TERRAIN AIDED NAVIGATION - CURRENT STATUS, TECHNIQUES FOR FLAT TERRAIN AND REFERENCE DATA REQUIREMENTS

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ABSTRACT

Terrain Referenced Navigation techniques are now well established as effective position fixing systems suitable for use in manned and unmanned vehicles. The GEC SPARTAN TRN technique, which has been selected for the UK Tornado GR4 update, provides accurate navigation with rapid initial capture without recourse to an initialisation mode.

The paper provides an overview of the SPARTAN technique and goes on to describe techniques for improving nvigation performance over very flat terrain. The benefits of the Terrain Characteristic Matching techniques are outlined and a summary of integrated navigation system performance is given.

Terrain Aided systems require appropriate reference databases. The availability of the data and its suitability is discussed. Finally the paper indicates the need for database quality and registration to be given careful consideration when Terrain Aided systems are being designed.

INTRODUCTION

The practice of using terrain features to provide a position fix is the oldest navigation technique known to man and has been in use by aircrew since the earliest days of flying. The significance of todays Terrain Aided Navigation (TAN) systems is that they are essentially continuous, they require no intervention by the crew and they provide a degree of position accuracy which even ten years ago would not have seemed possible or even useful. Todays military planners have come to expect that the position of any vehicle can be known to within a few tens of metres.

The technology developments which have made this possible include:-

- Algorithms capable of extracting very accurate information from noisy and ambiguous data.
- Processor architectures and performance which allow real time computation of the algorithms within a small volume.
- Mass Memory technology which enables data for operationally useful areas of the world to be held on board a vehicle.

While these developments will undoubtedly continue the situation for TAN has essentially stabilised. The concept has been developed, proven to work and committed to production. This does not mean that development has stopped or will stop - like the automobile which had reached a state of mass producibility in the form of the model T Ford some seventy or eighty years ago - we can still expect changes in TAN techniques.

The purpose of this paper is to first provide an overview of the current state of TRN or more correctly Terrain Contour Navigation. This is the most developed variant of the TAN family, certainly for continuous navigation, and is the first to achieve a wide level of acceptance. Second the paper discusses one of the newer techniques of TAN which extends the operational range of terrain based navigation into areas where data from terrain relief is sparse. The technique is that of Terrain Characteristic Matching (TCM) which uses cultural features instead of the shape of the terrain. Finally the paper reviews the important data base requirements of both navigation and other functions which use terrain referenced databases.

TERRAIN REFERENCED NAVIGATION

Terrain Referenced Navigation (TRN) techniques have been under development, in various forms, for well over ten years. During that time the aims have been to make it operate continuously, reliably and accurately. An important secondary aim has been to enable rapid 'capture' of accurate position from a large initial error.

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The basic concept of the GEC SPARTAN TRN system is shown in Fig. 1. This shows the data which are required to generate a measured profile of the terrain overflown. It is not necessary for the ground height to be sampled along a straight track, providing the dead reckoning system can measure the horizontal movements.

The length of the sample of measured terrain, the transect, is important. Early systems employed a transect of 5 to 10 km, which, when compared with a reference data base of terrain height gave a unique match. The unambiguous agreement between measured terrain and the data base gives a very good position fix but the vehicle has had to travel up to 10 km to gather the data. The position fix was true some 5 km back and is therefore unable to correct for recent drift in the dead reckoning system. Techniques to improve this have all aimed at reducing the length of the transect in order that the fix can be applied sooner. Another point which drove the development of SPARTAN was the need to avoid, if at all possible, any form of capture or initialisation phase. This has been considered of great importance, not because of the needs of pure navigation, but in order to rapidly enable additional terrain related functions after let down from high altitude or making land fall. Of these map directed terrain following and precision targeting are of obvious importance. In order to achieve this the SPARTAN concept, employing a short, 400 metre transect was developed.

