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Phase 2 Year 3

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1. Introduction

According to the CCI project guidelines (CCI, 2010), each CCI project should provide a separate document describing the product uncertainties. This is the updated version of the Uncertainty Characterisation Report (UCRv2) from Phase 1 (Glaciers_cci, 2013b). We updated the information related to improved data from new sensors and latest references of relevance. The further information described in the Phase 1 UCRv2 is still valid and thus unchanged.

As a common frame of reference, this document first repeats section 6.1 of the project guidelines (CCI, 2010) in Ch. 2. Afterwards we describe for each of the four products glacier area, elevation changes (from altimetry and DEM differencing), and velocity, the sources of error and uncertainties along with the methods to quantify them. This is largely based on the key lessons learned from the Product Validation and Intercomparison Report (PVIR) from Phase 1 (Glaciers_cci, 2012). We further describe how accuracy is finally determined considering the mostly very limited possibilities for proper product validation and where accuracy information is shown in the product. Finally, the summary and outlook section has been updated for all products.

Further updates to the document for year 3 of Phase 2 can be found in Paul et al. “Error sources and guidelines for quality assessment of glacier area, elevation change, and velocity products derived from satellite data in the Glaciers_cci project”, that has been submitted to a special issue of Remote Sensing of Environment. This document will be updated with the contents of the paper in case it is not accepted for publication.

2. Definition of terms

2.1 Describing error and uncertainty

A measurement is a set of operations having the object of determining the value of a quantity. Following BIPM (2008) it is helpful to define the term measurand as

- **Measurand**: particular quantity subject to measurement

so that the phrases 'true value of a quantity' and value of the measurand are synonymous. Very few instruments directly measure the measurand. Generally an instrument reports the effect of a quantity from which the magnitude of the measurand is estimated. As an example, an instrument sensitive to infrared light might be used to measure the temperature of an object. The process of measurement is inexact, so that difference between a measured value and the value of the measurand is called the error. Traditionally (e.g. Beers, 1975) the word 'error' has also meant a numerical value that estimates the variability of the error if a measurement is repeated (i.e. a width of the distribution of possible errors). This dual meaning of "error" can lead to confusion or ambiguity. To separate these meanings and avoid confusion the BIPM (2008) definitions are used, i.e.

- **Error (of measurement)**: result of a measurement minus a true value of the measurand
- **Uncertainty (of measurement)**: is a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Except in a few cases the "true" value of the error is not known, and the magnitude of the error is hypothetical. An error is viewed as having a random component and a systematic component.

Following BIPM (2008) the definitions of these terms are:

- **Random error:** result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions,
- **Systematic error:** mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions minus the true value of the measurand.

In general terms the random error is variable from measurement to measurement, whereas the systematic error is the same for each measurement. Although it is not possible to compensate for the random error, its effect on uncertainty in our estimate of the measurand can usually be reduced by averaging over a number of independent repeat observations.

The statistical distribution of random error can be described by a probability density function (pdf) of which the **expected value** (i.e., the average over the pdf) is zero. As the random error often arises from the addition of many effects the central limit theorem suggests that a Gaussian distribution is a good representation of this pdf. Therefore the random uncertainty value commonly adopted for a single observation is equal to the one-sigma standard deviation that would be obtained from repeated measurements of the same quantity under the same conditions. If N repeated uncorrelated observations are available, the random uncertainty is the one-sigma standard deviation multiplied by a factor of $1/\sqrt{N}$ (under the Gaussian assumption). The smallest possible change in value that can be observed can be taken as ½ the uncertainty. This value can also be used as the detection limit of the instrument.

The total uncertainty attributed is the combination of this random uncertainty and systematic uncertainty. Often a correction can be applied to compensate for the systematic effects. It is assumed that correction is done such that, after correction, the expected value of the error arising from a systematic effect is zero. A systematic uncertainty remains, however, characterized by the uncertainty in the correction. There are many reasons why a measurement is uncertain. For example, error components in satellite remote sensing may include terms such as

- instrument noise,
- error arising from simplifications in radiative transfer,
- calibration error,
- geolocation/interpolation error,
- error arising from the uncertainty in parameters used to derive the measurement.

Measurement here is used to include satellite retrievals (estimates by some process of inversion) of measurands, although by some strict usage of “measurement”, it is typically radiance that a sensor on a satellite actually measures.

An **Uncertainty budget** is a list of random and systematic errors with estimates of the uncertainty they contribute to the measurement (preferably with information about how component uncertainties combine). Standard methods of error propagation (e.g. Hughes and Hase, 2010) are used to transform uncertainties into measurement units. The total uncertainty is the total combined accounting for any correlation between component errors.

In some cases the measurement process returns a vector of measurands. The error between the components of the measurand may not be independent so is represented by an uncertainty covariance matrix of which each element i,j is defined by the expectation value $<\varepsilon_i\varepsilon_j>$ of the product of the respective errors ε_i of the ith measurand. If the measurands are independent then the off-diagonal terms are zero and the uncertainty on each measurand is given by the square-root of the corresponding diagonal element. For vector measurements, the uncertainty budget is a list of random and systematic errors with estimates of their associated uncertainty covariance matrices.

Two qualitative terms not defined in BIPM (2008) but commonly used to describe a measurement (e.g. Beers, 1957, Hughes and Hase, 2010) are precision and accuracy defined here as:

- **precision**: a measurement with a small random uncertainty is said to have high precision
- **accuracy**: a measurement with a small systematic uncertainty is said to have high accuracy

2.2 Validation of measurements

Validation is the assessment of a measurement and the uncertainty attributed to it. This is principally achieved by external validation, i.e. comparison of a measurement to an independent measurement and assessment of their consistency relative to their estimated uncertainties. This independent estimate of the measurand is termed the validation value. The discrepancy is then defined as

- **discrepancy**: the difference between the measurement and the validation value

A small average discrepancy with respect to the root-sum-square of the measurement and validation value uncertainties is indicative of an accurate measurement, but could also result from a fortuitous cancellation of error terms.

For a small number of measurements it is possible to report individual discrepancies. However, for the large number of measurements typical of satellite remote sensing validation involves statistically characterising the discrepancies. There are often regimes of instrument behaviour for which uncertainties can be expected to differ, so it is usual to characterize discrepancies for the minimum number of regimes of consistent instrument behaviour. The choice of regimes could come from a cluster analysis of discrepancy (if the difference in regimes causes differences in systematic error), but more commonly comes from knowledge of the measurement process.

The statistical characterization of the discrepancies within a regime is made through three **quality parameters**. Consider the set of n measurements $\{x_1 \pm \delta x_1, x_2 \pm \delta x_2, x_3 \pm \delta x_3, \ldots x_n \pm \delta x_n\}$ of some quantity together with the set of validation values $\{v_1 \pm \delta v_1, v_2 \pm \delta v_2, v_3 \pm \delta v_3, \ldots v_n \pm \delta v_n\}$ made of the same quantity. The quality parameters are then:

- **Bias b**: the mean value of the discrepancy, i.e.:

$$b = [\ \Sigma_{i=1}^{n} (x_i - v_i)\ ] / n$$

- **Chi-squared** χ^2: the goodness of fit between the actual and estimated uncertainties of measurement and validation values, defined by:

$$\chi^2 = [\ \Sigma_{i=1}^{n} (x_i - v_i)^2 / (\delta x_i^2 + \delta v_i^2)\ ] / n$$

- **Stability s**: the change in bias with time defined as:

$$s = [\ b(t+\Delta t) - b(t)] / \Delta t$$

The expectation value of the bias is the sum of the residual systematic errors in the measurement and the validation value. The bias can only be attributed to the measurement if the residual systematic error in the validation value is known a priori. In an ideal case the bias would be zero.

The expected value for χ^2 is unity. A value lower than this indicates the uncertainties attributed to the measurements or the validation values or both are too high. A value greater than unity indicates the uncertainties attributed to the measurements or the validation values or both are too low.

In the ideal case the stability would be zero over any timescale. In remote sensing the stability can display periodicity related to factors such as instrument drift or solar illumination of the satellite – both over an orbit and seasonally. It is suggested that the stability is estimated at the same temporal scale that any trends in the data are calculated.

It may be that the quality parameters are independent of the measurement magnitude and conditions of measurement and apply at all locations and times. In that case the three quality values adequately characterize the quality of measurement. More commonly, the quality values vary so a **validation table** is used to summarise the bias, χ^2 and stability for regimes of consistent instrument behaviour.

