EUROPEAN ORGANISATION FOR THE SAFETY OF AIR NAVIGATION

EUROCONTROL EXPERIMENTAL CENTRE

GNSS FREQUENCY PROTECTION REQUIREMENTS

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DERA have carried out a study for EUROCONTROL into the requirements for protection of Radio Navigation Satellite Service, RNSS, receivers, operating in the frequency band, 1559 - 1610 MHz. The signal structure used by services which operate in this band, the US Global Positioning Service, GPS NAVSTAR, and the Russian GLONASS as well as the proposed European Navigation Satellite Service, E-NSS-1 are assessed for their susceptibility to interference. Likely causes of interference are investigated and their effect on the RNSS receivers evaluated. A statement is made concerning the protection required for a GNSS receiver designed for optimum performance.
FOREWORD FOR GNSS FREQUENCY PROTECTION REQUIREMENTS STUDY

This report presents the results of a study into the susceptibility of GNSS receivers to radio frequency interference. The study was initiated after proposals were presented to the International Telecommunications Union (ITU) by Mobile Satellite Service (MSS) providers for sharing the frequency band currently allocated radio-navigation satellite services (RNSS). Frequency allocations are decided at the ITU World Radio Conference (WRC) that meets approximately every two years. WRC-1997 resolution 220 requested “the ITU to study the technical criteria and operational and safety requirements to determine if sharing between the aeronautical radio-navigation and radio-navigation satellite services operating, or planned to operate in the band 1559-1610 MHz, and the mobile satellite service in a portion of the 1559-1567 MHz frequency range is feasible.” The EUROCONTROL study was initiated in response to this resolution.

GPS and GLONASS are established radio-navigation satellite systems operating in the 1559-1610 MHz band. These systems are already widely used in many applications and it is expected that their use in Civil Aviation applications will increase significantly in the coming years. In addition to GPS and GLONASS plans have also been published for a second generation of satellite navigation systems, often referred to in Europe as GNSS-2, which would also make use of this frequency band. It is also expected that GPS-like signals will be transmitted from the ground by so called pseudolites that may be needed to support precision approach applications.

Applications for frequencies by Mobile Satellite Service (MSS) providers both in and around the RNSS frequency band are posing a significant threat of interference to RNSS users. Initial analysis of the influence of the proposed MSS systems on satellite navigation services indicates that interference will occur, particularly to GLONASS and to users of the ENSS-1 system planned by ESA. Interference to GPS would also be a problem if it were not for the fact that GPS satellites are broadcasting a more powerful signal than their specified minimum.

The work described here establishes the levels of interference that a GNSS receiver can tolerate whilst still meeting the navigation system performance requirements for various civil aviation applications. The report strongly recommends that the satellite navigation community bring this important issue to the attention of their respective radio regulation or frequency management agencies to help defend the RNSS frequency spectrum.

This work has been managed on behalf of EUROCONTROL from its Experimental Centre (EEC) situated at Brétigny-sur-Orge, south of Paris. The EEC is responsible for carrying out Air Traffic Control simulations, studies and research within the European Air Traffic Control Harmonisation and Integration programme (EATCHIP) managed by EUROCONTROL on behalf of the European Civil Aviation Conference (ECAC).

The EATCHIP Satellite Navigation Applications (SNA) Group is responsible for overseeing EUROCONTROL’s GNSS activities. Its work programme is carried out through two Task Forces, Operational and Certification Requirements (OCR) and System Research and Development (SRD). The work presented in this report has been carried out by the UK Defence Evaluation and Research Agency on behalf of the SRD Task Force.

Richard Farnworth
Edward Breeuwer
Andrew Watt

EUROCONTROL Project Officers
SUMMARY

Under contract to EUROCONTROL, Navigation Systems Research, Defence Evaluation and Research Agency, DERA, has investigated the protection requirements for the Radionavigation Satellite Service, RNSS receivers. The designated RNSS band is being used by the aviation community for Global Navigation Satellite Services (GNSS) that are intended to become the prime radionavigation system in the twenty-first century. The RNSS frequency band is designated as 1559 MHz to 1610 MHz, and currently contains the Global Positioning System, GPS NAVSTAR, and the Russian GLONASS. ESA on behalf of the European Tripartite Group has applied for a registration in the band for a proposed European satellite navigation system. Applications for frequencies by Mobile Satellite System operators have already resulted in a loss of the spectrum from 1610 to 1626.5 MHz and currently the International Telecommunications Union, ITU are discussing an application for the use of 1559 MHz to 1567 MHz that will overlap the lower 3.5 MHz of the registered GPS band. Spurious transmissions from the adjacent MSS transmissions and from harmonics generated by high power transmissions at lower frequencies such as TV broadcasts may also be a problem. Practically all aspects of radio transmissions are controlled by the ITU Radio Regulations, RR, however the enforcement of the regulations is the responsibility of the individual states. The protection required for GNSS receivers must therefore be specified and each EUROCONTROL and ICAO member must ensure that the specification is registered with their national authority or agency responsible for radio transmissions.

Background to the study

Power levels of satellite navigation signals provided by GPS and GLONASS are below receiver thermal noise levels on the earth’s surface. After detection by correlation processes in the receiver the signal level is typically only 20 dB above noise and only 5 dBs above the power level required to read the navigation data message with a low bit error rate. Any degradation in the signal to noise level is detrimental to receiver performance and an anathema to the use of GNSS for high integrity operations. For GNSS protection to be global, regulations must be proposed at the ITU that ensures no allocations are made to systems that cause harmful interference into GNSS receivers and the national authorities must ‘police’ operations.

Although several cases of harmful interference into GPS and GLONASS have been reported currently such occurrences do not appear to be widespread, and are usually attributable to local transmitters with high spurious outputs. However the ITU has approved applications from the Mobile Satellite Service, MSS for use of the band 1610 - 1625 MHz, for earth to satellite (E-s) transmissions. To reduce the price of the hand terminals some system developers have reduced the filtering of the high power amplifier (HPA) output and significant out of band noise is predicted. Analysis shows the interference is particularly disruptive to GLONASS reception. An application for frequencies at 1559 - 1567 MHz is being made by the UK for MSS transmissions space to earth, (S-e). The application is being made on behalf of INMARSAT although not specifically for INMARSAT. Unlike the Earth to space transmissions in the 1610 to 1626.5 MHz band INMARSAT’s satellite to earth (S-e) transmission will be visible from all locations between ±80 degrees of Latitude.
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1. FREQUENCY ALLOCATIONS AND NAVIGATION ACCURACY

1.1. Background to the Study

ICAO has stated an intention to move to Global Navigation Satellite System GNSS as the basis for radionavigation in the 21st century. Initial a GNSS-1 will be formed from the US Global Positioning System (GPS), and the Russian GLONASS combined with one or more augmentation schemes. To provide the sole means of navigation or even the sole means of radio navigation GNSS must be protected against interference and states must ensure that no harmful transmissions are present or radiated from their territory. This study reviews the effect of interference and derives a protection mask for GPS and GLONASS receivers. Protection requirements for the proposed European navigation satellite system are also evaluated.

High-powered ground transmitters, such as TV broadcasts, could generate sufficient spurious power to jam a GNSS receiver. However in the en-route phase of flight the aircraft's altitude, combined with reduced antenna gain beneath the azimuth plane and/or distance from the transmitter, provides a large attenuation factor; moreover, such accidental interference is likely to last only for a few minutes, unless deliberate 'jamming' is present. Test flights by UK National Air Traffic services NATS [1] demonstrated that interference from ground transmitters in some parts of Europe reduced the signal to noise in a GPS receiver but did not prevent it navigating. Satellite communications in the 1625 where identified as a problem and precautions taken in the design of the aircraft installation, diplexer and frequency planning to eliminate interference into GPS. Interference into GLONASS is a more difficult problem due to the closer frequency separation. No diplexers are available that are able to remove the out of band interference from SATCOM transmissions into GLONASS, but as the system has not yet been installed in western commercial aircraft the problem does not exist.

However recent allocations to communication systems in the 1610 - 1625 MHz and proposed allocations in the 1559 - 1567 MHz bands that represent the prime threat to continuous GNSS operation. Out of band spurious transmissions from these systems increase the noise level in GNSS receivers. Space to earth transmissions generate a uniform power flux density over large areas of the earth's surface. As the satellites are in the main beam of the aircraft's GNSS antenna radiation pattern the noise is continuously present. In the en-route phase of flight the effect of interference sources on the ground are reduced by the inverse square law and the low gain of the aircraft's antenna. It is only during the ‘approach’ phase of flight that interference sources on the ground become equally significant to satellite systems, as the range becomes small and the angle of incidence with the aircraft’s antenna statistically is at the azimuth plane where the antenna gain is considerably higher.

1.2. Frequency Issues

Without international co-ordination, the radio spectrum would rapidly become unusable due to incompatible signal formats, strengths and frequencies. Use of the radio spectrum is co-ordinated by the International Telecommunications Union through international conferences with the agreements published in the Radio Regulations; however, states are at liberty to make exceptions to the regulations for internal radio services and to transmit on any frequency within their national boundaries. Exceptions are usually registered as footnotes to the regulations; however, internal military transmissions are generally unregistered.

GPS [2] and GLONASS [3] were registered with the ITU when the frequency band designated for Aeronautical Radionavigation, Radionavigation Satellite service RNSS, (Space to Earth) at 1 559 to 1626.5 MHz was unused, Fig 1-1. Because GPS and GLONASS
signals have a low power flux density on the earth’s surface, a very low powered interference signal can significantly degrade the navigation performance. Co-frequency and adjacent frequency transmissions must therefore be analysed to ensure their compatibility with GPS [4] and GLONASS [5] signal characteristics.

At the time GPS was registered the primary source of near band interference was above 1626.5 MHz in the 1626.5 - 1645.5 MHz band, allocated to the Maritime Mobile Satellite communications for earth to space transmissions, Fig 1-1. Significant interference into GPS receivers was encountered from the spurious transmissions from the Maritime INMARSAT terminals operating in the band. When the ARINC specifications for aeronautical mobile satellite equipment were developed particular care was placed on the out of band performance into the GNSS band. Although the frequencies used were further from the GNSS band significant precautions were introduced in ARINC 741 [6] to prevent any accidental harmonic appearing in the GNSS band. These are discussed further in Section 5.

Development of direct broadcast satellites and personal communication terminals is generating a huge demand for spectrum. Such systems are designated by the ITU as Mobile Satellite Services, MSS, Mobile Earth Station MES and Satellite Personal Communications Networks S-PCN. For similar reasons that L-band was chosen for GNSS it is also highly suitable for MSS. Due to the shortage of suitable frequencies the MSS providers have become extremely predatory and are searching for any ‘spare’ frequencies in the L-band spectrum.

An application for MSS (Iridium and GLOBALSTAR) led to the designation by the ITU at the 1992 World Radio Conference, WRC of the 1610 - 1626 MHz band initially on a secondary basis; however the allocation was changed at the 1995 WRC to a primary allocation. The MSS allocation overlaps the frequencies currently used by GLONASS 1602.5 - 1615.5 MHz. This allocation together with a problem that GLONASS was interfering with the Radio-Astronomy band 1610.6 to 1613.8 MHz has caused the Russia’s to move GLONASS to 1597 - 1605 MHz, by the year 2005. Out of band spurious transmissions from MSS remain a problem and were one of the reasons why RTCA under SC159 commenced an investigation into radio frequency interference into GNSS. The results of the study were published in RTCA DO-235 [7].
In June 1997 ESA on behalf of the European Tripartite Group applied for three frequencies two of them in the ITU allocated RNSS band, from 1 55.05 to 1 563.14 MHz and at 1 587.69 to 1 591.78 MHz [8].

![Figure 1-2 Proposed Frequency Allocations at L-Band](image)

### 1.3. Interference Sources

Three types of interference can be identified for radio navigation receivers. In-band radio frequency interference contributes unexpectedly to the noise floor and can degrade performance. Spurious signals such as harmonics, intermodulation products, or simply high frequency noise can constitute RFI.

Near-band RFI might interfere with proper reception through saturation of the receiver’s RF detector or insufficient RF and IF filter rejection allowing low level noise into the correlator and detection processor. Near-band sources are identified by evaluating the components of the adjacent spectrum, including harmonics of transmitters at lower frequencies and likely wide band noise from transmitters in the near-band.

So far a small but growing number of instances of interference into GPS has been reported. A prime cause of such black outs are TV transmitters and Satellite Communication, SATCOM, terminals. A summary of the predominant sources of interference to GPS is summarised in Table 1-1. At WRC 97 the proposal for an MSS allocation from 1 559 - 1 567 MHz was referred to further studies and reappraisal at WRC 99. Several changes were made to allocation for aeronautical satellite communications although the precise details have yet to be published. Harmonics from the same transmission bands could also interfere with GLONASS, which due to its wider bandwidth is susceptible to a greater number of sources but it is likely only one satellite would be affected.

### 1.4. International Agreements on Spurious Transmissions

To protect essential services the ITU have made several regulations binding on member states [9]. However the use of the term *harmful interference* makes the regulations subjective.
## Harmonic Interference to GPS L1 ± 1 MHz

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>In band Harmonic Near Band</th>
<th>Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>787.21 - 788.24</td>
<td>2</td>
<td>TV Broadcasting: Channels 60, 61</td>
</tr>
<tr>
<td>524.80 - 525.48</td>
<td>2</td>
<td>TV Broadcasting: Channel 27, 28</td>
</tr>
<tr>
<td>393.6 - 394.1</td>
<td>4</td>
<td>Military UHF (London Control 393.9)</td>
</tr>
<tr>
<td>314.88 - 315.29</td>
<td>5</td>
<td>Military UHF (RAF Lynham 315.75)</td>
</tr>
<tr>
<td>262.40 - 262.74</td>
<td>6</td>
<td>Military UHF</td>
</tr>
<tr>
<td>224.90 - 225.20</td>
<td>7</td>
<td>Amateur Band / A/G Comm.</td>
</tr>
<tr>
<td>196.80 - 197.05</td>
<td>8</td>
<td>Broadcasting: VHF Comms</td>
</tr>
<tr>
<td>174.93 - 175.16</td>
<td>9</td>
<td>Broadcasting: VHF Comms (Police etc)</td>
</tr>
<tr>
<td>157.440-157.644</td>
<td>10</td>
<td>Comms Fixed, Mobile</td>
</tr>
<tr>
<td>143.127-143.313</td>
<td>11</td>
<td>Fixed, Mobile</td>
</tr>
<tr>
<td>131.37 - 131.20</td>
<td>12</td>
<td>Aeronautical VHF Airways London Control</td>
</tr>
<tr>
<td>121.26 - 121.10</td>
<td>13</td>
<td>Aeronautical VHF Dublin, Cardiff, Edinburgh</td>
</tr>
<tr>
<td>112.4 - 112.6</td>
<td>14</td>
<td>VOR</td>
</tr>
<tr>
<td>104.9 - 105.1</td>
<td>15</td>
<td>FM Broadcast (104.9, 105.1)</td>
</tr>
<tr>
<td>960-1215</td>
<td>near band</td>
<td>TACAN/DME (L2 GPS GLONASS)</td>
</tr>
<tr>
<td>1030,1090</td>
<td>near band</td>
<td>Mode S (L2 GPS GLONASS only)</td>
</tr>
<tr>
<td>1240-1370</td>
<td>near band</td>
<td>Air Route Surveillance Radar (L2 GPS GLONASS only)</td>
</tr>
<tr>
<td>1610 - 1626.5</td>
<td>near band</td>
<td>Mobile Satellite Systems In-band to GLONASS (prior to 2005) and near band after 2005</td>
</tr>
<tr>
<td>1626.5 - 1660.5</td>
<td>near band</td>
<td>SATCOM</td>
</tr>
<tr>
<td>1670 - 1675 (G→A)</td>
<td>near band</td>
<td>Terrestrial Telephone System</td>
</tr>
<tr>
<td>1800 - 1805 (A→G)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1-1 Summary of Potential Interference Sources to GPS L1**
(Examples of frequency allocations are given for UK allocations)
RR S4.10 (953) states that "members recognise that the safety aspects of radionavigation and other safety services require special measures to ensure their freedom from harmful interference; it is further stated that it is necessary to take account of this factor in the assignment and use of frequencies".

RR S1.169 (163) Defines harmful interference as "interference which endangers the functioning of radionavigation services or of other safety services or seriously degrades, obstructs or repeatedly interrupts a radiocommunication service operating in accordance with the Regulations".

RR S4.5 (343) requires that "the frequency assignment shall be separated from the limits of allocated band in such a way that no harmful interference is caused to services in the adjoining band".

There are several general statements and footnotes to the radio regulations.

a. Spurious emissions shall apply to all radiation from the equipment, not just that from the antenna.

b. Note 2 to Appendix S3 specifies that transmitters with a mean power exceeding 50 kW operating below 30 MHz and broadcasting over an octave or more, a reduction below 50 mW is not mandatory, although a minimum attenuation of 60 dB shall be provided. Note 7 is more general and has the same attenuation requirements for transmitters with a mean power in excess of 50 kWs using two frequencies with a range of an octave or more. Note 8 specifies that hand portable equipment of mean power 5 watts shall have an attenuation of 30 dB, but every practical effort shall be made to attain 40 dB attenuation. Similar exceptions are made in note 10 for multiple transmitters feeding a single or closely spaced antenna. Note 11 is a weak statement of intent to protect radio astronomy and space services, where more stringent levels may be considered.

c. Note 12, indicated that further studies were required under ITU-R Recommendation 66 for systems using digital modulation techniques, MSS Digital TV etc.

In all of these cases the regulations state that spurious emissions should be reduced to the lowest possible level. However there are three major issues that have to be considered:

a. States have sovereignty over their territory and may choose not to implement or enforce the RR within their national boundaries, although the RRs point out that more stringent requirements may be needed and agreed between states or introduced through WRCs.

b. Power levels of 100 mW (-10 dBW) falling in or near band to GNSS can cause performance degradation into a GNSS receiver at several kilometres.

c. A WRC can make changes to the allocated radio frequency bands and grant primary status to new services. If a service is awarded ‘primary’ status it can legally interfere with any other service operating in the band.

