Digital Terrain Elevation Mapping System

Harold A. Malliot
Lockheed Martin Missiles and Space
Research & Development Division
Org. 92-20 B/255
3251 Hanover Street
Palo Alto, CA 94304
415-424-2619
malliot@rddvax.decnet.lockheed.com

ABSTRACT—The Lockheed Martin Digital Terrain Elevation Mapping System (DTEMS) will be a commercial system for collection, processing and archive of sub-meter precision digital terrain matrix (DTM) and three meter resolution ortho-rectified digital polarimetric synthetic aperture radar (SAR) imagery. DTEMS will also produce commercial cartographic, terrain display, and topographic engineering products. DTEMS will use a synthetic aperture radar (SAR) mounted in an ER-2 aircraft[1] to obtain stereo polarimetric X-band SAR images. The SAR images will be processed to obtain estimates of the horizontal position and elevation at postings separated horizontally by three meters. These estimates will be used to form the DTM. In turn, the DTM will be used to geometrically correct and ortho-rectify the polarimetric SAR images. To minimize the operational costs, the system will collect data simultaneously on both sides of the aircraft. The effective area coverage rate will exceed 700 km^2/minute. For terrain with slopes of 45 degree or less, DTEMS will deliver DTMs with average one σ elevation precision of 0.3 meter, average absolute one σ elevation precision less than 0.6 meter, and three meter post spacing (posting). DTEMS data will satisfy National Map Accuracy Standards (NMAS) contour intervals of two to three meters.

[1] The ER-2 is the NASA remote sensing version of the US Air Force U2-R. Formerly designated the TR-1, the U2-R has replaced the older and smaller U2.

TABLE OF CONTENTS

1. INTRODUCTION

The primary mission of the Digital Terrain Mapping System (DTEMS) is to develop a commercial digital terrain matrix (DTM) archive containing the coordinates of the land surface at three meter intervals in rectangular coordinates. The initial emphases will be on development of the commercial archive of the entire United States. By accessing the archive, users will be able to obtain a low cost high quality DTM of any desired area. The products will be delivered electronically or over night on floppy or CD media.

0-7803-3196-6/96/$5.00 © 1996 IEEE

A study conducted by Lockheed Martin Missile and Space (LMMS) indicates there is a substantial emerging market for rapidly and easily available low cost high quality DTMs. A DTM is required for many topographic engineering activities, geological applications and production of a variety of cartographic products. Cartographic products that use a digital terrain matrix include digital elevation models, line maps, cultural land use maps, natural and agricultural land cover maps, and digital data maps.

Other potential uses for a high precision DTM include ortho-rectification of aerial and satellite imagery (i.e., generation of ortho image products from single images) and data bases for display of terrain in perspective view. A DTM is a fundamental component of any geophysical information system (GIS) and is required for any CAD/GIS applications that involve topography. A high precision DTM can be incorporated into AutoCad/GIS software packages for topographic engineering and geological applications. These packages will be used by construction, oil, utility, and cellular phone companies, and government agencies for highly accurate cadastral surveys, terrain perspective view display, line of sight determination, volumetric surveys, topographic analysis, flood plane surveys, and terrain trafficability surveys.

LMMS has determined that most of these emerging applications will require a DTM with post spacing (posting) of two to five meters and accuracy and precision of two meters or less. To be useful to many users across the United States, a DTM of any area must be easy to obtain in a short period at a cost well below the current cost of equivalent data. This requirement will be met by creating a DTM archive of the United States and other countries from which a DTM of any desired area can be extracted.

Presently no useful DTM archive is available to most users. Currently the primary sources of low resolution topographic data are USGS topographic maps and Digital Raster Graphics (DRG) data. A user must extract the DTM from these sources. (The process is time consuming and expensive.) The resulting DTM will have a minimum posting of 30 meters and precision, defined by the 90% probability standard deviation (90% σ), of five to seven meters[2]. The results of the LMMS analysis indicate that such a DTM will have relatively little utility in the emerging and future markets that require one meter precision and two to five meter posting.

Some of the USGS data is fifty years old. Over the years, land movements and cultural activities have caused many changes in topography. Consequently, some of the older USGS DRG data is no longer valid. Although the USGS DRG data is inexpensive, very little added value can be gained from its use.

DTEMS will provide a current DTM of the whole United States with six times higher precision and 1/10 the posting of the USGS data. DTEMS customers will be able to use a DTEMS DTM to improve current and develop new products.

For small areas, a DTM with posting of three to five meters and precision of one meter can be derived from 1/40000 scale stereo aerial photographs. A number of aerial photogrammetry firms offer such a service. This source is adequate for small areas in some regions of the country. However, due to inherent time delays and high production cost, the service will not be attractive in the emerging and future large volume markets that will demand rapid access to large quantities of data. Also, the buyers in these markets will not want to expend the

[2] Unless otherwise indicated, in this paper, elevation errors are the standard deviation for 90% provbability.

considerable time and effort needed to monitor the whole process from flight planning to DTM extraction.

A survey done by GIS World Magazine and Data Quest Inc. [1] indicates that the past slow growth in the GIS product market can be attributed to four barriers:

1. the high cost of entry into the business,
2. the high cost of data,
3. great difficulty in obtaining data, and
4. high difficulty of data use.

The researchers concluded that elimination of these barriers will stimulate rapid growth of a mass GIS market.

