, rather than the overall “rate” of RAIM not being available for a large number of flights. Thus the scenarios assume that that an IFR flight is required because of meteorological conditions. The use of “rate” averaged over a large number of flights is particularly misleading in the case of Australian operations, where most GA flights are conducted in VFR conditions. If “rate” were used, a hazardous situation occurring for a single IFR flight would be masked by the large number of VFR flights.

GPS Satellite Constellations

As satellites were added to the constellation in the 1990's, a new industry standard was published in RTCA/DO-229B. This constellation is also referred to as the optimised constellation or the Martinez 24 (M24), and is used for the design, testing and performance comparison of GPS. Further satellites have since been added to the constellation so that most of the time, the actual satellite constellation is usually better than M24. However, as the actual constellation varies from time to time, performance comparisons using actual constellations are not very meaningful. Hence, the standard satellite constellation M24 has been used in this study. This is the prudent choice as the actual performance will usually be better.

A recent development has been the provision for GPS compatible ranging signals to be radiated from geostationary satellites. This is equivalent to adding satellites to the constellation with beneficial effects. Although few of the existing GPS receivers are capable of receiving the ranging signals from the GEO's, the new TSO-C146 receivers are to have that capability. The beneficial effect of the GEO's is particularly noticeable when there is a failure in a critical satellite.

Receivers

Receivers with a wide variety of characteristics are presently in use and new models with greater capabilities are being developed. The study has therefore divided receivers into three broad groups :-

- Group 1 broadly represents the older receivers meeting TSO-C129 which would be used by General Aviation. They are characterised by having FD only and still assuming that SA is on.

- Group 2 represents the performance of receivers meeting FAA Notice N8110.6 for oceanic/remote operations. These receivers have FDE and mask angles down to 0° . Modifications may be available from the manufacturers to reconfigure them for SA off.
- Group 3 represents the likely performance of the new receivers meeting TSO-C146. These could have FDE, SA off, a mask angle specified as 5° when using WAAS corrections and can use of the ranging signals from MTSAT and WAAS.

RAIM Availability Plots

Simulations were carried out to examine RAIM Availability Performance for both FD and FDE as a function of time for Adelaide, Parkes and Toowoomba. The RAIM performance function (Horizontal Protection Level (HPL) in the case of FD and Horizontal Exclusion Level (HEL) in the case of FDE) was plotted for each minute of the time period (1436 min) of the GPS satellite constellation cycle.

Summary of RAIM Performance

1. There is an improvement in performance from Adelaide to Parkes and then to Toowoomba
2. Baro-Aiding (ie the use of local QNH) is of benefit, especially with SA assumed to be on.
3. The benefits of ranging signals from GEO's (with TSO-C146 receivers) are considerable, especially when a critical satellite is not in service.
4. There is little difference in performance between mask angles of 2° and 5° with SA off.
5. All the periods of unavailability of FD and FDE for both normal and fault conditions are repeatable and predictable based on the knowledge of the GPS satellite constellation, the receiver characteristics and the geographical location. With a comprehensive GPS forecast available before the flight, the RAIM unavailability does not constitute a safety hazard, provided it is taken in account when planning the flight. The forecast could be extended to a further stage of "what if" to show the forecast situation if a critical satellite were to fail during the flight and thus add an additional factor of safety.
6. The simulations show the benefit of the FDE receiver (either N8110.6 or TSO 146) which has the capability to exclude a faulty satellite from the position determination and thus allows the flight to proceed using the remaining satellites with the FDE or FD function. In most of the simulations, FDE was available after a faulty satellite was excluded. In all simulations, the receiver could revert to FD in the EnRte and TMA. Receivers with FD only (ie most of the TSO-C129) are rendered unserviceable by the radiation of an erroneous signal from any faulty satellite in view, even though there are sufficient remaining satellites to support the flight.

RAIM Availability under various Scenarios

There are two causes of RAIM being unavailable, firstly because of insufficient satellites of appropriate angular spacing and secondly because of a random failure of a satellite during the flight. The first cause of RAIM unavailability is predictable before the flight and if the GPS forecast is taken into account in the flight planning, it does not constitute a safety hazard. This procedure is assumed to take place during the following scenarios. The probability of the occurrence of the second cause of RAIM being unavailable during a flight because of a random failure of a satellite was examined in the six scenarios.

Scenario 1 is one of the baseline scenarios and is for a flight to a destination with an NDB when no alternate with a navaid is required.

Scenario 2 is another of the baseline scenarios and is for a flight to a destination with an NDB when an alternate with a navaid is required.

Scenario 3 is for a flight to a destination using GPS (FD receiver) when an alternate with a navaid is required. This scenario represents the procedures put into operation for the introduction of GPS NPA.

Scenario 4 is for a flight to a destination using GPS (FD receiver) when no alternate is required. This scenario represents what could be done with navigation by a GPS FD receiver alone (generally representative of TSO-C129).

Scenario 5 is for a flight to a destination using GPS (FD receiver) with no navaid at the alternate (the GPS FD receiver is used at alternate).

Scenario 6 is for a flight to a destination using GPS (FDE receiver) when there is no navaid at an alternate (the GPS FDE receiver used at alternate). This scenario represents what could be done with navigation by a GPS FDE receiver alone (generally representative of N8110.6 and TSO-C146). This scenario has the considerable advantage in that, if any satellite in view fails during the flight, it will be excluded and the flight can continue to the destination.

Conclusions

1. The many developments in the GPS satellite constellation and receivers over recent years have resulted in considerable improvement in GPS performance over that of the early 1990's. In particular, the operational availability of Receiver Autonomous Integrity Monitoring (RAIM) has been increased. In addition, receivers with Fault Detection and Exclusion (FDE) permit a flight to proceed to its destination with GPS navigation, even after a faulty satellite has been detected by the receiver.
2. Further developments are taking place, particularly increased reliability of the GPS satellites, ranging signals from Geostationary satellites (GEO's) and receivers with increased capabilities, which will further improve the performance of GPS with RAIM.

3. Current receiver standards require RAIM to provide, to an internationally agreed level of safety, a warning to the pilot of GPS satellite integrity failures as well as the loss of RAIM availability in the receiver to detect such failures. Even with external augmentation systems, RAIM is seen as essential for safe operations.
4. There are two causes of RAIM being unavailable :
 - a) because of insufficient satellites of appropriate angular spacing. This is predictable before the flight and if the GPS forecast is taken into account in the flight planning, it does not constitute a safety hazard. This procedure is assumed to take place for the scenarios examined in this study.
 - b) because of a random failure of a satellite during the flight.
5. A detailed examination of RAIM availability due to 4(a) shows,
 - a) the poorest performance occurs in the area around Adelaide and Albany
 - b) better performance is obtained elsewhere in Australia as shown by the improving performance from Adelaide to Parkes and then to Toowoomba
 - c) Baro-Aiding (ie the use of local QNH) is of benefit, especially with Selective Availability (SA) assumed to be still on
 - d) The benefits of ranging signals from GEO's (with TSO-C146 receivers) are considerable, especially when a critical satellite is not in service
 - e) Performance improves as the antenna mask angle decreases from 5^0 to 0^0 . There is little difference in performance between mask angles of 2^0 and 5^0 with SA off.
6. Receivers with FD only (ie most of the TSO-C129) are rendered unserviceable by the radiation of an erroneous signal from any faulty satellite in view, even though there are sufficient remaining satellites to support the flight.
7. The simulations show the benefit of the FDE receiver (either N8110.6 or TSO-C146) which has the capability to exclude a faulty satellite from the position determination and thus allows the flight to proceed using the remaining satellites with the FDE or FD function. In most of the simulations, FDE was available after a faulty satellite was excluded. In all simulations, the receiver could revert to FD in the EnRte and TMA. If there is a satellite failure during an NPA and RAIM is lost, it does not constitute a hazard because RAIM will be restored by executing a missed approach and switching to the TMA mode. RAIM for the NPA will then become available in a short time (the worst case in Adelaide averaged 10 minutes) for the NPA to be recommenced. The benefits of the FDE receivers in dealing random failures of satellites (as in 4b above) are shown in the improved probability of RAIM availability (see 9c below).
8. For a 2 hour flight to a destination where no alternate with a navaid is required, the use of GPS (even FD only) as in Scenario 4 results in better performance (higher availability of navigation signals for an NPA) than the baseline Scenario 1 for a flight to a single NDB.
9. For a 2 hour flight to a destination where an alternate with a navaid is required, a comparison of scenarios against the baseline Scenario 2 of NDB's at destination and alternate shows :-

