Examples of different techniques for glaciers motion monitoring using InSAR and RPAS

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ABSTRACT
Glaciers are an important part of Earth’s surface and play an important role in oceanology and climatology. Nowadays, in a changing climate it is necessary to monitor a glacier’s stay. For a large glacier area, satellite data is used, and for small areas or important parts of a glacier, other techniques can be used. It means, for example, photogrammetry, GNSS or the new RPAS (remotely piloted aircraft system) technology. RPAS measurements should be focused on the movement of a glaciers face. In this project, two different RPAS types (winged drone and multicopter) were tested in Greenland and in Iceland during the last two years. The second technology used for glacier movement detection was satellite images – in this case SAR and InSAR measurement. Satellite data were tested on an inland glacier area and the movement was based on the installation of four corner reflectors directly on a monitored area in western Greenland. TerraSAR-X data were used. First, four acquisitions were performed in 2015, directly after corner reflector installation, then two acquisitions in 2017. The project experience and results are discussed in this paper.

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Introduction
Since 2002, German sport and scientific expeditions to Greenland were carried out based on the enthusiasm of attendees; a part of them came from university staff and students (Beuth Hochschule für Technik, Berlin, BTU Cottbus-Senftenberg). Expeditions were financed partly by universities, partly by sponsors and the own finances of attendees. The main aim of the scientific part was always a geodetic survey of continental glacier height (Korth et al., 2008, Korth & Hofmann, 2013). Expeditions are a contribution to understanding the melting of glaciers. (Khan et al., 2015), (Zwally et al., 2002). The last expedition was performed in 2015 with a cooperation of the Czech Technical University in Prague (CTU). On this expedition, new methods for glacier movement monitoring were tested (Korth, Hitziger, Hofmann, Kuchenmaister, & Pavelka, 2017). The first method was InSAR technology; the second one was based on repeated overflights of winged RPAS near the glacier face (Pavelka, Šedina, Matoušková, Faltýnová, & Hlaváčová, 2016). For this, data from TerraSAR-X acquired in 2015 and 2017 were acquired and processed. Based on results from Greenland, a low-cost multi-copter and GNSS was used for glacier movement measurement in Iceland in 2017.

Measurement in Greenland

InSAR
For InSAR technology, four metal corner reflectors were manufactured in CTU and installed during the last expedition on an inland glacier border on the western part of Greenland near Disco Bay (Ilulissat region, Figure 1). All reflectors were made from separate and dismountable parts (metal sheets, bolts and steel anchor rods), and were constructed for easy transportation (Figure 2). Based on physics and theory, the side of the corner reflector was chosen with the minimum 60 cm (at least 10× wave length, for Terra SAR X it is 31 mm, frequency 9.6 GHz). The plan was to place two of them on the rocky ground (to make the reference) and the two remaining ones on the glacier, to monitor the glacier movement.

Geodetical coordinates of all four corner reflectors were measured using precise GNSS device Trimble with cm accuracy (Figure 2). Of course, nowadays there are other SAR systems like Sentinel 1A a 1B at disposal. However, the main aim of the project was to locate the corner reflectors, which would be invisible in the Sentinel-1 images due to their size and the geometric resolution of Sentinel-1 data. As the corner reflectors were carried by people (not by cars etc.), they could not have been larger. The processing of the Sentinel-1 images...
can be a subject of another project, without the attempts to locate the corner reflectors (a fully operational satellite pair for InSAR technology was completed by end of April, 2016). The main project aim was to test the possibilities of glacier movement monitoring from SAR satellite data (Dietrich, Metzig, Korth, & Perlt, 1999). Two methods were used: offset-tracking (estimation of the movement from intensity data, with subpixel accuracy, here about 0.5 m), and classical InSAR (estimation of the movement from phase data, with mm-to-cm accuracy), limited by reflective properties of the imaged surface (physical, material, technical).

In 2015, there were not many suitable radar satellites to choose from. Data from the TerraSAR-X satellite were ordered under the project via DLR (Gesellschaft für Anwendungen Raumfahrt, Germany). The satellite was programmed to acquire two ascending and two descending tracks on Sept. 10th (asc), Sept. 11th (desc), Sept. 21st, 2015 (asc) and Sept. 22nd (desc), just after the installation of the corner reflectors (Table 1, Figures 3 and 4). For satellite measurement, it was necessary to orient all metal corner reflectors in the direction of observation of the radar satellite (for radar device view in ascending track).