The high cost of entry into the GIS business has been due primarily to high hardware and software procurement cost. This barrier was eliminated by the computer revolution of the past few years. Within a year low cost personal computers with speeds exceeding several hundreds MHz will be available. DTEMS will offer its products on media formatted compatible with all workstation, PC and Power PC operating systems.

DTEMS will eliminate the other barriers to its products by:

1. establishing a data archive that can be accessed easily;
2. pricing data so that a large population can afford the data; and
3. making DTEMS products easy to use on engineering work stations and personal computers.

DTEMS initial operational capability is expected to be in the spring of 1997. Present plans are to conduct calibration flights and support a US Army field exercise in the October–November period. Ground truth data for calibration will be collected during the summer and fall of 1995.

2. System Configuration

DTEMS will produce a DTM archive of the United States with average 0.5 meter precision for terrain with slopes of 45 degree or less and three meter posting. An analysis of alternative techniques for collection of this data found that a wide swath interferometric synthetic aperture radar (IFSAR) carried in a high altitude aircraft would provide highest data quality at the lowest cost. The ER-2, which is the NASA version of the Air Force U2-R, was selected as the platform. The ER-2 offers a number of advantages over other aircraft:

1. low operational cost of $6500 per flight hour as compared to $10,000 or more for other jet aircraft;
2. operations between 60,000 and 70,000 feet provide the capability for large area coverage rate, avoids the impacts of weather and air traffic control on flight operations, and subjects operations to minimal turbulence and jet stream;
3. the 8.5 meter center to center separation of the wing pods provides an 8.5 meter IFSAR interferometer geometric baseline (IGB) and the rigid attachment of the wing pods eliminates excessive pod movement;
4. payload capacity of 4000 pounds and 25 kilowatts of power availability; and
5. missions as long as eight hours duration with over six hours of data collection time can be flown.

The major disadvantages of the ER-2 are special ground handling operations and use of an unusual fuel type. These eliminate ER-2 operations from most commercial airports. Also the single engine limits the off shore range of ER-2 operations to a few hundred miles.

Alternative techniques for sensing the terrain elevation include IFSAR [2,3], stereo photogrammetry, and laser ranging. IFSAR was selected for DTEMS for the following reasons:

1. IFSAR can provide a DTM with the desired data accuracy and posting;
2. IFSAR provides the maximum achievable area coverage consistent with the desired data quality;
3. data can be collected through cloud cover and day or night;
4. the data can be processed at relatively low cost on digital computers with minimum manual intervention;
5. topographic maps derived from IFSAR data are superior in many respects to topographic maps derived from stereo photographs [2]; and
6. production of marketable products and services that are presently not available (e.g., high resolution digital polarimetric SAR imagery, periodic measurements of terrain elevation changes, and detection of human activities).

The DTEMS system configuration, illustrated in figure 1, will use SAR receivers placed in the ER-2 wing pods to collect simultaneous images of the swath illuminated by the transmitter. At these locations, with zero roll, the horizontal baseline distance between the receivers will be 8.5 meters and the vertical baseline distance will be zero.

The transmitter will be located in the Q-bay which is in the fuselage behind the pilot. Four GPS antennas and receivers will be used, in the differential GPS (DGPS) mode, to collect aircraft position and altitude data which will be used for formation of the DTM. A GPS aided inertial navigation system will be used to collect the velocity data that will be needed for motion compensation during SAR image formation. The aircraft attitude, especially the receiver baseline roll about the aircraft velocity vector, will be measured using the GPS antennas and receivers for GPS interferometry (GPSI). An on-board clock, synchronized to the GPS 1 pps time signals, will provide system time.

To realize the maximum area coverage per flight, DTEMS will collect data in swaths on both sides of the aircraft. The coverage, illustrated in figure 2, will extend from swath inner edges at eight kilometers ground range to swath outer edges at 36 kilometers ground range. (Ground range is measured from the aircraft ground track.) This geometry will produce 28 kilometers of coverage in each swath and, at an effective ground speed of 210 m/s, the area coverage rate will be 706 km^2/minute.

The distance to the inner edges of swaths was selected to limit the smallest angle of incidence to 22 degrees to avoid excessive fold-over in the SAR images. The distance to the outer edges was selected to limit the largest angle of incidence to 61 degrees to limit shadowing in the SAR images.

Mission data includes I&Q samples of the received radar signals, mission time, and samples of the aircraft position, velocity, and attitude. These data will be combined and transmitted via the Satellite Transmission and Relay Link (STARLink) through a NASA TDRSS satellite to the TDRSS ground station at White Sands Missile Range, New Mexico. On board data recording will be used in the event that STARLink or TDRSS are not available. Data will be transmitted or data tapes will be transported to the DTEMS data processing facility (DPF). The location of this facility remains to be determined.