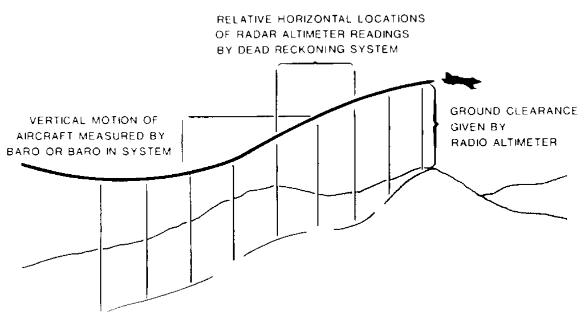

Fig. 1 TRN Principles

SPARTAN achieves accurate navigation by applying a refinement of Bayes theorem (1) to extract data from the convoluted surface shown in Fig. 2. This is an example of the highly ambiguous correlation surface which results when a short transect is compared with the reference data base. The essence of the technique is to fit a smooth quadratic surface to the data, the parameters of which are handed over to a Kalman filter. The filter treats the information as a standard fix update containing position, in the form of a correction to the current position estimate, and an uncertainty estimate. The fix quadratic is extracted from the original correlation surface and the residual retained in what is called the stockpot. This represents information about the terrain which has not yet been used. The next set of transect data, only 400 metres further on, is added to the stockpot and the process repeated.

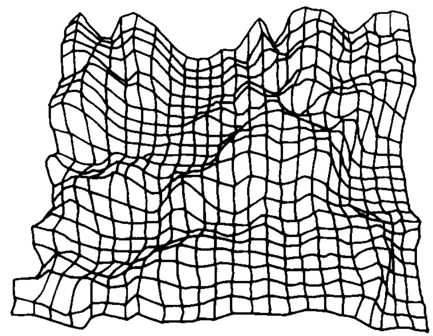

Fig. 2 Correlation Surface for a Short Transect

The system requires no initialisation mode, as soon as transect data is available, information is being fed to the Kalman filter, and as shown in Fig. 3 capture is extremely rapid. This shows an aircraft track as it comes in from the sea. The radar altimeter just detects the peninsular as can be seen from the terrain profile shown along the bottom edge of the figure. This enables a fix to be computed and the position error to be dramatically reduced. Once land fall is made the position error is further reduced and remains very good for the whole of the flight as shown. An early implementation of the SPARTAN technique is described in (2).

Once the viability of continuous very accurate navigation had been demonstrated, a host of new facilities were identified as being possible. Important amongst these is the possibility of supporting passive Terrain Following (TF); that is controlling an air vehicle in low level flight at a set clearance height without the use of a forward looking sensor. To date a vehicle requiring an automatic (or even directed manual) terrain following capability needed a forward looking radar. While the radar systems clearly work, as demonstrated by the UK Tornado GR1 and US F111, they are expensive, large and heavy and therefore impractical for many vehicles.

Also the forward radiation can be disturbed by weather or jammed, causing unwanted pull ups, and is hardly appropriate to missions requiring stealthy ingress. Map directed (Passive) TF systems, on the other hand, are available at low cost, are small and inherently immune to radiation related problems. They can also make use of knowledge of terrain beyond the next hill and thus, unlike the radar, prevent ballooning over peaks. A detailed description of the techniques is given by Morgan in (3).

TRN systems have been flight tested over several years both in Europe and the USA. Successful demonstration flights of the SPARTAN TRN and TF functions have also been completed on the AFTI F16 and the UK Tornado. The SPARTAN TRN and TF system has been selected for the UK Tornado GR4 Mid Life Update. The development of the system is well underway and B models will be delivered 2nd quarter 1990. The equipment is scheduled to be in service in 1995.

The equipment consists of a single $^3/_4$ ATR unit and includes an integral solid state database with a capacity equivalent to 600,000 square km. The unit supports obstacle cueing and passive target ranging in addition to the basic TRN/TF functions.

NAVIGATION OVER FLAT TERRAIN

Clearly if the ground is totally featureless a system which depends on the unique shape of the terrain will have difficulties. In the limit of transits over water the TRN function can provide no horizontal position information. (It can of course provide accurate height). For many applications, providing there are sufficient terrain features in an otherwise flat area, the combination of the rapid capture capability and the modelling of the IN drift in the Kalman Filter are enough to provide adequate navigation.

A problem can arise when the target is a long way from a convenient terrain feature resulting in reduced accuracy just when it is needed. Depending on the scenario and the target this can often be handled with a suitable target seeker, although there is still the requirement to achieve the position and pointing accuracy necessary for the seeker to lock on.