<table>
<thead>
<tr>
<th>Frequency Band (/Tx Power)</th>
<th>Minimum attenuation (After 1 Jan 1994)</th>
<th>Maximum power (After 1 Jan 1994)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 kHz to 30 MHz</td>
<td>40 dB</td>
<td>50 mW</td>
</tr>
<tr>
<td>30 to 235 MHz &gt;25 W</td>
<td>60 dB</td>
<td>1 mW</td>
</tr>
<tr>
<td>235 to 960 MHz &gt;25 W</td>
<td>60 dB</td>
<td>20 mW</td>
</tr>
<tr>
<td>0.960 to 17.7 GHz &gt;10 W</td>
<td>50 dB</td>
<td>100 mW</td>
</tr>
</tbody>
</table>

Table 1-2 ITU Maximum Permitted Spurious Emission Power Levels
1.5. GPS and GLONASS Frequency Protection

GPS and GLONASS should be protected under the above ITU regulations; however the ITU's policy of awarding allocations based on an analysis of non interference with existing services, does not appear to have been upheld. The required 'impartial analysis' is usually provided by the state or service provider claiming the compatibility. As states are using the electromagnetic spectrum as a source of revenue there are local pressures to prove compatibility of new systems with existing services. The allocation of the 1 610 to 1 626.5 MHz band to MSS was a blatant example of this practice. Further the fact that many older electronic devices generate noise and spurious emissions, if only momentarily, into the GNSS band is being used as a precedence to substantiate the international acceptance of higher noise levels and emissions from new devices. This issue was at the root of the problem with the agreement of the FCC in the US and ETSI in Europe to accept an out of band level of -70 dB/MHz for the Satellite Personal Communications Network (S-PCN) Mobile Earth Stations, MES the handheld MSS terminals.

There are a number of general issues arising from the RRs. Statements are made that encourage the sharing of frequency bands and allocations anywhere possible. Wherever possible has been taken to mean, where no harmful interference with existing services would be caused. This action has opened a channel for communication service providers to request allocations in bands hitherto specified for other services, e.g. Radionavigation. The definition of harmful interference now becomes the issue. New service providers are quick to produce papers that take advantage of every benefit they can find in the technical definitions of existing services.

*It has become the responsibility of the providers and users of existing services to demonstrate that a proposed new service will cause harmful interference and is therefore incompatible.*

Protection of specific frequency bands for defined services on a global basis can not be achieved, since there are no binding agreements between states. Following technical studies in ITU-R recommendations are made concerning compatibility of services in the same or adjacent frequency band. Where incompatibility is established it is the service in operation that is given precedence. However this does not prohibit state administrations proposing other services for the same band if they believe that harmful interference will not be caused to the existing service. The problem is what constitutes harmful interference.

Definition of harmful interference and therefore the protection require for a service, e.g. satellite navigation is assessed against a defined receiver susceptibility and system performance requirements. Here lies the problem for satellite navigation services, since the system performance is ill defined and there is no universally agreed definition of a generic receiver to assess susceptibility against. Obviously if the navigation message can not be read or carrier phase tracking is lost the interference can be assessed as harmful, but it is difficult to prove that a 1 dB degradation in signal to noise ratio or a temporary loss in the ability to acquire new satellites is harmful or is not a function of a particular receiver design that is sub-optimal. Radio frequency regulation agencies, spurred on by communications service providers hungry for spectrum are quick to point out any deficiencies they can detect in receivers that increase their susceptibility.

A further issue is that states have autonomy on transmissions in their territory. Thus what is agreed as harmful interference in one state may not be accepted by another. It is also the responsibility of the state to enforce the protection requirements. Under some circumstance this may be difficult, for example, where interference is time and position variant such as that generated by non-linearities in the antennas of communications systems operating at sub harmonics of the satellite navigation services.

An interference mask based on the performance achieved from a well-engineered satellite navigation receiver is derived in this report suitable for presentation to state authorities as a
basis for protecting GNSS. To define the required receiver mask the most stringent requirements for aviation use of GNSS equipment and the accuracies required are examined.

1.6. Aviation Safety Criteria

GNSS has the ability to provide navigation data to the accuracy specified in the Required Navigation Performance, RNP, for many of the phases of flight, particularly for en-route and terminal areas. However GPS or GLONASS cannot satisfy the RNP integrity requirements for any phase of flight, unless one or more of the following augments the navigation system:

- receiver autonomous integrity monitoring (RAIM)
- aircraft based augmentation systems (ABAS)
- satellite based augmentation system (SBAS)
- ground based augmentation system (GBAS)

The capability of GNSS to meet the other RNP parameters of availability and reliability has yet to be determined.

Radio frequency interference, RFI, presents the greatest threat to GNSS availability and continuity. The weak GPS signal makes RF interference from a variety of sources a serious threat and the possibility of deliberate interference cannot be dismissed. In the debate over the margin needed by aviation to ensure interference, particularly from spurious emissions from systems in adjacent bands does not cause harmful effects comparisons can be made with ILS and MLS. MLS has specified a margin of at least 20 dB between the powers of any satellite communications transmissions in the band and MLS signals at the edge of the coverage area. The power limit on the satellite feeder link is set at -164 dBW/m² in any 4 kHz bandwidth.

<table>
<thead>
<tr>
<th>Typical Operation</th>
<th>95% NSE Lateral</th>
<th>Continuity</th>
<th>Integrity</th>
<th>Time to Alert</th>
<th>Associated RNP Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>En Route</td>
<td>19.9 NM</td>
<td>1-10⁻⁷/h</td>
<td>1-10⁻⁵/h</td>
<td>5 min</td>
<td>RNP-20</td>
</tr>
<tr>
<td>En Route</td>
<td>12.44 NM</td>
<td>1-10⁻⁷/h</td>
<td>1-10⁻⁵/h</td>
<td>3 min</td>
<td>RNP-12.6</td>
</tr>
<tr>
<td>En Route</td>
<td>3.87 NM</td>
<td>1-10⁻⁷/h</td>
<td>1-10⁻⁵/h</td>
<td>1 min</td>
<td>RNP-4</td>
</tr>
<tr>
<td>Terminal</td>
<td>0.44 NM</td>
<td>1-10⁻⁴/h</td>
<td>1-10⁻⁵/h</td>
<td>15 sec</td>
<td>RNP-1</td>
</tr>
</tbody>
</table>

Table 1-3 Navigation System requirements for en-route

The basis of aviation safety is the statistical assessment of performance criteria and failure rates. Failure rate for aviation have been assessed as:

- no greater than 2 in 10⁸ for en route to reduce the possibility of mid air collisions,
- no greater than 1 in 10⁶ for the approach and landing phases of flight.

Radionavigation services that provide sole guidance to the aircraft require very high protection from harmful interference. To meet the above failure rates the possibility of interference occurring into the radio-navigation service must be substantially greater. Draft SARPs [10] under development by the ICAO’s Global Navigation Satellite Systems panel, GNSSP have specified that the navigation system shall meet the requirements defined in Tables 1-3 and 1-4.

Aircraft system accuracy requirements have been developed to support RNP operations for approach, landing and departure phases of flight, and to be as consistent as possible with ICAO Annex 10 ILS SARPs and RTCA/EUROCAE MOPS for the airborne equipment. There are additional constraints on the navigation system beyond those specified, including performance requirements at altitudes below the DA/H.
1.7. Signals-in-space performance requirements

The signal in space, SIS, characteristics derived by the ICAO GNSSP are given in, Table 1-5. From the SIS and RNP accuracy specifications the availability and navigation error that can be tolerated in a receiver’s tracking and signal processing functions can be derived.

Vertical guidance and navigation for precision approach present the most demanding measurement requirement. As the same equipment is used in the aircraft to receive and process satellite signals during the en-route, approach and landing phases of flight there is no reason to discriminate between the receiver’s required performance, in terms of its measurement accuracy under interference conditions. A means is required to relate navigation accuracy requirements to measurement accuracy.

1.8. Required Measurement Accuracy

Statistically the navigation accuracy is a function of the range accuracy and the satellite geometry, expressed as the dilution of precision, DOP.

\[
\text{navigation accuracy (1σ)} = \text{ranging accuracy (1σ)} \times \text{dilution of precision}
\]

For vertical navigation the associated DOP is the vertical dilution of precision, VDOP. Therefore the worst case VDOP likely to be encountered must be used in the analysis. However there is a limit to satellite geometry DOP under which the receiver can form a navigation solution. A Position Dilution of Precision, PDOP, of less than 6 must be available if a stable navigation solution is to be achieved. PDOP can be decomposed into the horizontal DOP, HDOP, and Vertical DOP, VDOP, the RSS of HDOP and VDOP producing PDOP.

The ratio between HDOP and VDOP for the current GPS constellation is typically 1:1.5; therefore a PDOP of 6 is made up of a HDOP of 3.3 and a VDOP of 4.95. With a full GPS constellation the worldwide median PDOP averaged over 24 hrs is 2.0 with a HDOP of 1.2 and VDOP of 1.6. A PDOP of 6 is therefore near a 3 sigma figure for navigation availability, however the actual availability is dependent on the number of operational satellites, their orbital positions and requirements for receiver autonomous integrity monitoring, RAIM. Calculations of availability are beyond the scope of this report; the reader is referred to recent EUROCONTROL studies into RAIM availability [11].
Using the ICAO accuracy requirements an independent check is made on the values specified for receiver measurement accuracy from other published sources. From the ICAO CAT 1 specification, Tables 1-5, the range of values for vertical accuracy are 7.7m to 4.4m 95%, (3.8 m to 2.1 m, 1σ). Assuming a 200 ft decision height and a worst case VDOP of 4.95, the vertical accuracy requirement of 4.4m 95% (2.1 m 1σ), requires a range accuracy of 0.45 m 1σ.

<table>
<thead>
<tr>
<th>RNP Type</th>
<th>Supported Operation</th>
<th>Continuity</th>
<th>Integrity</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 NM</td>
<td></td>
<td>1-10^{-6}/h</td>
<td>1-10^{-7}/h</td>
<td>0.999</td>
</tr>
<tr>
<td>12.6 NM</td>
<td>En route</td>
<td>1-10^{-6}/h</td>
<td>1-10^{-7}/h</td>
<td>0.999</td>
</tr>
<tr>
<td>4 NM</td>
<td></td>
<td>1-10^{-6}/h</td>
<td>1-10^{-7}/h</td>
<td>0.9999</td>
</tr>
<tr>
<td>1 NM</td>
<td>Initial Approach, Departure</td>
<td>1-10^{-6}/h</td>
<td>1-10^{-7}/h</td>
<td>0.9999</td>
</tr>
<tr>
<td>0.5 NM</td>
<td>Initial Approach, Departure</td>
<td>1-10^{-6}/h</td>
<td>1-10^{-7}/h</td>
<td>TBD</td>
</tr>
<tr>
<td>0.3 NM</td>
<td>Initial Approach, Departure, NPA</td>
<td>1-10^{-4}/h</td>
<td>1-10^{-5}/h</td>
<td>TBD</td>
</tr>
<tr>
<td>0.3 NM /125ft</td>
<td>Instrument Approach with Vertical Guidance</td>
<td>1-10^{-4}/h</td>
<td>1-10^{-5}/h</td>
<td>TBD</td>
</tr>
<tr>
<td>0.03 NM /45ft</td>
<td>Precision Approach down to 350ft HAT (supports CAT-1)</td>
<td>1-8 \times 10^{-6} (in any 15sec)</td>
<td>1-2 \times 10^{-7}/ approach</td>
<td>0.9975(1)</td>
</tr>
<tr>
<td>0.02 NM /35ft</td>
<td>Precision Approach down to 200ft HAT (supports CAT-1)</td>
<td>1-8 \times 10^{-6} (in any 15sec)</td>
<td>1-2 \times 10^{-7}/ approach</td>
<td>0.9975(1)</td>
</tr>
<tr>
<td>0.01 NM /14ft</td>
<td>Precision Approach down to 100ft HAT (supports CAT-II)</td>
<td>1-4 \times 10^{-6} (in any 15sec)</td>
<td>1-1 \times 10^{-9}/ approach</td>
<td>0.9985(1)</td>
</tr>
<tr>
<td>0.003 NM</td>
<td>Precision Approach, Landing and departure (supports CAT-III)</td>
<td>1-2 \times 10^{-6} (in any 30sec)</td>
<td>1-0.5 \times 10^{-9}/ approach</td>
<td>0.9990(1)</td>
</tr>
</tbody>
</table>

Table 1-5 Signals-in-Space Requirements

Note 1: The availability requirements for RNP Types below 0.3 assume an alternate destination equipped with an independent guidance system.
Assuming a ‘perfect’ augmentation system, with the error budget apportioned equally between the reference station measurement, airborne receiver measurement and clock, SA and ephemeris errors, a receiver measurement accuracy of 0.26 m 1σ is required. ICAO GNSSP meeting Wellington March 1998 derived a value of 0.23 m 1σ for pseudorange noise in a CAT 1 GBAS. How this value would be achieved with receiver design was not apparent at the meeting and is a recommended area for future investigations.

A similar result is achieved if the Boeing figures from a paper [12], presented to the ICAO AWOP are used, Table 1-6.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Units</th>
<th>CAT I</th>
<th>CAT II</th>
<th>CAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glideslope Receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>ft</td>
<td>6.4</td>
<td>4.14</td>
<td>4.14</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td>4.68</td>
<td>1.54</td>
<td>1.54</td>
</tr>
<tr>
<td>Localiser Receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>ft</td>
<td>24.08</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td>20.42</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1-6 Navigation Sensor Error Requirements

The RTCA DO-217 SCAT-1 [13] specifies a pseudorange measurement accuracy of 1.10 m RMS for the ground station with a suggested accuracy of 1.39 m RMS for the Airborne Sensor. Typical receiver noise components of 0.4 m 1σ for the ground station and 0.5 m 1σ for the airborne components are given. DO-229, January 1996, the WAAS MOPS [14] specifies a receiver pseudorange error due to noise and interference of 0.7 m 1σ; however the January 1996 version considered en route and non precision approach but did not fully specify CAT 1. Walter and Enge [15] in their work on vertical accuracy and WAAS RAIM requirements for precision approach, CAT 1. A vertical accuracy requirement of 3.5 m 1σ for CAT 1 was used, which is near the upper limit of the range generated by ICAO AWOP and GNSSP CAT 1 definition and corresponds to an RNP 350, i.e. a decision height of 350 ft. Reference 15 defined a total range error requirement of 0.93 m 1σ, with a receiver measurement noise of 0.22 m 1σ, Table 1-7.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Pseudorange Measurement 1σ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Correction UDRE</td>
<td>0.5</td>
</tr>
<tr>
<td>GEO UERE</td>
<td>0.5</td>
</tr>
<tr>
<td>Ionosphere 90 deg</td>
<td>0.5</td>
</tr>
<tr>
<td>Troposphere 90 deg</td>
<td>0.15</td>
</tr>
<tr>
<td>Receiver Noise</td>
<td>0.22</td>
</tr>
<tr>
<td>Multipath (45 deg)</td>
<td>0.22</td>
</tr>
<tr>
<td>Data Latency (GPS)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1-7 WAAS Error Budget

ESA [16] generated a comparative error budget for EGNOS as 1.8 m 1 σ total error and 0.4 m receiver tracking error, Table 1-8.

<table>
<thead>
<tr>
<th>UERE Budget 1σ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Clock + Ephemeris</td>
</tr>
<tr>
<td>GEO Clock + Ephemeris</td>
</tr>
<tr>
<td>Ionosphere 90 deg</td>
</tr>
<tr>
<td>Troposphere 90 deg</td>
</tr>
<tr>
<td>Receiver Noise</td>
</tr>
<tr>
<td>Multipath 45 deg</td>
</tr>
<tr>
<td>Latency GPS</td>
</tr>
</tbody>
</table>

Table 1-8 EGNOS Error Budget
1.9. **DO-235 Requirements**

RTCA DO-235 [7] produced data tables for reception criteria defining receiver ‘navigation requirements’, for En-route, Non Precision Approach, and CAT 1. However few details are contained in DO-235 concerning the derivation of the numbers; the numbers from DO-235 are including in Table 1-9 as a comparison to the numbers derived from the ICAO figures. Besides the navigation errors requirements for the GPS/GLONASS Bit Error Rate (BER) are included as a high BER can be viewed as an integrity or continuity failure. As will be shown the BERs are highly dependent on signal to noise ratio, and the required BER of at least $1 \times 10^{-5}$ is obtained at a signal to noise ratio only a few dBs above the level where the data is unintelligible. Dynamic manoeuvres experienced by aircraft during flight result in the signal power incident on the antenna changing by several dBs and the BER varies with attitude.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>En route/Terminal</th>
<th>NPA</th>
<th>Cat I PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudorange accuracy</td>
<td>5 Metres</td>
<td>5 Metres</td>
<td>0.7 Metres</td>
</tr>
<tr>
<td>(one sigma)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS/GLONASS BER</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>WAAS Word Error Rate</td>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**Table 1-9 Navigation Requirements**

1.10. **Conclusions**

A summary of the measurement accuracies obtained from RTCA documents, FAA and ICAO figures and derived from Cat-I RNP above is provided in Table 1-10. The required measurement accuracy is in the range 0.2 to 0.4 m $1\sigma$. However as can be observed from Table 1-10 there is no correlation between the declared vertical accuracy requirements and the receiver measurement performance, indicting a variety of methods have been used to determine receiver tracking accuracy. In Section 2, the signal to noise ratios required to achieve the desired measurement accuracy are discussed and values derived for the figures in Table 1-10.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Vertical Accuracy m ($1\sigma$)</th>
<th>Pseudorange Tracking Accuracy ($1\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-217 SCAT-1</td>
<td>4.8</td>
<td>0.4/0.5</td>
</tr>
<tr>
<td>ESA EGNOS [16] &amp; Table 1-8</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Derived from ICAO RNP (section 1-8)</td>
<td>2.1</td>
<td>0.26</td>
</tr>
<tr>
<td>ICAO GNSSP report Wellington</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAIM Studies WAAS [15] &amp; Table 1-7</td>
<td>3.5</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**Table 1-10 Pseudorange Measurement Accuracy**
2. SATELLITE NAVIGATION SIGNAL STRUCTURE

2.1. Vulnerability to Interference of the GNSS Signal

In Section 3 a theoretical analysis of the susceptibility of GPS, GLONASS and WAAS/EGNOS receivers to RFI will be undertaken. As an introduction the basic signal structure and interference resistance of the systems' coding signals structures are reviewed in this section together with generic receiver design and architecture. GNSS employs a spread spectrum modulation technique to transmit the ranging and navigation data. The satellite's carrier is modulated using Bi-Phase Shift Keying, BPSK, with a pseudo random code, which is combined with a slower navigation data message. Pseudorange measurements are made, and navigation message decoded, by correlating the received signal with a receiver-generated replica of the pseudo-random code. GPS and WAAS/EGNOS use Code Division Multiple Access, CDMA, assigning a different pseudo random code, but the same carrier frequency, to each satellite. GLONASS uses Frequency Division Multiple Access, FDMA, each visible satellite transmitting on its own frequency using the same pseudo random code.

