On the Synergistic Use of SAR Constellations' Data Exploitation for Earth Science and Natural Hazard Response

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***Abstract*—Several current and expected future SAR satellites missions (e.g., TanDEM-X (TDX)/PAZ, COSMO-SkyMed (CSK), and Sentinel-1A/B) are designed as constellations of SAR sensors. Relative to single satellite systems, such constellations can provide greater spatial coverage and temporal sampling, thereby enabling better control on interferometric decorrelation and lower latency data access. These improvements lead to more effective near real-time disaster monitoring, assessment and response, and a greater ability to constrain dynamically changing physical processes. Using observations from the CSK system, we highlight examples of the potential for such imaging capabilities to enable advances in Earth science and natural hazards response.**

***Index Terms*—COSMO-SkyMed (CSK), Earth science, interferometric SAR (InSAR), natural hazards.**

I. Introduction

SEVERAL current and expected future synthetic aperture radar (SAR) satellite missions (e.g., TanDEM-X (TDX)/PAZ [1], COSMO-SkyMed (CSK) [2], and Sentinel-1A/B [3], [4]) are designed as constellations of SAR sensors. The Sentinel-1 mission includes a constellation of two SAR satellites operating at C-band (∼5.6 cm wavelength) providing continuity with the European remote sensing (ERS) and ENVISAT missions. Sentinel-1's primary mission scope is to provide continuous extended coverage and operational interferometry capability for surveying and scientific applications under an open data policy [3], [4]. TDX was instead developed as a public–private partnership with its main objective to generate accurate digital elevation models (DEM) along with Earth science applications. PAZ is a dual-use military-civilian mission launched in 2013 into a compatible orbit with TDX. All three sensors are compatible for interferometric applications at X-band (∼3 cm wavelength). CSK is a constellation of four X-band SAR satellites devoted to defense and security, risk management, and scientific applications. From here on out, we focus only on examples derived from CSK observations.

The ability to monitor the Earth's land surface with a short revisit time (even just a few days in the case of CSK) has the potential to enable analysis of a variety of short timescale natural and anthropogenic processes that were previously inaccessible, thereby providing new insights into a variety of phenomena including landslides, earthquakes, typhoons, glaciers, and volcanoes.

Interferometric SAR (InSAR) measurements provide coverage of ground deformation at spatial scales not reasonably accessible with *in situ* measurements such as GPS (e.g., [5]). SAR satellites are also capable of acquiring data in remote areas, such as Antarctica, or areas affected by recent or ongoing natural disasters (e.g., Typhoon Haiyan in the Philippines), where *in situ* geodetic campaigns are logistically challenging and optical sensors may be ineffective due to darkness or clouds.

A reduced revisit time as well as an improved spatial resolution (∼1 m) of the X-band sensor satellites leads to both a better accuracy of the phase and a better constraint on fast-moving processes such as landslides and ice streams. Previous studies quantified an improvement of the coherent pixel density over urban areas achieved by exploiting the high-resolution X-band of the CSK SAR data resulting in an improvement of 320% and 550% with respect to RADARSAT-1 and ENVISAT data [6]. These studies describe the impact of the second-generation SAR systems on the analysis of ground deformation leading to important advancements in Earth science studies [7]. Due to decreasing repeat acquisition intervals and reduced latency in data availability, InSAR techniques are now beginning to provide effective short-term monitoring of regions prone to natural hazards.

In this paper, through a series of vignettes, we highlight examples of the potential of CSK to enable advances in solid Earth science and natural hazard response. In order to highlight the impact of a dense InSAR time series with short repeat time acquisitions and low latency availability, we focus on three ongoing case studies spanning different processes involving ice

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stream motion, volcano deformation, and devastation assessment mapping. The case studies include:

1) an observational campaign over Rutford ice stream (RIS) in Antarctica, where short repeat time observations provide sensitivity to rapid processes (e.g., tidal modulation of ice motion) not possible with other satellites (Section II).
2) monitoring of volcano deformation characterized by a small scale and/or rapid decorrelation (Section III);
3) rapid response to a natural disaster where the short repeat time, low latency data enabled near real-time devastation assessment needed following the landfall of Typhoon Haiyan in the Philippines (Section IV).