The reflectors were designed to be as small as possible due to their weight and transport, but they were still heavy; their side was 60 cm (for X-band and for high resolution mode). The orientation of reflectors on sites was 98.5 degrees west of north and the incidence angle was 45 degrees (for ascending track). Flat incidence angle acquisitions were chosen due to the expectation of horizontal movements. The compass cannot be used here (GNSS has been used for orientation) and the incidence angle was defined by a small protractor. Reflectors were stabilized in the glacier with three iron rods, which were drilled into the ice, on rocks stones that were used for stabilization.

After the expedition, SAR data was processed using GAMMA software. For InSAR processing, an external DEM is necessary to retrieve the movements; only GDEM from ASTER could be used in Greenland (today, the WorldDEM can be used, but at the time of processing, it was not available for Greenland); the quality of the DEM used is not very good, and in the glacier area the terrain changes seasonally (which is very important) and its accuracy is limited (Pavelka & Tollingerová, 2008).

InSAR computes the phase difference between two images of the same area and the movement can then be evaluated from the phase changes within the interferogram. In the case of datasets from Greenland, in the non-filtered interferograms, it is hardly possible to recognize fringes in the area of the glacier, which is, however, generally incoherent. Unfortunately, the hardly visible fringes got lost by spatial filtering, even if the filtering algorithm was designed especially for enhancing the fringes (Goldstein&Werner, 1998). Two sizes of filtering window were used, 32 × 32 pixels (GAMMA default) and 8 × 8 pixels, without the influence on fringe visibility. The fringes also got lost by georeferencing (Figure 5). The rock area is generally coherent (Goldstein, Engelhardt, Kamb, & Frolich, 1993). However, it was expected to be

Table 1. Four satellite acquisitions above the area of interest were performed in 2015; based on technical possibilities, eleven-day intervals were used (ascending track Sept. 10th and Sept. 21st, the descending track Sept. 11th and Sept. 22nd). In 2017, data set was completed with two overflights (Sept. 5th and Oct 8th).

| Overflight | Orbit   |
|------------|---------|
| 2015, Sept. 10 | orbit 103, asc |
| 2015, Sept. 11 | orbit 111, desc |
| 2015, Sept. 21 | orbit 103, asc |
| 2015, Sept. 22 | orbit 111, desc |
| 2017, Sept. 5 | orbit 103, asc |
| 2017, Oct. 8 | orbit 103, asc |

Figure 1. Position of expedition camp Nr.39, western Greenland near Disco Bay where the continental glacier ends (picture from Google Earth).
stable, although there were also fringes here, with more fringes in the ascending pair. If the fringe pattern was similar in both pairs, it could have been attributed to DEM error (perhaps, it can partially be attributed to it). And in addition, the fringes can be attributed to different atmospheric delay (both troposphere and ionosphere).

What could be the most important factor is the image coregistration, which was performed at the

Figure 2. (a), (b) installation of corner reflectors Nr.1 and Nr.3.

Figure 3. Whole scene (asc path), geocoded.

Figure 4. (a) asc, (b) desc path image crops (detail) with corner reflectors (geocoded).
beginning of the processing. During the coregistration, image shifts (with subpixel precision) are estimated within the whole image, and a polynomial is evaluated out of them. If (approximately) half of the image contains the rocks and the other half contains the glacier, the coregistration shifts are probable to be biased by the glacier movement, and due to the polynomial evaluation, it applies also for the rock area (however the density of "good" shifts was much lower in the glacier area). Unfortunately, we did not find any other way to perform the coregistration; extrapolation of the coefficients evaluated on the rocks to the glacier area did not give better results. What could be the most important factor is the image coregistration, which was performed at the beginning of the processing. During the coregistration, the shift between the two images is estimated for many points in the image (with subpixel precision), and a polynomial is evaluated out of them. For the rock area, the evaluated shifts are dense and of high quality, while for the glacier area, the number of sufficient-quality shifts is very low (also the quality is often near the threshold). In our case, (approximately) half of the image is covered by rock, while the other half is covered by ice. In such a case, the coregistration shifts are probable to be biased by the glacier movement, and due to the polynomial evaluation, it applies also to the rock area (however the number of points in the glacier area is much lower). "Classical" coregistration was performed, using all the points with high-enough quality (different thresholds were tested). Also, another method was tested, using only the shifts evaluated at the rock area, and extrapolating them to the glacier area. This method did not give better results, probably due to the extent of the glacier area, comparable to the extent of the rock area.

