Assessing the Navigation Data Input to Aircraft Flight Management Systems

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This paper gives details of the failure rates and the failure modes experienced with SPS GPS receivers certificated for aviation use to the TSO-C129 specification. These failure rates are significant compared to those from other modern avionics and the rates are comparable to that currently experienced from un-scheduled failures in the GPS signals-in-space. To achieve certification, Flight Management System (FMS) design should consider the way in which the satellite navigation receivers fail. The paper also gives details concerning the 2-D errors that have been experienced with these receivers, and indicates further work that needs to be done with C 129a receivers.

1. OBJECTIVES OF THIS PAPER. It would be straightforward for an aircraft's FMS to utilise a navigation system which has no anomalies and no errors. However, no navigation system yet produced has such ideal attributes. It is, therefore, important for a FMS designer to be fully aware of the particular deviations from the ideal that are exhibited by the system it is intended to use. In order to achieve the necessary safety levels within aviation, it has become axiomatic that prior to being offered for certification, new equipment or procedures must be thoroughly assessed to establish all the potential failure mechanisms, the likely rates at which these failures may occur, and the effectiveness of proposed mitigation. In the light of this, the objectives of this paper are:

(i) to make available data assembled for NATS on failures with modern GPS aviation receivers, and,
(ii) to describe the precision that has been observed on the output of four modern receivers.

It needs to be made clear from the outset that the receivers considered here are not research receivers, but off-the-shelf equipment designed and certificated for use in civil commercial aircraft to C129 standards. Future work to compile statistics on later C129a receivers required for basic RNAV is being progressed.

2. GPS SPS AND THE PANS WORK. The GPS Standard Positioning Service (SPS) performance is defined in two documents: the Federal Radionavigation Plan (FRP)[1] and the SPS Signal Specification.[2]

The FRP is issued every other year; the latest (1996) version, which was released during the Summer of 1997, states that SPS provides a predictable positioning accuracy of 100 metres (95 percent) horizontally. It has a further note that 'if the conditions on coverage and service availability are met, the probability that the horizontal positioning error will not exceed 500 metres at any time is at least 99·7%'.

The SPS Signal Specification is now in its second issue, and section 5.0 of Annex A gives further details on the precision: of potential relevance to this paper is the statement that the horizontal error will be equal to or less than 300 metres 99.99 percent of time 'based on a measurement interval of 24 hours for any point on the globe'. There would appear to be some conflict: better than 300 metres 99.99 percent of time is more attractive to the civil aviation user, than better than 500 metres 99.7 percent of time. Therefore, if the 300 metres requirement is met, then the 500 metres criterion in the FRP is superfluous. 'System reliability' is covered in the Signal Specification, in the sense that there is a given probability that there will be 4 or more satellites with a given geometry and mask angle. But this is 'predicated on 24 operational satellites, as the constellation is defined in the almanac'. The 'Service Reliability Standard' is given as 99.97 percent global average and 99.79 percent single point average, but this is based on a maximum of 18 hours of major failure behaviour over the one year sample interval. These availability figures imply a working receiver. However, if a receiver fails, then signals in space are not of any value when determining the achieved GPS performance. In understanding GPS performance, one must therefore examine receiver failure rates to identity how significant they are in relation to the rest of the system.

To verify that the performance delivered is up to the specification, a GPS Performance Analysis Network (PAN) has been set up, comprising three monitor stations located in Los Angeles (CA), Colorado Springs (CO) and Vienna (VA). Its objectives are to monitor independently the GPS SPS to ensure that SPS Signal Specification performance standards are maintained, and to disseminate and make available performance assessments and supporting raw data to the civil community. A report was given to the Civil GPS Service Interface Committee (CGSIC) on 15 September 1997. The report concluded that the performance delivered did indeed meet that laid down in the specification, both for reliability and precision. The precision had been 65 metres in 1994 (the year when PAN became operational) and was still 65 metres in 1997. These are 95 percent levels of 2-D errors.

3. NATS'S RECEIVER MONITORING PROGRAMME. Recognising that performance, both in terms of precision and reliability, is as much a matter of receiver design as it is of signals-in-space, NATS commenced a programme of monitoring in 1995. The emphasis was not on signals-in-space, but on the performance of the output from aviation receivers since that is all that matters to the user. This therefore incorporates three different factors:

(i) the adequacy or otherwise of the GPS constellation,
(ii) the degree to which the receivers, when they behave as designed, cope with and correct for signals-in-space misbehaviour, and
(iii) the malfunctions of the receivers themselves.