II. Antarctica Experiment

Among the fundamental problems in modern glaciology are understanding the potential instability of the West Antarctic ice sheet (WAIS) and the timescales over which WAIS may disintegrate. WAIS is the only extant marine ice sheet, an ice sheet whose bed is mostly below sea level, and contains enough ice to raise global sea level more than 3 m [8]. Nearly all of the mass transported from WAIS to the ocean is carried by fast-flowing ice streams and glaciers [9], whose rapid motion is accommodated primarily by slip at the bed [10]. While a number of studies have inferred the mechanical properties of portions of WAIS using observationally constrained numerical models, these studies offer only temporal snapshots of basal mechanics owing to a dearth of observational time series [10]–[16]. It has long been known that basal mechanics are sensitive to short-timescale (hourly to seasonal) forcings, such as water pressure fluctuations and tidal loading, as well as long-timescale (yearly to decadal) thinning, which motivates applications of SAR constellations to better understand the salient mechanics of glacier beds [17]–[20].

There are several important unanswered questions that underlie uncertainties about the mechanics of WAIS beds and inform our SAR-constellation-based observational strategy. How do grounding zones migrate on timescales characteristic of ocean tides and what role does this migration play in ice-stream-scale flow [21]–[24]? How are stresses transmitted over long distances (tens of km) in ice streams on hourly timescales (e.g., [20])? What are the roles of variations in basal water pressure and subglacial till rheology on ice-stream-scale flow (e.g., [25])? By observing RIS (Fig. 1), a relatively stable ice stream that flows into the California-sized Filchner–Ronne ice shelf and experiences significant ($\sim$20%) tidally induced flow variations [20], we can isolate the salient mechanisms that address the aforementioned questions and bolster our understanding of the mechanics of glacier beds. This increased understanding enhances our ability to constrain the range of plausible future WAIS states and the feedback mechanisms between WAIS and eustatic sea level.

We designed CSK observations of RIS to cover nearly the entire ice stream from ascending and descending orbital directions using every available CSK satellite (Fig. 1). This

