Multitemporal Multitrack Monitoring of Wetland Water Levels in the Florida Everglades Using ALOS PALSAR Data With Interferometric Processing

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Abstract—**We present an improved wetland interferometric synthetic aperture radar (InSAR) technique that uses multitrack SAR data and ground-based stage (water level) data to calculate a time series of high spatial resolution water level maps throughout wide wetland areas. The technique was applied to a wetland area in the northern Everglades, Florida, using a four-year-long Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Rada (PALSAR) data set acquired during 2007–2011. Although the temporal resolution of ALOS PALSAR interferograms is low (multiples of the satellite's 46-day revisit cycle), the multitrack algorithm combines results from the four tracks and significantly improves the observation frequency up to seven days in the best case. A quality control analysis indicates that the average root-mean-square error of the differences between the InSAR- and stage-based water levels is 4.2 cm. The end products of absolute water level time series with improved temporal and high spatial resolutions can be used as excellent constraints for high spatial resolution wetland flow models and other water resource applications.**

Index Terms—**Absolute water level, everglades, interferometric synthetic aperture radar (InSAR) time series, multitrack, small temporal baseline subset (STBAS), temporal resolution, Water Conservation Area 1 (WCA1), wetlands.**

I. Introduction

SPACE-based interferometric synthetic aperture radar (InSAR) observations, which are obtained with vast spatial details of 5–50 m resolution and a few centimeters vertical accuracy, can improve the spatial resolution of wetland water level measurements [1]–[5]. However, the basic InSAR observations measure water level changes, which have limited contribution for monitoring and understanding wetland surface flow. In order to transform the relative wetland InSAR observations to absolute measurements, stage (water level) information is needed to be integrated with the InSAR observations [1], [2]. Recently, the small temporal baseline subset (STBAS) approach has been developed to combine a series of single-track InSAR and stage observations to generate absolute water level time series maps [5]. However, the time span of produced water level time series is completely dependent on the SAR satellite revisit cycle (11–46 days, depending on the satellite), which is coarse compared with hourly or daily *in situ* stage observations. Hence, the usefulness of these maps from a single-track InSAR time series as a monitoring tool is still rather limited.

In this letter, we present an advanced wetland InSAR technique to retrieve absolute water level time series with high spatial resolution and improved observation frequency. The method builds upon the STBAS technique by integrating InSAR-derived water level change information from several satellite tracks into a single time series with higher observation frequency. The technique is applied to Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Rada (PALSAR) data acquired over the Everglades during 2007–2011. Although the revisit cycle of ALOS is 46 days, the new multitrack method enabled us to generate time series with a time span of up to 7 days. The end product of absolute water level time series is useful for both monitoring applications and constraints for high-resolution wetland hydrologic flow models.

II. Study Area

The Everglades is a unique wetland environment consisting of a very wide, shallow, and slow sheet flow in south Florida (see Fig. 1). Over the past century, human activity has significantly affected the drainage pattern in the wetlands, destroyed a significant part of vegetation, and reduced wildlife habitat. The northernmost Everglades, just south of Lake Okeechobee, was drained and proclaimed as an agricultural area. The northern and central Everglades were compartmentalized into several Water Conservation Areas (WCAs), which serve as large water reservoirs for the increasing population in south Florida. Only the southern section of the Everglades, about 30% of the original wetland area, was designated as a national park and has kept its natural wetland sheet flow.

Our study area consists of WCA1, which is located in the northern section of the Everglades wetlands, approximately 30 km southeast of Lake Okeechobee (see Fig. 1). We chose to apply the multitemporal water level monitoring technique to this area, because it is an independent water storage unit with a well-studied hydrological regime. For the same reason, we also used WCA1 for testing our STBAS technique [5]. The 85-km^2 tear-shaped WCA1 is bounded from all sides by levees. A peripheral canal, which is located within the area