- a) The use of GPS (FD only) for navigation to the destination and an NDB for navigation to the alternate as in Scenario 3 results in better performance (higher availability of navigation signals for an NPA) than the baseline Scenario 2.
 - b) The use of GPS (FD only) for navigation to both the destination and alternate as in Scenario 5 results in inferior performance (lower availability of navigation signals for an NPA) than the baseline Scenario 2. This remains so even with a ten-fold improvement in satellite reliability.
 - c) The use of GPS (FDE) for navigation to both the destination and alternate as in Scenario 6 results in better performance (higher availability of navigation signals for an NPA) than all other scenarios.
10. A study of the probability of harmful interference to GPS and other nav aids in the Australian environment needs to be carried out

1. INTRODUCTION

1.1 Background

Since the introduction of satellite navigation using GPS for civil aviation commenced in the early 1990's, many developments in the satellite constellation and receivers have taken place. Improved performance has resulted from :-

- The increase in the satellite constellation from 18 to more than 24 satellites
- Selective Availability (SA) has been set to zero
- Receivers are available with Fault Detection and Exclusion (FDE)
- GPS has been integrated with the Inertial Reference System (IRS) in the larger aircraft

Further improvements in GNSS can be expected from :-

- Increased reliability of the satellites
- Ranging signals from Geostationary satellites
- Additional ranging signal from GPS at the L5 frequency
- New satellite navigation systems eg Galileo
- More augmentation systems
- Development of MicroElectronicMechanicalSystems (MEMS) integrated with GPS and suitable for GA

It was therefore timely to review the performance and operation of the currently used and proposed navigation systems involving GPS for GA operations in Australian airspace. Accordingly, the Civil Aviation Safety Authority contracted FANS PLANS to undertake this study.

Aircraft navigation requires a navigation system to provide an acceptable level of accuracy, availability, integrity and continuity of function. The actual level of performance required varies according to the phase of flight eg en-route, terminal area, non-precision approach & departure and precision approach & landing. The basic satellite constellations such as GPS and GLONASS, of themselves, do not provide the levels of performance needed for the above phases of flight. Augmentation is needed and may take the form of Aircraft Based (ABAS), Satellite Based (SBAS) or Ground Based (GBAS) Augmentation Systems.

The only augmentation system which has been certificated and is in wide general use is ABAS where the GPS receiver incorporates Receiver Autonomous Integrity Monitoring (RAIM). RAIM is based on the premise that, under normal conditions, the aircraft position calculated from the satellite constellation is "overdetermined". The RAIM algorithm contains parity equations that measure the consistency of the redundant satellite measurements. RAIM or its equivalent is required for IFR operations, including Non Precision Approaches (NPA), in Australia. The basic type of RAIM detects a failure in the satellite system and is called Fault Detection (FD). Further development of RAIM into Fault Detection and Exclusion (FDE) allows the faulty satellite to be identified and excluded from the calculation of position, thus permitting the flight to continue. Aircraft Based Augmentation Systems have been

available for some years and are in everyday operation. They have the big advantage of not requiring any additional space-based or ground-based infrastructure.

To further improve availability and continuity of function, the satellite determined position can be integrated with other navigation sensors such as Inertial Reference Systems (IRS), altimetry, etc to form a multi-sensor system. While the integration of barometric altimetry with GPS is widely used to improve performance in GA aircraft, integration with IRS has been limited to the larger aircraft. However, the development of MEMS opens the way to small lower cost GPS/IRS navigation systems for GA in this decade.

1.2 Scope of Study

The focus of this study is on the determination of the levels of availability of high integrity navigation information from GPS receivers with augmentation from barometric altimetry and using RAIM for integrity monitoring. These determinations have been carried out for a wide variety of satellite constellations and receiver parameters under both normal and degraded conditions.

Chapter 2 explains the assumptions for the setting up of the satellite constellation and receiver parameters and the methodology used for the simulations of the GPS system performance.

Chapter 3 discusses the GPS Constellations considered in the study.

Chapter 4 discusses the characteristics of GPS receivers available and currently in use together with improved receivers which are likely to be available in the near future.

Chapter 5 shows the results of the RAIM availability determinations for a wide range of parameters for the satellite constellation (including GEO's) and receivers under both normal and degraded conditions.

Chapter 6 presents the probability levels of RAIM availability for six operational scenarios of GA flights to a destination and compares these with the base-line scenarios NDB's.

Chapter 7 sets out the conclusions of the study.

1.3 Acknowledgements

FANS PLANS provided Professor Brian O'Keeffe AO, LLD (Hon), BE, FIE Aust, FAIN as the principal consultant for this study.

Mr Graeme Challinor MA (Oxon), FIS provided valuable contributions.

FANS PLANS gratefully thanks HONEYWELL INTERNATIONAL for kindly providing the simulation data on the performance of GPS in Australian airspace under a wide variety of parameters.

2. ASSUMPTIONS AND METHODOLOGY

2.1 Overall Assumptions

The focus of this study is on actual systems (both satellite constellations and receivers) which are in operation and on new systems which could reasonably be expected to be available in the next few years. No attempt has been made to design new systems, but some new operational procedures are proposed in Chapter 6. Many unknowns still exist for these new systems and so prudent assumptions have been made as to their performance. Some updating of this study in the light of detailed developments, such as updating of the GPS signal specification and receiver performance, may therefore be required in the future.

The performance of the overall GPS system derives from the characteristics of the GPS satellite constellation and the receivers. The satellite constellation gives rise to variables in performance, because the number of satellites and their orbital positions vary. The standard (or optimised) Martinez 24 satellite constellation as defined in RTCA/DO-229B (Reference 2) was therefore used in the study.

As stated in Reference 6, "Each satellite completes one orbit in one half of a sidereal day and therefore passes over the same location on earth every sidereal day, or approximately 23 hours and 56 minutes." Thus, with a constant satellite constellation, the received signals will vary in a repeatable way over this GPS satellite constellation cycle with respect to the receiver and according to the geographic position of the receiver. Further detail of the satellite constellations are discussed in Chapter 3. Similarly, a wide variety of receivers with a correspondingly wide range of performance characteristics are in use and additional ones are being developed. These are discussed in detail in Chapter 4.

It would be impracticable to determine the performance of each possible combination of parameters of the satellite constellation and receivers. Rather, a range of likely combinations of parameters were selected for analysis and then a sensitivity analysis was carried out to discern trends.

The performance of GPS in the presence of interference was beyond the scope of this study. A discussion of the vulnerability of GPS can be found in the report "Vulnerability Assessment of the Transport Infrastructure relying on the Global Positioning System" prepared by the John A Volpe National Transportation Systems Center (Reference 8). An analysis of the probability of harmful interference to GPS in Australia needs to be carried out. In order to make valid comparisons of the performance of GPS with the performance of other navigation systems, an analysis of the probability of harmful interference to conventional navigation systems in Australia (eg NDB/ADF) by both man-made and natural sources (eg thunderstorms) also needs to be carried out.

2.2 Methodology

The study was carried out in three main stages.

In the first stage, the performance was determined by simulation of a typical satellite constellation and receiver over the whole of the Australian airspace. This was done by dividing up the Australian airspace into a large number of pixels ($1^{\circ} \times 1^{\circ}$) and determining the RAIM availability in each. The result is shown in Figure 2-1, for both Fault Detection (FD) and Fault Detection and Exclusion (FDE). The blue areas show an availability of 100% and the red areas show an availability of between 99.6% and 99.7%. It is seen that the “worst” areas over continental Australia are around Adelaide (SA) and Albany (WA). Adelaide was thus selected for the most detailed examination.

In the second stage, simulations were carried out for the Adelaide area over the GPS satellite constellation cycle using some 40 combinations of satellite constellation and receiver parameters to determine the performance of the most likely combinations and to show trends from the sensitivity analyses. This showed the performance at one of the “worst” locations. Better performance could then be expected at all other locations. A limited examination of two “better” locations, Parkes and Toowoomba, was then carried out to show what the “average” performance was likely to be. The plotting of the RAIM performance against time over the whole of the GPS satellite constellation cycle proved to be a powerful tool in analysing performance in detail. These plots are discussed in Chapter 5. They are presented and analysed in Appendices A, B and C.

In the third stage, six operational scenarios were constructed for GA flights to a destination. As base-lines for comparison, the first two scenarios were constructed for a flight to a destination using NDB's. The next four scenarios were for flights using GPS with FD or FDE receivers and with or without a navaid at an alternate. The probabilities for RAIM availability over each phase of a 2 hr flight to the destination were determined.

In performance assessments in this study, the “risk” of RAIM not being available for an IFR flight was determined, rather than the overall “rate” of RAIM not being available for a large number of flights. Thus the scenarios assume that that an IFR flight is required because of meteorological conditions. The use of “rate” averaged over a large number of flights is particularly misleading in the case of Australian operations, where most GA flights are conducted in VFR conditions. If “rate” were used, a hazardous situation occurring for a single IFR flight would be masked by the large number of VFR flights. The use of “risk” rather than “rate” is in accordance with the methodology developed at ICAO for the assessment of failure probabilities for ILS approach and landings. It is also in line with the thinking of FAA expressed at ION-2000.