In some case **internal validation** can be used to check reported uncertainty. Consider the situation where an instrument measures the same quantity under conditions where the reported uncertainty does not vary. Then the variability of the measurements should agree with the reported random uncertainty.

2.3 Comparing measurements with a model

Further understanding can be achieved through comparison of measurements with model output. In this approach, a model is sampled to give model values at the same place and time as the measurement values. The same three quality parameters can be calculated. However these caveats apply:

- the model error may not be reported and may have to be assumed,
- the bias cannot be attributed to the model or measurements without reference to additional information

An estimate of interpolation uncertainty must be included if the model reports results at different times and location from the measurements so that the model results are interpolated to the measurement location.

If the model is at a coarser resolution than the measurements, an approach could be to compare the model value with a (weighted) average of the measurements. The fact that the systematic uncertainty is correlated needs to be accounted for if this approach is taken.

The statistical comparison of model and measurement data must account for bias due to sampling. For example a monthly time series comparison between model output and averaged measurements may show bias due to conditions, such as cloud coverage, under which measurements are not possible.

3. Glacier area

3.1 Sources of errors and uncertainties

3.1.1 Impact of the algorithm used for glacier classification

A wide range of methods was and still is applied to map glaciers from optical images (e.g. to classify snow and ice). They mostly differ in complexity, pre-processing demands, required input bands and degree of automation, but not so much in the classification result. A review of the most often applied methods is given in section 3.3 of the ATBDv2 (Glaciers_cci, 2013a). With a focus on the most suitable optical sensors, the methods are largely independent of the sensor used, as the spectral bands cover very similar spectral ranges (see 3.1 in the DARD, Glaciers_cci, 2011b). We thus refer in the following to different spectral bands rather than sensors. From the existing algorithms we here exclude manual delineation as this is only used for improvement of product quality in the post-processing stage (e.g. adding debris covered parts) or for generating a reference dataset from high-resolution datasets without a SWIR band. We also exclude algorithms that were already considered as being less suitable or less accurate in previous studies such as all (scene-dependent) supervised (e.g. Maximum-Likelihood and principal component analysis) and unsupervised (e.g. ISODATA clustering) classification methods, as well as those which require atmospheric and topographic correction (Albert, 2002; Paul et al., 2003). The focus is thus here on the remaining two most often applied methods, simple band ratios (e.g. Paul et al., 2002) and the Normalized Difference Snow Index (NDSI) (e.g. Dozier et al. 1989; Racoviteanu et al., 2008). Past studies have already shown that both methods differ only at the level of individual pixels, with errors occurring in different regions of a glacier, but at about the same quantity (Paul and Kääb, 2005).

The key classification step when applying one of the band ratio methods is the (manual) selection of a threshold value to convert the ratio image in a binary glacier map. A potential additional threshold has to be selected if the TM1 equivalent band is used for improved mapping in cast shadow (cf. Paul and Kääb, 2005; Paul et al., in press). Under otherwise perfect mapping conditions, these two threshold values determine the accuracy of the product. If wrongly selected, too large or too small glacier areas result and the workload required for manual corrections can increase substantially. The main rule for threshold selection is thus the minimization of the workload for post-processing and this mainly concerns glacier parts in cast shadow as debris cover cannot be mapped with this method anyway. As a second step, it has to be considered that the application of a median filter (to reduce noise) also alters glacier extent. And finally, it has to be noted that all glacier outlines are visually controlled and corrected against the satellite image or other available datasets where required. In this regard, the above error sources (threshold, median filter) have more of a theoretical nature.

3.1.2 External conditions influencing product accuracy

Apart from the applied algorithm for the initial glacier mapping, a wide range of external factors influence product accuracy (e.g. Racoviteanu et al., 2009). This includes adverse snow conditions with seasonal snow hiding a part of the glacier perimeter, local clouds doing the same, regions with haze requiring a different threshold than the clear part of the image (Le Bris et al., 2011), or glacier parts in shadow that cannot be mapped due to missing contrast in the respective spectral bands (Paul et al., 2011a). The errors for the final product that can be introduced by these factors are about one to two orders of magnitude larger than those resulting from using a different threshold for the band ratio. Hence, only cloud-free images from the end of the ablation period in a year without snow outside of glaciers should be used to map glaciers.

3.1.3 Post-classification issues

After a raw glacier map has been created, post-processing is required to remove gross errors (e.g. wrongly classified lakes, missing debris cover, local clouds) and edit other misclassification (e.g. ice bergs, shadow). In general, this is done by visual comparison with a contrast-enhanced version of the satellite image used. From this 'glacier cover only' product a higher-level product can be derived, the individual glacier entities. This step requires a co-registered DEM to derive drainage divides and digitally intersect them with the corrected outlines. While this is in general straightforward for alpine glaciers surrounded by steep valley walls, it can be challenging for ice fields or ice caps (Racoviteanu et al., 2009; Rastner et al., 2012). In particular the division of ice caps into hydrologic catchments does often not make much sense and can thus be considered controversial. In this regard the drainage divide issue is a methodological problem (result changes with the purpose) rather than a technical one.

Manually removing wrongly classified water bodies is easy, as often a strong spectral contrast is found between water and ice. However, when the water surface is frozen or a largely dissected glacier calves into water with lots of icebergs close to the front, the issue is more challenging and requires some experience. In addition, while clear water can be mapped automatically and removed (e.g. Huggel et al., 2002), turbid water often remains and needs manual editing (Paul and Kääb, 2005; Gjermundsen et al., 2011).

The fully automated mapping of debris-covered glaciers is still not possible (e.g. Shukla et al., 2011) and the available semi-automated methods (e.g. Paul et al., 2004; Bolch et al. 2007) also require careful manual editing. As debris can cover more than 50% of a glacier tongue and is often difficult to identify in low-contrast (i.e. high elevation of the sun) optical images, wrongly mapped debris cover is actually the single most important factor influencing product accuracy when snow conditions are satisfactory. This step has thus to be done with great care to meet the accuracy specifications for the glacier area product (better than 5%).

3.1.4 Multi-temporal considerations

Further important aspects of product accuracy have to be considered when multi-temporal analysis is performed or when different datasets are combined. The most important one is the accuracy of the geolocation. As previous studies such as GlobGlacier have shown (Paul et al. 2009), only orthorectified satellite images can be used for product generation. Such a product is meanwhile provided by USGS for all Landsat scenes (called 'L1T' for terrain corrected), with a geolocation uncertainty of about 1 image pixel or less (RMSE). Though this is acceptable for the global glacier area product, a more detailed analysis of the geolocation error (listed in the metadata of the satellite scene) reveals much higher values in steep high-mountain topography or in regions where the used DEM has artifacts (Frey et al., 2012). For example, in regions with voids in the SRTM DEM, caldera like structures were visible in the hillshade of the DEM, pointing to a systematic underestimation of elevation in these regions. In consequence, geolocation shifts of about 5 pixels (150 m) or more were found by Frey et al. (2012) for such regions compared to an independent dataset (ASTER GDEM). Such a shift causes also problems for deriving drainage divides, topographic parameters and digital overlay with other orthorectified satellite images when their correction is based on a different DEM. As the L1T orthorectification of the Landsat scenes by USGS is an operational process, there is not much Glaciers_cci can do about it. On the other hand, the processing at USGS is continuously improved and hence also better DEMs (e.g. GDEM2) might be considered in the future for orthorectification.

When all scenes used for change assessment are orthorectified with the same DEM, a potential error in the geolocation does not matter. This becomes only an issue when the multi-temporal analysis combines data from different sources (e.g. from different sensors, internal DEMs or glacier outlines digitized from maps). Regarding maps, the transformation of coordinates from one projection to another is a most important issue. When details of the used ellipsoid/datum are only poorly known or implemented in the software used, non-systematic shifts between two datasets can occur that make a direct comparison challenging. However, differences in the interpretation of glaciers by cartographers might be even more severe and have also to be considered with care (Bolch et al., 2010; Paul and Andreassen, 2009). For this reason vector data available from other sources (e.g. mapping agencies) were not used for product validation. When satellite scenes are used that were orthorectified with an internal DEM (acquired from sensors such as ASTER, SPOT or Corona/Hexagon at image acquisition) larger positional differences can be expected as well, in particular in steep terrain off-glaciers and where glaciers have considerably changed in elevation. When the resulting geometry is too different, reported values for change assessment will get a larger uncertainty assigned, or instead of area changes a less influenced quantity will be reported (e.g. length changes for Corona and Hexagon scenes).