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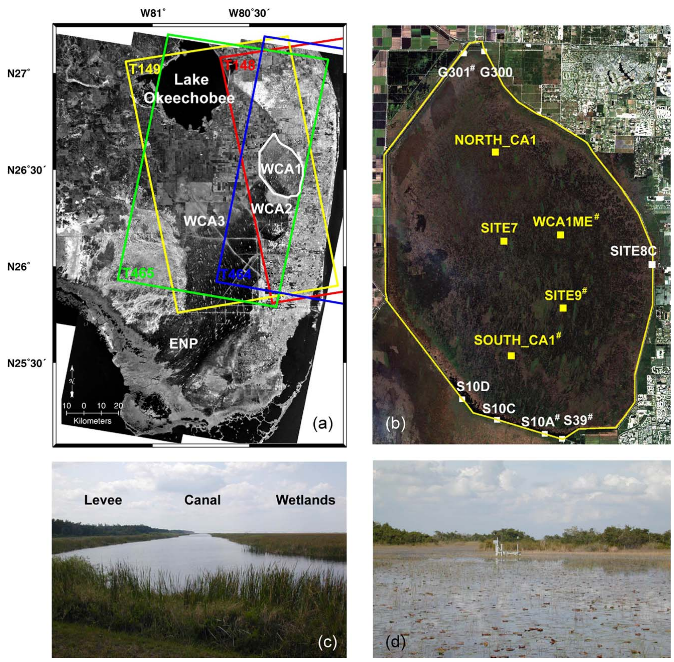

Fig. 1. (a) Japanese Earth Resources Satellite 1 (JERS-1) amplitude image of south Florida showing the SAR tracks used in this study. (b) Satellite image showing the location of stage stations in the WCA1 area. White squares mark station location along the peripheral canals, and yellow squares mark location of stations located within the interior of the area. The stations marked by # are used for calibration of absolute water level time series. (c) and (d) Photos showing surface water and vegetation along the peripheral canals and in the interior of WCA1. WCA: Water Conservation Area; ENP: Everglades National Park.

adjacent to the boundary levees [see Fig. 1(c)], transfers most of the water that enters or leaves the area from hydrological gates, mainly in the northern and southern parts of the area. The interior of the area consists of woody and herbaceous vegetation types and is flooded most of the year [see Fig. 1(d)]. The typical flow regime in the area is radial, from the peripheral canal to the interior wetlands, or vice versa, from the interior to the canal. WCA1 also serves as a wildlife refuge providing natural wetland conditions for a wide variety of plants and animals.

III. Observations

Our multitemporal analysis relies on two types of data, namely, space-based InSAR observations and ground-based stage (water level) measurements. InSAR observations provide high spatial resolution measurements of water level changes, whereas stage data provide high-temporal-resolution record of absolute water levels, which are used for calibrating and validating the InSAR observations.

The Japanese ALOS was operated during 2006–2011 with an L-band PALSAR (1.270 GHz center frequency, 23.62 cm wavelength). Our data consist of a total of 37 ALOS PALSAR images acquired along four tracks (two ascending: tracks 148 and 149; two descending: tracks 464 and 465) during the years 2007–2011 as part of a global acquisition plan (see Table I). Chirp extension processing in the range direction enables all four tracks to cover the WCA1 area, as shown in Fig. 1. We calculated all possible interferograms using the ROI_PAC [6] and Gamma software packages [7], which included phase unwrapping and topographic phase removal based on the SRTM-1 digital elevation model. The interferograms were calculated with temporal baselines ranging from 46 to 1196 days and absolute perpendicular baselines ranging from 41 to 3800 m. We applied an adaptive radar interferogram filter with four pixels of filter width [8] and a multilooking process with 8×24 factors in range and azimuth directions in order to improve fringe visibility in the interferograms and increase the signal-to-noise ratio. However, the filtering and the multilooking process also cause a reduction of the spatial resolution from 5 to 40 m. Nevertheless, the filtered results with 40-m pixel resolution still have sufficient spatial resolution to detect many surface details that cannot be observed from the ground.

