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by

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PASSIVE TERRAIN FOLLOWING (TF) SYSTEMS COMPOSED OF DIGITAL MAPPING AND GPS

Abstract: The combination of the Global Positioning System (GPS), which can provide sufficiently accurate airplane position, speed, and direction, with the digital mapping system, which can provide terrain data on the surroundings of an air route, can produce the TF controlling commands necessary for terrain-following flight. A terrain-following system composed of digital mapping and GPS is a passive system. It completely eliminates the possibility of exposure due to emission of electromagnetic waves.

Key terms: digital mapping, GPS, terrain-following system

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1 INTRODUCTION

Terrain following (TF) technology can be used in tactical blocking interception, tactical raids, penetration of defenses, and can also be used in search and rescue under various types of weather conditions. At the present time, TF technology is a relatively mature and also important technological means in low altitude defense penetration. It has already turned into one of the important indicators to judge the modernization of an air force. It is the foundation of various super low altitude defense penetration technologies.

From the 1960's to the end of the 1970's, TF technology has gradually developed to become a type of technology which is effective and, in conjunction with that, has achieved broad applications. Through following terrain contours in flight in order to reduce the exposure time to enemy defense systems, aircraft survivability is thereby increased. Before the 1980's, TF system terrain data was supplied by a forward looking radar. Aircraft configuration data, by contrast, was determined by electronic systems carried on the aircraft. Through scanning of the forward looking radar, it was possible to supply a series of sighted distances and sighted angles. These could be used in order to describe the terrain contour relative to the area forward of the aircraft. Early TF systems, in situations where radars provided point to point terrain data, made option for analog processing in order to calculate TF control commands, and it was not necessary to provide terrain contours. Following along with the appearance and development of

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[*] Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

digital electronics technology, the forward area terrain contour data detected in a few seconds by radar could be stored. In conjunction with this, it was possible to make use of these data to calculate TF control commands.

Practice clearly demonstrates that using forward looking radar to determine terrain profiles around flight paths has a great many advantages. However, following along with daily advances and improvements in defense systems--in order to reduce the possibility of discovery by the enemy--at the same time as maintaining low altitude flight along terrain profiles, it is necessary to reduce the emission of electromagnetic waves. Option is made for the use of global positioning systems (GPS). In conjunction with this, in combination with stored digital maps, it is possible to rapidly and precisely determine terrain profiles relative to the aircraft's immediate position.

Early in the 1980's, beginnings were made outside China on carrying out research using GPS receivers combined with digital maps to realize terrain following technologies. In conjunction with this, very great development has already been achieved. F- 117A combat aircraft equipped with GPS/MAP TF systems and "Tomahawk" cruise missiles demonstrated very great power during the Gulf War.

This article introduces the concept of terrain following technology. Going through classical terrain following systems and the development of terrain following technology, it discusses the structure and principles of new models of terrain following systems composed of GPS and digital maps. In conjunction with this, it takes the U.S. Texas company HDUE as an example and explains the operating principles and processing methods in detail.

2 BRIEF INTRODUCTION OF CLASSICAL TERRAIN FOLLOWING TECHNOLOGY

2.1 TF Concepts

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The basic concept of terrain following technology is that, on the basis of predetermined aircraft altitude off the ground-- in situations where the course of the aircraft is maintained and flying on the way in the vertical plane in accordance with terrain undulations--use is made of the aircraft's vertical maneuver capabilities to maintain the aircraft in flight at specified altitudes away from the earth. In conjunction with this, the flight path is made to adhere as much as possible to the terrain profile in order to take advantage of terrain cover so as to shelter itself, thereby effectively completing combat missions. Fig.1 is a schematic of a TF flight path on a three dimensional terrain map.

