

Evaluation and accuracy assessment of high-resolution IFSAR DEMs in low-relief areas

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The use of digital elevation models from remotely sensing systems has been restricted in the past to high-relief areas due to the lack of appropriate resolution and accuracy to map micro-relief variability in low relief areas. Interferometric synthetic aperture radar, a new technology that provides detailed elevation models from remotely sensed data, is evaluated. Main characteristics of this data are highlighted. Accuracy assessment is tested in detail for two high-resolution acquisition modes using higher accuracy sources of data. The accuracy results using the root mean square (rms) error were better than expected according to mission specifications. However, at the checkpoint locations where the signal backscatter generates an elevation measure, the accuracy depends considerably upon the site-specific surface characteristics, such as the land use, above ground biomass, adjacent forest areas and infrastructure features located within surrounding pixels.

1. Introduction

One of the most fundamental requirements for modelling landscape processes is the accurate representation of topography. A fine scale analysis reveals the subtle differences in low relief terrain, which are not perceivable at coarser scales of analysis. The relevance of topography is also well known in agriculture that predominately occurs on level to low slope areas. Many studies have examined the relevance of topography to determine landscape landforms and micro relief variability (Mueller *et al.* 2001), soil characterization (Moore *et al.* 1993), attributes that determine crop yield and the choice of farming management practices (Atherton *et al.* 1999). Digital elevation has been demonstrated to be a valuable tool in hydrologic modelling efforts for watershed and drainage network delineation, land levelling, terracing, and tile drainage system, and irrigation system design (Rango and Shalaby 1998). Primary terrain attributes, that measure the rate at which the elevation models (DEMs), such as slope, aspect and upslope contributing area (Gallant and Wilson 2000). DEMs have historically been

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produced using surveying and traditional cartographic and photogrammetric approaches. Stereo viewing techniques have been used employing satellite optical and radar pairs during the past decades with an acceptable performance in high relief areas, but these techniques are unable to adequately map variations over low relief areas (Toutin 2001). The most common DEM spatial resolution in the USA is 30 m with about 7 m of vertical absolute error (USGS 2001). In areas of relatively flat terrain, the errors have an important impact because errors in the data can be large compared to the topographic variations.

The need for better resolution and accuracy has been addressed by several authors. For interdisciplinary studies, NASA (1998) suggested the need to acquire local-scale data of 10m horizontal and 1m or better vertical. For the analysis of small watersheds in low relief areas, Renschler et al. (2002) suggests less than a 1 m horizontal and tens of cm vertical level accuracy. New applications are emerging which are dependent upon high-resolution and high-accuracy DEM products. Mapping micro-topography related to within field variability for precision agriculture applications requires not only a high accuracy but also a consistent representation of the field variation. Mercer and Schnick (1999) concluded that radar-derived DEMs, created on a 5 m grid, exhibit a noise floor at about the 35 cm level for operational altitudes in non-urban bald earth environments. Independent evaluations using the airborne IFSAR Star3i sensor in Germany described the vertical rms error as 1.3 m and 1.5 m in flat and moderately sloped terrain, respectively, with a 2.5 m DEM spacing (Mercer 1998). Airborne IFSAR can provide wide area coverage and consistency with an achievable vertical accuracy from 0.5 m to 3 m (Mercer 2004). However, most validations of this data used a small amount of ground reference data in the accuracy assessment and few results are exclusive to low relief.

Currently, two active sensing technologies based on radar interferometry and laser altimeters provide high-resolution DEM data for terrain analysis. While interferometric synthetic aperture radar (IFSAR) responds to changes in the distribution of scattered microwave characteristics, light detection and ranging (LIDAR) responds to the distribution of scattered optical and geometric characteristics and obtains highly accurate 3D topography. Some properties and characteristics of active remotely sensed DEMs differ from other elevation sources. The process of acquisition has a big influence on the properties and characteristics of the data according to different topographic settings, achievable accuracy and limitations (JPL 2000).

An experimental acquisition by an IFSAR sensor was used in this study. The collection of the digital elevation data took place in a largely flat typical agricultural region in the mid-west USA using two spatial and vertical resolution modes.

