Annex D – TORNADO-IDS IN-FLIGHT INVESTIGATION

D.1 MASKING INVESTIGATION

In order to verify the masking conditions a special simulation software was implemented, called VIEWSAT, which modelled the aircraft shape and accepted input data such as the aircraft heading, pitch and bank angles in flight (from the FTI recorders), and positions of the satellites tracked during flight in terms of azimuth and elevation (Figure D-1).

SV Number	20	21	22	23	24	25	26	27	28	29
Local Time	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ	EL:AZ
00:00:00	----	---------	---------	---------	-----	42:256	----	---------	-----	67:198	----	---------	-----
00:05:00	----	---------	---------	---------	-----	41:253	----	---------	-----	70:199	----	---------	-----
00:10:00	----	---------	---------	---------	-----	39:250	----	---------	-----	72:199	----	---------	-----
00:15:00	----	---------	---------	---------	-----	38:248	----	---------	-----	75:199	----	---------	-----
00:20:00	----	---------	---------	---------	-----	37:245	----	---------	-----	77:200	----	---------	-----
00:25:00	----	---------	---------	---------	-----	35:243	----	---------	-----	80:199	----	---------	-----
00:30:00	----	---------	---------	---------	-----	34:240	----	---------	-----	82:198	----	---------	-----
00:35:00	----	---------	---------	---------	-----	32:238	----	---------	-----	85:196	----	---------	-----
00:40:00	----	---------	---------	---------	-----	31:236	----	---------	-----	87:185	----	---------	-----
00:45:00	----	---------	---------	---------	-----	29:234	----	---------	-----	89: 83	----	---------	-----
00:50:00	----	---------	---------	---------	-----	27:232	----	---------	-----	86: 42	----	---------	-----
00:55:00	----	---------	---------	---------	-----	25:230	----	---------	-----	84: 37	----	---------	-----
01:00:00	----	---------	---------	---------	-----	24:229	----	---------	-----	82: 36	----	---------	-----
01:05:00	----	---------	---------	---------	-----	22:227	----	---------	-----	79: 35	----	---------	-----
01:10:00	----	---------	---------	---------	-----	20:225	----	-----	11:286	77: 35	----	---------	-----
01:15:00	----	---------	---------	---------	-----	18:224	----	-----	13:287	74: 36	----	---------	-----
01:20:00	----	---------	---------	---------	-----	17:222	----	-----	14:289	72: 36	----	---------	-----
01:25:00	----	---------	---------	---------	-----	15:221	----	-----	16:290	70: 37	----	---------	-----
01:30:00	----	---------	---------	---------	-----	13:220	----	-----	17:292	67: 38	----	---------	-----
01:35:00	----	---------	---------	---------	-----	11:218	----	-----	19:293	65: 39	----	---------	-----
01:40:00	----	---------	---------	---------	-----	10:217	----	-----	21:295	63: 40	----	---------	-----
01:45:00	----	---------	---------	---------	---------	---------	-----	22:296	60: 41	----	---------	-----
01:50:00	----	---------	---------	---------	---------	---------	-----	24:297	58: 42	----	---------	-----
01:55:00	----	---------	---------	---------	---------	---------	-----	26:299	56: 43	----	---------	-----
02:00:00	----	---------	---------	---------	---------	---------	-----	27:300	54: 44	----	---------	-----
02:05:00	----	---------	---------	---------	---------	---------	-----	29:301	52: 45	----	---------	-----

Figure D-1: Satellite Visibility from Receiver Almanac Data.

The VIEWSAT software provided a visibility matrix (one dorsal antenna) for the defined flight conditions (Figure D-2), and required definition of a simplified aircraft model, as shown in Figure D-3.

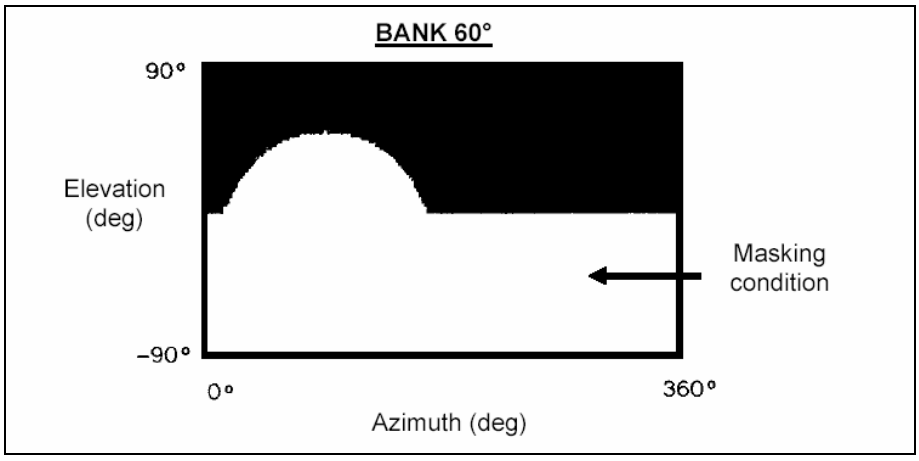

Figure D-2: Example of Antenna Masking Matrix.

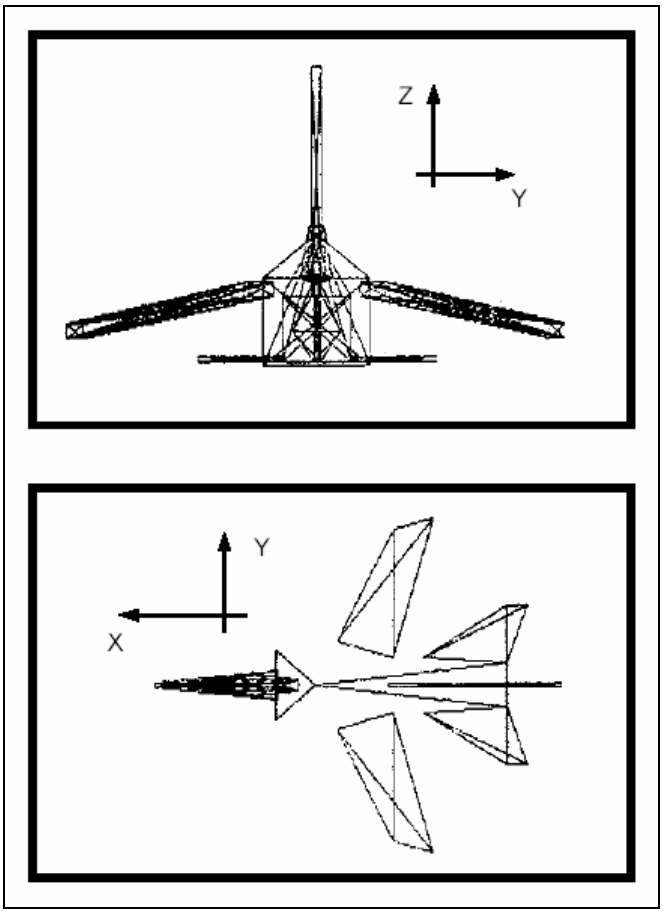

Figure D-3: Simplified Aircraft Model (TORNADO-IDS).

The result was a Global Masking Matrix (GMM), as shown in Figure D-4.