3.2 Methodology to determine uncertainties

3.2.1 Product validation using reference data

There are basically two different measures to assess product accuracy, one is validation with so-called ‘ground-truth’ or better ‘reference’ data and the other one is a relative comparison of results from different algorithms, analysts etc. (see 3.2.2). In regard to reference data, the major problem is that they seldom exist (depending on the criteria defining ‘reference’) and that the final product includes in most cases a manual correction (e.g. for debris-cover) that is obtained by correction against a ‘reference dataset’ (the satellite image itself). To circumvent these problems, there are two options:
(1) using data that have been independently acquired at the same date (week), e.g. from GPS ground surveys, high-resolution (1 m or better) aerial photography or satellite imagery, and
(2) a full manual digitization of the glacier extent without considering the result of the automated methods (band ratio, NDSI).

When (1) is available for an entire glacier, two kinds of validation are possible:
(i) comparison of the total area and
(ii) analysis of the omission and commission errors (cf. Gjermundsen et al., 2011).

When only parts of a glacier are covered, the digital overlay of the respective vector outlines can still be used for a qualitative statement about the agreement, but little can be said in absolute terms. In most cases differences in the interpretation of details (e.g. debris cover at the terminus) will drive the differences rather than shortcomings in the automated mapping. The latter is the reason to use the same satellite image for a full manual digitization. Such a vector line is at least independent of resolution and interpretation differences (Paul et al., 2003) but only works for debris-free glaciers. When this is done for several glaciers with different sizes, the differences between (i) and (ii) can be calculated and analysed statistically.

3.2.2 Relative comparisons

The second way to determine product accuracy is a relative one without considering a reference dataset. This includes points (i) and (ii) from 3.2.1 for the glacier extents resulting from (a) different algorithms, as well as (b) multiple digitisations of the same glacier. Whereas for (a) the overlay of grids is most suitable for illustrating the differences of algorithms, the overlay of vector outlines is more suitable for (b). A third kind of comparison (c) results from the round robin: different analysts map the same glacier (type many-to-one). This will be more suitable to reveal differences in the interpretation rather than for calculating absolute differences. The last comparison is also important to improve the consistency of the glacier outlines as available from the GLIMS database with related implications for analysis of glacier changes.

3.2.3 Quantitative measures for accuracy assessment

The measures to assess the accuracy of the glacier area product can be distinguished into qualitative and quantitative ones. The former describe the differences observed for an overlay of outlines from different sources, analysts or multiple digitization. They help to learn where methodological differences in image interpretation occur, for example in regard to the interpretation of tributaries, debris-cover, ice in shadow, disintegrating and calving glaciers, position of the glacier terminus, etc. Once these issues are considered, quantitative measures can be applied to assess product accuracy. They include the direct calculation of differences in glacier area to a reference dataset and can be appended by mean values and standard deviation for larger samples (scalar metrics). When the results of glacier mapping differ only locally, the comparison of omission and commission errors (visually and quantitatively) is a valuable measure to quantify product accuracy (raster metrics). This is required as the same area of a glacier can be obtained by two digitizations (indicating perfect agreement), but the regions considered for the total glacier area are different (e.g. missing debris cover is compensated by including a further tributary). In such a case the area difference alone has little meaning.

Another quantitative assessment of the error can be applied when multiple outlines are available for the same glacier by calculating the mean distances of the respective segments (vector metrics). These can be illustrated in box plots showing mean, median, standard deviation and percentiles in comparison to a reference dataset (Raup et al., 2014). In all cases it is required to also illustrate the outlines or raster maps with overlays to allow a meaningful interpretation (Paul et al., 2013). In Table 3.1 we provide an overview on possible accuracy assessments along with measures to be applied. The calculation of the quantitative accuracy measures is based on calculations of the glacier area as implemented in the GIS with subsequent statistical analysis of the derived values (e.g. mean, standard deviation). The in-depth analysis of the results compares mean values and standard deviations from the different datasets.

Comparison	Calculation	Statistics	Measure	Metrics
Satellite vs. ‘reference data’	relative difference	mean, std. deviation	absolute	scalar
Area from multiple digitizings	variability	mean, std. deviation	relative	scalar
Overlay of outlines	visual interpretation	none	qualitative	-
Distance of outlines	variability	overlay	qualitative	scalar
Comparison of algorithms	relative difference	omission/commission	relative	raster
Area change by threshold	relative difference	none	absolute	scalar
Impact of noise filter	pixel count	omission/commission	relative	raster

Table 3.1: Overview of the different possibilities to assess product accuracy for glacier area.

3.3 Accuracy to be reported

Given the range of possibilities for accuracy assessment and error characterization described above, the question arises which of these measures will be reported along with a dataset? At the first level of this decision one has to distinguish between (A) the mandatory entries in the GLIMS database and (B) the accuracy reported in a paper. In regard to (A) it is required to provide with each glacier outline the global uncertainty in x and y direction (that is related to geographic location and can be found in the metadata of each satellite scene) as well as the local (within-image) uncertainty (see Table 3.2 in the Phase 1 PSD (Glaciers_cci, 2011a)). The latter can in principle even be applied to individual segments of a glacier outline line as mapping accuracy of clean-ice parts can be very different from manually edited debris-covered parts. However, practically it is both very difficult and time consuming to determine accuracy in such a detailed way. Hence, this information is in general only provided for all glaciers in a scene in the same way (e.g. ±1 pixel for the global and ±2 pixels for the local uncertainty).

The GLIMS database also has a link to associated publications that can be used to describe other uncertainty measures (from Table 3.1). Depending on the availability of an appropriate reference dataset and in view of the project results achieved so far, we recommend a tiered strategy for accuracy assessment (with results to be reported in the respective publication):

Level 1
At the first level, glacier outlines can be compared to an independent dataset of a likely better quality. The latter implies that it has been derived from a higher-resolution dataset with the same or even better mapping conditions (e.g. less seasonal snow), in a year close to the acquisition date by a very experienced analyst (indeed, these constraints are difficult to match). Area differences should be calculated and the following information provided with each study:
(1a) mean area values for both samples, number of glaciers in the sample, absolute differences (accuracy) and standard deviation;
(1b) an overlay of glacier outlines as derived from both datasets;
(1c) a description and reasoning for the differences in text form.

Level 2
When a reference dataset is not available, an independent multiple digitization experiment should be performed for each study (minimum five different glaciers three times). This will provide important information on the analysts' accuracy for the manually digitized parts: The following information should be provided:
(2a) mean area values and standard deviation, sample size and a short characterization of the selected glaciers (debris-covered?, in shadow?)
(2b) an overlay of outlines obtained by the multiple digitizations
(2c) for clean ice glaciers (requiring no manual correction): a comparison of the automatically derived area values to the manually digitized ones (differences in percent), and
(2d) a discussion of the results.

Level 3
When multiple manual digitising cannot be performed for whatever reason, a buffer of ± a half pixel should be applied to all glacier outlines and a minimum and maximum total glacier area should be calculated from this buffered extent.
(3a) The range of the area differences should be calculated and provided as a relative measure.

(3b) The uncertainty range should be discussed in view of the glacier characteristics (e.g. are clean-ice glaciers dominant or should a ±1 pixel buffer be applied?) and mapping conditions.
(3c) An overlay of the derived glacier outlines in a region with challenging mapping conditions should be shown and discussed.

Level 4
At an absolute minimum, results from other studies should be considered (e.g. Paul et al., 2013) and the accuracy measures determined in these studies should be applied to the dataset considering the mapping conditions.
(4a) An uncertainty value should be selected from the literature, justified for the current study, and applied to the sample.
(4b) As (3c).

Due to the rapid glacier change with time and the wide range of possible outline interpretations by different analysts, it is not recommended using datasets from another epoch or digitized by another expert for validation. Using them for change assessment also requires careful evaluation, in particular when the accuracy is not given. Of particular importance is reporting of potential errors that might be much larger than those discussed above: This is required when seasonal snow or clouds/fog are part of the scene and hide glacier perimeters partly. In such cases it must also be described how these challenges were solved (e.g. using multi-temporal images, or exclusion from the sample) to derive accurate values.

The strategy of quantitative accuracy assessment described above will also be applied by Glaciers_cci for the generated glacier area product. In the case of an accuracy evaluation of an already existing product, the following qualitative measures will be applied:
(i) overlay of the outlines with existing satellite images (shapefiles and geotiff in the GIS or kmz files in Google Earth) and analysis of the differences focusing on debris cover, shadow, clouds, water and potential seasonal snow,
(ii) consideration of potential rapid glacier change and analysis of existing alternative satellite data to improve the quality,
(iii) contacting the responsible GLIMS Regional Centre for further steps to be performed.

