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1. Introduction

1.1 Document Purpose and Scope

This document gives an overview of the data requirements for Phase 2 of the Glaciers_cci project. The aim of the DARD is to identify all of the required input data, both satellite and auxiliary, for product generation and validation, and to assess its coverage and accessibility. The data overview presented is specific to the selected ECV parameters for Glaciers_cci as selected in Phase 1; these are glacier area, elevation change from altimetry and DEM differencing, and velocity. In accordance with the aims of Phase 2, we consider the data requirements of each technique from a more global-scale but regionally focussed perspective with the inclusion of data from new sensors available to Phase 2. The assessment of the data requirements and availability, together with the user requirements presented in the User Requirements Document (URD), will determine the Phase 2 product specifications as outlined in the Phase 2 Product Specification Document (PSD).

With this document, we provide an overview of our data requirements that is concise. For greater detail of the data types used in this project, please see the Phase 1 DARD (Glaciers_cci, 2011).

1.2 Document Structure

The following sections, sections 3 to 6, outline, for the area, elevation change and velocity products, the satellite and auxiliary data required for product generation and the data required for validation. In addition, overviews of the spatial and temporal coverage of that data, and it's accessibility to the project are given. A concise, tabulated summary of this information is provided for each technique at the end of each section for ease of future reference.

2. Glacier Area

The following sub-sections provide an assessment of the data required to generate the Glacier Outline product. An outline of the suitable satellite data is provided along with the spatial and temporal coverage, and availability. The coverage and accessibility of any auxiliary and validation data required is also assessed

2.1 Product Generation

The main satellite used for the product generation is Landsat with its TM, ETM+ and OLI sensors all providing multispectral data at 30 m spatial resolution and panchromatic bands with 15 m (only ETM+ and OLI). Spectral bands are located at about equal positions implying that the same algorithms can be used for data production. The new sensor OLI on-board Landsat 8 has additional spectral bands (see Fig. 2.1) and a 12-bit radiometric resolution. In individual cases also scenes from the Terra ASTER sensor might be used which has no band in the blue part of the spectrum but a higher spatial resolution (15 m) for the visible and near-infrared VNIR) bands. Unfortunately, its SWIR band failed after 2008. All Landsat, and now also ASTER scenes are freely available in an orthorectified format (LIT product) from various websites (glovis.usgs.gov, earthexplorer.usgs.gov, earth.esa.int/EOLi).

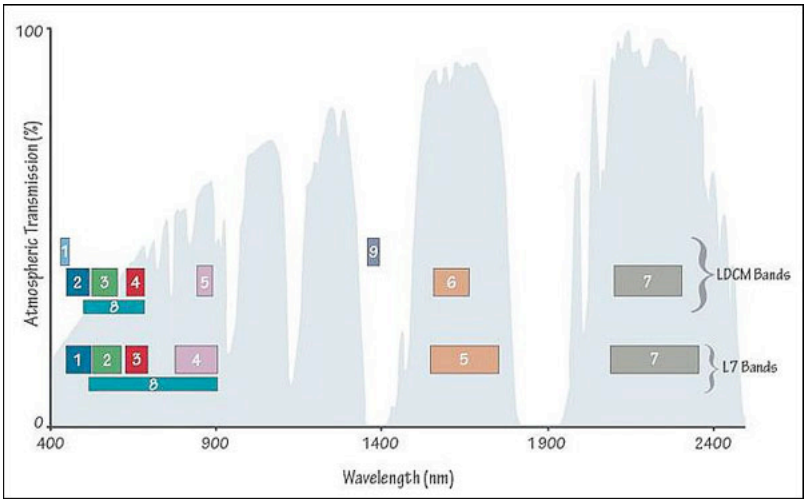

Fig. 2.1: Comparison of spectral bands from Landsat ETM+ and OLI (LDCM) sensors (Source: http://www.csc.noaa.gov/digitalcoast/_/img/Spectral_bands_of_landsat.jpg).

The recently launched Sentinel 2a satellite with its sensor MultiSpectral Imager (MSI) will enhance the possibilities for high-quality global glacier mapping and monitoring enormously. The sensor is equipped with the same and additional bands as the Landsat 8 OLI sensor (see Fig. 2.2), but has a higher spatial resolution (20 m in SWIR, 10 m in VNIR) and due to its wider swath (290 instead of 185 km) a higher repetition rate of 10 instead of 16 days (5 days when Sentinel 2b is in operation). S2 data are available from various webpages such as the Sentinel Science Hub, glovis.usgs.gov or https://remotepixel.ca/projects/satellitesearch.html.

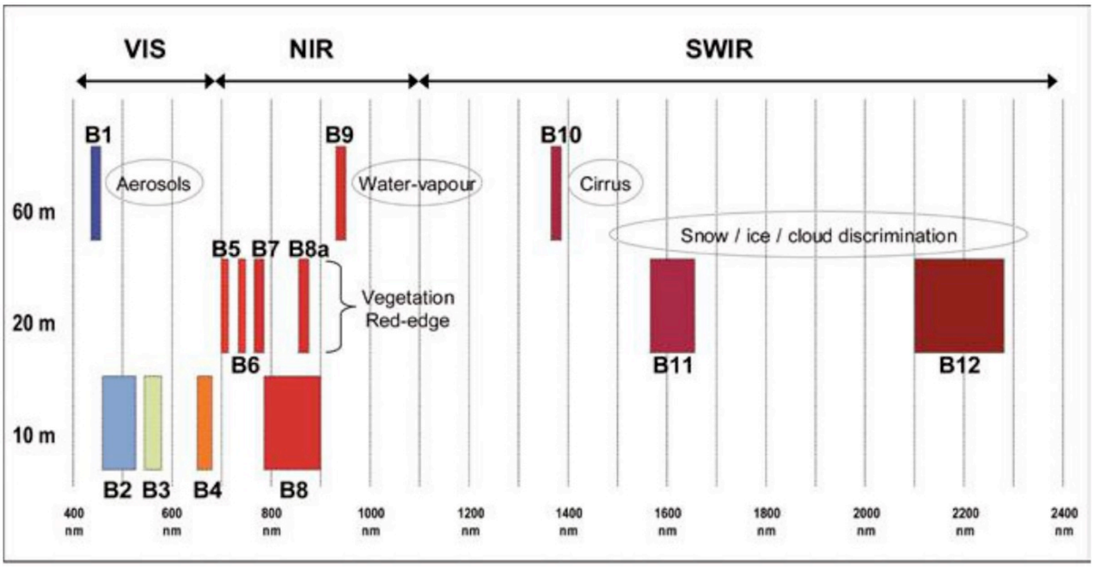

Fig. 2.2: Spectral range and spatial resolution of the 13 bands from the Sentinel 2a MSI sensors (Source: ESA SP-1322).

Three key requirements need to be fulfilled by the satellite data: (i) They have to be taken at the end of the ablation period (or dry season) with minimum annual snow cover, (ii) they need to be cloud free over glaciers, and (iii) they should have no snow outside of glaciers (potentially hiding the glacier perimeter). This has two consequences: (a) the number of appropriate scenes is strongly reduced, and (b) scenes have to be selected manually one by one to achieve best results. While the impact of (ii) can often be reduced by combining several scenes, (iii) is a key bottleneck that resulted in numerous wrongly classified datasets in the RGI. Finding better scenes for improving the quality in these regions requires repeat surveys in the EO data archives, as these are continuously extended and updated. The higher repetition rate of Sentinel 2 will be very beneficial in this regard.