As illustrated in figure 3, the GPS receiver, GPS aided INS, and time clock outputs are

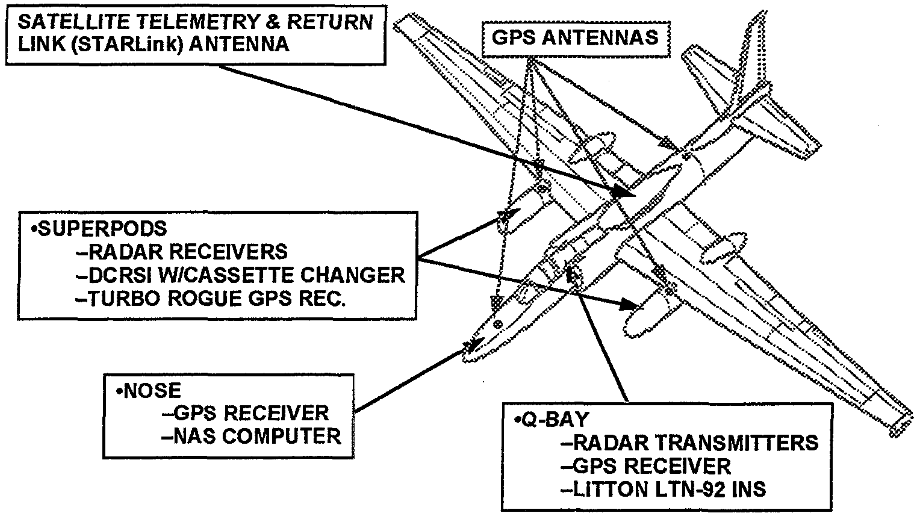


Figure 1. DTEMS will incorporate IFSAR, differential GPS, GPS interferometry and satellite data transmission.

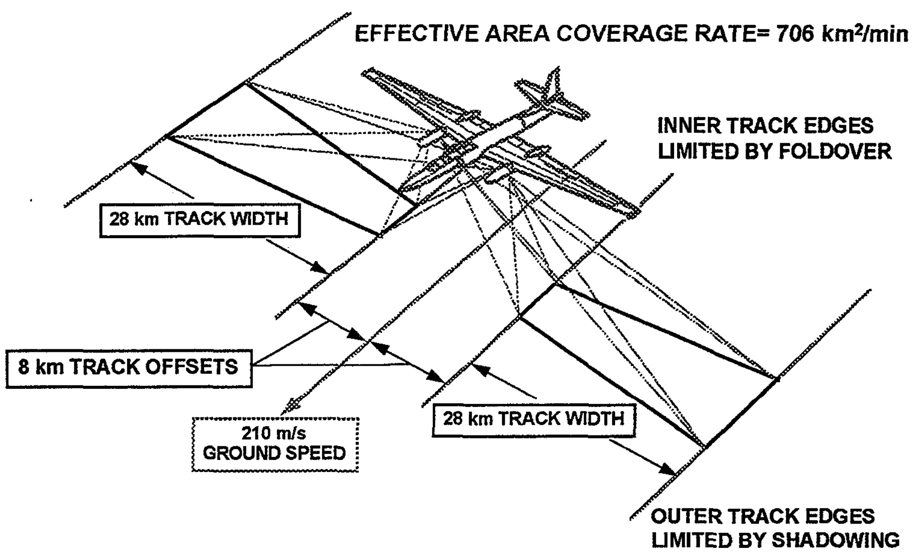


Figure 2. The IFSAR will collect IFSAR images in 28 km wide swaths on both sides of the aircraft ground track.

input to the navigation and attitude sensing computer (NASC). In the NASC the inputs are processed to and time tagged to obtain the aircraft position, velocity, and attitude vectors at each time interval. The NASC output is to a multiplexer that combines the NASC output data with radar data for either on-board recording or transmission via STARLink.

The data processing system at the DPF, shown in figure 4, will use an array processing architecture. The mission data will be input to the array processor via a work station or PC. The resulting DTM and SAR images will be added to the DTM and image archives.

Processing will include SAR image formation with motion compensation, SAR interferometry, extraction of the DTM, and coordinate transformations. The DTM will be used to geometrically correct and ortho-rectify the SAR images.

3. AREA COVERAGE

As shown in figure 5, the DTEMS mapping coverage will be done in two passes. In the first pass the radar will cover two swaths with average widths of 28 km. There will be a 16 km wide uncovered area between the two covered swaths. In the second pass the aircraft will fly a path parallel to the first pass but offset so that one of the swaths covers the uncovered area of the first pass. This will produce about 6 km overlaps and a total coverage width of 94 km.

A typical 6.5 hour DTEMS strip flight mission is illustrated in figure 6. After takeoff, the aircraft will climb to 18.2 km (60,000 feet). Data will be collected as the aircraft cruise-climbs at an average vertical rate of 9.86 m/s to 19.8 km (65,000 feet) altitude. During this cruise-climb, at an average ground speed of 210 m/s, the aircraft will have flown a ground distance of 1937 km. The aircraft will then make a 180 degree turn and continue cruise-climb to 21.3 km (70,000 feet) and will then start descent.

For the illustrated mission, the total collection time will be 5.1 hours and the distance covered will be 1937 km. Consequently, the total covered area will be nearly 182,000 km^2. With adjacent flight overlaps of 6 kilometers, the average effective area coverage per flight will be approximately 171,000 square kilometers. A rectangular area coverage mission is an alternative to the strip flight mission. The following table presents the length and width of the area that can be covered in a 6.5 hour mission. The coverage takes into account the collection time lost during turns.