Conclusion: Suitability of InSAR for glacier monitoring is limited by more factors:

- the coregistration (it would be better if the glacier would be contained in only a small part of the image, in order to limit the glacier movements, and influence on the coregistration polynomial)
- the glacier movements are too fast for InSAR (e.g. the front of the nearby Egi Glacier was at a speed of up to 4 m/day, internal glacier cm to dm/day), causing total decorrelation (Strozzi, Luckman, Murray, Wegmuller, & Werner, 2002): “…over glacier coherence is not retained for more than a few days”. They often work with 1-day to 3-day intervals between data acquisitions). The movements of the corner reflectors were not evaluated using InSAR, because their movement (estimated by offset-tracking, see below) was so big that it exceeded the half of the SAR wavelength many times.

The estimation of the movement of the corner reflectors can be done finding the signal peak of the intensity, separately for each reflector and for each image (without image coregistration).

Movements of the corner reflectors situated on the glacier were detected using this method in the ascending pair (the reflectors are not visible in the descending pair as they were oriented away from it). The position of the corner reflectors in the images was found easily due to the
precise geodetic localization on-site by precise GNSS with cm-accuracy. The easy to transport and cheap corner reflectors constructed on the CTU in Prague in the Laboratory of photogrammetry were tested and found to be sufficient to give high-enough response in the SAR images, but the shift of two reflectors located on the glacier in 11 days was comparable to the pixel size, and therefore also to its accuracy.

The estimated shifts for each reflector using this method are disclosed in Table 2.

Corner reflectors Nr.3 and Nr.4 are assumed to be stable, so their difference of 0.12px in range and 0.07px in azimuth can be considered as an estimate of the accuracy of this method.

In the following section, we are going to reference the movement of corner reflectors Nr.1 and Nr.2 to the average of corner reflectors Nr.3 and Nr.4 (Figure 6). From the estimations (disclosed in Table 3), it seems that corner reflectors Nr.1 moved to the East, while corner reflectors Nr.2 to the west. It should be noted here that the accuracy of the estimated movements is similar to the movements themselves. In future, this problem can be solved by ordering images with longer temporal baseline, making the movement bigger, with a similar accuracy.

To estimate the movement of the whole glacier, the offset-tracking method was used. Here, the images are oversampled (for better accuracy) and small image crops are correlated (one image to the other one) in order to evaluate the shift between them with a sub-pixel accuracy. In the offset-tracking method, it is not necessary to perform the coregistration. If no coregistration is performed, it is still necessary to estimate the “movement” on the rock areas (the coregistration shift or polynomial) and to subtract it from the movements detected in the glacier area. The offset-tracking method was performed on both ascending and descending pairs and the estimated movements are displayed in Figure 7. In the rock areas, trends are visible (can be possibly attributed to height changes). In the glacier area, the concentration of reliable points is visibly lower and the measured shifts are generally higher (measured points with very high values of estimated movement were excluded due to probable noise). The correlation of the two image crops is significantly lower on ice, meaning that the reliability and accuracy of the estimated shift is significantly worse.

Unfortunately, the evaluation of the dominant glacier motion is not possible even with the offset-tracking method. No patterns can be recognized, meaning...
that each part of the glacier moves in a different direction. If a reliability threshold is raised, to get only more reliable points, the number of measured points reduces significantly, giving again no useful information.

The histogram shown here (Figure 8) displays the estimated motion on ice between Sept. 10th and Sept. 21st (2015, asc. track), separately (a) in the azimuth direction and (b) in the range direction.

Table 4. Differential shifts (ice vs. rock, in meters in the ground range), after filtering values higher than 13 m for azimuth and 18 m for range.

|        | 10–21 azimuth | 10–21 range | 11–22 azimuth | 11–22 range |
|--------|---------------|-------------|---------------|-------------|
| Mean   | 0.007         | −0.025      | 0.036         | 0.44        |
| Median | 0.000         | 0.000       | −0.074        | 0.50        |
| Std dev| 0.531         | 0.610       | 1.73          | 2.35        |

Figure 7. Movements estimated by offset-tracking methods (without coregistration), separately for both data pairs, in the azimuth and range direction in pixels. (a), (b) Sept. 10–21, asc, (c), (d) Sept. 11–22, desc.

