Experimental Observations of Two Mountain Glaciers on the Eastern Slope of Mt. Tsurugi by Pi-SAR2 Airborne SAR

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Abstract

We performed airborne synthetic aperture radar (SAR) observations at two glaciers (San'nomado and Komado glaciers) on the eastern slope of Mt. Tsurugi, Japan, in August and October 2013, and August 2014. The Pi-SAR2 system used in this study consists of two X-band SAR antennas. Taking advantage of single-pass interferometry, we have generated digital elevation models (DEM) at each epoch. Differencing the DEMs at August and October 2013, the elevations at the glaciers were reduced by ~20 m or more with errors on the order of ~20 m or more. As we could visually identify the reduction in the snow-covered areas in the SAR images of August and October 2013, those changes are attributable to seasonal melting of the snow but are apparently overestimated. Full polarimetric observations were also performed, indicating significant changes over the glaciers from August to October that were largely due to the reduction in snow cover. We could further identify localized spots that indicated strong intensity in the cross-polarized HV channel (transmission of vertically polarized wave and reception in horizontally polarized channel) over the glaciers. Bright HV signals are unexpected, because HV signals are often interpreted as volume scattering and appear to originate from the inside of the glaciers that are unlikely in the X-band SAR system; no penetration deeper than 1 m is expected in the X-band over the snow/ice areas. We interpret the apparent HV signals as due to double bouncing from both sides of the valley, which were apparently imaged over the glaciers.

Key words: Japanese glacier, Pi-SAR2, Interferometry, DEM, Polarimetry

1. Introduction

Fukui and Iida (2012) have reported the presence of glaciers near Mt. Tsurugi (2999 m above sea level), central Japan (Fig. 1), based on ground penetrating radar soundings of the ice thickness and high-precision GPS measurements of the surface velocity. The glaciers had been previously regarded as perennial snow patches, partly because of the incorrect assumption that the equilibrium line altitude at the latitude of the central Japanese Alps was about 4000 m (Fukui and Iida, 2012). Logistics were another more serious problem for in-situ measurements. The eastern slope of Mt Tsurugi is not easily accessible, which is why the presence of glaciers was only recently discovered.

Remote sensing techniques are indispensable for observing such inaccessible areas. In particular, recent developments in satellite-based SAR provide us with a wealth of data such as surface velocities, terminus positions, and grounding lines at worldwide mountain glaciers and ice sheets, regardless of weather and time (e.g., Joughin et al., 2010; Rignot et al., 2011; Yasuda and Furuya, 2013). However, the glaciers at the eastern slope of Mt. Tsurugi cannot be readily monitored by satellite SAR. This is because the length and width of these glaciers are not large enough to be monitored by the presently available satellite SAR sensor whose spatial resolution is at most on the order of a meter. Moreover, the slope of those glaciers is much steeper than other mountain glaciers in the world. Because SAR is viewing the surface in a slant direction, and the viewing geometry (off-nadir angle) cannot be flexibly changed on satellites, image-skewing problems arise. In contrast, airborne SAR usually has better spatial resolution and is more flexible in terms of viewing geometry and the operation itself. Repeat-pass flights of airborne SAR are known to be more difficult than satellite SAR.

Here we report our observation results of the two glaciers, using the airborne SAR imaging system, Pi-SAR2, maintained by National Institute of Information and Communications Technology (NICT), Japan. The Pi-
SAR2 system is a follow-on sensor of the Pi-SAR system (Nakamura et al., 2005) and is equipped with two distinct functionalities, single-pass interferometric SAR (InSAR) and full polarimetric SAR (PolSAR), as detailed below. The objectives of this paper are to report our experimental observation results of both functions and to provide our interpretation of the derived data.

