Terrain Referenced Navigation Technique Using Correlation Algorithms for Cruise Vehicle

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Abstract

The Cruise vehicle is guided by an Inertial Navigation Systems (INS) and Satellite Navigation (SatNav). Where INS provide very accurate and reliable solution for navigation, but gyroscope and accelerometers errors accumulate with time, and accordingly navigation errors also grow w.r.to time leading to very high Position drifts for long duration missions. While in SatNav performance is poor due to the signal interference and jamming. The solution to these problems leads to an introduction of another device to perform precise measurements of the vehicle's geographical position along its flight path. TERCOM is a well approved navigation technique which deals with terrain elevation. TERCOM compares the measured elevation value and on-board stored elevation value using correlation algorithm. A TERCOM system is a self-contained and provides positional fixes to cruise vehicle, aircraft, and drones. TERCOM is the only fix-taking system that can operate autonomously in a RF/ SatNav denied scenarios. TERCOM can be used in both tactical and strategic systems and operates under ECM (electronic countermeasures) conditions and provides day/night, all weather capability in low altitude terrain following scenarios. This paper presents correlation algorithm and its performance evaluation in the Western Ghats of India.

Keywords: *Baro Altimeter (BA), Cruise Vehicle, MAD, MSD, Radio Altimeter (RA), TERCOM*

1.0 Introduction

A Cruise vehicle is a self-guided, continuously powered, pilotless, air-breathing which is supported by an aerodynamic surface. INS determine position, velocity & attitude of the vehicle [1-2]. With flight time, the drift and errors in inertial system increases as inertial system positioning errors are cumulative resulting in many kilometers of accumulated positioning error with flight duration. On the other hands, *SatNav* allows the vehicle to continuously correct its inertial errors, regardless of terrain and weather conditions and works well over water as well as land. These advantages were offset by problems with vulnerability to jamming.

Due to its long flight duration, navigational accuracy degrades with time especially in *SatNav* denied environments and lands into unacceptable error basket. A navigational aid like TERCOM which can correct the INS errors during midcourse phase of the flight is of great help to achieve the mission objectives in *SatNav* denied. Additionally, it also assists the vehicle to enter terminal phase with reasonable positional accuracy where a terminal sensor (RF or IR seeker) can take over. A Terrain-referenced navigation (TRN) is a well approved navigation technique which deals with terrain elevation [3, 14]. It compares the measured elevation value with on-board stored elevation value using correlation algorithm.

2.0 TERCOM Technique

Terrain Contour Matching (TERCOM) is defined as the process of finding the location of the vehicle through correlation with terrain over which the vehicle is flying [4]. It is also known as the correlation guidance as the comparison between the features of the terrain over which the vehicle is flying and pre-stored features of the planned trajectory. This navigation aid technique can be employed for any type of launch condition (air, ground, sea or

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underwater). The prerequisite being terrain hugging trajectory with very low cruising altitude as indicated in fig. 1.

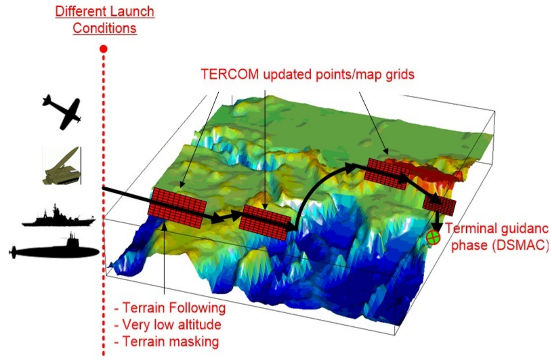

Figure 1: TERCOM Principle

These pre-stored features are obtained by measuring the terrain of interest prior to the mission. Terrain features are stored in the form of a horizontal matrix based on the elevation of the terrain of interest. Each map is then divided into equal size squares such that each square represents the average height of that region. This constitutes the Map Database and is stored in the on-board computer of the vehicle.

The profile of the terrain underneath is captured by a sophisticated data acquisition system composed of RA and BA. RA records the radio wave traveling time by sending and receiving back the reflected radio wave from the underlying terrain. This time is used in calculating the altitude of the vehicle [5-6]. The BA is used to measure vehicles altitude w.r.to mean sea level since it works on the principle of measuring atmospheric pressure.