Landsat data are in general globally available (the northernmost part of Greenland is not covered) for the period 1984-2014, but spatial coverage can strongly vary from year to year. An example for the USGS holdings of Landsat TM data is shown in Fig. 2.3. Further scenes might be available from other ground receiving stations (Goward et al., 2006) that are currently being integrated in the USGS archive within the framework of the Landsat Global Archive Consolidation (LGAC). The ETM+ sensor provides useful scenes for glacier mapping only over the 1999-2003 period; afterwards the malfunction of the scan line corrector resulted in severe striping so that only the central parts of a scene can be used or scenes have to be mosaiced (which works well when the striping is at different locations). An overview of the acquired scenes until July 2002 is shown in Fig. 2.4. Details for all years and sensors are listed in http://landsat.usgs.gov/documents/StateOfTheArchive_web.pdf. Scenes from ASTER are also available globally since 2000, but suffer from the malfunction of the SWIR sensors after 2008 and that only 1/9 of a Landsat scene is covered, resulting in a temporarily much more demanding survey of the archive (the size of the image quicklooks was also too small for identification of appropriate scenes, but this has improved now). They will thus not be analysed until the Landsat archive is fully exploited. The archive of Sentinel 2 scenes is rapidly growing but the end of the 2016 ablation period (NH) not yet included.

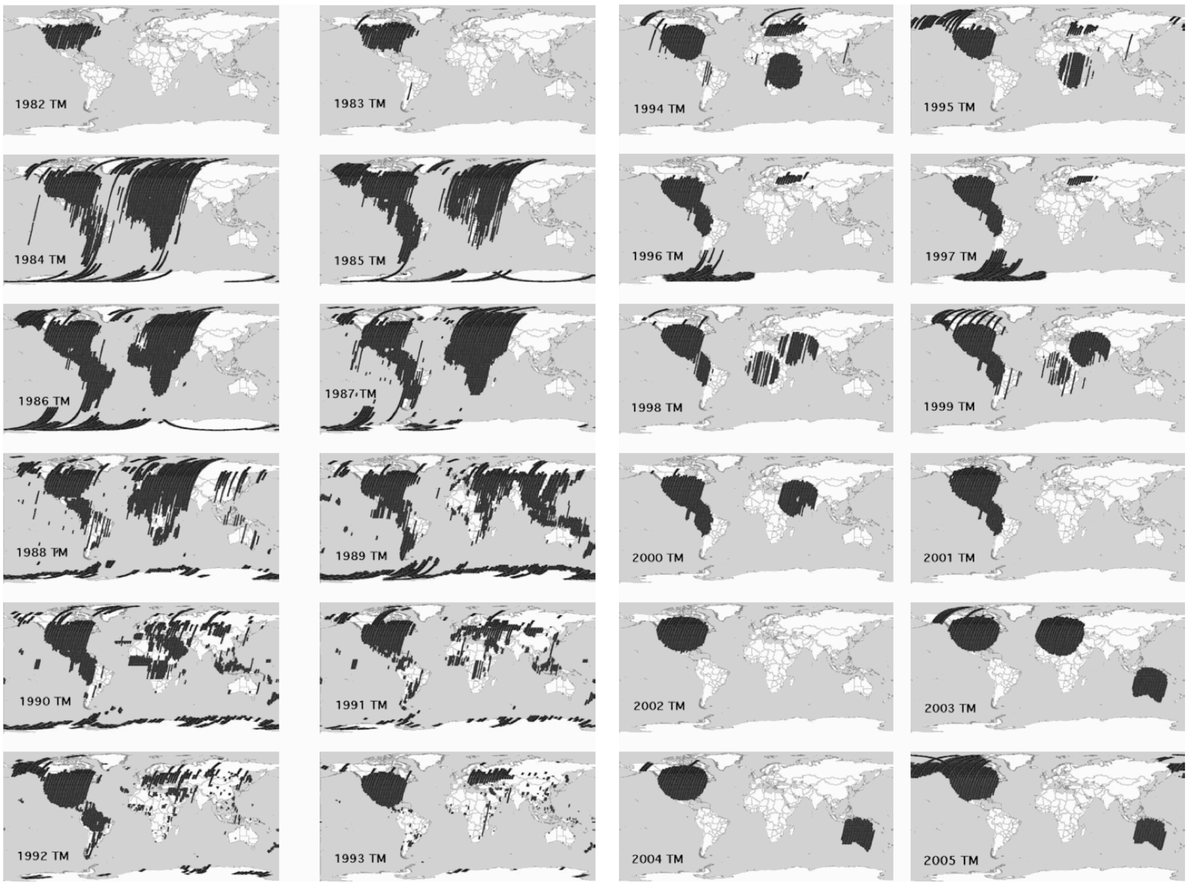

Fig. 2.3: Spatio-temporal overview of TM acquisitions in the USGS archive (from Goward et al. 2006).

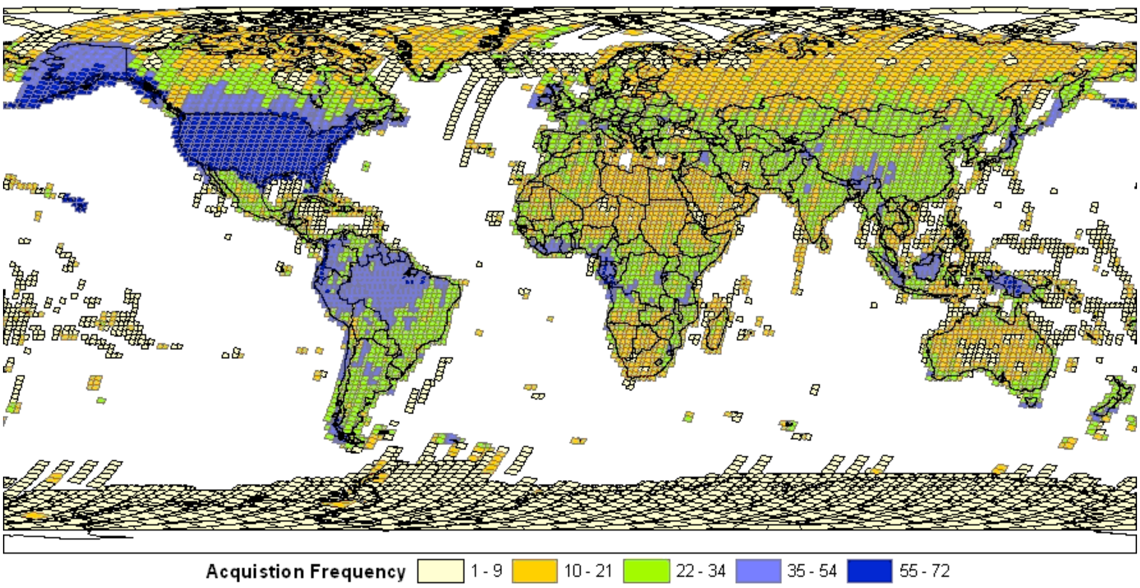

Fig. 2.4: Coverage of ETM+ acquisitions in the USGS archive until July 2002 (source: http://landsathandbook.gsfc.nasa.gov/images/orbit_coverage/acquisitions_7_31_02.gif).

Based on the above restrictions of the spatio-temporal coverage for the specific sensors, scenes for data production will be selected after key regions are defined and all data available from the respective archives have been analysed. Scenes to be selected for change assessment from other sensors (e.g. MSS and/or high-resolution declassified Corona and Hexagon images) will be presented in the next update of the CRDP technical document. A large number of Corona/Hexagon scenes over the Karakoram has been ordered by Glaciers_cci for processing and are now available for free from USGS for all users.