3. GPS SATELLITE CONSTELLATIONS

In the early 1990's, when there were fewer satellites in the GPS constellation, the avionics industry standard was for 18 satellites arranged in 6 orbit planes. This constellation was defined in RTCA/DO-208 (Reference 1) and a “snapshot” of the satellites in their orbital planes at one moment of time is shown in Figure 3-1.

As satellites were added to the constellation in the 1990's, a new industry standard was published in RTCA/DO-229B. This constellation is also referred to as the optimised constellation or the Martinez 24 (M24), and is used for the design, testing and performance comparison of GPS. A snapshot of the satellites in their orbital planes at one moment of time is shown in Figure 3-2.

Further satellites have since been added to the constellation and a snapshot taken from the almanac of 11 May 2001 is shown in Figure 3-3. It will be noted that some satellites are close together, eg F1 and F5. The additional satellite of the pair contributes little to the navigation position, because the angular spacing between them is so small. However, if one of the pair were to fail, there would be little effect on the overall performance. It is understood that such additional satellites are placed near existing satellites which may be reaching the end of their lives. The term "buddy" satellite has been used to describe the additional satellite. Where a satellite has a large angular spacing from the others in its plane and also from those in adjacent planes, its failure will have a large effect on the overall performance. As will be seen in Chapter 5, the removal of A2 from service has a large effect on RAIM availability over Australia.

Most of the time, the actual satellite constellation is probably better than M24. However, the actual constellation varies from time to time and thus performance comparisons based on the actual constellation at a point of time are not very meaningful. Hence, the standard satellite constellation M24 has been used in this study. This is the prudent choice as the actual performance will usually be better. In some of the simulations, Based on advice from the simulations to date, satellite A2 has been removed (set unhealthy) in some simulations to simulate the loss of a critical satellite. The simulations also include the simultaneous removal of A1 and F3.

A recent development has been the provision for GPS compatible ranging signals to be radiated from geostationary satellites. This is equivalent to adding satellites to the constellation with beneficial effects. The GEO's of importance to Australia are the Pacific Ocean INMARSAT satellite (also called the WAAS satellite), the INMARSAT Indian Ocean satellite and the MTSAT satellites. Although few of the existing GPS receivers are capable of receiving the ranging signals from the GEO's, the new TSO-C146 receivers are to have that capability. The simulations in this study include the effect of the additional ranging signals from the WAAS and MTSAT GEO's. As will be seen in Chapter 5, the beneficial effect of the GEO's is particularly noticeable when there is a failure in a critical satellite.

In RTCA/DO-229B Appendix B para B.4, it is stated that "the probability of a satellite integrity failure is 10^{-4} per hour for the GPS position solution (based on 3 major service failures / year / constellation, assuming 8 satellites in view)". This has been used to calculate the probabilities of RAIM unavailability in the study to compare current performances. Improved reliability of the GPS satellites could be expected in the future. To illustrate the effect of improved satellite reliability on system performance, the study has included probability calculations if a ten-fold improvement in satellite reliability could be achieved.

4. GPS RECEIVERS

4.1 Receiver Categories

Receivers with a wide variety of characteristics are presently in use and new models with greater capabilities are being developed. The study has therefore divided receivers into three broad groups :-

- Group 1 broadly represents the older receivers meeting TSO-C129 (Reference 3) which would be used by General Aviation. They are characterised by having FD only and still assuming that SA is on. However, some “high end” receivers may have FDE. Modifications to reconfigure the older receivers for SA off are unlikely to be available. Mask angles from 5^0 down to 0^0 are in use. Modifications to use ranging signals from GEO’s are unlikely to be available for GA receivers.
- Group 2 represents the performance of receivers meeting FAA Notice N8110.6 (Reference 7) for oceanic/remote operations. These receivers have FDE and mask angles down to 0^0 . Modifications may be available from the manufacturers to reconfigure them for SA off.
- Group 3 represents the likely performance of the new receivers meeting TSO-C146 (Reference 4). These would have FDE, SA off, a mask angle specified as 5^0 when using WAAS corrections and can use of the ranging signals from MTSAT and WAAS.

4.2 Selective Availability

With SA on, the ranging accuracy was taken as 33m (1 sigma). Even with SA now set to zero (SA off), most of the early receivers would assume this ranging accuracy for their calculation of RAIM functions. Hence, SA on has been used for the performance of Group 1 receivers.

With SA off, the ranging accuracy is set at 12.5m (1 sigma).

4.3 Barometric Aiding

Using the definitions of RTCA DO-229B, Appendix G, “Altimeter Aiding with GPS Calibration” seems to best match the Australian situation for Non-precision Approaches at remote aerodromes where no local baro correction (QNH) is available. This has been called “Altitude” in the simulations. However, the simulation results for “Barometric Altimeter Aiding Using Baro-corrected Pressure Altitude” have been included in the simulations (called Baro) to represent the case where the specific QNH of the aerodrome is available (as it would be in the Adelaide area).

4.4 Mask Angle

Antenna mask angles of 0^0 , 2^0 and 5^0 have been used in the simulation. The actual notation used is eg 2/2, which indicates that the signal is acquired for angles above 2^0 and deleted for angles below 2^0 . A number of industry standard receivers use 2/0.

Most GA receivers seem to use 0/0 because of marketing pressures. The receivers conforming to FAA N8110.6 are specified as 0/0. Although the TSO-C146 receivers are specified as 5/5 when using WAAS, it remains to be seen what figure manufacturers will use for a new receiver when WAAS is not enabled. The effect of mask angle is included in the simulations as a sensitivity analysis. 2/2 seems a reasonable figure to use for most simulations, as it represents neither to best nor the worst.

4.5 Receiver Alert Limits

GPS receivers must indicate an alert when inadequate or invalid navigation signals would cause unacceptable navigation for a particular phase of flight/navigation mode. The Horizontal Alert Limits (HAL) implemented in receivers are set out in RTCA/DO-208 and RTCA/DO-229B as shown in Table 4.1 below :-

Table 4.1 Receiver Alert Limits

Phase of Flight/Navigation Mode	HAL
En-route (EnRte)	2NM = 3704m
Terminal (TMA)	1NM = 1852m
Non-precision Approach (NPA)	0.3NM = 555.6m

4.6 Summary of Receiver Characteristics

Table 4-2 summarises the likely situation regarding the characteristics of receivers in use and proposed.

Table 4.2 Receiver Characteristics

Receiver Characteristic	Receiver Group		
	Group 1 TSO-C129	Group 2 FAA Notice 8110.6	Group 3 TSO-C146
FD	Yes	Yes	Yes
FDE	? (Note 1)	Yes	Yes
SA off	No	No (Note 2)	Yes
GEO Ranging	No	No	Yes

Note 1

Unlikely in GA models, modification possibilities limited.

Note 2

Modification may be possible in later models.

5. RAIM AVAILABILITY FOR VARIOUS CONSTELLATIONS AND RECEIVER PARAMETERS

5.1 RAIM Availability Plots

Simulations were carried out to examine RAIM Availability Performance for both FD and FDE as a function of time for Adelaide, Parkes and Toowoomba. Using each set of parameters set out in the Tables at the beginning of each of the following Sections, the RAIM performance function (Horizontal Protection Level (HPL) in the case of FD and Horizontal Exclusion Level (HEL) in the case of FDE) was plotted for each minute of the time period (1436 min) of the GPS satellite constellation cycle.

Horizontal Alert Limits (HAL) for the receiver modes of Non-Precision Approach (NPA), Terminal Area (TMA) and En-Route (EnRte) are plotted as horizontal lines using the values from Table 4.1. Thus, when the RAIM performance function exceeds the HAL for the particular phase of flight, an alert is given. In the case of a receiver with FD only, navigation service will then not be available. In the case of a receiver with FDE, exclusion will then not be possible and the receiver will revert to FD only. A description of the RAIM algorithm is covered in the paper “Implementation of a RAIM Monitor in a GPS Receiver and an Integrated GPS/IRS” by Mats Brenner of Honeywell presented at ION GPS-90 (Reference 3)

It should be stressed that RAIM Performance in all these plots is predictable and repeatable based on the knowledge of the GPS satellite constellation, the receiver characteristics and the geographical location. With this foreknowledge, the RAIM availability is known before the flight and thus does not constitute a safety hazard if it is taken into account when planning the flight. The flight can be planned to avoid the forecast periods of RAIM unavailability in much the same manner as the flight needs to take into account the forecast weather, NOTAMS, etc. This, of course, would require a comprehensive GPS forecasting service. RAIM unavailability has only an economic effect on operations in terms of constraining when the flight can proceed. The better the characteristics of the receiver, the wider the window for the flight. The safety aspect comes into contention where there is an un-forecast failure in the GPS system and this is analysed in Chapter 6.