2. Functions and Details of Pi-SAR2 Observations

The Pi-SAR2 system consists of two X-band (3 cm wavelength) SAR antennas (Fig. 2) with a maximum nominal spatial resolution of 0.3 m and allows us to perform both single-pass InSAR and PolSAR observations (Matsuoka et al., 2009). The observations of the present study were experimental in its scope, and those from August 25 and October 17, 2013 and August 21, 2014 were successfully done; no regular or operational data acquisitions are planned at the moment. The start times of the data acquisitions and weather information are listed in Table 1; a single set of raw SAR data was derived within a couple of minutes. While the two start times for October 2013 indicate two different south-north tracks, only Figure 9 is acquired from the earlier acquisition, and all the other images are derived from the later acquisition. Because there are no local weather data, we show the weather data at Japan Meteorological Agency’s Kami‘ichi station located at 36°40.2′ N, 137°25.4′ E, ~20 km WNW from the glaciers. The elevation of the station is 296 m, and thus the temperature at the glaciers should be lower by 10℃ or more. The Pi-SAR2 image coverage is an area of 6 km×6 km (Fig. 1). A radar pulse is
transmitted to the left of the flight direction. Because the glaciers are located on the eastern slope of Mt. Tsurugi, the flight path from the south to the north is effective. The platform airplane is Gulf-Stream 2, and the flight altitude is ~9000 m.

Conventional repeat-pass satellite InSAR employs two SAR imageries acquired at different epochs from a single antenna and allows us to derive surface displacements during the period after phase correction from orbital separation and local topography. In contrast, as accomplished by the Shuttle Radar Topography Mission in 2001 (Farr et al., 2007) and the recent TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement, https://tandemx-science.dlr.de), single-pass InSAR exploits two antennas separated in space and allows us to derive DEM from a single flight. The two antennas on the Pi-SAR2 system are attached on the right and left side of the platform and are separated by 26 m (Fig. 2). The accuracy of the derived height is 2 m when the incidence angle is 45° and the aircraft altitude is 8000 m (Kobayashi et al., 2013). While the incidence angle is variable from 10-65°, the off-nadir angle in the present observation is set at 60° in the image center, because of the steep slope (~20°) at the glaciers. The local incidence angle is thus ~40°. Repeating the single-pass InSAR over time, we can acquire multiple DEMs at different epochs and can infer temporal changes in elevation.

The presence of glaciers in central Japan is due to the very high snow accumulation in winter, which is known to reach more than 20 m. This is particularly the case on the eastern slope of the studied area, which is on the leeward side of the strong northwesterly wind in winter and, thus, can receive the driven snow. Over the last four decades, there have been in-situ snow depth measurements at Murudodaira (2450 m above sea level), which is ~6 km to the south of Mt. Tsurugi and becomes accessible in spring (e.g., Osaka et al., 2000). At the studied glaciers, however, quantitative snow-depth measurements are extremely difficult due to logistical problems. Evans and Kruse (2014) used Ku-band (1.8 cm wavelength) airborne single-pass InSAR to detect the snow depth at Mammoth Mountain, California, where a snow depth as high as 2.5 m can be expected. To our knowledge, there are no other snow-depth change measurements in airborne single-pass InSAR data.

Classical SAR observations have been performed mostly with single linear polarization, in which both transmitted and received microwaves are either horizontally or vertically polarized; they are designated as either HH or VV. The single-pass InSAR data in this study is derived from the VV channel. For realistic scattering targets, however, even if the transmitted wave is horizontally polarized, the scattered wave will include both horizontally and vertically polarized components, which can reveal details about the targets. PolSAR is developed to achieve such a goal by transmitting both horizontally and vertically polarized waves and receiving the scattered waves in the two channels. Hence, in contrast to the single polarization SAR image, each resolution cell of PolSAR image consists of four elements, HH, HV, VH, and VV, forming a scattering matrix. For natural targets, the HV and VH can be regarded as identical per the reciprocity theorem (Yamaguchi, 2007). While a single polarization SAR intensity image is illustrated only in grayscale, a PolSAR intensity image is often shown as a color composite image by assigning the intensity of HH, HV, and VV channels to Red, Green, and Blue, respectively. In particular, the convention to assign Green to HV signals is applied because cross-polarized HV signals are often stronger over forested (green) areas, where volume scattering is dominant. Depending on the actual targets, there are a variety of scattering processes such as surface scattering, double bounce, volume scattering, and helix scattering (Yamaguchi, 2007; Cloude, 2010; Van Zyl and Kim, 2011). A number of techniques have been developed to analyze PolSAR images so that one can categorize the targets and understand scattering processes (Yamaguchi, 2007; Cloude, 2010; Van Zyl and Kim, 2011). However, because this is the first experimental PolSAR observation of the study area, and no detailed ground-truth data are available, we only show the most conventional RGB images for simplicity. Nevertheless, we have encountered unexpected signals that require careful interpretation, as discussed below.