2.2 Auxiliary Datasets

A key auxiliary dataset for deriving higher order products is a digital elevation model (DEM). It is mainly used to derive drainage divides for separating glacier complexes into individual glaciers (e.g. Kienholz et al., 2013) and to derive topographic attributes for each individual glacier (e.g. Paul et al., 2009). In an initial step (e.g. at the space agencies or at USGS), a DEM is used for orthorectification of satellite scenes. If this DEM has quality issues and another DEM is used to derive drainage divides, a spatial mismatch between glacier outlines and the divides can occur, resulting in thousands of sliver polygons after digital intersection and a very demanding manual correction (e.g. Frey et al. 2012). In a best case, the DEMs that have been used for orthorectification are also made freely available to the community.

DEMs that are globally and freely available are the SRTM DEM which has 90 m resolution and was obtained interferometrically by C band RADAR in February 2000 (with voids from USGS and filled voids from CGIAR) and the ASTER GDEM 2, which has 30 m resolution and was compiled from all ASTER scenes (i.e. optical stereo) acquired between 2000 and 2012 with photogrammetric techniques. While the SRTM DEM only covers the regions between -57 and 60° latitude, the GDEM has a ±81 degrees coverage. Sensor specific artifacts result in the requirement of a more detailed analysis (e.g. through subtraction or creation of a hillshade) of the respective DEM before application. If the SRTM DEM is available in the region of interest, it might be preferable over the ASTER GDEM due to its use for orthorectification by USGS. Regionally and north of 60° N further DEMs are freely available (e.g. the NED over Alaska, the CDED for the Canadian Arctic and the GIMP DEM for Greenland) that might be more suitable for the above applications than the GDEM. Given that DEM availability is also subject to frequent changes (new versions or datasets) we will select the most appropriate DEM(s) on a case-by-case basis.

The respective DEMs have to be downloaded for the regions of interest in case they are not already covered by a previous analysis. All DEMs are freely available from the following websites:

SRTM: http://dds.cr.usgs.gov/srt m/version2_1/SRTM3
CGIAR: http://srtm.csi.cgiar.org/s election/inputCoord.asp
GDEM2: http://www.gdem.aster.ersdac.or.jp
NED: http://seamless.usgs.gov/ned1.php
CDED: http://www.geobase.ca/geobase/en/data/cded
GIMP: http://bprc.osu.edu/GDG/gimpdem.php

2.3 Product Validation

Validation of glacier outlines is a tricky thing. In principle, a higher resolution dataset from about the same date is required, at best derived by another person using the same rules of interpretation. As this is difficult to achieve, the glacier area product is in general not validated, but the accuracy is determined, e.g. from an independent and manual multiple digitizing of the same glaciers and calculation of a mean and standard deviation of the resulting glacier areas (Paul et al. 2013). In particular for debris-covered glaciers product accuracy can be improved by a visual comparison with higher resolution datasets (e.g. as available in Google Earth) and coherence images from microwave sensors (e.g. ALOS PALSAR). However, different acquisition dates and snow conditions need to be considered for terminus positions and accumulation areas. Coherence images will only be used if suitable scenes are available in the archives and in case they are required, i.e. the position of the outline is still unclear after analysis of other datasets. As access conditions to PALSAR data and other sensors change through time, their use will also be decided on a case-by-case basis.

For Phase 2, a three-level strategy will be applied for product validation:
(1) Visual comparison with high-resolution data or coherence images will be performed to improve the quality of the outlines.
(2) For selected glaciers requiring manual corrections, a multiple digitizing will be performed to determine the internal accuracy of the person performing the corrections.
(3) Outlines are compared to those derived by manual digitization from high-resolution data.
The latter will only performed for selected glaciers in regions with suitable data (e.g. acquired in the same period or under identical conditions). With the 10 m resolution Sentinel 2 data product quality will strongly increase. For the first time, glaciers can be identified as glaciers (with crevasses etc.) and the debris-covered parts are much better visible (Paul et al., 2016).

2.4 Summary

A summary of the attributes of the data required for generating and validating the glacier area products are given in Table 2.1 below.

Data Class	Data Type	Source	Spatial Coverage	Temporal Coverage	Repeat Periodicity	Availability
Production	Landsat TM	USGS, ESA	81 N/S	1984-2011	16 d	earthexplorer glovis, eolisa
Production	Landsat ETM+	USGS, ESA	81 N/S	1999-2003	16 d	
Production	Landsat OLI	USGS, ESA	81 N/S	2013-	16 d	
Production	Terra ASTER	USGS, GLIMS	83 N/S	2000-2008	variable	reverb, glovis
Production	Sentinel 2	ESA, USGS	56 S - 84 N	2015-	10 (5) d	science hub
Auxliary	SRTM DEM	USGS	57 S - 60 N	Feb 2000	once	ftp
Auxliary	GDEM2	ERSDAC	83 N/S	2000-2012	mean value	http
Auxliary	GIMP DEM	bprc.osu.edu	Greenland	variable	once	http
Auxliary	NED DEM	USGS	Alaska / US	1960s	once	http
Auxliary	CDED DEM	geobase.ca	Canada	1960s	once	http
Validation	HighRes Sat	Google Earth	global	after 2000	irregular	Google
Validation	HighRes Aerial	swisstopo	Switzerland	after 2000	irregular	http
Validation	Coherence images	PALSAR S1	global	2006-2010	irregular	ESA / JAXA (details TBD)

Table 2.1: Overview of the datasets required for product generation.

3. Surface Elevation Change – Altimetry

The following sub-sections provide an assessment of the data required to produce surface elevation change measurements from altimetry over ice caps and large glaciers globally. An outline of the suitable satellite data is provided along with the spatial and temporal coverage, and availability. The coverage and accessibility of any auxiliary and validation data required is also assessed.

3.1 Product Generation Datasets

Satellite altimetry will be used to measure surface elevation change (SEC). The most suitable method for deriving SEC from satellite altimeters over large ice caps is the repeat track method, which calculates SEC along repeating satellite ground tracks (e.g. Smith et al., 2009; McMillan et al., 2014). The data requirement for this method is for products which contain, or for which may be derived, high rate elevation measurements and precise orbit locations corrected to the point of closest approach of the radar or laser signal. The elevation measurement needs to be waveform re-tracked and fully corrected for instrument, geophysical and atmospheric delays. The data products must also contain quality and validity flags in order to filter out erroneous data. In Phase 1, the above requirements were met for large ice caps by the Level-2 EnviSat, and ICESat products, in Phase 2, CryoSat-2 data, which has since become available, will be used. To derive SEC from altimetry over smaller ice caps and mountain glaciers, the most suitable method is differencing altimetry elevation measurements from DEMs. The altimetry data requirement for this method is for an altimeter with a ground footprint small enough to obtain well located and accurate elevation measurements in steep and complex mountainous terrain. This requirement is met with ICESat data.

The spatial coverage of the CryoSat-2 and ICESat tracks is global up to the latitudinal limits of the sensors (81.5°, 86° and 88° respectively). For CryoSat-2, which operates in three different modes (LRM, SAR and SARIn) depending on the nature of the surface being measured, we will use only SARIn mode (point) data, as the more precise nature and distribution of this data is best suited for SEC measurements over ice caps. The global distribution of CryoSat-2 SARIn mode data is shown in Fig 3.1. The density of the elevation measurements is governed by the spacing of the satellite ground tracks which varies by sensor and latitude. For ICESat the across track spacing is 80 km at the equator and 25 km at 70°, whereas for CryoSat the across track spacing is 7.5 km at the equator and 2.5 km at 70°. The coverage of the SEC estimates will be further affected by data quality and the performance of the sensors relative to the surface conditions in a given region.