NO. PASSES	WIDTH (km)	LENGTH (km)
2	94	1937
4	182	968
6	270	646
8	358	484
10	446	387

4. ELEVATION MEASUREMENT

The methodology of IFSAR for terrain elevation sensing has been described by Zebker and Goldstein [3], Li and Goldstein [4], Rodriguez and Martin [5], and Madsen, Martin, and Zebker [6]. Figure 7 illustrates the IFSAR geometry used for DTEMS. The elevation, h, at a post position, measured relative to a suitable datum, is given by the simple equation (see Martin & Zebker, [6]):

$$\begin{aligned} h &= H_0 - R\cos\alpha\cos(\alpha-\theta) \\ &-R\sin\alpha\sin(\alpha-\theta) \end{aligned} \qquad (1)$$

where H_0, is the aircraft altitude above the datum, R is the slant range to the post position and α is the interferometer geometric

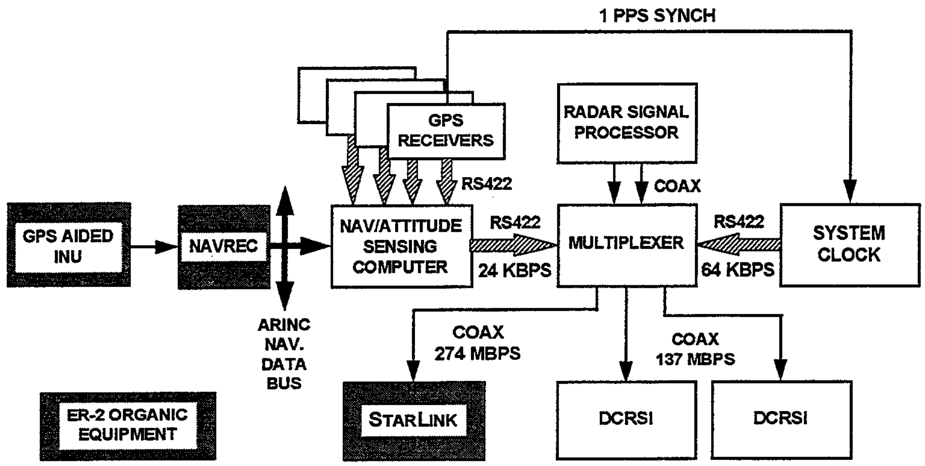


Figure 3. INS, GPS and time data will be multiplexed with radar data for digital recording or transmission.

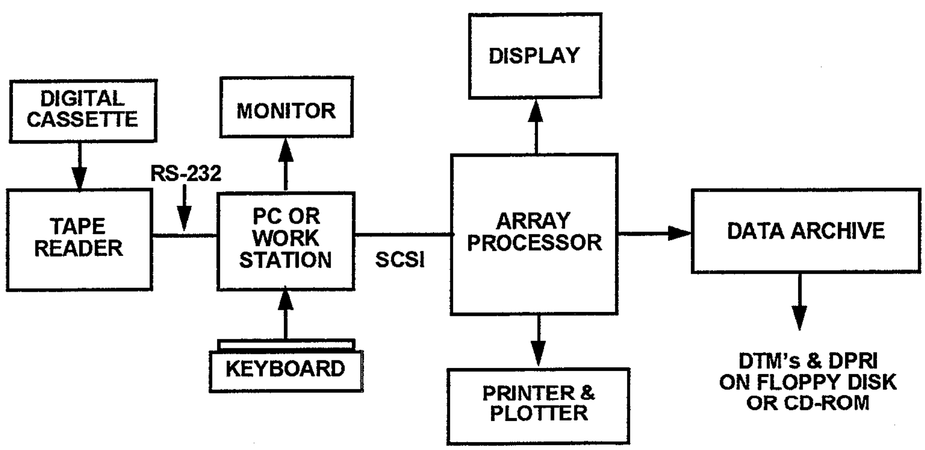


Figure 4. The data processing will be done on an array processor and the products will be stored in a digital archive.

baseline (IGB) tilt in the nadir/cross-track plane. The elevation angle is related to the geometry and phase difference, ϕ, by [6]

$$\sin(\alpha-\theta)=\frac{(R+\phi/k)^2-R^2-B^2}{2RB} \qquad (2)$$

where $k=2\pi/\lambda$, λ is the radar wavelength, and B is the distance between the receivers. Since the DTEMS baseline is horizontal, α is zero. Also, $B=8.5$ meters and the slant range varies from 21 km to 42 km.

5. Terrain Elevation Errors

Two primary components of system related elevation errors are the IFSAR system errors that determine the relative elevation prec-ision and aircraft positioning system errors that determine the absolute terrain elevation accuracy. [7]

IFSAR System Related Error

The sources of system related terrain elevation errors can be placed into three categories:

1. IFSAR phase measurement error,
2. IFSAR IGB errors, and
3. IFSAR range measurement error.

IFSAR Phase measurement Error—In the previous section it was shown that θ is needed to compute the terrain elevation and that this angle is determined from phase difference measurements. Consequently, the radar phase measurement error, σ_α, will contribute directly to the elevation error:

$$\sigma_h^\phi=\frac{R\lambda}{2\pi B}\cdot(\sin\alpha-\cos\alpha\cdot\tan(\theta-\alpha))\cdot\sigma_\phi \qquad (3)$$

The phase measurement error includes contributions from radar receiver noise, signal processing, and environmental phenomena.

The phase error contribution due to receiver thermal noise is

$$\sigma_\phi^N=\frac{1}{\sqrt{N\cdot CNR}}, \qquad (4)$$

where CNR is the ratio of the radar signal carrier power to the power of receiver thermal noise and N is an integration factor that depends on the post spacing and pixel dimensions. The term under the square root is the effective IFSAR signal-to-noise ratio (SNR).

The integration factor is

$$N=\frac{4P^2\cos\psi}{\rho_a\rho_r} \qquad (5)$$

where P is the post spacing and ρ_a and ρ_r are the pixel dimensions ψ is the grazing angle at the surface and ρ_a is the azimuth or along track resolution. The DTEMS azimuth resolution is 0.5 m.