TABLE I
List of ALOS PALSAR Data and Their Acquisition Parameters

Parameter	Track 148	Track 149	Track 464	Track 465
Date (imaging mode)	2008-05-14 (FBD)	2008-01-14 (FBS)	2007-11-02 (FBS)	2008-10-06 (FBS)
	2008-06-29 (FBD)	2008-05-31 (FBD)	2008-11-04 (FBS)	2008-11-21 (FBD)
	2008-08-14 (FBD)	2009-10-19 (FBD)	2008-12-20 (FBS)	2009-11-24 (FBS)
	2008-11-14 (FBS)	2010-01-19 (FBS)	2009-03-22 (FBS)	2010-04-11 (FBD)
	2008-12-30 (FBS)	2010-04-21 (FBS)	2009-11-07 (FBS)	
	2009-10-02 (FBD)	2010-06-06 (FBD)	2010-02-07 (FBS)	
	2010-02-17 (FBS)	2010-09-06 (FBD)	2010-03-25 (FBS)	
	2010-04-04 (FBS)	2010-12-07 (FBD)	2011-02-10 (FBS)	
	2010-05-20 (FBD)	2011-01-22 (FBS)		
	2010-07-05 (FBD)	2011-03-09 (FBS)		
	2010-08-20 (FBD)			
	2010-10-05 (FBD)			
	2010-11-20 (FBD)			
	2011-01-05 (FBS)			
	2011-02-20 (FBS)			
Orbit direction	Ascending		Descending	
Incidence angle	38.7°			
Azimuth pixel spacing	3.17 m			
Range pixel spacing	4.68 m (FBS), 9.36 m (FBD)			

FBS - Fine Beam Single Polarization; FBD - Fine Beam Dual Polarization

Stage data have an essential role in the calibration of the relative InSAR observations. WCA1 is monitored by 12 stage stations, which collect hourly water level data [see Fig. 1(b)]. Seven of the stations are located along the peripheral canal [marked by white squares in Fig. 1(b)], and the other five stations are located within the wetland interior [marked by yellow squares in Fig. 1(b)]. The stage stations are operated by the U.S. Geological Survey (USGS) and the South Florida Water Management District (SFWMD), and their data are provided via the Everglades Depth Estimation Network (EDEN) archive (http://sofia.usgs.gov/eden/stationlist.php). In some stage stations, the data are measured with respect to the NAVD88 datum and the other with respect to the NGVD29 datum (see Table II). For consistency, stage data with NGVD29 datum were converted to NAVD88 datum [5]. Although the stage data are a very good resource for calibrating the InSAR-derived water level observation, careful analyses are required because some stage stations that operate near hydraulic structures, such as gates, are affected by flow dynamics and, hence, can provide inaccurate stage values [9]. We checked the consistency of the peripheral stage data by assuming flat canal water level conditions. Data that showed deviation from flat conditions were edited.

TABLE II
TYPE AND DATUM OF WCA1 STAGE STATIONS

Station	*Type*	*Datum*	*Cp (cm)*
SITE8C	Marsh	NGVD29	-44.81
S39_H#	Canal structure	NAVD88	-
S10A_H#	Canal structure	NGVD29	-45.42
S10C_H	Canal structure	NGVD29	-44.81
S10D_H	Canal structure	NGVD29	-44.50
G301_T#	Canal structure	NAVD88	-
G300_T	Canal structure	NAVD88	-
NORTH_CA1	Marsh	NAVD88	-
SITE7	Marsh	NGVD29	-44.50
WCA1ME#	Marsh	NAVD88	-
SITE9#	Marsh	NGVD29	-45.11
SOUTH_CA1#	Marsh	NAVD88	-

Cp is reported vertical conversion parameter at gauge from NGVD29 to NAVD88 datum.
The stations marked by (#) are used for calibration of absolute water level time series.

IV. METHODOLOGY

The new multitrack algorithm builds upon our previous STBAS study, where we used InSAR observations from a single track and ground-based stage data to calculate high spatial resolution time series of absolute water levels in wetlands. The STBAS methodology is based on the SBAS algorithm, which combines a large number of SAR acquisitions to calculate displacement time series. Whereas the SBAS uses small geometrical baseline subsets, the STBAS algorithm uses small temporal baseline subsets, because in a wetland environment, interferometric coherence strongly depends on the short time span between the observations. The STBAS algorithm consists of five steps: 1) selection of interferometric pairs with small temporal baselines; 2) interferogram generation, including phase unwrapping; 3) calibration of water level changes with terrestrial stage water level data; 4) singular value decomposition inversion of vertical change of water level to estimate relative water level time series from the calibrated water level changes; and 5) estimation of absolute water level time series by tying the relative time series to reference water level. A detailed description of the five-step STBAS algorithm is provided by Hong *et al.* [5]. The end products of the STBAS algorithm are high spatial resolution water level maps that are calculated for each SAR acquisition date of a single track. Although the InSAR observations provide relative measurements of water level changes between two SAR acquisitions, their integration with the stage data allows us to transform the relative InSAR observations to the same datum as the stage data and calculated water level maps for each SAR acquisition date.