5.2 Adelaide

The set of satellite constellation and receiver parameters used for the plots of the RAIM Performance Function for Adelaide is shown at Table 5-1. The resulting plots and their analysis are at Appendix A.

5.3 Parkes

The set of satellite constellation and receiver parameters used for the plots of the RAIM Performance Function for Parkes is shown at Table 5-2. The resulting plots and their analysis are at Appendix B.

5.4 Toowoomba

The set of satellite constellation and receiver parameters used for the plots of the RAIM Performance Function for Toowoomba is shown at Table 5-3. The resulting plots and their analysis are shown at Appendix C.

5.5 Summary of RAIM Performance

1. The improvement in performance from Adelaide to Parkes and then to Toowoomba is shown in :-
 - FD 01, FD 16 and FD 22 respectively for FD receivers (TSO-C129)
 - FDE 09, FDE 17 and FDE 23 respectively for FDE receivers (N8110.6 and TSO-C146).
2. Baro-Aiding (ie the use of local QNH) is of benefit, especially with SA assumed to be on (FD 01 and FD 03).
3. The benefits of ranging signals from GEO's (with TSO-C146 receivers) are considerable, especially when a critical satellite is not in service.
4. There is little difference in performance between mask angles of 2/2 and 5/5 (FD 08 and FD 09) with SA off.
5. As previously mentioned, all the periods of unavailability of FD and FDE for both normal and fault conditions are repeatable and predictable based on the knowledge of the GPS satellite constellation, the receiver characteristics and the geographical location. With a comprehensive GPS forecast available before the flight, the RAIM unavailability does not constitute a safety hazard, provided it is taken in account when planning the flight. The forecast could be extended to a further stage of "what if" to show the forecast situation if a critical satellite were to fail during the flight and thus add an additional factor of safety. A GPS forecast before the flight is assumed for the scenarios in the next Chapter.
6. The simulations show the benefit of the FDE receiver (either N8110.6 or TSO-C146) which has the capability to exclude a faulty satellite from the position determination and thus allows the flight to proceed using the remaining satellites with the FDE or FD function. In most of the simulations, FDE was available after a faulty satellite was excluded. In all simulations, the receiver could revert to FD in the EnRte and TMA. Receivers with FD only (ie most of the TSO C129) are rendered unserviceable by the radiation of an erroneous signal from any faulty satellite in view, even though there are sufficient remaining satellites to support the flight. The benefits of the FDE receivers are shown in the probability calculations in the next Chapter. It is interesting to note how FDE was foreshadowed the statement in RTCA/DO-208 Appendix J :-

"Failure detection can be performed by an internal and /or an external monitor. As defined for supplemental navigation, paragraph 1.5.2 specifies a Receiver Autonomous Integrity Monitor (RAIM) that requires at least one redundant measurement for failure detection. For sole means, RAIM will require at least two redundant measurements to provide not only failure detection, but also isolation capability to enable continuous navigation."

6. *PROBABILITIES OF RAIM AVAILABILITY UNDER VARIOUS SCENARIOS*

6.1 Scenario Assumptions

There are two causes of RAIM being unavailable, firstly because of insufficient satellites of appropriate angular spacing and secondly because of a random failure of a satellite during the flight. As discussed in Sections 5.1 and 5.4, the first cause of RAIM unavailability is predictable before the flight and if the GPS forecast is taken into account in the flight planning, it does not constitute a safety hazard. This procedure is assumed to take place during the following scenarios. The probability of the occurrence of the second cause of RAIM being unavailable during a flight because of a random failure of a satellite is discussed in this Chapter.

Little quantitative information could be obtained on GPS receiver reliability. RTCA/DO-229B merely states “The equipment should be designed to maximise reliability”. However, it was interesting to note that NovAtel publish a Mean Time Between Failures (MTBF) of 60,000 hours for their model CMA 4024 receiver developed jointly with the Canadian Marconi Company to meet TSO-C145. This study uses the conservative assumption that GPS receivers have a reliability equal to ADF's. This allows the receiver reliability to be removed from the comparison of GPS with ADF/NDB operational system reliability.

The GPS satellite reliability of 10^{-4} per hour used in this study is taken from RTCA/DO-229B and was discussed in Chapter 3. The study has also extended the probability calculations to illustrate the effect of a 10-fold improvement in satellite reliability.

The probabilities of RAIM availability are calculated over four scenarios. Each scenario is for a 2 hr flight from an origin, where notams, weather and a comprehensive GPS forecast is available, to a destination, which may have an NDB, GPS approaches and an alternate with a navaid. It should be noted that a 2 hr flight is only a small fraction of the GPS satellite constellation cycle of 23 hr 56 min and thus RAIM unavailability for a few short periods still leaves “windows” of many hours for a flight. This can be seen in the RAIM availability plots at Appendices A, B and C.

Relevant probability calculations and data are shown in Appendix D.

6.2 Scenario 1 : Flight to a Destination with an NDB when no Alternate with a Navaid is required.

This is the baseline scenario, which represents the procedures in operation for a long time and against which the GPS scenarios are compared.

The scenario assumes that a briefing (notams, weather, etc) is obtained before departure and, if the conditions are favourable, the 2 hr flight to the destination with the NDB is commenced. No other nav aids are assumed : the EnRte phase is carried

using Dead Reckoning (DR). At the destination, an NPA using the NDB is commenced.

Informal data from Australia and Japan indicates that the Mean Time Between Failure (MTBF) for an NDB is about 10,000 hrs. Hence the probability of the failure of the NDB during the 2 hr flight is 2×10^{-4} . The scenario assumes that the NDB is, in fact, serviceable before the flight commences. This is probably an optimistic assumption for a remote NDB subject to pilot monitoring : it may have failed before the commencement of the flight and the failure may not be noticed until the aircraft arrives to within the coverage of the NDB.

The probability of the NDB not being available for an NPA when the aircraft has arrived at the destination is 2×10^{-4} . If the NDB has been received some 30 min before the NPA is to be attempted, the probability of failure during the next 30 min is 5×10^{-5} . The probability that the NDB fails during the period of an NPA (assumed to be about 6 min) is 1×10^{-5} .

6.3 Scenario 2 : Flight to a Destination with an NDB when an Alternate with a Navaid is required.

This is another baseline scenario, which has been in operation for a long time and against which GPS scenarios can be compared.

The scenario assumes that a briefing (notams, weather, etc) is obtained before departure and, if the conditions are favourable, the 2 hr flight is commenced. NDB's are assumed at the destination and the alternate. The EnRte phase is carried using Dead Reckoning (DR). At the destination, an NPA using the NDB is commenced and, if unsuccessful, the aircraft proceeds to the alternate (an assumed flight of 30 minutes) where another NPA is commenced.

As in Scenario 1, the probability of the NDB not being available for an NPA when the aircraft has arrived at the destination is 2×10^{-4} . If the NDB has been received some 30 min before the NPA is to be attempted, the probability of failure during the next 30 min is 5×10^{-5} . The probability that the NDB fails during the period of an NPA (assumed to be about 6 min) is 1×10^{-5} . The probability of the NDB at the alternate not being available after 2.5 hours of the flight is 2.5×10^{-4} . Thus the probability of both NDB's being unavailable is 5×10^{-8} .

6.4 Scenario 3 : Flight to a Destination using GPS (FD receiver) when an Alternate with a Navaid is required.

This scenario represents the procedures put into operation for the introduction of GPS NPA and are a justifiably prudent way to introduce a new system such as GPS.

The briefing before the flight now includes the GPS predictions. If FD availability for the NPA is predicted to be available at the destination at the time of arrival, the flight can proceed. If not, a short delay will provide FD availability for the NPA. GPS will then be used, rather than DR, for the EnRte phase of the flight. The operational

advantage over the NDB scenario is that the availability of GPS at the destination can be monitored throughout the EnRte phase of the flight and not, as for the NDB only in Scenarios 1 and 2, until the aircraft arrives to within coverage of the NDB. If a fault is detected in the GPS (by the FD receiver) during the first hour of the flight, the aircraft could return to the origin, fly to an alternate along the route, fly direct to the alternate with the Navaid, etc.

Because the FD availability prediction has been taken into account in planning the flight before departure, the major cause of RAIM unavailability during the flight is a random failure of any satellite in view, ie 1×10^{-4} per hr. Hence, the probability of unavailability of FD for the NPA at the destination may be calculated from the probability of satellite failure during the second hour of the flight and is 1×10^{-4} . The probability that RAIM will become unavailable during the 30 min prior to the NPA is 5×10^{-5} . The probability that FD will become unavailable during the period of the NPA (assumed to be about 6 min) is 1×10^{-5} .

