CHAPTER 1: INTRODUCTION

1.1 Introduction

National Remote Sensing Centre (NRSC) is one of the leading centers of Indian Space Research Organization (ISRO) under Department of Space, Govt. of India, engaged in operational remote sensing activities. Main activities of NRSC are remote sensing data reception from space borne and airborne platforms, data processing, data dissemination, data archival and carrying out remote sensing applications for providing value added information to cater to national imperative needs and disaster services. NRSC provides capacity building to remote sensing data users in India and distributes data from Indian and foreign satellites such as IRS satellites, Radarsat, Ikonos, Quickbird, Orbview, Envisat, ERS, Terrasar to Indian and foreign users. NRSC has its own Integrated Multimission Ground segment for Earth Observation Satellites (IMGEOS) at Shadnagar, to acquire, process and disseminate remote sensing satellite data from Indian Remote Sensing and Microwave Remote Sensing satellites (All Data Users’ Handbooks of IRS missions 2012). The data processing operations are carried out at NRSC for IRS missions. Two modern Aircrafts having INS, K-GPS fitted with Multi-spectral Scanner, Photogrammetric Cameras, SAR, ALTM, Large Format Cameras, and Electromagnetic Sensors are in use for aerial remote sensing. Laser data based DEMs are obtained from aerial ALTM instrument. The
acquired remote sensing data are processed in-house to produce wide range of data products for distribution among the user community.

The satellites with optical sensors do not provide images during night time, when there is no sun illumination and cannot image in cloudy and rainy conditions. Besides, polar sun synchronous orbits are required for optical sensors to provide constant sun angle and illumination conditions. To supplement such gaps in optical remote sensing data, ISRO is planning to place RISAT series of satellites in orbit with microwave SAR imaging radars on board from 2012. SAR imaging radars can operate in day or night or in cloudy weather conditions. With both optical and microwave sensors, NRSC will be able to provide all time, all weather remote sensing data to meet national applications requirements.

Demand for use of DEMs derived from remote sensing data is on increase as DEMs are required not only for various applications of science and technology (Juha Oksanen et al 2000, Felix Hebeler and R.S. Purves 2007, Hebeler F. and Purves R.S. 2009), but also for remote sensing data processing chain, for generating ortho rectified data products in operational mode. To meet these requirements and to build SAR DEM archives, suitable methodologies and error quantification frame works are required to be explored. The topographic maps produced by SAR interferometry have the advantages of all weather condition, high accuracy and automatic
processing (Yonghong Huang et al. 1996, Bryan Mercer J. et al. 1998) and useful in such cases where optical methods cannot be used due to constraints such as constant cloud cover.

From remote sensing data, DEMs can be produced either by Optical means (Photogrammetry, Stereoscopy and Airborne Lidar) or by Synthetic Aperture Radar images (Radargrammetry and InSAR or IfSAR) acquired from airborne or space borne platforms. Even though the Airborne Lidars, Aerial Cameras and Radar systems can provide data for generation of the higher resolution DEMs, DEMs generated with space born sensors extend wider data coverage, especially in some remote regions quickly and with low cost. Synthetic Aperture Radars (SAR) are basically imaging radars that operate by illuminating the topographic surface with coherent pulses in microwave frequencies, preserving both amplitude and phase details in the radar echoes throughout the acquisition chain. Radargrammetry works with amplitude SAR images utilizing similar approach as that of Photogrammetry, whereas Interferometry SAR (InSAR) technique utilizes the phase difference between two similar complex SAR images of same area taken in one or more repeat orbit cycles. In InSAR DEMs generation, elevation data values are computed from absolute phase values. Though it is found to be feasible to generate small InSAR DEMs with much better than ±10m accuracies, generation of large area DEMs are limited by optimum
base line requirements, the temporal and spatial correlation requirements between the input data pairs, suitable phase unwrapping algorithms resulting in reduced accuracies in hilly terrain with steep slopes. InSAR DEMs are more useful for applications that tolerate lower accuracy, but require larger areas when compared to Lidars (Xiaopeng Li, A. Bruce Baker 2003).

Generation of DEMs over large area requires a large number of identifiable and spatially distributed Ground Control Points for precise co-registration of SLC image pairs and to provide absolute height reference, for phase to height conversion. Identification of GCPs with geographic features in SAR SLC image pairs is very cumbersome and this constraint can be avoided using alternate techniques.