2.2. Civil GPS Signal Structures

Civil users of GPS have access to the Standard Positioning Service (SPS); specifically the Course Acquisition C/A-code transmitted on the GPS L1 frequency of 1575.42 MHz. Each GPS satellite transmits a unique C/A-code made up of a 1023 bit sequence, called a Gold Code [17] transmitted at a clock rate of 1.023 MHz. Superimposed on the L1 C/A code signal is a 50 baud navigation message, containing the transmitting satellite's precise position, clock offset, health and the coarse positions (almanac) of all the satellites in the constellation. The modulo-two combination of the C/A code and navigation message is phase modulated onto the carrier. The resulting L1 SPS GPS frequency spectrum for the L1 signal has a sinc-squared function with a 2.046 MHz bandwidth to the first spectral null, Fig 2-1. Several of the sidebands of the C/A-code are also transmitted as the bandwidth of the filter in the GPS satellites is designed for the P-code. The wide bandwidth enables the sidelobes on the C/A-code to be used in the receiver to enhance the accuracy of the C/A-code measurements and provide a means of rejecting multipath.

C/A code signal power from a satellite above 5 degrees elevation to the user is specified at -160 dBW at the output of a 0 dBic antenna. Actual received GPS C/A code signal power from a zero dBi antenna near the earth's surface is currently approximately 3 dB higher than the minimum specified signal strength due to the satellite manufacturer's tolerances and need to ensure the satellite can maintain its specified output power throughout its lifetime. Satellite transmissions are band-limited to ensure that the registered bandwidth of ±12 MHz

1 is not exceeded and all spurious emissions outside of this band are suppressed. There are no specific filters for C/A code allowing the power in the sidebands of the sinc function to be transmitted. GPS receiver manufacturers have taken advantage of the signal power in spectrum outside of the first nulls to increase the measurements accuracy of the code tracking loop.

1 International Frequency registration 083908702 for GPS L1 1/05/1985
The US DoD has degraded the accuracy available from the SPS GPS using a technique termed Selective Availability (SA). Under normal conditions the accuracy available from the SPS GPS is 100 m 2DRMS. However under a Presidential Decision Directive of March 1995 [18] the Department of Defence was instructed to remove SA by early 2000’s. The accuracy of SPS GPS will then be approximately 10 metres depending on the uncompensated ionospheric delay. To enhance accuracy further, a second civil signal is required particularly to meet the FAA WAAS requirements. An attempt was made to find a frequency for a second civil signal but no agreement could be reached in the original time-scale. In March 1997 DoD agreed not to disturb the phase of the L2 GPS Y-code signal. GPS L2 had hitherto not been specified for civil use as it carries the encrypted Y-code that can not be decoded by a civil user using traditional detection techniques. By using ‘code-less’ tracking techniques the L2 carrier’s phase can be compared with that of L1 to derive the phase difference and hence an indication of the ionospheric delay. It is planned to use code-less receivers in the WAAS ground reference stations to measure the ionospheric delay. However code-less tracking introduces a loss of approximately 14+ dB and therefore makes the receiver highly sensitive to interference.

In the receiver a replica of the selected satellite’s C/A code is generated and by a correlation detection process aligned in time and frequency with the incoming satellite signal. The range to the satellite is derived from the position of the receiver’s code generator and the navigation data message. Once the code is removed by subtracting the prompt code from the received signal, the carrier modulated with the 50 Hz navigation message is produced. The signal power in the navigation data bandwidth of 100 Hz is now above the thermal noise level and can be tracked with conventional phase detectors. Phase tracking and demodulation of the data message is now performed either in an arc-tan or Costas detector.
2.3. **GLONASS**

GLONASS uses the same PRN code from all satellites with each satellite transmitting a different carrier frequency. The L1 carrier frequencies are based on 1 602 MHz at spacing of 562.5 kHz, defined by the expression:

$$f_{01} = 1,602 \text{ MHz}; \Delta f_1 = 562.5 \text{ kHz}$$

$$f_{K1} = f_{01} + n \Delta f_1,$$

where

$$n = -7,..., 0,1,...,24$$

$n$ represents the carrier numbers (frequency channels) of the RF signal. Currently channel $n = 0$ is not used by GLONASS users and is designed to test GLONASS satellites during constellation deployment. The distribution of frequency channels $n = 1,2,...,24$ with orbit positions $1,2,...,24$ is contained in the almanac data transmitted by all GLONASS satellites. In launches since 1994 to conserve spectrum the Russians have used the same frequency channels for some GLONASS satellites in anti-podal positions. The L2 GLONASS frequency and channel spacings are given by:

$$f_{02} = 1,246 \text{ MHz}; \Delta f_2 = 437.5 \text{ kHz},$$

The L1 and L2 frequencies are in the ratio: L1:L2=9:5

For civil use a C/A code of 511 bits is transmitted on each L1 carrier at 0.511 MHz. Its spectrum is shown in Fig 2-2. Received powers for the C/A-code is similar to GPS with a minimum signal power of -161 dBW from a 0 dBic antenna. GLONASS does not transmit the C/A-code on the L2 frequency, but the Russians have indicated\footnote{Discussions at ICAO GNSS panel technical meeting} that they are considering this option for the GLONASS-M satellites, scheduled to be launched from 1999. A P-code is also transmitted on the L1 and L2; however the Russians have stated the P-code is not for public use, although it is unencrypted and has been published by several research institutes.
Several changes are proposed for the GLONASS transmission frequencies over the next decade, to avoid interference from an allocation made by the International Telecommunications Union (ITU) for radio astronomy between 1 610 and 1 613 MHz and for Mobile Satellite Systems, at 1 610 MHz to 1 626.5 MHz. However there is a significant interference issue with MSS terminals due to their out of band spurious emissions.

To begin the transition of the operating frequencies the latest satellites launched up to 1994 operate using frequency channels \( k = 0 \) to 12, 22, 23 and 24, that is they will not use the 1610.6 - 1613.8 MHz frequency band (GLONASS channels \( k = 16, 17, 18, 19, 20 \)) for normal operations. Frequency channels \( k = 13, 14 \) and 21 may be used under exceptional circumstances. Satellites to be launched before 1998 will use nominal frequency channels \( k = 0 \) to 12, however it is possible that frequency channels \( k = -7 \) to -1 and 13 may be used.

Between 1998 - 2005 GLONASS satellite will use frequency channels \( k = 0 \) to 12, with channel \( k = 13 \) used in exceptional circumstances. After 2005 GLONASS satellites will use frequency channels \( k = -7 \) to +6, with channels \( k = 5 \) and \( k = 6 \) used for engineering purposes and for limited periods of time during orbital insertion or 'exceptional' operating circumstances. Filters that limit out-of-band emissions in the bands, 1610.6...1613.8 MHz and 1660...1670 MHz, will be incorporated into the satellites. It is known from a collaborative test with Joderall Bank in the early 1990's that GLONASS satellites have a capability to switch their transmitted frequency over a limited range. It is anticipated that GLONASS-M satellites will have enhanced capability for frequency switching.

The ranging signal modulation is generated by the modulo 2 summation of three binary components:
- pseudo-random (PR) ranging code with a repetition period of 1ms transmitted at bit rate of 511 kbps:
- data of navigation message transmitted at rate of 50 bps:
- meander sequence transmitted at rate of 100 bps.

2.4. WAAS/EGNOS - SBAS

The WAAS/EGNOS signal is defined in ICAO Draft GNSS SARPs and the Satellite Based Augmentation System, (SBAS) [10]. The signal mimics an SPS GPS transmission in frequency, modulation, and uses additional PRN codes that are compatible with the GPS codes, Fig 1-2. WAAS/EGNOS data signals are binary phase shift keyed (BPSK) onto the carrier at the code rate of 1.023 MHz. However the message data has a symbol rate of 500 symbols per second, which is decoded to determine the 250 bit per second message data. The PRN code belongs to the same family of 1023-bit Gold codes as the 36 C/A codes reserved for GPS. The received power from a 0 dBi antenna near the surface of the earth is not less than -161 dBW at elevation angles greater than 5 degrees and does not exceed -155 dBW.

2.5. E-NSS-1

ESA have registered with the ITU [5] an intention to use currently unassigned frequencies in the ARNS/RNSS band, at 1 587.696 - 1 591.788 MHz, and 1 559.052 - 1 563.144 MHz, Fig 1-2. A third frequency at 1 215.068 - 1 215.580 MHz was also registered. A 2.046 MHz PRN code rate is proposed resulting in a 4 MHz bandwidth. Details are not available for the code's structure, but it will be longer than GPS (and GLONASS) avoiding the 1kHz line spectrum. Use of long codes requires parallel processors in the receiver to achieve synchronisation in an acceptable time from switch on. Power at the earth's surface is in excess of specified GPS power but not significantly in excess of the current actual received power from GPS. A power of -155 dBW from a 0 dBi antenna will be assumed for this study. ESA are designing the system to generate a C/No of 47 dB-Hz under 'normal' operating conditions.
2.6. Interference Resistance of C/A-codes

The spectrum of the PRN code is fundamental to the interference resistance of the GNSS signal. PRN spreading codes are generated from maximum-length shift-register sequences. The susceptibility of a particular GPS satellite is highly dependent upon the frequency spectrum of the particular C/A code and that of the interference. The C/A-codes of GPS, WAAS and GLONASS all repeat at 1 ms intervals and therefore have 1 kHz line spectra with the sinc power spectrum. CW interference can coincide with a spectral line of the C/A code, and generate a spurious response from the receiver’s correlator. Some codes are more susceptible than others are since they contain spectral lines significantly higher than the normal sinc spectrum suggests.

GPS C/A-code PRN#6 is particularly susceptible to CW interference because its 163 kHz and 227 kHz spectral components are 8 dB above the sinc squared power level. A CW interferer at L1 ± 227 kHz is likely to cause the receiver to loose lock with interfering powers significantly less than would be the case if the interferer were not tuned to these, or any other significant spectral lines.  Spectral plots of PRN#6, Fig 2-3 show the two large spectral components at 163 and 227 kHz the 227 kHz spectral line being 21.3 dB below the total signal power.

The envelope of the GLONASS C/A-code spectrum is illustrated in Figs 2-2, with the line spectra in Fig 2-4.  As can be observed the single GLONASS CA code are uniform and do not diverge from the power envelope by more than a dB, hence worst-case processing gain loss, L_PG, is less than GPS.  DO 235 assumes a worst-case processing gain loss for carrier wave interference of 10 dB for GPS and 6 dB for GLONASS.
2.7. GNSS Receiver Signal Processing

The basic signal processing in GPS and GLONASS receivers is similar. The major components of a receiver are discussed below and a detailed analysis of the code and carrier measurement errors caused by interference is carried out in section 2. Although there are numerous receiver designs, it is useful to consider a generic receiver with the following components:

1. Antenna;
2. RF and IF rejection;
3. Code and Carrier Signal Processing;
4. Demodulation of the navigation message.

Aircraft GNSS antennas are designed to achieve optimum signal reception over as much of the hemisphere as possible; however, as the signals are circularly polarised, a compromise is made between reception performance for low elevation satellites and a low profile to maintain efficient aerodynamic performance. It is important to maintain antenna gain at low elevation levels to ensure satellite near the horizon can be acquired and tracked to provide optimum satellite visibility for navigation and Receiver Autonomous Integrity Monitor (RAIM) algorithms.

A sample of an aircraft GPS antenna radiation pattern is shown in Fig 2-6. The data in Fig 2-6 was measured using a 9th scale model of a BAC 1-11 with the GPS antenna mounted on the fuselage top surface in front of the wings. The antenna radiation pattern shown in Fig 2-6 is relative to a peak gain of +2 dBiC. As aircraft antennas are low profile, they have a high rejection of vertical signals near the azimuth plane and the gain falls to approximately -8 dBiC. However it is reported aircraft antennas can have gains as high as 7 dB at peak [7]. RTCA have defined a specification for aircraft GPS antenna in DO-228 [19]. Antenna bandwidth can be several tens of MHz to make the antenna responsive to both GPS and GLONASS frequencies, although maintaining circularity over such a wide bandwidth is difficult. It is also difficult to make the antenna narrow-band and selective to just GPS.
Diffraction and reflections from fuselage and wings generates a highly broken gain pattern below the azimuth plane, where typical gains are between -20 to -25 dBic. However the gain can be as high as -10 to -15 dBic, in small areas due to focusing of the diffracted energy.

Using a single antenna the interference can not be distinguished from the satellite signal e.g. by polarisation or arrival angle. Interference is typically randomly polarised; particularly if the source is below the azimuth plane e.g. ground bases interference to aircraft on an approach and may arrive from varying directions as the wave is diffracted around the aircraft structure.

Due to the low power of the GPS signals, and the long lengths of cable required for many aircraft fits, the antenna often contains a low-noise amplifier LNA, to ensure that signal to noise ratio is maintained. Near-band interference at the antenna output is amplified by the LNA. At high powers the LNA will be driven into a non linear region; this point is specified as the 1 dB gain compression level. The RTCA GPS MOPS [20] specify a 1 dB compression point 3 dB greater than the maximum near-band interference power, that is -20 dBW for high near-band and -40 dBW for low near-band. A burn out limit of 1w continuous input power is specified. The output rapidly becomes unstable as the amplifier is saturated, so that the entire positioning function can be interrupted before any signal processing begins. The susceptibility of the LNA to high-power noise is the first potential weakness in GPS receiver design particularly in the vicinity of high power radar that may be in-band to the antenna.

2.8. Ambient Noise Environment

At the antenna output the signal is below thermal noise and it is only after the signal has been despread by the removal of the pseudo random code in the correlation detection process that a positive S/N ratio is produced. Receiver noise is generated by the antenna noise temperature and noise figure of the first amplification stage. However any losses in the cables, feeders and filters between the antenna and the first active stage add to the noise figure. Noise power is given by the following expression:
Figure 2-6 Measured Aircraft (Model) GPS Antenna Radiation Pattern*
*Gain in dBi RHC and is referenced to a +2 dBi peak

\[ N = KTB \]  \hspace{1cm} (2-1)

where:

- \( N \) = Noise power dBW
- \( K \) = Boltzman’s constant \( 1.380662 \times 10^{-23} \) JK\(^{-1}\) or \(-228.6\) dBJK\(^{-1}\)
- \( T \) = System Temperature degrees Kelvin
- \( B \) = Bandwidth Hz

System temperature is the sum of the antenna temperature \( T_a \) and the equivalent temperature of the receiver \( T_e \). By making the gain of the low noise amplifier LNA high, and putting the device at the antenna, the input noise can be fixed. However, the protection devices incorporated into the RF input to prevent burnout from lightning or high stray electric fields adds to the noise. The system noise temperature can be calculated from the antenna temperature, protection device losses, the noise figure of the receiver’s LNA and where applicable cable losses define the operating temperature by the relationship:

\[ T_s = T_a + \frac{(L - 1)T_0}{L} + (NF - 1)T_0 \]  \hspace{1cm} (2-2)

where, by definition \( T_0 = 290 \) K

\( T_a \) for L-band is approximately 100 K depending on antenna pattern, rain and tropospheric temperature. NF for a LNAs can be 1.5 dB or lower. For aircraft receivers a power limiter circuit is added to prevent ‘burn out’, typically these circuit add 1 dB to the noise figure. These figures lead to an overall temperature of 500 K and a noise power of -201.5 dBW/Hz.
However there are aircraft installations where a cable with additional loss is placed between the antenna and LNA. Other factors that increase the noise are older amplifiers with higher noise figures and noise due to aircraft mounting. RTCA took a noise temperature of 500 K and a noise power of -201.6 dBW/Hz as its standard. The other possibility is for a zero loss installation. Here the antenna temperature and a 1.5 dB NF LNA result in a noise temperature of 220 K and a noise power of -205 dBW/Hz. Where appropriate in the analysis comparisons will be made using a range of noise powers.

Assuming a noise density of -202.5 dBW/Hz, in the C/A-code 2 MHz bandwidth the receiver’s noise power will be -139.5 dBW, 20 dB above the received signal power. Not until after the correlator does the signal appear above the noise. Typical 1 dB is lost in the down conversion process, due to cables and imperfect RF and IF filters, resulting in a received signal power for a satellite at 5 degrees elevation (-4.5 dBic antenna and specified signal power) of -165.5 dBW. Correlation losses are typically 1 dB due to imperfect modulators in the satellite and receiver, producing a carrier to noise ratio, C/No, of 36 dB-Hz for GPS, 35 dB-Hz for GLONASS.

For high elevation satellites the signal strength can be -155 dBW (+2 dBic antenna and -157 dBW signal), reduced front end noise of -205 dBW/Hz produces a C/No of 48 dB-Hz for GPS. Data from some receivers suggest that a C/No of 50 + dB-Hz can be achieved, but as the number produced by the receiver is a manufacturer’s calibration it is sometimes inaccurate. A detailed evaluation of the correlator and its susceptibility to interference will be examined later in this section.

2.9. Downconversion to Inter and regulation

Following the first RF LNA the signal is down converted to an intermediate frequency. Depending on the receiver RF and IF architecture, the processing after the LNA contains several pre-processing filters that reject signals outside the GPS bandwidth. RFI which overlaps the GNSS frequency spectrum is unaffected by this filter. An interference rejection requirement is contained in the RTCA MOPS [20] as reproduced at Fig 2-9.
The importance of good RF and IF rejection of out of band signals cannot be over emphasised. Without the filter protection high power energy outside of the signal band will saturate the AGC and A/D converters. There is no protection to high power in band signals without the use of special antenna or adaptive filtering systems. It is also essential that the filters are linear so that they do not cause any harmonics that could fall in-band to the wanted signal from the product of two or more out of band signals. Front end linearity must be maintained to a high power, typically -50 dBW and a high burn out power typically 1 W constant are specified.

The high SATCOM transmission powers require filters with sharp cut-offs to prevent interference into the GPS receiver. Although interference from out-of-band signals into GPS may be reduced by incorporating high order RF and IF filters, a limit is imposed by the devices phase linearity, size and weight in respect of the rejection that can be achieved against nearby strong signals. Unfortunately, however sharp the filter response, it can not protect against wide band noise generated by frequency synthesis in adjacent transmission systems that falls within the receiver’s pass-band. The only jamming resistance against such noise is provided by the GPS processing gain, the ratio between the despread signal, 20 MHz and the carrier tracking bandwidth, typically 5 Hz.