A further difficulty can arise when a terrain following aircraft or missile flies out of the hills over a flat plain. While over the hills the vehicle can make maximum use of terrain screening to avoid detection and engagement by enemy defences. Once it leaves the hills and TRN cease to provide accurate fixes the horizontal uncertainty grows. This tends to cause the vehicle to fly higher - not to avoid the terrain but to clear the various obstructions - particularly cables - which may be in its path. Because of the reduced accuracy of the horizontal position estimate, even if the locations of the obstacles are known precisely from the on board data base, they must be given a wide berth. The vehicle must fly higher for longer, and risk the consequences.

Current TRN systems which only use elevation features begin to suffer performance degradations if the terrain slope is substantially less than a few %. Under these conditions, to ensure mission success additional fixing aids are required.

A range of possible fixing aids exist which will improve the situation. First consider Doppler aiding. This is easy and well understood but it entails an additional sensor and is not very covert (although improvements are being made). Additionally it can only reduce the growth of the position error - it can never reduce the error itself - so that prolonged flight over flat terrain will ultimately lead to a poor position estimate. Navstar GPS is clearly an attractive solution to the problem and work on the refinement of GPS and TRN integration is currently under way at GEC Avionics and elsewhere. However GPS is not quite the panacea it was hoped. It certainly provides very good navigation accuracy, comparable with or even better than TRN. It is not fundementally limited by terrain characteristics although terrain masking of satellites can be a problem at very low altitude. However because it depends on signals received from the satellite constellation it is vulnerable to jamming. It is not easily jammed but a determined opponent with reasonable knowledge of the likely targets will inevitably achieve some disruption of satellite reception. And unfortunately this is likely to be most effective over flat ground where screening of the jammers by terrain is less of a factor. There is also concern that while GPS can provide accurate position with respect to the WGS84 spheroid, the obstacles to be avoided are more likely to be located with respect to a different reference but more of this later. Aware of these problems various groups have developed techniques to use characteristics of the terrain, other than vertical relief, to provide accurate position fixes. In general, these methods are most effective when the terrain is flat