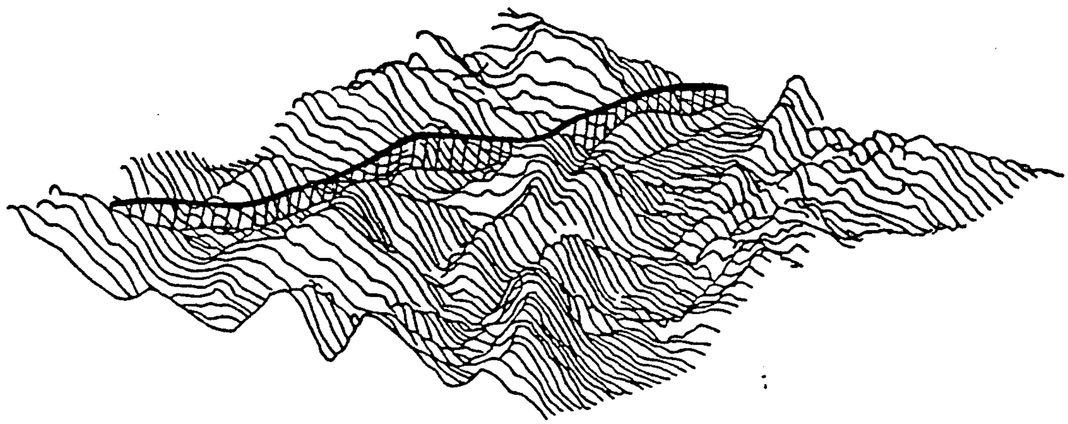

Fig.1 TF Flight Schematic on Three Dimensional Terrain Map

2.2 Classical TF Technology

Classical TF technology began to develop in the 1960's. It went into a practical utilization phase in the 1970's. The U.S. B-1 long range strategic bomber, the F-111 fighter-bomber, and the West European "Tornado" fighter-bomber were all equipped with TF systems.

The basic functional structure of classic TF systems is as shown in Fig.2.

From the Fig., it is possible to see that classical TF systems are basically closed loop systems composed of forward looking radars, TF computers, radar altimeters, flight control systems, as well as inertial navigation systems (INS).

As far as forward looking radars are concerned, they are also called terrain following radars (TFR). They are used in probing the terrain in front of the aircraft.

Through measurements of sighted distances and sighted angles relative to the aircraft at points measured directly in front of it, it is possible to continuously measure the vertical terrain contour right in front of the aircraft.

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TF computers receive terrain data coming from TFR (sighted distances and sighted angles), aircraft attitude data given by inertial navigation systems, such as, flight speed, course angle, and radar altimeter data (flight altitude and altitude rate of change). In conjunction with this, a synthesis is made of flight operation modes set by pilots and passenger quality levels, and it is used in order to calculate aircraft normal acceleration commands. TF computers also produce display control data on terrain in front. When TF systems show the appearance of malfunctions, warning signals are put out to the pilot.

Radar altimeters are one auxiliary terrain measuring apparatus in TF systems. They are used to measure aircraft clear air altitude. Radar altimeters have a different function based on the smooth level of the area the aircraft is flying over. When the aircraft is flying over level terrain or water, TFR does not receive adequate terrain echo signals. At this time, the radar altimeter output data are used to calculate TF flight commands to guarantee that the aircraft flies at predetermined altitudes. When the aircraft is flying over undulating terrain, radar altimeters are used to do safety monitoring of TF flight. When aircraft flight altitudes are smaller than a danger value, then, a warning is immediately put out to the pilot. In conjunction with this, maximum aircraft normal accelerations are initiated to pull out and avoid the aircraft hitting the ground.

Terrain display devices are used to display the forward situation when aircraft are making terrain following flights.

flights. They supply pilots with monitoring of terrain changes.

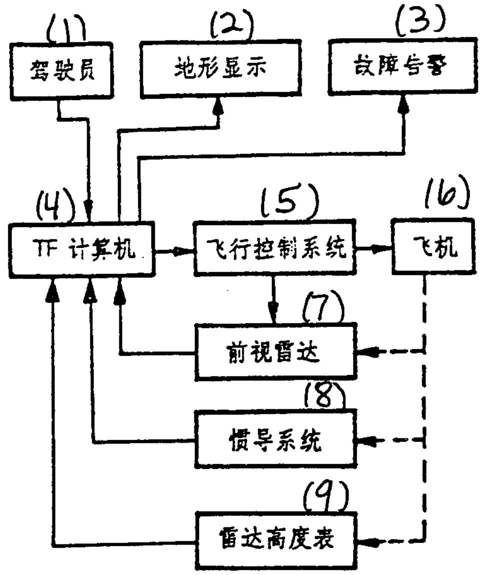

Fig.2 Functional Line and Block Chart of Classical TF System (1) Pilot (2) Terrain Display (3) Malfunction Warning (4) TF Computer (5) Flight Control Systems (6) Aircraft (7) Forward Looking Radar (8) Inertial Guidance System (9) Radar Altimeter

