Terrain contour matching (TERCOM): a cruise missile guidance aid

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Abstract

The Cruise Missile is guided by an inertial guidance system aided by an updating technique called Terrain Contour Matching (TERCOM). Chance-Vought first proposed the terrain correlation technique in the late 1950's. Since that time TERCOM has evolved into a reliable, accurate, all weather, day and night method of position fixing and updating for cruise missiles. A brief history of TERCOM development will be presented giving results where possible. A description of TERCOM and how is works will be discussed. A snapshot of the present TERCOM status and future planned developments will be addressed.

Introduction

The family of Navy and Air Force weapons known as cruise missiles are being developed under the management of Joint Cruise Missile Project Office (JCMPO). These missiles are characterized by the ability to penetrate enemy defenses by flying at very low altitudes at subsonic speeds and have the capability to carry a nuclear warhead for a distance of at least 1,500 mi, or a conventional warhead for a somewhat shorter distance. The missile flight is controlled by an inertial navigation system which is updated periodically from position data obtained by means of TERCOM fixes. The nuclear land attack versions of the system under development are the Air Force Air Launched Cruise Missile (ALCM), the Navy Sea Launched Cruise Missile (SLCM) and the Air Force Ground Launched Cruise Missile (GLCM). The Navy has a land attack version with conventional warhead called Tomahawk Land Attack Missile (TLAM-C). The latest cruise missile under development by the JCMPO for the Air Force and Navy is the Medium Range Air to Surface Missile (MRASM). In addition, a short range anti-ship version of the Tomahawk missile is being developed that does not use TERCOM.

The objective of this paper is to provide an overview of the TERCOM process and how it functions in relation to the Cruise Missile inertial guidance system. A brief history of the development of TERCOM for the Cruise Missile is necessary to understand and appreciate the maturity of the technique.

The TERCOM process requires several major missile components to be integrated together. Missile altitude above Mean-Sea-Level (MSL) is derived primarily from a barometric altimeter, while the radar altimeter gives the missile height above terrain. The difference of these two altitudes gives the flight terrain profile (called sensed or measured altitude) which is correlated against the TERCOM map (terrain profiles references to MSL) stored in the on-board guidance computer. The TERCOM algorithm determines a position-fix relative to the TERCOM map and issues an update command to the guidance set to correct for drift error in the inertial system. The missile then proceeds on to the next TERCOM map or to the target.

To be successful, a TERCOM system requires maps of terrain that is sufficiently unique at each fix site to enable the missile to traverse from launch to target. The TERCOM maps are produced by the Defense Mapping Agency (DMA).[1]

Developmental History

The TERCOM concept has not been unique to cruise missile application; for example, it has been considered for use on submarines, ballistic missiles, drones, aircraft, etc. However, this effort will focus on the cruise missile application and related items of interest.

Chance-Vought originally conceived TERCOM in 1958 for application on a nuclear-powered supersonic low-altitude missile (SLAM). The concept at this time was called "Fingerprint". The SLAM program was cancelled in early 1959, but Chance-Vought continued company-funded research studies. The Aeronautical Systems Division (ASD), Wright-Patterson Air Force Base in April of 1960 awarded Chance-Vought a contract to continue research and development of this concept for potential use on long-range low-flying cruise missiles. The contract extended through July 1961 where emphasis was placed on flight test demonstrations using an off-the-shelf Government Furnished Equipment (GFE) radar altimeter with post flight correlations. The primary objective of this contract was to demonstrate the feasibility of TERCOM to perform a position fix using terrain profile uniqueness and to subsequently update the vehicle's inertial navigation system.

Chance-Vought became part of Ling-Temco Vought Electrosystem, Incorporated (LTV-E), and ASD awarded LTV-E a contract in 1963 that ran through 1965 to continue research work on the TERCOM concept which could be applied to low flying aircraft. This program was called Low Altitude Contour Matching (LACOM) and was to design and develop a complete fix/update subsystem as well as development of a semi-automatic technique for making the TERCOM maps stored on-board in the vehicle computer.

Between 1963 and 1966 LTV-E, under contract with Air Force Avionics Laboratory, performed flight tests using a small laser ranging unit instead of a radar altimeter to possibly improve on position accuracy.