In spite of post processing of InSAR DEMs, these elevation data sets are likely to contain inherent errors due to phase noise. Phase noise springs up from thermal noise, temporal de-correlation, spatial de-correlation, baseline errors, phase unwrapping errors due to geometrical distortions, atmospheric influences. The phase noise introduces phase errors and these in turn contribute to random and systematic elevation errors in InSAR DEMs which need to be quantified for making DEMs useful for various applications.
1.2 Initiative for the Thesis

One of the remote sensing value added products most suited in the study of earth surface is Digital Elevation Model. DEMs are widely used in domains such as ortho-rectification, tele-communications, defense and are becoming very useful data source for Geographical Information System (Fernando J. Aguilar et al. 2005). Literature shows ERS SAR images are very useful to provide basic information for DEM generation. InSAR technique can be used to establish thematic maps such as the flood hazard prediction map and so on. However, it works best when coherence, baseline and phase unwrapping are balanced optimally (Hongbing Hu et al. 2010).

To generate and build elevation model data bases, it would be feasible with wide area DEMs for which adequate methodologies and suitable techniques are required to be in place. It is also necessary to investigate new ways of quantifying uncertainty of the elevation model data sets in microwave area. DEMs are useful to extract terrain parameters, modeling water flow, study of landslides, creation of relief maps (http://classes.yale.edu/fractals/), cartographic applications, Geo-morphological analysis and modeling, biogeographical analysis and modeling, hydrological applications, studies of landscape dynamics, climate studies, geological applications, agricultural applications, road and dam planning, automatic drainage basin delineation and flood-risk analysis, geophysical

InSAR DEMs and their derivates are widely used in many remote sensing applications, in which the knowledge on the quality of a DEM is a major concern. DEM evaluation knowledge has become a prerequisite to many applications. The quantification of accuracy of the DEMs is an important requirement for effective use of DEM in the remote sensing applications. Geo-spatial community seems to have begun to accept airborne and Spaceborn InSAR as an additional cost-effective three dimensional mapping technology for many applications. This is acknowledged by the importance of the role played by Shuttle Radar Topographic Mission (SRTM) InSAR DEM. However, InSAR has not yet reached its full potential as a mapping tool in the Geo Spatial market place due to low availability of repeat pass SAR DEMs and the knowledge on the accuracies (Joachim Höhle and Marketa Potuckova 2006). Till recent years, this process is a technology demonstrator, but now, an effective methodology is needed to be evolved for operational production of elevation models using repeat pass techniques for larger areas. In this backdrop, it is necessary not only to evolve and identify suitable methodology to produce accurate
InSAR DEMs for the benefit of application users, but also to bring out frameworks for quantification of errors and to suggest processes to evaluate, quantify uncertainty of the produced large area InSAR DEMs. Quantification of the accuracy of DEMs is necessary for effective use for various applications (David Jonas Nils Mathews 2006, Ayman H. Nasr 2005).

1.2.1 InSAR DEM Errors

InSAR based Elevation models derive heights from the phase difference information from the SAR SLC interferometry image pairs. SAR interferogram is generated by cross-multiplying, pixel by pixel, the first master SAR SLC image phase with the complex conjugate of the slave or the pair (Bamler 1998A, Massonnet 1998, Franceschetti 1999, Rosen 2000). InSAR DEMs for this research study are produced using repeat pass interferometric technique that makes use of phase difference information extracted from two complex valued SAR images acquired from different orbit positions with same look angle over the same geographical area with certain baseline requirements (Kesava Rao P. et al. 2003). Horizontal and vertical errors in InSAR DEMs spring up mainly from phase errors or phase noises from various sources. While Horizontal errors refer to the pixel location error or difference between true location of the pixel and measured location on ground, Vertical error refers to the difference in model height value from the true height value at that pixel. InSAR
DEMs suffer from a wide variety of artifacts (Blackwell P.R et al. 1999), clinometric or slope related errors (Audenino P et al. 2003), voids of various sizes, spikes or outliers. Once the knowledge on the origin of the errors is derived, appropriate steps could be taken to minimize the errors or improve the DEM accuracy. Phase errors contribute to elevation errors in InSAR DEMs due to thermal noise, temporal de correlation, spatial de correlation, baseline errors, phase unwrapping errors due to geometrical distortions, atmospheric influences (Laurent Polidori et al. 1996). These will result in systematic and random errors like voids, blunders. Elevations are underestimated for slopes facing radar sensor (fore slopes) and are overestimated in the opposite direction (back slopes) (Bernard Bourgine et al. 2005). Error quantification frame work is required to be explored, so that NRSC will be able to produce good quality SAR DEMs to supplement existing CartoDEM data archives.

