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Extraction of Absolute Water Level Using TanDEM-X Bistatic Observations With a Large Perpendicular Baseline

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***Abstract*— The application of Wetland synthetic aperture radar interferometry (InSAR) has often been restricted in practical hydrological monitoring because it is based on relative estimates of water level changes between two synthetic aperture radar acquisitions, as opposed to absolute water levels obtained by ground measurements. TanDEM-X bistatic observations can provide absolute water level estimates using simultaneous phase measurements by a two-satellite constellation with TerraSAR-X. We evaluated two datasets of TanDEM-X bistatic observations acquired during an experimental science phase on August 26 and 31, 2015, with a very large baseline configuration to extract absolute water levels of Everglades wetland in southern Florida, USA. The perpendicular baselines are 1.43 and 1.36 km, and the ambiguities of height were calculated as 3.61 and 3.90 m in each interferometric pair, respectively. Hourly water level measurements provided by the Everglades depth estimation network (EDEN) were used to verify the estimated absolute water levels. Several stage stations located in densely vegetated areas that showed incoherence were excluded from the verification as outliers. The verification results show an excellent agreement (degree of determination > 0.95) between the InSAR derived absolute water levels and the stage station measurements. The root mean square error (RMSE) between the TanDEM-X results and stage records was 0.77 and 0.66 m, respectively. Severe volume decorrelations over the vegetated area, owing to the large perpendicular baselines, were detected, despite near zero temporal baseline of the bistatic observations. The absolute water levels can be used as excellent constraints for wetland surface flow models.**

***Index Terms*— Absolute water level, Everglades, perpendicular baseline, synthetic aperture radar interferometry (InSAR), TanDEM-X science phase, wetland.**

I. Introduction

WETLAND synthetic aperture radar interferometry (InSAR) techniques have been successfully used to estimate relative water level changes demonstrating ample spatial details in a resolution of 5–50 m and a few centimeters of vertical accuracy [1]–[6]. The wetland InSAR technique is based on a returned radar pulse that contains phase information of the water surface in vegetated wetland, resulting from double-bounce scattering between the water surface and vegetation [7]. However, monitoring relative water level changes has often been of limited applicability in hydrological observations of water surface flow in herbaceous wetland environments. The small temporal baseline subset (STBAS) technique, a wetland InSAR approach using multitemporal SAR observations, was proposed to transform relative water level changes to absolute measurements using *in situ* stage station measurements [1], [3]. However, the STBAS method requires more than year-round multitemporal SAR observations and a flatwater level condition during the dry season. Although satellite radar altimetry has been a favorable tool for monitoring surface levels of large water bodies, its spatial resolution is much coarser than that of imaging sensors such as SAR [8], [9].

Here we demonstrate the feasibility of TanDEM-X bistatic observations in constellation with TerraSAR-X satellite to extract topographic elevation and absolute water levels in wetland, yielding very high topographic sensitivity in such environments. We selected the Everglades wetland in South Florida, USA, which is dominated by herbaceous vegetation such as sawgrass marsh, with a low-gradient surface called the "River of Grass," as a study area. Repeat pass InSAR observations can retrieve only relative water level changes between two consecutive SAR images, but not absolute water surface elevations at any of the acquisition times. However, the simultaneous TanDEM-X bistatic observations measure the actual surface elevation mostly of solid land, which are mostly used for determining digital elevation models (DEMs). In case of wetland, the measured surface is aquatic, providing information on absolute water levels during the acquisition time. The extracted water level was assessed using water level measurements obtained by a network composed of densely distributed *in situ* stage stations. The calculated high-resolution maps of the absolute water level are useful for hydrological monitoring and water surface model constraints. Preliminary results of this study were presented in the EUSAR'21 meeting [10].