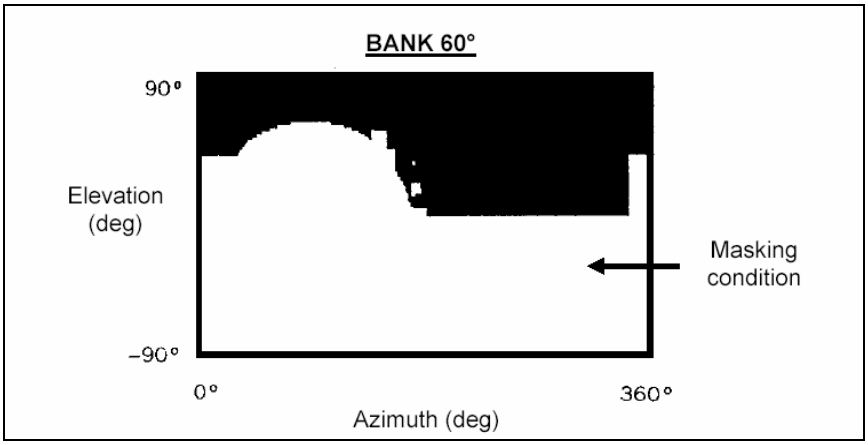

Figure D-4: Example of Global Masking Matrix.

The program output was a binary diagram in which for every satellite masked a “0” was shown, while unmasked satellites corresponded to the status “1”. An example of VIEWSAT output, together with the related flight conditions, is shown in Figure D-5.

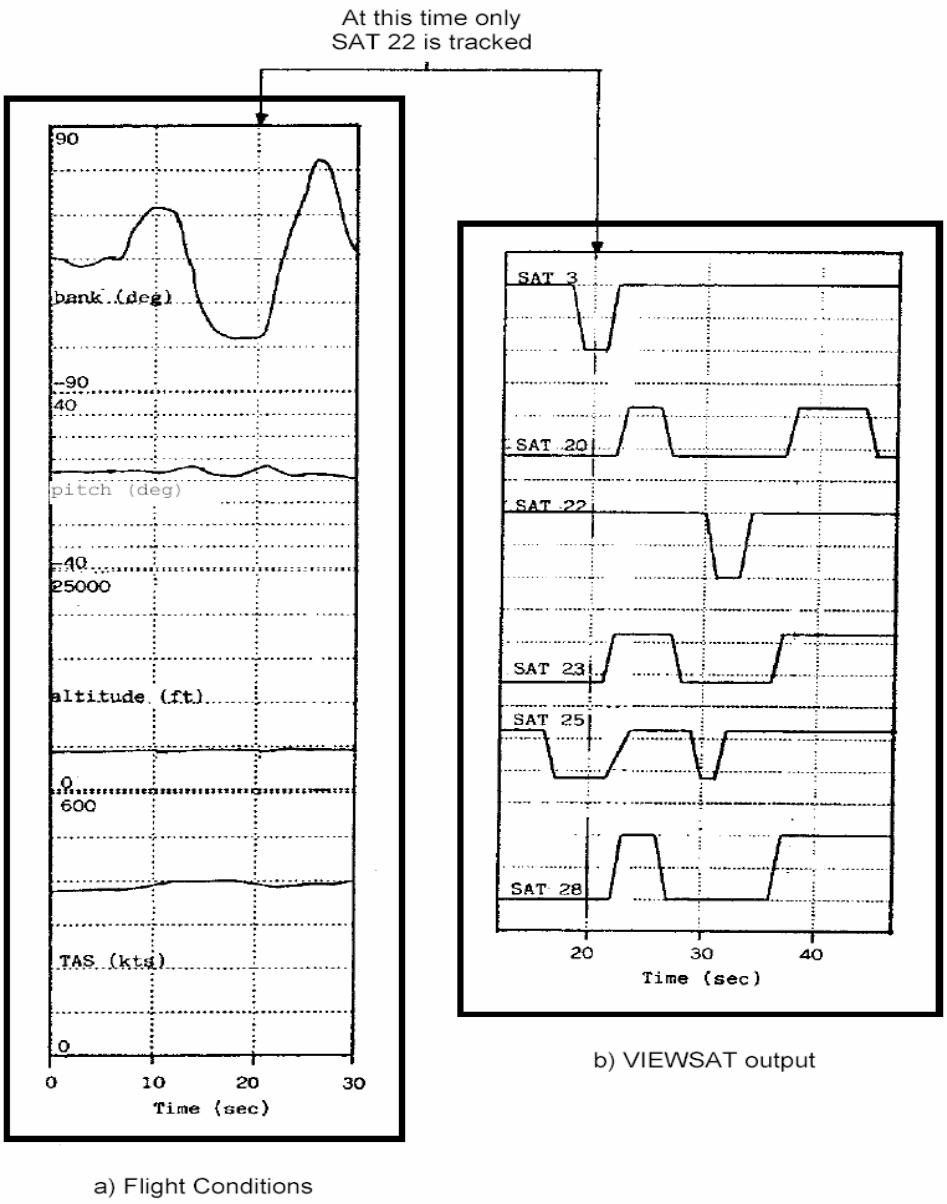

Figure D-5: Example of VIEWSAT Output and Relevant Flight Conditions.

For every flight segment with loss of GPS data satellite masking was investigated using VIEWSAT. This was done in the attempt to determine the critical aircraft manoeuvres using the time histories of the recorded flight parameters (particularly: heading, bank and pitch angles, TAS, barometric-altitude and radar-altitude).

D.1.1 Critical Manoeuvres and Flight Conditions

The following considerations are referred to a flight carried out with a number of 7 visible satellites (Figure D-6). During the trial the maximum variation of the satellite positions was in the order of 30° in azimuth and 20° in elevation. Satellites with low elevations above the horizon (elevation < 10°) were not tracked. During manoeuvres, it was observed that the satellites more likely to be lost were those with an elevation lower than 35°.

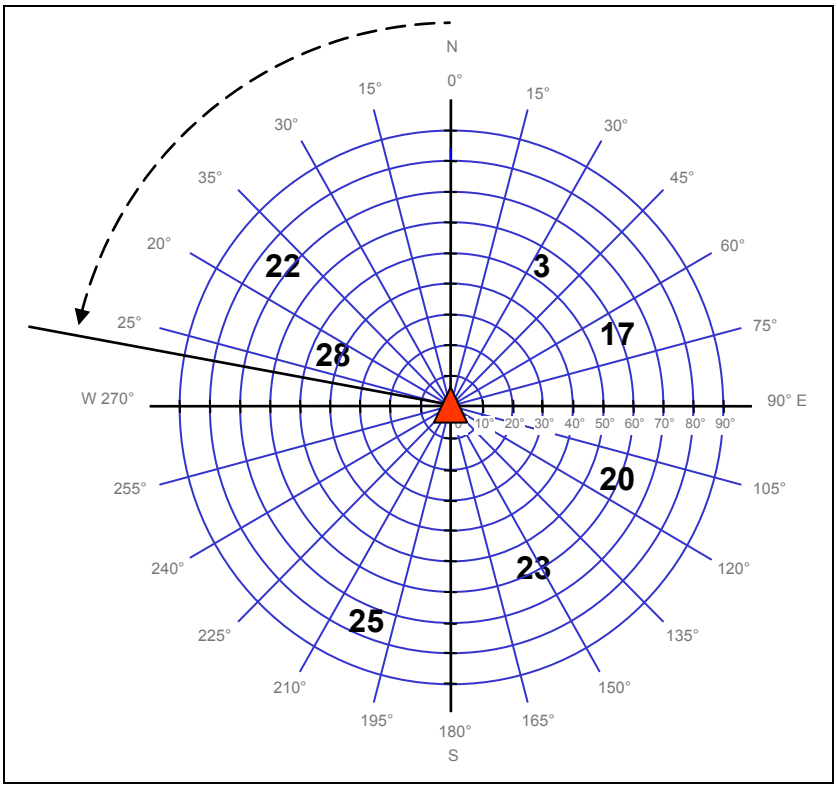

Figure D-6: Relative Geometry of the Aircraft and Satellites.