This paper mainly describes about the TERCOM implementation and performance analysis. Different techniques are explored in literature, where effective use of **data correlation** and **image processing** techniques have been used to navigate a flying vehicle during mid-course trajectory. In this paper, TERCOM navigation technique is presented where data correlation-based guidance is achieved [8-9]. As the flying vehicle reaches the matrix area, the profile of the terrain beneath the flying vehicle is obtained by the combination of the two altimeters, each giving its output specific intervals. These real time actual data values are then correlated with the pre-stored terrain elevations [2] which then provide the horizontal position.

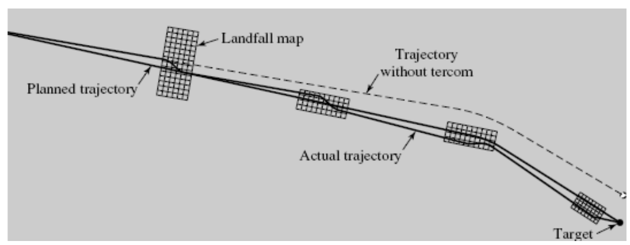

Figure 2: Vehicle flying over stored maps (TERCOM)

In view of high positional error at the start of TERCOM, the requirement of map size is high & as the flight path corrected to the desired path the map size reduce as shown in fig. 2.

3.0 STEPS IN TERCOM

The determination of vehicle position by means of terrain contour matching involves three basic steps mainly the first step is an off-line planning, sampling and correlation need to take place in real time at flying vehicle OBC.

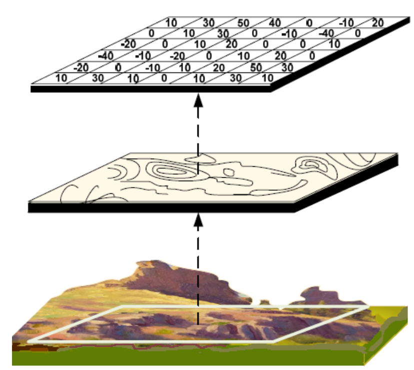

Figure 3: Data Preparation

Mission Planning: It is the process which takes place much prior to any flight. It is also known as Data Preparation Stage, where the maps of the area of interest are acquired either using topographic charts or stereo aerial photographs. These maps are then digitized and converted into matrix form as shown in fig. 3. Each cell is replaced with discrete average terrain height with respect to the reference datum WGS84.

The size of map (matrix) corresponds to the resolution of the cell size. The digitized map is stored in on-board computer of the flying vehicle.

Data Sampling: The altitude above the terrain is generated by taking difference of BA and RA measurements. The difference in altitudes indicates terrain height w.r.to reference datum which is similar to stored map elevations. It is always not possible to acquire the altitude information for BA and RA at equal interval. It is required to synchronize output of these two sensors w.r.to cell size. This synchronized data is ready for correlation. The data sampling or acquiring process is depicted in the fig. 4.

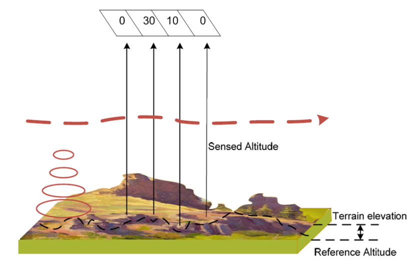

Figure 4: Data Acquisition Process

Data Correlation: The acquired data and the digitized map are correlated to get the highest similarity along the columns. The column which matches with highest correlation, is the trajectory of the terrain where the vehicle has flown. Normally this should be center column of map, assuming no navigation error. In case the correlating column is other than the center column, distance from the center column are called the cross-track and along-track errors as shown in fig. 5. These errors are used to correct the trajectory of the vehicle such that the center column becomes the steering track. All this happens in real time as the flying vehicle has to be kept on the intended track all the time and any delay here would allow the vehicle to go beyond controllable bounds.

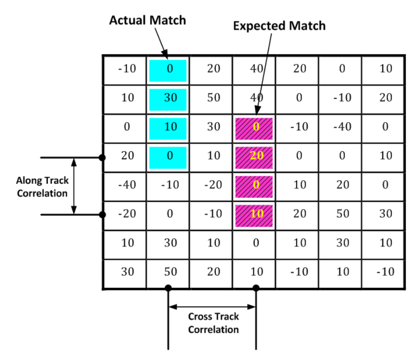

Figure 5: Data Correlation

The most computationally efficient correlation techniques used are Mean Absolute Difference (MAD) and Mean Square Difference (MSD).