1.3 Objectives of the research study

Digital Elevation Models are becoming an essential requirement in a variety of remote sensing applications. The need for generation of InSAR DEMs, quantification of errors and modeling the uncertainty for application oriented research with InSAR DEMs is on increase. Error assessment models have been limited to single point statistics, ignoring the quantitative description of spatial distribution and structure of errors. For InSAR DEM user, a good understanding of the
nature and size of errors present in the elevation data sets is of essential importance to arrive at insight into the value of information derived from the data sets. The Literature survey indicate that there is yet much scope for examination of the methods of generation of large area InSAR DEMs, novel ways of quantification of errors, simulation of error fields, and presentation of the accuracy of InSAR DEMs for proper usage of DEMs (Heywood et al. 1998). This research aims to bring out suitable methodologies to generate InSAR DEMs and evolve error quantification frame work to enable the production of good quality InSAR DEMs at NRSC and enable to supplement existing CartoDEM data archives.

Assessment of the quality of an elevation model is usually done by deriving a statistical measure of DEM accuracy and thereby expressing how near the DEM's elevation values are to true elevation. Statistical measures such as Root Mean Squared Error and Standard Deviation of error are commonly used. These measures of course summarize elevation errors in a DEM as a single global value. Intrinsically, InSAR DEMs contain artifacts and errors due to inherent characteristics. These inherent errors can be remedied to some extent during various processes of DEM generation. It would be interesting to the DEM provider to probe and ensure that the elevation values in the model are commensurate with the quality metrics or maps that
are furnished with DEMs and this requires obviously novel methods to enable for wider spectra of applications (Bruce H. Carlisle 2005).

The research study therefore rightly aimed to address the following innovative objectives and present the study results.

- It is aimed to explore and analyze suitable methods, and devise new techniques for generating value added products in microwave remote sensing using repeat pass SAR data sets. Conventional methods need GCPs as input reference in phase to height conversion process and others by pass these GCPs.

- Next objective is to examine uncertainty in the generated InSAR DEMs. This involves to develop a novel and comprehensive framework for characterization of DEMs, for error presentation or error quantification by statistical, spatial, graphical and simulation measures.

  - Statistical error quantification measures adopted are: RMSE, Standard Deviation of DEMs, Standard Error, NIMA LE 90, Accuracy ratio, mean, minimum, maximum and these are quantified using:
    - Digitized contour heights,
    - Surveyed bench mark heights,
    - GPS measurements based GCPs
    - Pixel matching method using Carto, Laser DEMs
Study is extended to find out Error variation with number and accuracy of test points

- Spatial measures considered are
  - Coherence maps
  - slope maps
  - Fractal Dimension by DBC, variogram, WPS methods
  - Roughness Indices

- Graphical Methods considered are
  - Histograms of errors
  - Horizontal elevation Profiles
  - Vertical elevation Profiles
  - Error maps

This research topic addressed statistical error analysis of InSAR DEMs using discreet check point method, pixel matching method, and GPS control points. The objective is extended to examine the influence of number of check points on reliable quantification of DEM error and comparison with statistical results obtained with GPS measurements. An attempt is made to find out the robustness of statistical error quantification measures by varying the number of reference check points systematically and also by varying the type of reference check points (Kesavarao P. et al. 2010).
Normally, Root Mean Square Error (RMSE) is used to quantify uncertainty in InSAR DEMs. This statistical parameter alone is inadequate to reveal spatial distribution of errors in elevation models. Hence, coherence maps, error maps, average slopes are generated and considered in the error quantification framework.

Fractal dimension of Optical and InSAR DEMs is estimated using three different methods and performance comparison of the methods and their suitability is studied. Digital Elevation Models represent three dimensional complex, irregular shaped topographic surfaces. Since Euclidean Geometry is confined to regular shaped objects, Fractal Geometry is made use of to express the geometrical dimension of DEMs. In this study, FD is computed for Synthetic Aperture Radar (InSAR, SRTM) and Optical (Carto) DEMs by Differential Box Counting, Semi-Variogram and Wavelet Power Spectral method. Adequacy of each of the method to compute a single fractal dimension for entire DEM and performance of these methods for SAR and Optical DEM data sets is studied. In case of Variogram method, it is attempted to bring out additional clarity on the technique to identify the extent of linear segment of variogram. The methods are compared and the results are discussed (Kesavarao P. et al. 2011).

Roughness is variability of elevation of a topographical surface at a given scale that is decided based on the size of landforms or geomorphic features. Thesis aimed to compute the roughness index
and correlate these roughness profiles of the DEMs with estimated statistical error parameters.