2.3 Passive TF Technology

Classic TF technology has limitations in the several areas below:

(1) Classical TF systems depend on forward looking radars (TFR) in order to obtain terrain data to the front. TFR require continuous unbroken emission of electromagnetic waves toward the front of the aircraft. In this way, they are easily detected by the enemy--so much so that the enemy is capable of luring friendly aircraft into making erroneous maneuvers through opting for the use of electronic interference technology.

(2) Classical TF systems primarily depend on a certain point obstacle on the terrain in front of the aircraft in order to calculate TF flight commands, ignoring, however, data on surrounding terrain. In this way, it is not possible to calculate flight paths with the highest degree of adhesion to terrain contours. Calculated flight paths are then also not optimal. As a result, there are then also limitations on the altitudes of aircraft flying nap of the earth.

(3) Classical TF technology is not capable of realizing automatic terrain avoidance (TA) flight. Terrain avoidance is a type of very effective low altitude flight mode. It and TF technology combined are capable of more comprehensive utilization of terrain in order to carry out low altitude defense penetration.

Following along with the development of microelectronics technology, computer technology, modern control theory, and optimization theory, there have been many improvements and much development of classical TF technology outside China. Opting for the use of TF computers with large amounts of storage capacity and fast operational speeds, utilizing radar scanning data storage technology, applying optimized TF algorithms, as well as improving aircraft maneuver capabilities, and so on are all effective methods of improving TF system performance. However, the most basic method is opting for the use of passive type TF flight technology. In this way, it is possible to basically eliminate electromagnetic emissions. Using digital maps (MAP) and GPS in combination to realize passive TF flight is one type of very good method among these.

In the early 1980's, plans opting for the use of digital maps and GPS together to realize passive TF flight were put forward outside China. After the 1980's, GPS began partial utilization. The principles of passive range finding and positioning make aircraft capable of hiding their geographical positions, and there is no need to emit any electromagnetic signals toward the outside. At the present time, high performance airborne microcomputer systems are capable of completely loading up terrain data within aircraft combat radii. These all act to provide a technological foundation to realize GPS/MAP TF systems.

3 GPS/MAP TERRAIN FOLLOWING SYSTEMS

We know that the purpose of TF flight lies--while satisfying restrictive conditions such as aircraft maneuver limitations, system accuracies, and so on--in making aircraft fly as much as possible along terrain profiles. In order to produce TF control commands, it is necessary to have the three basic data below:

1) terrain altitude profiles along the flight path

2) position of aircraft relative to terrain

3) aircraft configuration data, such as, speed, course direction, acceleration, as well as aircraft performance parameters, and so on.

As far as classical TF systems are concerned, the first two items are provided by forward looking radar. The third item is obtained from airborne INS. In GPS/MAP TF systems, it is also possible, in the same way, to obtain the three types of data above with adequate precision. MAP provides terrain profiles along the direction of the aircraft's course. GPS and MAP together precisely determine aircraft position relative to terrain. GPS and automatic flight control systems or other airborne electronic equipment jointly control aircraft flight configuration.

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Having the three sets of data above, GPS/MAP TF systems are then capable of calculating TF control commands on the basis of TF algorithms. Fig.3 is function principle line and block chart for TF commands produced by GPS and MAP combined. From the chart it can be seen that pilot, aircraft, and GPS compose a closed cycle control system drive function based on terrain data.

The next section goes through the U.S. Texas company HDUE system in order to explain GPS/MAP TF processes for acquiring and processing the data above as well as TF control command calculation algorithms.