The stage data are required for calibrating both the relative InSAR-derived water level changes (step 3 of the algorithm) and the time series of absolute water level (step 5). The first calibration is needed to translate the unwrapped phase measurements to water level changes, because the relative InSAR measurement is calculated with respect to a reference point, which is unstable in wetlands. In many solid Earth applications (e.g., earthquake-induced deformation), the reference point is chosen to be in the far field, where the deformation is negligible. However, in wetlands, such reference point cannot be used, and hence, the relative motion is calibrated with respect to stage measurements of water level changes. The second calibration is needed for translating the relative InSAR measurements to an absolution reference frame. It is conducted at the final stage of the algorithm and is explained at the end of this section.

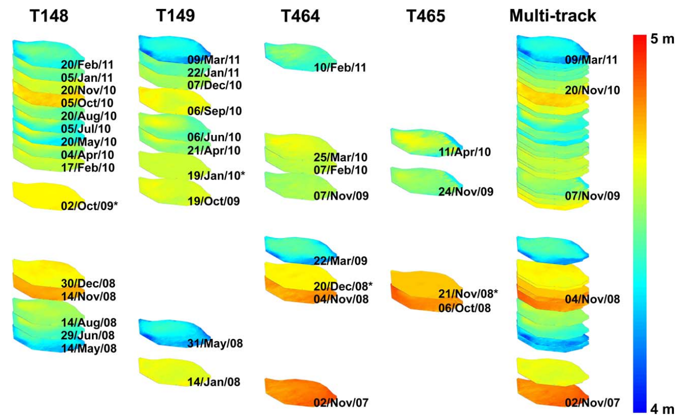

Fig. 2. Single- and multitrack time series maps of water levels in WCA-1. The time span between maps in the single-track solutions is 46 days and its multiples. The time span between maps in the multitrack solution varies between 7 and 194 days, depending on the data availability. Acquisition dates marked by * indicate the InSAR-stage calibration date.

The multitrack algorithm takes advantage that all single-track end-product water level time series share the same datum of the stage stations. In this multitrack algorithm, we simply combine the information from the various tracks into a single time series with a higher acquisition frequency than the individual single-track time series. Since the area of interest is located at different range distances in each multitrack, the incidence angle is different at the line of sight. Thus, we calculated the InSAR-derived water level change considering the effect of the local incidence angle in the multitrack algorithm. A visual illustration of the multitrack algorithm is provided in Fig. 2.

We applied the multitrack algorithm to ALOS PALSAR data set, consisting of SAR data from four individual tracks (see Table I and Fig. 2). The end product of the multitrack algorithm is a single time series with high spatial resolution maps of absolute water levels in WCA1 covering the time period 2007–2011. The transformation of the InSAR-determined water level changes to absolute water level requires *a priori* knowledge of absolute water levels throughout the study area during one of the acquisition dates. Toward the end of the wet season (October–January), the water levels in WCA1 tend to be flat as no gate operation occurs during that period. For each track, we searched the stage record for such flat water level conditions by finding the SAR acquisition date with the least deviation between all stage stations. We use that date as the InSAR-stage calibration date by assuming flat water level conditions throughout WCA1 (see Fig. 2—dates marked by *). The water level maps in the other dates are calculated with respect to the assumed flat conditions that occurred during the calibration date.

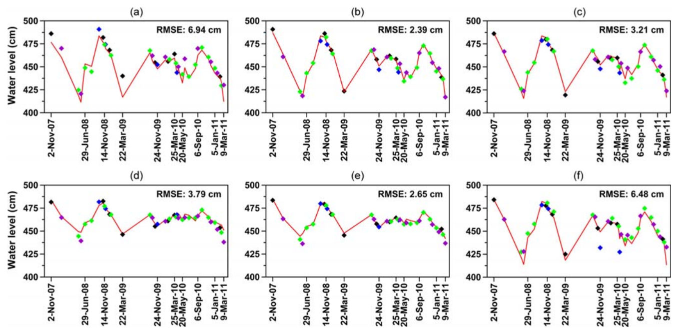

Fig. 3. Comparison between stage (red line) and InSAR-determined water level time series. Green dots: track 148; purple: track 149; black: track 464; blue: track 465. (a) G300_T. (b) S10C_H. (c) S10D_H. (d) NORTH_CA1. (e) SITE7. (f) SITE8C.