If RAIM is not available at the destination, the aircraft proceeds to the alternate to commence an NPA using the Navaid at the alternate. The probability that the Navaid is not available is 2.5×10^{-4} . Thus, the cumulative probability of RAIM unavailability and the Navaid inoperative at the alternate is 2.5×10^{-8} . If the GPS satellite reliability was improved by a factor of 10, this cumulative probability would be 2.5×10^{-9} .

6.5 Scenario 4 : Flight to a Destination using GPS (FD receiver) when no Alternate with a Navaid is required

This scenario represents what could be done with navigation by a GPS FD receiver alone (generally representative of TSO-C129).

The briefing before the flight includes the GPS predictions and may, as a result of further study, require a more comprehensive prediction service as discussed in Section 5.4.5. If FD availability for the NPA is predicted to be available at the destination at the time of arrival, the flight can proceed. If not, a short delay will provide FD availability for the NPA. GPS will then be used, rather than DR, for the EnRte phase of the flight. The availability of GPS at the destination can be monitored throughout the EnRte phase of the flight.

Because the FD availability prediction has been taken into account in planning the flight before departure, the major cause of RAIM unavailability during the flight is a random failure of any satellite in view, ie 1×10^{-4} per hr. If the failure occurs during the first hour of the EnRte phase of the flight, a number of alternatives are available eg return to origin, fly to an alternate along the route, etc. Thus, for the reasons explained in Scenario 3, the probability of this random failure during the second hour of the flight is 1×10^{-4} and this would make RAIM unavailable for the NPA. The probability that RAIM will become unavailable during the 30 min prior to the NPA is 5×10^{-5} . The probability that RAIM will become unavailable during the period of the NPA (assumed to be about 6 min) is 1×10^{-5} .

Thus with this scenario, the probability of having guidance available for an NPA is likely to be about the same as for a flight to a single NDB. However, the operational

advantage over the NDB scenario is that the warning of the unavailability of RAIM at the NPA at the destination is received as soon as it occurs during the flight and the opportunities for hazard reduction are improved.

If the GPS satellite reliability was improved by a factor of 10, the probability of RAIM being unavailable for the NPA would be 1×10^{-5} .

6.6 Scenario 5 : Flight to a Destination using GPS (FD receiver) with no Navaid at the Alternate (the FD receiver is used at the alternate)

This scenario represents what could be done with navigation by a GPS FD receiver alone for EnRte, and NPA at destination and alternate.

The briefing before the flight includes the GPS predictions and may, as a result of further study, require a more comprehensive prediction service as discussed in Section 5.4.5. If FD availability for the NPA is predicted to be available at the destination and alternate at the time of arrival, the flight can proceed. If not, a short delay will provide FD availability for the NPA at both destination and alternate. GPS will be used, rather than DR, for the EnRte phase of the flight. The availability of GPS at the destination and alternate can be monitored throughout the EnRte phase of the flight.

Because the FD availability prediction has been taken into account in planning the flight before departure, the major cause of RAIM unavailability during the flight is a random failure of any satellite in view, ie 1×10^{-4} per hr. If the failure occurs during the first hour of the EnRte phase of the flight, a number of alternatives are available eg return to origin, fly to an alternate along the route, etc. Thus, for the reasons explained in Scenario 3, the probability of this random failure during the second hour of the flight is 1×10^{-4} and this would make RAIM unavailable for the NPA. If RAIM is unavailable at the destination due to satellite failure, it would be most unlikely to be available at the alternate. Thus, the probability of RAIM being unavailable at both the destination and alternate is 1×10^{-4} . If the GPS satellite reliability was improved by a factor of 10, the probability of RAIM being unavailable for the NPA would be 1×10^{-5} .

6.7 Scenario 6 : Flight to a Destination using GPS (FDE receiver) with no Navaid at Alternate (the FDE receiver is used at the alternate)

This scenario represents what could be done with navigation by a GPS FDE receiver alone (generally representative of N8110.6 and TSO-C146). The exclusion capability represents an improvement over the receivers with FD only.

The briefing before the flight includes the GPS predictions and may, as a result of further study, require a more comprehensive prediction service as discussed in Section 5.4.5. If FDE availability for the NPA is predicted to be available at the destination and alternate at the time of arrival, the flight can proceed. If not, a short delay will provide FDE availability for the NPA at both destination and alternate. GPS will be used, rather than DR, for the EnRte phase of the flight. The availability of GPS at the destination and alternate can be monitored throughout the EnRte phase of the flight.

This scenario has the considerable advantage over scenarios using a receiver with FD alone, in that, if any satellite in view fails during the flight, it will be excluded and the flight can continue to the destination. As shown in Chapter 5, the GPS constellation will always support FDE receivers to continue at least with FD for the EnRte and TMA phases after satellite failures.

The probability of a random satellite failure during the 6 minutes of the NPA is 1×10^{-5} . As shown in the FD availability plots in Appendices A, B and C, the probability that the receiver cannot revert to FD and immediately provide RAIM is 1×10^{-2} . The cumulative probability that RAIM is unavailable immediately the satellite fails is therefore 1×10^{-7} . It does not constitute a hazard because RAIM will be restored by executing a missed approach and switching to the TMA mode. RAIM for the NPA will then become available in a short time (the worst case in Adelaide averaged 10 minutes) for the NPA to be recommenced.

The probability of 2 satellites failing prior to the NPA is 1×10^{-8} . Taking into account the probability that these will be critical to the FDE to FD reversion and the probability that the reversion cannot take place immediately, the probability of this case is reduced further and is much smaller than the above.

With a more comprehensive prediction service, the probability of RAIM unavailability can be reduced further.

6.8 Comparison of Scenarios

A comparison of the six scenarios, in terms of the navigation information provided and the probabilities of navigation information not being available at the destination and alternate, is shown in Table 6.1 below.

Table 6.1 Comparison of Scenarios

Scenario	Navigation En-Route	Navigation for NPA at Destination	Navigation for NPA at Alternate	Probability of Unavailability (Note 1)	Comparison	Probability of Unavailability (Note 2)
#1	DR	NDB	Not Req'd.	2×10^{-4}	Baseline	2×10^{-4}
#2	DR	NDB	NDB	5×10^{-8}	Baseline	5×10^{-8}
#3	GPS (FD)	GPS (FD)	NDB	2.5×10^{-8}	Better than #2	2.5×10^{-9}
#4	GPS (FD)	GPS (FD)	Not Req'd.	1×10^{-4}	Better than #1	1×10^{-5}
#5	GPS (FD)	GPS (FD)	GPS (FD)	1×10^{-4}	Worse than	1×10^{-5}

					#3	
#6	GPS (FDE)	GPS (FDE)	GPS (FDE)	Less than 1×10^{-8}	Better than all	1×10^{-10}

Note 1

Probability of the unavailability of navigation information at destination or destination and alternate with the current specification of satellite reliability.

Note 2

Probability of the unavailability of navigation information at destination or destination and alternate with a 10-fold improvement in satellite reliability.

7. CONCLUSIONS

1. The many developments in the GPS satellite constellation and receivers over recent years have resulted in considerable improvement in GPS performance over that of the early 1990's. In particular, the operational availability of Receiver Autonomous Integrity Monitoring (RAIM) has been increased. In addition, receivers with Fault Detection and Exclusion (FDE) permit a flight to proceed to its destination with GPS navigation, even after a faulty satellite has been detected by the receiver.
2. Further developments are taking place, particularly increased reliability of the GPS satellites, ranging signals from Geostationary satellites (GEO's) and receivers with increased capabilities, which will further improve the performance of GPS with RAIM.
3. Current receiver standards require RAIM to provide, to an internationally agreed level of safety, a warning to the pilot of GPS satellite integrity failures as well as the loss of RAIM availability in the receiver to detect such failures. Even with external augmentation systems, RAIM is seen as essential for safe operations.
4. There are two causes of RAIM being unavailable :
 - a) because of insufficient satellites of appropriate angular spacing. This is predictable before the flight and if the GPS forecast is taken into account in the flight planning, it does not constitute a safety hazard. This procedure is assumed to take place for the scenarios examined in this study.
 - b) because of a random failure of a satellite during the flight.
5. A detailed examination of RAIM availability due to 4(a) shows,
 - a) the poorest performance occurs in the area around Adelaide and Albany
 - b) better performance is obtained elsewhere in Australia as shown by the improving performance from Adelaide to Parkes and then to Toowoomba
 - c) Baro-Aiding (ie the use of local QNH) is of benefit, especially with Selective Availability (SA) assumed to be still on
 - d) The benefits of ranging signals from GEO's (with TSO-C146 receivers) are considerable, especially when a critical satellite is not in service