3.4 Summary and outlook

The product intercomparison performed for the PVIR and the study by Nagai et al. (2016) confirmed the above points. It was shown that seasonal snow can introduce by far the largest product errors and that debris-covered glaciers should be carefully checked and corrected (Paul et al. 2015). For the former it is recommended to either use a scene with better snow conditions to mask the seasonal snow or to make use of datasets that might already be available (e.g. in the GLIMS database). The latter issue (debris) should be improved (consistency in interpretation) by creating illustrated guidelines for the community with a large number of good practice examples. These are currently being prepared for Phase 2 of Glaciers_cci.

The choice of the above measures applied for determination of product accuracy should be documented in a related paper. The local uncertainty provided in the GLIMS database should consider the results of this assessment as far as applicable. A potential addition of other quality measures to the meta-information stored in the GLIMS database should be evaluated.

4. Elevation change (Altimetry)

4.1 Sources of errors and uncertainties

4.1.1 External conditions influencing product accuracy

The input uncertainties for the altimetry platforms are described in individual papers, e.g. Shuman et al. (2006) and Kääb et al. (2012) for ICEsat, Brenner et al. (2007) for Envisat, and McMillan et al. (2014) for CryoSat-2. Each platform will have different and time-variant sources of uncertainty, based on atmospheric corrections to the measured range, different footprints and instrument sensitivities and, in the case of ICESat, cloud effects. They also have different reference orbits and sampling strategies.

A significant factor in the input elevation and location uncertainties is due to the slope of the underlying terrain. Again, each platform has a different specific response. However, in general the uncertainty rapidly increases towards higher slope, and low slope surfaces (less than 5 degrees) still work. In regions of low slope elevation changes will be estimated using a fitted model, for reasons given in section 4.2.2.

4.1.2 Impact of the algorithm used

The plane fitting method, described in section 4.2.3 of the revised ATBDv2 (Glaciers_cci, 2014), involves the selection of along-track 'segments', representing areas sampled repeatedly over time.

The main model assumptions are:

1. a plane is a suitable approximation to the segment surface
2. the segment surface experiences height change uniformly at all locations
3. the segment surface height changes in a regular, unidirectional manner

There are many possible surface models, but the one used should fit a segment in order to encompass enough datapoints to be statistically meaningful for all the altimeters to be used (e.g. for Cryosat-2 we use grid sizes of 2x2 km). In flat terrain a tilted, time-variant plane is an appropriate model. Over significant topography, if the second assumption is correct, then regardless of the actual surface a fitted plane will retain the same orientation over time and is thus still a valid model. In very rugged terrain, any attempt to fit a more complex surface would be open to errors in its own right.

The height change may vary with location within a segment, due to, e.g., removal of snow by wind, capture of rockfalls or differential ice movement within a glacier. This effect cannot be countered, as there is no sufficiently detailed data to define the variation with, but is likely only to be significant over terrain that varies greatly within a 1km distance.

The third assumption is reasonable as long as a suitable, multi-year time range is covered. In this way possible seasonal variation is accommodated, and will be seen in the residuals to the model fit.

4.2 Methodology used to determine uncertainties

4.2.1 External validation

The uncertainty associated with the estimated elevation trend can be assessed by means of a validation process based on better reference remote sensing data sets, like airborne lidar measurements, which need to coincide temporally with the satellite altimeter overpasses. Due to this large constraint, a relative comparison of results from different algorithms or different sensors or sources can provide an alternative way to assess the uncertainty.

In both cases, the validation criteria are based upon the absolute difference of the elevation change maps obtained using different methods and/or sensors. In addition, the quantitative analysis is provided by means of the root mean square error, *RMSE*, and the correlation coefficient, R. Since in this case the statistics are used to compare two sampled variable time-series, neither of which is an accepted 'standard', the formulae are:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(x_{1,t} - x_{2,t}\right)^2}{n}} \qquad (4.1)$$

$$R = \frac{\sum_{t=1}^{n}\left(x_{1,t} - \overline{x_1}\right)\left(x_{2,t} - \overline{x_2}\right)}{\sqrt{\sum_{t=1}^{n}\left(x_{1,t} - \overline{x_1}\right)^2}\sqrt{\sum_{t=1}^{n}\left(x_{2,t} - \overline{x_2}\right)^2}} \qquad (4.2)$$

where the two time series, dh/dt, from the two altimeters being compared, are shown as x_1 and x_2 for convenience.

When two different sensors, radar versus laser, are used in the validation process, a number of challenges will occur, mainly due to the fact that the two datasets need to be collected during the same time/period. In fact, the laser altimeter data are temporally sparser compared to radar and in addition they are only available during the cloud free days of the operation periods. Then, laser and radar measurements will not always refer to the same location, but to two locations close to each other. Finally, if the snow surface is dry, laser and radar measure a different surface elevation due to the penetration of the radar beam, whereas in case of a snowfall or rapid densification of the upper snowpack due to liquid water, the laser measurement will be misleading due to its insensitivity to the density and moisture of the snowpack. As a consequence, the RMS value of the difference between radar and laser product can be interpreted as the maximum uncertainty of both instruments.

4.2.2 Quantitative measures for accuracy assessment

Each segment's parameter values are derived from the fitting of a time- and location-dependent elevation-plane model to an input dataset of time, location and elevation values from a single altimetry platform. The fitting uses a Levenberg-Marquardt least-squares minimisation approach. The plane equation is:

$$h = ax + by + ct + d \qquad (4.3)$$

where h = elevation
a/b = coefficient of elevation change due to X/Y component of location
x/y = X/Y component of location
c = coefficient of temporal elevation change, i.e. dh/dt
t = time at which elevation is wanted
d = mean elevation of plane at t=0

The fitting approach works by iterating the coefficient values a, b, c and d until they best match the input data in a least-squares sense. The uncertainties on the input elevations have to be calculated beforehand and depend on the external conditions given in section 4.1.1 above.

Since the slope of the plane is constant, the weighting due to the slope will be equal across all datapoints and will not affect the model fitting. Once a slope has been calculated it will be seen in the residuals and is incorporated into the statistics of the model fit. Using internal evidence to calculate the slope is preferable to introducing a new set of errors by using a separate DEM.

The output uncertainties are given as one standard deviation on each coefficient, computed from the covariance matrix. The reduced chi-squared parameter for the model fit is also returned. The reduced chi-squared value is a measure of how the initial errors provided to the fitting algorithm compare to those derived from the model fit. If the reduced chi-squared value is in the region of unity, this indicates that both input and modelled errors are similar and therefore the model fit is likely to be of good quality. In that case the estimated parameter uncertainties can be computed by scaling the output uncertainties by the reduced chi-squared value. These statistics implicitly include a measure of how good the model assumptions are.

4.3 Accuracy to be reported

The data product as defined in the PSD (Glaciers_cci, 2014), Table 3.2, will output a set of parameters for each ‘repeat track grid cell’ (another name for a segment).

In the data product the only uncertainties to be recorded are the RMS of the residuals on the plane fit for the rate of elevation change, in m/yr. In terms of the plane equation, 4.3 above, these are the uncertainties on the coefficient c.

These uncertainties will incorporate contributions from the altimetry platform measurement uncertainties, and the model assumptions. They can only be deemed valid if the model fit has a reduced chi-squared statistic near unity. It has been assumed that poorly-modelled segments would not be included in the data product, however, at earlier processing stages the reduced chi-squared statistics for each segment are produced.

The plane fitting method is appropriate for regions where dense altimetric coverage (mainly the Arctic and Antarctic) through time allows for an approximation of the terrain slope over the plane size. In steeper terrain, positioning errors are amplified in the differences, also making it difficult to provide a robust, representative estimate of the slope. Thus, for high mountains with steep topography and glaciated mountain ranges with lower altimetric coverage, the ICESat footprints will be intersected with a reference DEM as available (e.g. SRTM). Provided proper co-registration, the error budget includes the accuracy of the ICESat elevation (see above) and the accuracy of the reference elevation model (described in section 5). Both errors are combined as root sum square. At what point of terrain steepness one or the other method provides 'better' results has to be decided on a case-by-case basis.

4.4 Summary and outlook

The uncertainties returned by this method can only be numerically calculated on a platform by platform basis, as they rely primarily on the instrumental and geophysical corrections used to derive the range from the altimeter data. However, this does imply that uncertainties can be calculated for any characterised altimeter.