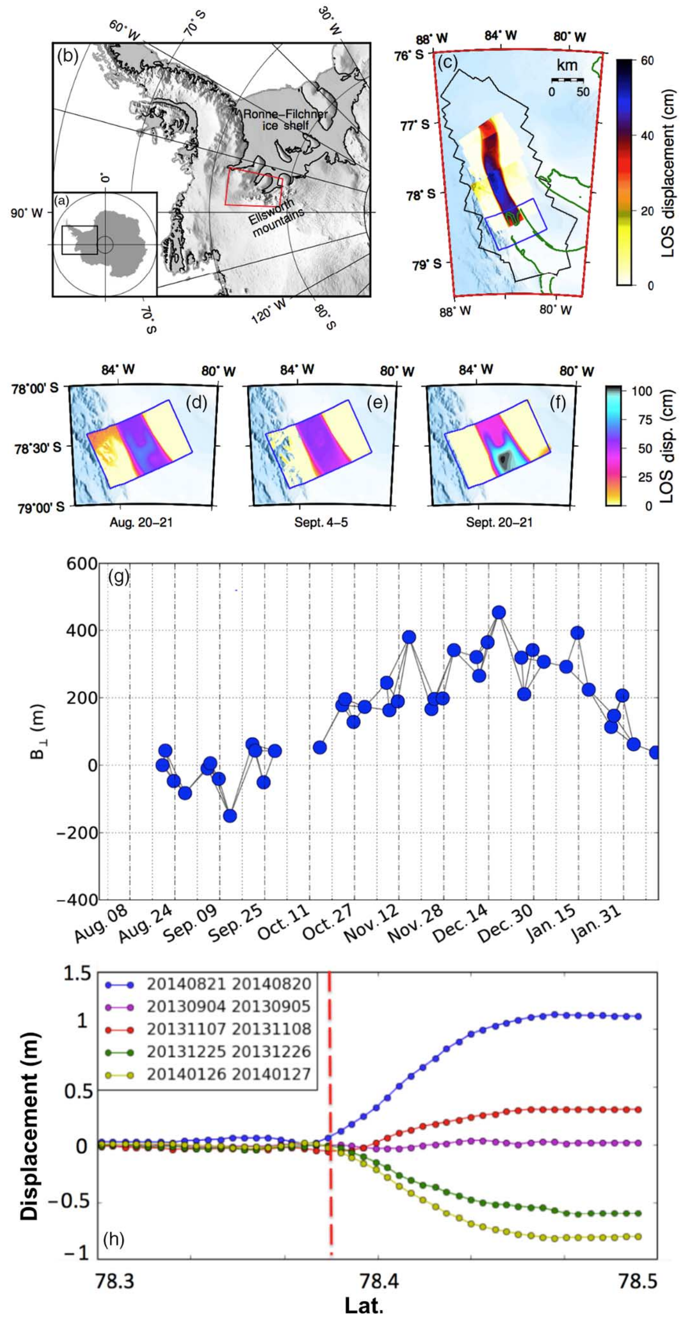

Fig. 1. LOS displacement of RIS from CSK InSAR data collected August–September 2013. (a) Antarctica with region shown in (b) outlined with black box. (b) Shaded relief map of a portion of West Antarctica and the Antarctic Peninsula; the red outline shows the extent of (c). (c) Mosaic of unwrapped interferograms formed from 1-day repeat imagery. Interferograms do not necessarily cover the same time period. Black outline shows spatial extent of CSK coverage and the green irregular line shows approximate grounding line location from [15]. Blue outline indicates the footprint of data shown in (d)–(f). (d)–(f) unwrapped interferograms formed with scenes acquired on the indicated dates. All data were collected at the same time of day (about 19.00 UTC). The southern half of the ice stream in these scenes is floating as part of the Ronne ice shelf and the large difference in LOS displacement is due primarily to tidal forcing. (g) Example distribution of B_{perp} versus time. Each dot is an acquisition; each line is an interferometric pair that was formed. (h) Section plot of several interferograms showing how tidal forcing deforms floating ice. A red dashed line indicates the grounding line.

spatially comprehensive observational scheme will eventually allow us to derive time series of the three-dimensional (3-D) surface displacement for the entire ice stream, facilitating studies of ice stream mechanics with unprecedented spatial extent and temporal resolution. Having a constellation with occasional 1-day repeat time and an average 4-day repeat time is beneficial when looking at displacements of more than a meter per day. The magnitude of the displacement requires interferograms with temporal baselines no longer than 8 days and stability of the perpendicular component of the interferometric baseline B_{perp}. Preliminary results indicate that significant variations in line-of-sight (LOS) displacement are readily observed in the vicinity of the grounding zone [Fig. 1(d)–(f)]. Mean LOS displacements are consistent with previous InSAR [26] and GPS [20] observations showing periodic tidal signals [Fig. 1(h)]. Variations in LOS displacement on the grounded and floating ice agree with GPS data [20]. In the near future, such time series will enable us to go from simply detecting the effects of ocean tides to actually quantifying their impacts at various tidal periods.

III. Monitoring Active Volcanoes

Use of satellite InSAR to detect and monitor ground deformation associated with volcanic activity is already well established (e.g., [27]–[30]). During the more than 20 years since the launch of the European Space Agency's ERS mission, a number of successful results have been obtained from various kinds of volcanic environments. The high spatial (X-band, 3-cm wavelength) and temporal resolution of the second-generation SAR systems plus the increasing number and accuracy of surface deformation measurements allow us to better investigate and constrain small-scale and rapid volcano processes. Surface deformation of volcanoes often precedes other signs of renewed volcanic activity and in some cases, the new deformation occurs without leading to an immediate eruption (e.g., [31]).

A significant limitation of earlier satellite missions was their relatively long repeat intervals. Short-term pre-eruptive displacements and a complex conduit system were recently reported for the first time on a very small spatial and temporal scale at Volcàn de Colima, Mexico [27]. Detailed observations of short-term volcano transients in the proximity of the dome are rare because of the high spatial and temporal resolution required. In this case, GPS and tiltmeters provide point measurements that are not feasible in close proximity to the crater especially if it is in a high-activity or temperature state like that of Kirishima (Shinmoe-dake) volcano (Fig. 2). High-resolution spotlight SAR interferometry proved to be an effective tool for monitoring ground deformation over natural terrain [32], providing the highest spatial resolution (up to 1 m) and temporal sampling, than currently available. Short repeat time acquisitions allow us to better constrain the deformation patterns at the volcano crater and detect the beginning and the end of the ongoing deformation processes. The fine resolution of the spotlight mode acquired in both ascending and descending geometries allows us to constrain the depth of the magmatic or geothermal source by measuring the peak-to-peak distance of the ascending and descending time series. In this particular case, we generated