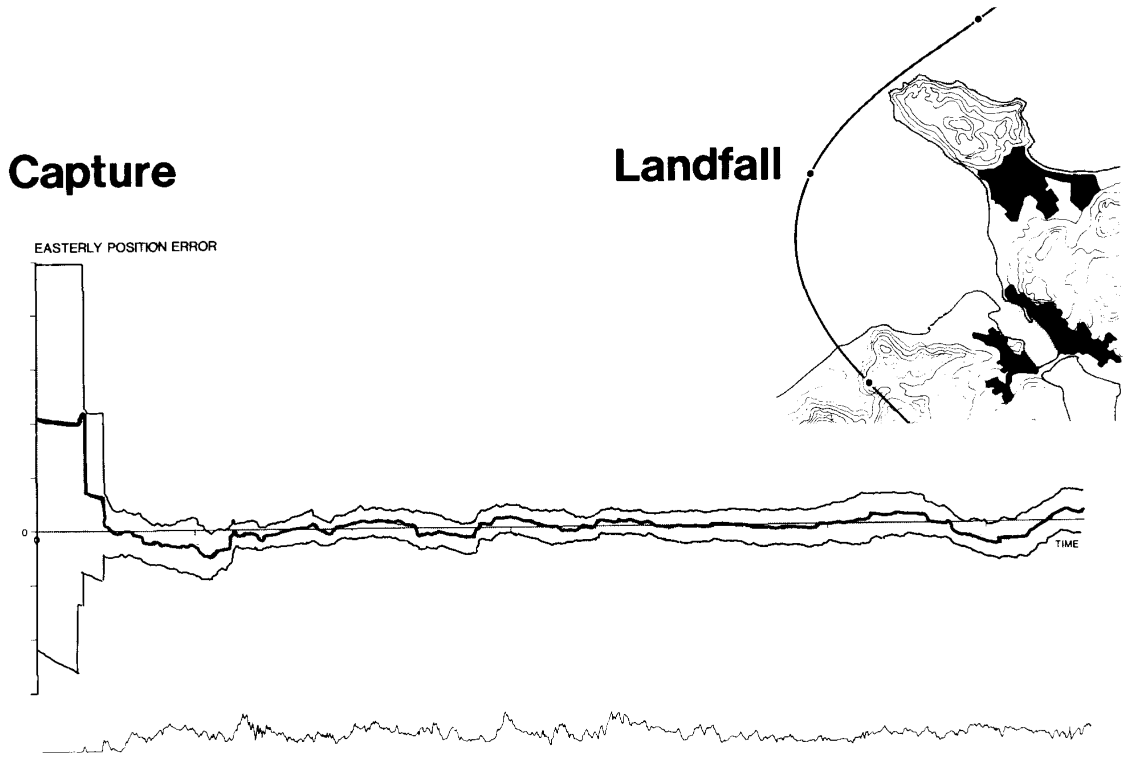

Fig. 3 SPARTAN Performance

which makes them complementary to TRN. They also tend to be more accurate than TRN, primarily because of the type of features used. An example of such a system is Scene Matching Correlation (SMAC). This is described in the Reference (4) and only an overview will be given here. The Intelligent Sensor System (ISS) described in (5) offers an alternative approach.

SMAC typically makes use of an Infra Red line scanner (IRLS) to generate an image of the terrain being overflown. This is then compared with a stored reference scene. If a match is achieved a fix is generated. Normally, because of the need to correlate on unique features and because of the difficulties in generating the reference scenes, the system is used to provide discrete, very accurate fixes at intervals of a few kilometres. The system is well proven and live trials of integrated SPARTAN and SMAC have taken place under the auspices of the Royal Aerospace Establishment (RAE) Farnborough. Such a system has been proposed for Stand Off Missile programmes.

The system requires a dedicated sensor, an IRLS and this can make it expensive. This cost overhead can be reduced if the sensor is configured to be multipurpose, for example using the IRLS as a target seeker in the terminal phase. A technique which provides accurate navigation over flat terrain without an additional sensor is TCM.

Terrain Characteristic Matching

Terrain Characteristic Matching is the technique of matching various cultural features of the terrain with a stored reference. The method relies on the fact that the signal strength of the radar altimeter return signal varies with the characteristics of the surface causing the reflection. Whilst it is obvious that water will reflect more effectively than, say, a ploughed field it is not readily apparent that hedgerows, roads, tracks, ditches etc. can also be detected. The great merit of the technique is that it makes use of a sensor which is already available. The only additional requirement is a reference database and some specialised processing. Early attempts at the method involved the classification of the terrain feature prior to matching it with the reference data base. This technique exhibited some success but was overly complex for practical applications. A refinement of the method has now been developed which makes use of the boundary events or feature transitions to provide accurate position fixes. The performance that can be achieved is comparable with the best that

Table 1 Navigation System Performance

		Nominal Performance (order of magnitude figures)	Performance under conditions of				Operational Area
			Rough Terrain	Smooth Terrain	Water	Jamming	
IN		1 nm/hr	Good	Good	Good	Good	Total Coverage
IN AIDED with	TRN	< 100 m	Good	Medium	Poor	Good	All Mapped Land
	TCM	< 50 m	Poor	Good	Poor	Good	Way Patches
	GPS	30 m	Limited by Screening	Good	Good	Medium to Poor	Total Coverage
	TRN + GPS	30 m	Good	Good	Good	Good	Total Coverage
	TRN + TCM + GPS	< 30 m	Good	Good	Good	Good	Total Coverage

GPS can offer and it is essentially immune to hostile jamming.

The technique has been developed with support from the RAE Farnborough, and Integrated SPARTAN TCM performance is currently being assessed using flight data from fixed and rotary wing aircraft.

When suitable information is available, preparation of the TCM reference database is straightforward but requires significant operator interaction. Techniques are currently being developed which will enable automatic database preparation from suitable sources and the TCM correlation method is being refined to allow it to use more readily available data sources including 1:50K scale maps and commercial satellite photographs.

Integrated Navigation

To conclude this part of the paper it is useful to consider the relative navigation accuracy which can be provided by the integration of various navigation techniques. This is summarised in Table 1. The use of a 1 nm/hr IN system is not essential and the navigation accuracy achievable with a lower grade INS will be sufficient for most applications.

The important point to note is that a configuration of fixing systems can be selected which will provide a universal navigation solution.

REFERENCE DATABASES

The paper has considered the capabilities of the SPARTAN TRN system and, for use in flat terrain, the TCM and SMAC systems. The correct operation of these systems is critically dependent on the availability of suitable reference data. This section of the paper will address the reference data requirements.

Table 2 provides a list of avionic functions which require some form of ground referenced database. While it is unlikely that any air vehicle would employ all the functions listed they do give an indication of the importance of ground referenced databases to future airborne systems.