4.0 TERCOM SYSTEM ARCHITECTURE

Functional block diagram of the TERCOM is indicated in fig. 6. TERCOM system uses following onboard hardware & software modules:

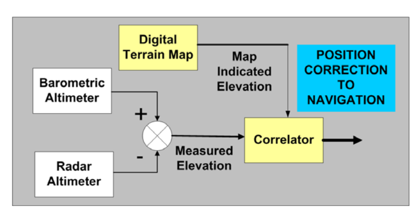

Figure 6: Major Subsystems of TERCOM

1) ***Radar Altimeter***: Measures the ground clearance or altitude above Ground Level (AGL) [5-7].
2) ***Barometric Altimeter***: Provides altitude above Mean Sea Level (MSL)

3) ***On-board Digital Elevation Map (DEM)*** as a reference terrain
4) ***Correlator:*** Computation of MAD or MSD algorithm to find best match.

The critical part of TERCOM process is the data correlation. The RA acquires altitude measurement above terrain and BA provides w.r.to mean sea level. The difference between BA and RA is the sensed vertical terrain profile w.r.to WGS-84. This terrain profile is correlated with the sequence of altitudes retrieved from the DEM for parallel paths that are offset from the predicted flight path by increments in the cross-track & along-track directions.

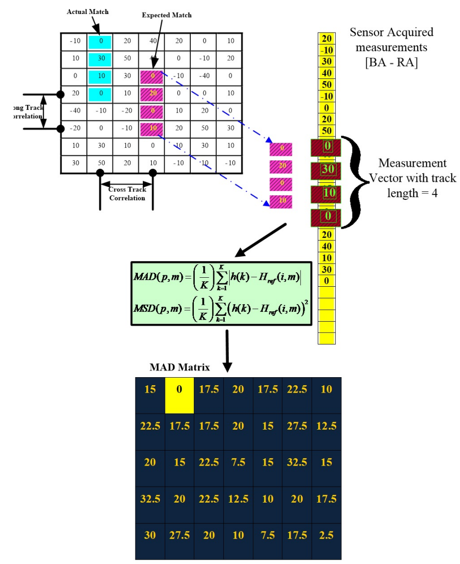

Figure 7: MAD & MSD Correlation Algorithms

5.0 TERRAIN NAVIGATION TECHNIQUES

There are several varieties of algorithms available in literature [2], which can be used for navigational aiding. In general, they are categorized as:

Batch Processing: In this method, the location update takes place in one go. A set of measurements called track are processed (correlated) together. TERCOM, TERPROM, CAROTE, GOEBEL etc. are falls under this category. Batch processing algorithm is generally selected for cruise vehicle, because no linearization of terrain profile is necessary & this technique is applicable to both small discrete and large maps which can support continuous navigation updating [10-11].

Recursive Processing: In this processing, a filter is employed to estimate the offset from desired location eg. SITAN, VATAN [12-13] etc. Here, the location offset is highly coupled with the filter states performance. It is best suitable for small maps with fairly small initial position error.

There are number of batches processing-based correlation algorithms of varying complexities and accuracies are available in literature as follows:

1. Mean Squared Difference (MSD)
2. Mean Absolute Difference (MAD)
3. Normalized MAD (N-MAD)
4. Normalized MSD (N-MSD) and
5. Product Method

5.1 MEAN ABSOLUTE DIFFERENCE CORRELATION ALGORITHM

The MAD method calculates the mean of absolute value of differences between corresponding measured sample (i.e., difference between BA and RA) and the reference map indicated terrain elevation values. The MAD algorithm provides the best combination of accuracy and computational efficiency for performing real-time terrain contour matching in an on-board computer environment. The formulation of MAD is as follows:

$$MAD(p,m)=\frac{1}{K}\sum_{k=1}^{K}|h(k)-H_{ref}(i,m)| \qquad (1)$$

5.2 MEAN SQUARED DIFFERENCE CORRELATION ALGORITHM

The MSD method, as the name implies is mean of the squares of differences between the measured sample (i.e., difference between BA and RA) and the corresponding reference map indicated terrain elevation profile. This is a quadratic function of error and hence affected by outliers. However, the major advantage of using this method is that it provides higher weightage to large errors, in turn narrowing down the uncertain zones.

$$MSD(p,m)=\frac{1}{K}\sum_{k=1}^{K}\left(h(k)-H_{ref}(i,m)\right)^{2} \qquad (2)$$

Where,

N = the number of rows of reference matrix

M = the number of columns of reference matrix

K = Track length (the number of samples measured/used for correlation)

k = Track length index, & p = MAD starting index

m = column index, $1< m \leq M$

n = row index, $1< n \leq N$

$i = p+k-1$ which is reference terrain altitude from MAD starting point to track length