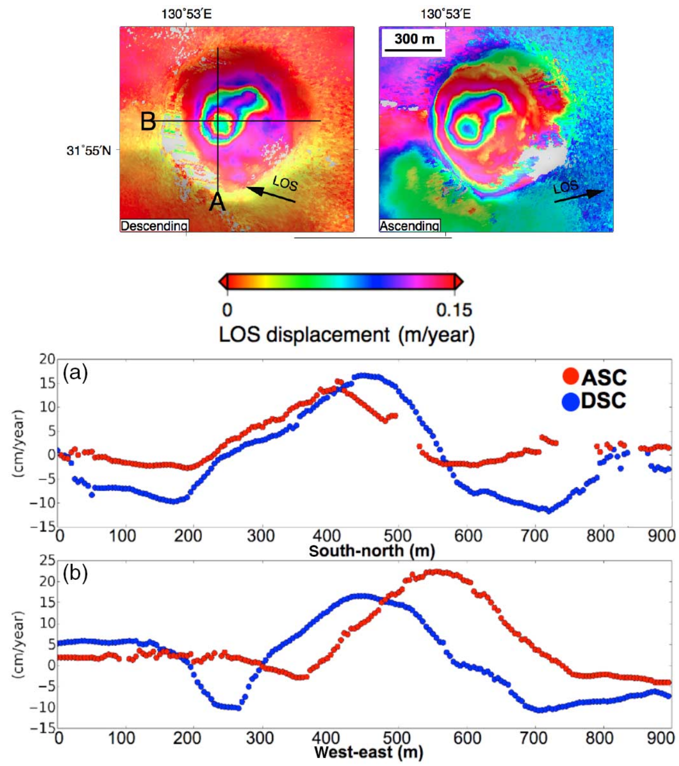

Fig. 2. Surface deformation velocity at Kirishima Volcano, Japan. The observations span the period from February to July, 2013. Each velocity map has been wrapped (15 cm/year rate) for display purposes.

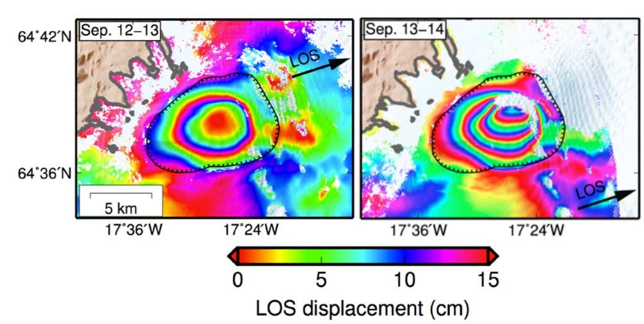

Fig. 3. Deformation of the ice surface overlying Bárðarbunga Caldera in Iceland. Each interferogram has been unwrapped (original wrap rate 1.5 cm) and rewrapped (15-cm wrap rate) for display purposes.

two velocity maps fitting a linear trend to the CSK time-series analysis [33] using 32 and 26 image acquisitions for the ascending and descending tracks, respectively. These data were used to infer a very shallow source for the deformation at a depth of about 100 m below the surface.

We illustrate the importance of short-interval acquisitions provided by CSK using an example from Bárðarbunga Caldera in Iceland. The actual caldera lies below the temperate Vatnajökull ice cap, making long-interval (> 3 days) InSAR measurements of deformation usually impossible due to temporal decorrelation associated with large deformation (> 30 cm/day) and changes in dielectric properties due to melting ice. Starting in August 2014, Bárðarbunga began to undergo caldera collapse (Fig. 3) with magma leaving the central caldera and propagating northward into a 40-km-long rift system and