The specific requirements of the different functions clearly vary considerably in a number of aspects and space does not allow a detailed discussion of them all. However before any terrain based system can be considered viable it is self evident that the required database must be available and of adequate quality.

Considering first the issue of data base availability, Table 3 provides an overview of the products which are currently being used to support research and development activities. At present the small number of full scale development and production programmes which are active, are mainly using a variety of ad hoc data sources rather than standard products. This is clearly unsatisfactory if only because of the difficulty of providing the required integrity guarantees. It also risks a plethora of unique data products being developed which will be expensive to

Table 2 Class of Reference Data Required

Avionic Function	Elevation Data	Culture with Vertical Extent	Vertical Obstruction	Intelligence Data (Threats, Targets)	Digitised Paper Chart	Full Culture	High Resolution Culture
SPARTAN TRN	*						
Terrain/Threat Avoidance	*	*	*	*			
TCM							*
SMAC							*
Passive TF	*	*	*				
Terrain Situation Awareness	*	*	*	x			
Ground Collision Avoidance	*	*	*				
Perspective Displays	*	*	*	x			
Plan Map (Digitised Paper Chart)	x			x	*		
Plan Map (Vector)	x			x		*	x
Passive Target Ranging	*	x		x			

* - Essential   x - Desirable

generate and maintain. However as can be seen from the table, the Digital Land Mass Simulation (DLMS) data products, either current or potential, will meet many of the requirements. The DLMS products are available, with restrictions, from the various national data agencies notably the Defense Mapping Agency DMA - Washington D.C. in the USA and the Directorate General of Military Survey (D.G.Mil Svy) Feltham, in the United Kingdom.

It is worth noting that the available products were, in general, not developed for the purposes to which they are now being put. This can occasionally limit the potential performance of the resulting system, particularly in regard to the use of cultural data for navigation or routing.

The mapping agencies are very aware of these problems and are endeavouring to respond within the limits of their resources. This response will primarily result in the refinement of a range of standard products with wide applicability with the result that, over the next few years, the current limitations caused by data base availability will be removed.

For TRN there is now a large body of evidence derived from extensive flight trials in Europe and the USA which clearly indicates that good quality DLMS DTED Level 1 is perfectly adequate. This data source (which is typically derived from sources equivalent to 1:50K mapping) consists of a grid of height posts with a nominal 100 metre spacing and a vertical resolution of 1 m. The SPARTAN technique makes use of all the grid points although, where appropriate, to minimise data storage requirements, it can operate over rough terrain with a coarser vertical resolution of 4 or even 8 metres. Other TRN systems have employed a lower density of grid points.

For TCM (and SMAC) the resolution required of the reference database is much finer as the correlation process makes use of the width of linear features, typically in the 1 to 10 metre range. These features include woods, roads, rivers, railways, hedges and ditches many of which can only be found on reconnaissance photographs or large scale maps. Standard paper maps, when they do record the required features, are not ideal data sources because of the map makers tendency to shift adjacent, linear features laterally in the interests of clarity. However current developments of the TCM technique will result in a system largely immune to such effects. Efficient techniques for preparing suitable reference data from standard products including 1:50K scale maps and commercial satellite photographs will soon be available. A summary of the DLMS data products is provided in (6).

Two aspects of Reference Data quality must be considered when using TAN techniques. The first, registration, relates to the presence and magnitude of any wholesale lateral or vertical shift of an area of database with respect to a reference point. This includes effects due to apparent stretching of the data field. The second quality factor relates to the presence of local errors in the database. These include local misplacement of individual features, cut off hill tops, filled in valleys and omissions of any sort. The consequences for TAN of these two classes of errors are very different.

Considering first registration errors. These are included in the Absolute vertical and horizontal errors normally quoted for each DLMS data cell. Errors of this sort, whether due to lateral or vertical displacement or stretching are not in general detrimental to local navigation. This is particularly true for systems in which the accurate navigation is required to support terrain registered displays (perspective views, obstruction cueing etc) or passive terrain following. These functions require position information relative to the terrain and are essentially independent of registration problems.