Analysis of the aircraft attitude data allowed the identification of some important critical manoeuvres. In general, these manoeuvres were characterized by a simultaneous non-gradual variation of two attitude angles (i.e., pitch, roll and yaw).

A very rapid variation of height (if not associated with a considerable variation in pitch and/or roll) was not sufficient alone to determine satellite losses (Figure D-7).

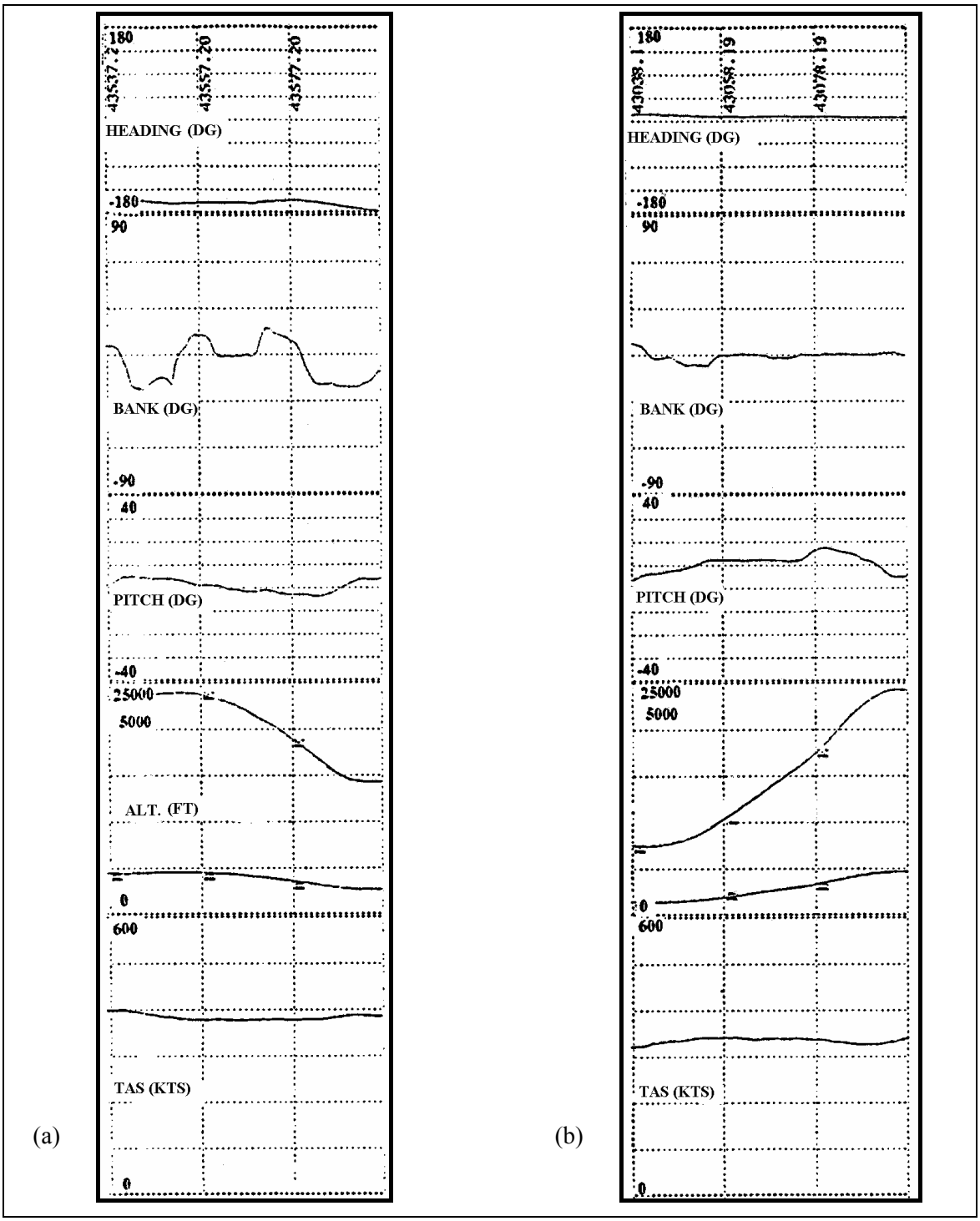

Figure D-7: Altitude Variations Without Satellite Signal Losses During Low Bank Manoeuvres (a) and in Vertical Flight (b).

A manoeuvre that was found to be very critical was the turn in the following conditions:

- Bank ≥ 50°; and
- Heading change > 90°.

Figure D-8 shows two flight data slices in which these elements can be identified.