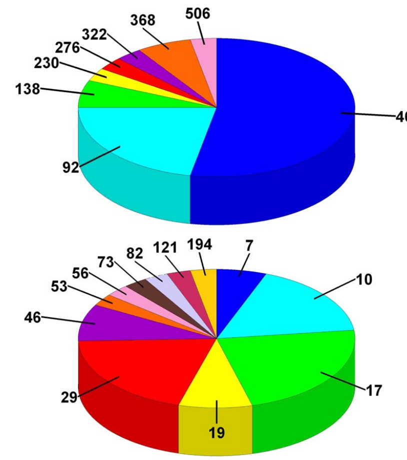

Fig. 4. Pie plot showing the time span (days) between acquisitions in the (top) single-track and (bottom) multitrack methods.

The calibration is conducted with only half of the available station. We chose six stage stations (marked by # in Table II) for the calibration of absolute time series. The selected stage stations show very similar water levels, with little variation in all of satellite tracks. The other half is used for the validation of the final time series.

V. Result

The main contribution of the multitrack algorithm with respect to the STBAS algorithm [5] is the improvement in time span between acquisitions, which is dependent on the SAR satellite's revisit cycle. Instead of the 46-day repeat orbit of ALOS, which is also the best temporal resolution of the STBAS algorithm, the multitrack method produces water level maps with time span between acquisitions of only 7 days in the best case.

In order to evaluate the quality of the multitrack algorithm results, we conducted a quality control analysis based on the root-mean-square error (RMSE) estimator. For each SAR acquisition date and for all stage stations, we calculated the differences between the InSAR-based and stage measured water levels. The InSAR-based water level values were determined from several pixels (3×3 pixels) located at the high interferometric coherence area near the actual station location. This procedure, which we termed "virtual station" analysis in our STBAS study [5], significantly improved the InSAR-based water level values, because some of the stage stations were installed in canals or other open areas, where wetland InSAR does not perform well.

We present both the InSAR and stage data as time series plots for all the stage stations used in the validation procedure (see Fig. 3). The best results were obtained in the comparison with stage station S10C_H, showing a 2.4-cm RMSE value, and the worst results were obtained in the comparison with stage station G300_T, showing a 6.9-cm RMSE value. Overall, the peripheral stage stations near canal structures represent relatively higher accuracy with an average RSME value of 4.2 cm, whereas stations located in the interior of WCA1 show an average RSME value of 4.3 cm. The RMSE difference between the peripheral and interior stage stations reflects the higher interferometric coherence in the interior vegetated area compared with the reduced coherence in the canals and nearby areas, where vegetation is sparse, as shown in Fig. 1(c) and (d). We calculated a 4.2-cm average value of RMSE for all stage stations, which represents the vertical accuracy of the multitrack method for retrieving high-resolution water levels in wetland areas. We also calculated 3.4-, 4.5-, 3.0-, and 5.6-cm average values of RMSE, respectively, in each single-track (T464, T465, T148, and T149) STBAS approach with a common time span. This 3- to 5-cm vertical accuracy is an improved result compared with the result of our STBAS study, which used Radarsat-1 C-band data and yielded a 6- to 7-cm RMSE misfit level [5]. The improved accuracy of the ALOS data is a surprising result, because L-band (24 cm) phase changes are less sensitive than C-band (5.6 cm) phase changes in detecting small surface displacement changes. In vegetated areas, the lower coherence of C-band observations degrades their detection sensitivity and reduces the accuracy of the C-band data. However, the high coherence values of L-band observations over wetlands allow full usage of the L-band detection capability, which results in higher accuracy than C-band data.

VI. Conclusion and Discussion

Our new multitrack multitemporal algorithm enabled us to calculate absolute water level time series with improved frequency of acquisitions and very high spatial resolution (40 m). We applied the multitrack algorithm to a four-year-long L-band ALOS PALSAR data set acquired during 2007–2011 and the stage record acquired by 12 stations operating in WCA1. Our results yielded high spatial resolution maps of absolute water level with vertical accuracy of 4.2 cm. We estimate the atmospheric noise level to be in the range of 1–3 cm, which is 25–75% of the total noise level. Based on the weather pattern in south Florida, we estimate that the higher atmospheric noise occurs in summer (June–October) due to the high atmospheric moisture in Florida's wet season and that the lower noise levels occur during the winter dry season. The main contribution of the multitrack algorithm over the STBAS algorithm is the improved time span between acquisitions, from 46 days in the single-track STBAS algorithm down to 7 days in the multitrack STBAS algorithm. A comparison between the single- and multitrack methods demonstrates significantly reduced time span of acquisitions in the multitrack method (see Fig. 4). The maximum time span between acquisitions of each track is 276, 506, 368, and 368 days in tracks 148, 149, 464, and 465, respectively. However, the maximum time span between products of the multitrack method was only 194 days [see Fig. 4(b)].