Phase errors introduced during signal processing are produced by multiplicative noise generated during SAR image formation:

$$\sigma_\phi^{MN}=\sqrt{\frac{MNR}{N}}, \qquad (6)$$

where MNR is the so called multiplicative noise ratio and by pixel registration error:

$$\sigma_\phi^{MR}=\frac{\pi(\Delta\rho/\rho)}{\sqrt{6N}}. \qquad (7)$$

where $\Delta\rho/\rho$ is the ratio of registration error to pixel size.

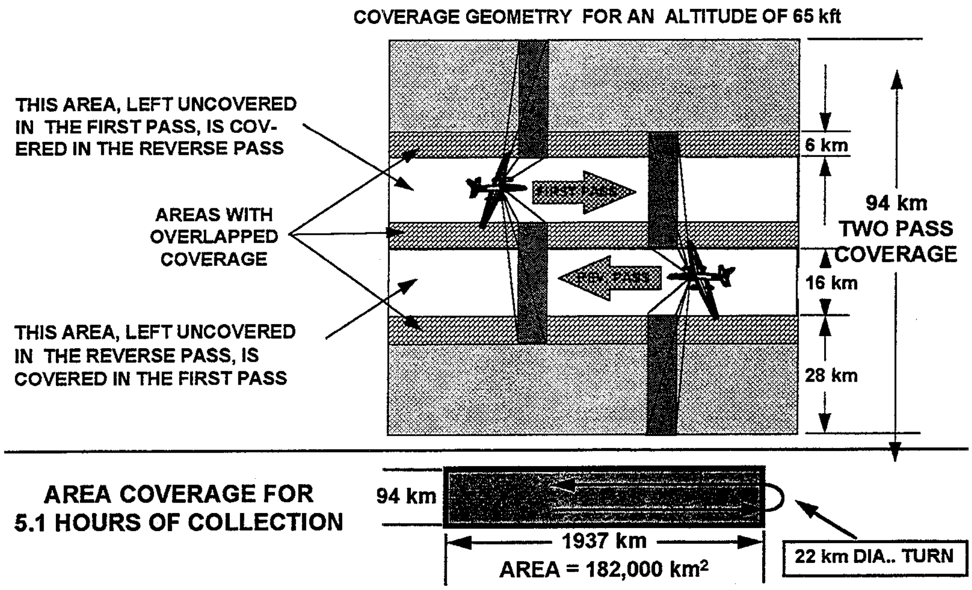
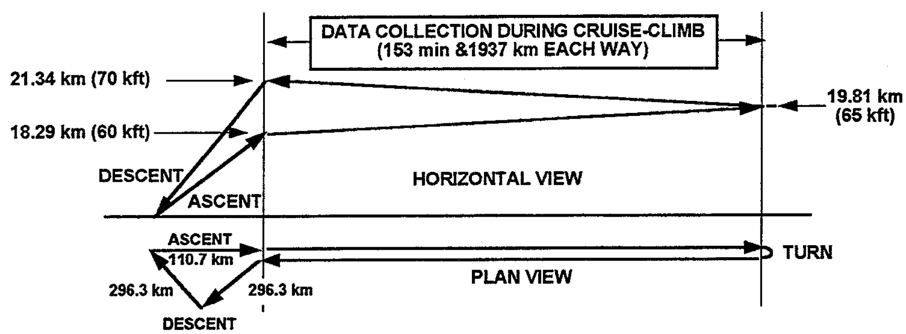


Figure 5. In two overlapping passes, DTMS will cover an area 94 km in width. (Illustration is for 65,000 ft altitude.)



	ASCENT	CRUISE-CLIMB	TURN	DESCENT
PERIOD (MIN)	44.4	306.3	2.7	36
HORIZONTAL VELOCITY (km/min)	8.54	12.65	12.65	16.46
RATE OF CLIMB (m/min)	411.9	9.86	0.0	- 609.5
ALTITUDE VARIATION (m/min)	--	+/- 30.48	+/- 30.48	--

TOTAL FLIGHT TIME: 390 min (6.5 hr) DATA COLLECTION TIME: 306.3 min (5.1 hr)
TOTAL DISTANCE: 4760 km (2570 nmi) COLLECTION FLIGHT DISTANCE: 1937.3 km (1046.1 nmi)

Figure 6. A typical 6.5 hour mission profile yields 5.1 hours of collection time & covers 1937 km surface range.

The two radar receivers view the surface with small but significant difference in incidence angle. This difference in incidence angle produces an IGB de-correlation contribution to phase error given by [8]

$$\sigma_{\phi}^{DC} = \sqrt{\frac{B\rho_r \tan\psi_e}{\lambda NR}}, \quad (8)$$

where ρ_r is the resolution in the cross track or range direction and ψ_e is the error in terrain slope knowledge. The cross track resolution varies over the swath:

$$\rho_r = \rho\frac{1}{\cos\psi}, \quad (9)$$

where ρ is the slant range resolution (1.0 m).

IFSAR IGB Related Errors—As we have seen in equations (1) and (2), computation of the terrain elevation requires knowledge of the IGB tilt. An error in IGB tilt knowledge, σ_α, will cause a corresponding terrain elevation error given by

$$\sigma_h^\alpha = R\sin\theta\sigma_\alpha. \quad (10)$$

This equation can be written in terms of surface cross-track range, R_g:

$$\sigma_h^\alpha = R_g\sigma_\alpha. \quad (11)$$

Since the cross-track range will be large it is apparent that the IGB tilt must be known with high precision. For a 1.0 m error contribution at 36 km cross-track range, the IGB tilt must be known with a precision of 0.0016 degree. The method to be used for IGB tilt determination with a precision less than 0.001 degree is described in the companion paper in these proceedings [10].