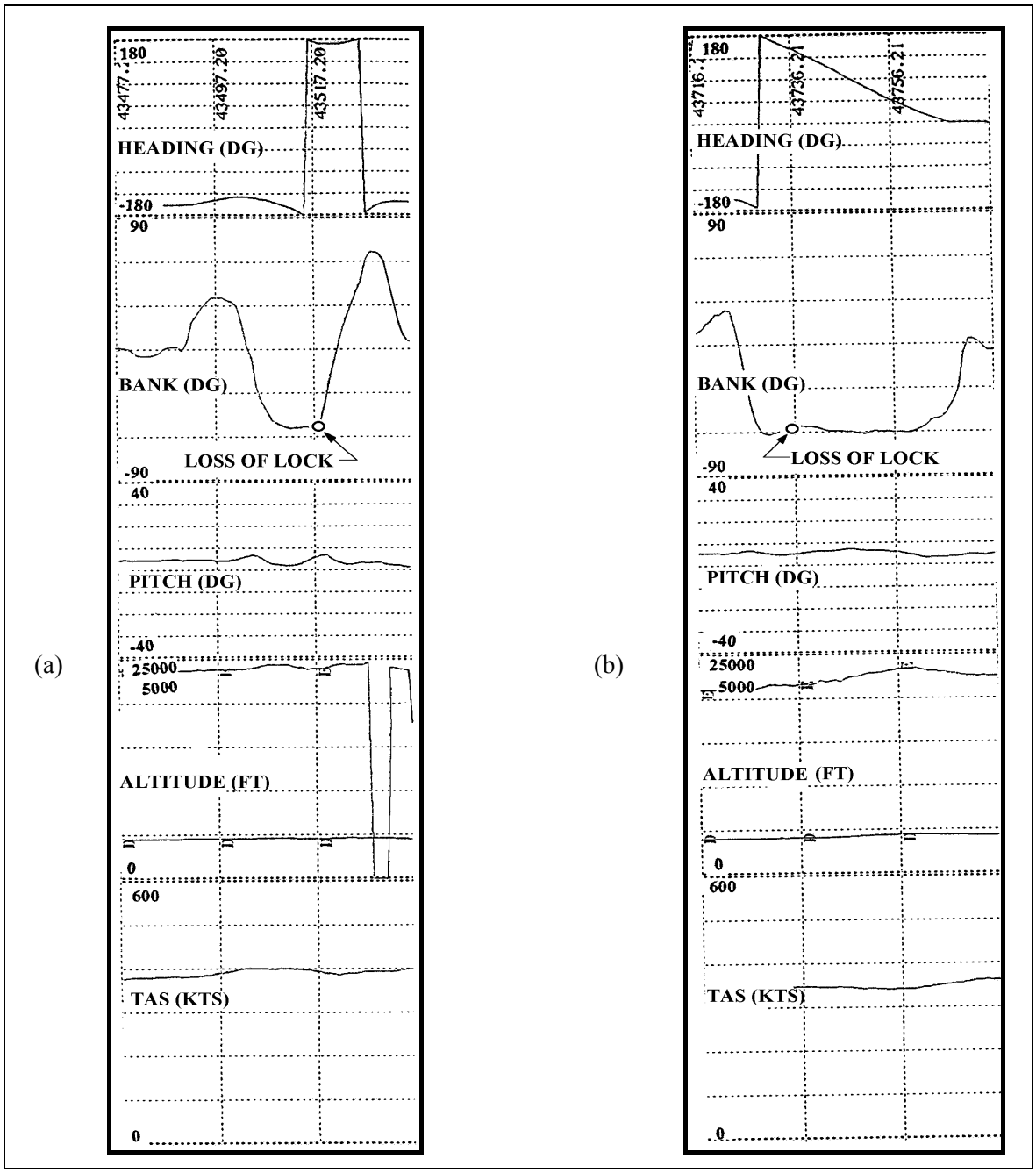

Figure D-8: Critical Manoeuvres (Loss of Satellite Signals).

It was also noticed that, after loss-of-lock to all satellites (after turns with bank ≥ 50°), the signals were generally reacquired shortly after the turns were interrupted (a few seconds), but in case of rapid altitude variations the satellite signals reacquisition could be significantly delayed (up to 2 minutes), also during periods of gradual heading variations and low bank (i.e., less than 5°).

There are some important considerations about the Critical Bank Angle (CBA). It is in fact necessary to take into account that, during the turns, the satellites lower on the horizon were likely to be masked; but in

most cases the manoeuvre was critical only if the CBA was reached and maintained for a period of time exceeding about 5 seconds and with a large heading change (usually greater than 90°). In these cases, after 5 seconds, the number of satellites lost (n) was greater than (m – 4), being m the initial total number of satellites (Figure D-9).

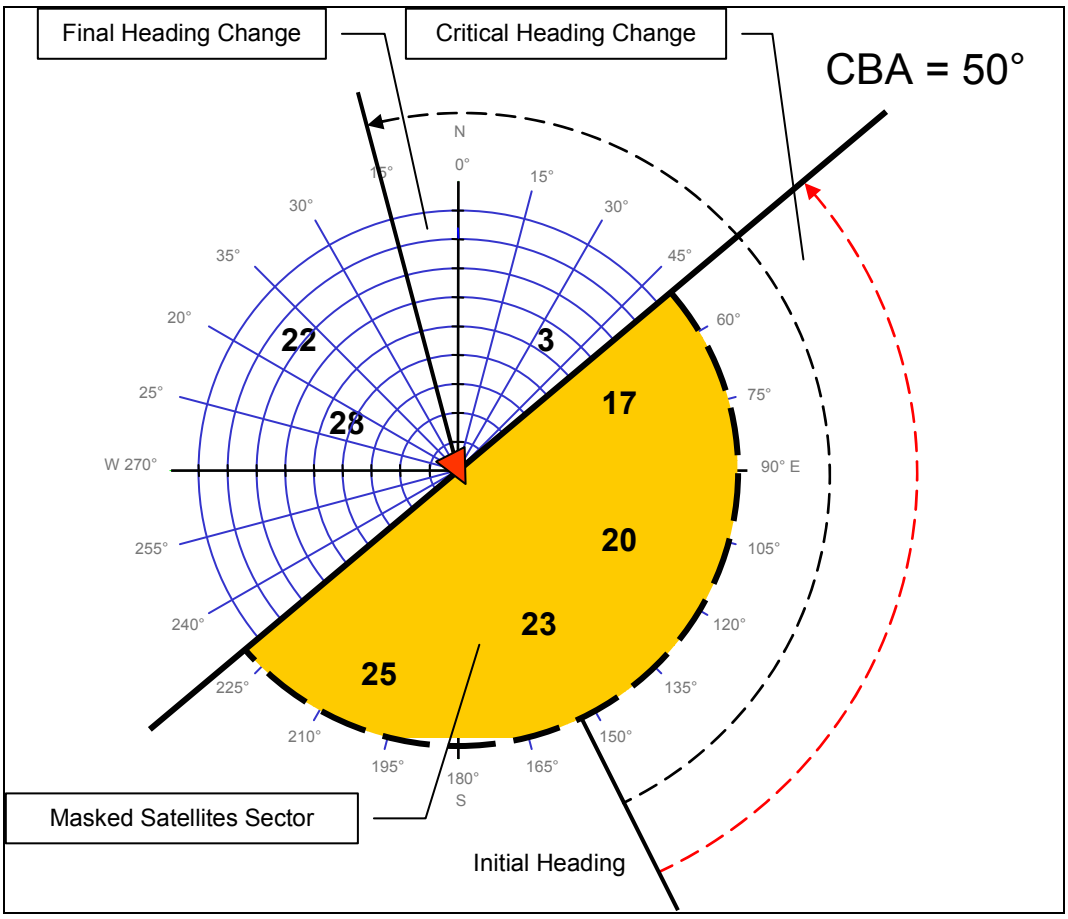

Figure D-9: Satellite Masking (SVs 17, 20, 23 and 25).

In many situations, however, the same manoeuvres did not determine the loss of lock to the satellites. The difference between the two cases (loss and no-loss) was represented by the fact that in the no-loss case the turns were following periods of stabilized flight (without significant heading, bank and height variations) longer than about 40 seconds. Figure D-10 shows a manoeuvre in which both the bank and the heading angles exceeded the critical values, but loss of GPS data did not occur. Similarly, also in the approach phase of a flight, a number of turns with high bank angles, progressively performed at lower altitudes, did not determine the signal loss (Figure D-11).