E-Systems, Incorporated, which was formed after dissolution of the LTV conglomerate, continued TERCOM development under ASD sponsorship during the period 1972 through 1975. The aim was to integrate TERCOM into a reconnaissance drone under a program called Project Update. Mission planning procedures, source data requirements and source data updating requirements were included in this contract.

Space and Missile System Organization (SAMSO) sponsored several TERCOM type programs between 1963 and 1971 for potential application on ballistic missiles, such as Terminal Position Location System (TPLS), Terminal Sensing Experiment (TERSE), Terminal Fix (TERF), and the Terminal Sensor Overload Flight Test (TSOFT).[2]

The Air Force sponsored a Subsonic Cruise Armed Decoy (SCAD) program through ASD beginning in 1968. This work was shelved in 1973. The Boeing Aircraft Company (BAC) began working on TERCOM during the SCAD program. From the Air Launched Cruise Missile (ALCM) program inception in 1973 until 1977, BAC was the sole-source system contractor for ASD including responsibility for guidance (within Department of Defense commonality guidelines).

In 1971, the Naval Air Systems Command (NAVAIR) sponsored a Johns Hopkins University/ Applied Physics Laboratory (JHU/APL) study which recommended a TERCOM aided inertial navigation system for strategic Cruise Missile Guidance. As a result of this study NAVAIR placed E-Systems under contract in mid 1972 to perform a TERCOM Aided Inertial Navigation System (TAINS) flight test. The TAINS flight test demonstrated that the concept of TERCOM for the Cruise Missile was a viable one. The TAINS flight test also demonstrated the importance of terrain selection. During the period JHU/APL conceived the key elements of what has become the operational technique for selecting sites for TERCOM maps. MDAC and E-Systems conducted their own studies on the subject and collected flight data supporting JHU/APL's findings.

NAVAIR, based on the success of the TAINS test, issued during early 1974 a Request for Proposal (RFP) for Cruise Missile Guidance to which four companies responded. McDonnell Douglas Astronautics Company (MDAC) and General Dynamics/Convair (GD/C) (both of which had conducted company-funded TERCOM flight test in 1973 in preparation for this competition) responded along with E-Systems and Vought Systems Division of LTV-E.

MDAC and E-Systems won the paper competition and were selected to competitively develop prototype SLCM guidance sets. Each contractor developed and tested a number of units. E-Systems demonstrated TERCOM in captive tests flown in a Navy A-7E Aircraft; MDAC employed a company-owned Queen Air aircraft for developmental testing. The competition culminated in 1975 with an Air Force C-141 aircraft flight test program which demonstrated the accuracy and reliability of the MDAC implementation and was a principal factor in awarding the Cruise Missile Guidance Set (CMGS) contract to MDAC.

It was also in 1975 that the Department of Defense directed that, in the interests of cruise missiles commonality, the SLCM program provide guidance hardware and the TERCOM algorithm to the ALCM program.

While a guidance competition was taking place, another competition between LTV-E and GD/C was taking place for the cruise missile air frame. After a series of design hurdles, GD/C won. The first fully guided missile flight was flown in October 1976. A series of missile captive and free flights took place during this period to support a Defense System Acquisition Review Council (DSARC) II decision in January 1977.

During this period an optical Scene Matching Area Correlation (SMAC) device, developed by the Naval Avionics Center, was integrated into a SLCM guidance set and gave spectacular navigation accuracies. An improved version of SMAC will become part of the TALM-C guidance system.

As a result of DSARC II, JCMPO was formed under the leadership of Rear Admiral Walter M. Locke, USN. Also at DSARC II, the decision was made to develop a GLCM that was basically the same as SLCM, except for launch support equipment. Later in 1977 the B1 bomber program was cancelled and the ALCM, to be launched from B-52 aircraft, was selected as an addition to the air-breathing leg of the nuclear triad. An ALCM competition between the Cruise Missile airframe developers (BAC and GD/C) was announced. MDAC, the navigation and guidance set system integrator, provided guidance hardware to both GD/C and BAC. MDAC also supplied the software for guidance sets to GD/C; however, BAC provided software for its version of the ALCM guidance set.