At the operational altitude, the ER-2 is very stable. During collection operations the ER-2 will be on auto-pilot. Measurements of the aircraft roll show that, for relatively long periods of time, the aircraft flies with a roll bias in the range of +/- 0.5 degree and peak-to-peak variations are within +/- 0.25 degrees. The actual IGB tilt will be measured at one second intervals.

An error in baseline length, σ_B , will also cause an error contribution to the terrain elevation error:

$$\sigma_h^B = \frac{S\sin\psi\cos\psi}{3.46B}\sigma_B \quad (12)$$

where S is the swath width (28 km). At a grazing angle of 45 degrees the baseline length error is multiplied by a factor of 476. For the error contribution to be 0.1 m the baseline length must be known to 0.2 mm. Shorter baseline systems, such as IFSARE and TOPSAR require much higher precision of baseline length.

IFSAR Range Measurement Error—The IFSAR range measurement error is equal to the range error which depends on the effective SNR and slant range resolution

$$\sigma_h^R = \frac{\rho}{\sqrt{N\cdot CNR}} \quad (13)$$

Environmental Effects— Various enviornmental phenomena can affect the IFSAR signal and produce additional contributions terrain elevation error.

Fog, clouds and rain will have negligible effects on the signal propagation. Unusually

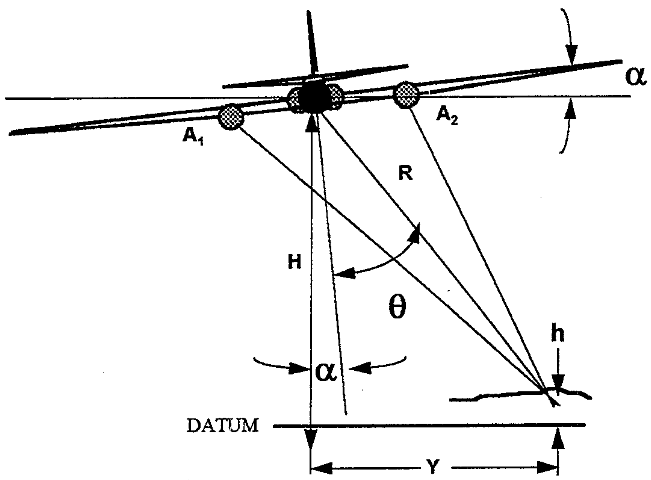


Figure 7. In iterferometric SAR, the terrain elevation is determined by measurement of the angles α and θ.

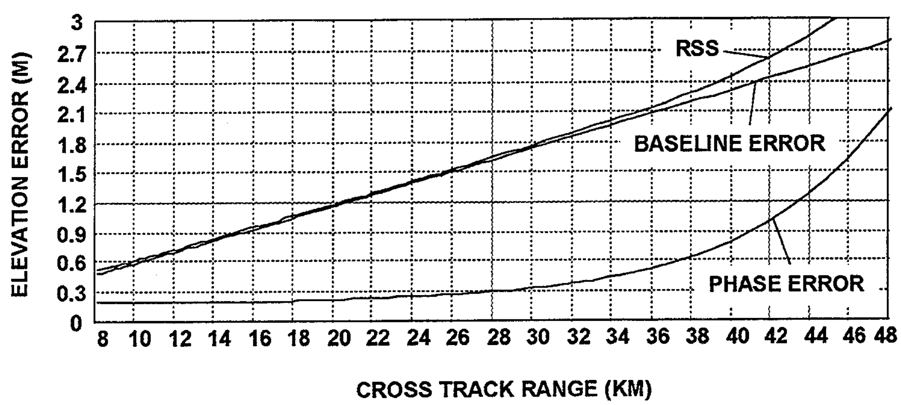


Figure 8. To a ground range of 36 km, baseline tilt related errors are the dominant component of terrain elevation error.

heavy rain rates can cause signal loss, but the volumetric expanse of such rain rates is usually small and the probability of encountering them is very small.

Time delays due to troposphere water vapor will also have negligible effects on the DTEMS IFSAR. Troposphere water vapor slows the speed of microwave propagation, and therefore, increases the propagation time in proportion to the slant path distance of propagation through the troposphere. However, the round trip paths to each IFSAR receiver will be within the same volume of atmosphere so the two signals will undergo nearly equal round trip propagation time delays. Consequently, when the phase difference is computed, the delays on the two signals will almost totally cancel. TOPSAR and IFSARE experience indicate that the residual differences are very small and have negligible affect on the terrain elevation error.

Troposphere time delay cancellation is not realized in airborne or satellite single pass IFSAR. Consequently an airborne or satellite repeat pass IFSAR system will suffer a significant error due to the large residual troposphere propagation time delay. Estimates of these errors range from one to several meters.

Radar returns from foliage will be a, presently not quantified, significant cause of terrain elevation error. At X-band the radar signal backscatters from tree, brush and dense grasses foliage. Volumetric scattering from these media causes increased phase dispersion and range error. The effects can be reduced by performing operations at times when the volumetric moisture in the media are minimum or when the foliage are frozen. Polarimetric SAR data may be used to discriminate ground returns from foliage returns and repeat operations at lower frequencies such as C, S and L bands can be obtain greater penetration depth. This will be an area of continuing investigation.