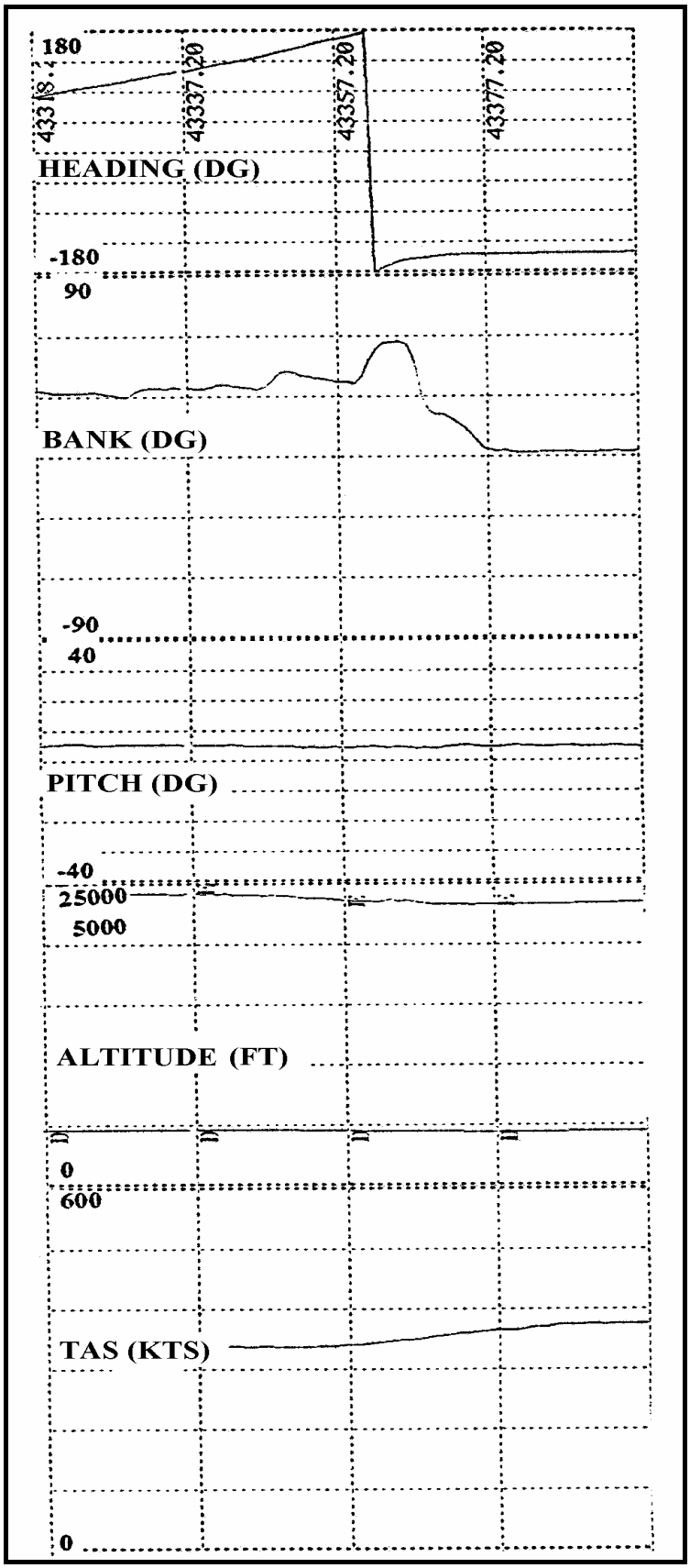

Figure D-10: Critical Conditions (CBA, Heading Change) without Loss of GPS Data.

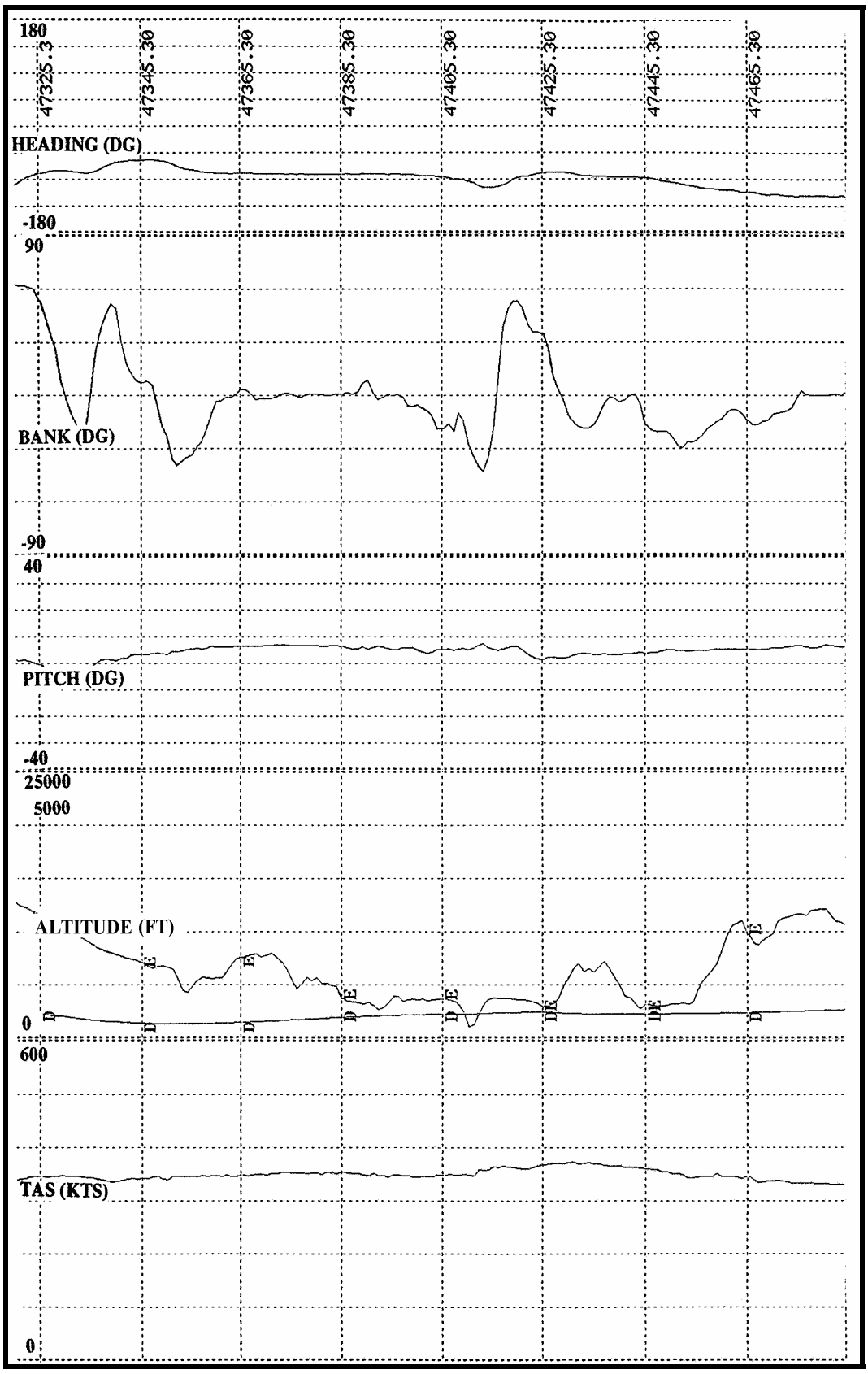

Figure D-11: Approach Manoeuvres with High Bank and No Loss of GPS Data.

Further analysis of the experimental data showed that the signal losses were maximised if the turns were started with an initial aircraft heading in the sectors from north-east to south-east in case of left turns and from south-west to north-west in case of right turns. In order to assist in the investigation of this evidence, we started examining the characteristics of typical "sky-plots" (i.e., satellites azimuth and elevations observed from certain locations on the hearth surface and for a certain period of time) that can be obtained at our latitudes. Figure D-12 shows a sky-plot relative to the city of Rome (date: 25th June 2005; coordinates: North 41° 52', East 12° 37', h = 0; duration: 24 hours).