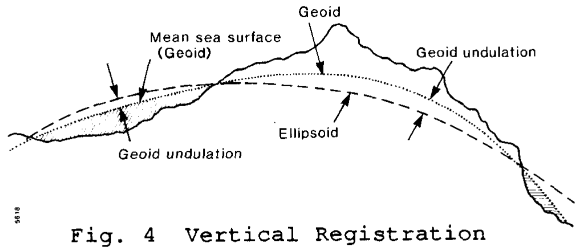

Fig. 4 Vertical Registration Errors

Registration does become important when TAN systems are integrated with Navstar GPS and indeed, when two independently referenced TAN systems are combined. An example of the sort of problem that can arise is shown in Fig. 4. (This only shows the vertical case but similar considerations apply to the horizontal). GPS is accurately referenced to the WGS84 ellipsoid - shown dashed in Fig. 4 - while the DLMS DTED vertical reference is Mean Sea Level (MSL), essentially the Geoid. Because of natural irregularities in the earths shape and the varying gravitation vector MSL does not coincide particularly well with the ellipsoid. Correction terms are available to cater for this referencing difference but there always remains a local fixed bias.

A related problem occurs when a target position is determined using one reference say GPS, while navigation to it employs a different system, TRN plus TCM for example. If targetting accuracy of significantly better than 100 metres is re-

Table 3 Navigation System Performance

Data Class	Available Sources	Remarks
Elevation Data	DLMS Digital Terrain Elevation Data (DTED)	Level 1 (nominal 100m grid) is sufficient for most requirements
Culture with Vertical Extent	DLMS Digital Feature Analysis Data (DFAD) Subset	Selected features with 'significant' height
Vertical Obstruction	• DLMS DFAD Subset • National Databases	
Intelligence Data	Developed as required to meet specific needs	All available Threat, Target and Routing information
Digital Paper Chart	DMA Standard Raster Product 2 (SRP2) ARC Digital Raster Graphics	
Full Culture	• DLMS DFAD • SPACE (Structured Production of Automatic Charts Europe) • DMA DCW (Digital Chart of the World)	For Perspective Displays } For Plan Maps
High Resolution Culture	• High Resolution Paper Maps • SPOT Data • Aerial Photography	All require further special processing prior to use

quired then careful allowance must be made for the registration errors. This is in general possible providing precise registration information is available.

The second aspect of database quality relates to the presence of local or relative errors in the database. Clearly if the frequency and magnitude of these errors are large then degraded TRN accuracy will result. Under these conditions the TRN fixing process will achieve only poor correlation of the measured terrain with the database. The area of database searched for subsequent fixes is increased and a reduced accuracy estimate for each fix is passed to the Kalman filter. In this way the system is prevented from gaining an over confident opinion that it is at any particular location. It will output a nominal position with a large uncertainty. Immediately an area of accurate database is overflown, fix confidence is increased and overall accuracy improved.

A special case does arise however when a single local error exists in an otherwise good database. The TRN will suffer a small disturbance and as soon as good data is available it will rapidly recover full navigation accuracy. The effect of this on overall navigation performance is small. However if the position estimate is being used to drive passive terrain following it is essential that the navigation error estimate is not over optimistic. This is not a problem if the Relative Error estimate provided with the database correctly indicates the magnitude of the expected errors. The system will indicate a larger navigation error to the TF which will fly the vehicle higher. For the UK Tornado the TRN and TF algorithms both include additional independent monitors to continuously assess database quality and terrain consistency. While these monitors are able to trap the majority of local database errors, the integrity of the database accuracy statements remains paramount if safety considerations are involved.

CONCLUSION

TAN is available today as a practical, very accurate navigation technique. The SPARTAN concept of Terrain Contour Navigation is now mature and has been selected for the Tornado GR4 in the UK.

For operation over large areas of exceptionally flat terrain, navigation can be enhanced by the use of Terrain Characteristic Matching at little additional cost - because it uses the existing sensor set. To provide very high accuracy navigation under the widest possible conditions the three way integration of SPARTAN, TCM and Navstar GPS is optimum. This approach is being actively pursued today.

In the supporting field of reference data much progress has been made. For navigation the data either exists as standard products or it can be derived from them. The integrity of the available data must always be of some concern particularly for Passive TF. However even here, with appropriate database accuracy statements, robust algorithms and independent monitoring, accurate safe systems are possible.

Finally when database requirements are being defined it is essential that the current dialogue with the various Mapping Agencies be maintained. As suppliers of the basic reference data they have a crucial role in the success of Terrain Aided Navigation.

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