- e) Performance improves as the antenna mask angle decreases from 5^0 to 0^0 . There is little difference in performance between mask angles of 2^0 and 5^0 with SA off.
 - f) Receivers with FD only (ie most of the TSO-C129) are rendered unserviceable by the radiation of an erroneous signal from any faulty satellite in view, even though there are sufficient remaining satellites to support the flight.
 - g) The simulations show the benefit of the FDE receiver (either N8110.6 or TSO-C146) which has the capability to exclude a faulty satellite from the position determination and thus allows the flight to proceed using the remaining satellites with the FDE or FD function. In most of the simulations, FDE was available after a faulty satellite was excluded. In all simulations, the receiver could revert to FD in the EnRte and TMA. If there is a satellite failure during an NPA and RAIM is lost, it does not constitute a hazard because RAIM will be restored by executing a missed approach and switching to the TMA mode. RAIM for the NPA will then become available in a short time (the worst case in Adelaide averaged 10 minutes) for the NPA to be recommenced. The benefits of the FDE receivers in dealing random failures of satellites (as in 4b above) are shown in the improved probability of RAIM availability (see 9c below).
 - h) For a 2 hour flight to a destination where no alternate with a navaid is required, the use of GPS (even FD only) as in Scenario 4 results in better performance (higher availability of navigation signals for an NPA) than the baseline Scenario 1 for a flight to a single NDB.
 - i) For a 2 hour flight to a destination where an alternate with a navaid is required, a comparison of scenarios against the baseline Scenario 2 of NDB's at destination and alternate shows :-
 - i) The use of GPS (FD only) for navigation to the destination and an NDB for navigation to the alternate as in Scenario 3 results in better performance (higher availability of navigation signals for an NPA) than the baseline Scenario 2.
 - ii) The use of GPS (FD only) for navigation to both the destination and alternate as in Scenario 5 results in inferior performance (lower availability of navigation signals for an NPA) than the baseline Scenario 2. This remains so even with a ten-fold improvement in satellite reliability.
 - iii) The use of GPS (FDE) for navigation to both the destination and alternate as in Scenario 6 results in better performance (higher availability of navigation signals for an NPA) than all other scenarios.
6. A study of the probability of harmful interference to GPS and other nav aids in the Australian environment needs to be carried out

8. REFERENCES

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2. Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA/DO-229B, October 6, 1999.
3. FAA Technical Standard Order TSO-C129a, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS), 20 February 1996.
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Appendix A

RAIM Availability Performance for Adelaide (FD and FDE)

The receiver characteristics referenced in FD 01 to FD 03 represent the GA receivers described in Group 1 (see para. 4.1) as the older TSO-C129 receivers.

FD 01 represents the base case as the minimum TSO-C129 receiver. Such a receiver would have full RAIM FD availability for the en-route (EnRte) and terminal area (TMA) phases of flight, but experience two periods of 16 min of FD unavailability for the non precision (NPA) phase of the flight. Provided an NPA was not attempted during these two periods (which can be forecast before the flight), FD would be available for the whole flight.

FD 02 shows that, if a critical satellite (such as A2) had failed, there would be no effect on the EnRte phase, a small period of unavailability in the TMA and an increase in unavailability for NPA.

FD 03 shows the beneficial effect (compared with FD01) of having the local QNH to feed into the receiver for the NPA. FD is now available for the whole period.

The receiver characteristics referenced in FD 03 to FDE 06 represent the performance of receivers described in Group 2 (see para. 4.1) as those meeting FAA Notice N8110.6 for oceanic/remote areas.

FDE 04 represents the base case where the receiver assumes that SA still operates.

The plot shows exclusion is available full time for the EnRte phase. There are a number of periods of about 15 minutes when the exclusion function is not available in the TMA and NPA phases. However, if the receiver experienced a period of unavailability of the exclusion function, it would revert to FD. As shown in FD 04, FD is available for all but two periods for the NPA phase.

FDE 03, when compared with FDE 01, shows the benefit for the availability of the exclusion function of having the local QNH to feed into the receiver for the NPA.

FDE 06 to FDE 15 and FDE 20 represent receivers modified to take account of SA having been reduced to zero.

FDE 06 shows the improved performance of the receiver thus modified. Exclusion availability has been reduced to two periods of a few minutes and when the receiver then reverts to FD, as shown in FD 06, FD is available for the whole period.

FDE 05 shows the effect of A2 being out of service, resulting in periods of exclusion unavailability. During the periods, the receiver reverts to FD and, as shown in FD 05, FD is then available for EnRte, briefly unavailable for TMA and unavailable for periods of up to 30 minutes for NPA.

FD 06, FD 08 and FD09 show the effect on FD of mask angles of 0/0, 2/2 and 5/5 respectively. There is little difference in performance between 2/2 and 5/5.

FDE 06, FDE 08 and FDE 09 show the effect on FDE of mask angles of 0/0, 2/2 and 5/5 respectively. Again, there is little difference in performance between 2/2 and 5/5.

FDE10 and FDE 08 show a small benefit for the availability of the exclusion function of having the local QNH to feed into the receiver for the NPA.

FDE 11 shows the effect of A2 being out of service. During the periods when the exclusion function is not available, the receiver reverts to FD and the FD availability is shown in FD 11. FD is available, except for two periods of about 7 minutes.

FDE 12 shows the effect of both A1 and A4 being out of service. During the periods when the exclusion function is not available, the receiver reverts to FD, which is then available for all phases of flight for the whole period.

The receiver characteristics referenced in FDE 13B, FDE 15 and FDE 20 would represent the performance of receivers described in Group 3 (see para. 4.1) as meeting TSO-C146. These receivers will have provision for receiving ranging signals from GEO's and two of these, MTSAT and WAAS, have been simulated.

FDE 13B shows the availability of the exclusion function if A2 is out of service, but a ranging signal is obtained from MTSAT. There is a large improvement in performance over that shown in FDE 12 which did not use MTSAT.

FDE 15 shows even greater benefits when WAAS is used. If A2 became faulty during a flight, the receiver would exclude A2 and the flight would proceed with the exclusion function still available except two short periods. If one of these periods was encountered, the receiver would revert to FD and proceed with FD until FDE shortly became available again.

FDE 20 shows the exclusion performance when both MTSAT and WAAS are used and the mask angle increased to 5/5. The exclusion function is available except for one short period and then FD is available as shown in FD 20. This would represent the normally expected performance of a TSO-C146 receiver.

It should be remembered that all the above represent the performance of GPS at one of the worst locations in Australia. The performance at all other locations are better than Adelaide. To show this, simulations were carried out for Parkes and Toowoomba, which are set out in the next Appendices.

Appendix B

RAIM Availability Performance for Parkes (FD and FDE)

FD 16 represents the base case of the typical TSO-C129 receiver in the Parkes area. The performance is improved over Adelaide (shown in FD 01). FD is now unavailable for less than 1 minute for NPA.

FDE 17 to FDE 19 and FDE 21 show the performance expected of TSO-C146 receivers.

FDE 17 shows a small improvement in performance over Adelaide.

FDE 18 shows the effect of A2 being out of service. In the periods when FDE is then not available, the receiver reverts to FD with the availability then shown in FD 18.

FD is then provided at all times for EnRte and TMA. There are two short periods of unavailability for NPA.

FDE 19 shows the effect of having the ranging signal from the WAAS GEO when A2 is out of service. FDE is available for the whole of the EnRte and TMA. There is one short period of unavailability for NPA.

FDE 21 shows what could be expected for a normal 24 satellite constellation and the two GEO's. FDE is available for the whole time for all phases of flight. The increase in performance resulting from the GEO's is seen by comparison with FDE 17.

Appendix C

RAIM Availability Performance for Toowoomba (FD and FDE)

FD 22 shows the further improvement in performance over Adelaide and Parkes for a TSO-C129 receiver. FD is available over the whole period of the flight.

FDE 23 to FDE 26 show the performance expected of TSO-C146 receivers.

FDE 23 shows FDE available for the whole period of EnRte and TMA and unavailable for a period of 7 minutes for NPA. During this period, the receiver reverts to FD which is available for the whole period.

FDE 24 shows the effect of A2 being out of service. During the periods when is then not available, FD is available for the whole period of EnRte and TMA and unavailable for a period of 7 minutes for NPA.

FDE 25 shows the effect of having the ranging signal from the WAAS GEO when A2 is out of service. In the periods when FDE is not available, the receiver reverts to FD which is available for the whole period for all phases of flight.

FDE 26 shows what could be expected for a normal 24 satellite constellation and the two GEO's. FDE is available for the whole time for all phases of flight. The increase in performance resulting from the GEO's is seen by comparison with FDE 23.