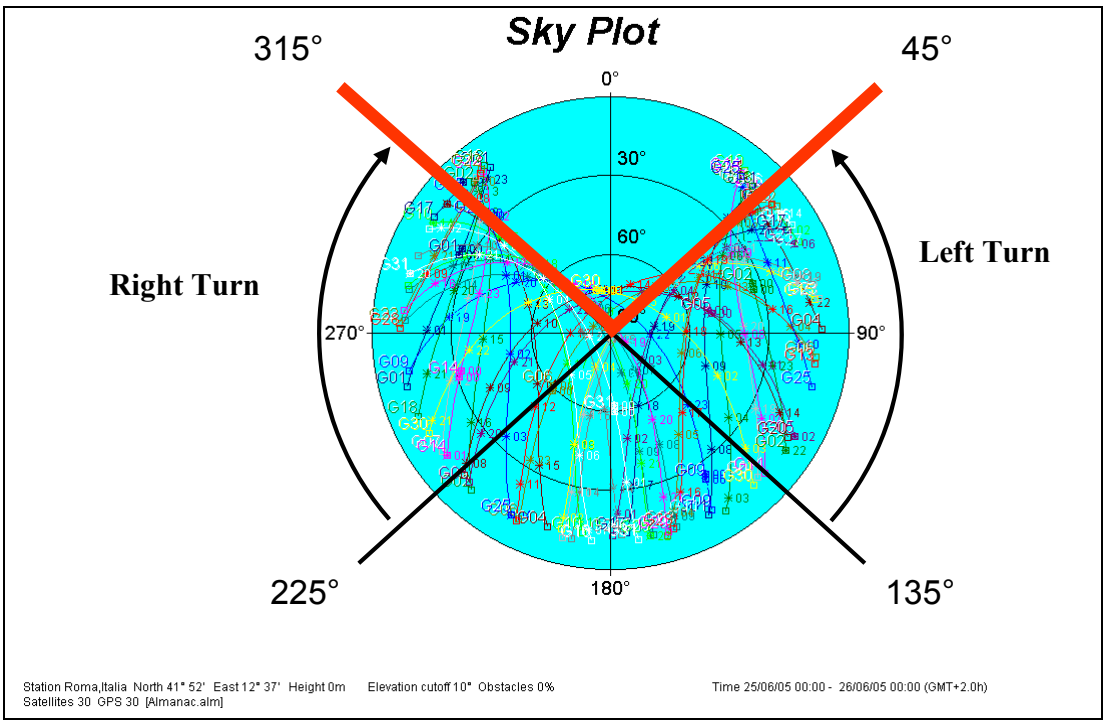

Figure D-12: GPS Sky-Plot.

It is evident that in the northern hemisphere/mid-latitudes the majority of satellites are available in the azimuth range 45° ÷ 315°, and that a left turn of an aircraft with an initial heading in the range 45° ÷ 135° (i.e., north-east ÷ south-east) would be prone to GPS data losses, due to the reduced number of satellites available in the direction of the turn. Similar considerations apply for the right turns performed with an initial heading in the range 225° ÷ 315° (i.e., south-west ÷ north-west).

D.1.2 Reacquisition Time

On average the ASHTECH receiver was able to give a new position solution within about 20 seconds from restoration of the line-of-sight conditions to the satellites. Therefore, it was generally sufficient to maintain a low bank angle for about 20 seconds in order to obtain a new solution. However, if the height was kept constant the time required was reduced to about 10 seconds. This can be seen comparing the diagrams in Figure D-8(a) with the corresponding VIEWSAT diagram shown in Figure D-13.

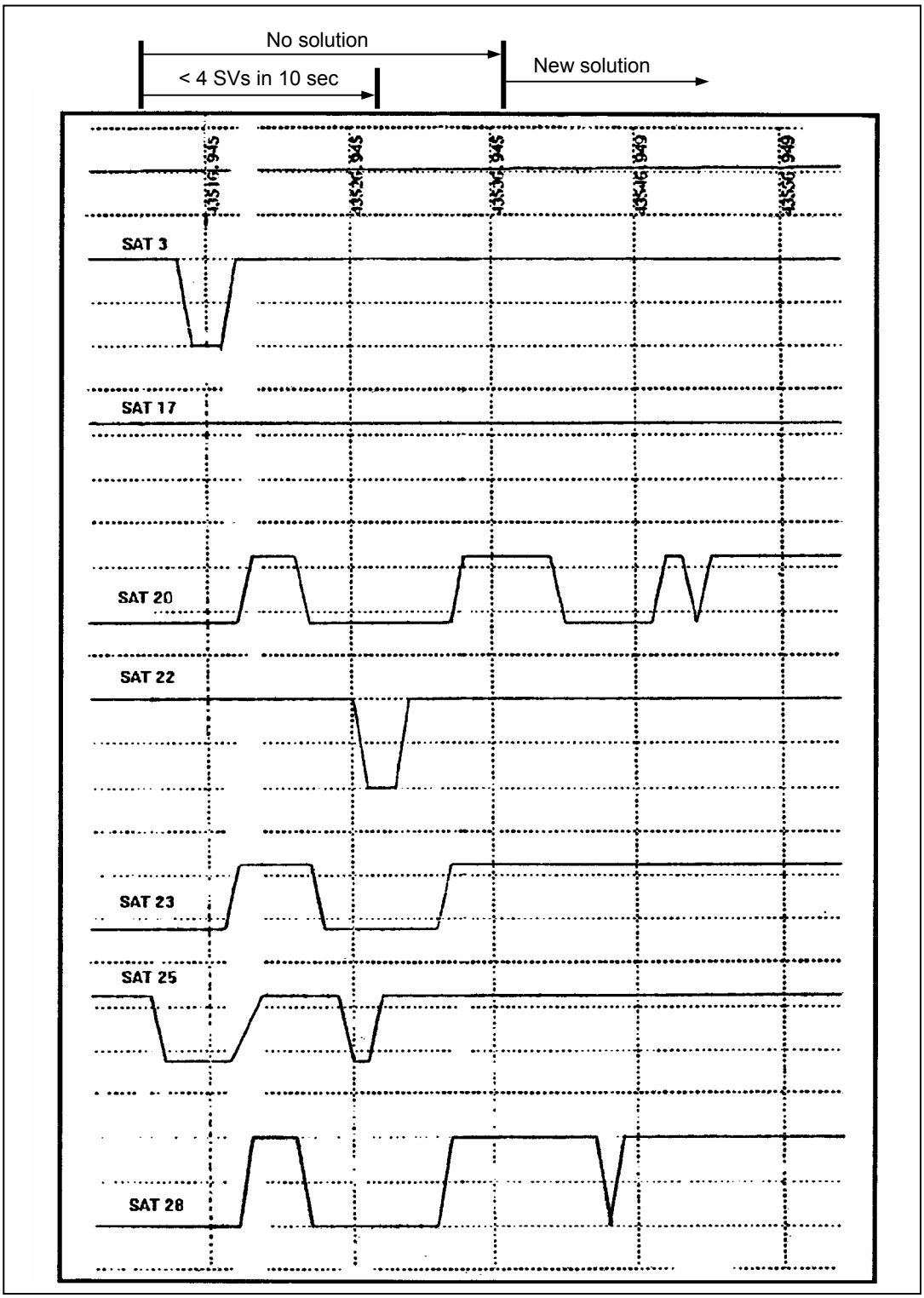

Figure D-13: VIEWSAT Diagram Corresponding to GPS Data Loss and Reacquisition.

It is in fact possible that the receiver was able to store in its internal memory, for about 10 seconds, the last positioning data computed and that it used these data to provide a positioning solution even without the inclusion of new measurements.

D.2 SIGNAL-TO-NOISE RATIO

Another significant aspect taken into account was the influence of the Signal-to-Noise Ratio (SNR) on satellite reacquisition. It was in fact thinkable that the availability at the user location of a number of satellites with high SNR could facilitate the computation of a new positioning solution after data losses. In order to investigate on this aspect the ASHTECH receiver B-files were examined.