The objectives of this research were to:

- 1. Conduct a review of current sources of DEMs.
- 2. Evaluate and analyse IFSAR DEM characteristics in a low relief area.
- 3. Assess the vertical accuracy that IFSAR DEMs can obtain within the scope of two frequent application scales in low relief studies, watershed and field scale level.

1.1 Sources and types of DEMs

Many applications of DEMs are sensitive to grid resolution and vertical accuracy. Different sources of elevation data can provide DEMs with similar scales but with

different characteristics in some cases. The applications at detailed scales have a wide variety of competing sources, from improved photogrammetric products to LiDAR and at some point IFSAR DEMs as optimal choices. Different methods for data collection and generation of the elevation values are used, which provide distinctive and sometimes unique characteristics of the dataset. A comprehensive classification of digital elevation datasets according to the source of data provides insights into where the new remote sensing DEM alternatives are positioned. A summary of digital elevation data sources, including their estimated general vertical accuracies, is shown in table 1.

1.2 Radar interferometry

Active and coherent radiation can produce topographic data by two main techniques for extracting height: stereo radargrammetry, stereo viewing techniques using synthetic aperture radar (SAR) data, and interferometry. Estimation of topographic heights with SAR has been described by Li and Goldstein (1990) and Gens and Van Genderen (1996). Interferometry SAR systems can be single-pass, which requires two antennas separated by a baseline viewing the same surface simultaneously, or two separate passes viewing the same surface with a single antenna and a well-known baseline between them. The IFSAR technique basically exploits the phase information in SAR imagery by taking the difference in phase, which is a measure of the difference in path length from a given pixel to each antenna. Table 2 summarizes some of the sensor parameters of the most important current systems with IFSAR capabilities (also referred to by some sources as InSAR).

2. Materials and methods

2.1 Study area

The IFSAR data acquisition covered the Wildcat Creek Watershed in north central Indiana using a GT3 acquisition mode and a Purdue University research farm for the high resolution GT1 mode. From a geomorphologic perspective, the study areas are located within a nearly flat to gently undulating glacial plain (figure 1). Agriculture is the predominant land use of the study area, with corn and soybeans the main crops. The research farm test site is a group of fields that cover 48.4 hectares in a gently undulating landscape with some parts of the field having from 4% to 6% slopes.

2.2 IFSAR Star3i data

The acquisition took place on the night of 13 November 1999 in good weather conditions. No precipitation was registered for 5 days immediately preceding the acquisition. Table 3 shows an array of standardized IFSAR products from the STAR3i sensor. The operating wavelength is X-band. The data used in this study were provided in 32-bit IEEE float format, with a spatial resolution of 5 m and 10 m post spacing for GT1 and GT3, respectively, and expected absolute horizontal accuracy of 2.5 and 5 m, respectively. A total of 2927.6 km² of GT3 data tiled in 7.5-minute grids, and 61 km² of GT1 data were collected without overlap.

Each acquisition has an accompanying orthorectified radar image (ORI or ORRI) of 2.5 m pixel resolution (8-bit GEOTIFF file format). The Universal

Table 1. Digital elevation sources.	Table 1.	Digital	elevation	sources.
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Data collection system	Sensor or technique	Vertical accuracy (rms error)
Ground surveying DGPS x, y, z Laser surveying 	Geodesic DGPS Laser beacon DGPS	Up to 2 cm 10–15 cm
 Traditional photogrammetric methods Derived from topographic map (elevation from contours, ground survey, hypsography) Stereo aerial photography 	e.g. USGS 7.5′ quadrangles Conventional film cameras—analogue	7 to 15 cm—maximum 50 cm Variable
Remote sensing generated DEMs Passive optical systems sensors Aerial data • Stereo aerial photography (digital)	Black and white orthophotography	$0.3-2.5 \mathrm{m}^{(1)}$
Satellite dataAcross track stereoscopyAlong track stereoscopy	Spot, IRS, IKONOS, etc JERS, ASTER	$\sim 20-50 \mathrm{m}^{(2)}$ $\sim 25 \mathrm{m}$ or better
Active optical systems Airborne Laser Mapping – LIDAR Active Microwave Systems Bader Stores (SAB)	Laserscanners	0.15–1m
Stereo (SAR) Stereo (across track) Interferometric SAR (IFSAR)	RADARSAT, ERS 1/2	10–50 m
Two-passes (repeat pass) IFSARSingle pass IFSAR	ERS 1/2—JERS RADARSAT IFSAR Star3i, TOPSAR, SRTM	5–10 m 0.50, 10m, 16 m

(1) and (2) Depends on the sensor model, angle of acquisition, the characteristics of the stereo-pair, and the availability and location of the ground control points. It also applies to Quickbird and Landsat adjacent areas. Sources: Toutin 2001, Intermap 2002, USGS 2001, JPL 1995.