Appendix D

GNSS Satellite Failure Probabilities

(On separate photocopied pages)

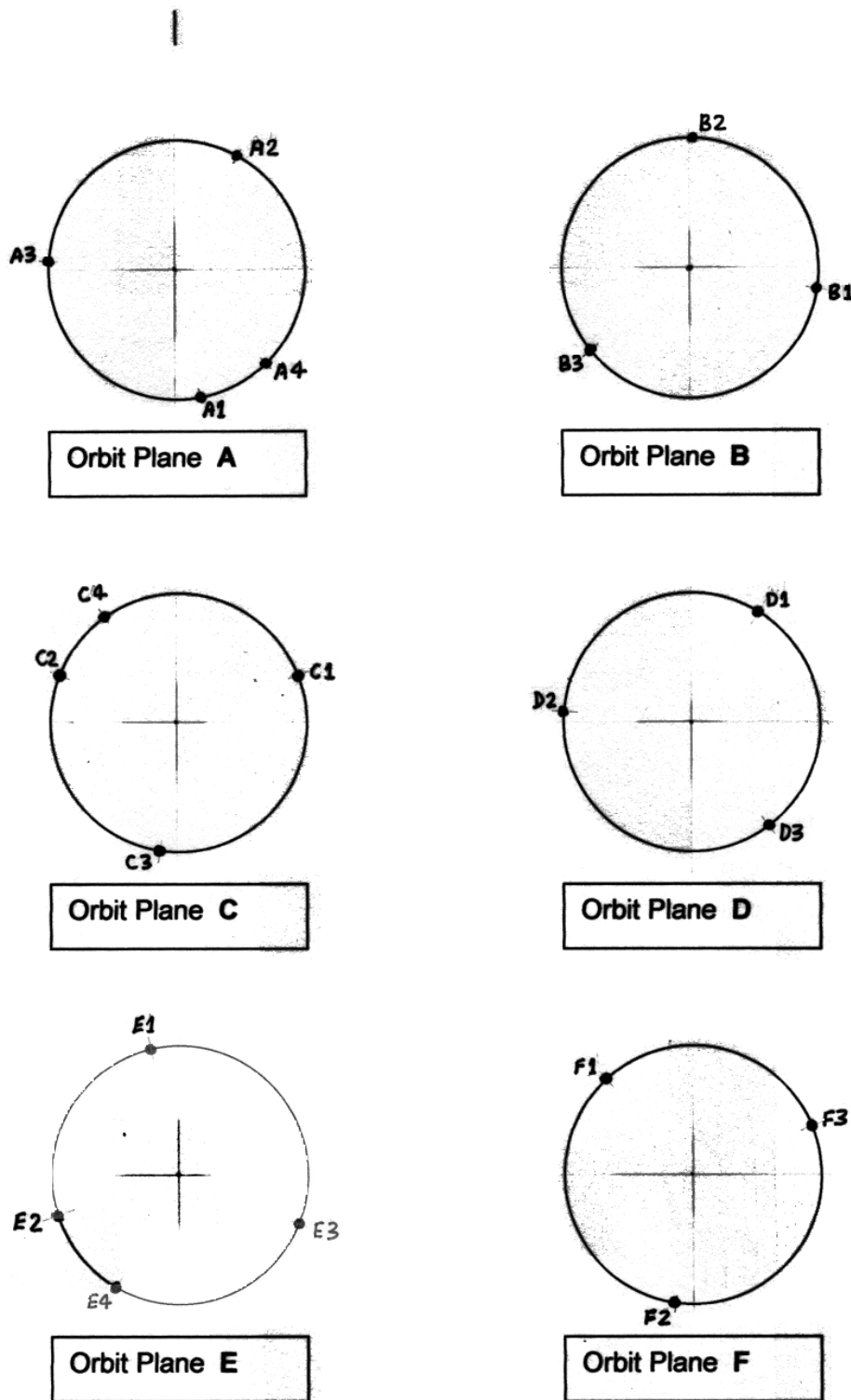
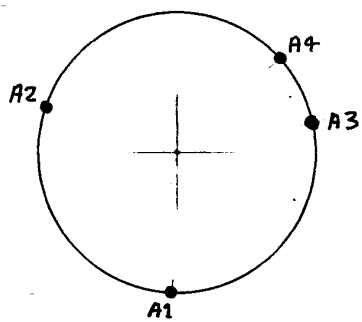
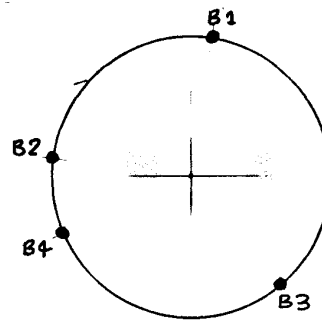


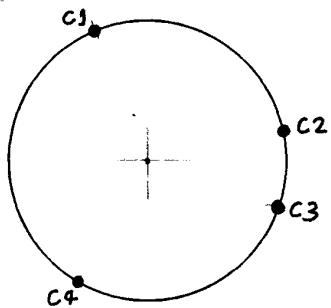
Fig. 3.1 Spacing of Satellites in 6 Orbital Planes
Optimised 21 Satellite Constellation – DO 208