- Another objective is to use graphical approach to generate and analyze Elevation Profiles of large extents in range and azimuth directions and compare with reference DEMs to know along track or across track elevation offsets.

- Another objective is InSAR DEM error field simulation.

Apart from quantification of errors, the following uncertainty assessment schemes and simulations are applied:

  - Visual Analysis of Error Maps
  - Error surfaces using Simulation
  - Bipolar Error maps could be derived using accurate reference DEMs by pixel matching

- Simulation of error surfaces using Monte Carlo methods, realization of synthesized InSAR DEMs, and comparison with generated InSAR DEMs and reference DEMs is the path adopted to meet this objective successfully.

### 1.4 Thesis Contribution

The research study has brought in new methods, and innovative techniques for generating value added products in microwave remote sensing. During this research, novel measures are developed to quantify and evaluate InSAR DEM errors. These would provide value addition for future microwave satellite products value addition and
supply to various users. This research activity has resulted in publication of two papers in international journals, one paper in national journal and one publication in national conference proceedings and three papers in international conference proceedings.

Thirty InSAR DEMs of $1^0 \times 1^0$ and $15' \times 15'$ sizes are generated with separate methods using ERS-1/2 tandem repeat pass interferometry technique and analyzed. It is shown that even though both methods yielded DEMs of similar accuracy level, the second method without the use of input reference points appeared to be superior in terms of operational turnaround time. Results indicate that it is possible to routinely generate, post process and provide DEMs at NRSC with an absolute accuracy of around $\pm 10$m to $\pm 40$m and on an average around $\pm 21$m. Though the recommended method is adequate for generation of DEMs with above stated accuracy, further scope exists for accuracy improvements.

More accurate CartoDEM s obtained with Panchromatic (PAN) stereographic cameras placed onboard Indian Remote Sensing Satellites (Rao K.M.M et al. 1994, Rao K.M.M et al. 1996) are considered as prime reference data source. Shuttle Radar Topographic Mission (SRTM) InSAR DEMs and Laser based surface elevation models obtained by Airborne Laser Terrain Mapper (ALTM) for the same segmented topographic areas are considered as secondary reference data sources. Produced InSAR DEMs are compared at pixel
level with reference DEMs for estimation of Root Mean Square Error (RMSE). InSAR DEM errors derived using pixel matching techniques, and estimated errors using GPS measurements are compared and analyzed. Minimum number of reference points needed for error quantification of InSAR DEMs is established using the study results.

It is shown that the coherence and slope estimates are useful metrics to express InSAR DEM uncertainty.

Existing methods for estimation of FD values of InSAR DEMs are compared and extent of linear segment for estimation of slope for variogram is newly ascertained. RI is shown to have strong correlation with RMSE and SD of respective DEMs. RI and FD together are found to provide a way to understand the terrain complexity of the DEMs.

A novel and comprehensive framework has been developed for uncertainty quantification of large area InSAR DEMs using statistical, spatial, and graphical measures. InSAR DEM assessment schemes are brought out with error maps; error histograms derived using reference DEMs and compared with simulated error surfaces.
1.5 **Structure of the thesis**

This thesis covers the topics, concepts and issues that are central to InSAR DEMS generation using repeat pass interferometry, their quality, accuracy and error field simulation. The thesis is organized into twelve chapters. First three chapters covered introduction, literature surveyed, hardware and software developed for use in the thesis work. Experimental data and design details are described in chapter four. Methodologies adopted for generation of InSAR DEMs and techniques evolved for identification of suitable method for large area DEMs are given in fifth chapter. A framework developed for quantification of uncertainty of generated DEMs using statistical approach, spatial measures, graphical patterns and simulation scheme are detailed in next four chapters. Discussion of results, summary, conclusion and recommendations are organized in tenth and eleventh chapters. List of technical papers referred and bibliography is given in the next pages. Contents of thesis are:

Chapter 1 Introduction: Introductory chapter has highlighted the importance and need for this research work, outlined objectives, described new framework developed to fulfill these objectives and presented the contribution from thesis. Organization structure of thesis is described. Literature surveyed on research topic is discussed in second chapter.
Chapter 2 Literature Survey: Literature surveyed on the research topic is summarized in this chapter. Current research methodologies used in generation of large area InSAR DEMs on operational basis, procedures followed for developing frame works for error quantification are assimilated through literature survey and presented in this chapter. Resources used for the research study are presented in chapter 3.