Sensor	Agency/commercial company	Wavelength (band)	System	Platform	Absolute vertical height accuracy	Baseline length	Main characteristics
GeoSAR	EarthData JPL	P-band (UHF) C-band (5.6 cm)	Single pass dual frequency	Gulf Stream II	1–3 m (X-band) 2–4 m (P-Band)	X: 2.6 m P: 20 m	FoPen: foliage penetrating
TOPSAR (AirSAR instrument)	JPL	P-band (70 cm) C-band (VV) L-band (24 cm)	Cross-track	DC-8		2 m	Cross track mode
IFSAR Star3i	Intermap Ca.	X-band (3.4 cm)	Single pass	Cessna	0.5 to 3 m (table 3)	1 m	Several standard operating modes
Aero commander (formerly known as AeS-1)	Intermap Ca. (formerly Aero-Sensing Radar systeme GmbH)	P-band X-band	Single pass	Dornier DO228	0.0 5 to 2 m	0.5–1.8 m	Several operating modes
Shuttle radar topography mission (SRTM)	NASA/JPL, NIMA, USGS DLG	C-band X-band	Single Pass	Space shuttle Endeavor	≤ 16 m	60 m	Data over 80% of the Earth's land mass at $30 \text{ m} \times 30 \text{ m}$ spatial sampling
RADARSAT ERS-2 (ESA)	RSI, CSA ESA	C-band C-band	Two passes Repeat pass	Spaceborne Spaceborne	e 10–100 m e 50–100 m	_ 1100 m	ERS1/ERS2 tandem mission

Table 2. Summary of interferometric systems for elevation data collection (two-antenna, single-pass, two-passes one antenna).

Several other sensors and missions have collected data like the Seasat, Sir-C/X, and recently new sensors like Envisat are available. Sources: Madsen and Zebker, 1998; Mercer, 1998; JPL, 2000; Toutin 2001.



Figure 1. Location of the IFSAR acquisition in North-Central Indiana. Continental US shaded relief map is adapted from USGS. Indiana relief is a representation from 1:250,000 DEM and Global Terrain 1 (GT1) and GT3 acquisitions.

Transverse Mercator (UTM) co-ordinate system was used. Both datasets were referenced to the World Geodetic System 1984 (WGS84) horizontal and vertical datum, which is based on the Earth Gravitational Model 1996 (EGM96) geoid.

2.3 Reference data

Two higher quality physical elevation measurements were selected as references: marked benchmarks (BMs) from the National Geodetic Survey (NGS) to validate the IFSAR GT3 data broad area coverage and automated laser levelling elevation points to validate the GT1 accuracy. The three-dimensional geodetic network of NGS first order points include some checkpoints that belong to the High Accuracy Reference Network (HARN). Data from NGS have many internal accuracy and uncertainty reports, which make them a valuable source. The NGS benchmarks are published North American Datum of 1983 (NAD83) positions, with less than 4–5 cm shift for these first order points as uncertainty of the true location (NGS, 1998).

A high precision elevation survey was conducted during fall 1999 and spring 2000 using automated laser levelling and pseudo-range DGPS with a density of 32 checkpoints per hectare for the validation of the high resolution GT1 DEM at the research farm. The surface roughness conditions were uniform—mouldboard ploughed and disked. The targeted specification for elevation accuracy was 15 cm,

Туре	Description	Vertical accuracy (rms error)	Resolution	Map scale suitability
GTF	(First surface)	0.5 m	5 m	1:5000 or less
GT1	(First surface)	1 m	5 m	1:5000 to 1:10000
GT2	(First surface)	2 m	10 m	1:10000 to 1:12000
GT3	(First surface)	3 m	10 m	1:12000 to 1:24000

Table 3. IFSAR Star 3i sensor modes.