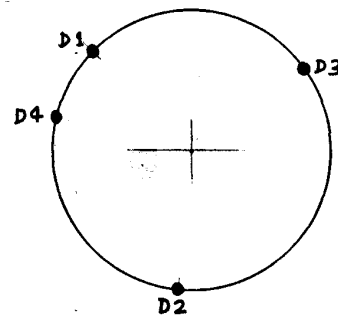
Orbit Plane A



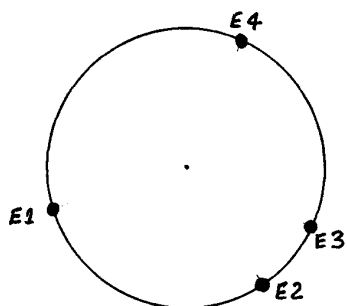
Orbit Plane B



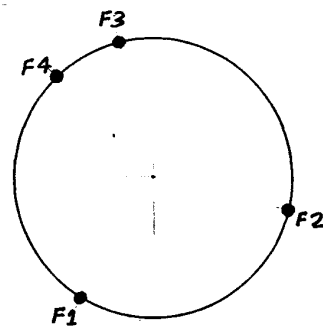
Orbit Plane C



Orbit Plane D



Orbit Plane E



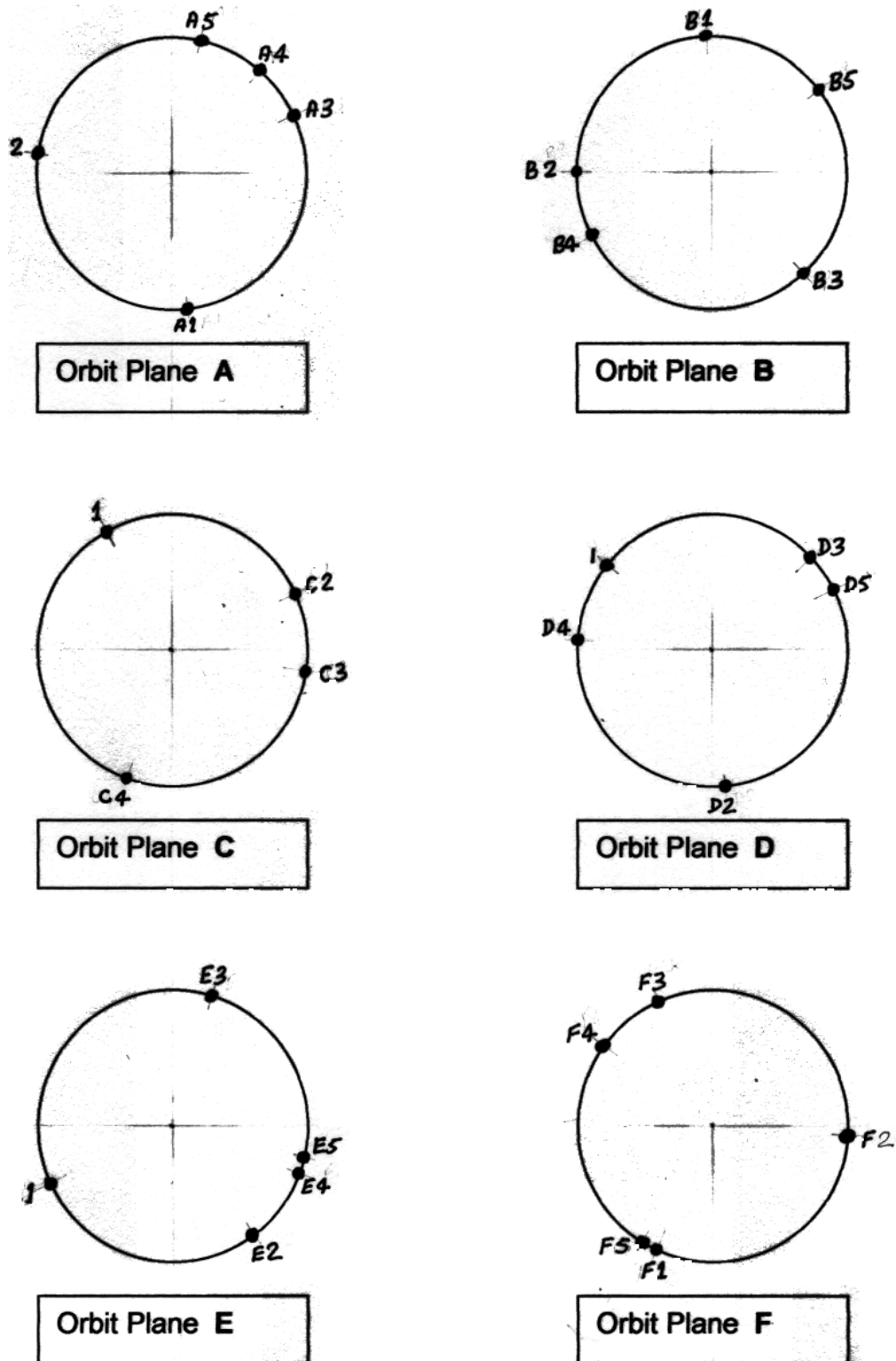


Fig. 3.3 Spacing of Satellites in 6 Orbital Planes
Actual Constellation at 11-05-01

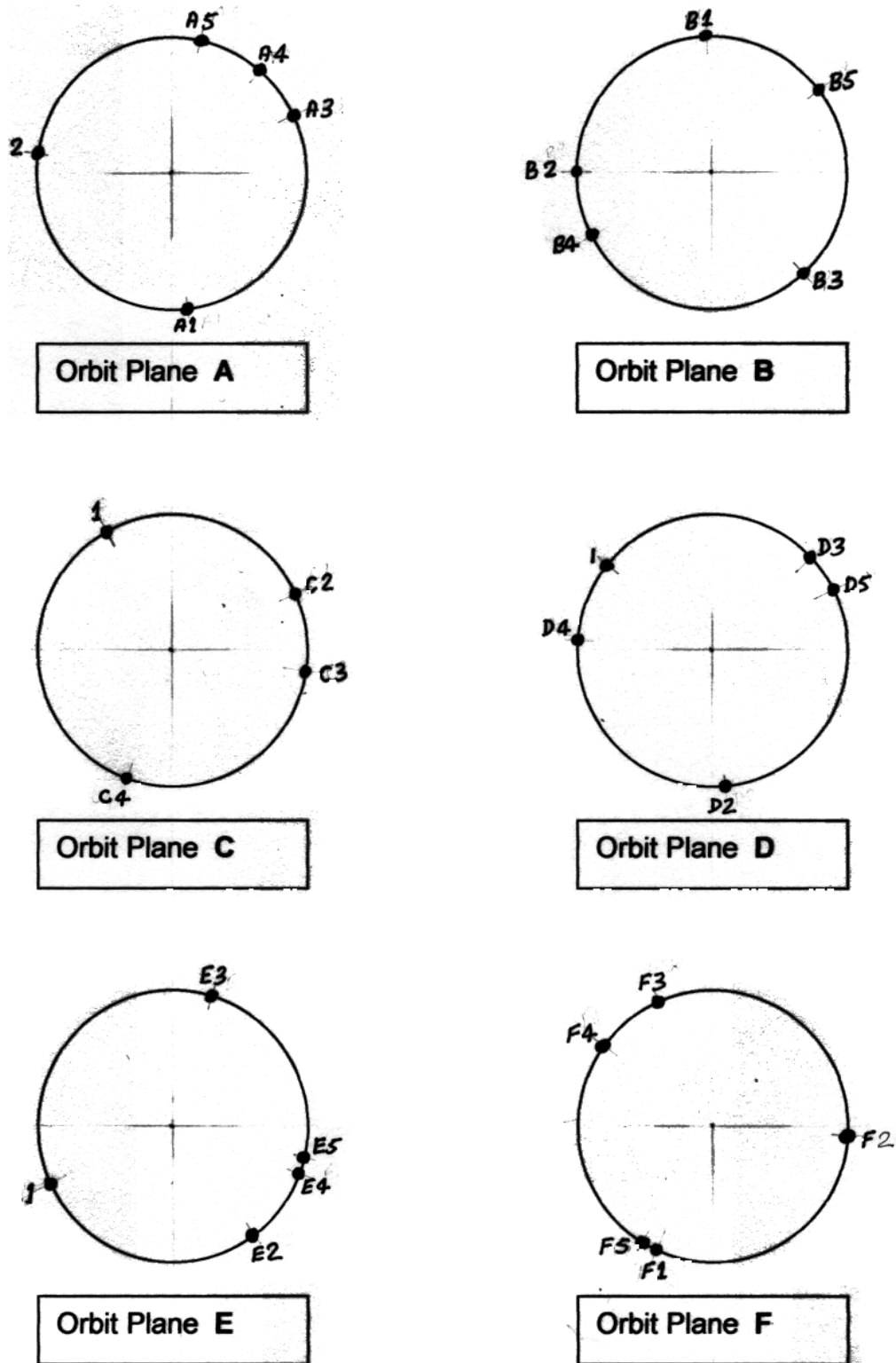
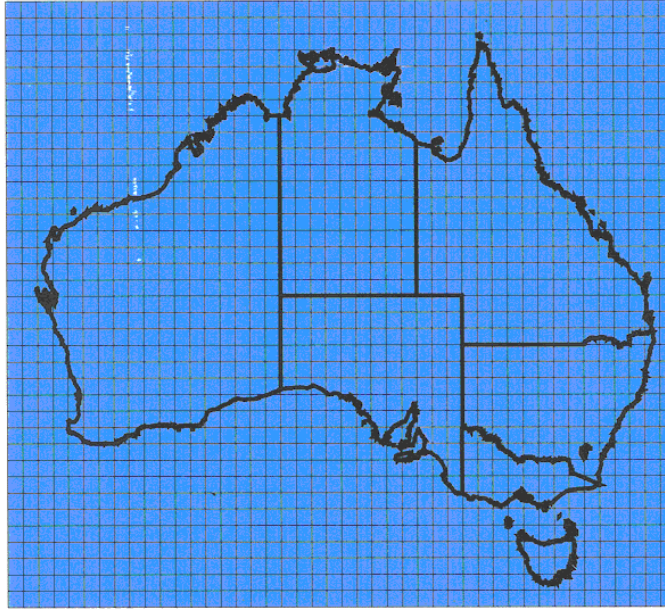


Fig. 3.3 Spacing of Satellites in 6 Orbital Planes
Actual Constellation at 11-05-01

0.6nmi RAIM Detection Availability (RNP 0.3)
No SA DO-229 Baro Aiding Martinez 24 2/2 Mask

■	0.99999 to 1	(1628)
■	0.99995 to 0.99999	(0)
■	0.999 to 0.9995	(0)
■	0.995 to 0.999	(0)
■	0.99 to 0.995	(0)



0.6nmi RAIM Exclusion Availability (RNP 0.3)
No SA DO-229 Baro Aiding Martinez 24 2/2 Mask

■	1.000 to 1.000	(1598)
■	0.996 to 0.997	(30)

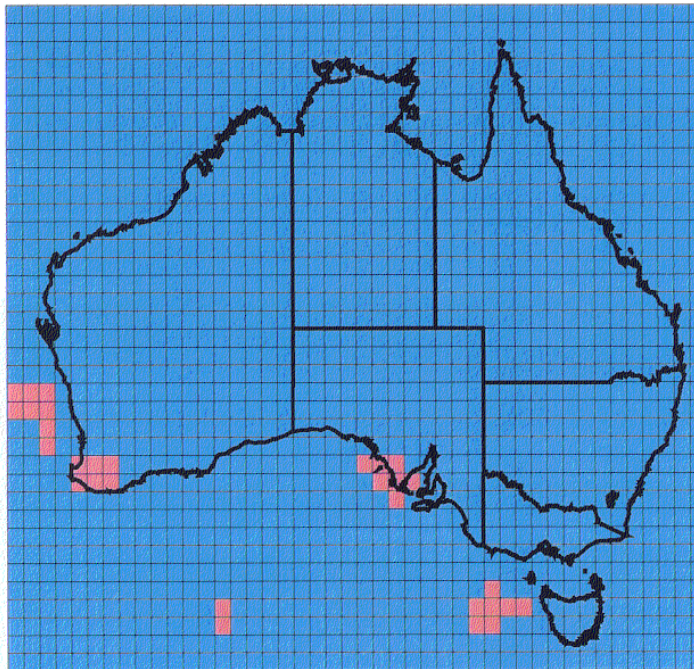


Fig. 2.1