Methodological uncertainties are mitigated by an internal statistical test of model suitability.
This method has been tested using ICESat Antarctic data over Lake Vostok by Smith et al, 2009, and using CryoSat-2 data by McMillan et al, 2013. Other projects in preparation use the same approach. The final outputs will be in a format that makes comparison with other data products possible.

For high mountains no regional dh/dt will be derived, so that the main error influences are the accuracy of the ICEsat elevation and reference DEM. Further work will be conducted to better characterise the accuracy of ICEsat elevations over different mountain topographies (Kääb et al, 2012 for Himalaya; similar error assessment work undergoing for Scandinavia).

Constraints on the methods used are related to the availability of suitable amounts of data, and the ruggedness of the glacial surface, but with a variety of altimeters that have produced/are producing datasets it should be possible to find usable data for most glaciated regions.

5. Elevation change (DEM differencing)

5.1 Influences on product accuracy

The reliability of glacier elevation changes derived from comparison of multi-temporal DEMs is influenced by the individual accuracies, precisions and resolutions of the DEMs to be differenced, the combined co-registration of the DEMs, and the resampling required to merge the DEMs into a single grid of elevation differences. DEM accuracy is dependent upon the data acquisition techniques used, mainly photogrammetric principles on optical images (i.e. aerial, ASTER or SPOT), interferometric techniques on repeat radar images (i.e. SRTM), or laser distance point clouds of measurements (i.e. LIDAR DEMs) and partly also the environmental conditions at the time of acquisition. In addition, the resolutions of the products from these techniques vary considerably depending upon whether data is acquired from the air or space. A number of studies have outlined various accuracies for the different DEMs and elevation data types (Kääb, 2005; Fricker et al., 2005; Rodriguez et al., 2006; Berthier et al., 2007; Toutin, 2008) mainly by comparison to other DEMs or measurements of elevation (i.e. GNSS, ICESat). The common approach is for comparison over terrain known or assumed to have not changed. This requires the masking of glaciers, (hydro-power) lakes, and also pro-glacial areas that are subject to frequent change. Glaciers_cci will follow this standard for product validation and algorithm selection.

The comparison of two or more multi-temporal DEMs require that the models be horizontally and vertically aligned (*co-registered*) to ensure that multi-temporal pixels represent the same location on the Earth's surface. Methods for co-registration range from manual translations (VanLooy, 2011) to automated algorithms that minimize elevation residuals (Gruen and Akca, 2005; Schenk et al., 2005; Berthier et al. 2007; Miller et al. 2009; Nuth and Kääb, 2011). The round robin performed in Phase 1 aimed at testing the co-registration approaches in search of the most reliable, robust and universal algorithm. An important consideration in terms of co-registration, DEMs of varying resolutions (pixel areas) depict different elevations at the same pixel centre location depending upon the acquisition technique (radar, lidar, photogrammetry) with the characteristics of the terrain (i.e. vegetation, surface roughness, visible contrast, material etc.) at the time of acquisition. Recent studies have emphasized the influence of varying DEM resolutions and resampling strategies on elevation-dependent biases detected within DEM differences (Paul, 2008; Gardelle et al., 2012). The datasets chosen for product validation and algorithm selection have varying resolutions to further investigate resampling and topographic effects on DEM difference accuracies.

Finally, the detection of significant glacier elevation changes is not only a function of DEM accuracy, but largely a function of time and the particular characteristics of the glaciers being measured in the environments they reside. Therefore, the data availability and the time span between DEMs have a major impact on glacier elevation change reliability. Choice of data is an important manual interaction step necessary to provide quality data products.

5.2 Methods for accuracy determination

5.2.1 Validation

The validation involves verification of a satellite DEM using a high accuracy DEM when available (e.g. from laser scanning that is increasingly available for glaciers also in polar regions, or airborne photogrammetry). The process begins with co-registration of the datasets using stable terrain, and then resampling of one dataset to another. If the data is temporally consistent, the comparison can be made over the glacier to analyze/detect any glacier specific biases related to the acquisition strategy (e.g. radar wave penetration into snow/firn within the SRTM DEM). In most cases, however, the DEMs will temporally not be consistent and the analysis can only be made over stable terrain (e.g. off-glacier terrain). After co-registration, visual analysis of the changes over stable terrain is performed to detect any internal scene biases that may exist. If detected, procedures for removal will be investigated. This step is however case-study specific as it depends on the site topography and the sensors/procedures used for DEM generation, and therefore cannot be universally standardized such as the co-registration pre-processing step.

Alternate components of the validation involve comparing the topographic attributes such as mean, minimum and maximum glacier elevation and derivatives of slopes and aspects over glaciers (Frey and Paul, 2012). For this purpose, the variability and mean difference between topographic parameters of the medium resolution DEMs (SRTM, ASTER, ASTER GDEM, etc.) and the high resolution DEMs have to be calculated. Of further importance is to understand how potential elevation changes affect the topographic parameters, especially when incorporating them into the glacier database (i.e. GLIMS).

5.2.2 Uncertainty

Uncertainty assessment refers to the quantification of random and systematic errors in elevation differences between the DEMs using the DEMs themselves. In principle, this is not different from the validation, except that there may not be one DEM that is clearly more accurate than the others. The two multi-temporal DEMs (no. 1 and no. 2) are first co-registered to remove a potential systematic linear bias (horizontal and vertical) (co-registration vector 2-1). Random errors are estimated through statistics (i.e. RMSE) of the stable terrain. The bias is more complicated to detect as it is dependent upon the acquisition techniques of the DEMs (i.e. radar penetration on glaciers using interferometric DEMs) and the quality/resolution of the multi-temporal datasets. To this avail, a third elevation dataset (no. 3) is then co-registered to both the other two DEMs (co-registration vectors 1-3 and 3-2). Elevation data set no. 3 may be elevation profiles acquired by satellite laser altimetry (i.e. ICESat) or simply another DEM. This process returns three co-registration vectors (2-1, 1-3, 3-2) between the data products that should form a perfect triangle (vector sum). Any mismatch in a vertex of the triangle is an estimate of the remaining un-removed bias. In practice, the un-removed linear vertical bias can be added to the error budget for elevation change. The resulting parameters of this uncertainty assessment are an estimate of the random error and an un-removed linear vertical systematic bias.

5.3 Accuracy to be reported

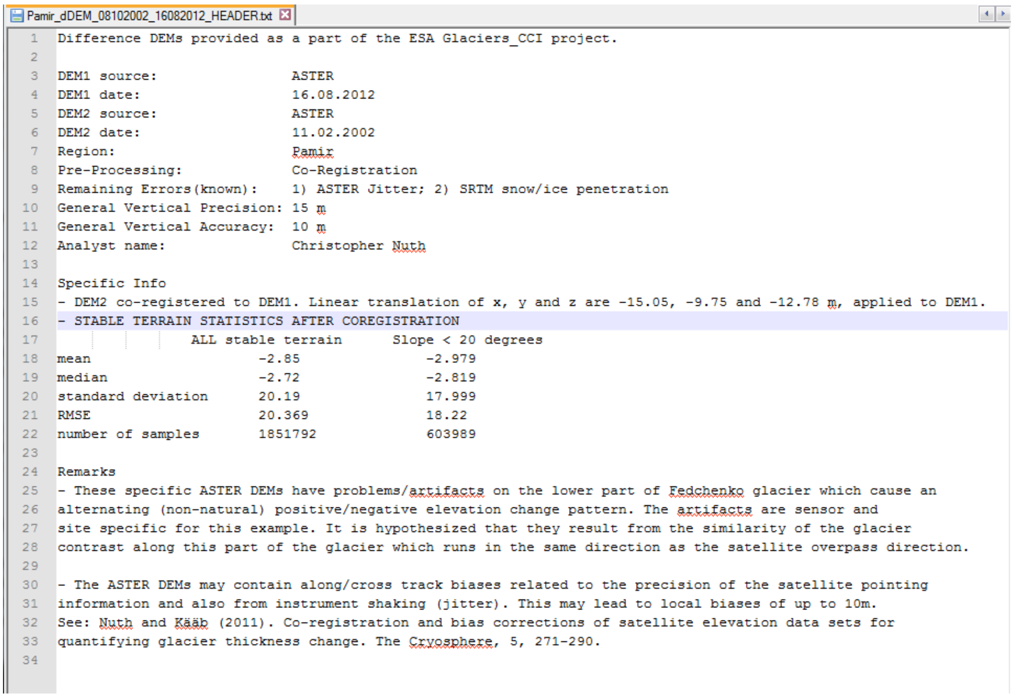
The accuracy to be reported depends on the input data available for DEM differencing. For each DEM differencing product (e.g. each DEM difference pair), both off and on glacier changes are provided, along with a logical mask (glacier = 0, non-glacier = 1), such that each user can estimate errors using their own preferred methods. Glaciers_cci products will report the general accuracy as statistics of surrounding stable terrain (i.e. non-glacier) for each pair of DEMs that are differenced. The statistics provided include mean, median, standard deviation, root mean square error and number of samples for all stable terrain differences and for only those differences on slopes less than 20 degrees. All information is provided in the metadata supplied with the product (Fig. 5.1). Thereby, three constellations can be distinguished:

(1) Two DEMs/elevation data sets of different times and comparable accuracy (typical case for product generation):
The two elevation data sets are co-registered using stable ground. Together with the co-registration parameters the statistical accuracy for these is provided. As the co-registration uses analytical solutions, namely sinusoidal fits (for horizontal offsets) and linear fits (for vertical offsets), the fit accuracies are directly output as statistical standard errors of the fitted offsets. In addition, the mean, median, standard deviation and RMSE of the elevation differences on stable ground after co-registration is provided. This information is provided for each individual Glaciers_cci product as shown in Fig. 5.1.

(2) Three DEMs/elevation data sets of different times:
In addition to the standard errors of offset parameters for all three possible co-registrations, and the RMSEs of stable ground after co-registration (as of case 1), the sum of offset vectors can be computed and reported. This information is not reported in the header of Glaciers_cci products since each product contains a difference between two DEMs, rather than three. However, in cases where time series are being generated, this is an internal check to assure that the co-registration was successful. The remaining bias will be reported, if available.

(3) One elevation data set typical for product generation and one of high accuracy (validation case):
In principle, the accuracy is reported as in case (1), with the difference that this accuracy can mainly be attributed to the less accurate DEM and characterizes thus this DEM. For sufficiently temporally consistent elevation data sets (i.e. no significant glacier elevation changes to be expected) on-glacier elevation differences can be treated similarly to off-glacier ones, and the co-registration accuracy be reported as in case (1). Since this does not result in glacier elevation changes through time, Glaciers_cci will not provide elevation differences between temporally consistent DEMs. Additionally, only stable ground co-registration can be performed and the resulting on-glacier elevation differences analysed and offsets be reported (vertical bias, RMS, standard deviation, trend with elevation and its statistical error) as shown in Fig. 5.1.

Expert observations on remaining elevation differences after co-registration are added in a comment field, if assessed by an experienced operator. Such observations include for example higher-order errors such as those from satellite jitter or unsolved orbit deformations, or imperfect co-registrations. The uncertainties given are valid for the product, despite such higher-order errors. Any expert comments and remarks are also provided in the header as shown in Fig. 5.1.



```
Difference DEMs provided as a part of the ESA Glaciers_CCI project.

DEM1 source:                ASTER
DEM1 date:                  16.08.2012
DEM2 source:                ASTER
DEM2 date:                  11.02.2002
Region:                     Pamir
Pre-Processing:             Co-Registration
Remaining Errors(known):    1) ASTER Jitter; 2) SRTM snow/ice penetration
General Vertical Precision: 15 m
General Vertical Accuracy:  10 m
Analyst name:               Christopher Nuth

Specific Info
- DEM2 co-registered to DEM1. Linear translation of x, y and z are -15.05, -9.75 and -12.78 m, applied to DEM1.
- STABLE TERRAIN STATISTICS AFTER COREGISTRATION
                ALL stable terrain      Slope < 20 degrees
mean                    -2.85               -2.979
median                  -2.72               -2.819
standard deviation      20.19               17.999
RMSE                    20.369              18.22
number of samples       1851792             603989

Remarks
- These specific ASTER DEMs have problems/artifacts on the lower part of Fedchenko glacier which cause an
alternating (non-natural) positive/negative elevation change pattern. The artifacts are sensor and
site specific for this example. It is hypothesized that they result from the similarity of the glacier
contrast along this part of the glacier which runs in the same direction as the satellite overpass direction.

- The ASTER DEMs may contain along/cross track biases related to the precision of the satellite pointing
information and also from instrument shaking (jitter). This may lead to local biases of up to 10m.
See: Nuth and Kääb (2011). Co-registration and bias corrections of satellite elevation data sets for
quantifying glacier thickness change. The Cryosphere, 5, 271-290.
```

Figure 5.1: Example metadata provided in the header to one of the CCI products.

5.4 Summary and outlook

The quality of the glacier elevation change products from globally available multi-temporal DEMs currently restricts change assessment to glaciers with large changes and commonly over long time periods (such that enough change has occurred to be above the significance level). Tests within the Pamir region (PVIR) reveal an accuracy of ±10 m with a precision of about 20m as derived from ASTER and SRTM DEM products. The rather large uncertainty (accuracy) derives from the known internal biases that exist in both ASTER and the SRTM data products. These internal biases are mainly caused from satellite shaking (jitter) or from penetration of the radar waves into snow, firn and ice. Future enhancements to these data products may be able to constrain these independent internal biases to improve both the accuracy and precision of the datasets. We assume that an improvement of accuracy to ±5 m is achievable on these medium resolution data products if high precision base datasets are available, for example from the global TanDEM-X products, to constrain and remove the biases. This new global DEM has the potential to be a very valuable new baseline DEM. Tests on the global product that eventually will be provided for free will be conducted within Glaciers_cci subject to availability.

Finally, in some cases, large blunders may occur which may require special intervention to detect and remove from the products. We experienced one such problem in the Pamir region that affected optical image matching and further DEMs derived from optical imagery. This blunder has not been observed on other glaciers (yet) and we suspect it is a very case-specific example. Nonetheless, the current accuracy of the elevation change products require long time periods (>7-10 years) between the DEMs and/or large glacier changes to derive significant changes from the DEM differences.

6. Velocity

6.1 Sources of errors and uncertainties

6.1.1 Impact of the algorithm for uncertainty characterisation

As a result of the round-robin experiments, intensity cross-correlation was selected as the primary algorithm for ice surface velocity estimation using both optical and SAR satellite images. Criteria used for algorithm selection were robustness, reliability, accuracy and information content.

The implementation of the algorithm with regard to the matching window size and the oversampling factor has a direct consequence on the precision of the estimates and on the computational time. The former also depends on the target under observation: For SAR sensors, estimates with very large window sizes (e.g. 512x512 pixels) are generally more precise for large structures, but this is not applicable for narrow (e.g. < 500 m) glaciers and does not provide information in shearing zones. This can be overcome by an iterative algorithms with variable matching window size. For optical sensors, typical window sizes are around 10-30 pixels. But still, the same rule applies that large windows are in principle able to produce better accuracy for large structures. A trade-off between these parameters is therefore necessary in the implementation of the algorithm (Debella-Gilo and Kääb, 2012). Also the post-processing of the matching outcomes (i.e. filter) is a critical processing step. Here a trade-off is necessary in terms of number of estimates versus level of confidence, or between the number of mismatches kept and correct matches lost through the filter process.

The implementation of the cross-correlation algorithm and of the post-processing step have a direct impact on the noise of the resulting estimates. A further element which also affected the noise is the presence and the temporal persistence of features to be tracked in the two acquisitions. This depends in particular on the surface conditions over the glaciers and are discussed in the next section.

For SAR sensors, excluding noise, the image offsets in the slant-range and azimuth directions are related to stereo offsets, the different satellite orbit configurations of the two SAR images, the displacement occurring between the acquisition time interval of the image pair, and, depending on the frequency of the system, ionospheric effects. In order to accurately determine the displacement, all the other terms must be carefully characterised. Orbital and stereo offsets are discussed in this section as part of the internal uncertainty characterisation, ionospheric effects are considered external factors and discussed in the next section.

The orbital offsets are determined by fitting a bilinear polynomial function to offset fields computed globally from the SAR images assuming no displacement for most parts of the image. Residual errors on stable ground might be used to inspect the results against systematic residual offsets. Stereo offsets DR are relevant for the range offset-field:

$$DR = z * B / (R * \sin(\theta))$$

where z is the height, B the baseline, R the height of the SAR platforms above the Earth's surface, and θ the incidence angle.

In the case of an ALOS PALSAR image pair with a 700 m baseline and for a height of 700 m:

$$DR = 700 * 700 / (879762.8985*\sin(35)) = 0.97 \text{ m}$$

For an ALOS PALSAR slant-range pixel of 9.37 m, a stereo offset of 0.97 m corresponds to 1/10th of a pixel.