The prefix GT refers to global terrain and the number indicates the maximum expected rms error. Source: Intermap, 2002.

and 1 to 2 m for horizontal accuracy. These elevations were initially referenced to the NAVD 1929 vertical datum.

Ground reference data were collected at the same time of the IFSAR flight to verify the influence of different land uses and agricultural practices on the radar return and the DEMs. Agricultural fields were harvested at that time, so the categories are different types of post harvest residue, e.g. 'harvested corn but chisel ploughed', 'harvested corn, residue on surface' and 'winter wheat' (about 5–15 cm tall).

The National Elevation Dataset (NED), 1 arc-second, 30 m resolution, from the US Geological Survey (USGS) and Topographic Quadrangles 7.5' Digital Raster Graphics (DRG) were also used as references.

2.4 Evaluation of the quality of reference benchmark points by the influence of the site characteristics

Since all the checkpoints are not located in open terrain positions, the effect of the characteristics of the test site where the benchmarks are located was evaluated on a case-by-case basis. For the set of NGS data points, a category was built from a subset of all the geodetic locations available where the site is unobstructed bare terrain or an open terrain location. From radar principles a uniform scattering surface at the test site should be considered to avoid interaction with objects that produce a biased elevation value rather than measuring the real height, hence invalidating the objective of the accuracy test. The accompanying ORI image was useful in recognizing these locations. The decision regarding whether to include locations was based on the proximity of objects to the benchmark considering a



Figure 2. A total of 23 benchmarks from the NGS network were used for DEM accuracy assessment (GT3). An example of a HARN benchmark Q094, PID LB0933 (40 25 00.66248N, 086 55 52.80779W) is shown.

uniform scattering surface for each site of at least one pixel surrounding the one where the benchmark is located. A second category, which includes all the first order benchmarks available within the flight line without site characteristics discrimination, was considered to compare the results in the accuracy assessment of the reference location too. A total of 23 first order BMs were selected as open terrain, from 43 available (figure 2).

2.5 The notion of height

DEMs are three-dimensional representations of the surface of Earth. Because of the link with GPS during the process of acquisition, IFSAR DEMs are provided in WGS84 coordinates, usually expressed as latitude, longitude and ellipsoid height. It is important to know for height data not only the horizontal datum, but also the vertical support: datum, ellipsoid and geoid.

The ellipsoid is a two-parameter model of Earth that closely approximates the size and shape of Earth. Although the height above sea level is the usual reference used for topographic height information, it is a close approximation to another surface, defined by gravity, the geoid, which is the proper reference surface for measuring elevations. While the ellipsoid is a geometric model, the geoid is a physical figure of Earth.

Because of the natural lack of coincidence between the geoidal surface, which is irregular, and the regular ellipsoid surface (figure 3), the difference must be computed. The separations are referred to as geoid undulations or geoid heights (NGS, 1998). Figure 5 shows the relationship between the ellipsoid, the geoid, and Earth's surface. To compute orthometric height (H), the height above the geoid is used as the reference surface for height measurements (Milbert and Smith, 1996; NGS, 1998):

$$h = H + N \tag{1}$$

where h is the ellipsoid height (it can be positive or negative, the distance above or



Figure 3. Schematic graph showing the height systems and relationships for measuring surface elevation. Note that for all points in the conterminous USA, the geoid is beneath the ellipsoid. The difference H - h, is the geoid height. Thus the geoid height is negative, and the ellipsoidal height is smaller in magnitude than the orthometric height at a given point (Daniels 2001, NGS 1998).

Data source	Horizontal datum	Vertical datum/geoid
NGS benchmark points	NAD 83	NAVD 88/Geoid 99
USGS 7.5' quad (DRG)	NAD 27	NGVD 29
IFSAR	WGS 84*	NAVD 88/EGM96
Laser levelling	NAD 83	NGVD 29
NED	NAD 83	NAVD 88

Table 4. Datum, heights and geoids of dataset used for the accuracy test.

*The World Geodetic System 1984 (WGS84) is based on the GRS 1980 ellipsoid and provides the basic reference frame for GPS (global positioning system) measurements.

below the ellipsoid), and N the geoid height (the separation between the geoid and the ellipsoid).