The temporal coverage of *dh/dt* measurements is dictated by the operational and repeat periods of the sensors. Combined ICESat and CryoSat-2 missions provide cover from 2003 to present, as shown in Fig. 3.2. The repeat periods differ by sensor: ICESat operated on a campaign basis with several campaigns a year, lasting between 12 and 55 days and totaling 18 over the lifespan of the sensor; CryoSat-2 operates on a 30 day near repeat sub-cycle and a 369 day repeat full cycle. All of the required data is currently available to SEEL, at no cost, from ESA, NSIDC and the UCL archive by network transfer.

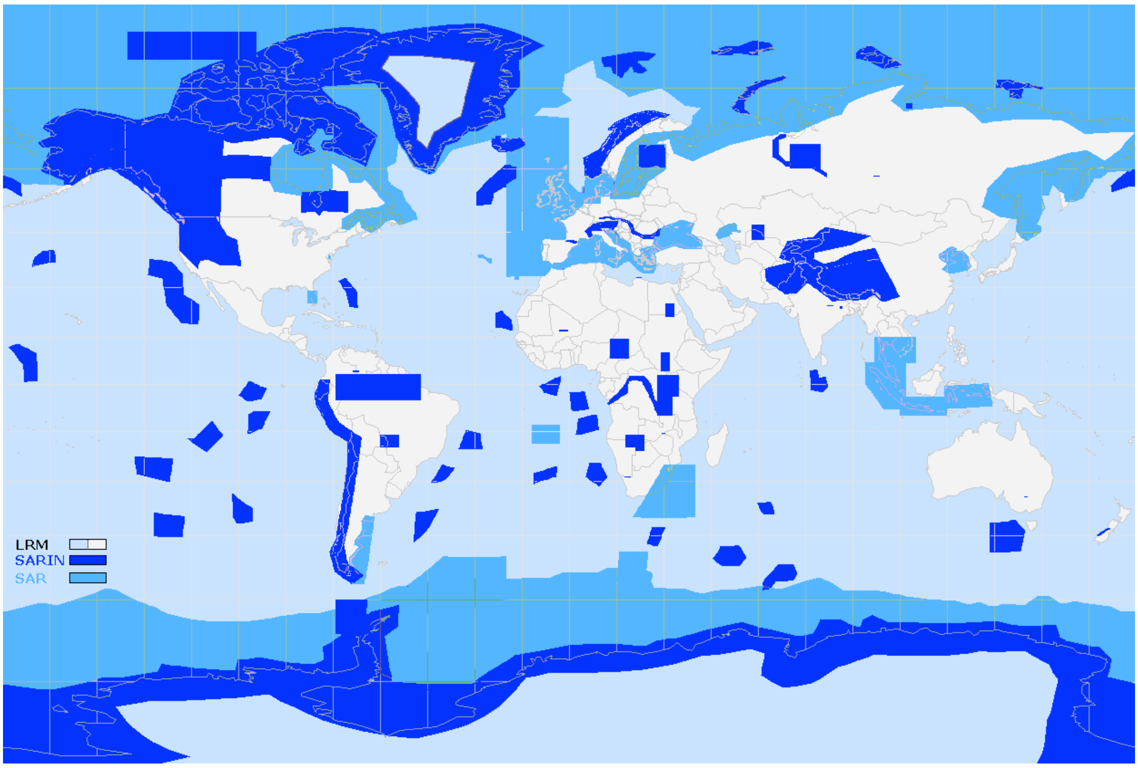

Figure 3.1: CryoSat-2 mode mask.

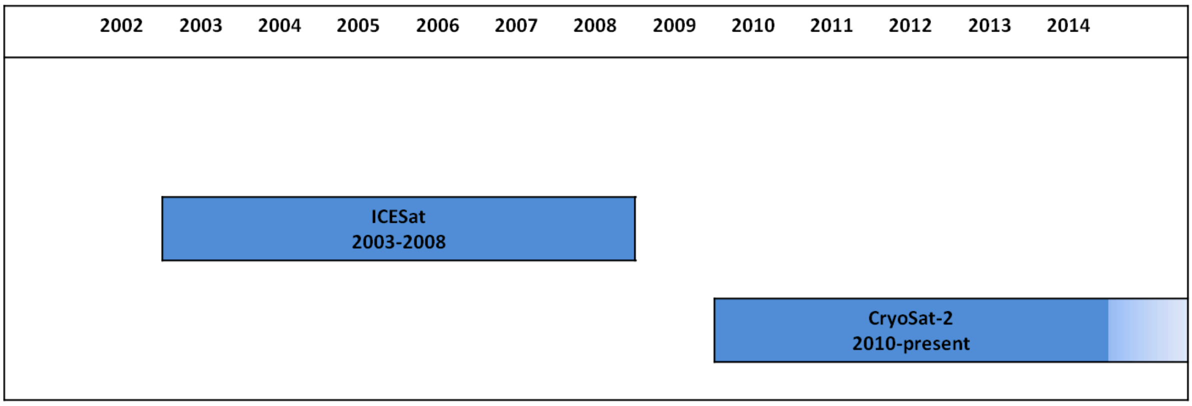

Figure 3.2: Temporal coverage of the satellite altimeters to be used during Phase 2 of Glaciers_cci.

3.2 Auxiliary Datasets

Generating SEC estimates over glaciers and ice caps (GIC) requires several datasets that are auxiliary to the altimetry data. These include:

- DEMs will also be required for differencing with ICESat elevations over glaciers in steep topography to obtain elevation differences between the DEM date and ICESat date (Kääb et al., 2012). For this purpose, DEMs should be from data acquired at a single time or over short time intervals to ensure temporal consistency. Several DEMs of this kind are available freely or to the consortium including SRTM (see above), national DEMs (e.g., Switzerland, Norway, USA), and SPOT SPIRIT DEMs. DEMs that are merged from datasets of different acquisition times are less suitable. For example, the ASTER GDEM is not suitable due to the unknown time stamps of individual grid cells.

- Glacier outlines are required for the accurate delineation of glacier extent. The highest quality outlines available will be used, with priority given to those produced within this project.

3.3 Product Validation

Surface elevation change measurements will be validated with those derived from airborne laser altimetry for select regions where repeat measurements are available during periods contemporaneous to the satellite data. Surface elevation data from airborne laser altimetry data are available from both ESA and NASA as part of the CryoVEX, and Pre-IceBridge and IceBridge campaigns respectively. CryoVex data are available for 2003, 2008, 2009, 2010 2011 and 2012, and the NASA pre- and IceBridge data are available from 1993 onwards. All campaigns are flown over targeted regions, which include Greenland, Svalbard, Arctic Canada, Alaska, Patagonia and Antarctica. All data are freely available by network transfer from ESA or NASA.

3.4 Summary

A summary of the attributes of the data required to generate and validate SEC estimates from satellite altimetry is given in Table 3.1 below.

Data Class	Data Type	Source	Spatial Coverage	Temporal Coverage	Repeat Periodicity	Availability
Product Generation	ICESat	NSIDC/NASA	Global	2003-2008	18 campaigns	Freely available from NSIDC
Product Generation	CryoSat-2	ESA	Global	2010-present	30 day sub-cycle & 369 day full repeat	Freely available from ESA
Auxiliary Data	ASTER GDEM	METI/NASA	Global	2000-2011 (snapshot-not repeats)	-	Freely available from NASA/USGS
Auxiliary Data	SRTM	NASA/USGS	Global	2000	-	Freely available from NASA/USGS
Validation Data	Pre- and Icebridge ATM	NSIDC/NASA	Campaign Arctic and Antarctic	1993 onwards	-	Freely available from NSIDC
Validation Data	CryoVex ALS	ESA	Campaign-Arctic and Antarctic	2003-2012	-	Freely available from ESA

Table 3.1: Attributes of the data required to generate and validate SEC estimates from satellite altimetry.