Figure 8. Histogram of the measured movement (in pixels) on ice between Sept. 10th and Sept. 21st (2015, asc. track), separately (a) in the azimuth direction and (b) in the range direction.
The interpretation of the movement of the whole glacier is uncertain. Either the movement of the points is really different in directions or there is an error possibly caused by the inaccurate orientation of the reflector Nr.1. The values do not match the average values for the CRs themselves (see Table 3), but values for the whole glacier are noisy and there is no reason to believe that the entire glacier is moving the same way.

Detection of corner reflectors from SAR data in 2017

In 2017, two TerraSAR-X/TanDEM-X satellites images were ordered in the Greenland area (same as in 2015) on the same track (acquired on 5.9.2017 and 8.10.2017). Unfortunately, the data was (by mistake) ordered in SpotLight mode, while in 2015 it was in HighResSpotLight mode, with the resolution in the direction of flight being half (0.90 m in range vs. 1.27 m in azimuth). The images have been co-registered to each other, but due to the different resolution they cannot be co-registered to 2015 data.

Reflectors Nr.3 and Nr.4, not expected to move, were easily found in the images, reflector 3 with approximately the same intensity as in 2015, reflector Nr.4 with intensity 10x lower (may be cause by clogging of the reflector by dirt or snow). The expected intensity in the 2017 images is half of the intensity in the 2015 images due to the difference in resolution, plus possible attenuation due to abrasion.

On the other hand, the position of the two reflectors, placed on the glacier, is unknown. It is difficult to estimate the direction of the movement, and it is almost impossible to estimate the distance. In addition, the (peak) intensity of the reflectors is comparable to many other object on the glacier (partially due to the lower resolution), and the intensity of reflector Nr.1 was lower even in 2015 due to improper orientation.

In order to find the CRs in the 2017 images, the following criteria were used: the similarity between the two 2017 images and the direction of the movement between the two 2017 images, together with the direction of the movement between 2015 and 2017 images. Therefore, for the reflectors Nr.1 and Nr.2, there are several possible locations, but it is difficult to decide which one is the most probable.

Radar data – conclusions

Figure 9. Positions of the corner reflectors in 2017 within the whole imaged area. The original positions of corner reflectors (2015) are displayed as red crosses, possible positions in 2017 are as red crosses with reflector numbers (expected movement to the north-west).

After two years, the same data was acquired with the aim of finding all the reflectors. Small reflectors, on the glacier after two years can be destroyed or moved onto another place with a different azimuth, which make it impossible to find them in the data.

The intensity of the reflectors Nr.3 and Nr.4 has dropped over the past two years since the installation (a decrease in intensity can also be due to worse resolution or another imaging mode). Due to the (assumed) stable position, they are still easy to find in the image (Figure 6). The position of the reflectors Nr.1 and Nr.2 is uncertain (Figure 9). Points with the intensity similar to what was expected were found in the images, but there are more such points in the two images. There are some results presented some results from the project “Greenland 2015” based on four corner reflectors, Terra SAR – X data sets and data processing with the aim to detect reflectors and estimate the partial motion of the glacier part. Comparison with other SAR satellite data (Sentinel
Using of RPAS

Greenland

Satellite measurements have already been mentioned. However, SAR data may be used in some special cases only. Optical data are often used for the time analysis of changes, but in this project it was not used. It should be mentioned that for the detection of ice movement, they usually do not have the necessary geometric resolution, with the problem also being with time resolution. Although the repeat cycle is only a few days, scenes often have different geometry and angles, which limits the photogrammetric 3D evaluation. Unless we use satellite data, other technology for glacier movement detection and measurement is terrestrial or aerial photogrammetry. The glacier face often falls into the sea and it is not easy to get relevant terrestrial photos (of course it is possible partly from a boat); aerial photogrammetry is more suitable, but it is expensive. A good and inexpensive solution was found to be the use of RPAS (Pavelka, Rezniček, Faltýnová, & Matoušková, 2014).