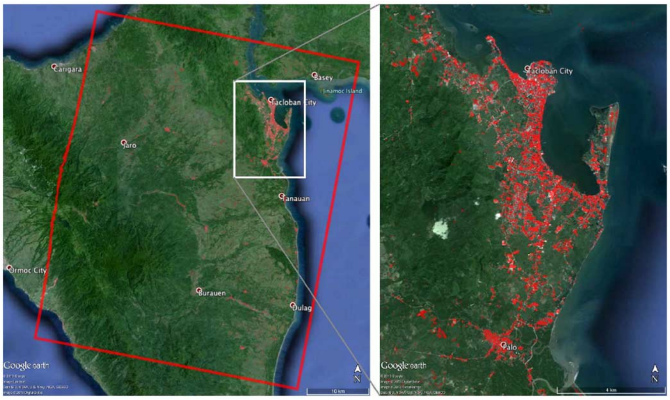

Fig. 4. DPM of the Tacloban area, Philippines, derived from CSK data. Areas with little-to-no destruction are transparent. Increased opacity reflects damage, with areas in red reflecting the heaviest damage to cities and towns in the storm's path. Data span from August 19 to November 11, 2013.

inducing a subaerial extrusive eruption north of the ice cap [34], [35].

We exploited the ability of CSK to acquire ascending and descending tracks with a 12-h time lag to image deformation of the surface of the ice cap—deformation that directly reflects movement of the underlying caldera floor. In Fig. 4, we show two interferograms with different incidence angles that were acquired in rapid succession indicating a rapid (50 cm/day) subsidence of the glacier surface overlying the collapsing central caldera. The InSAR data, together with seismicity, show highly nondouble-couple earthquake source mechanisms providing a mechanical link to the dynamics of the collapsing magma chamber [36]. These low-latency observations (within 24 h) were used to notify authorities in Iceland of the previously unrecognized collapse of the caldera.

IV. Natural Hazard Response

The ability to track anthropogenic and natural changes on the Earth's surface underpins modern natural disaster assessment and response, and will grow in importance as societal exposure increases. SAR can become an essential source of information on the spatial distribution of devastation due to its all weather, day/night acquisition capability [37], [38]. For example, the advanced rapid imaging and analysis (ARIA) project team at the Jet Propulsion Laboratory and California Institute of Technology, in collaboration with the Italian Space Agency, used CSK observations to provide assessments of devastated regions resulting from Super Typhoon Haiyan (Fig. 4).

The tropical cyclone was category 5 before its landfall on the city of Tacloban, Philippines, on November 8, 2013, resulting in powerful winds and a storm surge causing widespread devastation. Within three days of landfall, we produced a devastation proxy map (DPM) with approximately 30-m spatial resolution and covering about 2000 km^2 of area including Tacloban [39], with latency only limited by bureaucratic issues. The approach relies on detailed analysis of the time-dependence of interferometric decorrelation. Technically, such estimates are possible within a few hours of data acquisition. The resulting map was shared with international responding agencies through U.S. Geological Survey's Hazard Data Distribution System (HDDS) and emails. The map was used to support damage assessment, logistics, supply and rescue operations, and identification of landing zones for relief response. The reliability of the map was assessed by comparing it with independent analyses by the European Commission Copernicus Emergency Management Service based on pre- and postevent high-resolution optical imagery [40]. The red pixels in Fig. 2, derived from radar data, show high spatial correlation with the Copernicus damage grade polygons in areas where comparisons are possible.

V. Discussion and Conclusion

We have illustrated how the short repeat interval and low latency potential of SAR constellations can improve our understanding of basic Earth science, as well as facilitate efficient natural disaster response. The RIS example illustrates the role of short repeat times to disentangle secular velocities from tidal effects deforming the ice stream periodically. The joint analysis of redundant acquisitions will allow reconstruction of a 3-D vector field of deformation and potentially isolate tidal components. Volcano applications benefit from high spatial resolution and short repeat interval SAR observations. We showed how high-resolution spotlight data reveal an intriguing, shallow deformation process within the summit crater and lava dome of Kirishima volcano. The large magnitude deformation of the ice above the collapsing Bárðarbunga Caldera could not have been observed without the 1-day sampling provided by the CSK constellation. The importance of low latency access combined with short-interval imaging was illustrated by the Typhoon Haiyan test case. Being able to generate a devastation map in three days after a natural disaster proved to be a powerful near real-time tool for providing effective support to the humanitarian efforts. In the future, we expect such latency to decrease dramatically, thus making such devastation maps even more useful for rapid response applications.

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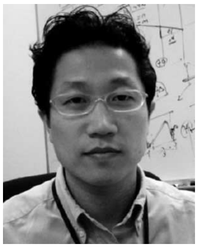

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Mark Simons, photograph and biography not available at the time of publication.

Paul Lundgren, photograph and biography not available at the time of publication.