4. Elevation Change – DEM differencing

The following sub-sections provide an assessment of the data required to produce surface elevation change measurements from DEM differencing over glaciers and ice caps globally. An outline of the suitable satellite data is provided along with the spatial and temporal coverage, and availability. The coverage and accessibility of any auxiliary and validation data required is also assessed.

4.1 Product Generation

The DEM difference product will mainly rely on ASTER DEMs, SRTM, SPOT5 HRS SPIRIT, and where available on national DEMs combined with ICESat GLAS elevations for georeference. New datasets that should soon be available to the consortium in the future include the 'World DEM' from the TanDEM-X mission.

ASTER DEMs
ASTER DEMs (not to be confused with the ASTER GDEM global product) have a spatial resolution of 30 m over 60 by 60 km and a vertical accuracy of roughly 15 m for suitable surface conditions (e.g. Hirano et al., 2003; Kääb, 2002). We will mainly use the AST14DMO on demand product that is automatically generated and comes with orthoprojected satellite image bands and are available globally, from 2000 onwards, though with individually varying cloud cover and suitability for DEM matching due to acquisition conditions (snow, sensor saturation). These data are freely available to registered GLIMS participants and provided from the USGS NASA LP DAAC through NASA Reverb as AST14DMO on demand product (https://lpdaac.usgs.gov/lpdaac/products/aster_products_table).

SPOT5 HRS SPIRIT
For selected polar regions DEMs from SPOT5 high resolution stereo are available as compiled during the IPY-SPIRIT programme. SPOT5 HRS consists of a forward looking and a backward looking channel. The resulting stereo DEMs were produced by the French mapping agency and have a reported uncertainty of 10–25 m vertically and greater than 15 m in the horizontal plane (Korona et al., 2009). The SPOT5 HRS SPIRIT DEM is available from: http://polardali.spotimage.fr:8092/IPY/dalisearch.aspx (browse the list on the top right for an overview of products). Useful products exist mainly in the Arctic: Svalbard, the Russian and Canadian Arctic, Alaska and Greenland.

SRTM DEM
The Shuttle Radar Topography Mission (SRTM), launched in February 2000, mapped the Earth from 60° N to 56° S using single-pass synthetic aperture radar (SAR) interferometry. We will use the SRTM3 V2 dataset without void filling available from the USGS (http://dds.cr.usgs.gov/srtm). Typically reported vertical uncertainties of the dataset are ±10 m, which (e.g. Rodriguez et al., 2006) is lower than the mission objectives of ±16 m (Farr et al., 2007). However, vertical biases are present due to instability of the sensor and/or platform, and elevation-dependent biases have also been shown due to penetration of the C-band radar waves (centre frequency at 5.3 GHz) into snow and ice of 1 to 10 m depending upon the snow conditions (i.e. dry versus wet) in Greenland and Alaska (Rignot et al., 2001).

National DEMs

National DEMs have been generated in many countries from photogrammetric techniques applied to aerial photography, in most cases, as a base for topographic maps. These DEMs often come with national restrictions for redistribution and can be rather expensive for small regions covered (also depending on the acquisition technique and accuracy or spatial resolution of the DEM). For this reason such data sets will only be applied in Glaciers_cci when they are freely available and of sufficient quality. In some glacierized regions such as Canada and Alaska national DEMs are freely available but are rather old or of limited quality. In other regions the consortium has access to more recent and high quality data and can use it for product generation (e.g. Norway, Switzerland, Austria, parts of Italy) or validation.

TanDEM-X

The TanDEM-X mission operated by DLR and Astrium intends to release a 90 m global DEM that is generated using SAR interferometry. Higher resolution DEMs are available for selective regions, including Arctic GIC. The 90 m product is now available for selected regions in the Arctic, but higher-resolution products over selective regions are awaiting license approval for the Glaciers_cci consortium. After approval of our proposal by DLR it was declined by Airbus (ADS) and is now re-opened by DLR. The quality of the product is not yet certain, but is expected to contain vertical and horizontal accuracies better than 10 m. It is uncertain how the acquisition date will be maintained within the WorldDEM.

The temporal coverage of the different datasets to be used for product generation from DEM differencing are outlined in Figure 4.1 below.

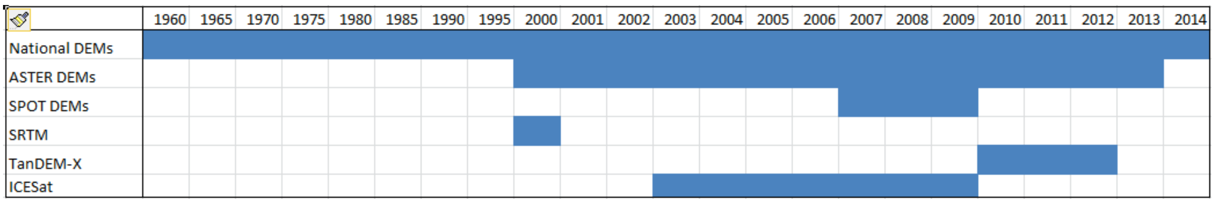

Figure 4.1: Timeline of available DEM products.

4.2 Auxiliary Datasets

To generate elevation change estimates over GIC requires several datasets that are auxiliary to the DEMs. These include:

- Glacier outlines are required for the accurate delineation of GIC area and extraction of non-stable terrain for pre-processing procedures; the best ones available, typically those produced within this project, will be used.
- Water bodies and ocean / land masks are also required for extraction of stable terrain for pre-processing. These shapefiles are freely available from a number of websites and data archives, for example the SRTM water bodies mask. Whereas the latter has been locally used for identification of stable terrain, the land/ocean mask used by other CCI projects (provided by Landcover_cci) is too coarse for our purposes.

4.3 Product Validation

External product validation will be through testing individual DEMs contributing to the elevation change product against each other. Therefore, elevations on glaciers require data from similar times, while this is not important for elevations outside glaciers. DEMs used in the elevation change product will be cross-validated using laser altimetry and other DEMs on stable terrain:

- ICESat GLAS will be used for georeferencing. For coverage and availability, see Section 3 above.
- In addition, high-resolution and high-accuracy DEMs are available for validation sites, partly with temporal overlap (validation of glacier and non-glacier elevations), partly without (validation of stable terrain). These include DEMs from airborne laser scanning and DEMs from aerial photogrammetry for a number of regions in the world, including among others Alaska, Svalbard and Switzerland.

4.4 Summary

A summary of the attributes of the data required to generate and validate elevation change estimates from DEM differencing are given in Table 4.1 below.