A fierce competition[3] was held for ALCM culminating with an extensive fly-off between July 1979 and February 1980. BAC was declared winner of the ALCM competition in March 1980. ALCM successfully passed DSARC III (production approval) in April 1980. GD/C continues to produce GLCM and SLCM and other variations of the cruise missile. MDAC continues to supply guidance sets to both GD/C and BAC. Both MDAC and BAC are conducting further development and enhancement work on TERCOM while MDAC provides refined selection criteria to DMA. JHU/APL continues to provide technical support to the JCMPO on all aspects of TERCOM development working closely with MDAC, BAC and DMA. BAC is responsible for providing Mission Planning tools to the Strategic Air Command (SAC) who will develop a complete Mission Planning System (MPS). MDAC is developing a MPS for the other missile systems.

Management of the ALCM program has transfered back to the Air Force with ASD as manager while the rest of the cruise missile management remains at JCMPO.

Cruise Missile Operational Concept

Figure 1 shows an artist's conception of a possible mission for any of the land attack Cruise Missiles. The launch platform receives firing orders via a communication network and may choose to update its position reference using data from any of several sources. The fire control system inserts the current position into the missile's digital computer and assists the missile's inertial platform in self-leveling and gyrocompassing alignment. Mission data in the form of altitude and heading schedules, TERCOM update locations, and TERCOM terrain elevation data (TERCOM maps) are loaded into the missile computer. After launch the turbofan engine comes up to power and the missile aerodynamic surfaces deploy to flight position.

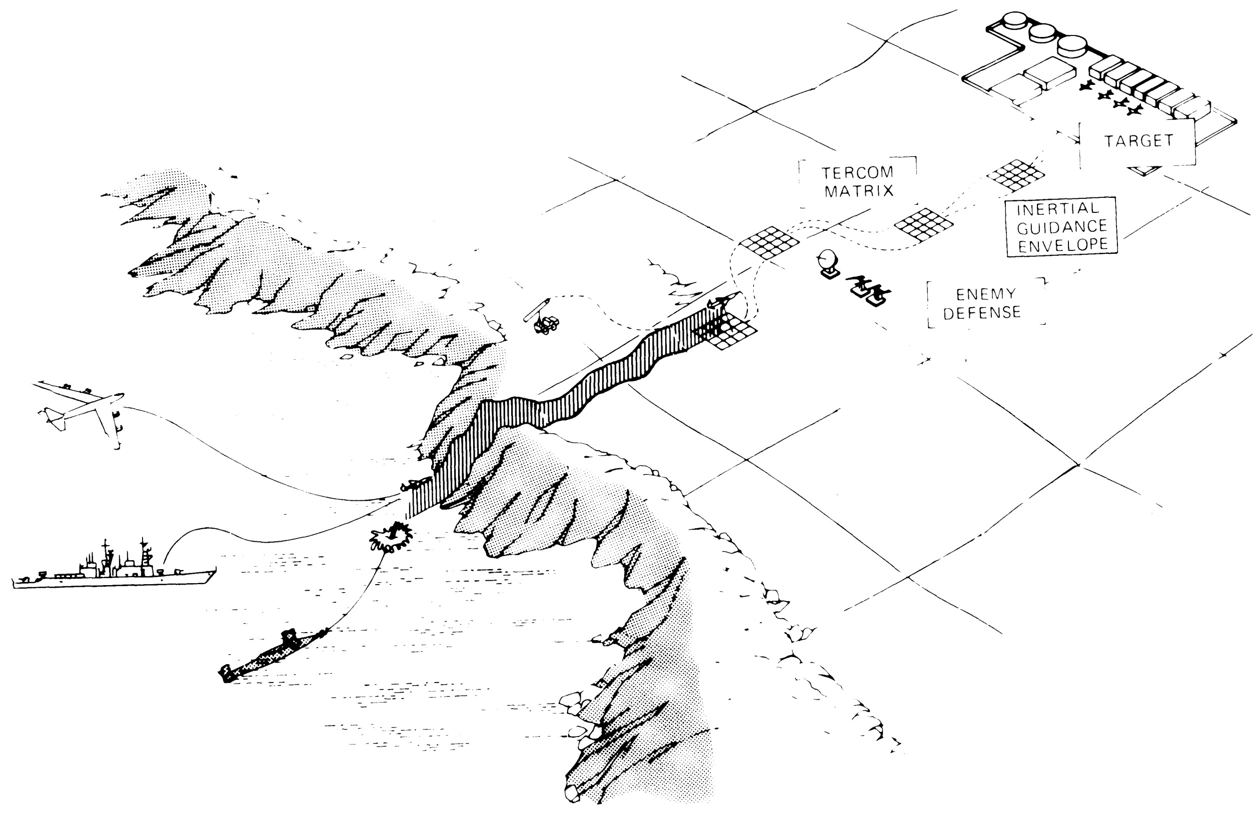

Figure 1. Operational concept for land-attack cruise missile.