During analysis of the time histories, VIEWSAT diagrams and satellite visibility data, it was not possible to explain all data "holes" in the C-files only in terms of satellite masking. In other cases, masking situations given by the VIEWSAT did not correspond to satellite losses. In order to explain these events, the B-files (containing the measurements data) were examined. Since they were in binary format an ASHTECH software package was used to convert the B-files into ASCII Format. Reading the files it was possible to determine the quality of the signals received from the different satellites especially in terms of SNR. A typical B-file in ASCII format is shown in Figure D-14. It contains the following data:

- Record number (RECORD);
- GPS time (RECEIVE TIME);
- Satellite identifier (SV);
- The channel allocated to each satellite (CH);
- A diagnosis parameter relative to the receiver clock status, the phase of the signal carrier and the loss of signal tracking (WN);
- A parameter relative to the synchronisation of the received signal (P);
- A parameter for measurement quality for positioning calculation (G);
- The time interval in msec between transmission and reception of the GPS signal (TXMTIME);
- Doppler frequency measurement in 10-1 Hz, positive when the satellite gets farther from the receiving antenna and negative when it gets closer (DOPPL); and
- The SNR (S/N).

```
RECORD = 2675  RECEIVE TIME = 389766.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL    CARRIER_PH  EL  AZ S/N  DT
 3  3   0 5 24 0.9270  21882853  26117310     184380.200  0   0  24   L
22  6   0 5 24 0.9304  20866062 -13418220   -5913972.448  0   0  48   L
23 10   0 5 24 0.9221  23343366 -35951450     -18099.512  0   0  16   L
17 11   0 5 24 0.9319  20408722   9882530    -776080.344  0   0  38   L
SITE       NAVX              NAVY              NAVZ              NAVT
??84   4854639.850000     827511.800000    4041537.260000      56519.87
PDOP      NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
   5       129.910           -17.720           -156.700             0.00
```

Figure D-14: Typical B-File in ASCII Format.

For the aim of our analysis, looking at the variations of the S/N ratio parameter, we verified that the loss of some satellites often corresponded to bad SNR (S/N < 10), while reacquisition after a signal loss (also with bad geometrical conditions) correspond to good SNR (S/N > 30). Examples of B-files for loss and reacquisition of the GPS satellites are shown in Figure D-15 and Figure D-16.

```
RECORD = 3314   RECEIVE TIME = 390405.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH  EL  AZ S/N  DTYPE
 3  3   0 5 23 0.9263  22095070  11120630     166127.424   0   0  32   L1
22  6   0 5 23 0.9310  20688639 -13163430   -6846332.016   0   0  28   L1
17 11   0 5 23 0.9316  20510615   6844480    -240609.592   0   0  38   L1
SITE        NAVX              NAVY              NAVZ              NAVT
??84    4837195.240000    833057.340000   4062806.670000    33073.103967
PDOP       NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
   11      -135.990            63.410           152.770          0.000000
```

Figure D-15: B-File for GPS Data Loss (the quality parameter "G" = 23 indicates the phases of the code and the carrier have been measured and the navigation message has been acquired, but the positioning solution has not been calculated).

```
RECORD = 3390   RECEIVE TIME = 390481.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH  EL  AZ S/N  DTYPE
28  1   0 5 24 0.9233  22991374 -28014730    -118781.704   0   0  32   L1
22  6   0 5 24 0.9310  20672491 -11540130   -6931209.464   0   0  40   L1
21  7 128 5 24 0.9179  24613557 -45882240          0.376   0   0  22   L1
17 11   0 5 24 0.9315  20529652  15629200    -140577.288   0   0  42   L1
SITE        NAVX              NAVY              NAVZ              NAVT
??84    4844069.780000    833229.060000   4054941.930000    30665.770529
PDOP       NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
    5       147.350            -62.450           -161.090          0.000000
```

Figure D-16: B-File for Signal Reacquisition.

Looking at the various records of B-files it was possible to identify short periods of signal loss, which did not correspond to data "holes" in the C-files. This confirmed the hypothesis that the receiver was able to store data in its memory for short periods. An example is shown in Figure D-17.

```
RECORD = 2669   RECEIVE TIME = 389760.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH  EL  AZ S/N  DTYPE
 3  3   0 5 23 0.9270  21879892  26164440     168877.048   0   0  40   L1
22  6   0 5 23 0.9304  20867613 -14035390   -5905822.256   0   0  26   L1
17 11   0 5 23 0.9319  20407625   9873000    -781837.576   0   0  28   L1
SITE        NAVX              NAVY              NAVZ              NAVT
??84    4853695.960000    827678.870000   4042789.890000    56912.600227
PDOP       NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
    4       128.780            -56.080           -141.360          0.000000

RECORD = 2670   RECEIVE TIME = 389761.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH  EL  AZ S/N  DTYPE
 3  3   0 5 24 0.9270  21880390  25913520     171481.792   0   0  34   L1
22  6   0 5 24 0.9304  20867346 -13758060   -5907210.560   0   0  28   L1
23 10 128 5 24 0.9221  23346821 -35783970         -0.352   0   0  30   L1
17 11   0 5 24 0.9319  20407815   9646100    -780860.712   0   0  34   L1
SITE        NAVX              NAVY              NAVZ              NAVT
??84    4853986.980000    827571.040000   4042311.870000    56705.743431
PDOP       NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
    5       131.280            -20.950           -150.090          0.000000
```

Figure D-17: Signal Loss Shown in a B-File with No GPS Data Interruption in the C-File (examining the VIEWSAT diagrams, masking was confirmed for SV 23, but the receiver was able to reacquire SV 23 in a short time and to maintain tracking to the satellite for a period sufficient to compute a new positioning solution; the WN parameter at 128 indicates the loss of tracking to the satellite in previous epochs).

It was demonstrated by data analysis that the ASHTECH receiver provided a positioning solution only if the SNR of at list four satellites was above a pre-defined value (presumably between 15 and 30 dB), which was not selectable by the user at the ground programming stage. An example is shown in Figure D-18, in which four satellites were in view, but no data were recorded in the C-files. As the SV 28 was lost (S/N < 30), the receiver was no longer able to compute the position (G = 23) of the aircraft (the SV 24 has SNR = 14).

```
RECORD = 2975  RECEIVE TIME = 390066.000000
SV CH  WN P G TXMTTIME  CDPHASE     DOPPL    CARRIER_PH  EL  AZ S/N  DTYPE
22  6   0 5 23 0.9307  20778694 -13415070   -6373110.248  0   0  32   L1
25  9   0 5 23 0.9225  23241264  20208680     436358.008  0   0  14   L1
23 10   0 5 23 0.9227  23175309 -33561880     -36627.432  0   0  30   L1
17 11   0 5 23 0.9318  20451247  12684420    -552601.040  0   0  38   L1
SITE        NAVX              NAVY              NAVZ              NAVT
??84   4849452.470000     832295.880000    4048610.790000      45046.814739
PDOP       NAVXDOT           NAVYDOT           NAVZDOT           NAVTDOT
   51       142.900           -72.010           -154.740             0.000000
```

Figure D-18: B-File Corresponding to Data Loss in the C-File with Four Satellites Tracked.

D.3 FLIGHT TEST MISSION PLANNING AND OPTIMISATION

As a result of the analysis carried out some recommendations were formulated in order to optimise the use of DGPS as a datum in flight test missions (i.e., in order to reduce signal loses). In particular, the following criteria's should be taken into account:

- It should be assured the visibility of at least 6 satellites, possibly with 4 at elevations near 50°;
- The maximum bank angle allowed is 50°;
- A stabilisation of at least 20 seconds should precede and follow the significant flight phases;
- The heading variations should be as gradual as possible;
- It should be minimised the number of left turns performed with initial heading ranging from 45° to 135°, and the number of right turns performed with initial heading between 225° and 315°; and
- The distance between the aircraft and the ground receiver should be always less than 200 NM to obtain accuracies of less than 5 metres.

These restrictions, of course, imply operational limitations that reduce the spread of possible DGPS applications in the flight test environment.

Some flight trials were performed in order to verify the validity of the criteria's mentioned above. Figure D-19 shows the variations of heading, bank, pitch, height and TAS during one of these trials. It can be seen that the manoeuvres always followed periods of stabilised flight and the height was kept constant.