There are other problems, not only the far distance, like the transportation of the fragile drone, batteries and their charging (solar cells and a wind generator were used for electrical instruments charging), strong wind and finding of an accurate place for landing etc. For flight planning, there are satellite images from Google Earth only (out of date), highly inaccurate DEM and the unattainability of the Internet.

In this project, the Ebee winged RPAS was used; it is small and light, but for piloting, a common notebook computer is necessary with flight software. Ebee is a fixed wing drone, prepared from styropore foam with a wingspan of 96 cm. It weighs less than 1 kg, but includes INS (IMU and GNSS with absolute accuracy of about 3-5 m in position; a relative precision is much better and reaches decimetres), a vertical view camera (different replaceable types of cameras), a piloting instruments, a radio modem, and a high-resolution optical sensor. Propulsion provides an electric engine (which uses one LiPol battery) with a push propeller. The flight endurance is up to 40 min (with a falling temperature but the flight time decreases, which is unpleasant in polar conditions). In areas without electricity it is necessary to recharge the batteries in the notebook computer as well as for the RPAS by a wind generator and a solar array (it takes quite a while) and the battery must be kept warm. In Greenland, the Canon NIR camera with 16MPix was used. NIR spectral range is better in hazy weather and NIR rays better pass through the atmosphere; a sparse vegetation can be classified from images based on NIR channel. For piloting the eMotion software is used; it prepares a flight plan, controls the flight and makes data pre-processing and transferring to photogrammetric software’s (Pix4D, Agisoft PhotoScan etc.).

Problems with piloting and navigation occurred, mainly because of the inaccurate detection of flight height (on the Ebee drone, there are two possibilities for measurement of flight height – GNSS device and optical sensor) above sea level and very approximate DEM. RPAS has often been exposed to the danger of destruction; on the iceberg Moraine, it was also difficult to find a place to start and land a drone. As a testing place, the famous Egi glacier opposite Disco island near to Ilulissat was selected (it was destination point of expedition to Greenland in 2015). The Egi glacier moves relatively quickly – it flows at a speed of up to 4 m/day, which is based on the immense pressure of the Inland Glacier. This is written on info-tables directly on Ilulissat airport, however other sources refer about a much bigger speed, up to 46 m per day (Joughin, Smith, Shean, & Floricioiu, 2014). The truth is that it depends on the season and the place of observation. The centre is moving much faster than the edges, and in 2017 it was 14 m per day (Gervaix, 2018). Undeniably, the speed increases in recent years. If we take a lowest cited speed 4 m per day, it can be calculated that the face of the Egi glacier moves 17 cm per hour, which is good for motion detection using aerial photogrammetry.

Based on the SenseFly Company materials (SenseFly, 2018), the Ebee RPAS takes images in theoretical resolution (pixel size) up to 1,5 cm using the drone’s supplied camera and based on flight height above ground of 42 m. Results are also dependent upon environmental conditions (light, wind, surface type). However, it is a very low flight altitude (not an ordinary flight) and images can be blurry.

Theoretically, the glacier face (Figure 10) movement could be detected within one hour (based on GSD and speed of glacier movement). Theoretically, the glacier face movement could be detected within one hour (based on GSD and speed of glacier movement). The measurement in this project is based on two over flights only (from the weather reason; there was no more time). From aerial images, an orthophoto can be produced such as DSM (digital surface models). The movement detection and measurement use changes in calculated DSM’s between at least two over flights. The movement detection presumes that some parts are stable (it means mainly the bedrock) and some parts of DSM were moved from their original position in time (Pavelka & Šedina, 2015).
In this case, there wasn’t more time for better or repeated glacier parts movement monitoring. Strong wind and the transportation deadline were the reasons. Use of drone measurement was only an attempt to verify the method; after image data processing it can be stated, that it is possible to detect the movement of a glacier in decimetres based on stability of the uncovered bedrocks in the neighbourhood of the ice. This method was tested in real arctic conditions and it can be used as a modern method which serve referenced image data from an area (not only single point measurement).