The missile employs inertial guidance to the first TERCOM map, solving the navigation equations in the missile computer. If the flight to the first map is largely over water, the missile can fly at a low constant altitude. When over land the missile may enter a terrain-following mode, using as a sensor the downward-looking radar altimeter. The missile clearance altitude may be adjusted to compensate for the varied terrain encountered along the flight path. This low altitude flight enables the missile to avoid detection. If detection avoidance is not necessary, the missile can fly at a higher constant altitude, thereby using less fuel.

Beginning at the first TERCOM map the missile measures with its radar altimeter a sequence of terrain elevations along the flight path. The missile guidance computer then matches this measured profile to a series of stored terrain profiles (the TERCOM map) and determines the geographic location of the measured sequence. This is the TERCOM system as used by the cruise missile. The fix thus determined is used to update the inertial navigator's estimate of position, and to compensate for biases in the inertial measuring unit. After correcting its course, the missile proceeds to the next TERCOM map. Since the course between TERCOM maps needs not be a straight line, any desired deviation in flight path to avoid enemy defenses can be accommodated.

TERCOM concept

In simple terms, a TERCOM system compares a measured terrain profile to terrain profiles stored in the system computer and determines by the best match the geographic location of the measured profile. TERCOM operates on the premise that any single geographic location on the land surface of the earth is uniquely defined by the vertical contours of the surrounding terrain. Figure 2 depicts the TERCOM process.

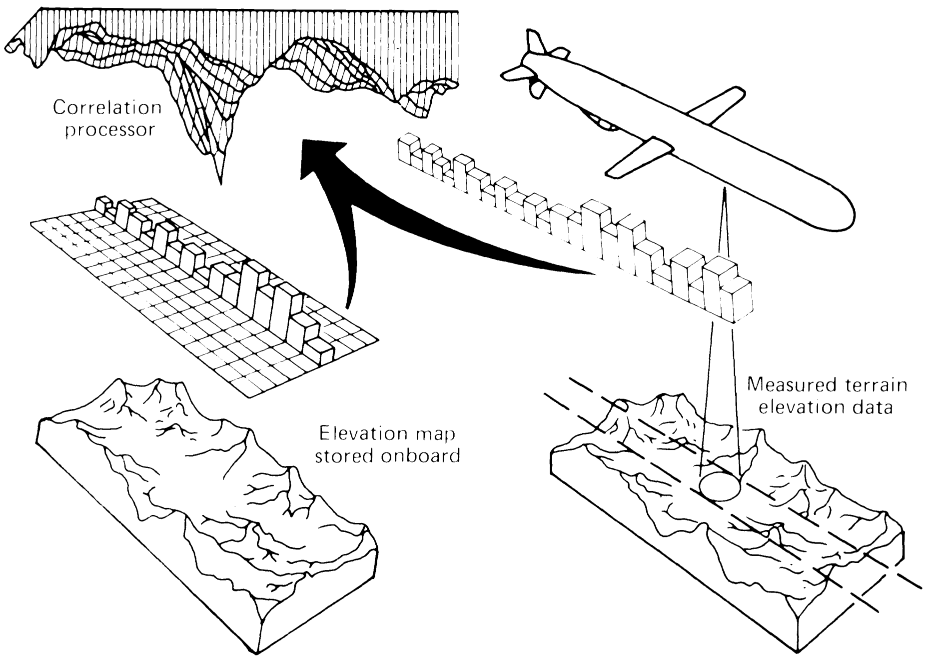

Figure 2. The TERCOM process.

The hardware required to accomplish TERCOM consists of standard avionics equipment. Figure 3 portrays the functional relation between the principal elements: radar altimeter, barometric altimeter, inertial measurement unit, and digital computer.