$H_{ref}(n, m)$ = the stored reference matrix data: $1 \leq n \leq N$ and $1 \leq m \leq M$

$H(k) = k^{th}$ measured terrain elevation. The size of MAD matrix is $(N - K + 1) \times M$

6.0 SIMULATION STUDIES

Simulation studies are carried out by considering the real time data collected from the RA and BA information from su-30 MKI aircraft. The required digital elevation database collected from NRSC, ISRO Hyderabad. In order to assess the efficacy of MAD & MSD algorithms simulation studies are carried out using Ideal Measurement (Error Free), Erroneous Measurement (By Injecting Random Errors), and Real Measurement. Correlation is carried out with available sortie data around Western Ghats.

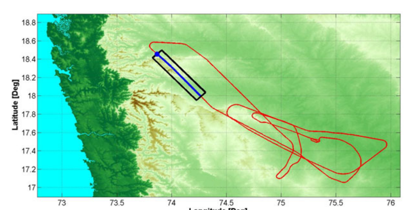

Figure 8: Su-30 aircraft sortie

Case 1: Ideal Measurement (Error Free): The performance of MAD and MSD are evaluated under error free situation. This is an ideal situation for correlation. The correlation output is presented in terms of surface plot. The fig. 9 and 10 indicates one distinct peak over the surface of 1/MAD and 1/MSD. This indicates perfect correlation w.r.to desired column.

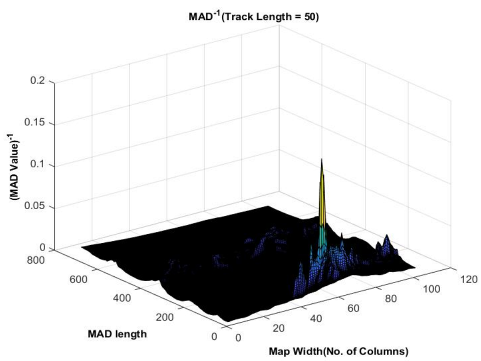

Figure 9: Case-1: MAD method

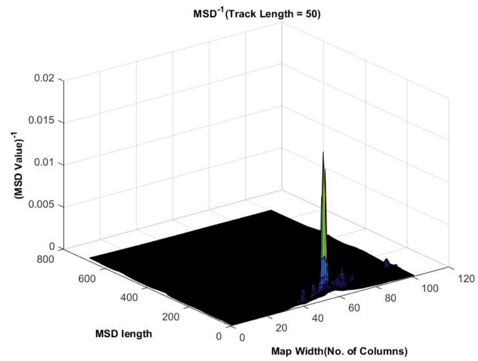

Figure 10: Case-1: MSD method

Case 2: Erroneous Measurement (By Injecting Random Errors): Measurement vector is generated similar to case 1 and corrupted with random noise within the sensor 3σ noise characteristics. Correlation is carried out with corrupted measurement, this gives accuracy of position estimate w.r.to noisy measurements. Fig. 11 indicates the effect of error on estimated position. These results are arrived by carrying out 500 Monte Carlo runs using normal distribution. Present study can be used to decide the gross error budget for given terrain area. So, the contribution of errors in BA, RA and Map database are accounted together.

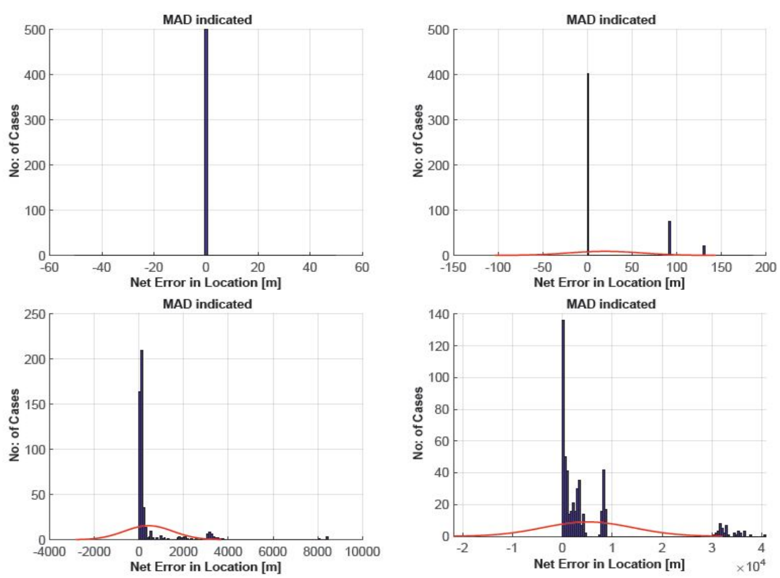

Figure 11: MAD: Location error with Track Length = 50 &Measurement error = 10, 50, 100 & 200m

Case 3: Real Measurement: Measurement vector in generated by using the RA [7] and BA readings as indicated in the eq. 3.