Two overflights of the famous Egi glacier face were acquired by RPAS equipped with the NIR camera (from the short time given to this experiment due weather and transport, only a right end part of the whole Egi glacier face from the sea view was documented (Figure 11), approximately...
200 × 200 m, 120 and 82 images). Images taken with NIR camera were in our study better quality (images from the RGB camera have on the edges a visible chromatic aberration and we haven’t other camera types at disposal during the greenling expedition). Two sets of overlapped photos were taken in the time span of one hour. From each dataset, a Digital Surface Model (DSM) has been calculated and both DSM’s were subtracted. Data processing was done in Pix4D software; DSMs subtraction was calculated in ArcGIS. It should be noted, that in software Pix4D (like in other similar software) IBMR technology based on image correlation (image based modelling and rendering) doesn’t work well on a flat texture (such as snow), but glaciers on the end of its track and life are structurally and coloury different enough. This supports the image correlation technology. Based on the fact that rocks surrounding the glacier face are stable, a small ice movement has been detected. On Figure 12 some movement of good identifiable parts is visible in dm. Of course, the detected movement is adequate to the 2–3 pixels on aerial images and it isn’t a statistically convincing value for the decision of movement for such systems like Ebee. Both overflights are made in limited time span due to transportation and weather conditions, but it can be noted that this technology was useful in documenting similar projects – for

![Figure 12. (a), (b) Point cloud differences from two overflights.](image-url)
example monitoring of the same glacier in 2017 (Gervaix, 2018).

The experiment result is satisfactory – it is possible to detect a measured movement of the glacier using low cost RPAS; there is of course lot of problems, and it would be very good to stabilise some signals as control points on the glacier (it is very dangerous or simply impossible) and the nearby glacier on bedrock (they must be measured with precise GNSS). The glacier face moves incoherently, with the changes after some hours in DSM being big while there are only a few in the same common areas; you can use CloudCompare software or a good idea is to split DSM into several parts that reference each other better.

The potential movement of the Egi glacier was measured directly from DSMs differences on good visible parts (an arithmetic mean from 10 sites on the glacier) of the documented glacier (Figure 12). The idea was simple: we haven’t time and possibilities to create a precisely measured control points; as stable as it should be on the stone coast (moraine) nearby the glacier. This part has been joined into one identical point cloud using 3D affine transformation, the part of glacier shows after transformation a detectable expected movement to the Disco Bay. The analysis could not be better due to the short time and flight configuration. It doesn’t refer to the absolute movement of the glacier (the glacier movement is not the same on different parts – the most speedy glacier movement can be detected in the middle nearby the glacier face); this refers only to the possibility of the movement detection – here on the side of the glacier (Figure 13).

**Iceland 2017**

Glaciers are found not only in Greenland but also in closer and more accessible areas. Larger areas are better mapped with fixed wing drones, smaller areas can be used with cheaper and wider multicopters. Their advantage is the perpendicular start and landing, which may be limiting, for example, for glacier moraines. For example, finding a suitable landing area on the face of the Egi glacier in Greenland was not easy.

Here is a small example how to measure the glacier flow rate or the 3D status documentation using today’s fairly common Dji Phantom 4 hexacopter and the available Agisoft PhotoScan processing software. Aerial photogrammetric technology is the same, but the device is fundamentally different in this case. In 2017, several flights with quadcopter Dji Phantom 4 were made in Iceland. On the Myrdalsjökull Glacier a suitable area outside the hiking trails, full of tourists, was selected. Four simple ground control points were stabilized and measured by tourist GNSS (they were used for scale of documented area); two overflights were performed in a time span of 3 hours.

There was again a major problem with weather which changes on Iceland at very short intervals. Finally, both over flights successfully passed with (both about 15 minutes at a height of about 50 meters above the glacier). The front of the Myrdalsjökull glacier is a bizarre mixture of ice and black volcanic sand that has been fed by the volcanic eruptions (the last active volcano was the Eyjafjallajökull in 2010). The glacier receded back into the mountains in hundreds of meters over a few decades thanks to global warming (it is particularly on the northern
The melting of ice creates truly incredible shapes. As in Greenland, a glacier mill – a kind of melting ice creek, which is lost to the creation of fantastic shapes and sounds in the glacier, was also discovered here (of course on a whole different scale). Both the landscape and the ice are made up of glacial activities, which are changing from time to time loudly and completely silently before the eyes. Even in this case, it was confirmed that the use of drones for research even under extreme conditions is possible; the batteries had to be warmed up before the flight, and the resulting flights took place without complications. Dji 4 is equipped with a remotely controlled two axis gimbal which carries a very good camera (4k). It supports to take vertical and also oblique images. It helps to create a 3D model of vertically structured objects.