Mean sea level elevation is roughly equivalent to orthometric height on a global basis. The geoid surface is beneath the ellipsoid and this is a constant in the USA. Thus, geoid heights are negative, and the ellipsoidal height is smaller in magnitude than the orthometric height at a given point (Milbert and Smith 1996). Also due to advances in the study of Earth's gravity, the geoid model may have frequent updates.

The zero surface to which elevations or heights are referenced is called a vertical datum. Several datum conversion issues must be taken into account to identify systematic offsets and to adjust the elevation data to local geodetic points (Daniels 2001). An essential part of the height analysis to avoid introducing biases and to prevent inconsistencies when comparing or merging multiple elevation datasets is to achieve a common geodetic reference.

2.6 Vertical datum adjustment and geodetic conversions

The different sources of data used in this research are based on different datums and geoids, which introduce the need for conversions (Table 4). With regard to the horizontal datum, the North American Datum 1983 (NAD83) was preferred, because it is best suited for a local solution. In North America, models for vertical datum conversion are designed to provide the datum shift between the recent North American Vertical Datum 1988 (NAVD 88), and the old National Geodetic Vertical Datum of 1929 (NGVD 29). Then, when reference data are given (derived) from topographic maps using NGVD29, a conversion to NAVD 88 is desirable. The global reference system (GRS) is the geodetic reference for the global positioning system (GPS).

Height conversion conventions and software toolkits can be obtained from geodetic agencies to perform this operation (e.g. NGS, NIMA for the USA). The differences of height grids NAVD88 minus NGVD29 represent the datum shift model. The difference must be added algebraically to the given NGVD29 height to solve for h_{NAVD88} and to achieve the orthometric height using equation (1):

$$H_{88} = h_{\rm NAVD88} - N_{99} \tag{2}$$

For one of the test sites (latitude 40 25 0.66248; longitude 85 52.80779) the magnitude of the datum shift found was around -0.141 m, which is almost constant for a small agricultural field, however for the entire study area, it was between -0.11 to -0.17 m.



Map: Rossville in the wildcar Creek watershed in north central Indiana . Scale 1:2400 (7.5 minute)

Figure 4. Representation of the area corresponding to the USGS Topographic Quadrangle. Topographic colour representation using intensity hue and saturation relief method. Top image: Digital surface model (DSM) or first return. Bottom image: Digital terrain model (DTM) or bald-earth produced using TerrainFit algorithm (Intermap Co.).

Although both IFSAR and NGS are vertically constrained to orthometric heights, there is a need to solve for a common geoid model. Then, the IFSAR elevations need to be coupled with the geodetic control network of the NGS, which is NAVD88 (*h*), and geoid 99 (*N*) which is the latest available in a local area or nationwide for the USA. The updated version of WGS84 (NIMA 2000) used relies on the Earth Gravitational Model 1996 (EGM96). On-line calculators or toolkits from NIMA and NGS can be used to obtain the offset value. The height difference for this example location EGM96 (-34.57 m) minus GEOID99 (-33.696) represents the offset value between the two models. The computed difference (Δ_{geoid}) is 0.874 m between both geoids, and the average difference is 0.68 m for the Star3i sensor acquisition area. All the flight coverage was arithmetically adjusted to

Geoid99. The offset is subtracted to cancel EGM96, hence eliminating the geoid difference:

$$IFSAR H_{88} - \left| \Delta_{\text{geoid}} \right| \tag{3}$$

Although the correction for the geoid is significantly less than the standard deviation of the dataset, the need to generate a reliable absolute accuracy assessment justifies the extent of these conversions and adjustments. It is a deviation of almost the same magnitude as the expected error of high-resolution elevation datasets.

2.7 Quantifying vertical accuracy

The rms error is a widely used measure for reporting accuracy for DEMs. In general σ corresponds to the relative or in-scene accuracy, while the rms error corresponds to the absolute accuracy (average deviation) over the test area between two datasets (equation (4)). It involves the use of checkpoints ('true' values). It is an unbiased estimator of the standard deviation σ :

$$rms.error = \sqrt{\frac{\sum \left(z_{data i} - z_{check j}\right)^2}{n}}$$
(4)

where z_i and z_j are two corresponding elevation values, *n* is the number of elevation data points being checked. The larger the value of this estimate the greater the difference between two sets of elevation points. If *n* is large enough, a confidence interval (CI) of 95% (2σ) provides a more conservative estimate of the vertical height accuracy using equation (5):

$$Accuracy_z = 1.96 \times rms \ error_z \tag{5}$$

3. Results and discussion

3.1 Relevant characteristics of IFSAR DEMs in low relief areas

While *DEM* is used as a general acronym for digital topography, and it is most likely to be related to the bare terrain or true ground surface, new data from remote sensing sources can be at different processing levels that represent heights or surfaces.