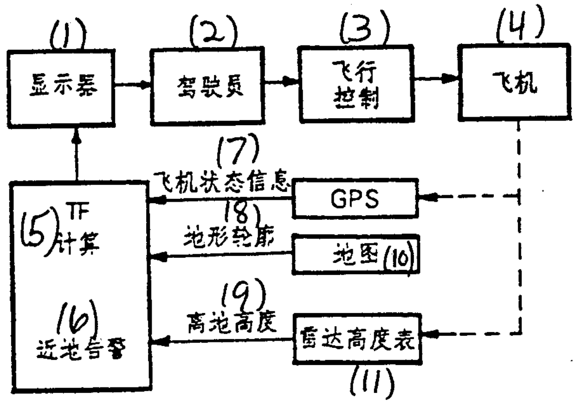

Fig.3 GPS/MAP TF System Functional Line and Block Chart (1) Display Device (2) Pilot (3) Flight Controls (4) Aircraft (5) TF Computer (6) "Ground Near" Warning (7) Aircraft Status Data (8) Terrain Profile (9)Altitude Off the Ground (10) Maps (11) Radar Altimeter

4 ANALYSIS OF ACTUAL EXAMPLE OF GPS/MAP TF SYSTEM

With regard to the GPS/MAP TF systems discussed above, the U.S. Texas company carried out simulation test analyses. In conjunction with this, test flights were carried out on UH-1 helicopters. Simulations opted for the use of highly dynamic user equipment (HDUE).

The HDUE system functional line and block chart is as shown in Fig.3.

HDUE is composed of three parallel Texas 9900 microprocessors. In it, one completes GPS receiver signal identification and tracking functions. One is used in timing and control for the whole system. The third goes through processing of measured satellite data in order to calculate navigation parameters.

HDUE possesses area navigation route point flight capabilities. It also has a pilot control display port. In conjunction with this, it is capable of making records of data in flight tests. HDUE has adequate storage capacity and handling capacity in order to operate TF command algorithms. It is capable of storing data for over six terrain profiles. Each profile is approximately 11 English miles long.

Airborne radar altimeters do not directly participate in the processing of GPS/MAP TF systems. They are primarily used in warnings and evaluations of TF capabilities.

For GPS/MAP TF system flight processes, see Fig.4. When the first route point WP1 is about to be reached, aircraft have already approached the TF flight terrain section. At that time, TF functions are selected. By a TF algorithm controled dive of the aircraft, it makes the selected altitude Ho pass through WP1. Through WP1, the aircraft does TF flight between WP1 and WP2.

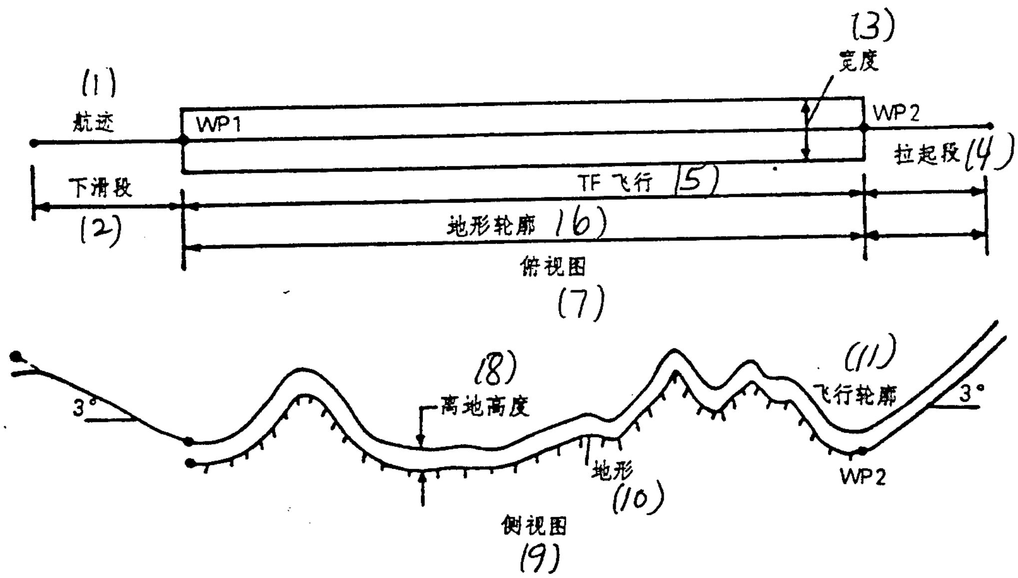

Fig.4 GPS/MAP TF Flight Process (1) Flight Track (2) Dive Section (3) Width (4) Pull Out Section (5) TF Flight (6) Terrain Profile (7) Vertical View (8) Altitude Off the Ground (9) Side View (10) Terrain (11) Flight Profile

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During the whole flight process, aircraft flight tracks are controled by TF algorithms within HDUE. At route point WP2, aircraft terminate TF flight and use a certain angle of climb to climb to a predetermined altitude.