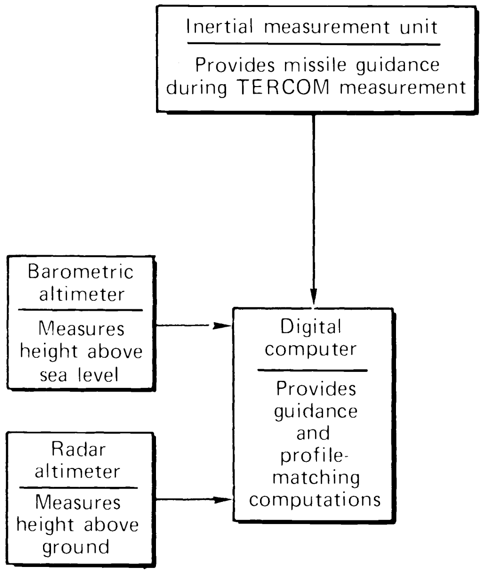

Figure 3. Block Diagram of TERCOM equipment.

The radar altimeter provides the altitude of the missile above the ground. The barometric altimeter measures the vehicle altitude above MSL. The signal is augmented by the inertial measurement unit's vertical accelerometer output in the digital computer's "baro-inertial system" to produce a higher quality absolute altitude signal. The difference between the absolute altitude (provided by the baro-inertial system) and the radar altimeter's measurement of clearance altitude is a measure of the terrain elevation above MSL, as shown in Figure 4. The measured terrain elevation profile (with mean removed) is the signal used to match against the reference terrain profiles stored in the missile's digital computer.

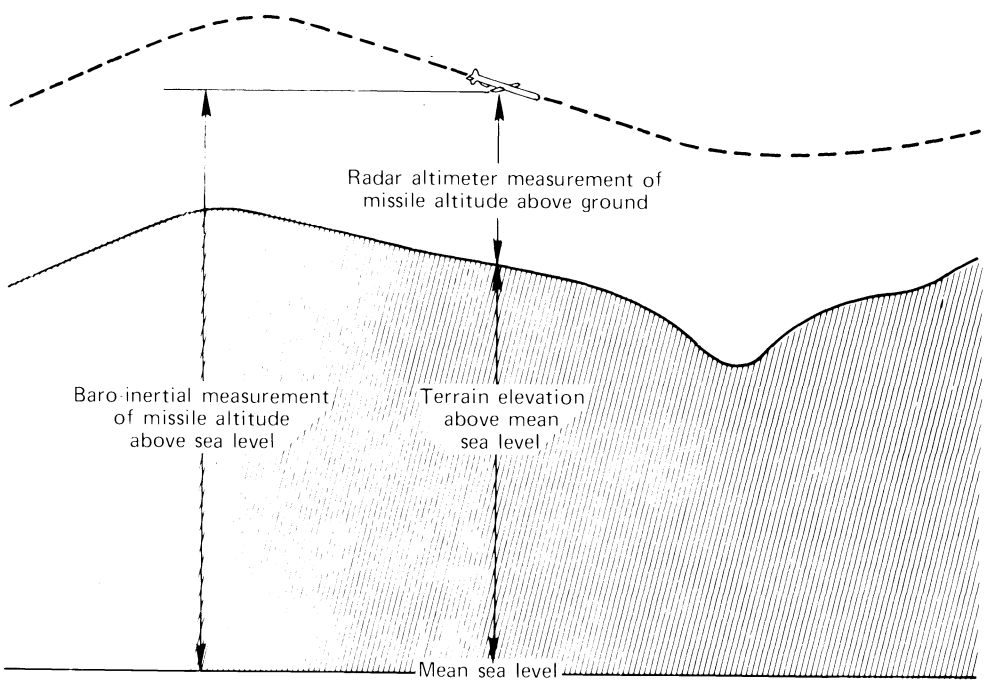

Figure 4. Illustration of TERCOM inflight measurement of terrain elevation above MSL.

The inertial measurement unit consists of accelerometers and gyros that provide the primary measurements for inertial navigation. The inertial navigation computations are accomplished in the digital computer. The inertial navigation system as a whole is the fundamental means of guiding the missile; TERCOM is used to periodically update the inertial navigator. Thus the inertial navigator guides the missile to the first map, between TERCOM maps and from the last map to the target. With each succeeding TERCOM update the accuracy of the Inertial Navigation System (INS) is improved as illustrated in Figure 5. In addition it enables the missile to fly parallel to the columns of the TERCOM map.