A digital surface model (DSM) is the first return from the surface that interacts with the pulse of a radar sensor: buildings, treetops, man-made features and objects on the ground, as well as the earth surface. A digital terrain model (DTM) is a baldearth, bare-surface DEM. Several applications for low relief areas are best served by a model that only contains the underlying terrain and ignores other features. Consequently, the use of a DSM does not allow hydrologic models to properly predict the density of channel networks in areas where trees or tall vegetation are present. Automated algorithms and manual editing efforts support the generation of a DTM, removing vegetation and man-made features from the first return product. Figure 4 shows an example of both models for an entire topographic quadrangle. Digital terrain elevation data (DTED) is used by some national cartographic and military agencies and refers to DEM.

Several issues related to the acquisition of digital elevation include:

One-time acquisition. In contrast to traditional image-based remote sensing, digital topography is usually a one-time acquisition for multiple applications, unless the objective is surface change detection or the acquisition of better quality data.

Post spacing or postings. This refers to the density of the observations (the distance between the sample points); IFSAR has a dense uniform posting.

Data format. The Star3i high resolution DEMs are provided in regularly spaced grids stored in 32-bit generic binary format. The use of decimal floating points enhances the capability to observe relative small changes in elevation in low relief areas.

Time of acquisition. Low vegetation cover, or when most agricultural fields are in bare soil or residue-covered conditions (early spring–late autumn), are the suggested land cover to avoid vegetation interaction with the signal. IFSAR sensors are all-weather capability systems with collection that often takes place at night to enhance the stability of the airborne platform, because of quiet atmospheric conditions (Intermap 2002).

Microwave interactions. A wavelength of 5.6 cm, band X, is used for Star3i DEM acquisition, which is a high frequency dominated by canopy scattering; which means, for moderate to heavy vegetation, the mapping takes place near the canopy top. This produces a rough pattern of uneven surfaces over forested areas. If the vegetation is sparse, or has no leaves, one can get a return from the ground. However, if the dimensions of the scatter are much smaller than the wavelength, the scatter shape is unimportant. It is also important to analyse the acquisition parameters and their interaction, since radar backscattering is different depending on the incidence angle for various land covers or roughness heights. The backscattering properties in relationship with tree and manmade features are shown in figure 5, emphasizing the strong effect of the power line poles. Other features of interest are water bodies, which are surface areas that are edited and flattened in remotely sensed generated DEMs and assigned map specified or estimated surface elevations.

Statistical distribution of the data. The continuous and dense collection of data over low relief areas shows a bell shaped uniform distribution (figure 6). The land cover of the fields was post harvest covers at the time of acquisition. The seamless USGS DEM (NED) histogram was calculated for the same area showing an increased frequency at the data contour elevation, due to the influence of contour-to-grid interpolation used in the generation process.

Precise reference system. Remotely sensed DEMs are usually in WGS84 due to the linkage with GPS. The WGS84 based on EGM96 provides ellipsoidal and geoidal heights on a global scale, which agree with mean sea level. The geodetic base incorporates information in which the size and shape of the Earth has been taken into account.

Noise and radar artifacts. Foreshortening, layover, shadows (non-imaged areas), noise, decorrelation, DEM mosaic seams, phase unwrapping, calibration and aircraft motion issues can be contained in radar data and its derivatives (Intermap 2002). However, a certain amount of high frequency noise in IFSAR DEMs, which decreases from the near to far range across the track, is a very evident characteristic of the data in flat terrain. Spurious anomalous high values can appear as a bumpy texture on the surface. This random noise caused by inherent characteristics of the geometry and coherent imaging process is emphasized in the



Figure 5. Effect of an electric pole on the IFSAR DEM.