3. Results and Discussion

3.1 Seasonal Snow-depth Changes revealed by Single-Pass InSAR Observations

The derived DEMs over San'nomado and Komado glaciers on August 25, October 17, 2013 and August 21, 2014, are shown in Figs. 3a, 3b, and 3c, respectively. Not only the western sides of Mt. Tsurugi but also some slopes are in the shadows of the ridges, and thus, some data are missing as the target area is only illuminated from the east in a slant direction. This is one of the disadvantages of SAR measurements, which can only be circumvented by observing from multiple directions.

Figure 4a indicates the changes around San’nomado glacier between August 25 and October 17, 2013, which are derived by simply taking the difference between the DEMs of the two epochs. We confirmed that there were no significant elevation changes between August 2013 and August 2014. Although we observe significant changes over the glacier as expected, we also notice that systematic and apparently unrealistic long-wavelength trends are left. It is uncertain why the apparent long-wavelength signals are generated, but the systematic changes toward higher elevations might suggest an effect from the differences in the tropospheric delays of the microwave in the near- and far-side of the area, due to the large elevation changes, as much as 1500 m in a single image. As it is apparent that the significant changes
should be detected only over the glaciers, we simply removed the long-wavelength trend by fitting a second-order polynomial surface at each glacier, and the detrended differences and fitted surfaces are shown in Figs. 4b and 4c, respectively. Figures 5a, 5b, and 5c show the same features for Komado glacier. The fitted surfaces in Figs. 4c and 5c not only indicate larger differences toward higher elevations but also show parabolic surfaces across the glaciers, suggesting again that the systematic differences are possibly related to the topography.

In order to quantify the elevation changes and errors, we examined the distribution of elevation changes at the selected five sites shown in Figs. 4 and 5, each of which contains $50 \times 50$ pixels ($2500 \text{ m}^2$). The two histograms in each panel of Fig. 6 indicate the distribution of elevation changes at each site before and after the removal of the long-wavelength trend, and the peak shifts are consistent with the amplitude of the fitted surfaces in Figs. 4c and 5c.

At site 1, which has no snow cover, the changes are distributed nearly symmetrically, and the dispersion is less than 20 m, which we may regard as measurement error. The estimated error is much larger than the estimate by Kobayashi et al (2013), partly because the DEM in this study is derived from only one direction, in contrast to the multiple measurements from four orthogonal directions in Kobayashi et al (2013). Moreover, the histogram for site 1 is not symmetric around zero, indicating, at least, a 5 m bias even after the removal of the long-wavelength trend. One possible solution that will reduce and more rigorously evaluate errors will be to perform the observations from multiple directions.