Data Class	Data Type	Source	Spatial Coverage	Temporal Coverage	Repeat Periodicity	Availability
Product Generation / Validation	ASTER AST14DMO	METI / NASA	Global (83S-83N)	2000-2013	-	Freely available from NASA/USGS
Product Generation / Validation	SPOT5 HRS SPIRIT	NSIDC / NASA	Selected polar glaciers	2007-2009	Single dates	Freely available from NSIDC
Product Generation / Validation	SRTM DEM	NASA / USGS	Global (56S-60N)	2000	-	Freely available from NASA/USGS
Product Generation / Validation	National DEMs		Canada, Italy, Alaska, Nor-way, Austria, Switzerland,	1960s - present	Single dates	Some freely available, others available to consortium
Product Generation	TanDEM-X	DLR	Global	2010-2012		Awaiting licensing
Auxiliary Data	Glacier outlines	RGI and Glaciers_cci	Global			Freely available
Auxiliary Data / Validation Data	ICESat	NSIDC / NASA	Global	2003-2008	18 campaigns	Freely available from NSIDC
Validation Data	Pre- and Icebridge ATM	NSIDC / NASA	Campaign Arctic and Antarctic	1993 onwards	-	Freely available from NSIDC
Validation Data	CryoVex ALS	ESA	Campaign-Arctic and Antarctic	2003-2012	-	Freely available from ESA

Table 4.1: Attributes of the data required to generate and validate elevation change estimates from DEM differencing

5. Velocity

The following sub-sections provide an assessment of the data required to estimate glacier velocity from satellite SAR and optical data over glaciers and ice caps. An outline of the suitable satellite data is provided along with the spatial and temporal coverage, and availability. The coverage and accessibility of any auxiliary and validation data required is also assessed.

5.1 Product Generation

Repeat satellite SAR and optical data will be used to measure ice surface velocity over Ice Caps and large glaciers. The most suitable method for deriving surface velocity is offset-tracking, which calculates velocity by matching repeat images (e.g. Paul et al., 2015). The data requirement for this method is that the displacements have to be statistically significant and that corresponding intensity or phase features are maintained in the data sets, which determine the suitable temporal baselines. In special cases, SAR interferometric techniques (Bamler and Hartl, 1998) can be also considered, but are less suitable for operational and global-scale applications because current SAR missions have repeat-cycles of several days. Main differences between tracking from SAR and optical data are that (i) displacements in optical data are typically obtained in ground-projected geometry while in SAR geometry they are obtained in slant-range geometry, (ii) different coherence properties between optical and SAR data, such as different type of features tracked and different optimal time differences, and (iii) limitations of optical data during night and due to clouds. The data products must also contain quality and validity flags in order to filter out erroneous data. In addition to the Phase 1 sensors, in Phase 2 Sentinel-1, Sentinel-2, Landsat 8 and ALOS-2/PALSAR-2 data, which have since become available, will also be used.

For SAR tracking, satellite images need to be of high to very-high resolution, i.e. 20 m for larger glaciers and ice caps down to 3 m for smaller glaciers. The preferred repeat times depend on the satellite track and are typically between 11 and 46 days. The most suitable datasets available for global-scale analysis before 2014 were Radarsat 1 and 2, ALOS PALSAR and ENVISAT ASAR, while for local scale studies ERS-1/2 InSAR, JERS-1, TerraSAR-X and Cosmo-SkyMed are suitable choices. Since the end of 2014 two new SAR sensors with global coverage are available, Sentinel-1 and ALOS-2 PALSAR-2. The capabilities for Sentinel-1 IW mode data for mapping ice flow fields is described in Nagler et al. (2015). The Interferometric Wide Swath Mode (IWS) is the main acquisition mode of Sentinel-1 over land. The spatial resolution is 3 x 22 m in range and azimuth direction and suitable for large glaciers and ice caps. PALSAR-2 data have a high potential to provide important results using offset tracking, as demonstrated in a limited number of cases, but unfortunately the PALSAR-2 Basic Observation Scenario (http://www.eorc.jaxa.jp/ALOS-2/en/obs/pal2_obs_guide.htm) does not include repeated acquisitions with short time intervals over glacierized areas. Data from ESA sensors (ERS-1/2, ENVISAT and Sentinel-1) are freely available through ESA archives. Those from the Canadian (Radarsat), German (TerraSAR-X), Italian (Cosmo-SkyMed) and Japanese (ALOS PALSAR) space agencies are in general commercially available, although announcement of opportunities offer limited free data to the scientific community. In the project team it was decided not to purchase commercial SAR data, but use only free data sets. ENVEO has limited access to TerraSAR-X data, while GAMMA has limited access to ALOS-2 PALSAR-2 data. The situation regarding JERS-1 and ALOS-1 PALSAR data is in evolution. JERS-1 and ALOS-1 PALSAR data are now unrestricted at the Alaska Satellite Facility, where a large amount of data covering the American continent are available. Both ENVEO and GAMMA have access to a good number of ALOS-1 PALSAR data available in the ALDEN archive at ESRIN. A limited quota of ALOS-1 PALSAR data archived at JAXA can be obtained by GAMMA via a specific proposal to JAXA. Finally, the whole 1992-1998 archive of JERS-1 data at JAXA is now open to the public free of charge, while that at ESA still needs to be opened.

For optical tracking, satellite images need to be of medium to high resolution, i.e. better or equal to 30 m for larger glaciers, better or equal to 15 m for medium-size glaciers, and even better for smaller glaciers. The preferred repeat times depend very much on the glacier type and its dynamics. Over glaciers in dry and cold regions, or over glaciers with substantial debris cover, annual displacements can be tracked, however maritime-type glaciers with large mass turnover flow faster and exhibit rapid surface changes requiring repeat times of a few months maximum. The most suitable datasets are from the Landsat series (in particular the ETM+ panchromatic band with 15 m resolution) and the Terra ASTER sensor. The new Landsat 8 OLI improves offset tracking significantly through its improved geometric and radiometric properties (see Section 2). Landsat TM/ETM+/OLI series data are freely available globally from the mid 1980's on with a nominal repeat period of 16 days, though with considerable data voids over a number of regions for the older satellites (see Fig. 2.2). Data are available from USGS and ESA (for European cover of Landsat 5 and 7). ASTER data are globally available since 2000, also with 16 days nominal repeat cycle, but without a systematic acquisition plan as Landsat. Some Glaciers_cci partners are members of GLIMS and have free access to all ASTER data. ASTER data will be used in instances where Landsat data is unavailable. Sentinel-2 MSI data, with 10 m resolution in visible and near-infrared bands, are freely available from 2015 onward, with a nominal repeat time of 10 days (5 days when Sentinel-2B is in orbit).

5.2 Auxiliary Datasets

Satellite SAR data will require DEMs for the purposes of geocoding to a map geometry. Several DEMs are freely available for download, these include the ASTER GDEM, which has global coverage, SRTM data which covers from 56° S to 60° N, SPOT SPIRIT, available over selected Polar regions, and national DEMs (see Table 4.1). Global Digital Elevation Data are available at www.viewfinderpanoramas.org, developed and uploaded in Scotland by Jonathan de Ferranti. The optical satellite data will not require auxiliary DEMs, as already orthorectified data will be used (Landsat L1T, ASTER DMO). Glacier outlines (see Section 2) will be used to classify displacements as on-glacier and off-glacier. Additionally, TANDEM-X Interim DEMs can be obtained for a certain number of areas through a proposal at DLR lead by GIUO.

Glacier outlines are required for the quality assessment of the generated products. The highest quality outlines available will be used, with priority given to those produced within this project.

5.3 Product Validation

Strict independent product validation for glacier velocities derived from space data is a difficult task because it would require reference measurements performed at exactly the same time. Due to short-term and seasonal velocity variations of glaciers, even small differences in the observation time window may introduce significant velocity differences. In addition, point measurements such as ground measurements represent a different surface area (points) than the satellite measurements (averaging over pixel windows). Similar to external validation approaches by reference measurements, a number of internal validation measures are defined, but also not all of these are conclusive, and provide only indications. In order to evaluate the quality of the ice velocity products a set of tests is defined in the Product Validation and Intercomparison Report (PVIR). It includes internal and external validation. Displacements from SAR and optical data are validated in the following ways:

External validation

- Comparing satellite-derived velocity products against ground-based velocity measurements, in particular in-situ GNSS on Svalbard. Coverage: specific sites detailed below; availability: details below, consortium has dates.
- Comparing results from medium resolution satellites (e.g. ERS, ENVISAT, Radarsat 1, Landsat, ASTER) against those from high-resolution ones (e.g. Radarsat-2, TerraSAR-X, high-resolution optical). Thereby, also results from optical data can be compared to ones from SAR data and vice-versa. Coverage: in principle global upon archive holding; availability: see Section 5.1.
- Comparing different medium resolution data against each other (Landsat 5/7/8 vs. ASTER or ALOS-2 PALSAR-2 vs Sentinel-1). Coverage: global; availability: see Section 5.1).