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$$H_{meas} = H_{baro} - H_{rc} \qquad (3)$$

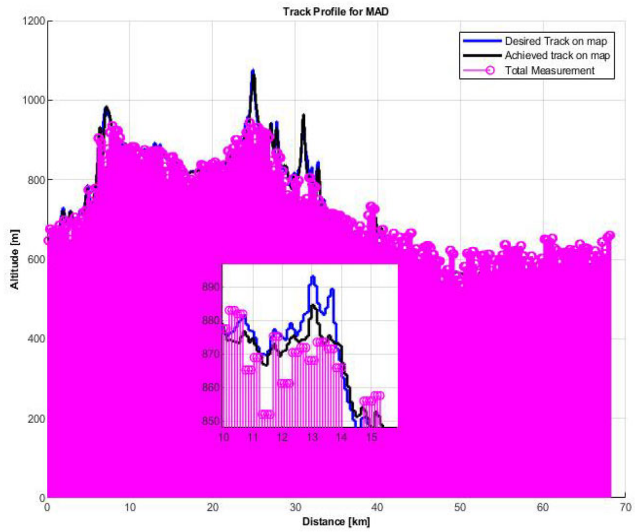

Figure 12: Measurement Vector

Table 1. MAD Position Error with varying Track length

Track Length	MAD		MSD	
	CRE [km]	DRE [km]	CRE [km]	DRE [km]
10	3.0610	52.4100	4.3590	3.0611
20	3.7104	3.1539	3.7104	3.1539
50	2.7828	2.6901	3.7104	4.7308
150	3.2466	3.8032	3.2466	3.7104
250	2.3190	2.8756	3.1539	3.7104
500	1.7625	2.1335	1.3914	1.9480
734	1.2040	0	1.2040	0

H_{baro} is the direct measurement and H_{rc} is the corrected measurement from radar altimeter. Figure 8 indicates the selected section of trajectory and respective terrain. Figure 12 indicates measurement vector and the desired terrain elevation. The obtained cross range error is 1204 m and downrange error is 0m for full track length. This figure also indicates the track with maximum correlation (i.e., Achieved track). The position error also depends on track length, in addition to the errors associated with measurement, data association, and database and flight errors. Figures 13 and 14 indicates the convergence of distinct peaks as the track length increase from 10 to 150. The effect of track length on position error is tabulated in table 1 for both MAD and MSD correlation algorithms.

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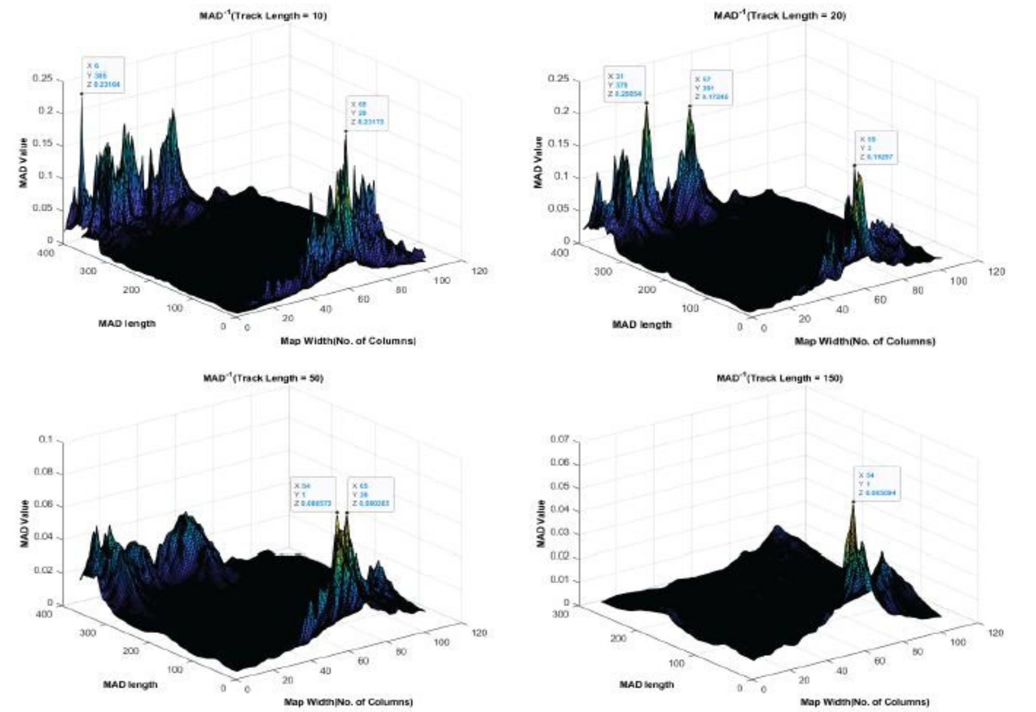