4.1 GPS Positioning and Aircraft Status Data Acquisition

One of the primary functions of HDUE is precisely determining aircraft positions. Generally speaking, GPS receivers go through measurements of precise arrival times for code signals sent out by four satellites in order to precisely determine aircraft position. These measurement time values correspond to the distances from the various satellites to the GPS receiver. At any instant, all satellite positions are already known with respect to GPS users. Through four already known satellite positions as well as the relevant distances, GPS receivers are then capable of accurately positioning themselves.

The handling processes described above are completely passive.

Basic measurements associated with GPS receivers are the distances from satellites to receivers. These measurement data go through filtering and navigation algorithm processing. It is possible to obtain aircraft locations in predetermined coordinate systems. HDUE navigation processing includes a Kalman filter of 11 condition quantities capable of processing three dimensional position, speed, acceleration, and time deviation quantities. The filters in question guarantee aircraft position estimates reaching optimization. However, this is paid for by damaging the estimate accuracies of other condition quantities. What needs to be pointed out is that speed estimates must guarantee having adequate precision in order to satisfy the requirements of flight path angles needed by TF calculations.

In order to facilitate matters, HDUE calculations all opt for the use of WGS-72 coordinate systems. This coordinate system is used in the same way in digital mapping systems. In this way, the mapping data is capable of relatively easily corresponding with aircraft positions.

4.2 Terrain Contour Descriptions

One key part of GPS/MAP TF systems is stored terrain contour data. It is the basic driving function of the whole system. Digital mapping data comes from the U.S. Defense Mapping Agency (DMA)'s 1 radian second latitude and longitude map data base.

In order to reduce the HDUE storage capacity and amounts of calculations--under conditions not influencing the precision of TF control command calculations--there is a need to carry out compression of DMA terrain altitude data within terrain contours. The compression process is as shown in Fig.5. The compression method is to take WP1 as a starting point and WP2 as an end point. The terrain section between these two points is uniformly divided up. In the Fig., the crossing points are division points. In conjunction with this, they act as reference terrain points in this section of terrain. When aircraft make TF flights between WP1 - WP2, then, these reference terrain points are used in order to substitute for DMA terrain data points. In this way, DMA terrain altitude data within a certain range around flight paths are reduced to be this set of reference terrain points.

Due to route points WP1 and WP2, it is possible to store them before the fact. Moreover, reference terrain points are distributed along flight paths at equal distances. In that case, so long as altitude data and sequence for reference terrain points are stored, it is then possible to precisely determine their position. To precisely determine the altitude of any reference point, option is made for the methods below. Take the reference points in question as the center. Make a rectangular frame with a length and width respectively 500 English feet and 150 English feet. Carry out comparisons on DMA data point values which fall within the rectangular frame. Pull out all the maximum altitude values among the DMA to act as altitudes for reference terrain points.

As far as the work of using DMA data to precisely determine terrain reference points is concerned, it is possible, before the fact, to complete it by ground computer. The reason is that TF flight terrain sections are usually set beforehand. What needs to be pointed out is that using reference terrain points to take the place of DMA terrain data points will not have a very large influence on TF control command calculations. The precision is basically capable of satisfying requirements. The reason is that, based on the reference point calculation methods discussed above, the most dangerous terrain points within terrain profiles are all capable of taking shape from this envelope belt. If one takes the width of the envelope belt and selects it to be the beam width of the forward looking radar in the horizontal direction, then, the terrain height data obtained this envelope belt is completely the same as the results of forward looking radar scanning.

For the sake of safety, with regard to ground computers, it is still necessary to carry out checks on DMA data within a certain range of tracks along the earth outside the two points WP1 and WP2 in order to guarantee that, before aircraft dive to WP1 and when they fly away from WP2, the various terrain points are all below the aircraft dive and climb lines. These surface checks produce an add on number used in calibration tests. In conjunction with this, together with reference terrain points loaded into HDUE, guaranteed the compression of DMA data, it is possible to operate normally.