Four aviation receivers were purchased off-the-shelf and should, therefore, be representative of the market's interpretation of the published standard. In this paper, these receivers will be referred to as receivers 1a, 1b, 2a and 2b. Receivers 1a and 1b were nominally identical from one avionics manufacturer, and receivers 2a and 2b were nominally identical from a second avionics manufacturer. Both designs were approved according to specification TSO-C129. Each receiver was connected to its own antenna, and each receiver was also connected to a Personal Computer on which key parts of the receiver output were stored at approximately 15-second intervals all day and every day. A figure illustrating the general interconnections was included with the first report on the results of the programme published in Reference 3. A second report was delivered to ICAO GNSSP[4]. The receivers were installed at London's Stansted airport with approximate co-ordinates 51° 53′ N 000° 14′ E.

4. RECEIVER FAILURES. Where an aircraft's FMS is using GPS/GLONASS/GNSS receiver data, it must be able to:

(i) recognise that a failure has occurred, and
(ii) react to failures in such a way as to preserve as far as is required the safety of the aircraft.

It was therefore a key objective in the programme to observe and identify the way typical receivers fail and measure the frequency of occurrence. Accordingly, the stored receiver output information was examined to identify the failures and the circumstances surrounding them. Annex 1 contains data for 30 failures that occurred in the period since GPS Full Operational Capability (FOC) was declared until the end of July 1997. The period of failures ranged from 0.8 of a minute to 8 days. All receivers experienced failures. For the purpose of providing data on the impact of these outages, they were divided into four categories. These were defined as follows:

Cat I covers those outages where a receiver locked up and provided no output to the logging PC, and the receiver display requested a power-down which was manually effected,
Cat II covers those outages where a receiver provided no position output to the logging PC but recovered by itself after a period of a few minutes,
Cat III covers those outages where a receiver provided no position output to the logging PC but recovered by itself after a few days,
Cat IV covers those outages where a receiver continued to provide position to the log but the position was seriously in error, a condition which recovered by itself.

Table 1 shows the distribution of outages by category.

TABLE 1. NUMBER OF OUTAGES PER CATEGORY

Category	I	II	III	IV	Total
No	6	12	1	11	30

The high number of Cat I and II cases shows how important it is that, if the GPS position information is displayed through the FMS, any message from the GPS to the effect that a manual reset is required must be clearly passed on to the crew through the FMS display. It is also important that if the GPS receiver freezes in a manner that prevents latitude/longitude from being provided, this must also be passed on to the crew and the means whereby they can effect a reset must be within their easy reach. There is a further aspect which needs to be considered by designers. When a receiver locks up in a manner which stops the output of latitude/longitude information, it will not always be clear whether the receiver will recover by itself within a couple of minutes (as, for instance, in failure no. 17) or whether it will remain locked up for days (as in failure no. 2). If a manual reset is effected, then recovery could take less than a minute if the receiver can use its current almanac. However, if the problem is associated with a mismatch between almanac and ephemeris, then recovery may take much longer.

5. PROBABILITY OF ENCOUNTERING A RECEIVER FAILURE. On 18 October 1995, receiver 2a had a failure from 1608 UTC to 1610 UTC (failure no. 3) followed by a failure from 1611 UTC to approximately 1612 UTC (failure no. 4). Receiver 2b had a failure from 1609 UTC to 1614 UTC on the same day (failure no. 9). Here was clearly an overlap such that both receivers were affected simultaneously. For the purpose of computing the probability of two receivers having a simultaneous outage, these three events are considered as one case of two receivers having a simultaneous failure. ('D01' is noted in column 9 of Annex 1, to indicate this). There was another case on 6 May 1997 when two receivers experienced a simultaneous failure: the two failures are referenced 25 and 26 in Annex 1. In column 9 they are marked 'D02' All the other cases affected a single receiver only, for which reason a 'S' (for single) is indicated in column 9. The cases are marked 'S01', 'S02' up to 'S25' since there were 25 such cases. The 30 cases cited in Annex 1 have therefore been reduced to 2+25 failures when estimating failure probabilities for a dual receiver installation. The above outages arose during a time span when the four receivers between them clocked up 61935·6 receiver running hours. One might view it as 30967·8 hours during which an aircraft had been flying with a set of two identical receivers. This may now be used to compute the probability of an aircraft encountering a failure in one of its two GPS receivers, and the probability of an aircraft encountering a failure in both receivers simultaneously. The results are in Table 2.