II. Study Area

Everglades is a unique subtropical wetland ecosystem characterized by extensive, shallow, and slow sheet flow with a flat

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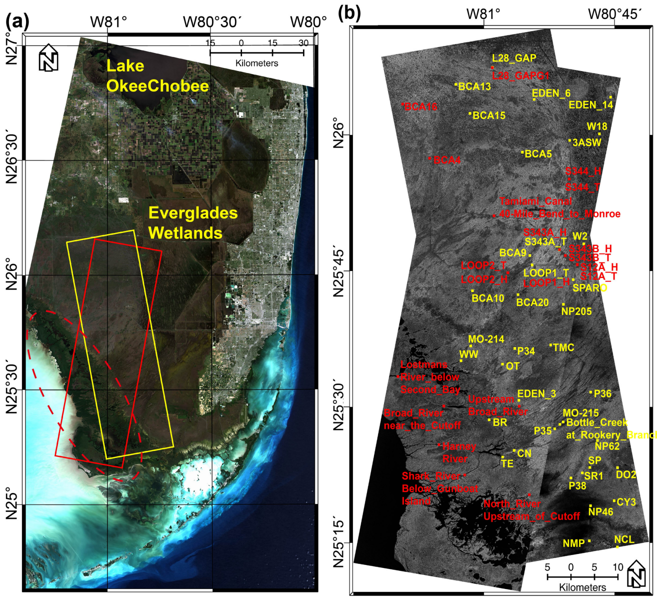

Fig. 1. (a) Landsat-8 operational land imager (OLI) optical image of southern Florida showing the TanDEM-X SAR tracks collected on August 26 (yellow rectangle) and 31 (red rectangle), 2015. Red ellipse marks high and dense mangrove vegetation area. (b) TanDEM-X SAR amplitude images of the two swaths showing the locations of stage stations in the ENP wetland. Yellow circles mark stage locations to validate the estimated absolute water level, whereas red circles indicate the excluded stage station locations as outliers.

topography along southern Florida. Anthropogenic changes over the past century have significantly altered the natural drainage pattern and the Everglades landscape ecosystem. The northern section of Everglades is currently compartmentalized into several water conservation areas, restricting water flow from Lake Okeechobee to the Gulf of Mexico. The natural wetland sheet flow in the southern section of Everglades has been preserved as Everglades National Park (ENP). Here, one of the densest networks of stage stations worldwide monitors surface water levels to conserve and restore the wetland hydrological system.

We focus on the western part of the ENP, which consists of freshwater and saltwater wetland [see Fig. 1(a)]. Herbaceous vegetation, such as sawgrass, is dominant in freshwater swamps in the northeastern part of the study area, whereas saltwater woody and dense mangrove forests are distributed in the saltwater wetland in the southwestern area. There is a transition zone with mixed vegetation between the freshwater swamps and saltwater mangroves, containing prairies and shorter scrubs. This entire area was selected to extract the absolute water level in natural wetland environments with different vegetation types using simultaneous TanDEM-X SAR observations.

III. Data

Our study relies on TanDEM-X co-registered single-look slant range complex (CoSSC) observations collected during the science phase. The TanDEM-X science phase was temporarily operational from October 2014 to December 2015 to demonstrate new SAR techniques with unique orbital configurations. A large perpendicular baseline configuration inversely proportional to the height of ambiguity enables the construction of more accurate DEMs in low-sloped areas such as intertidal or glacial surfaces [11]. We utilized two datasets of two consecutive TanDEM-X CoSSC interferometric pairs in the bistatic StripMap (SM) mode acquired on August 26 and 31, 2015. The X-band radar carrier frequency was 9.6 GHz (3.1 cm in wavelength) with horizontal–horizontal polarization. The detailed characteristics of the collected TanDEM-X images are summarized in Table I. The pursuit of monostatic TanDEM-X acquisition composed of two independent TerraSAR-X and TanDEM-X images with only 10 s of temporal baseline can also be utilized to extract the surface topography [11]. However, the bistatic TanDEM-X observations were preferable for water level extraction because of its zero temporal baseline, which means that the water level did not change during the period between two SAR observations.

TABLE I
TanDEM-X Bistatic SAR Data Characteristics

Parameter	TanDEM-X Bistatic SAR	
Acquistion date	August 26, 2015	August 31, 2015
Carrier frequency	X-band (9.65 GHz)	
Wavelength	3.1 cm	
Polarization	HH	
Incidence angle	33.48 deg	34.01 deg
Pulse repetition frequency	3832.52 Hz	3599.52 Hz
ADC sampling rate	164.8 MHz	
Azimuth pixel spacing	0.91 m	
Range pixel spacing	1.85 m	1.97 m

To validate the extracted absolute water levels, we used hourly stage water level data from a total of 38 stations [see Fig. 1(b)] and interpolated water surface map from the everglades depth estimation network (EDEN). The U.S. Geological Survey (USGS) and the South Florida Water Management District (SFWMD) operate the stage stations, and the EDEN archive distributes the stage data [12]. Because of inconsistency in vertical datum of all stage records, we converted measurements acquired in the NGVD29 datum to NAVD88, using the vertical conversion parameter [1], [3]. The EDEN water surface maps were spatially interpolated using daily median values of the water level stage network and compared with the constructed water level maps. The EDEN water surface map was generated on the spatial referencing grid with a resolution of 400 m $\times$ 400 m [13]. Unfortunately, the daily water surface maps are constructed without containing the water level in the mangrove tidal zone along the coast.