The 3D models of the documented area with the size of a football stadium with a GSD of 4 mm were created. Finally, about 80 vertical images and 20 oblique images per flight were taken. Since in this case the flight was not autonomous and planned in advance using flight plan software, it was necessary to manually pilot the quadcopter. It is not easy in this case to adhere precisely to flight rows and photographing structure, visual contact is required (this type is not yet equipped with VR elements such as Mavic pro with interactive glasses).

For bundle adjustment computing support, which is nowadays a basic approach in photogrammetry, about 10 images from greater height were added (typical flight height was 50 m, added images were taken from 80 m approximately). AgisoftPhotoScan, fully automated photogrammetric processing software was used for creating Figure 14 of basic 3D model (which consists from

Figure 14. Digital surface model of glacier part.

Figure 15. (a), (b) Textured digital surface model created from photos taken using Dji Phantom 4 in August 2017.
point cloud and mesh TIN – triangle irregular network). It uses IBMR (image based modelling and rendering) technology. Other cartographic outputs were derived from the model like the orthophoto and the digital surface model (DSM, Figure 15). As a part of the documented area was a stable rocky glacier moraine and the other part was a plastic ice in motion, a small movement detection (approximately 10 pixels – 4–5 cm) of the glacier over the nearby rocky surface in time was expected (premise) apart from discrete GNSS measurements. From both overflights the DSM’s were created; after that they were subtracted to get a glacier movement in time. Only a small change was detected at the limit of measurability (only a few pixels) – of course, this glacier moves not so quickly and the time span was very short. But the technology can be used with multicopters too – it is simple and low cost.

Conclusion

The Greenland expedition of 2015 also included the installation of four reflectors so that two were on a moving glacier and two were on a stable base (two on the rock as a stability reference or fixed points and, two on the ice assumed to be moving). The orientation of all reflectors was made for the over flight of the TerraSAR-X satellite (parameters: ascending track, High-Resolution SpotLight data, HH polarisation). Side looked radar data was used in this case with the assumption of detecting the horizontal movement of the glacier. The glacier face moves with speed some meters per day. In case of the Egi glacier, there was a prediction of inland ice movement in decimetres per day, which was not detected. In addition, a descending image pair was acquired for other experiments (in this case corner reflectors are not visible here). Processing was performed with the GAMMA software. All reflectors were geodetically measured using precise GNS; radar data from four over flights has been processed with pixel size 50 cm (after oversampling). Based on this data set, the approximate movement of all corner reflectors was estimated. After statistical processing, changes 30–50 cm in position within the time span between both image pairs in both eastern/northern directions was detected (but it is comparable to the estimated accuracy of the offset-tracking method).

Radar data was processed by InSAR technology to. Unfortunately, the surface of the examined glacier was completely incoherent after eleven days, which was confirmed by some expert articles. Surface changes can be explained, for example by the melting of ice, changing ice crystals and their exposure. Based on this finding, an offset data analysis was performed to determine the movement of the entire area. The effort was to verify the calculated movement of the corner reflectors. The quality of calculated offsets at the glacier surface is much lower in comparison to the bedrock part.

The calculation of the movement from the geometry component is very problematic based on the fact that the glacier doesn’t cover whole image area. In 2017, a new data set was captured. Unfortunately, the resolution and measurement mode was not the same as in 2015, but some outputs were done. After data analysis, it is possible to say that corner reflectors on the rock are still visible; the other two reflectors on the glacier can probably be verified too and it was possible to compute the movement of both reflectors in the time span 2015–2017, which is some hundred meters.

For the part nearby glacier face, photogrammetrical RPAS technology was used. Two overflights of the well-known Egi glacier were taken using winged drone EBee. From the captured images, orthophotos and DSM were computed. Based on differences in point cloud or in DSM, glacier motion can be verified. Similar to the Greenland RPAS project, a glacier motion detection using low cost hexacopter Dji Phantom 4 on the Iceland was made; the results are similar, with the main aim from both RPAS projects was technology testing. As a conclusion it can noted that the RPAS technology can be used as an inexpensive measurement in an arctic area, but there are a lot of technical problems like batteries, small area for monitoring (some square km), absence of Internet and inaccurate geographic or geodetic data such as DSM, old satellite imagery etc. for piloting.

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