GT3 acquisition over broad areas, due to a higher altitude acquisition (Intermap 2002). Therefore, due to the radar nature of the DEMs being studied, specific nonlinear filters for speckle suppression might have some advantages. Adaptive filters preserve important high spatial frequency characteristics of the image while removing and smoothing the high frequency random noise (Lopes *et al.* 1993). Successful implementation of topographic mapping requires the reduction of the phase noise. However, the goal is to obtain an improved surface representation and a minimum degradation of the topographic detail and spatial variability of the surface. For this reason, the process of filtering and the size of the filter to be used is application dependant.



Figure 6. Comparison of the distribution of elevation values for a bare terrain agricultural area (without forest patches or above ground features) of about 260 ha.



Figure 7. Results of the accuracy test GT3. Columns are rms error estimates, error bar 95% CI. The seamless National Elevation Dataset (NED) from USGS is used as a comparative reference.

3.2 GT3 acquisition elevation accuracy assessment

The accuracy assessment was done considering the characteristics of each pixel where the geodetic points are located and was based on a case-by-case evaluation. If all the points were used regardless of their location, the rms error would be higher than 7 m, but not representing strictly bare-earth heights. The test performed over the open terrain category test sites yields 1.472 m rms error (figure 7). This estimate encompasses both the IFSAR capabilities and random and systematic errors introduced during the production process. At this level, the 95% CI (2σ) is also within the specifications of accuracy for this acquisition mode.

3.3 GT1 acquisition elevation accuracy assessment

Vertical accuracy of IFSAR GT1 at the field level was performed using a dense ground laser levelling survey as check points over a group of harvested and disked fields (figure 8). The same approach was applied differentiating the checkpoints as a function of the characteristics of the site and computing accuracy before and after removing pixels with scattering effects from above ground objects and features. The largest differences occurred along the boundaries due to the influence of man-made features, especially electric poles along the road (east side), vegetation along roads and timber areas located around the field (west and north side). Although the plot of height difference including all 1530 check points shows overall good agreement, after removing the borders the accuracy improves significantly, 0.46 m rms error with 1335 points within the field, open terrain or bare terrain check points (figure 9). Nevertheless, most of the largest errors that remain correspond to sloping relief and to the laser transects made in an east–west direction (for collection of DPAC south



Figure 8. Accuracy assessment: Selection of bare-earth checkpoints, height differences between GT1 and ground survey laser and slope from survey positions.



Figure 9. Results of the GT3 DEM accuracy test. Columns are rms error estimates and the error bar is the 95% CI. The last column to the right shows the effect of the application of an adaptive filter to the raw DEM.

Table 5. Estimates of Vertical Accuracy for IFSAR GT1 and GT3 Acquisitions: mission specifications for expected rms error vertical accuracy and pixel size of each IFSAR DEM, sample size (*n*), mean (μ), elevation range (range), standard deviation (σ), coefficient of determination (r^2), root mean square error (rms) and 95% confidence interval (CI). Units are metres.

	Expected	Pixel	Chee	ekpoints						
Dataset	accuracy	size	п	Density	μ	Range	σ	r^2	rms	CI
GT3 All points	3	10	43	$0.015/km^2$	254.34	96.32	40.1	0.96	3.69	7.24
GT3 Bald-earth points	3	10	23	0.008/km ²	256.68	95.24	26.1	0.98	1.47	2.88
GT1 All points	1	5	1531	31.3/ha ²	295.47	11.16	1.54	0.89	0.70	1.37
GT1 Filtered all points	1	5	1531	31.5/ha ²	295.36	10.25	1.46	0.91	0.28	0.55
GT1 Bald-earth points	1	5	1335	28.5/ha ²	295.34	8.22	1.32	0.95	0.46	0.90

fields the laser transects started as a north-south direction then switched to an eastwest direction).

In this case the geometry of the acquisition is expected to contribute to error since it is a side-looking sensor and the acquisition was in the same east-west direction. Although the GT1 IFSAR DEM exhibits lower levels of noise (low altitude acquisition) if a 3×3 moving window adaptive filter (gamma map) is used in a homogeneous land cover class (bare earth), a smoother DEM is obtained improving the accuracy. The results obtained from the accuracy test for both acquisition levels are summarized in table 5.