Internal validation

- Matching of synthetic images (real images with analytic deformation and noise added). For algorithm testing; no restrictions on coverage and availability.
- Reconstruction of the first image from the second image using measured displacements between first and second image, and comparison to the real first image. Will be applied for algorithm testing; no restrictions on coverage and availability.
- Matching quality indicators such as signal-to-noise ratio (SNR) or cross-correlation coefficient. No restrictions on coverage and availability.
  - Analysis of stable ground where no velocity is expected. This gives a good overall indication for the bias introduced by the end-to-end velocity retrieval including co-registration of images. Ice masking will be done using the highest quality outlines available.
  - Coverage of valid ice velocity measurements for the glacier area. This is given as fraction of the overall glacier area. Again, ice masking will be done using the highest quality outlines available.

Details on the product quality assessment tests are found in the PVIR of Phase 2 / Year 2 (Glaciers_cci, 2015).

Test site *Svalbard*: Four locations on Svalbard are selected as validation test sites: Vestfonna, Kronebreen, Austfonna and Edgeøya. GPS data from the Vestfonna, Kronebreen and

Austfonna sites are available to partner GUIO. Three very-high resolution Radarsat-2 images 24 days apart were acquired over both Austfonna and Edgeøya during the winter 2016 within the EU FP7 SEN3APP (sen3app.fmi.fi) project.

Vestfonna was a major target of multi-disciplinary field campaigns launched within the KINNVIKA project during IPY. The geodetic measurements were done both as static surveying of stakes and as continuously recording GPS stations (Fig. 5.1).

Annual velocity measurements (from stakes) are available on Kronebreen since 2003, mainly above the lower crevassed zone. Since 2007, code based GPS receivers have been placed in the lower crevassed zone. From 2011, continuous dual frequency GPS receivers have been monitoring velocities close to the ELA of the glacier.

On Austfonna, code based receivers have been monitoring velocity since 2008 over 2 basins, Duvebreen and Basin 3. Since 2011, continuous dual frequency GPS has also been operated on these basins.

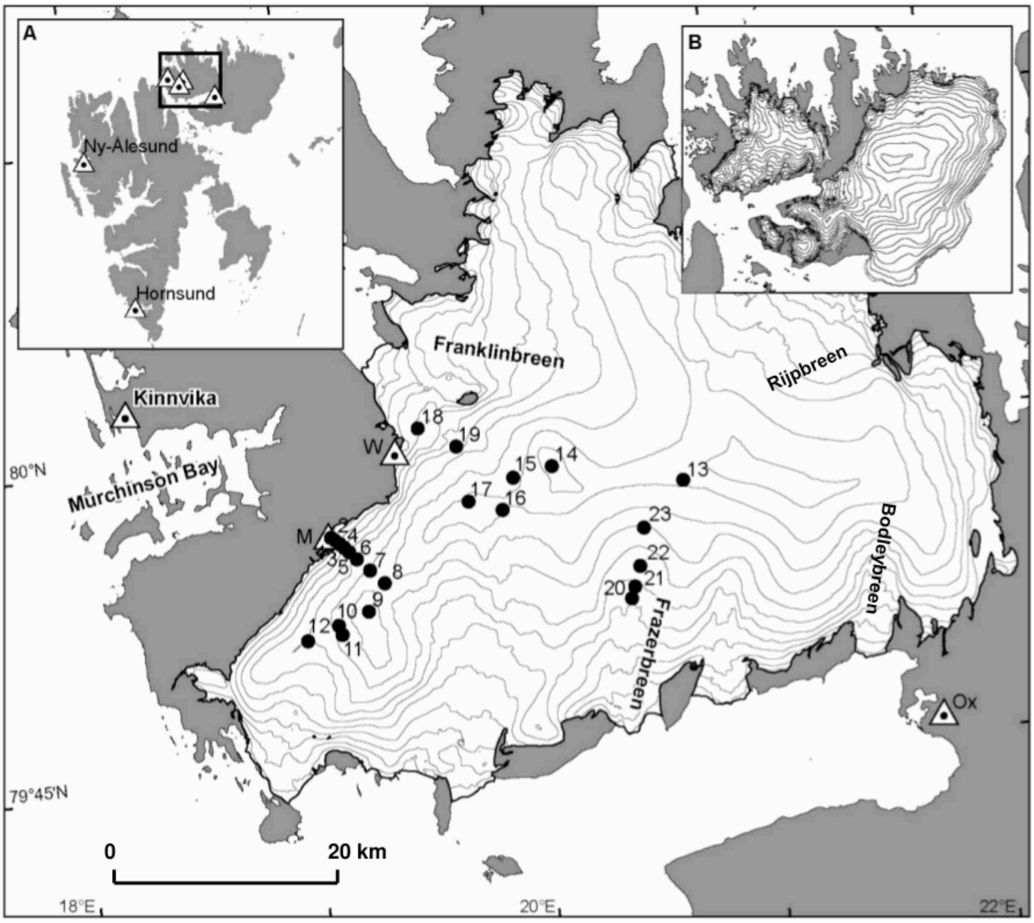

Fig. 5.1: Svalbard, Nordausdlandet and the ice caps Vestfonna and Austfonna. Elevation- and coast line contours are from the Norwegian Polar Institute DEM. The elevation contour spacing is 50 m. The black dots mark the position markers used for DGPS surveys within the KINNVIKA project over Vestfonna. The triangular symbols are the fixed points / base stations, the letter at each fixed point / base station refers to the first letter of its name. Taken from Pohjola et al. (2011).

5.4 Summary

A summary of the attributes of the data required to generate and validate velocity estimates from satellite SAR and optical sensors are given in Table 5.1 below.

Data Class	Data Type	Source	Spatial Coverage	Temporal Coverage	Repeat Periodicity	Availability
Product generation	Landsat	USGS / ESA	Global	1984 – today	16 days (but not complete)	Freely available
Product generation	ASTER	METI / NASA	Global (83S-83N)	2000-2013	16 days	Freely available to GLIMS members
Product gene-ration / validation	ERS-1	ESA	Global	1991-1994	3 days	Freely available
Product gene-ration / validation	ERS-1/2	ESA	Global	1995-2000	1 day	Freely available
Product gene-ration / validation	ERS-2	ESA	Global	2011	3 days	Freely available
Product gene-ration / validation	JERS-1	JAXA	Global	1992-1998	44 days	JAXA & ASF archives freely available, ESA archive not available
Product gene-ration / validation	ENVISAT	ESA	Global	2002-2010	35 days	Freely available
Product gene-ration / validation	Radarsat-1	CSA	Global (upon request)	1995-	24 days	Commercial
Product gene-ration / validation	Radarsat-2	CSA	Global (upon request)	2006-	24 days	Commercial
Product gene-ration	ALOS -1 PALSAR	JAXA	Global	2006-2010	46 days	ASF archive freely available*
Product gene-ration / validation	ALOS-2 PALSAR	JAXA	Global	2014 -	14 days	Commercial or AO projects of partners
Product gene-ration / validation	TerraSAR-X	DLR	Global (upon request)	2006-	11 days	Commercial or AO projects of partners
Product gene-ration / validation	Cosmo-SkyMed	ASA	Global (upon request)	2006-	1-2-3-8-16 days	Commercial
Product gene-ration	Sentinel-1	ESA	Global	2014-	12 days	Freely available
Validation	High-res satellite data	DigitalGlob e etc.	scattered	scattered	various	commercial
Validation	Automatic GNSS	GUIO	Sites on Svalbard	various	daily	Selected time periods to consortium
Auxiliary Data	Glacier outlines	Glaciers_c ci	Global	-	-	Freely available
Auxiliary Data	ASTER GDEM	METI / NASA	Global	2000-2011 (snapshot-not repeats)	-	Freely available from NASA/USGS (Section 4)
Auxiliary Data	SRTM	NASA / USGS	Global	2000	-	Freely available from NASA/USGS (Section 4)
Auxiliary Data	SPOT SPIRIT	CNES/AS TRIUM/IG N	Selected polar regions	2007-2009	Single dates	Available from CNES/ASTRIUM/IGN (see Section 4)
Auxiliary Data	National DEMs	Various national data bases	Selected nations (e.g. Switzerland, Norway, USA)	One-time (1960s – today)	One-time	Various sites (see Section 4)