In the receiver the RF signal is down converted to an intermediate frequency, IF and then to a frequency near the codes baseband. All frequencies used in the down conversion process are derived from the receiver’s fundamental oscillator by Numerical Controlled Oscillators (NCOs). To achieve optimum performance a two stage down conversion prior to digitising the signal is used. Sophisticated designs can have three stages and ‘build to cost’ designs have used a single stage. The advantage of multiple down-conversion architecture is the control it affords to the rejection of out of band signals and from internally generated interference.

A LO frequency is required for each down-conversion stage. The LO frequency is generated from the receiver’s fundamental oscillator using numerically controlled counters. Usually the LO frequencies are fixed and not under control of a feedback detection process. Each down-converter requires an image rejection filter to remove the unwanted sideband, usually the lower sideband is selected, and any leakage signal, that could be a cause of noise in the detection circuits. The rejection of signals, which will cause aliasing at the sampling rate usually between 2 - 8 MHz for GPS C/A-code, is essential to ensure noise does not enter the correlator. In order that signal fidelity is preserved during down conversion all components, filters, amplifiers and mixers must have a flat phase response. Any phase distortion added at these stages will degrade the spread-spectrum signal and introduce a correlation loss. In order to achieve an optimum result phase preservation has been of concern in the specification of adaptive antenna anti jamming systems.

In order to preserve the phase information in the detection process during the final down-conversion process to near baseband, I and Q components are generated, by sine and cosine LO signals. Following the final down-conversion stage the signal is sampled by an analogue to digital converter. An AGC function must be applied prior to the A/D to ensure the process is not saturated or under-powered. The number of bits in the A/D conversion process is an important factor in the rejection of in-channel noise, particularly CW signals. Single bit A/D converters, which theoretically have a loss of 3 dB to a perfect converter, have susceptibility in excess of 10 dB to CW signals. Designs which use two or two and a half bit A/D converters reduce the loss to 0.5 dB, but have a significant advantage in CW interference environments. Some sophisticated designs have used three or even four bits to reduce any losses to <0.1 dB but at increased complexity in the correlator architecture as each bit has to be processed independently prior to being summed in the detector.
2.10. Signal Processing Functions

A satellite navigation solution is produced from measurements made of the range to the satellite from the code correlation process and its Doppler frequency by a phase or frequency tracking of the transmitted carrier. In the receiver replicas of the code and carrier are produced that are synchronised with the received satellite signal. The synchronisation process is performed in code and carrier tracking loop and the 'loop is locked' when synchronisation is achieved. Correlation functions are employed in the code and carrier loops with the output power used as the discriminator to detect synchronisation. In order to maintain a high integrity navigation solution a GPS receiver must maintain lock on the satellite signal and continually read the navigation data message.

![Figure 2-8 Generic Architecture for a Receiver Channel](image)

A GPS receiver tracks both the signal code and carrier, however to acquire the signal, the receiver must commence an acquisition process once the approximate frequency is located. The replica code is slipped past the received signal usually in half chip intervals. When synchronisation with the code is achieved, the prompt code is injected into the received signal, Fig 2-8 removing the code modulation and generating the carrier plus navigation signal. The navigation signal is phase tracked to extract the navigation data and the carrier frequency.

Several variations of the same fundamental DLL design have been produced. By using one eight chip early-late correlator the ‘narrow correlator’ used by NovAtel provides enhanced protection against multipath distortion of the code range measurements. A similar improvement in performance can be achieved by using a correlator run at the P-code rate, e.g. at a sampling rate of 20+ MHz but fed with the C/A-code. The technique has been used in military GPS receivers for many years.

2.11. Code and Carrier Tracking

GNSS pseudo-random codes use BPSK modulation of the carrier wave to represent the PRN code. Each pseudo-random bit change results in a 180° phase angle change of the carrier signal. In the receiver the phase changes must be matched to the replica code. To initiate this process the carrier loop must first be set to bring the code into the capture range.
of the code correlator. The bandwidth of the code correlator is inversely proportional to the integration and dump filters, however the wider the bandwidth the more susceptible the receiver is to interference.

![Figure 2-9a Code Correlation](image)

The replica code is slipped in time passed the received signal, Fig 2-9a until the detector is triggered by a rise in the power at the output of the correlator. Detection and tracking of the GNSS codes relies upon the auto-correlation and cross correlation functions of the C/A codes. When the codes are synchronised to within half a chip the power at the output of the detector rises. The code structure must ensure that only one correlation peek occurs, that is the auto-correlation function, Equation 2-3, is unique.

\[ R(\tau) = \int_{-\infty}^{\infty} C(t)C(t+\tau)dt \]  

where,

- \( R(\tau) \) = the power in the auto-correlation product
- \( C \) = the code function (an irregular square wave)
- \( \tau \) = The code offset

The auto-correlation function (power) of the GPS C/A code PRN#5 is illustrated in Fig 2-9b. A high power output is produced when the receiver generated code is aligned within ± 0.5 chips of the received code. When the codes are not aligned the auto-correlation function has a low power with a noise component of 1/1023 or -30 dB of the peek power. However the C/A-codes do not produce zero power for all time differences and the C/A-codes have a number of smaller correlation peaks at various time and Doppler offsets which can lead to false locks and increase susceptibility to interference.

Correlation in the time domain is equivalent to convolution in the frequency domain. The frequency spectrum of the code is therefore of major concern. The power spectrum of the pseudo-random code, \( S_{cc}(\omega) \), can be obtained from the Fourier Transform of the auto-correlation function:

\[ S_{cc}(\omega) = \ImaginaryPart(R(\tau)) \]
If the code is modelled as a rectangle, the auto-correlation function, the code function convoluted with itself, has a triangular shape, Fig. 2-9b. The resulting power spectrum has a sinc²(ω) distribution (sin²(ω)/ω²). When assessing the wide-band interference effects on correlation performance this model is sufficient, however, when narrow-band interference is present the true correlation properties of the pseudo-random code must be used. The sinc²(ω) distribution approximates as an envelope around the pseudo-random code’s spectrum with the discrete spectral lines fluctuating above and below the envelope.

As all GPS satellites transmit on the same frequency the cross correlation between code must be high enough to reject all but the desired satellite. The discrete spectral lines in the C/A-code spectrum, Fig 2-10 & 1-3 produce high values for the cross correlation function at particular time and Doppler combinations, where the nominal 30 dB reject is reduced to approximately 20 dB. This result means that if a C/A code appears at a power 20 dB above the desired code enough power will be detected in the correlation function to activate the lock detector. Normally cross correlation is not a problem as no one-satellite signal should be 20 dB above another. However aircraft antenna radiation patterns can cause high gains in certain directions and very low gains in others that can lead to false locks. There is also the
problem of intelligent jammers as the signal power level required to capture the correlator using a replica of the satellite code is significantly less than that of a noise like signal.

The codes are also particularly sensitive to CW interference if it has the same frequency as one of the spectral lines. In the correlator the CW signals can cross correlate with individual lines reducing the processing gain provided by the C/A-code. Typically the power required to jam the receiver is approximately 10 dB less due to the line spectral nature of the C/A code. False locks can also be generated as the detector can not distinguish between a true C/A-code and a CW signal. Only by verifying that the navigation message data is present can a receiver detect true lock on satellite signals. The result is that the signal processing gain is reduced by 10 dBs to narrow band signals. In the case of GPS the loss can be greater than 10 dB due to the variation in the cross correlation product for the particular C/A-code. In contrast the GLONASS C/A-code has a spectrum that follows the sinc function within a dB and does not suffer this additional loss.

Several other factors in the receiver design influence the rejection of interference, particularly the RF and IF filter shapes, the analogue to digital conversion process, the AGC action and the configuration of the tracking loop control software. For a well designed receiver 1 dB is lost in these processes.

2.12. Code Detection and Tracking Processes

The ability of the receiver to accurately correlate its replica code with the received signal is directly related to the pseudorange error and therefore navigational accuracy. A delay lock loop (DLL) is used to track the code phase of the satellite signal using half chip early and late versions of the code generated in the receiver. By taking a linear interpolation between the early and late codes a prompt code is produce that is used to remove the code modulation from the received signal and regenerate the carrier.

![Generic code-tracking Loop](image-url)
2.12.1. The Delay Lock Loop

Generic code tracking processes in GPS and GLONASS receivers is illustrated in Fig. 2-11. Practically all receivers employ a Delay Locked Loop, DLL to track the code. In a DLL early, prompt and late versions of the in-phase and quadrature samples are used to generate a discriminator, which is used to control the code phase position and to a first order its frequency.

Two common non-coherent DLL discriminators are the early minus late power and the dot product. A simple $I^2 + Q^2$ is used by many receivers. Others have used a more sensitive, early minus late power discriminator given in equation 2-5.

$$\sum (I_{ES}^2 + Q_{ES}^2) - \sum (I_{LS}^2 + Q_{LS}^2)$$  \hspace{1cm} (2-5)

where,

$I_{ES}$ and $Q_{ES}$ are in-phase and quadrature early samples

$I_{LS}$ and $Q_{LS}$ are in-phase and quadrature late samples.

The output power of the detector together with the prompt early and late correlators as a function of $\tau$, the displacement of the received pseudo-random code, are shown in Figure 2-12. More elaborate discriminators have been described including the Dot Product implementation, which is more sensitive than a power law:

$$\sum (I_{ES} - I_{LS}) I_{PS} + \sum (Q_{ES} + Q_{LS}) Q_{PS}$$  \hspace{1cm} (2-6)

![Diagram of correlators and discriminator](image)

**Figure 2-12 Early Minus Late Discriminator, ½ chip spacing**
2.12.2. Code Tracking Noise

A reduction in the signal to noise ratio results in a decrease in the code tracking accuracy and pseudorange estimation. The relationship is given in several sources e.g. [21] & [22]. However there are minor variations in the expressions given, we have used the fundamental equation 2-7 from [22].

\[
\sigma_{PR}^2 = \frac{4F_1L_c^2B_1 d^2(\alpha / 2)}{S / N_0} \left[ 2(1 - d) + \frac{4F_2d}{S / N_0 T} \right]
\]  \hspace{1cm} (2-7)

where,

- \( B_1 \) is the one sided noise bandwidth of the code loop filter (\(~1 \text{ Hz})\),
- \( d \) is the correlator chip spacing (\(0.1<d<0.5\)),
- \( T \) is the pre-detection integration time (20 ms GPS and GLONASS 2ms WAAS),
- \( S/No \) is the post-correlation signal to equivalent noise power density,
- \( L_c \) is the spatial length of the a PRN code chip
  - 293 m for GPS C/A-code
  - 586 m for GLONASS C/A-code
- \( F_1 \) is the DLL correlator factor
  - \(1\) for time-shared \(\tau\)-dithered early/late correlator
  - \(1/2\) for dedicated correlators.
- \( F_2 \) is the DLL discriminator factor
  - \(1\) for an early/late power discriminator
  - \(1/2\) for a dot product type estimator,
- \( \alpha \) is the carrier smoothing constant (0.02 in this example).

As an example, a plot of the tracking accuracy, standard deviation of the pseudorange measurement with C/No for a carrier aided code receiver, with dedicated correlators, 1/2 a chip early prompt spacing and a dot product code loop discriminator, is given in Figure 2-13. RTCA [7] suggests the code tracking jitter be reduced by a factor of \(\alpha/2\) if a carrier smoothing filter is used. However, if the code loop bandwidth is less than the smoothing update rate, the smoothing function has little effect since the pseudorange measurements will be highly correlated. Current receivers use a code loop aided by the carrier to reduce the code loop bandwidth to sub 1 Hz. Variation on the half chip early late correlator have been derived. The narrow correlator uses a 1/10 chip spacing which increases tracking accuracy at a given S/N but does not provide additional interference protection.

The performance of the code-tracking loop is highly dependent on reliable carrier phase tracking. Measurement accuracy will be degraded by a factor of at least 2 and higher at low signal to noise ratios if carrier tracking is lost. The use of carrier smoothing filters with time constants, \(\alpha\) of 100 seconds is suggested by the US at the ICAO GNSSP, particularly for local area augmentation systems for approach and landing. The theoretical result is to reduce the tracking noise by 50 % on that shown in Fig 2-13. However, receivers with such filters are only just becoming available and no independent performance data is available. It is recommended that the performance of these receivers be investigated as soon as examples can be procured.
2.13. Carrier Tracking

Following the de-spreading process, performed by code correlation, a GNSS receiver’s carrier tracking loop phase locks onto the recovered carrier, Fig. 2-14. The carrier phase reversals caused by the navigation data remain. A discriminator that is insensitive to carrier phase reversals is used. In-phase, I, and quadrature, Q, samples are used to supply feedback to the numerically controlled oscillator. When the loop is locked, the I arm of the quadrature detector contains the navigation data. The discriminator implementation can be a Costas $(Q_{pk} I_{pk})$ or $\text{Arc-tan} \left( \frac{Q_{pk}}{I_{pk}} \right)$ function-tracking loop.

The carrier tracking filter is usually third order, which make it insensitive to acceleration but a constant error is generated under steady jerk. As jerk is of very short duration for transport
aircraft tracking errors from his source are minimal. RTCA in WAAS MOPS specify a max jerk of 0.25 g/sec. After carrier lock, the accurate Doppler shift estimate from the carrier tracking loop can be used to aid the code tracking performance by providing velocity data allowing the code loop bandwidth to be decreased to improve the code tracking accuracy.

2.13.1. Carrier Tracking Noise

Ultimately the interference resistance of a GNSS receiver is limited by the characteristics of the carrier-tracking loop. The carrier tracking jitter variance can be expressed as the sum of the tracking noise and oscillator noise variances.

\[
\sigma^2_{\phi} = \sigma^2_{\phi,\text{noise}} + \sigma^2_{\phi,\text{osc}}
\]  

(2-8)

The oscillator phase noise is made up of the satellite oscillator and that in the receiver. Satellite specifications allow oscillator noise of 0.1 rad (5.7 degrees). High quality oscillators would limit receiver-induced noise to 0.5 degrees for a 10 Hz loop bandwidth. To reduce costs temperature compensated crystal oscillators are used for most civil receivers that produce a carrier phase jitter similar to that of the satellite at 5 degrees, resulting in an overall \(\sigma_{\phi,\text{osc}}\) of 7.5 degrees. Receiver oscillator noise limits the extent to which the loop bandwidth can be reduced as the phase noise rises to the point where the loop can not be stabilised.

![Figure 2-15 Carrier Phase Jitter as a function of C/No](image)

If we require that the rms. noise be such that the probability of an excursion that looses lock is small, e.g. \(10^{-3}\) a maximum rms. jitter of 0.15 rad or approximately 8 degrees is required. This equates to a signal to noise ratio in the loop of 10 dB.
The carrier tracking noise is a function of $C/N_o$:

$$\sigma_{\phi,\text{noise}}^2 = \frac{B_L}{C/N_0} \left(1 + \frac{B}{2C/N_0}\right) \quad (2-9)$$

where

- $B_L$ is the single sided tracking loop bandwidth
- $C$ is the regained carrier power
- $N_0$ is the noise density per Hz.
- $B$ is the input noise bandwidth

It is noted that

$$SN(\text{loop}) = \frac{C}{2N_0B_L} \quad (2-10)$$

A plot of $\sigma_{\phi,\text{noise}}^2$ against $C/N_o$ is given in Figure 2-15. Typically a phase lock loop will become highly unstable with tracking errors of 0.15 radians, although RTCA [7] gives 15 degrees as the rms. lock threshold.

### 2.13.2. Data Demodulation

The carrier is phase tracked to demodulate the navigation data. A bit error rate, $BER$ of $1:10^5$ or one error in 20 sub-frames has been adopted as the benchmark for data reception, which. A BER of $1:10^5$ for PSK requires an energy-per-bit ($E_b/N_o$) of 10 dB. However BER increases rapidly with decreasing $E_b/N_o$, at 9 dB the BER is $1:10^4$ and at 8 dB it is $1:10^3$, at which point the data is unreadable. Also, under aircraft dynamic conditions the $C/No$ fluctuates by several dB. In order to ensure high integrity data a high $C/No$ must be specified. To ensure a 50 Hz detection bandwidth the noise bandwidth is nearer 100 Hz, and the required $C/No$ rises to 30 dB-Hz. An increase in the background input noise to the receiver of 5 dB resulting in a total noise power of -134.5 dBW would begin to degrade the BER.

BER is given by the classic error function equations for the detection of signals in Gaussian noise. RTCA [7] gives equation 2-11 as the bit error probability for a BPSK GPS signal in the presence of wide-band interference that causes a carrier tracking error of $\phi$.

$$P_{be}(\phi) = \frac{1}{2} \text{erfc}\left(\frac{S}{\sqrt{N_o R_b}} \cos \phi\right) \quad (2-11)$$

where $R_b$ is the data rate (bits per second).

A similar expression can be used for GLONASS. However WAAS uses GPS signal but with a rate - one half convolution coding at 500 Hz BPSK symbols of the 250 bits/s data. WAAS MOPS requires that the receiver flags a word error if a bit error is detected by the cyclic redundancy coding, CRC. RTCA [7] gives the bit error rate as equation 2-12

$$P_{be,\text{WAAS}}(\phi) \geq 0.5(36D^{10} + 211D^{12} + 1404D^{14} + 11633D^{16}) \quad (2-12)$$

where,

$$D = \exp\left(-\frac{E_b}{2N_o} \cos^2 \phi\right) \quad (2-13)$$
The pdf of $\phi$, assuming a Costas loop, can be approximated by:

$$p_\phi(\phi) = \frac{1}{2\pi_0(1/\sigma_\phi^2)} \exp \left( \frac{\cos \phi}{\sigma_\phi^2} \right)$$ (2-14)

Combining the probability distributions $P_{be}(\phi)$ and $p_\phi(\phi)$ enables $P_{be}$ to be computed for a given S/No, equation 2-15.

$$P_{be} = \int_{-\pi/2}^{\pi/2} P_{be}(\phi)p_\phi(\phi)d\phi$$ (2-15)

The probability of an error in an N-bit series can be approximated as:

$$P_N = 1 - (1 - P_{be})^N$$ (2-16)

Using the above equations bit and word error probabilities as a function of S/No are plotted in Figure 2-16.

![Figure 2-16 GNSS Bit and Word Error Rates](image)

Of more significance in GPS and GLONASS is the probability of receiving a GPS sub-frame or GLONASS string without error. The parity detection code of GPS and GLONASS are not good enough to use to correct errors. As the noise tends to be statistically burst like, if an error has occurred there is a high probability other bits have been corrupted. If more than one error occurs the error correction code is corrupted. Most receiver check for parity and if it is not achieved read the entire sub-frame again. However for GPS and GLONASS a 30-second delay is incurred.