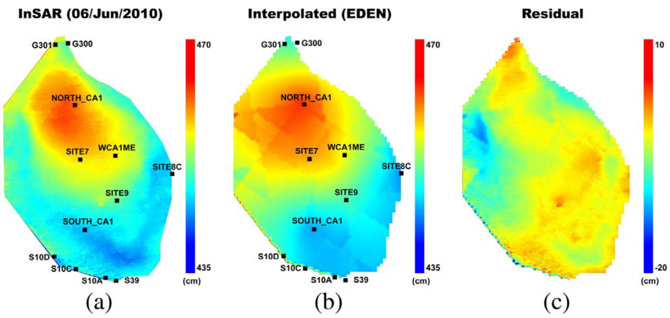

Fig. 5. Comparison between the (a) InSAR-derived water surface and (b) interpolated water surface. The interpolated surface is obtained from the EDEN website (http://sofia.usgs.gov/eden/models/watersurfacemod.php). The linear patterns shown in the map reflect the interpolation scheme used by the EDEN project. (c) Residual map showing deviation of up to 20 cm.

The InSAR-based water level maps provide a significant improvement over interpolation-based maps in terms of accuracy and spatial resolution, as shown in Fig. 5. Our space-based water surface maps provide real observed values with high resolution of 40 m [see Fig. 5(a)]. The interpolation-based maps, which are produced by the EDEN [10], [11], are based on a limited amount of stage data, separated by 3–8 km from one another, and a spatially continuous interpolation method. The EDEN maps are composed of interpolated values with coarse resolution of 400 m [see Fig. 5(b)]. Similar water level height variation in the range of 435–470 cm can be found in the comparison, but the EDEN map shows a truncated pattern resulting from limited stage station points. The residual map calculated with both maps shows a similar truncated pattern due to the limited stage station points and shows significant differences in areas located farthest from the stage stations [see Fig. 5(c)]. The residual map shows that the differences between the two maps can reach 20 cm, which is a significant portion (44%) of the total range of water level changes (55 cm).

The improved results of the multitrack multitemporal algorithm can be used for two purposes, namely, for water management monitoring and high spatial resolution flow modeling. The high spatial and improved temporal resolution observations can be used by water authorities to detect flow patterns, possible anomalous behavior, and overall better management of the water resources. Another important application of the improved observations is constraining high spatial resolution water flow models, which eventually can be used as a decision support tool for water managers.

Although the multitrack algorithm provides a significant improvement of time span between acquisitions, the temporal resolution is quite long compared with daily or even hourly measurements by stage stations. Because the ALOS satellite was designed for global observations with a well-organized schedule, the revisit cycle over a target area is 46 days, which is longer than the revisit cycle of other SAR satellites. The next L-band satellite, i.e., ALOS-2, which is scheduled to be launched in 2014, will provide data with improved spatial resolution (3–10 m in strip map mode) and the shorter revisit cycle of only 14 days. We expect that the new ALOS-2 observations will significantly improve the temporal resolution of wetland monitoring, particularly when used with the multitrack algorithm.

Another possible development of the multitrack method is extending it to a multisensor method. In this letter, we were able to combine data from various tracks, because the multitrack data were calibrated and tied to the stage's NAVD88 datum. The same procedure can be applied to data from various sensors, as long as the data will be calibrated with the same set of stage stations. For example, multisensor analysis can include InSAR data acquired by currently operating satellites, such as TerraSAR-X or Radarsat-2, and in the near future by Sentinel-1 or ALOS-2. However, we suspect that uncertainties associated with the different sensor frequencies (X-, C-, or L-band) can vary from one acquisition date to another. Thus, the development of a multisensor algorithm should also include a careful evaluation of the uncertainty levels.

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