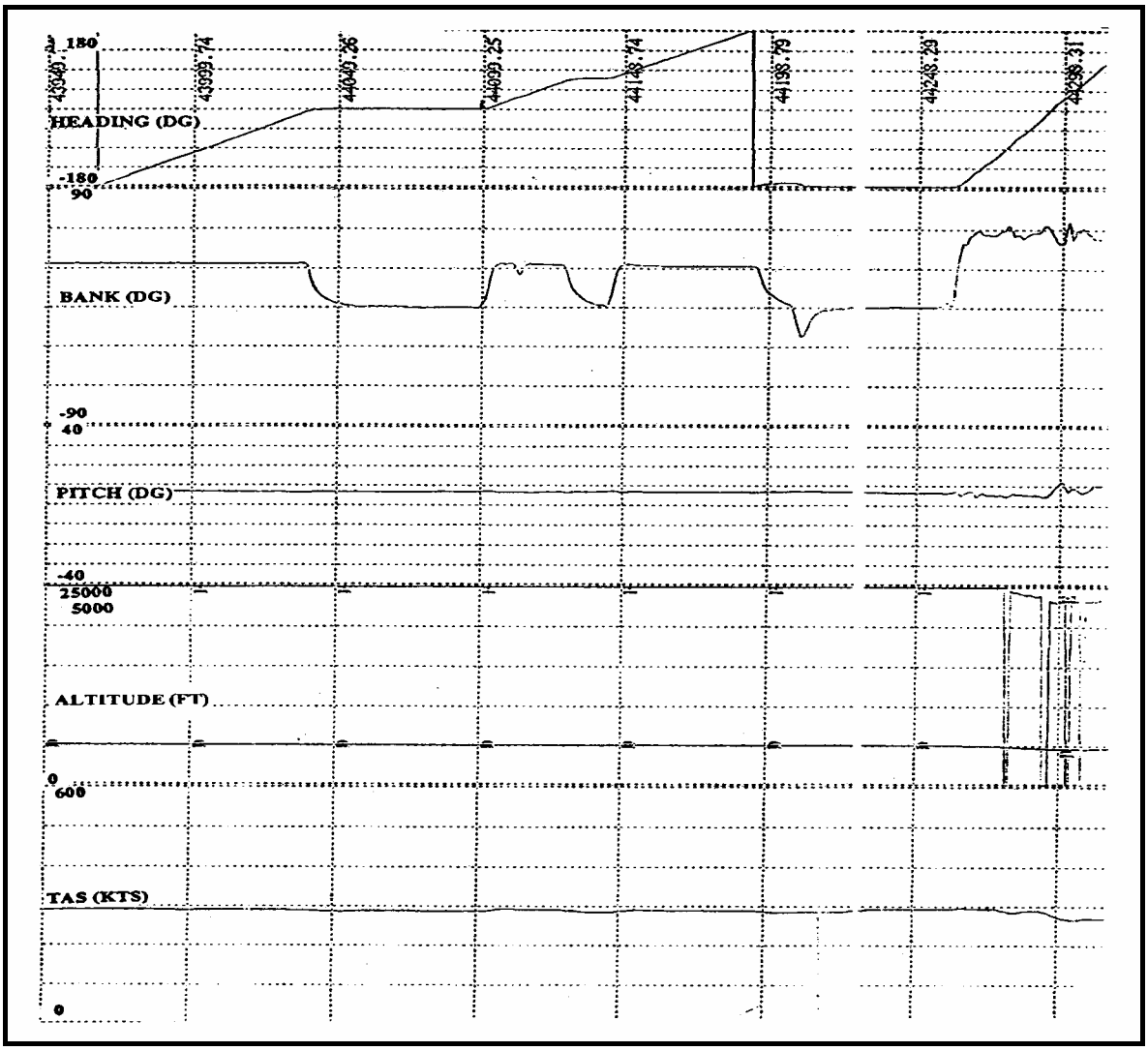

Figure D-19: Optimised Manoeuvres for DGPS Data Gathering.

The visible constellation during the flight sortie included a total of eight satellites, with at list four having an average elevation grater than 50° and two with an elevation always greater than 30°. The trajectory diagram shown in Figure D-20 is completely free from signal losses.

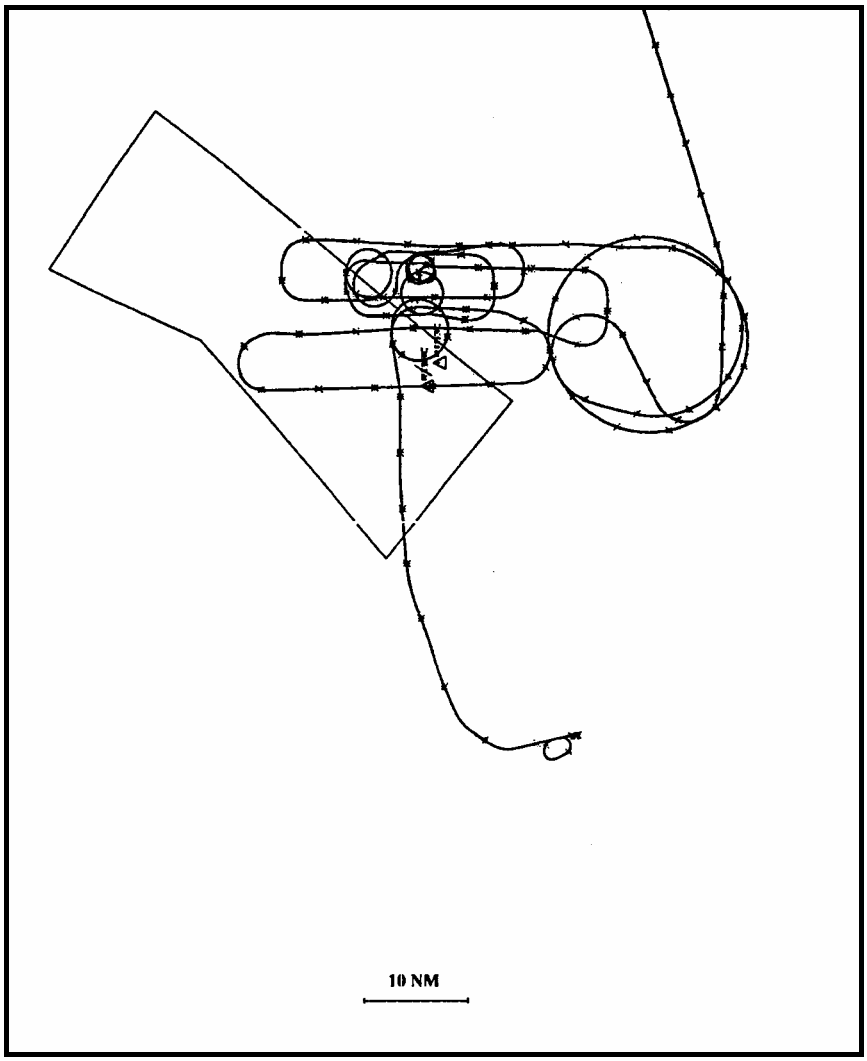

Figure D-20: Measured Aircraft Trajectory with Mission Optimisation Criteria.

In the light of the optimisation criteria previously mentioned, whose validity was demonstrated in several flight trials (also after completion of the test campaign carried out on TORNADO-IDS/EF-2000), it appeared obvious that the resulting flight profiles were not sufficient for some specific test missions requiring high dynamics manoeuvres to be performed within a few seconds (i.e., fighter/attack aircraft testing).