For WAAS a word must be received uncorrupted and the CRC is used to detect a bit error. The WAAS word error rate is therefore the most sensitive function.
2.14. Carrier Tracking and INS Aiding

Enhanced resistance to interference can be produced by narrowing the carrier tracking loop bandwidth. Narrower bandwidth improves interference resistance but decreases the response to dynamics. However, digital receiver design has enabled high order tracking filters to be used. A third order filter is insensitive to acceleration and is only affected by jerk. Under commercial aircraft operations, jerk is experienced only for periods which are short compared to the effective loop time constant and any tracking error introduced is small. Loop bandwidth is not limited to 50 Hz and can be reduced until the phase noise from the receiver's oscillator dominates. Current oscillator performance prevents the loop from being smaller than 5 Hz if phase tracking is to be maintained through typical transport aircraft dynamics.

Generally, receiver manufacturers implement the correlator - code tracking as a first order system. Without an external control, usually provided by the carrier-tracking loop, the code-tracking loop will build up a large error whenever acceleration is applied to the GPS antenna; (all navigation in a GPS receiver unaided by an inertial system is referenced to the antenna). Under dynamic conditions, range data is noisy and of low integrity. To produce accurate range measurements, the tracking loop bandwidth must be reduced to less than 1 Hz. To maintain code lock, the tracking loop must be steered with Doppler information derived from the carrier loop. If under dynamic conditions interference unlocks the carrier-tracking loop, code lock is also lost and the receiver is effectively jammed. Aiding from INS can extend the interference level sustainable by several dBs before code lock is lost.

INS aiding has not been demonstrated to increase the interference resistance of GPS receivers. GPS signals have a Doppler shift of 5 Hz per m/s of relative velocity between the satellite and receiver antenna. As carrier tracking loops are operating with 5 Hz bandwidths, if an INS is used to maintain the loop at the correct Doppler frequency, it has to be accurate to ±0.5 m/s. Typically, the best aircraft INS will experience errors of 1.5 m/s over the course of the flight, indeed GPS is usually used to correct the INS error in an integrated navigation filter. Although the INS could be used to position the loop in the frequency domain near the correct Doppler, it cannot be used to reduce the bandwidth to improve the interference resistance as the bandwidth is limited by oscillator noise. Also, it is the antenna’s position

<table>
<thead>
<tr>
<th>GPS and GLONASS Power</th>
<th>GPS C/A code</th>
<th>GPS Code-less Tracking</th>
<th>WAAS</th>
<th>GLONASS C/A code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Received Power @ 5 deg dBW</td>
<td>-160</td>
<td>-163</td>
<td>-161</td>
<td>-161</td>
</tr>
<tr>
<td>Receiver Antenna Gain @ 5 deg dBic</td>
<td>-4.5</td>
<td>-4.5</td>
<td>-4.5</td>
<td>-4.5</td>
</tr>
<tr>
<td>Cable and down-conversion losses (minimum) dB</td>
<td>1.0</td>
<td>1.0</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Pre correlation Received Power dBW</td>
<td>-165.5</td>
<td>-168.5</td>
<td>-166.5</td>
<td>-166.5</td>
</tr>
<tr>
<td>Noise Power Spectral density ‘KTB’ dBW/Hz</td>
<td>-201.5</td>
<td>-201.5</td>
<td>-201.5</td>
<td>-201.5</td>
</tr>
<tr>
<td>Correlator/Processor Loss dB</td>
<td>1.0</td>
<td>~14*</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>C/No Carrier to Noise ratio dB-Hz</td>
<td>35.0</td>
<td>19.0</td>
<td>34</td>
<td>34.0</td>
</tr>
<tr>
<td>Energy per bit Navigation Data dB</td>
<td>18.0 (50 Hz)</td>
<td>N/A</td>
<td>16 (250 Hz)</td>
<td>14.0 (100 Hz)</td>
</tr>
</tbody>
</table>

Table 2-1 Power Budget and Signal Processing Margins
* Correlator loss for code-less receivers is highly dependent on signal strength, a mid range figure is used here
that must be considered which requires a computation of level arm between the INS and antenna. Processing time for data transfer and applying the results within the receiver is a significant limitation. However if carrier tracking is lost INS data can be used to aid the code tracking loop to keep the loop locked, reduce the measurement noise or if all tracking is lost position the code tracking Doppler which is less sensitive to platform velocity error at the correct frequency.

2.15. Power Budget

The power budget for GPS and GLONASS receiver At the signal levels given in Table 2-1 a noise power of -195.5 dBW/Hz is required to degrade the C/No to 30 dB-Hz. To produce this noise level for a narrow band interference source (not CW) an input noise power of -132 dBW is required, as the noise is spread by the correlation process across the code bandwidth. For a higher elevation satellite the noise power is typically 9 dB higher at -123 dBW. These numbers agree with data measured from practical experiments using satellite signal simulators and real satellites.

2.16. Carrier Phase Integration

If the phase of the carrier is constantly integrated the occurrence of cycle slips are important. There is a probability that the phase tracking loop will momentarily loses lock and slip a cycle. Cycle slips may be undetected by the normal lock detector of a receiver’s carrier tracking circuits. The mean time between cycle slips is given by several sources:

$$\tau_o = \frac{\pi}{4B_\phi} \exp\left(\frac{1}{2\sigma^2 \phi}\right)$$  \hspace{1cm} (2-17)

where

- $\tau_o$ = mean time to slip a cycle
- $\sigma^2 \phi$ = variance of tracking error in loop


$$T = \frac{\pi^2}{8\sigma^2 \phi^2} I_0^2(1/4\sigma^2 \phi)$$  \hspace{1cm} (2-18)

where $I_0$ is the modified Bessel function of the first kind and of zero order. When a bias angle, $\gamma$, is added to the loop, due to the presence of aircraft dynamics and/or SA, the mean time between cycle slips, for a first order Costas loop, can be expressed as:

$$T = \frac{\pi}{2B_\phi \gamma} \tanh\left(\frac{1}{4\sigma^2 \phi}\right) \left[I_0^2\left(\frac{1}{4\sigma^2 \phi}\right) + 2 \sum_{n=1}^{\infty} (-1)^n I_n^2\left(\frac{1}{4n\sigma^2 \phi}\right) I_{4n}\left(\frac{1}{4n\sigma^2 \phi}\right)\right]$$  \hspace{1cm} (2-19)

The probability of a cycle slip can then be approximated as:

$$P_{\text{slip}} = 1 - e^{-T/\tau}$$  \hspace{1cm} (2-20)

The probability of a cycle slip is plotted as a function of S/No in Fig 2-17.
2.17. Conclusions - Required Signal to Noise

From the above analysis and using the range measurement requirements derived in Section 1, Table 1-10, the corresponding C/No values are derived and shown in Table 2-2. It is observed that the C/No values for GLONASS are approximately 6 dB greater than for GPS. The values are derived using equation for the code tracking accuracy assuming a $\pm$ half bit DLL with carrier aiding to reduce tracking loop bandwidth. The results indicated in Table 2-2 will be used in section 3, where the effect of interference and the signal processing margins are considered.

<table>
<thead>
<tr>
<th>Performance Requirement</th>
<th>Pseudorange Measurement Accuracy (1σ)</th>
<th>Required C/No dB-Hz (GPS)</th>
<th>Required C/No dB-Hz (GLONASS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-217 SCAT-1</td>
<td>0.4/0.5</td>
<td>33.5/32.5</td>
<td>39/37.5</td>
</tr>
<tr>
<td>ESA EGNOS [16]</td>
<td>0.4</td>
<td>33.5</td>
<td>39</td>
</tr>
<tr>
<td>Derived from</td>
<td>0.26</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>ICAO RNP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICAO GBAS SARPs</td>
<td>0.23</td>
<td>39</td>
<td>45.5</td>
</tr>
<tr>
<td>RAIM study</td>
<td>0.22</td>
<td>39.5</td>
<td>46</td>
</tr>
<tr>
<td>WAAS [15]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-2 Required C/No for receiver measurement accuracies
3. INTERFERENCE RESISTANCE

3.1. In-band Interference Rejection

The spectrum of the C/A-code as discussed in Section 1, consists of a two sided bandwidth with a sinc envelop with nulls at \( n/T_c \), \( (n*1.023 \text{ MHz}) \), where \( T_c \) is the code chipping period. Wide-band interference of bandwidth greater than 100 kHz is spread by the ranging code over its bandwidth, resulting in a power density of approximately \( 2 \times 10^{-6} \) (-63 dB) of the input power per Hz in the post correlation circuits.

The resultant C/No is given by:

\[
\frac{C}{N_0} = \frac{C_{\text{postcorrelation}}}{N_0 + \frac{P_I}{R_C}}
\]  

where

- \( C/N_0 \) = Carrier tracking carrier to noise ratio
- \( C_{\text{postcorrelation}} \) = Carrier power after correlation and receiver losses
- \( P_I \) = Received interference power
- \( R_C \) = Chip rate of PRN code
- \( N_0 \) = Receiver noise floor

From Equation 3-1 the ratio of the input signal bandwidth, which is the C/A-code bandwidth to the bandwidth in which \( C/N_0 \) is measured (1 Hz) is termed the processing gain. From the above the ratio is 63 dB.

Due to the 1 ms repeat in the C/A-codes, their spectrum is not continuous but has discrete lines at 1 kHz intervals as discussed in Section 1. The spectral lines increase the susceptibility of the C/A-code to extremely narrow band interference by approximately 10 dB. The exact effect of the interference is highly dependent upon the frequency spectrum of the particular C/A-code and the Doppler present. If the interference’s frequency coincides with a spectral line of the C/A code, then the receiver’s correlator produces a spurious output which if of sufficient power, will jam the tracking process. The power of the spurious output depends on the power in the code spectral line.

3.2. Interference Mechanism

Noise in the code and carrier-tracking loop is the result of the convolution of the interference with the code spectrum. The interference spectrum in the correlator, \( I(f) \) is itself the convolution of the free space spectrum convoluted with the RF/IF filter shape and the sampling process in the receiver. The sampling process can be represented by a delta function at the sampling rate, \( \delta(f_s) \) which is usually equal to the sampling rate of the receiver’s internally generated code. Power in the input signal above the Nyquist rate is folded back to lower frequencies. At the correlators output the noise power is the convolution of the input noise with the GNSS signal \( S_{\text{gnss}}(f) \):

\[
\text{Noi} = \int_{-\infty}^{\infty} S_{\text{gnss}}(f) I(f) \delta(f_s) df
\]  

Tight filtering is required in the RF and IF sections to ensure that any interference above the Nyquist rate of the sampling frequency is removed. Any noise not filtered out appears at the input to the analogue to digital converter. If this noise has high power components it will
saturate the A/D automatic gain control which will significantly degrade tracking performance. AGC for satellite navigation are set up for a small dynamic range of approximately 20 dB, and high powers entering the gain control circuit will cause saturation with a non linear output. Sampling rates for the A/D depend on receiver architecture, but the rate must be at least the chipping rate of the PRN code. Substantially higher sampling rates are used in narrow correlator designs to reduce errors caused by multipath signals. Maximum rates can be as high as 40 MHz, if the receiver is also capable of P(Y)-code operation. Prior to the A/D any power above the Nyquist rate of the sampling process, half the sampling frequency must be removed. Otherwise the power in the interference spectrum at frequencies above the Nyquist rate will be aliased and folded over into the lower frequency spectrum. Any noise entering the correlator adds to the noise in the detector. Assuming that the filters remove the noise above the Nyquist rate and the effect of $\delta(f_s)$ can be approximated as a 1 dB loss, the power out of the correlator can be written for an interfering signal $I(f)$ of 1 W/Hz from frequency $F_1$ to $F_2$:

$$\text{Noi} = \int_{F_1}^{F_2} S_{\text{gnss}}(f) \text{df} \quad (3-3)$$

### 3.3. Bandwidth Effect on Interference Susceptibility

A GPS receiver’s susceptibility to an interference signal is dependent upon the signal’s central frequency and bandwidth, due to the convolution of the interference with the PRN code in the correlation process. The effect of the interfering signal’s bandwidth on the correlation process can be analysed by modelling the correlation process as the convolution of two Power Spectral Densities, PSDs. The convolution is performed because the multiplication of the receiver’s correlator in the time domain is equivalent to a convolution in the frequency domain.

The effect of the interfering signal bandwidth on processing gain can be analysed by making three approximations as depicted in Figure 3-1:

1. For interference with bandwidths $> 100$ kHz, the code PSD is modelled as a continuous

![Figure 3-1 Model of Correlation Process for varying Interfering Bandwidth](image-url)
sinc² function.

2. For interference bandwidths between 1 and 100 kHz the code PSD is modelled as a series of multiple spectral lines with a single large spectral line 8dB above the average sinc² envelope, reflecting the fluctuation of the GPS C/A-code spectrum from the sinc² distribution.

3. For interference bandwidths of less than 1 kHz a single spectral line is assumed to dominate the model.

By applying the three simple approximations of the C/A-code PSD, a graph of the variation in processing gain as a function of bandwidth is derived Figure 3-3.

For large bandwidths, line ‘a’ the filtering effect of the C/A-code bandwidth convoluted with the interference results in a 10dB/Decade variation in the processing gain. As the interfering bandwidth reduces to the C/A-code bandwidth, the processing gain levels off to 60 dB (10log(1.023×10^6) with respect to 1 Hz. If the PRN code spectrum was continuous the processing gain would remain at 60 dB (the dotted line in Fig 3-4) as the bandwidth of the interference reduced.

For bandwidths of less than 100 kHz, the fluctuation of the discrete spectral lines from the sinc² envelope becomes significant. Line ‘b’ indicates the reduction in processing gain as the bandwidth reduces from 100 to 1 kHz when the C/A-code PSD is modelled as a series of discrete spectral lines with a maximum single line 8 dB above the sinc² envelope.

Line ‘c’ is the result of the interference bandwidth reducing to 100 Hz, assuming once again that the C/A-code PSD can be modelled as a single discrete spectral line 8dB above the sinc² envelope.

As the interfering signal bandwidth reduces below 100Hz the likelihood of the interference being aligned with a C/A-code spectral line is so small that no further

![Figure 3-2 Variation of Processing Gain as a function of Bandwidth](image-url)
A reduction in processing gain occurs, line ‘d’.

If the C/A-code spectral line conform to a sinc² envelop the processing gain would follow the Path a,e,f. A dotted line is shown in Fig 3-4 from the ‘b’ to ‘f’ line. This represents the processing gain that is most probable as the likelihood of the interference coinciding a high spectral line is as likely as it is with a low powered line. In a constantly changing dynamic situation for narrow band interference the relative frequencies of the satellite and
interference are constantly changing, providing a rational explanation for the above statement. RTCA SC-159 specified the minimum relative processing gain for narrow band interference to be -10 dB, corresponding to a bandwidth of 700 Hz.

The same logic and convolution processes can be used to analyse the effect of interference that is not centred at or near the GPS carrier. The results are shown in Fig 3-3. From the figures the noise the interference causes per unit Hz in the carrier tracking circuits can be derived. It is necessary to determine the centre frequency and bandwidth of the interference. Once the processing gain has been established from the graph the figure is subtracted from the total interference power at the input to the receiver. To calculate the resultant C/N0 the receiver’s own noise must be added and compared to the post correlation signal power. A plot of the Processing gain for GLONASS is given in Figure 3-4.

3.4. Interference and C/No

Most GPS receiver manufacturers calibrate their carrier-tracking loop in terms of C/N0 where N0 is the ambient noise level in the receiver. C/N0 can be derived theoretically from calculations of the signal and interference power at the antenna. However it is essential to take into consideration any difference in antenna gain that may exist between the satellite direct and the direction of the interference. Calculations of received post correlation carrier power, C, must include aircraft antenna gain which for the lowest elevation satellite usable is typically -4.5 dB. Allowance in the calculated carrier power must also be made for down conversion and correlation losses of approximately 2dB.

Noise power density N0 is the sum of the ambient receiver thermal noise power density, Nt, and the interference power density Ni. The theoretical carrier to noise ratio is given by:

\[
\frac{C}{N_0} = S_{FR} - L_A - \alpha - N_{oi}
\]

where,

- \(S_{FR}\) is the GPS signal power at the antenna port (dBW)
- \(N_{oi}\) is the sum of the interfering signal power in the carrier tracking loop bandwidth and receiver thermal noise power (201.5 dBW/Hz ) referenced to the antenna port (dBW)
- \(L_A\) is the loss (dB) due to IF filtering, analogue to digital conversion, correlation /modulation imperfection of the GPS signal and other miscellaneous losses e.g. RF component imperfections.
- \(\alpha\) is a loss due to the use of imperfect codes. This loss is more pronounced with CW interference (above the signal power) where the loss approaches 10 dB.

It is noted that ITU regulation (ITU-R) concerning spurious emissions from MSS terminals in the 1 610 - 1 66.5 MHz band into the GNSS band has effectively raised the receiver noise floor by approximately 1 dB to -200.5 dBW/Hz in the vaccinate of a transmitter. The effect is to limit the maximum C/No that can be achieved from the satellites. However in this analysis the MSS is not included.

Theoretical results for C/N0 in a carrier loop versus interfering power are plotted in Figure 3-5 for CW and wide-band interference. Losses assumed when plotting Fig 3-4 are based on the calculations shown in Table 2-1, but using a radiated satellite power of -157 dBW, which is equivalent to the current GPS signal with a 0 dBi antenna. The maximum C/No for a low elevation satellite is 38 dB-Hz. The C/No decrease by 3 dB as the interference noise reaches the receiver’s thermal noise power at approximately -140 dBW, thereafter the C/No falls rapidly and approximately linearly with increased interference power. For CW signals the receiver’s signal processing is more sensitive and -150 dBW is the 3 dB threshold.
If the specified GPS satellite power is used the maximum C/No is approximately 35.5 dB-Hz although the interference power to cause a fall of 3 dB is the same at -140 dBW for wide-band noise. For high elevation satellite maximum, where the antenna gain can be +2 dB, C/No values of 45 dB-Hz can be obtained. For non-aircraft receivers, lower receiver thermal noise powers are achievable and typical values can be as low as -204 dBW/Hz, resulting in C/No values of 48+ dB-Hz.

GLONASS will suffer a similar reduction in performance, however as shown in Table 2-1, due to the lower satellite powers of -161 dBW, the higher C/No values can not be achieved with aircraft antennas.

Effects of interference are therefore highly dependent on the gain of the antenna towards the GPS satellite and source of the interference.