Surface penetration is another potential cause of phase and range errors. At X-band the penetration depth in most soils will be a fraction of a wavelength so the error due to penetration will be negligible. However, in very dry sand (less than ten percent moisture content) the penetration depth can amount to several centimeters that will cause small but significant terrain elevation errors. This error will increase with lower frequency so it will be larger at C, S and L bands respectively.

Multiple reflections, for example a reflection off an object followed by a reflection off another object or the ground will produce ambiguities and large elevation errors. This problem will be most severe in areas that have many large vertical structures (e.g., urban areas and dense forests) that form corner reflectors among parts of structures or between struct-ural parts and the ground. Methods for mitigation of this problem are under study.

6. Simulation Results

A simulation was used to compute the IFSAR system errors over the covered swath. The simulation used an aircraft altitude of 65,000 feet and was over terrain with constant slope of 45 degrees.

A SAR with 528 Watts average power with azimuth resolution of 0.5 m and slant range resolution of one meter was assumed. A discussion of the SAR simulation is provided in Malliot [10] in these proceedings.

Figure 8 shows the plot of the ground range distribution of terrain elevation error over the 28 km swaths. The RSS of phase error

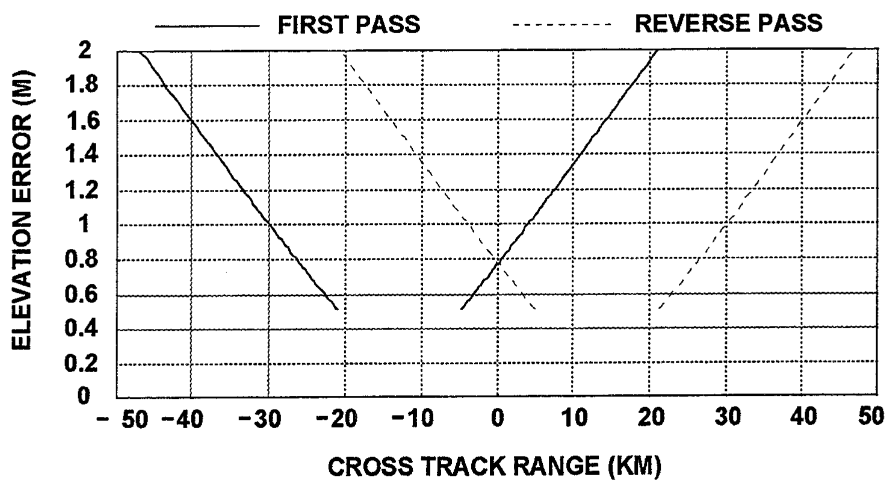


Figure 9. Prior to IGB tilt correction, the two pass elevation error ranges from 0.5m to 1.6 m over an 80 kilometer swath.

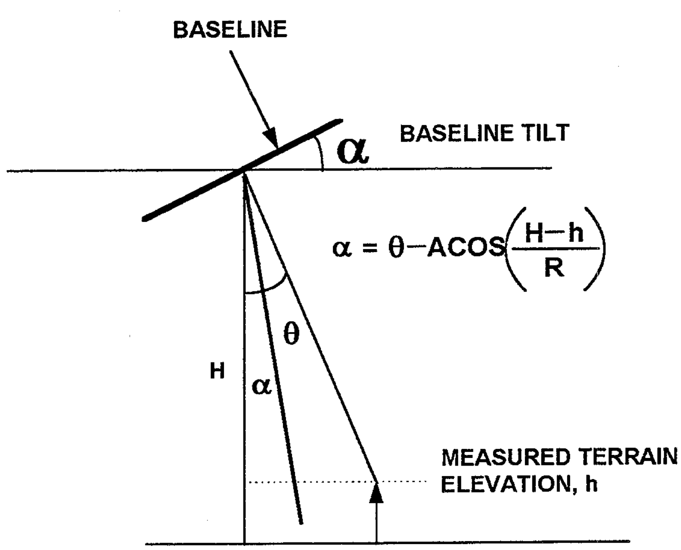


Figure 10. Given the measured terrain elevation, h, and the angle of arrival, θ, the baseline tilt can be computed.

contributions is an upward bending curve. The phase error contribution is 0.2 m at 8 km ground range and increases to 0.6 m at 36 km ground range.

The baseline error contribution to terrain elevation error is a straight line with a positive slope of 0.042 m/km. The error is 0.4 m at 8 km ground range and increases to about 2.0 m at 48 km ground range. Out to 36 km ground range the baseline tilt error is the dominant source of terrain elevation error.

The RSS error curve for two overlapping passes, such as illustrated in figure 6, is presented in figure 9. The error ranges from 0.5 to 2.0 m over a 94 km width of the covered area.

It is obvious in figure 8 that the IGB tilt error produces the major contribution to the overall error. Recursive estimation of the IGB tilt can be used to reduce the terrain elevation error.

Consider the geometry relationship illustrated in figure 10. Solving the geometry for the IGB tilt obtains

$$\alpha = \theta - \cos^{-1}\left(\frac{H_o - h}{R}\right). \tag{14}$$

The parameters H_o, θ, and R are measured so, after the initial estimate of terrain elevation h is obtained, the IGB tilt can be computed. The new estimate of IGB tilt can then be used to compute a new estimate of h.