IV. Data Processing

We applied the InSAR technique assuming that the topographic phase information at the water surface reflects the absolute water level using simultaneous TanDEM-X SAR bistatic observations without any surface change over time. A severe volume decorrelation in the tall and dense vegetated area can be expected at the large perpendicular baseline configuration in the bistatic observation mode. However, a sensitive height of ambiguity owing to the large geometric

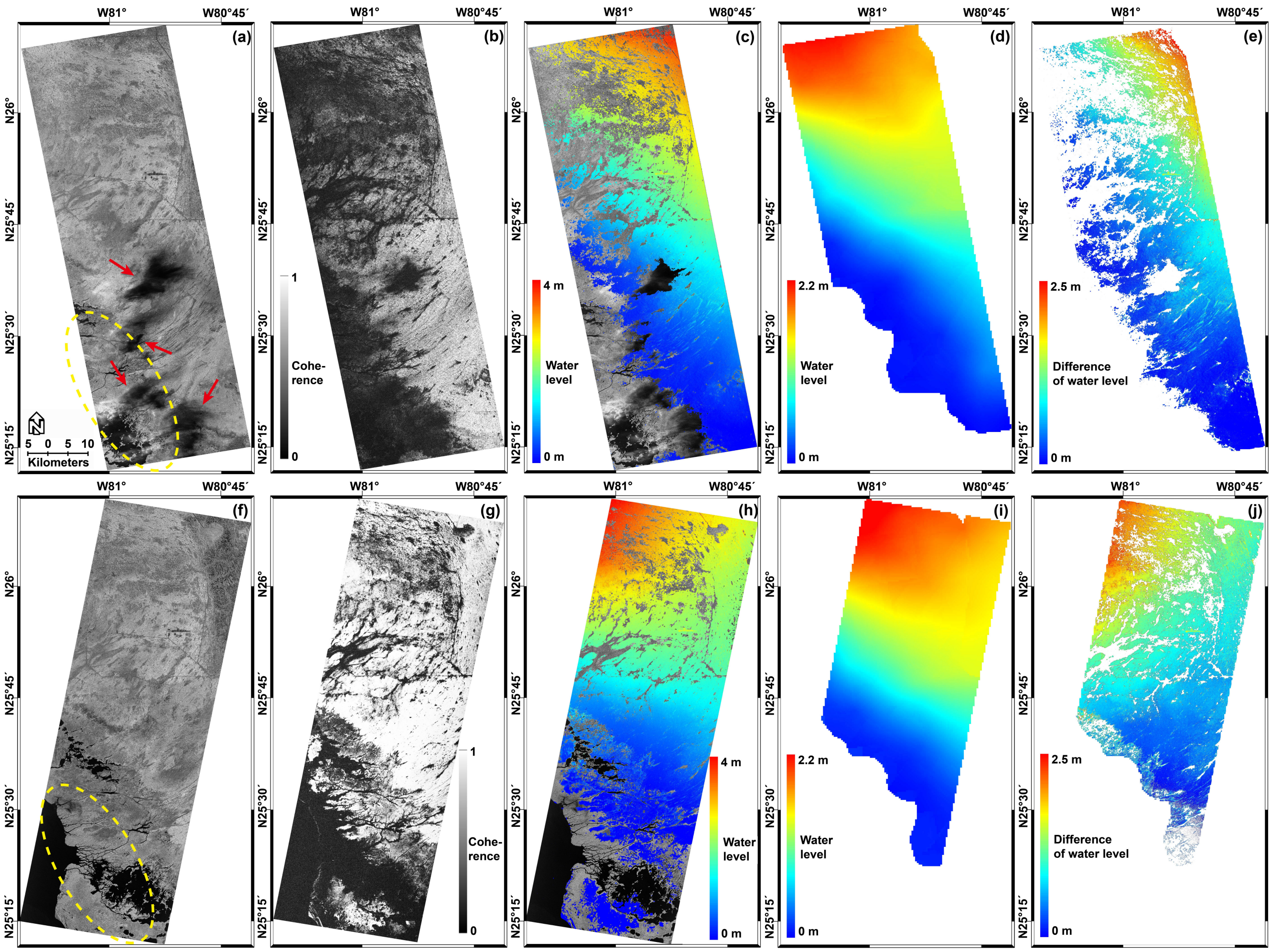

Fig. 2. (a) and (f) Backscattered amplitude images and (b) and (g) coherence maps of the August 26 (top) and 31 (bottom) 2015 acquisitions. Severe coherence degradations were detected in the high and dense vegetated areas and tree islands [yellow dot ellipse in (a) and (f)]. Significant radar signal attenuation by atmosphere was identified in the middle and lower part of images, marked by red arrows in (a), leading to a loss of coherence. (c) and (h) Extracted absolute water level maps scaled from 0 to 4 m. (d) and (i) EDEN interpolated water surface maps obtained from the daily median stage data [14]. (e) and (j) Residual map between the InSAR-derived and EDEN water surfaces showing deviation up to about 2.5 m. Linear ramps in both residual maps indicate systematic disagreements between the two maps.

baseline is very useful in retrieving accurate topographic phase height in a low-sloped surface. Nevertheless, a careful spectral filtering and phase unwrapping procedure should be applied to compensate for the spectral shift in the range direction and undesirable interferometric phase aliasing owing to the small height of ambiguity.

We utilized the Gamma software package to process the TanDEM-X CoSSC acquisitions to generate topographic interferograms [14]. Although the TanDEM-X CoSSC products have already been co-registered during the synchronization of the two bistatic observations, we conducted precise co-registration at a sub-pixel scale to reduce the decorrelation effect [15]. Common band filtering was applied to consider wavenumber shifts in the range direction owing to a large geometric baseline. The spectral common band filtering in azimuth direction was also applied, although the difference in the Doppler central frequency of only 9.3 and 28.6 Hz is small enough not to result in Doppler decorrelation. The