The snow coverage is known to reach a minimum in October, and ice bodies are exposed in places, according to field observations. At sites 2–5 that are covered with snow in August, elevation changes are distributed around 20–40 m, depending on the site, but reveal much larger dispersions, exceeding 40 m (Fig. 6). The dispersions at higher-elevation sites become larger than those at lower elevations. In view of the bias at site 1 noted above, it is also likely that some biases are included in the estimated height changes. Field-based visual inspection suggests that the snow depth reduction from mid-August to mid-October 2013 was, at most, 5–6 m, and thus these elevation changes of 20 m or more are apparently overestimates, while the dispersions are also large. Comparing Figs. 4a and 5a with Figs. 4b and 5b, uncorrected residuals still remain, and it turns out that the apparent long-wavelength trends are spatially heterogeneous and not simple enough to be removed by a low-order polynomial plane. Some of the large dispersions can also be caused by errors in the phase unwrapping process, which could generate spurious values. However, using equation 31 in Rosen et al (2000), the height difference related to one phase cycle (height ambiguity) ranges from 165 m in the near range to 309 m in the far range. The derived dispersions are much smaller than the height ambiguity, suggesting that the integer ambiguity resolution in the phase unwrapping itself is not a problem.

### 3.2 Full-Polarimetric Observations

Figures 7 and 8 are RGB composite images for San'nomado and Komado glaciers at the three epochs; the black area is a shadow zone that does not receive any incident microwaves. We observe brighter violet in August 2013 and 2014 at both San'nomado and Komado glaciers, whereas it becomes darker in October, with a notable exception for the brighter HV (green) spots along the center axis. The violet region indicates that HH (red) and VV (blue) signals are dominant, which is generally interpreted as due to single-bounce surface scattering. We also notice that the width of the violet region (glacier) becomes narrower in October, which clearly indicates a reduction in the snow cover area and is consistent with a reduction in elevation shown in the previous section. In October 2013, we can also identify the presence of crevasses at San'nomado glacier that were not clear in August, probably due to the snow cover (Fig. 7).

Vegetated regions such as the side slopes of the glaciers are mostly green, which is consistent with the...
Fig. 4. DEM differences over San'nomado Glacier between August and October 2013. Images are shown in radar coordinates. (a) Original. (b) After removal of long-wavelength trends. (c) The second-order polynomial plane used for the removal of the long-wavelength trends. The three squares indicate the area in which we examined the distribution of height differences, see Fig. 6.
Fig. 5. DEM differences over Komado Glacier between August and October 2013. (a) Original. (b) After removal of long-wavelength trends. (c) The second-order polynomial plane used for the removal of the long-wavelength trends. The two squares indicate the area we examined the distribution of height differences, see Fig. 6.
widely accepted interpretation that volume scattering
from the vegetation is responsible. We notice that a part
of the side slopes in October 2013 appears violet (Figs. 7b
and 8b), which appears mostly green in August (Figs. 7
and 8). We interpret that defoliation in the late fall has
assisted more significant penetration of the microwave to
the surface and subsequent scattering.

The darker violet in October indicates that surface
scattering intensity is weaker than in August. The
surface of the two glaciers on October 17, 2013 was no
longer covered by thick wet snow as in August. The first
snowfall at Mt. Tateyama in 2013 was October 11, and a
fresh snowfall of 20–30 cm on October 17, 2013 was
reported in the blog of Hotel Tateyama (Hotel Tateyama,
2013; last accessed in October 2015); Mt. Tateyama is
~5 km to the south of Mt. Tsurugi. It has been empirically
known that ice bodies were exposed in places before
snowy season. Thus, the surface of both glaciers was
probably much drier than August, which probably led to
weaker surface scattering.

Besides the darker violet at the glaciers in October,
brighter HV (green) spots are clearly visible along a part
of the center axis, particularly at San’nomado glacier (Fig.
7b). Although the sizes of the spots become smaller, we
also notice such HV spots in August 2013 and 2014 at
nearly the same locations as those in October 2013 (Figs.
Fig. 7. RGB composite images at San’nomado glacier acquired on (a) August 25, 2013, (b) October 17, 2013, and (c) August 21, 2014. Red, Green, and Blue colors are assigned to HH, HV, and VV images, respectively. Each image is shown in radar coordinates, and the flight and look directions are shown.