The positions selected for the calculation should be those with the minimum elevation error. In figure 9 these areas are located at ground distances of at +/-4 km and +/-22 km where the terrain elevation error is about 0.52 m. Using points in these areas obtains the improved error distribution shown in figure 11. After correction the RSS error ranges from 0.14 m to 0.58 m and the mean is 0.29 m.

Additional discussion of sequential IGB tilt estimation can be found in the companion paper in these proceedings[10].

7. Conclusions

DTEMS is a system for collection processing and archive DTM and digital polarimetric radar imagery for commercial and government applications. The system will use an interferometric SAR in a high altitude ER-2 aircraft to

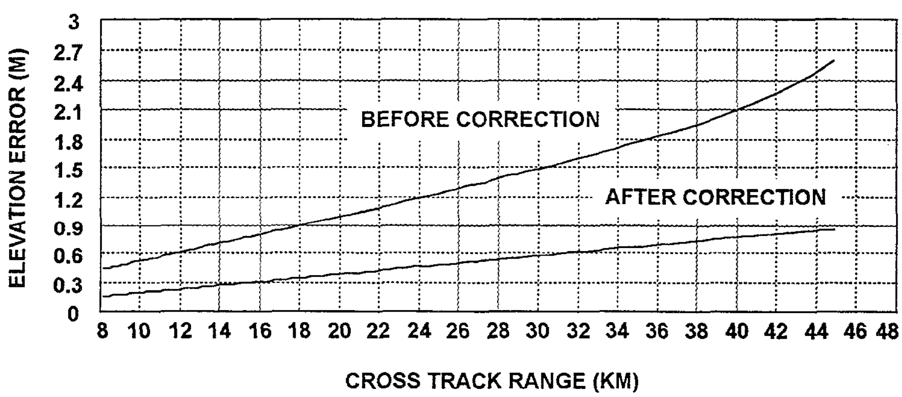


Figure 11. Baseline tilt correction reduces the elevation error to 33 percent of the pre-correction error.

collect data over areas as large as 190,000 km^2 in a single flight. For terrain with 45 degree or less slope, after baseline tilt correction, the system will provide a DTM with relative average 90%σ precision of 0.5 m and posting of three meters. The average absolute 90%σ accuracy will be 0.96 m.

DTEMS operations will be conducted at altitudes between 60,000 and 70,000 feet. The IFSAR will collect data simultaneously in 28 km swaths on both sides of the aircraft. DTEMS will use differential GPS to obtain high precision aircraft position and velocity and GPS interferometry to obtain high precision SAR IGB attitude. IFSAR, aircraft position, aircraft velocity, GPS time and GPS IGB attitude data can be recorded on on-board digital cassette recorders or can be transmitted via the ER-2 STARLink at a rate of 274 Mbps to the TDRSS ground station at White Sands Missile Range, NM.

DTEMS data will be processed and DTM and ortho-rectified polarimetric radar image files stored in an archive at a location to be determined. Requests for data will be received by mail, telephone fax or Internet. The data will be delivered by Internet and over night delivery on floppy , CD and hard disk.

REFERENCES

[1] ''A Profile of GIS Users,'' GIS Strategies, Vol. 2, No. 3, Third Quarter 1993, GIS World, Fort Collins, CO.

[2] Ledner, R.; ''IFSAR earns high marks in mapping applications'', Vexel Inc., Vexel Visions, Vol. 1, No. 3, Oct. 1994

[3] Zebker, H. A., and Goldstein, R. M.; ''Topographic mapping from interferometric synthetic aperture radar observations'', *J. Geophys. Res.*, Vol. 91, pp. 4993-4999, 1986

[4] Li, F. K., and Goldstein, R. M.; ''Studies of multibaseline spaceborne interferometric synthetic aperture radars'', *IEEE Trans. Geoscience & Engineering,* Vol. GE-28(1), pp. 88-98, 1990

[5] Rodriguez, E. and Martin, J. M.: ''Theory and design of interferometric synthetic aperture radars'', *IEE Proceedings-F,* Vol. 139, No. 2, pp. 147-159, 1992

[7] Madsen, S. N., Martin, J. M., and Zebker, H. A.: ''Analysis and evaluation of the NASA/JPL TOPSAR across-track interferometric SAR system'', *IEEE Trans. on Geoscience & Remote Sensing,* Vol. 33, No. 2, pp. 383-391, 1995

[8] Malliot, H. A., ''A Wide Swath Topographic SAR'', *Proceedings of the Interferometric SAR Technology and Applications Symposium,* April 13-14, 1993, Ft. Belvoir, VA, pp. 459-476

[9] Banach. M., Swiger, M., and Wright, T.: ''Exploration of Rapid Mapping Concepts'', *ERIM,* Final Report, Dec. 1993

[10] Malliot, H. A., ''DTEMS interferometric SAR design and method of baseline tilt determination method'', paper number 7.2 of this conference.

AUTHOR BIOGRAPHY

Harold A. Malliot has been employed for 20 years at the Lockheed Martin Missiles and Space (LMMS) Research and Development Division in Palo Alto, Ca where he has worked on electromagnetic remote sensing systems and synthetic aperture radar. Mr. Malliot is the Chief Systems Engineer on the Digital Terrain Elevation Mapping System (DTEMS) program. Prior to working at LMMS, Mr. Malliot was employed for six years at ESL Inc. and, prior to ESL, six years at SRI International. Mr. Malliot received the BSEE from San Francisco State University (1963), MSEE from the University of Santa Clara (1969) and completed two years of additional graduate work at the University of Santa Clara and other institutions.