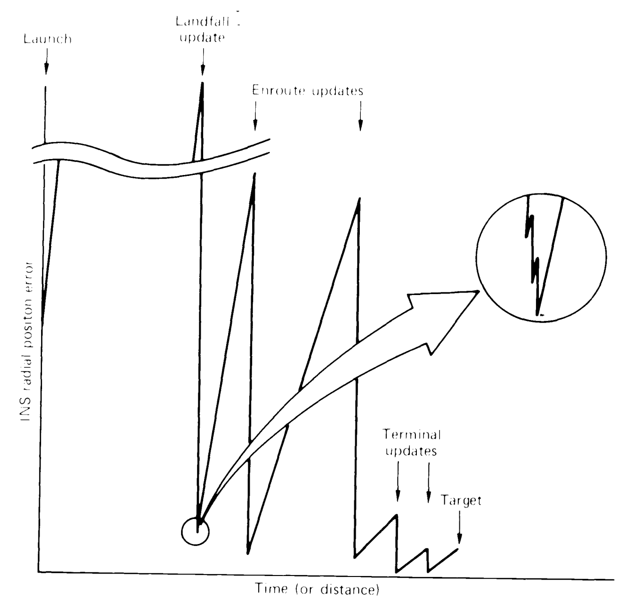

Figure 5. Navigation error variation in an example cruise missile mission.

The digital computer performs all TERCOM and inertial navigation computations. It initiates and terminates TERCOM operation based on the inertial navigation estimated missile position. In particular the digital computer performs the "Mean Absolute Difference" (MAD) computation and defines the TERCOM match. The missile estimated position is calculated using a multi-state Kalman Filter technique. After the TERCOM fix has been determined, the update is obtained by adding the appropriate delta change to the state-vectors in the Kalman Filter equations. These calculations are performed in real-time as the missile continues along its flight path.

The MAD algorithm has proven to be an effective correlation scheme for the cruise missile and meets it's accuracy and real-time computational requirements. The correlation algorithm compares the mean absolute difference between measured elevations and map elevations for a given map profile and is defined mathematically in Figure 6. The "match" is indicated by a minimum value of the summation of altitude differences between a subset of the measured profile and one reference profile. The reference profile giving the minimum MAD locates the crosstrack position of the missile; a subset of the measured profile identifies the downtrack position.

MEAN ABSOLUTE DIFFERENCE $$MAD = \frac{1}{N}\sum_{i=1}^{N} |S_i - M_i|$$

M_i = STRIP ON REFERENCE MAP

S_i = MEASURED SAMPLE SUBSET

N = MATCH LENGTH

EXAMPLE "MAD MAP"

9	9	8	9	12	13	15	19	20
9	7	8	8	11	14	15	18	21
10	6	$\boxed{5}$	7	12	15	16	19	19
12	9	9	11	13	16	17	14	20
13	14	12	13	$\boxed{14}$	19	18	18	22
15	17	16	17	18	20	19	21	22
21	14	15	22	23	22	22	25	24
26	26	27	25	25	26	27	28	27
27	25	28	27	26	27	28	30	29

Figure 6. TERCOM match algorithm.

Cruise Missile TERCOM software is the computer program which matches, at the appropriate time, the measured terrain elevation profile to the TERCOM reference map stored in the computer memory. The reference map consists of a digital representation of those terrain elevation profiles over which the missile is most likely to fly at the time a TERCOM update is required. The cruise missile guidance set is programmed to measure, in flight, the terrain profile located in the center of the reference map; but due to navigation position errors, the missile generally flies over a profile offset from the center as illustrated by the example "MAD MAP" in Figure 6. When the computer compares the measured profile to each profile on the reference map, the reference profile that matches best should be the one representing the terrain over which the missile flew. TERCOM is thus used to determine the missile position error. The inertial navigator is updated and the missile corrects its course.

TERCOM map application terminology

TERCOM maps for cruise missile application, are produced by the DMA. To simplify DMA's task in dealing with various cruise missile users, JCMPO has promulgated instructions that standardize the TERCOM maps.