The following Fig. 6.1 shows the slant-range offsets distribution over the Austfonna ice cap as a function of height for a region without outlet glaciers. In order to avoid stereo offsets, the two SAR images can be co-registered with consideration of the topography, a procedure which is becoming standard in particular for the very-high resolution X-band data. Optical velocity products from Glaciers_cci are based on orthorectified nadir images, so that above distortions are negligible. Effects from errors in the DEMs used for orthoprojection are treated below.

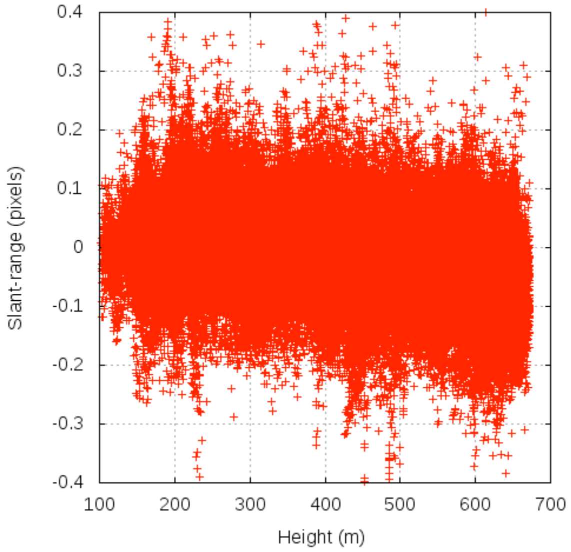


Fig. 6.1: Visualisation of the slant-range offsets distribution over the Austfonna ice cap.

6.1.2 External conditions influencing product uncertainty

Surface conditions over the glaciers have a direct impact on the quality of the matches. In general, the algorithm performs best if there are clear intensity features to be tracked with regard to the size of the employed window. For optical sensors, the presence of clouds or snow cover will mask underlying structures and reduce precision. In the case of SAR sensors, wet snow will drastically change the signal and the employed wavelength has an impact on the penetration depth within ice and snow, allowing in some cases (L-band) the retrieval of information over ice caps where other sensors (X-band) do not provide information.

As a further important remark, valid for optical and SAR sensors, it should be noted that image cross-correlation strictly provides displacements for the time period between the acquisitions used. Thus, the glacier velocity product is the mean velocity over the observation period, and does not take any velocity variations between the image acquisitions into account. This fact is of particular importance when analysing time series of glacier velocities.

In the case of SAR sensors, ionospheric conditions during the acquisition of the images also have an impact on the accuracy of the results (see Fig. 6.2). The free electron density in the ionosphere varies with the activity of the Sun, the Earth's magnetic field and atmospheric parameters, with higher concentrations and stronger spatial variations in polar regions. The free electrons interact with electromagnetic waves as a dispersive medium, with inverse effects on the phase and group velocities and stronger effects at lower frequencies. Electron density fluctuations result in variations in the interferometric range phase. Furthermore, delay phase ramps across the synthetic aperture cause significant azimuth positional shifts ("azimuth streaking"). Ionospheric streaks detected on the azimuth offset maps might be high-pass filtered along the range direction (Wegmüller et al., 2006). It is in any case suggested that careful inspection of the azimuth offset field is conducted to highlight possible ionospheric effects.

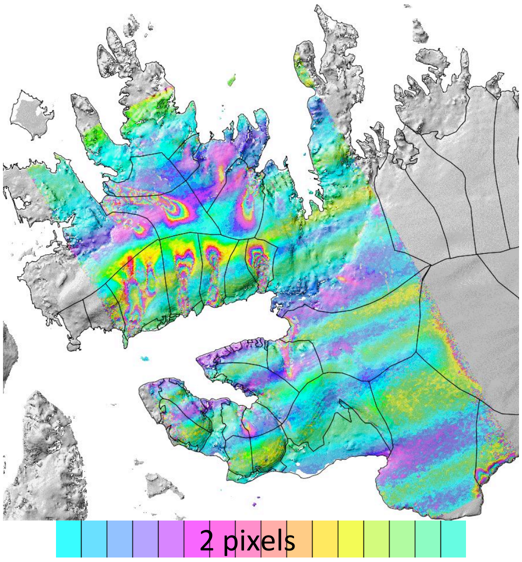


Fig 6.2: Azimuth offset-field over Vestfonna in the case of an ALOS PALSAR image pair. Azimuth streaks show up along with the motion of the outlet glaciers.

The most important external conditions influencing uncertainty for displacements from optical sensors are (more details are given in the PVASR, see Glaciers_cci, 2012b):

- Vertical error components in the DEMs used for orthoprojection will translate in horizontal displacement errors. This effect becomes typically negligible when data from the same orbit are used for tracking, similar to the SAR case. For data from different orbits the effect typically becomes visible in stable ground offsets that thus can serve as estimates for such effects. DEM errors propagated into orthoimages cannot be undone or cancelled as they are not of analytical nature.
- Higher-order distortions (e.g. jitter) from errors in the provided or modelled attitude angles will lead to an according error pattern in the displacements. Depending on their nature (e.g. for ASTER) and provided that sufficiently many and distributed stable-ground offsets are available, they can be modelled statistically and the glacier displacements corrected accordingly (Nuth and Kääb, 2011; Kääb et al., 2013).
- Matching tests between Landsat 7 ETM and Landsat 8 OLI data (ATBD (2014)) suggest that the co-registration accuracy of Landsat 7 ETM data (i.e. the relative geolocation

accuracy after removal of an overall shift, also called the absolute geolocation accuracy) is on the order of 5-10 m, but on the order of 2-3 m for Landsat 8 OLI. This accuracy improvement for Landsat 8 directly translates into more accurate displacements derived from these data.

- Ground and illumination conditions (provided that the data are taken under day-light and clear-sky conditions at all) can complicate the matching process. Optical tracking methods rely on corresponding visual contrast in both images that defines offsets in both horizontal dimensions in a unique way. Optical matching problems occur therefore, for instance, under lack of contrast (e.g. fresh snow), self-similar features (e.g. seracs or ogives), or contrast that defines only one offset dimension (e.g. longitudinal moraines or flow stripes without transverse or contrast variations). The transition from 8-bit to 12-bit radiometric resolution from Landsat 7 ETM to Landsat 8 OLI, together with the much improved detector signal-to-noise ratio enables detection and subsequently tracking of visual features that were not contained in the data before (see examples in ATBD (2014)). As a result, displacements can for instance also be matched in shadow areas, or over shorter time intervals than previously possible. From spaceborne optical sensors the temporal resolution and spatial coverage of velocity estimates increases through the various missions with monthly to annual estimates possible with the historic Landsat sensors while weekly coverage at best can be expected with the newer Landsat and Sentinel-2 satellites.

(Remark: the latter two external factors apply similarly for creating DEMs from optical stereo).

6.2 Methods for accuracy determination

6.2.1 Background

Glacier motion retrieval from space-borne sensors is characterised by some inherent methodological drawbacks, which complicate the validation of glacier displacements from space against independent data with equal or better resolution, accuracy and precision. The main reasons are:

(1) Coincident observation of EO and validation data

Glacier motion often follows diurnal to seasonal cycles and year-to-year variations, among others as a consequence of the varying sub-glacial hydrology, therefore glacier motion is highly variable temporally, at scales from hours to seasons and years. A strict validation of glacier velocity products would therefore require simultaneous acquisitions of product generation and validation data, which can only be achieved by continuous ground measurements.

(2) Adjusting spatial scales

Glacier displacement measurements from repeat images require image windows to be compared, i.e. the motion of feature ensembles rather than single features is estimated. Therefore, the derived displacement is not representative for a certain finite point, but rather for an area. Further, this representativeness is not a strict analytical function of the real displacement field, but a statistical relation of it, its gradients, image features and contrast, as well as the tracking algorithm and its implementation.

(3) **Observation of different velocity components**

Depending on the sensor (SAR, optical) and applied method, different components of the true 3D velocity are observed. For example, SAR interferometry is sensitive to the Line-Of-Sight (LOS) velocity component of the ice, but it is in-sensitive to along track motion. Image Cross correlation techniques using SAR data measure displacement in LOS and along track direction, but are also sensitive to net elevation changes (e.g. melting, vertical velocity components). In addition, the movement of the ice particles on a glacier does not follow the surface. In general, there is submergence in the accumulation area and emergence in the ablation area. Additionally, in summer, changes of the ice surface motion of glaciers are a combination of ice displacement and surface melt. In the field, ice velocity is measured with stakes at various depths or with continuous GPS on the surface. In order to validate and/or compare the products from various methods, the transformation to the same velocity component is a pre-requisite.