![Figure 3-5 Theoretical GPS Post Correlation Interference Power to C/N0 (Low elevation GPS satellite with current radiated power)](image)

C/No values in excess of 39 dB-Hz can only be achieved by a combination of satellite power and higher antenna gains. Current GPS radiated powers are 3 dB above the specified values result in C/No of 38 dB-Hz. At higher elevation angles the aircraft antenna gain increases and higher C/No values can be achieved. A gain of greater than -2.5 dBi is difficult to achieve in aircraft antennas below approximately 25 degrees elevation, Fig 2-6 and [7]. Unavailability of satellites below an elevation of 25 degrees significantly affects availability of navigation and therefore the navigation accuracy due to the increased PDOP.

### 3.5 Summary - Tolerable Interference

Interference powers that can be tolerated by a receiver tracking the satellite signals to the accuracies required for CAT 1 operations are now reviewed. C/No values required to produce the measurement accuracies identified in Table 1-10 were derived in Section 2 and summarised in Table 2-2. Accuracies of 0.4 m 1σ require a C/No of 33.5 dB-Hz for GPS and 39 dB-Hz for GLONASS. A 0.22 m accuracy requires a C/No of 39.5 dB-Hz for GPS and 46 dB-Hz for GLONASS. It should be noted that the power budget, Table 2-1, for low elevation GPS satellites which are needed to maximise navigation accuracy, integrity from RAIM and
availability, produce a maximum C/No’s of 35 dB-Hz for GPS and 34 dB-Hz for GLONASS, at their specified power.

At the current GPS radiated power a maximum C/No of 38 to 39 dB-Hz is achievable for low elevation satellites, which is just sufficient to meet the requirement for the higher accuracy measurements. However only high elevation GLONASS can meet the lower accuracy requirement of 0.4 m 1σ. For low elevation satellites the maximum range error that can be achieved using conventional receiver techniques is 0.9 m 1σ.

Interference from MSS terminals has been omitted in the above values which when present at the assumed minimum separation distance of 100 ft increase the noise level No to -200.5 dBW/Hz reducing the C/No by 1 dB.

Although the required measurement accuracy was calculated using CAT 1 vertical accuracy requirements, the result is applicable to satellites in the horizontal plane as consistency in measurement accuracy is required if a high integrity is to be achieved.

Interference power that will cause harmful effects are difficult to define in absolute terms as C/No is the ratio of received satellite and interference powers, which for an aircraft are functions of the antenna gain towards the satellite and interferer.

<table>
<thead>
<tr>
<th>Source</th>
<th>Pseudorange Measurement Accuracy m 1σ</th>
<th>Required C/No dB-Hz (GPS)</th>
<th>Tolerable Wide-band Interference dBW (specified GPS)</th>
<th>Tolerable Wide-band Interference dBW (as is GPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-217 SCAT-1</td>
<td>0.4/0.5</td>
<td>33.5/32.5</td>
<td>-144/-142</td>
<td>-139/-137</td>
</tr>
<tr>
<td>ESA EGNOS [16]</td>
<td>0.4</td>
<td>33.5</td>
<td>-144</td>
<td>-139</td>
</tr>
<tr>
<td>Derived from ICAO RNP</td>
<td>0.26</td>
<td>38</td>
<td>Not Achievable from satellites below approximately 40 degrees elevation</td>
<td>-150</td>
</tr>
<tr>
<td>ICAO GBAS SARPs</td>
<td>0.23</td>
<td>39</td>
<td>&quot;</td>
<td>Not achievable for satellites below 10 degrees *</td>
</tr>
<tr>
<td>RAIM Study WAAS [15]</td>
<td>0.22</td>
<td>39.5</td>
<td>&quot;</td>
<td>Not available for satellites below 15 degrees*</td>
</tr>
</tbody>
</table>

* assumes standard aircraft antenna gains

Table 3-1 C/No v Interference Level (Low Elevation GPS)

Calculation of the minimum interference powers that would cause the tracking accuracy of a GPS receiver to fall below that required for the range of accuracies identified in Section 1 are produced in Table 3-1. Table 3-1 indicates the tolerable interference power at which the C/No is degraded below that consistent with the required accuracy values discussed in Sections 1 and 2. As can be observed for all but the lowest accuracy value of 0.4 m the C/No is only achieved if the GPS satellites continue to radiate at their current powers which is 4 dB above specified minimum levels. Higher accuracies are available only when the satellites above approximately 25 degrees are used due to the gains standard aircraft antennas.

Interference powers of -150 dBW for noise and -160 dBW for CW signals have a detrimental effect on the receiver performance.
4. GNSS RECEIVER EVALUATION

Tests were performed on a number of GPS and GLONASS receivers to evaluate their performance under interference conditions.

4.1. 3S Navigation R100/40 GNSS receiver

3S Navigation R100/40 GNSS receiver system layout is described in Figure 4-1. The R-100/40 is a L1, L2 twelve channel P-Code GLONASS receiver together with a further twelve channels of C/A code GPS/GLONASS at L1. The system is supplied with an active antenna system, RF/IF unit and an industrial dual PC that performs the channel tracking and navigation functions.

The output from the active antenna is connected to the input of the RF unit via 45m of low loss coaxial cable. The RF unit down-converts and splits the incoming signals to baseband for each of the L1 and L2 GLONASS and GPS frequency bands (note that L2 GPS is not available). These outputs are then sampled with A/D converters within the RF unit and the resulting digital signals are sent via cabling to DSP cards in the PC system. The DSP cards perform the channel tracking and demodulation of the navigation messages for each navigation satellite signal.

The first of the PC processors in the dual PC system can only process GLONASS signals. Each of the twelve channels available can be assigned to track GLONASS on L1 or L2 using C/A or P-Code. The second processor handles twelve channels but is L1 C/A code only. Each of these channels can be assigned to track a single GPS or GLONASS satellite navigation signal.

![Figure 4-1 3S Navigation R100/40 GNSS Receiver System](image-url)

3S Navigation R100/40 GNSS receiver architecture is given in Figure 4-2. The receiver The RF unit employs a single RF synthesiser to generate the mixer frequencies for both GPS and GLONASS. The RF unit splits the incoming signal into L1 and L2 paths. Each path contains one mixer, a splitter and further band-pass filters to isolate GPS and GLONASS. Note that on the current design, the L2 path does not contain any circuitry for GPS.
The filtered signals are then sent to I and Q phase analogue to digital converts. The digital outputs from these converters feed the PC unit where channel demodulation (channel tracking) takes place.

The R-100/40 GPS channel tracking system is C/A code only, so the bandwidth of the RF front end and intermediate frequency stages need only be 2MHz.

For GLONASS, the R-1000/40 system is able to receive all 24 channels of P-Code in a given band (L1 or L2). The RF unit therefore has band-pass filters 20MHz wide in the GLONASS path. The RF design of the first band-pass filter for GLONASS does not have the same roll off characteristics compared to the band-pass filter fitted for GPS. As such, the GLONASS section of the receiver is more susceptible to out of band interference compared to GPS. This in practice means the R-100/40 receiver is prone to GLONASS interference from transmissions in the MSS band.

![3S Navigation R100/40 GNSS Receiver Architecture](image)

**Figure 4-2 3S Navigation R100/40 GNSS Receiver Architecture**
The R-100/40 receiver was tested using live satellites and a signal generator as the interference source. A Northern Telecom STR2760/01 GPS simulator was used to verify signal power levels used in the tests. Interference was injected into the band 1550MHz to 1625MHz for both GPS and GLONASS. The receiver performance was recorded for both CW and wide-band (1MHz) interference sources. Figs 4-3 and 4-4 show the absolute antenna J/S required to reduce the receivers C/No values from 40 to 30 dB-Hz.
4.2. **GEC Semiconductors GPS Builder Card**

Tests were performed using a ‘GEC GPS builder card’ to examine the processing gain loss caused by a carrier wave interferer tuned to a significant spectral line of a CA code. The GEC Builder Card is a 12 channel GPS receiver. It possesses a 2 Bit A/D, a tau-dithered correlator and an early-late power code discriminator.

As the spectrum of the interfering signal becomes narrower, the line spectra of the ranging code has an increasing effect resulting in increased processing loss. For interference with bandwidths of less than 700Hz only one line on the C/A code spectrum is involved. However, for the effect of CW to be observable the spectral line needs to be narrower than 100Hz. Numerical analysis indicates the loss against wide band noise is approximately 10 dB.

To assess the performance of a GPS receiver a CW signal was slowly swept over a frequency band that included significant spectral lines. The results are shown in Figure 4-5 to Figure 4-8. Figure 4-5 illustrates the susceptibility of the C/A-code when a carrier wave interfering signal at an I/S of 18 dB was swept at a rate of 50 Hz/s across the GPS frequency band. Carrier lock was lost when the C/NT falls below 28 dB-Hz, which is observed when the interfering signal was tuned to the 163 and 227 kHz sidebands.

![Figure 4-5](image)

**Figure 4-5** *Carrier Frequency Sweep 50 Hz/s 18 I/S*

Tests were repeated with a sweep rate of 4 Hz/s and with interfering signals at I/S values of 18,15 and 12 dB (Figs 6-6, 6-7 and 6-8). Carrier lock was lost with I/S values of 18 and 15, but not with an I/S value of 12. Lock was just lost with an I/S of 15 dB, a degradation of approximately 15 dB, over broadband noise or if the CW interference were not tuned to the 163 kHz PRN#6 C/A-code spectral line. The results indicate a susceptibility of 5 dB above the 10 dB theoretical value.
Figure 4-6 Carrier Frequency Sweep 4 Hz/s 18 I/S

Figure 4-7 Carrier Frequency Sweep 4 Hz/s 15 I/S
4.3. NAVSTAR XR5

The NAVSTAR XR5 receiver was tested using a Northern Telecom STR2760/01 GPS simulator and a signal generator as the interference source. Interference was injected into the band 1550MHz to 1625MHz. Figure 4-9 shows the absolute antenna J/S required to reduce the C/No to 30 dB form a variety of pre-interference levels. The results indicate that a J/S of approximately 30 dB results in the C/No being reduced to 30 dB-Hz.

Tests were also performed to examine the effect of interference on the ability to perform post-processed carrier phase ambiguity resolution. Figs 4-10 to 4-15 show carrier phase noise, code tracking noise and ambiguity drift as calculated by the NAVSTAR Postpro 2cm software. The ambiguity drift indicates the speed at which the software is able to converge onto the correct navigation solution. Figs 4-10 to 4-12 were produced when no interference was present and a C/No of 40 dB-Hz. Figure 4-13 to Figure 4-16 were obtained when a wide-band jammer was applied producing a J/S of 20 dB. With this low level of jamming, slight increases in carrier and code tracking performance is visible as is a slight decrease in the ambiguity convergence.
Figure 4-9 Wide Band Interference Rejection

Figure 4-10 Carrier Phase Noise, No Interference
Figure 4-11 CA Code, No Interference

Figure 4-12 Ambiguity Drift, No Interference

Figure 4-13 Carrier Phase Noise, 20 dB J/S
4.4. **DASA ASN-22 GPS/GLONASS Receiver**

Interference susceptibility results, obtained by DASA, of the ASN-22 GPS GLONASS receiver are given in Figures 4-18 and Fig. 4-16. Results from the testing of a revised RF section of the ASN-22 receiver are given in Figure 4-18.
Figure 4-16 Interference susceptibility of the GPS path with respect to Carrier to Noise ratio C/No

Figure 4-17 Interference Susceptibility of the GPS with respect to Carrier-to-Noise ratio C/No
4.5. Summary

Overall the susceptibility to interference of the GPS and GLONASS receivers are similar and in agreement with theoretical predictions. A CW signal causes significant interference at a power into the receiver of -130 dBW or an I/S of 25 to 30 dB. For broadband the I/S increases by approximately 5 to 10 dB depending on how the receiver manufacturer has implemented his RF to IF conversion and correlator architectures.

Figure 4-18 Interference susceptibility of GLONASS reception with respect to S/N of the 4.31 MHz intermediate frequency
5. THREATS TO GNSS

A variety of electronic and communications devices were examined to evaluate the potential to cause harmful interference into GNSS.

5.1. Mobile Satellite Services

5.1.1. Interference of MSS 1 559 - 1 567 MHz into GPS Tracking

In 1997 INMARSAT made an application through the UK Radio Regulation Agency for the use of 1 559 - 1 567 MHz for the earth to space link of a mobile satellite communications service. Few details of the INMARSAT signal structure are available. A total power of -112 dBW/m²/MHz was specified, with 144 kbit channels. The power level was stated as an absolute maximum for in-band radiation.

Post correlator noise density convolution of received interference spectral density \( I(f) \) with the GPS C/A-code may be derived using the procedure outlined in the previous sections.

Interference Power for C/A code case \( I(f) = -112 \) dB(W/m²/MHz) \( \sim -136.4 \) dBW/MHz

Therefore the total MSS power in the 8 MHz band from 1559 to 1567 MHz represents an I/S (-136.4 + 10 log 8 +160) to the C/A-code minimum signal power of 32.6 dB.

The interference power can be calculated by the convolution of the noise and the GPS signals.

\[
\text{Noi} = 10^{-19.7} \int_{8.42 \text{MHz}}^{16.42 \text{MHz}} \text{Sgnss}(f) df
\]

Correlation with C/A-code: \( \text{Noi} = 0.0031 \times 10^{-19.7} = -221.8 \) dBW/Hz

With an ambient noise power of -201.5 dBW/Hz the MSS transmissions result in a total thermal noise + interference powers of -201.45 dBW/Hz for C/A-code

There does not appears to be a problem with this transmission, however if the transmissions are CW, and INMARSAT are known to use a CW signal to equalise their channels the noise power would rise by 20 dB, and the overall post correlator noise would rise to -198 dBW/Hz, a significant increase. Tests were performed on several receivers using the GPS RF environment simulator at Farnborough. Little effect on GPS operation was observed, except for a code-less tracking receiver.

A typical code-less tracking receiver (Ashtech Z12) used extensively the surveying community was tested using precisely controlled code and interference powers.

<table>
<thead>
<tr>
<th>Ashtech Z12 Tracking results</th>
<th>C/No (dB-Hz)</th>
<th>C/No (dB-Hz)</th>
<th>C/No (dB-Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No MSS Tx</td>
<td>MSS @ -113 dB (W/m²/MHz)</td>
<td>MSS @ -108 dB (W/m²/MHz)</td>
</tr>
<tr>
<td>C/A-code track</td>
<td>45.1</td>
<td>45.1</td>
<td>45.0</td>
</tr>
<tr>
<td>Code-less P(Y)-code</td>
<td>28.8</td>
<td>27.1</td>
<td>26.1</td>
</tr>
</tbody>
</table>

**Table 5-1 Receiver Test Results to MSS Interference**
The results of this test may be summarised as follows:

- the degradation in code-less tracking of $1.5 \, \text{dHz}^{-1}$ exceeded the theoretical value of approximately $0.26 \, \text{dHz}$;
- it was apparent from the tests that at an I/S of $30 \, \text{dB}$ code-less lock was slow to obtain;
- at an I/S of $33 \, \text{dB}$, $2 \, \text{dHz}$ loss in C/No was noted and it was difficult (very slow) to obtain code-less lock;
- at the declared MSS pfd (-112) there is an observed loss of $1.8 \, \text{dB}$ in tracking power. Although the simulator tests indicated a C/No of $27 \, \text{dHz}$ the tests were not worst case, antenna and down-conversion losses were minimal.

The UK Radio Regulation Agency reported:

It is believed that the effects noted above are the result of the receiver's sampling, increasing the losses above the theoretical value. However this should be confirmed by further tests since the degradation is calculated from $(I_o+No)/No$. In addition, more tests are needed on a larger sample of GPS receivers with the differences in architecture identified earlier. Test arrangements and measurement uncertainties should be developed and reported.

5.1.2. Co-sharing of the $1561 \pm 2 \, \text{MHz}$ band with E-NSS-1.

ESA have made an application for the registration of the band $1561 \pm 2 \, \text{MHz}$ for a European satellite navigation system E-NSS-1. Powers from E-NSS-1 will be approximately equal, to GPS and GLONASS at $-160 \, \text{dBW}$ from a $0 \, \text{dBic}$ antenna on the earth's surface.

Assuming the MSS signal is wide-band and noise-like the power in the E-NSS-1 bandwidth is $-112 \, \text{dB}(W/m^2/\text{MHz})$, which results in $-136.4 \, \text{dBW/MHz}$ from the antenna and a total power of $-130.4 \, \text{dBW}$ in the $4 \, \text{MHz}$ bandwidth. Typically an interference signal power of $-140.5 \, \text{dBW}$ for a $1 \, \text{MHz}$ bandwidth signal, in-band to the GPS C/A-code is at the point of degrading GPS operations. E-NSS-1 with a proposed code chip rate of $2 \, \text{MHz}$ should have a $3 \, \text{dB}$ advantage against wide-band interference over GPS. The graph for GPS may therefore be easily

![Graph](image-url)

**Figure 5-1** Effects of In-band Interference on C/No for GPS C/A-code
(Low Elevation GPS Satellite with Specified Radiated Power)
interpreted for E-NSS-1 by adding 3 dB.

Assuming the MSS transmissions are noise like and contain no narrow band or CW components they would cause significant degradation to an E-NSS-1 receiver during acquisition of the satellite signal. The noise power in the 4 MHz band is -131 dBW. This power produces a Noise to post correlation carrier (C_{pc}) of 29 dB assuming a -160 dBW received signal power. If low elevation satellites and a margin for down-conversion and correlation loss are included (-166 dBW into the correlator) the N/C_{pc} ratios is 35 dB. Typically the maximum Acquisition can not be achieved at such power levels. Typically for GPS we specify 24 dB N/S ratio.

Results of tests that simulated the INMARSAT transmissions with noise and the E-NSS-1 signals with GPS C/A-codes, indicated that at a 30 dB N/S ratio the receiver did not achieve code lock within 60 seconds.

5.1.3. Mobile Satellite Services in the 1 610 to 1 626.5 MHz Band

The band 1 610 to 1 626.5 MHz was granted a primary allocation to MSS. Out of band spurious emissions from the MSS transmitters particularly the Code Division Multiple Access (CDMA) systems are a cause of potential interference. An alternative Time Division Multi Access (TDMA) system causes fewer problems. RTCA [7] spent significant time debating the issue with the MSS manufacturers without a clear understanding of each other’s position being formed.