A TERCOM reference map is simply a rectangle matrix of numbers, each number representing the average elevation above MSL of the terrain in a square area on the surface of the earth. These squares, which are called cells, are of fixed size within a map. The reference map is then a grid of squares projected onto the surface of the earth. DMA determines the average elevation within each cell and assigned that number to that cell. The completed TERCOM map can be called a digital topographic map.

The cruise missile flys over a TERCOM area at a specified heading. The reference map matrix consists of columns parallel to this intended flight heading and rows perpendicular to it. Each column is a sequence of numbers that describes a unique terrain profile. When the missile flies over a reference map area, it measures the average elevation of the terrain directly below, averaging over intervals equal to the cell size of the map.

The number of cells in the length of the TERCOM map is called the match length. The match length is the number of elevations in each reference profile (column) that is compared to the measured profile. Typically, the greater the match length the greater the chances are that the TERCOM fix will be correct.

TERCOM will not work over all types of terrain. Generally the rougher the terrain, the better TERCOM works. However, good terrain must be more than just rough, it must be unique. That is, a given profile out of the TERCOM map must not resemble any other in the map. Uniqueness is illustrated by Figure 7.

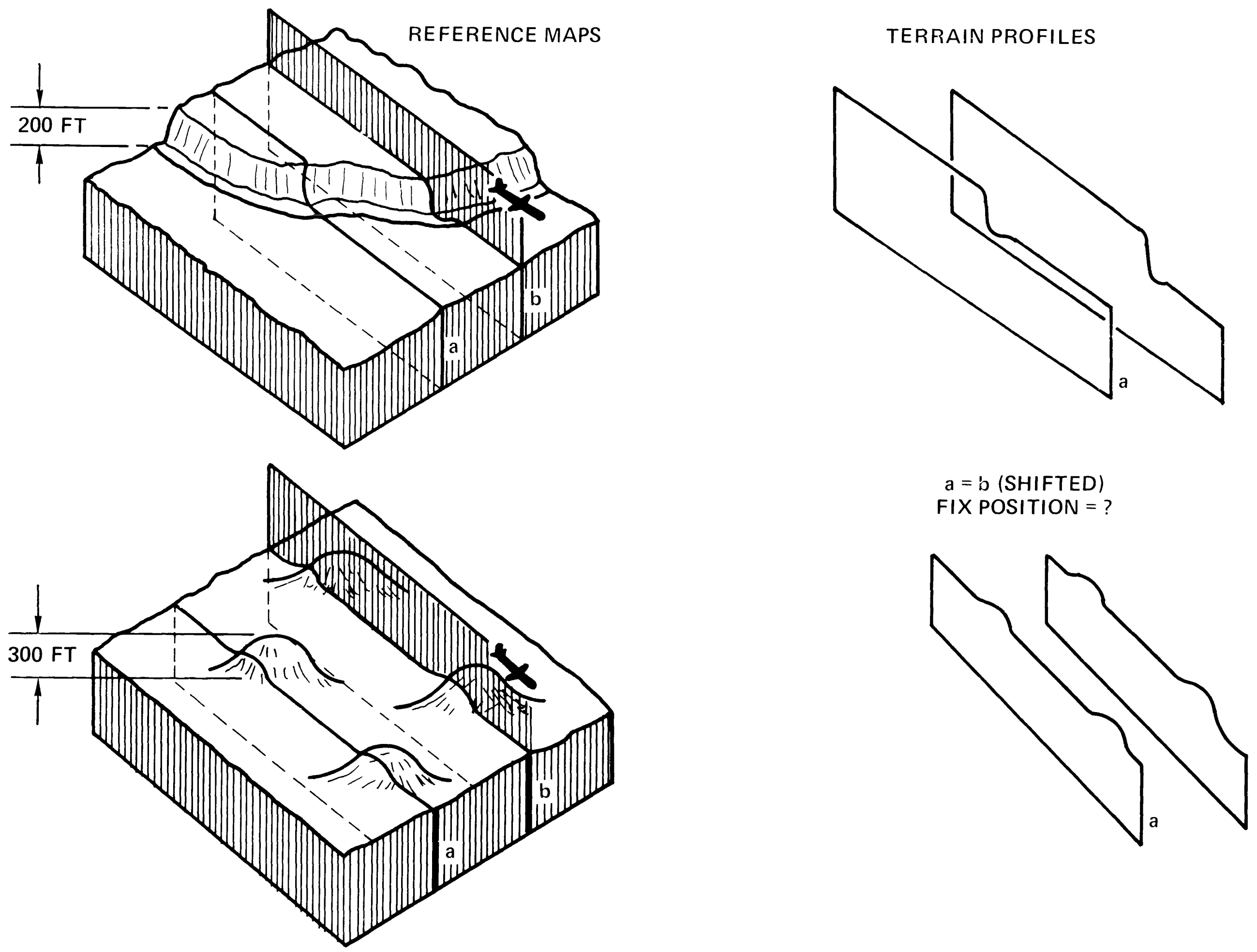

Figure 7. Good terrain roughness bad position fix.

TERCOM maps used by the cruise missile are of four types (in decending order by size): Landfall, Enroute, Midcourse and Terminal. The map types differ in width, length and cell size. The map width determines how far that map can be spaced from either the launch site or a previous TERCOM map and still yield an acceptably high probability of overflight. The cell size determines, in part, the accuracy of the TERCOM fix. The TERCOM maps become smaller and are spaced closer together as the missile approaches the target. Because of the decreasing cell size, the updates become more accurate.

When the terrain permits, TERCOM maps are placed in groups of three to support voting in order to reduce the probability of a false-update. Therefore, when speaking of a TERCOM map, one is addressing a map set of three or less. A TERCOM position fix is made on each map of the set; however, an update takes place only after the three fixes have been voted. If the voting criteria is not met, there will be no update and the missile continues on to the next map set or to the target. Voting is not necessary, but desired.