As a summary, accuracy determination of the glacier velocity product should not only be based on external data, as these provide only a limited reliability. Glacier displacements from repeat optical and SAR imagery should thus also be validated internally (i.e. from the product itself), for instance algorithms can also be tested against synthetic images.

Further, it should be noted that image matching (or: offset tracking for the entire procedure) strictly provides displacements. Glacier velocities are estimated by dividing the displacements through the time period between the acquisitions used. Thus, the product is a mean velocity over the observation period, and does not take into account velocity variations in-between. This fact is of particular importance when analysing time series of glacier velocities. Also, between sensors, velocity estimates from optical sensors are mostly of seasonal, annual resolution while velocities from SAR sensors are at higher frequencies.

6.2.2 Validation

In principle, two methods of validation can be applied:

- Comparison against products from independent image data: Glacier velocities from repeat image data can be compared against those from image data of equal or better resolution, accuracy and precision. The discrepancy between both velocity fields is then a function of (error budget):
  - the accuracy of both matches;
  - the co-registration between both image sets (i.e. same georeference), which can be tested by matching stable ground. Typically, discrepancies are related to absolute image orientation and orthoprojection;
  - the representativeness of the displacement obtained compared to the real displacement;
  - temporal, real velocity variations between the acquisition dates of the two image sets.
- Ground-based measurements: Satellite derived displacements can be locally compared to ground measurements such as those from GNSS, ground-based radar, lidar, tachymetric survey, etc. Though highly precise, the temporal and spatial representativeness of such data compared to the area and time covered by the image data to be validated will vary and is not strictly known.

6.2.3 Uncertainty

Determination of uncertainty is possible from a large number of methods:

- Visual interpretation of the derived velocity field by a glaciologist:

  - Visual evaluation of the spatial consistency of ice flow field taking flow direction and magnitude of ice flow into account;
  - Check for outliers or other features in the field;
  - Check for unnatural patterns; check for (roughly) downslope direction.
- These qualitative checks are subjective but rely on basic physical laws such as the incompressibility of ice. Although subjective, this type of validation should be done in any case.
- Matching quality measures: Most matching algorithms provide directly, or after additional processing, quantities that describe the degree of similarity between the matching image windows, e.g. the correlation coefficient (CC) or signal-to-noise rations (SNR). These parameters are an indication for the reliability of an individual match. However, the measure is not strict, i.e. bad matches might actually accurately reflect the true displacement, or vice-versa. As a consequence, the measure cannot be used alone for validation.
- High and low pass versions of the velocity field: Due to the physical properties of glacier ice, such as incompressibility and stress transfer, and the low spatial variations of gravity that drives glacier flow, glacier velocities are usually smooth and coherent. This experience can be employed to compare different frequencies of the velocity field, and to disregard results that differ too much from a value expected from a field version at lower frequency. Practically, the original result can be compared to a low-pass filtered result and individual measurements be kept or disregarded based on the differences between both versions of the velocity field. Whereas, this validation or filter gives often good results, it fails where entire zones of the measurements are actually inaccurate, or where a glacier actually shows in reality high local velocity gradients
- Inversion of displacement: An image 2 can be inversely deformed using a displacement field between image 1 and 2, and the reconstructed image 1r compared to the actual image 1. The similarity between both can be quantified e.g. by using the cross-correlation (CC) coefficient. This method is less suitable to judge velocity products as the overall CC level depends on the content of the individual images, but the method is useful for judging the performance of different algorithms applied to the same set of images.
- Stable ground: Matching stable ground in the image set, if present, gives a good indication for the overall co-registration of the repeat images, and some general idea of the matching accuracy under the specific image conditions. The representativeness of the latter indication for the glacier velocities depends on the image content similarity between the stable ground and the glacier areas.

6.3 Accuracy to be reported

Summarizing the above possibilities of validation and uncertainty determination, the accuracy of offsets tracked between two optical or SAR images will be reported as

- A comment from an experienced operator based on visual inspection of the resulting displacements (consistency of ice flow field, sensor effects, etc.)
- Characterisation of the matching quality of individual ice velocity estimates: map of correlation coefficient and / or signal-to-noise ratio, depending on the algorithm implementation, given for each displacement estimation.
- Similarity between original measurements and low-pass filtered ones for each displacement, given as deviations in x- and y-offsets, or vector magnitude and direction;
- Statistical measures for stable ground matches (mean, standard deviation, RMS).

For validation, offsets between two images can in rare cases be compared to temporally consistent matches based on images with higher resolution, or to ground-based measurements of displacements. In these cases, in addition to the above accuracy measures the following numbers will be reported:

- Deviations between product-type displacements and validation displacements for x- and y-offsets or vector magnitude and direction for each location with both results available.
- Summary of deviations (mean, standard deviation, RMS, min, max)

6.4 Summary and outlook

As a very general statement, the accuracy of individual glacier displacement measurements from repeat satellite optical data using offset tracking is on the order of one pixel. For a one year Landsat panchromatic image pair this corresponds to an accuracy of 15 m /year. However, in case of good visual contrast, such as given for crevassed and snow-free glaciers, and satellite optical data of the latest generation (Landsat 8 and Sentinel-2) surface displacement accuracies of 10-20% of a pixel can be reached. This corresponds e.g. for Landsat 8 data (15 m) to 1.5-3 m or 24-48 m/yr for a time interval of 16 days.

For SAR sensors, we estimate the reliability of the cross-correlation algorithm to return co-registration parameters as accurate as 1/10th of an image pixel. This corresponds for the ALOS PALSAR and TerraSAR-X data separated by a temporal interval of 46 respectively 11 days to an accuracy of about 10 m/yr, for the ENVISAT ASAR data separated by a temporal interval of 35 days to an accuracy of about 20 m/yr, and for the Sentinel-1 IWS data separated by a temporal interval of 12 days to an accuracy of about 30 m/yr.

Very high resolution SAR sensors (TSX Stripmap/Spotlight, PALSAR Fine beam) data are thus excellent tools for monitoring ice dynamics of glaciers, while SAR systems with high geometric resolution (ENVISAT and Sentinel-1) provide more noisy results with lower quality. The archive holdings and mission continuity from TSX and ALOS, however, will not allow for global, long-term monitoring. So, their application is more related to local specific studies and validation. On the other hand, Sentinel-1 is an excellent tool for large scale studies due to its well managed global acquisition strategy.

The first direct inter-comparison of SAR and optical velocities (Landsat 15 m) showed reasonable results over short time periods but revealed image matching problems when averaged over a year for the Pamir. They were related to fast glacier flow and self-similarity of the surface in the direction of flow as well as due to the lower spatial resolution. At a higher spatial resolution the matching problem might have been overcome, but the high variability in flow speed would have required a shorter time frame for the fast flowing regions than for the other regions. We thus conclude that the temporal baselines for optical data may not be constant for all glaciers in a scene. At the very base, this is also true for SAR velocities, but with different baselines, though. The very good results obtained in other regions of the world (e.g. Svalbard) confirm that Fedchenko Glacier is a rather special case in this regard.

The high radiometric and geometric fidelity of Landsat 8 OLI data enable more successful and more accurate image matches compared to Landsat 7 ETM and ASTER. Sentinel-2 data are expected to have a similar, i.e. much improved quality for offset tracking, together with an even larger swath width compared to Landsat. The velocity products derived from spaceborne sensors are rather complimentary to what can be obtained from ground-based measurements. In consequence, it is very hard finding data for external validation. Capabilities of very high resolution optical data (Ikonos, Quickbird, Pleiades) for velocity mapping might thus be used as an alternative for local-scale validation.

7. References

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Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
CC	Cross-Correlation
CCI	Climate Change Initiative
DARD	Data Access Requirements Document
DEM	Digital Elevation Model
ESA	European Space Agency
GCM	General Circulation Model / Global Climate Model
GCOS	Global Climate Observing System
GDEM	Global DEM (from ASTER)
GLIMS	Global Land Ice Measurements from Space
ICESat	Ice, Cloud, and Elevation Satellite
L1T	Level 1 T (terrain corrected)
NASA	National Aeronautic and Space Administration
NDSI	Normalized Difference Snow Index
PALSAR	Phased Array type L-band SAR
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SPOT	System Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
USGS	United States Geological Survey