However the CDMA and TDMA were also in dispute between themselves over the out of band interference levels, as the CMDA systems were interfering with the TDMA. It is believed the CDMA gave up one of its allocated channels to prevent interference into TDMA. The closest CDMA frequency to GNSS is allocated to Globalstar at 1 610.73 MHz with a maximum power of 5 dBW (nominally 33 dBm EIRP), although a -2 dBW ( 26 dBm EIRP) power conservation mode is usually used.

At the higher power output the power amplifier spurious output is -50 dBW/MHz at the centre of the top GLONASS frequency (after 2005). The problem for GLONASS is providing sufficient rejection against the out of band MSS carrier. In order to prevent saturation of the A/D converter approximately 100 dB of attenuation are required, assuming at least 3m separation of MSS terminal and GLONASS receiver. Assuming the post 2005 frequency allocation and the top frequency for navigation is 1 604.25 MHz and allowing 1 MHz for a pass band above this frequency, the 100 dB must be provided in 5.5 MHz. Classical filtering techniques are unable to provide this attenuation with a size and weight suitable for a mobile GNSS receiver. However it is claimed the CSF - CEPE 120.000 BL 2M, quartz filters can provide 80 dBs of rejection in 1.75 MHz.

Provided there are no other problems with the filter, e.g. non linear phase in the pass-band, the filter should provide satisfactory protection for the two GLONASS engineering channels at 1 604.812 and 1 605.375 MHz. Protection would also be provided for the P-code GLONASS up to 1 604.25 MHz.

Out of band spurious emissions have been agreed at -70 dBW/MHz (-130 dBW/Hz) for wide-band signals and -80 dBW/MHz for CW signals with the US frequency management agency. Some sample calculation of the effect of this radiated power is provided below. However the predominant factor in all the scenarios considered is the range between the MSS terminal and the GNSS antenna. The effect of range is considered first.
5.1.4. Range of Effective Interference

In order to assess the threat of interference, the fundamental physical laws that define the transmission of electromagnetic radiation must be considered. The incident power at range $R$ from a radiating source is given by the inverse-square law.

$$P_R = \frac{P_T G_R G_T A_p}{(4\pi R^2/\lambda)^2} \quad (5-1)$$

where:

- $P_R$ = Noise power from the receiving antenna’s RF output
- $P_T$ = Power into transmitter (interferer) antenna
- $G_R$ = Receiving antenna gain towards interference source
- $G_T$ = Transmission antenna gain towards GNSS receiver
- $R$ = Distance between transmitting and receiving antenna.
- $\lambda$ = Wavelength
- $A_p$ = Polarisation factor between transmitting and receiving antennas

![Figure 5-2 Path loss](image)

Equation (1) may be expressed in decibel notation and a term included for rejection of out of band frequencies by the RF and IF filters, equation 2.

$$P_R = P_T + G_R + G_T + A_p + F_R - 20\log 4\pi - 20\log R \quad (5-2)$$

Where:

- $F_R$ = Attenuation provided by receiver filter and signal processing, dB
- Power is expressed in watts relative to 1 watt (0dBW).

A 0 dBi GPS antenna’s gain is equivalent to a -25.4 dB path loss (dBW/m² → dBW).
Interference range can therefore be seen to be a function of the transmitting antenna gain, the receiving antenna gain in the direction of the interference source and the attenuation provided by receiver filtering and the processing gain of the GNSS signal.

![Figure 5-3 Path loss of Interference signals](image)

<table>
<thead>
<tr>
<th></th>
<th>Current GPS Satellite power 0 dBi antenna</th>
<th>Specified GPS Satellite power 0 dBi antenna</th>
<th>Specified GPS Satellite Power -4.5 dBi antenna (Worst case Situation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Received Power</td>
<td>dBW</td>
<td>-156</td>
<td>-160</td>
</tr>
<tr>
<td>Receiver Antenna Gain</td>
<td>dBic</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feeder and correlation losses</td>
<td>dBi</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Post correlation carrier power</td>
<td>dBW</td>
<td>-158</td>
<td>-162</td>
</tr>
<tr>
<td>Receiver Thermal Noise Power</td>
<td>dBWHz⁻¹</td>
<td>-201.5</td>
<td>-201.5</td>
</tr>
<tr>
<td>Antenna Gain towards MSS</td>
<td>dB</td>
<td>0</td>
<td>-15</td>
</tr>
<tr>
<td>Minimum Range to achieve required C/No (33 dB-Hz)</td>
<td>m</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Minimum Range to achieve required C/No (35 dB-Hz)</td>
<td>m</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Minimum Range to achieve required C/No (41 dB-Hz)</td>
<td>m</td>
<td>41</td>
<td>Not Achievable (Thermal noise limits C/No to 39 dB-Hz)</td>
</tr>
</tbody>
</table>

Table 5-2 Signal Processing Margins GPS to MSS
5.1.5. MSS Scenarios

The effect of an MSS transmission in the band 1610 - 1626.6 MHz with spurious emissions at the -70 dBW/MHz level are analysed below. Three interference cases are discussed and the range at which C/No values of 33 dB-Hz and 41 dB-Hz derived.

1. The current received satellite power i.e. -156 dBW using a 0 dBi antenna to the GPS and to the MSS transmitter.
2. Using the specified satellite power i.e. -160 dBW with a 0 dBi antenna to the GPS and a -15 dBi antenna to the MSS, i.e. the MSS is below the aircraft.
3. Using the specified satellite power, i.e. -160 dBW with a -4.5 dBi antenna gain towards the GPS satellite and a -10 dBi antenna gain towards the MSS, i.e.. a low elevation GPS with the MSS just below the aircraft’s azimuth plane.

As can be seen from Table 5-2, the MSS terminal with a -70 dBW/MHz spurious emissions has an effect on a GPS receiver out to approximately 50 m. After 50 m the noise is less than the thermal noise of the GPS receiver. In the US the debate over MSS emissions resulted in RTCA, the FAA and ultimately the ITU agreeing that the affective noise floor of a GPS receiver could be increased to -200.5 dBW/Hz by the MSS transmissions. However if the emissions from the MSS terminal are CW signals at the same power then the minimum range must be increased by a factor of 3.3.

5.1.6. Aeronautical Satcom

The Racal/Honeywell MCS-3000/6000 SATCOM system is an airborne SATCOMS terminal equipment designed to transmit digital communication data at L band using INMARSAT. The equipment can select multiple frequency transmissions in 2.5kHz steps between 1626.5075 to 1660.4925 MHz at 0.6 kbps or 1626.5175 to 1660.4825 MHz at 21.0 kbps. The 0.6 kbps signals are modulated onto a carrier using Bi-Phase Shift Keying (BPSK) and the 21.0 kbps signals are modulated using Quad-Phase Shift Keying (QPSK). The total power emitted from the airborne transmitter is specified as 25.5dBW that is 6dB above the requirement for INMARSAT 3.

Output power can be controlled by the HPA over an 18dB range in 1-dB steps. The power level changes in response to commands from the INMARSAT control segment. This can happen every ten seconds. The control segment should ensure no commands are sent to the airborne equipment which allow it to exceed the transmitted 25.5dB maximum. The
5.1.7. MC3000/6000 System tests

The minimum attenuation of spurious signals and intermodulation products from the output of the MC3000/6000 devices is specified relative to the transmitted power as follows:-

*The maximum power of other unwanted products transmitted in the GNSS band from the output of the transmitter must be below -55dBc/MHz. The single channel MCS-3000/6000 system achieves -65dBc/MHz whereas the multi-channel system achieves -62dBc/MHz. No account is taken for any intermodulation products that can be produced in the antenna system. The effect of any non-linearities (and hence intermodulation products) as a result of these transmissions arriving at a GPS/GLONASS receiver’s antenna and RF stages will degrade GNSS performance, Fig 5-3.*

Currently the SATCOM band is divided into sub-bands for Maritime Mobile, Land Mobile, Mobile Satellite, Aeronautical Mobile. At the 1997 WRC the band was redesigned as generic with the band 1 626.5 1 660.5 MHz open to all users. Aeronautical systems apply an algorithm to protect GNSS from intermodulation products of the transmitted frequencies. With the opening up of the band such algorithms become more difficult to apply and may not be applied at all be other users. the potential for interference has risen significantly.

![Figure 5-5 Satellite Communications Terminal Noise Specification](image)

5.2. Television Broadcast Interference

Second and third harmonics of commercial television broadcasts can occur in the GNSS band. In the UK, television broadcasts occur in the band 471.25MHz to 847.25MHz. The band is split into 48 channels and the channels are assigned to transmitters by the Independent Television Commission (ITC). Each of the channels is sub-divided for vision and sound. The third harmonic of channel 27’s sound carrier (at 525.25MHz) is
1575.75MHz. A transmitter broadcasting 500kW on channel 27 is located at Rowridge on the Isle of Wight. A time-averaged plot of the audio signal from the Rowridge transmitter at 200m is given in Figure 5-6.

Spurious emissions of the television transmitter are required to be attenuated by at least 60 dB. If the transmitter just met the requirement and a third harmonic was broadcast with an ERP of 0.5 W, a GPS receiver would be jammed for several kilometres from the interfering source.

Considering a GPS receiver positioned d meters from the Rowridge transmitter, the power received by the GPS receiver can be expressed as:

\[ J = ERP - 20\log\left(\frac{4\pi d}{\lambda}\right) + G \]

where the GPS receiver antenna gain can be assumed to be -3 dBi.

If the receiver is assumed to be jammed with a J/S of 30 dB, and the received GPS signal power assumed to be -160 dBW, then the receiver would be jammed at distances of 24 km or less from the Rowridge transmitter. There is an economic incentive for television broadcasters to reduce the power of spurious transmissions as they have a detrimental effect on both picture quality and reception area. If therefore, the spurious transmission was attenuated by 100 dB, then the jamming radius d is reduced to just 239 m.

Tests on the transmitter output at Rowridge show that better than 80 dB of attenuation is achieved at the third harmonic and a Garmin GPS receiver operated at the recording site showed no signs of impaired performance.
GNSS interference flight trials conducted by DERA in 1995 over the UK and Europe showed a potential problem with TV broadcasts from some transmitters located in France and Italy. Detected power levels at the aircraft were recorded at -128dBW, well above the noise floor of the recording equipment. No such interference was observed during a similar flight trial over the UK.

With the introduction of digital television, the incentive for broadcasters to attenuate spurious transmissions by more than 60 dB may not be as great as for analogue broadcasts, because there is little picture quality gain to obtained from a purer digital transmission.

![Figure 5-7 Spurious emissions from Nokia portable telephone](image)

5.3. Mobile telephones

Mobile telephones operating on the GSM 1800 network rely on wide-band transmissions centred at 1.8GHz. A Nokia mobile phone connected to the Orange network was tested for signals transmitted in the GNSS band. A spurious signal of -126dBW was detected at 1610MHz. Signals generated in the GPS band were limited to -154dBW.

The unit under test was new and both the alignment and the RF output filter fitted to the phone have not had enough time to degrade as would be the case with other older units. Mobile telephones that have been dropped or incorrectly serviced could potentially produce more in band GNSS power. It is therefore possible that operation of this terminal close to GNSS (especially GLONASS) equipment could cause a degradation in navigation performance.

5.4. Laptop PC

The processors fitted to modern desktop and laptop PCs rely on fast processors clocked at well over 100MHz. Spurious emissions from such devices normally cover a wide spectrum because the basic CPU clock speed is not the only source of RF signal within the PC’s design. Video boards, CD-ROM players and even floppy disk drives all emit RF energy during operation.
Tests were conducted on a Panasonic CF-25 Laptop PC to determine the levels of RF emitted in the GNSS band. The testing included the operation of the internal floppy disk drive.

![Spurious emissions from Panasonic CF-25 laptop PC](image)

**Figure 5-8 Spurious emissions from Panasonic CF-25 laptop PC**

The plots show CW signals detected at 1575 MHz of -145.3dBW and another at 1580 of -149.7dBW. There is also a peak detected at 1600MHz of -145.3dBW. Operation of this equipment with an insecure case or other means of increasing the effective radiated power could cause problems with any GNSS equipment near by.

### 5.5. Portable CD players

The following plots show power levels detected at 1 metre in the GNSS band from a Sony Discman D-231 during the playback of a CD. Portable CD players have long been know to cause possible interference to aircraft VHF systems during flight and their use during takeoff and landing is forbidden by the CAA/FAA.
5.6. Summary

A number of sources of noise into the GPS and GLONASS bands have been identified. Apart from the MSS powers from the equipment tested were too low to cause harmful effects in a receiver. However it is known that the spurious powers from identical devices can vary significantly. This effect is the subject of an investigation by Boeing and the FAA in the US. It is recommended that as GPS is introduced into the aircraft fleet, the situation is monitored to ensure that any interference caused by the use of portable electrical equipment on aircraft is identified.

Figure 5-9 Spurious emissions from Sony D-231 portable CD player
6. CONCLUSIONS AND RECOMMENDATIONS

In order to protect the GNSS frequency band it is necessary to specify a receiver frequency and power mask that define the onset of harmful interference. The problem is, that there is no agreed definitive GNSS receiver architecture or specification that can be use to define receiver susceptibility. In this report we set out to establish what constitutes harmful interference to an optimally designed receiver and to draw up such a mask.

Harmful interference is assessed as:

a. reduction in signal to noise to a level where the intended operation can not be completed due to the uncertainty of the pseudorange and range rate measurements

b. increase in the bit error rate (BER) of the navigation message

c. increase in undetected cycle slips

The results from sections 2 and 3 indicate the (a) is the most sensitive component if the error budgets for CAT 1 using WAAS/EGNOS or a LAAS are to be met. Table 6-1 provides a summary of the required measurement accuracies, carrier-to-noise ratio and maximum tolerable interference levels for CAT 1 precision approach and landing operations derived from figures published by ICAO and RTCA. Figures are given for wide-band interference into GPS using the specified power and the ‘as is’ radiated power.

<table>
<thead>
<tr>
<th>Source</th>
<th>Pseudorange Measurement Accuracy (m_{1\sigma})</th>
<th>Required C/No dB-Hz (GPS)</th>
<th>Tolerable Wide-band Interference dBW (specified GPS)</th>
<th>Tolerable Wide-band Interference dBW (as is GPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-217 SCAT-1</td>
<td>0.4/0.5</td>
<td>33.5/32.5</td>
<td>-144/-142</td>
<td>-139/-137</td>
</tr>
<tr>
<td>ESA EGNOS [16]</td>
<td>0.4</td>
<td>33.5</td>
<td>-144</td>
<td>-139</td>
</tr>
<tr>
<td>Derived from ICAO RNP</td>
<td>0.26</td>
<td>38</td>
<td>Not Achievable from satellites below approximately 40 degrees elevation</td>
<td>-150</td>
</tr>
<tr>
<td>ICAO GBAS SARPs</td>
<td>0.23</td>
<td>39</td>
<td>&quot;</td>
<td>Not achievable for satellites below 10 degrees *</td>
</tr>
<tr>
<td>RAIM Study WAAS [15]</td>
<td>0.22</td>
<td>39.5</td>
<td>&quot;</td>
<td>Not available for satellites below 15 degrees*</td>
</tr>
</tbody>
</table>

*Table 6-1 Summary of Interference Tolerance for GPS*
It is observed from the analysis that it is only because the current GPS satellites are radiating at a higher power than the specified minimum that the accuracies required by ICAO and RTCA can be met for low elevation satellites. Accuracy values at specific C/No values for GLONASS are significantly worse due to the effect of the longer code phase. The maximum accuracy that can be achieved using conventional receiver technology for GLONASS is 0.9 m $\sigma$, well below that required for CAT 1 operations.

The level of interference that results in harmful degradation for GPS is -150 dBW for noise and as low as -160 dBW for CW signals. CW signals as low as -145 dBW were found to unlock carrier tracking loops in laboratory tests. Due to the variation in the sidebands of the GPS C/A-code power spectrum the CW power level that generates harmful interference can vary by up to 10 dB. The same effect does not occur in GLONASS due to the uniformity in the sidebands of the power spectrum.

Concessions already given to Mobile Satellite Systems for communication terminals in the 1610 to 1626.5 MHz band allowing a spurious power emission in the GPS and GLONASS bands of -70 dBW/MHz. These transmissions are a potential problem, which is avoided only if separation distances greater than 150 m are maintained. Results for GLONASS are similar however the proximity of the MSS 1 610 - 1 626.5 MHz band to the top of the GLONASS band means that additional filters are required in the IF down-conversion chain that will add significantly to the costs. The current DASA and 3S receivers tested in the work would both suffer significant degradation from MSS transmissions.

The proposed INMARSAT MSS would cause unacceptable interference into ESA's E-NSS-1. The INMARSAT power density of -197.6 dBW/Hz requires a E-NSS-1 carrier power at the receiver's input of -162 dBW to acquire the signal and a carrier power of -155.6 dBW to track the signal at the C/No required to achieve measurement accuracy sufficient for CAT 1 operations.
It is recommended that the members of EUROCONTROL take these matters up with their respective radio regulation or frequency management agencies, to represent the requirements of aviation at national, European and World meetings. The interference susceptibility as shown in Fig 6-1 can be used as the bases for GPS protection. A protection mask for GLONASS can be produced by using Fig 6-1 at each satellite frequency. At the ICAO GNSSP meeting in March 1998 the US presented proposals for a LAAS that used a receiver employing carrier smoothing that claimed significant improvements in tracking accuracy. It is recommended that the susceptibility of this type of receiver to interference is assessed.

Several techniques are appearing for mitigation of interference it is recommended that these are assessed to investigate their ability to remove harmful interference.