Data Class	Data Type	Source	Spatial Coverage	Temporal Coverage	Repeat Periodicity	Availability
Auxiliary Data	Viewfinderp anoramas	SRTM, Russian topogr. maps, national databases	Global	1960s – today	-	Freely available from www.viewfinderpanoramas.org (see Section 4)
Auxiliary Data	TanDEM-X	DLR	Global	2010-2012	-	Limited access via AO projects
Auxiliary Data	TanDEM-X	Astrium	Global	2010-2015	-	Commercial
Auxiliary Data	GIMP DEM	Various	Greenland	2007	-	Freely available from BPCRC
Auxiliary Data	RAMP DEM v2	NSIDC/OSU	Antarctica	80s-90s	-	Freely available from NSIDC
Auxiliary Data	Rock outcrops	SCAR-ADD	Antarctica	2013-2015	-	Freely available from ADD

*Table 5.1: Attributes of the data required to generate and validate velocity estimates from satellite SAR and optical sensors. *The ESRIN ALDEN archive is available through AO projects and the JAXA archive commercial or through AO projects.*

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Abbreviations

ALOS	Advanced Land Observing Satellite
ALS	Airborne Laser Scanner
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATM	Airborne Topographic Mapper
CDED	Canadian Digital Elevation Data
CGIAR	Consultative Group on International Agricultural Research
CryoVEX	CryoSat Validation Experiment
DARD	Data Access Requirements Document
DEM	Digital Elevation Model
ECMWF	European Centre for Medium Range Weather Forecasts
ERA	European ReAnalysis
ETM	Enhanced Thematic Mapper
GDEM	Global Digital Elevation Model
GUIO	Geosciences Universitetet i Oslo
GIC	Glaciers and Ice Caps
GIMP	Greenland Ice Mapping Project
GLAS	Geoscience Laser Altimeter System
GLIMS	Global Land Ice Measurements from Space
GPS	Global Positioning System
ICESat	Ice, Cloud and Elevation Satellite
IPY	International Polar Year
LDCM	Landsat Data Continuity Mission
LP DAAC	Land Processes Distributed Active Archive Center
LRM	Low Resolution Mode
METI	Ministry of Economy, Trade and Industry
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NED	National Elevation Dataset
NSIDC	National Snow and Ice Data Center
OLI	Operation Land Imager
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PSD	Product Specification Document
SAR	Synthetic Aperture Radar
SARIn	Synthetic Aperture Radar Interferometric
SEC	Surface Elevation Change
SPOT HR5	Satellite Pour l'Observation de la Terre 5 High Resolution
SPIRIT	Stereoscopic survey of Polar Ice: Reference Images and Topography.
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
UCL	University College London
URD	User Requirements Document
USGS	United States Geological Survey
VNIR	Visible Near Infrared

Appendix (Internet links)

Data access

Data	URL for Download
Landsat	http://glovis.usgs.govor http://earthexplorer.usgs.gov
Sentinel 2	https://scihub.copernicus.eu, https://remotepixel.ca/projects/satellitesearch.html
ASTER (satellite data)	http://reverb.echo.nasa.gov
SPOT	http://catalog.spotimage.com or http://eoli.esa.int
HR Sat. (screen-shot)	http://maps.google.com
HR Sat. (procurement)	http://www.npoc.ch (IRS, Quickbird, Ikonos/Geoeye/Worldview, etc.)
Aerial photogr. (Norway)	http://norgeibilder.no
Aerial photogr. (Switzerland)	http://map.lubis.admin.ch/
ERS-1/2 & ENVISAT	http://catalogues.eoportal.org/eoli.html
Radarsat	http://www.mdacorporation.com
TerraSAR-X	http://www.infoterra.de/direct-access-services (ordering)
ALOS PALSAR	https://ims1d.palsar.ersdac.or.jp/palsar_ims1_public/ims1/pub/en
ALOS PALSAR 2	http://en.alos-pasco.com
Sentinel 1	https://scihub.copernicus.eu
COSMO-Skymed	http://www.e-geos.it
SRTM (USGS)	http://dds.cr.usgs.gov/srtm/version2_1/SRTM3
SRTM (CGIAR)	http://srtm.csi.cgiar.org/selection/inputCoord.asp
GDEM (ASTER)	http://www.gdem.aster.ersdac.or.jp/
NED (USGS)	http://seamless.usgs.gov/ned1.php
CDED (Canada)	http://www.geobase.ca/geobase/en/data/cded/
viewfinder	http://www.viewfinderpanoramas.org/dem3.html
SPIRIT (SPOT)	http://polardali.spotimage.fr:8092/IPY/dalisearch.aspx
ASTER (AST14DMO)	https://lpdaac.usgs.gov/lpdaac/products/aster_products_table
GLS DEM (USGS)	ftp://ftp.glcf.umd.edu/glcf/GLSDEM/

Data descriptions

Satellite	URL for detailed descriptions
Satellites (general)	http:// database.eohandbook.com/database/missionindex.aspx
Landsat	http://landsathandbook.gsfc.nasa.gov/
ASTER	http://asterweb.jpl.nasa.gov/content/03_data/04_documents/aster_user_guide_v2.pdf
SPOT	http://www.spotimage.com/web/en/229-the-spot-satellites.php
ERS 1 / 2	http://earth.esa.int/object/index.cfm?fobjectid=1016
Envisat ASAR	http://envisat.esa.int/pub/ESA_DOC/ENVISAT/ASAR/asar.ProductHandbook.2_2.pdf
Radarsat 1	http://gs.mdacorporation.com/includes/documents/R1_PROD_SPEC.pdf
Radarsat 2	http://gs.mdacorporation.com/includes/documents/RN-SP-52-1238 RS-2 Product Description 1-8_15APR2011.pdf
TerraSAR-X	http://www.infoterra.de/asset/cms/file/tx-gs-dd-3302_basic-product-specification-document_v1.7.pdf
ALOS PALSAR	http://earth.esa.int/object/index.cfm?fobjectid=5195
COSMO-SkyMed	http://www.e-geos.it/products/pdf/csk-product%20handbook.pdf
ICESat (GLAS)	http://nsidc.org/data/icesat
SRTM DEM	http://srtm.usgs.gov
CGIAR DEM	http://www.cgiar-csi.org/
GDEM	http://www.ersdac.or.jp/GDEM/E/2.html