TABLE 2. MTBF AND FAILURE PROBABILITIES

Parameter	Single receiver failures	Double receiver failures
Base data	25 cases in 30967·8 hours	2 cases in 30967·8 hours
Probability per flying hour	$8{\cdot}07 \times 10^{-4}$	$6{\cdot}46 \times 10^{-5}$
MTBF in hours	1238·7	15483·9

It is worth noting that, if the failures on one receiver had been random compared to those in the second of a pair, then the probability of having a double failure should be approximately the square of that for a single receiver failure.

The probability observed is tending to indicate that there may be a common cause effect rather than a random failure. It must however also be stressed that the sample size is small; indeed, the sample size for double failures will always be small unless a monitoring program which examines a very large number of receivers is funded. (Note: The draft ICAO GNSS SARPS[5] requirement is currently 10^{-4} failures per hour per aircraft.)

6. OTHER COMMON CAUSE FAILURES. It must be emphasised that the results in this paper relate only to GPS reception at the Stansted installation. Other locations may result in additional failures. As this paper was being finalised, reports were received concerning failures in a commercial DC-10 aircraft which on 3 successive days lost all GPS receivers while flying over southern France. While detailed reports are not yet available, the indications were that the failures were caused by interference. This locked the receivers, requiring them to have a power-down reset. This type of failure has implications for the FMS and also for the Air Traffic Service provider who may experience a significantly increased workload if several aircraft simultaneously lose their navigation capabilities.

7. OTHER POINTS CONCERNING THE STANSTED FAILURES. Three observations may be made concerning the failures noted in our trials:

(i) In every case the receiver either recovered itself or recovered after manual reset. No repair was required during this period.

(ii) A particularly interesting feature is represented by failures numbered 12, 15, 22, 24 and 27, all of which arose within the 3-minute period before the Saturday/Sunday midnight. In GPS, time is counted in weeks and seconds within the week, measured from the Saturday/Sunday change-over. At that midnight, various counters are reset and, unless special care is taken in the receiver, there may be problems if the ephemeris and the almanac, as stored in the receiver, refer to different week numbers. A pre-TSO receiver had been used for earlier airborne trials referred to in the preliminary report[3]; it had also exhibited signs that time within the week had posed a problem for that particular receiver manufacturer.

(iii) Of the 30 failures listed in Annex 1, a number can be 'grouped'. For instance, failures 3–11 have to do with a common event in signals-in-space; both the receivers of that type suffered, whereas the two receivers of the other manufacturer had no difficulties. Failures 16–20 can also be grouped, so that the event which triggered the receiver malfunctions moved 4 minutes forward each day in sympathy with the constellation which advances 4 minutes per day. A similar pattern may be seen for failures 28–30.

These factors between them indicate strongly that the problem was not a receiver hardware problem, but rather that the receiver software was unable to cope with a particular combination of circumstances. That would also be consistent with the probability of double failures being so much higher than the square of the probability of a single failure.

8. AIRCRAFT WITH A SINGLE GPS RECEIVER. The draft ICAO GNSS

SARPS[5] permits a loss of continuity of between 10^{-4} and 10^{-8} per hour depending on the operation. Data from the trial suggest that using a single receiver, the aircraft would lose continuity at $4{\cdot}84 \times 10^{-4}$ per hour. (30 failures, listed in Annex 1, experienced during the course of 61935·6 hours, leading to a probability of failure of 30/61935·6). Currently this suggests that single receiver (TSO-129) operations does not meet the minimum ICAO requirements.

9. RELATIVE SIGNIFICANCE BETWEEN RECEIVER OUTAGES AND SATELLITE OUTAGES. The availability for the GPS satellites can be determined by examining the Notice Advisories placed on the Bulletin Board operated by the US Coast Guard[6]. Such an examination was carried out by NATS covering the period 17 July 1995–16 March 1997. The first of these dates was the date when GPS declared FOC and the latter date was the last day for which the analysis was done. During this period the satellite constellation had 358059·5 satellite hours (i.e. the number of satellites multiplied by the number of hours for each satellite), and there were 77 'scheduled' outages (where 'scheduled' indicates there was prior warning with the particular satellite set as unusable). There were also 37 'unscheduled' outages. Both kinds of outages are important in computing system availability. However, when it comes to events that a receiver or FMS has to be prepared to cope with, it is the 37 unscheduled events that are important. The Mean Time Between Unscheduled Events (MTBUE) was 358059·5/37 = 9677·3 hours per satellite. Considering that a receiver will be using five satellites in order to do Supplemental Means RAIM, the probability that a receiver encounters an unscheduled satellite outage is $5/9677{\cdot}3 = 5{\cdot}17 \times 10^{-4}$. This corresponds to a MTBUE of 1935·5 hours which is of the same order as the rate for receiver failures. However, in some of the unscheduled cases, (the proportion was not available to the authors) the satellite is set to a non-standard code, such that a receiver will simply switch to a different satellite and the FMS will be unaware of the change. Furthermore, if the satellite is not switched to non-standard code, a ground monitor within the WAAS or EGNOS network will detect any malfunction and warn accordingly. Receiver failures, in contrast, will not be detected by, nor in current designs be known to the ground integrity monitoring network. This shows how important it is to have reliable data on both the frequency and the nature of receiver failures, and in particular on the rate at which both receivers in a duplicated set fail.