4.3 TF Command Calculations

GPS data and stored reference terrain point data combined, produce TF control commands. HDUE--within each 0.64 seconds in reference coordinate systems--calculates a new aircraft position, speed, and flight path angle. These data and stored reference terrain points put together are capable of producing a new flight path angle control command γc within each 0.1 seconds. If γc goes through climb limitations, and, in conjunction with that, is smaller than the current actual flight track angle, one gets the flight track angle difference value. Going through enlargement and transformation, this difference value signal is shown on the pilot's control display. The pilot, through controlling aircraft flight path angles comes to control the flight of the aircraft.

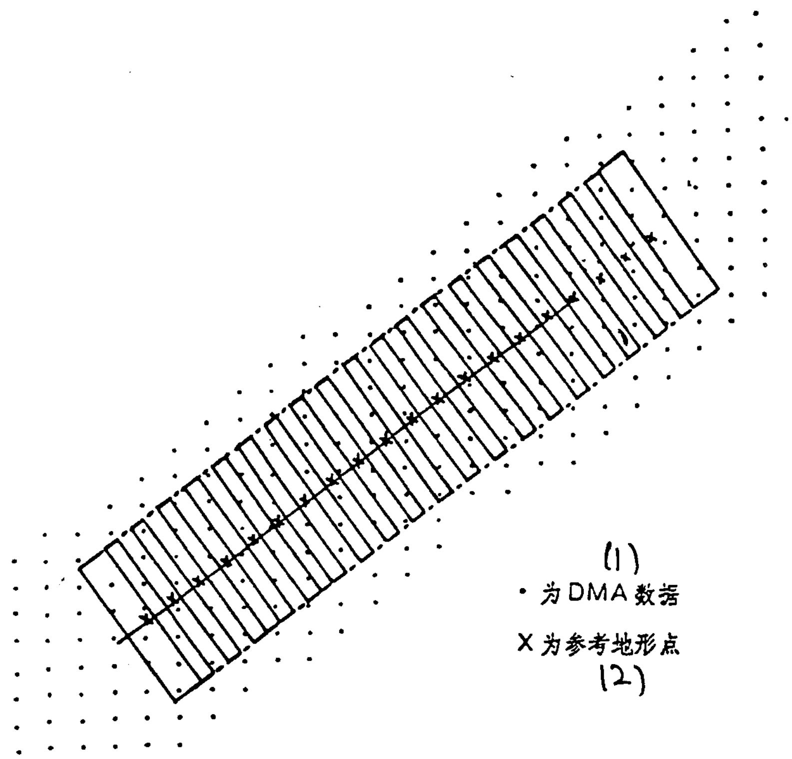

Fig.5 Terrain Profile Description (1) Is DMA Data (2) Is Reference Terrain Point

Within each 0.64 seconds, command production circuits need to carry out one by one calculations on the 350 reference terrain data in front of aircraft at that time. Due to the fact that precision requirements for γ_c calculations on distant and near terrain data are not the same, the precision of distant terrain data can be somewhat off. Close distance ones, by contrast, are relatively high. In order to reduce amounts of calculations, it is possible to carry out division into groups and compression of reference terrain points. The actual method is--among 350 reference terrain points--to do one by one calculations on the relatively close 80 points. For the relatively distant 270 points, take two adjacent points and make them into one group. Altogether, 135 groups are formed. After group formation, as far as reference terrain point altitudes are concerned, option is made for the use of the relatively higher point between the two. Distances are then chosen as the distances associated with the relatively closer point to the position of the aircraft. Going through this sort of processing, altogether, it is only necessary to calculate 215 individual γ_c.

On the basis of the actual situation and the requirements of TF flight, it is also possible to carry out further compression on reference terrain points. Of course, when required TF precision are relatively high, it is necessary to do complete calculations for all points.

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5 CONCLUDING REMARKS

Opting for the use of TF systems composed of digital maps and GPS has the advantages below:

1) Using GPS and digital maps to replace forward looking radar avoids the possibility of exposure due to emission of electromagnetic waves;

2) Digital map storage of terrain data around the aircraft flight path allows calculated TF flight paths to be able to achieve optimization;

3) GPS/MAP TF systems are capable, in combination with terrain avoidance (TA) systems, of composing TF/TA systems more able to make use of terrain data.

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