The rms error is a single global measure of dispersion to estimate the absolute error. However, tests using a high and dense number of checkpoints can reveal the effect of spatial variations in errors, communicating insights about both, the consistency of the data values and random errors. The application of other spatial analysis tools might be required to see variations in structure that often are not revealed by only the estimation of the rms error.

The high correlation obtained shows that a spatial pattern of strong correlation exists for the high resolution GT1 DEM associated with a very dense and accurate data points used as reference (figure 10a). The outliers are related to field boundaries and end rows that, once removed, improve the relationship between both datasets (figure 10b). These outliers are due to adjacency effects produced by nearby manmade features that in this analysis have shown a strong influence on the resulting height values of surrounding pixels, such as electric and telephone poles, buildings and farmsteads and therefore need to be considered in any application requiring bald terrain. Second, areas with a mixed land cover/use with a predominance of forest patches, riparian forest and trees between agricultural fields are another source of error affecting elevation values of adjacent pixels. A general source of error even present in clear areas includes the relative noise contributions, observed as a bumpy texture in low relief areas. This also clearly indicates that accuracy assessment should be performed on 'bald earth' terrain, free of any object that can distort the analysis.



Z Ground Laser Levelling no fields borders (m)

Figure 10a. Linear relationship between GT1 DEM and Ground Laser survey including field boundaries with 95% confidence bounds; 10b. Linear relationship between GT1 DEM and ground laser survey dataset without end rows and field boundaries and 95% confidence bounds.

	La	ANOVA				
Source	Harvested corn (chisel)	Harvested soybeans	Wheat	Alfalfa	<i>F</i> -value	Pr > F
GT3 GT1	2.42 1.14	1.62 1.05	1.80 0.75	1.27 0.96	18.11 14.31	$0.000 \\ 0.000$

Table 6. Mean difference in elevation by land cover class for constant USGS contour height (m).

3.4 Effects of agricultural land cover in the vertical accuracy

Most of the land cover classes at the end of the fall season were very similar in terms of height. However, the surface roughness was different due to different types of crop residues and post harvest tillage practices, and some fields had winter wheat in early stages and alfalfa was also present in some fields. Using contour lines of the same elevation from USGS DRGs, values from georeferenced fields on the DEM were extracted to calculate the mean error for predominant land cover classes. A one-way ANOVA was performed to test the accuracy of the mean error for a contour length of 1000 m within fields of similar land use, showing that the surface heterogeneity can be significantly correlated with the surface error using a significance level of 0.05 (table 6). Although this is a relative comparison and there is variability between the land use classes within the expected error, a trend is observed towards an increase in roughness. However, the main offset over the expected error is related to manmade features like poles lines, trees, forest patches and riparian forest classes.

4. Conclusions

The vertical accuracy of two DEMs obtained from an airborne IFSAR sensor at different horizontal resolutions and vertical accuracies was tested in low relief areas. Certain characteristics of IFSAR data require close attention to ensure final applications are not adversely affected. The noise, one of the main artefacts affecting the data obtained from active microwave sensors, also applies to IFSAR data. In low relief areas the relative noise level can obscure or reduce micro-relief variability mapping. This noise is a more significant issue when the acquisition takes place at high altitudes like the GT3 mode. The results of independent tests of accuracy for GT3 and GT1 Star3i elevation datasets fell within the expected vertical error according to mission specifications. However, the results of the GT3 mode (10 m pixel size) showed a rms error of 1.47 m and 2.88 m at 95% confidence interval if site characteristics are considered to avoid the presence of man-made features and vegetation, results that can be inadequate for several applications at low relief since variations of the surface can be smaller than the expected error.

The GT1 5 m pixel size DEM demonstrated good agreement with checkpoints of higher accuracy achieving an rms error of 0.28 m and 0.55 m at 95% confidence interval after a filter was applied. These results suggest that high resolution IFSAR can meet the requirements of many applications in low relief areas since it can capture small variations in relatively flat relief and bare-earth fields. The adjacency of manmade feature and trees and forest patches nearby test sites, impacted the results of the accuracy test. Therefore, a key issue for obtaining consistent results is

to consider not only the x and y location, but also the three-dimensional spatial relationships at each checkpoint location.

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