10. POINTERS FOR ACHIEVING GOOD RELIABILITY IN THE FUTURE. A MTBF of 2064·5 hours (61935·6/30) is rather poor compared with other modern avionics which regularly achieve better than 10000 hours. Since the bulk of the events, if not all, are due to software, it is likely that as one adds more complications into that software the MTBF will deteriorate further. Such complications may be:

(i) combining GPS with GLONASS,
(ii) adding in WAAS and/or EGNOS,
(iii) incorporating pseudolites,
(iv) enhancing RAIM,
(v) incorporating two-frequency ionospheric correction.

There clearly is a strong case for keeping the receiver software as simple as possible: many satellites transmitting in identical format is better than mixing formats. Ground monitoring which simply allows a receiver to read a health flag is simpler and therefore potentially more reliable than making complex consistency checks through RAIM. Whilst in principle it is apparently easy to perform any data manipulation in software, the evidence from these results shows that practical limitations do exist and currently we are not achieving the necessary standards. Keeping the software simple is therefore important.

11. MAGNITUDE OF 2-D ERRORS. From a FMS point of view, it is important to be aware of large errors and their probability of occurrence. The NATS monitoring program has taken the opportunity to explore these aspects using the same TSO-approved receivers. Data associated with the malfunctions described above were ignored but all other samples were considered in an analysis covering 1996. Table 3 summarises the results on a per-month basis for the 95 percent value; 99·99 percent; and the largest 2-D error seen that month. Column 4 gives the value of that largest error and column 5 identifies which of the four receivers had the largest error that month. Column 6 is the number of samples of 2-D position obtained that month with all the receivers grouped together.

TABLE 3. 2-D ERRORS FOR ALL RECEIVERS GROUPED TOGETHER ON A MONTH-BY-MONTH BASIS DURING 1996

Col 1 Month	Col 2 95%	Col 3 99·99%	Col 4 Worst error	Col 5 Receiver	Col 6 *n*
Jan	65 m	159 m	673 m	2a	641 317
Feb	66 m	195 m	278 m	2a	534 419
Mar	65 m	166 m	244 m	1b	710 339
Apr	67 m	194 m	362 m	2b	688 043
May	66 m	166 m	260 m	2a	708 225
Jun	66 m	178 m	324 m	2a	616 864
Jul	65 m	162 m	333 m	2a	600 448
Aug	67 m	257 m	491 m	1b	614 247
Sep	67 m	170 m	561 m	1a	626 023
Oct	70 m	158 m	214 m	2a	469 669
Nov	68 m	177 m	540 m	2b	630 740
Dec	68 m	178 m	291 m	2a	609 147
Total					7 449 481

Scanning columns 2 and 3 shows clearly that the performance expressed through both the 95 percent and the 99·99 percent levels is much better than that promised by the SPS signal specification[2]. The value is also consistent with that reported through the PAN programme referred to earlier in this paper. It is important to remember that these precisions were achieved relatively early in the life-cycle of GPS while the number of satellites in the constellation exceeds that promised. Some degradation must therefore be allowed for in case the number of active satellites were to be reduced. Apart from the 95 percent and the 99·99 percent values of 2-D error that are defined in the SPS signal specification[2], that document also records (in Figure 5–7 of its Annex B) an observed maximum 2-D error of 261 metres. Table 3 above shows that the Stansted project has recorded several cases with greater errors.