Figure 13: MAD: Convergence of distinct peaks as track length varies from 10 to 150

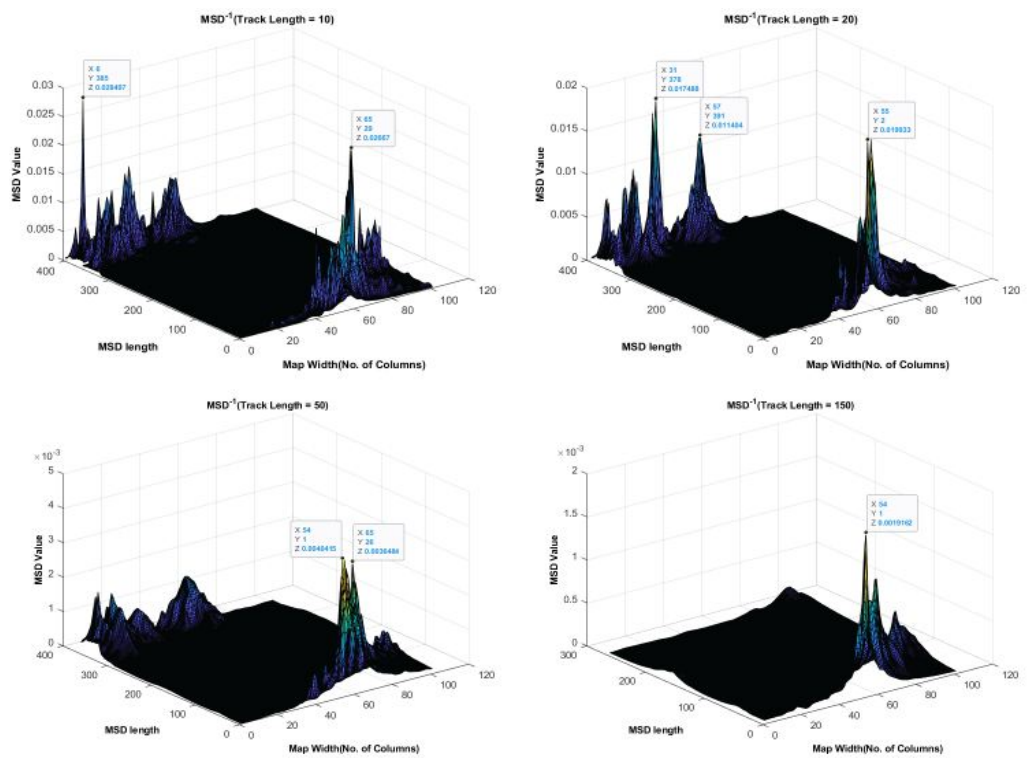

Figure 14: MSD: Convergence of distinct peaks as track length varies from 10 to 150

COMPARISON OF MAD AND MSD

MAD works better in cases of high terrain roughness and difference in correlation terms are higher than 1. MSD works better even in cases of flatter terrain and when difference in correlation terms are in fraction. Since in MSD the correlation terms are squared, so the separation between fractions increase further. So, while processing, both algorithms are executed simultaneously and based on the selection is made to choose MAD or MSD. Computational burden is more for MSD.

7. CONCLUSION

In the present study, correlation algorithm for TERCOM navigational aid has been developed.

Efficacy of TERCOM algorithm under different situations like, ideal measurements, intentionally corrupted measurements and under realistic measurements has been studied. Based on the available literature, the basic MAD and MSD algorithms are developed. These algorithms are analyzed over the realistic sortie data obtained from Su-30 Aircraft sortie trial. Monte Carlo simulation runs (500) were carried out to ascertain the effect of track length for given terrain. Different terrain database like DTED, SRTM and GEOTIFF formats were analyzed and necessary interface developed.

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