Fig. 8. RGB composite images at Komado glacier acquired on (a) August 25, 2013, (b) October 17, 2013, and (c) August 21, 2014. Red, Green, and Blue colors are assigned to HH, HV, and VV images, respectively. Each image is shown in radar coordinates, and the flight and look directions are shown.
7 and 8). The emergence of HV signals over the glaciers is interesting, because we usually attribute HV signals to volume scattering, and the HV signals appear to originate from the glaciers. Also, the stronger HV intensity at San'nomado glacier than at Komado glacier seems to be consistent with the independent ice thickness measurements; the ice thicknesses at San'nomado and Komado glaciers are 70 m and 40 m at maximum, respectively (Fukui and Iida, 2016). However, the penetration depth of X-band microwave should be, at most, 10 m in dry ice and less than 1 m in wet snow, depending on the dielectric constant (Curlander and McDonough, 1991). Hence, the localized HV signals in August are unlikely due to the volume scattering from the internal ice. Therefore, the differences in the HV intensity at the two glaciers in October cannot be explained by the ice thickness differences.

What is the origin of the HV signals over the glaciers? We interpret that the apparent HV signals would be due to the double-bounced signals that come from the side slopes, which worked as tilted dihedral corner reflectors. Cross-polarized power is at maximum when a dihedral reflector is rotated by 45 degrees relative to the horizontal axis (Van Zyl and Kim, 2011). While there would exist numerous randomly oriented local bumps on both side slopes, two surfaces from the bumps on each side slope would form a natural rotated dihedral reflector. When the look direction is nearly parallel to the flow direction (Figs. 7 and 8), the HV signals that originate in the side slope are once reflected on the other side of the slope and further reflected back to the antenna, thus forming the apparent HV signal at the center of the flow line. Namely, the local topography of the side slopes and the illuminating direction would be responsible for the apparent HV signals. This interpretation can also explain the HV spots at the same location in the August images. Moreover, when the look direction is slightly shifted (Fig. 1), the HV signals are also shifted from the centerline (Fig. 9), which is again interpreted as double bouncing on the side slope. The observation of Figure 9 was performed 21 minutes before the other images in October 2013 (Table 1).

In order to validate our interpretation above, we need to examine the phase differences between HH and VV, because if the HV signals are due to double-bounced signals, the HH and VV phases will become out-of-phase (Freeman and Durden, 1998). Meanwhile, the arrangement of H and V polarization antennas in the Pi-SAR2 system generates topographic phases in the scattering matrix (Moriyama and Satake, 2014), and hence, we may regard the phase data in the VV channel as a cross-track interferogram of H and V antennas (Fig. 10a). Whereas Fig. 10a indicates phase changes that are largely correlated with topography, the quality of interferogram is degraded when HH and VV are out-of-phase with each other, and can be quantified through interferometric coherence. The coherence in Figure 10b is estimated, by setting a 10-by-10 pixel window. The higher and lower coherence areas correspond to in-phase and out-of-phase between the HH and VV channels, respectively. The lower coherence region clearly matches the significant HV spots in Figures 7 and 8, indicating the out-of-phase differences between HH and VV data. The interferometric phases in Fig. 10a are indeed less clear over the low coherence region.

This observation suggests that we need to correct for the apparent effect of double bouncing, due to local topography and incidence angle upon the final PolSAR image, a general lesson of high-resolution PolSAR image analysis when the target area has a rugged topography.

4. Summary

We have observed two valley glaciers near Mt. Tsurugi, Japan, in August and October 2013, and August
using the airborne Pi-SAR2 system. Differencing the
digital elevation models at each epoch, the elevation
changes between August and October 2013 reached
~10–20 m with errors of ~10 meters, which are attrib-
utable to seasonal changes in snow thickness. Full-
polarimetric images indicated unexpectedly significant
intensity in the HV channel over the glacier areas, which
we interpreted as due to double-bounce signals from the
side slope of the valley glaciers.

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