12. TIMING OF WORST ERRORS. It is clearly important to know if large errors occurred simultaneously in more than one receiver. This was examined in some detail and the results are shown in Table 4. This shows that, in the first case, when receiver 2a had its worst error, and in the third case, when receiver 1a had its worst error, the other three receivers had small errors. In the second case, when receiver 1b had its worst error and in the fourth case, when receiver 2b had its worst error, two other receivers were experiencing small errors. In these cases, one other receiver was out of service; in the case of 29 August 1996, receiver 1a was operating but the hard disk in the recording system had failed; in the case of 24 November 1996, receiver 1b had just recovered from failure no. 23.

TABLE 4. RECEIVER COMPARISONS WHEN THEIR WORST 2-D ERROR AROSE

Time of occurrence of worst error	Rx1a	Rx1b	Rx2a	Rx2b
09.01.96 at 1923 UTC	23 m	23 m	673 m	67 m
29.08.96 at 2131 UTC	N/A	491 m	26 m	42 m
15.09.96 at 1458 UTC	561 m	23 m	101 m	10 m
24.11.96 at 1558 UTC	28 m	N/A	45 m	540 m

The vertical dimension in a flight clearance is generally with respect to a barometric altimeter. Large errors in a barometric output matter little in safety terms since all aircraft use the same scale and therefore have the same errors and separation is maintained albeit at a different absolute altitude. The analysis in this paper, so far, shows clearly that the same assumption may not be made concerning 2-D errors in GPS. Quite the contrary, when any one receiver has a large error it must be assumed that other receivers flying in the same airspace have an error which is random by comparison. The only exception is clearly if the number of satellites visible is so low that it can be guaranteed that all receivers will be using the same set of satellites and that there is only one algorithm that can be used in order to find the 2-D position.

TABLE 5. OVERALL RESULTS WHEN ALL 12 MONTHS ARE CONSIDERED TOGETHER

Parameter	Value
2-D error level containing 95% of samples	67 metres
Percentage with 2-D error below 100 metres	99·473%
2-D error level containing 99·99% of samples	182 metres
Percentage with 2-D error below 300 metres	99.999%
Largest 2-D error ever seen	673 metres
Number of samples in the population	7449481

13. OVERALL GPS PERFORMANCE STATISTICS FOR 1996 (AS SEEN AT THE STANSTED SITE). When all the data from 1996 were gathered and analysed as a combined population the results were as in Table 5.

14. PERFORMANCE STATISTICS FOR 1997 (SO FAR). Approximately 3·5 million 1997 samples of 2-D error had been analysed at the time this paper was drafted. The sample covers the period 1 January 1997 to 30 June 1997. The 95 percent and 99·99 percent 2-D errors remained approximately the same as for 1996. The largest error seen during the period was 491 metres and that occurred on 21 February 1997.

15. FUTURE PROGRAMME. As noted earlier, the receivers tested were approved to TSO C 129. GPS receivers are evolving to take into account the transition to the new TSO specification (such as TSO-C129a which may have improved performance) and to incorporate new facilities such as EGNOS and WAAS. A second civil frequency is also likely to become available. It is important that FMS designers should not assume that the performance of receivers designed to one specification and working with one set of facilities will necessarily carry on to new specification. Further monitoring of receiver performance is required and the results must be regularly reviewed by those designing FMS.

16. CONCLUSIONS. Based on the results from the TSO-approved receivers at Stansted, an FMS utilising GPS for position determination must assume that:

1. The GPS receiver may have a failure rate which is significantly higher than that of other modern avionics.
2. In a dual aircraft installation the probability of a failure arising in one of the receivers is of the order of $8{\cdot}07 \times 10^{-4}$ per flying hour and the probability of both receivers having a failure simultaneously is of the order of $6{\cdot}46 \times 10^{-5}$ per flying hour.
3. The failures will be dominated by software errors.
4. The most common form of failure is that the receiver ceases to provide new latitude/longitude information.
5. The 2-D error at both the 95 percent and the 99·99 percent have remained within the SPS specification.
6. When one GPS receiver has severe errors (exceeding say 300 metres) it must *not* be assumed that other receivers in the same airspace have errors of similar magnitude and direction.
7. If the GPS receiver is not close to the field of view of the pilots, it is important that the FMS must clearly signal to the pilot when a manual reset of the GPS receiver is required. It is also important that the means for such manual action must be within easy reach of the pilot.

It is considered that in the light of the results reported, detailed discussions should take place between the designers of the FMS and of the GPS receiver, so that failure modes and impact of failure can be addressed fully to ensure aircraft safety.