A typical cruise missile mission configuration may begin with a Landfall map set followed by several Enroute map sets and end with one or two terminal map sets. However, any of the four types of TERCOM map sets may be used at any place in the mission as determined by the needs of the mission planner. For example, due to the lack of suitable terrain, the planner may not be able to place an Enroute map set close enough to the previous TERCOM map set to assure an acceptable probability of overflight. He may therefore elect to use a wider Landfall map at this midroute location. Also, a planner may not need the high fix accuracy obtained with a Terminal map set when attacking a soft target. In this case he may elect to fly directly from an Enroute map set to the target. Or, he may choose a Midcourse map set for the pretarget update.

The mission planner requests that DMA supply TERCOM maps of the appropriate type at candidate update locations; the planner specifies the heading and the center coordinates of each map set. Once the TERCOM maps have been digitized, the maps must be validated by DMA to ensure that all of the map selection criteria has been met. JCMPO is responsibile for providing DMA with the map selection and validation criteria for TERCOM used in the cruise missile. The development of the map selection procedures and technology has been and still is an iterative process.

TERCOM status

A basic TERCOM system has been developed. Operational flight hardware and software has been extensively and successfully tested. Operational support hardware and software is also in place. TERCOM has been successfully demonstrated by several thousand successful position fixes during the cruise missile development cycle. Test bed aircraft and missiles, both captive and free flight, have been flown over a vast variety of terrain. Many complex problems have been overcome. The specific missiles to which it is being applied are the Navy SLCM, and the Air Force ALCM and GLCM.

Future development plans

As mentioned earlier, TERCOM development has been and continues to be an iterative process and at times appears to be more of an art than a science. Nevertheless, many questions remain to be answered concerning TERCOM application. Selection criteria to aid DMA in preparing maps continues to be an area of needed improvement. Flight tests over operational type maps and terrain remains an issue of concern.

A TERCOM enhancement program is underway now at JCMPO to address these and other questions related to the application of TERCOM for cruise missiles.

Acknowledgements

The objective of this paper is to provide a broad overview of an extremely complex technology. There is certainly no claim of originality in the presentation of this material; the only intent is that it be factual and informative to the terrain sensing community. The credit for most of this material goes to JHU/APL who will soon be publishing, for JCMPO, a very comprehensive treatise of TERCOM for the cruise missile program. The author would like to thank the ones at JCMPO, MDAC, DMA and JHU/APL for reviewing and providing helpful comments and corrections for this paper. A special thanks goes to the typist for constantly accepting the challenge of turning disorder into semi-coherent statements. This was demonstrated time and again through the wizardry of modern word processing techniques.

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