Radiated power into the GPS and GLONASS bands from portable electrical equipment was not found to be a problem from the equipment tested. However it is known that the power in radiated spurious signals can vary significantly. As GNSS is introduced into the aircraft fleets, it is recommended the situation is monitored to ensure that any interference caused by the use of portable electrical equipment on aircraft is identified.
7. **ABBREVIATIONS AND GLOSSARY**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DRMS</td>
<td>Two Dimensional RMS</td>
</tr>
<tr>
<td>AEEC</td>
<td>Airlines Electronic Equipment Committee</td>
</tr>
<tr>
<td>AMSC</td>
<td>American Mobile Satellite Corps</td>
</tr>
<tr>
<td>ARINC</td>
<td>Aeronautical Radio Incorporated</td>
</tr>
<tr>
<td>ARS</td>
<td>Aeronautical Radio-Navigation Services</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>AWOP A</td>
<td>All Weather Operations Panel Sub-group A</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>C/A code</td>
<td>GPS Coarse Acquisition Code</td>
</tr>
<tr>
<td>CAA</td>
<td>Civil Aviation Authority</td>
</tr>
<tr>
<td>CCIR</td>
<td>International Committee on Radio</td>
</tr>
<tr>
<td>C/No</td>
<td>Carrier to Noise</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBi</td>
<td>Decibel Isotropic</td>
</tr>
<tr>
<td>dBc</td>
<td>Decibels relative to the carrier wave frequency</td>
</tr>
<tr>
<td>dBm</td>
<td>dB Relative to 1 mW</td>
</tr>
<tr>
<td>dBW</td>
<td>Watts (in units of decibels)</td>
</tr>
<tr>
<td>DRMS</td>
<td>Root Mean Square of Horizontal Accuracy</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential GPS</td>
</tr>
<tr>
<td>DLL</td>
<td>Delay Lock Loop</td>
</tr>
<tr>
<td>DPSK</td>
<td>Differential Phase Shift Keying</td>
</tr>
<tr>
<td>DERA</td>
<td>Defence Evaluation and Research Agency</td>
</tr>
<tr>
<td>D/U</td>
<td>Desired to Undesired Signal Ratio</td>
</tr>
<tr>
<td>EBU</td>
<td>European Broadcasting Union</td>
</tr>
<tr>
<td>EGNOS</td>
<td>European Global Navigation Overlay System</td>
</tr>
<tr>
<td>EIRP</td>
<td>Effective Isotropic Radiated Power</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EUROCAE</td>
<td>European Organisation for Civil Aviation Equipment</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Authority</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Centre</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary Orbit</td>
</tr>
<tr>
<td>GES</td>
<td>Ground Earth Stations</td>
</tr>
<tr>
<td>GLOBALSTAR</td>
<td>Low Earth Orbit Satellite System made by Qualcomm/Lorcal</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Russian Navigation Satellite System</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HIPERLAN</td>
<td>High Performance Radio Local Area Network</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organisation</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical Engineers</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IFL</td>
<td>International Frequency List</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>INS</td>
<td>Integrated Navigation System</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbiting Satellite</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>METS</td>
<td>Mobile Earth Terminals</td>
</tr>
<tr>
<td>MOPS</td>
<td>Minimum Operational Performance Standard</td>
</tr>
<tr>
<td>MSS</td>
<td>Mobile Satellite System</td>
</tr>
<tr>
<td>MOU</td>
<td>Memorandum of Understanding</td>
</tr>
<tr>
<td>NATS</td>
<td>National Air Traffic Service</td>
</tr>
<tr>
<td>NM</td>
<td>Nautical Mile</td>
</tr>
<tr>
<td>PPS</td>
<td>Precise Positioning Service (GPS)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>PR</td>
<td>Protection Radio</td>
</tr>
<tr>
<td>PL</td>
<td>Pseudolite</td>
</tr>
<tr>
<td>R&amp;O</td>
<td>Report and order</td>
</tr>
<tr>
<td>RAIM</td>
<td>Receiver Autonomous Integrity Monitoring</td>
</tr>
<tr>
<td>RDSS</td>
<td>Radio-Determination Satellite Service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>RNP</td>
<td>Required Navigation Performance</td>
</tr>
<tr>
<td>RR</td>
<td>Radio Regulation</td>
</tr>
<tr>
<td>RTCA</td>
<td>Radio Technical Commission for Aeronautics</td>
</tr>
<tr>
<td>SA</td>
<td>Selective Availability</td>
</tr>
<tr>
<td>SARPs</td>
<td>Standards and Recommended Procedures</td>
</tr>
<tr>
<td>SATCOM</td>
<td>Satellite Communications</td>
</tr>
<tr>
<td>SATNAV</td>
<td>Satellite Navigation</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SNS</td>
<td>Satellite Navigation Services</td>
</tr>
<tr>
<td>SPS</td>
<td>Standard Positioning Service</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitter</td>
</tr>
<tr>
<td>US DoD</td>
<td>US Department of Defense</td>
</tr>
<tr>
<td>VHF</td>
<td>Very high frequency</td>
</tr>
<tr>
<td>VOR</td>
<td>Very High Frequency Omni-directional Range</td>
</tr>
<tr>
<td>WAAS</td>
<td>Wide Area Augmentation System</td>
</tr>
<tr>
<td>WRC</td>
<td>World Radiocommunications Conference</td>
</tr>
</tbody>
</table>
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Traduction en Français de l'avant-propos, du resumé et des conclusions et recommandations.

AVANT-PROPOS

Ce rapport présente les résultats d'une étude sur la sensibilité des récepteurs GNSS aux interférences des fréquences radio. L'étude a été lancée à la suite de propositions faites à l'Union International des Télécommunications par des fournisseurs de "services mobiles par satellite" (MSS), en vue de partager les bandes de fréquence actuellement allouées aux services de radio-navigation par satellite (RNSS). Les allocations de fréquence sont décidées par la conférence mondiale de la radio (WRC), organisée par l'UIT, qui se réunit environ tous les deux ans.

La résolution 220 prise lors de la WRC en 1997 demandait que l'UIT étudie les critères techniques et opérationnels, ainsi que les besoins en matière de sécurité, afin de déterminer s'il serait possible de partager une bande de fréquence entre d'une part, la radio-navigation aéronautique et les services de navigation radio par satellite déjà en fonction, ou prévus dans la bande de fréquence 1559-1610 Mhz, et d'autre part les services mobiles par satellite (MSS) sur une partie de la bande de fréquence 1559-1567 Mhz. L'étude d'Eurocontrol a été lancée pour répondre à cette résolution.

GPS et GLONASS sont des systèmes de radionavigation par satellite établis émettant dans la bande 1559-1610 Mhz. Ces systèmes sont déjà largement utilisés pour de nombreuses applications et il est prévu que leur utilisation pour l'aviation civile augmente de façon significative dans les années à venir.

En plus de ces prévisions GPS et GLONASS, des projets concernant une deuxième génération de systèmes de navigation par satellite ont été publiés, souvent appelés GNSS-2 en Europe, et ceux-ci utilisereraient également cette bande de fréquence.

It est également prévu que des signaux de type GPS seront transmis du sol par ce qu'on appelle "pseudolites", qui pourraient être nécessaires aux approches de précision.

Les demandes de fréquences par les fournisseurs de services mobiles par satellite (MSS), à la fois dans et autour de la bande de fréquence RNSS, s'avèrent être une menace significative d'interférence pour les utilisateurs RNSS. L'analyse initiale de l'influence des systèmes MSS proposés sur les services de navigation par satellite indique que des interférences se produiraient, en particulier sur le système GLONASS et pour les utilisateurs du système ENSS-1 prévu par l'ESA.

Des interférences sur le GPS poseraient également un problème s'il n'y avait pas le fait que les satellites GPS émettent en réalité un signal plus puissant que le minimum donné par leur spécifications.

Le travail ici décrit établit les niveaux d'interférence qu'un récepteur GNSS peut tolérer tout en répondant aux critères de performance de système de navigation pour diverses applications de l'aviation civile. Le rapport recommande fortement à la communauté de la navigation par satellite de soumettre ce problème important à l'attention de leur réglementation radio respective ou aux agences de gestion des fréquences afin d'aider à la défense des fréquences RNSS.

Ces travaux ont été menés par le Centre Expérimental EUROCONTROL, situé à Brétigny-sur-Orge, au sud de Paris. Le CEE est responsable des simulations de contrôle du trafic aérien, des études et recherches dans le cadre du Programme européen d'harmonisation et d'intégration du contrôle du trafic aérien EATCHIP, programme géré par EUROCONTROL pour la Conférence de l'Aviation Civile Européenne (ECAC).

Le groupe Applications de la Navigation par Satellite SNA (Satellite Navigation Applications) dans le cadre d'EATCHIP est responsable des activités GNSS d'Eurocontrol. Son programme de
travail est déployé au travers de deux «task forces», Operational and Certification Requirements (OCR) et System Research and Development (SRD).

Les travaux présentés dans ce rapport ont été menés par l’Agence anglaise «Defence Evaluation and Research (DERA) » pour le compte du SRD.

Richard Farnworth
Edward Breeuwer
Andrew Watt

Responsables du projet
RESUME

Sous contrat avec EUROCONTROL, le service NSR (Navigation System Research) du DERA (Defence Evaluation and Research Agency) a étudié les besoins en protection des services de radionavigation par satellite des récepteurs RNSS. La bande de fréquence RNSS désignée est utilisée par l’aviation pour le GNSS, (services satellite de navigation globale). GNSS entend devenir le système de radio navigation prédominant au vingtième siècle.

La bande de fréquence attribuée au RNSS va de 1559 MHz à 1610 MHz et contient actuellement le NAVSTAR GPS(Global Positioning system), et le système russe GLONASS. L’ESA, pour le compte du Groupe Tripartite Européen, a émis une demande d’inscription sur cette bande de fréquence pour un système européen de navigation par satellite.

Les demandes des fréquences par les opérateurs MSS ont déjà abouti à une perte du spectre de 1610 à 1626.5 MHz et l’UIT (Union Internationale des Télécommunications) est en train d’étudier une demande pour l’utilisation de la bande 1559 à 1567 MHz qui chevauchera la bande inférieure 3.5 MHz de la bande GPS. Des transmissions indésirables provenant des MSS adjacents et des harmoniques générées par des transmissions de haute puissance à des fréquences inférieures telles que des diffusions TV pourraient poser problème. Presque tous les aspects de transmissions radio sont contrôlés par les réglementations radio (RR) de l’UIT, cependant la mise en application de ces réglementations est sous la responsabilité individuelle de chaque état. La protection nécessaire aux récepteurs GNSS doit être spécifiée et chaque Etat Membre d’EUROCONTROL et de l’OACI doit s’assurer que cette spécification est enregistrée auprès des autorités nationales ou de l’agence responsable des transmissions radio.

Antécédents

Les niveaux de puissance des signaux de navigation satellite émis par GPS et GLONASS sont en dessous du niveau du bruit thermique à la surface de la terre. Après détection par les processus de corrélation dans le récepteur, le niveau du signal est seulement de 20 dB au-dessus du bruit et seulement 5dB au-dessus du niveau de puissance requis pour lire le message contenant les données de navigation avec un faible taux d’erreur. Toute dégradation du rapport signal-bruit nuit à la performance du récepteur et pose un problème de fond pour l’utilisation du GNSS pour les opérations à haute intégrité.

Pour que la protection de GNSS soit globale, des réglementations doivent être proposées à l’UIT pour garantir qu’aucune attribution de fréquence ne soit faite à des systèmes qui provoqueraient des interférences nuisibles pour les récepteurs GNSS, et les autorités nationales doivent contrôler les opérations.

Bien que plusieurs cas d’interférence dommageable au GPS et au GLONASS aient été rapportés, de tels incidents ne semblent pas très répandus et sont en général attribués à des émetteurs locaux à fort débit néfaste. Cependant l’UIT a approuvé les demandes de MSS (Mobile Satellite Service) pour l’utilisation de la bande de fréquence 1610 – 1625 MHz, pour des transmissions terre vers satellite (T-s).

Pour réduire le prix des terminaux portables, certains développeurs de systèmes MSS ont réduit le filtrage de la sortie de l’amplificateur de forte puissance (HPA), et un phénomène important de bruit en dehors de la bande est prévu. L’analyse montre que l’interférence est particulièrement perturbatrice pour les réceptions de GLONASS. Une demande du Royaume-Uni pour les fréquences 1559 – 1567 MHz est en cours pour des transmissions MSS de l’espace vers la terre (S-t). La demande est faite pour le compte d’INMARSAT, bien qu’elle ne lui soit pas uniquement destinée. Contrairement aux transmissions terre-espace dans la bande 1610 à 1626.5 MHz, les transmissions INMARSAT satellite-terre (S-t) seront visibles en tout point de la terre pour une altitude comprise entre + et - 80 degrés.
CONCLUSIONS ET RECOMMANDATIONS

Pour protéger la bande de fréquence GNSS, il est nécessaire de spécifier une fréquence de récepteur et un masque de puissance qui définissent le début de l’interférence nuisible. Le problème est qu’il n’existe pas encore de spécification ou d’architecture définitive approuvées du récepteur GNSS qui pourraient être utilisées pour définir la sensibilité du récepteur. Dans ce rapport nous cherchons à établir ce qui constitue une interférence nuisible sur un récepteur conçu de manière optimale et à concevoir un tel masque.

Une interférence nuisible se traduit par :

a. une réduction du rapport signal-bruit à un niveau tel que l’opération souhaitée ne puisse être menée à bien en raison de l’incertitude sur les mesures de pseudo-distances et le variation de pseudo-distances
b. une augmentation du taux d’erreur de bits (BER) du message.

c. une augmentation de sauts de cycles non détectés.

Les résultats des sections 2 et 3 indiquent que (a) est l’élément le plus sensible si les budgets d’erreur pour une approche type CAT1 utilisant WAAS/EGNOS ou LAAS doivent être respectés. Le tableau F-1 fournit un résumé des précisions de mesures requises, du rapport porteuse-bruit nécessaire, et des niveaux maximums tolérables d’interférence pour une approche de précision (CAT1) et pour des opérations d’atterrissage, provenant de chiffres publiés par l’OACI et RTCA. Les chiffres sont donnés pour une interférence large bande sur le système GPS utilisant la puissance répondant aux spécifications d’une part, et celle effectivement utilisée d’autre part.

<table>
<thead>
<tr>
<th>Source</th>
<th>Précision de la mesure de pseudo-distance m – 1 σ</th>
<th>C/No dB-Hz (GPS) requis</th>
<th>Interférence large bande tolérable dBW (GPS spécifications)</th>
<th>Interférence large bande tolérable dBW GPS réel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do-217 SCAT-1</td>
<td>0.4/0.5</td>
<td>33.5/32.5</td>
<td>-144/-142</td>
<td>-139/-137</td>
</tr>
<tr>
<td>ESA EGNOS Ref 16</td>
<td>0.4</td>
<td>33.5</td>
<td>-144</td>
<td>-139</td>
</tr>
<tr>
<td>Tiré des RNP de OACI</td>
<td>0.26</td>
<td>38</td>
<td>Impossible pour des satellites en dessous d’une élévation de 40 degrés</td>
<td>-150</td>
</tr>
<tr>
<td>OACI GBAS/SARPS</td>
<td>0.23</td>
<td>39</td>
<td>„</td>
<td>Impossible pour des satellites en dessous de 10 degrés</td>
</tr>
<tr>
<td>Etude RAIM WAAS Ref 15</td>
<td>0.22</td>
<td>39.5</td>
<td>„</td>
<td>Non-disponible pour des satellites en dessous de 15 degrés</td>
</tr>
</tbody>
</table>

Tableau F-1 Résumé du seuil de tolérance des interférences pour GPS

A partir de cette analyse on observe que c’est simplement parce que les actuels satellites GPS rayonnent à une plus forte puissance que le minimum spécifié, que la précision demandée par l’OACI et RTCA peut être atteinte par des satellites placés à faible degré d’élévation.

Les valeurs de précision à des valeurs spécifiques C/No pour GLONASS sont considérablement plus mauvaises en raison de l’influence d’une phase de codage plus longue. La précision maximale qui
Exigences pour la protection de la fréquence GNSS

pourrait être atteinte pour GLONASS en utilisant la technologie d’un récepteur conventionnel est de 0.9 m (1 σ), ce qui est bien en dessous de la précision requise pour les opérations CAT1.

Le niveau d’interférence qui se traduit par une dégradation nuisible pour le GPS est de –150 dBW au niveau du bruit et descend jusqu’à –160 dBW pour les signaux continus (CW). Des signaux continus aussi faibles que –145 dBW ont même réussi à perturber les boucles d’acquisition de la porteuse dans les tests de laboratoire. En raison de variations dans les bandes latérales du spectre de puissance du code C/A-GPS, le niveau de puissance CW qui provoque l’interférence nuisible peut varier au maximum de 10 dB. Le même effet ne se produit pas pour GLONASS en raison de l’uniformité des bandes latérales du spectre de puissance.

Une partie de la bande 1610 à 1626.5 MHz a déjà été allouée à des systèmes mobiles par satellite pour des terminaux de communication entrainant une émission de puissance indésirable dans les bandes GPS et GLONASS à -70dBW/MHz. Ces transmissions posent un problème potentiel, qui ne peut être évité que si des distances de séparation supérieures à 150 m sont maintenues. Les résultats pour GLONASS sont similaires, cependant la proximité de la bande MSS 1610 – 1625.5 MHz du haut de la bande GLONASS indique que des filtres supplémentaires sont nécessaires pour la chaîne de conversion FI, ce qui augmentera les coûts de manière significative. Les récepteurs actuels DASA et 3S testés lors de l’étude seraient atteints de dégradations significatives dues aux transmissions MSS.

![Figure F-1 Sensibilité de la bande GPS aux interférences](image)

Les services mobiles par satellite proposés par INMARSAT provoqueraient des interférences inacceptables sur l’ENSS-1 de l’ESA. La densité de puissance INMARSAT de –197.6 dBW/Hz nécessite une puissance porteuse en entrée du récepteur de –162 dBW pour que le récepteur capte le signal et une puissance porteuse de –155.6 dBW pour suivre le signal au rapport signal-bruit (CNo) requis pour atteindre une précision suffisante pour les opérations CAT1.

Il est recommandé que les Etats Membres d’EUROCONTROL rapportent ces faits à leurs organismes de réglementation radio ou de gestion des fréquences respectives, pour représenter les besoins de l’aviation aux réunions de niveau national, européen et mondial. La sensibilité aux
interférences telle que montrée en Figure F-1 pourrait servir de base à la protection du GPS. Un masque de protection pour GLONASS peut être conçu en utilisant la figure F-1 à chaque fréquence satellite.

Lors de la réunion GNSSP de l’OACI, en mars 1998, les États-Unis ont présenté des propositions pour le LAAS qui utilise un récepteur équipé de lissage de portée, revendiquant des améliorations significatives au niveau de la précision de la poursuite. Il est recommandé que la sensibilité de ce type de récepteur aux interférences soit aussi étudiée. Plusieurs techniques se présentent pour atténuer ces interférences. Il est recommandé d’étudier ces techniques afin d’évaluer leur capacité à supprimer ces interférences nuisibles.

La puissance irradiée, dans les bandes de fréquence GPS et GLONASS, provenant d’équipement électrique portable n’a pas posé de problème pour l’équipement testé. Cependant on sait que la puissance des signaux nuisibles peut considérablement varier. Puisque GNSS a été introduit dans les avions, il est recommandé que l’on veille à s’assurer qu’aucune interférence ne soit causée par l’utilisation d’équipement électrique portable sur l’appareil.