Chapter 3 Resources used for Research Study: The computer systems used, software developed by me exclusively for this study, available standard software packages used, actual data for generation of InSAR DEMs, external reference DEMs, GCPs details are discussed in this chapter. Chapter four deals with experimental data design related aspects.

Chapter 4 Experimental Design: Input SAR SLC Data pairs are needed for generation of InSAR DEMs. Experimental data design criterion, design of software utilities used for this research, Methodology for DEM generation, process sequencing, post processing steps followed are discussed in this chapter. Large area InSAR DEMs Generation process, characteristics and results are discussed in Chapter 5.

Chapter 5: Data Processing of Large InSAR DEMs: InSAR DEM generation process used for large areas is discussed in this chapter. Three sets of InSAR DEMs are generated using two methods; two
sets using input reference height points by first method and the third set by a method without using any input reference height points. DEM generation steps followed, details of data used for study, images of generated InSAR DEMs, process flow chart are presented. In next Chapter 6, error quantification of all generated DEMs by statistical measures is addressed.

Chapter 6 : Error Quantification by Statistical Measures : In this chapter InSAR DEMs Error quantification by statistical measures is addressed for all the generated DEMs. Estimation of RMSE, SE, AR, NIMA LE 90 and other statistical parameters is carried out using SOI bench marks as check points and results are presented. Error estimation is redone with GPS measurements and by pixel matching method and the results are analyzed. In addition to this, error quantification reliability is assessed by systematically varying the number of check points, type of reference check points, accuracy of check points and the results are presented. In the next Chapter 7, spatial measure adopted for InSAR DEM error presentation is discussed.

Chapter 7 : InSAR DEM uncertainty by Spatial Measures : Fractal dimensions are estimated for InSAR DEMs, Optical DEMs and SRTM DEMs and the results are compared. Suitable methods for estimation of FD for InSAR DEMs is brought out and discussed in this chapter. Study of Fractal Dimension for SAR and Optical DEMs
by three approaches viz., Differential Box Counting, Semi-Variogram and Wavelet Power Spectral method are presented and the results are presented in this chapter. Adequacy of each of the method to compute a single fractal dimension for entire DEM and performance of these methods for SAR and Optical DEM data sets is studied. In case of Variogram method, it is attempted to bring out additional clarity on the technique to identify the extent of linear segment of variogram in order to estimate slope, H and then fractal dimension. The methods are compared and the results are discussed. RIs are estimated for InSAR DEMs and optical DEMs and compared. Correlation between RIs and RMSE is studied and the usefulness of RI for indication of quality of InSAR DEMs is studied and summarized in this chapter. After this, the error representation and quantification is addressed using the graphical methods by means of and Elevation profiles. These are presented in Chapter-8.

Chapter 8: InSAR DEM Uncertainty by Graphical Methods: In this Chapter, DEM Error histograms are presented and discussed. For generated InSAR DEMs, Horizontal and Vertical profiles at some typical line number and pixel number respectively are plotted covering a length of around 13.5 km and the graphical results are discussed. After detailed study of error quantification, error assessment methods applicable are presented in chapter 9.
Chapter 9: InSAR DEM Error Field Simulation: Estimated and simulated error fields are discussed in this chapter. Visual analysis reveals the clustering of errors associated with low coherence areas, identification of large voids. InSAR DEMs with accurate reference DEMs and the output bipolar error maps are analyzed to validate the elevation deviation between the reference and the generated InSAR DEMs. With the available estimated statistical error parameters, InSAR DEM error surfaces were simulated using Monte Carlo technique. The real spatial error maps and the simulated error surfaces are compared and results presented. In next chapter 10, overall results are discussed.

Chapter 10: Discussion of Results: Results obtained from the study are discussed in this chapter. In chapter 11, the research work summary is brought out, conclusions and recommendations are given.

Chapter 11: Summary, Conclusion and Recommendations: Summary of the entire research study on methods of generation of large area InSAR DEMs, development aspects of a novel framework for uncertainty quantification using independent methods and by using more accurate optical and SAR reference DEMs, uncertainty assessment using real error maps and simulated error maps are presented. Conclusions drawn from the analysis of results of this study are reported and recommendations are highlighted.
Literature survey is done at various libraries of ISRO centers, JNTUH, India and browsed through online journals and published material using internet. National and international journals relevant to the research study are referred, research papers studied and published are referred in the thesis.

1.6 Conclusion of first chapter

First chapter is an introductory chapter, wherein the initiative for this research work, objectives of the research, thesis contribution, and the structure of the thesis are presented.