ACRONYMS

CGSIC	Civil GPS Service Interface Committee
EGNOS	European Geostationary Navigation Overlay Service
FMS	Flight Management System
FOC	Full Operational Capability
FRP	Federal Radionavigation Plan
ICAO	International Civil Aviation Organisation
MTBF	Mean Time Between Failures
MTBUE	Mean Time Between Unscheduled Events
NATS	National Air Traffic Services Limited
PAN	Performance Analysis Network
PC	Personal Computer
RAIM	Receiver Autonomous Integrity Monitoring
SARPS	Standards, Recommended Practices and Procedures
SPS	Standard Positioning Service
TSO	Technical Standards Order
UTC	Universal Time Co-ordinated
WAAS	Wide Area Augmentation System

REFERENCES

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[4] ICAO GNSSP WG B&D, October 1997, Brussels–Belgium, Working Paper 117.

[5] Report and draft SARPS (Version 5.0) of ICAO GNSSP WG B&D, October 1997, Brussels–Belgium.

[6] The Bulletin Board closed at the end of 1997, but the data can be obtained through the USCG website.

KEY WORDS

1. Air. 2. Navaids. 3. GPS. 4. Data.

APPENDIX

Summary of the receiver failures

Failure number Col 1	Start of receiver failure			Receiver affected Col 5	Duration of failures Col 6	Characteristics Col 7	Category	
	Col 1 Day	Col 3 Date	Col 4 Time				Col 8	Col 9
1	Friday	08.09.95	1022	1a	Manual	No pos	I	S01
2	Monday	25.09.95	1916	1b	8 days	No pos	III	S02
3	Wednesday	18.10.95	1608	2a	2 min	Bad pos	IV	D01
4	Wednesday	18.10.95	1611	2a	1·5 min	Bad pos	IV	D01
5	Wednesday	18.10.95	1631	2a	5.3 min	Bad pos	IV	S03
6	Wednesday	18.10.95	1637	2a	6.3 min	Bad pos	IV	S04
7	Wednesday	18.10.95	1658	2a	1·0 min	Bad pos	IV	S05
8	Wednesday	18.10.95	1559	2b	1·8 min	Bad pos	IV	S06
9	Wednesday	18.10.95	1609	2b	5·0 min	Bad pos	IV	D01
10	Wednesday	18.10.95	1622	2b	0·8 min	Bad pos	IV	S07
11	Wednesday	18.10.95	1650	2b	0·8 min	Bad pos	IV	S08
12	Saturday	09.12.95	2359	1a	Manual	No pos	I	S09
13	Saturday	30.12.95	2231	1b	7·3 min	No pos	II	S10
14	Saturday	30.12.95	2255	1b	4·5 min	No pos	II	S11
15	Saturday	20.01.96	2358	1b	Manual	No pos	I	S12
16	Saturday	17.08.96	0122	1a	2·5 min	No pos	II	S13
17	Sunday	18.08.96	0118	1a	3·5 min	No pos	II	S14
18	Monday	19.08.96	0114	1a	3·8 min	No pos	II	S15
19	Tuesday	20.08.96	0110	1a	3·3 min	No pos	II	S16
20	Wednesday	21.08.96	0106	1a	0·8 min	No pos	II	S17
21	Friday	23.08.96	0324	1b	1·3 min	No pos	II	S18
22	Saturday	12.10.96	2358	1b	Manual	No pos	I	S19
23	Sunday	24.11.96	1549	1b	2·8 min	No pos	II	S20
24	Saturday	08.02.97	2357	1b	Manual	No pos	I	S21
25	Tuesday	06.05.97	0110	2a	4·0 min	Bad pos	IV	D02
26	Tuesday	06.05.97	0058	2b	16·5 min	Bad pos	IV	D02
27	Saturday	17.05.97	2359	1b	Manual	No pos	I	S22
28	Sunday	27.07.97	1013	1a	0·8 min	No pos	II	S23
29	Monday	28.07.97	1005	1a	2·8 min	No pos	II	S24
30	Wednesday	30.07.97	0958	1a	1·0 min	No pos	II	S25

Column 1 is a failure reference number, columns 2, 3 and 4 are the day of week, date and UTC when the failure arose. Column 5 indicates the receiver affected. Column 6 gives the duration of the failure indication (Note: Where column 6 had 'Manual' for duration this indicates the receiver had to be manually reset after which it resumed normal operation) and column 7 summarises the characteristics of the failure. Column 8 is a failure category and column 9 contains information used to compute the probability of single and double failures described in this paper. ('D' indicates 'double' and '01' indicates it was the first double failure).