flat earth phase removal was performed with half of the baseline, considering the bistatic SAR configuration. The height of ambiguity in each interferometric pair was 3.61 and 3.90 m at 1434.3 and 1355.7 m of the perpendicular baseline, respectively (see Table II). The residual interferometric fringes were removed by estimating the fringe rate using a 2-D fast Fourier transform and a least square quadratic polynomial model using the unwrapped phase. A multilooking process with 4 by 4 factors and adaptive radar filtering with a window size of 32 pixels was applied to increase the signal-to-noise ratio. Despite a loss of spatial resolution from approximately 2 to 8 m by the multilooking factor, a spatial resolution of less than 10 m provided sufficiently detailed information of water flow that cannot be measured at a stage station. A coherence analysis using a 5×5 pixel window was conducted to evaluate the InSAR quality between two SAR observations. The minimum cost flow algorithm was used with a mask to remove the area where coherence was lower than 0.9 to unwrap the differential interferometric phase [14]. Finally, the unwrapped phase was converted into a height map and

TABLE II
LIST OF TANDEM-X X-BAND BISTATIC INTERFEROMETRIC PAIRS

No	SAR IMAGE		B_P[a]	HOA[b]	B_T[c]	γ_{MEAN}[d]
	PRIMARY	SECONDARY				
1	August 26, 2015		1434 m	3.61 m	0 sec	0.40
2	August 31, 2015		1355 m	3.90 m	0 sec	0.61

[a] B_P - absolute perpendicular baseline.
[b] HOA - absolute height of ambiguity.
[c] B_T - temporal baseline.
[d] γ_{MEAN} - an average coherence.

an absolute water level map on the water surface through a geocoding process. The absolute offsets for the derived height maps were estimated by comparison with stage station water level measurements.

V. RESULT

The constructed TanDEM-X bistatic interferograms in Fig. 2 show very high coherence over the water surface. This has been achieved as a result of zero temporal baselines owing to the low temporal decorrelation compared with repeat-pass interferometric SAR pairs [2]. However, a significant coherence degradation owing to volume decorrelation from a large perpendicular baseline was detected in dense and highly vegetated areas at the southwestern part of the image. The boundary of the degraded coherence, where the vegetation was well developed [yellow dot ellipse in Fig. 2(a) and (f)], was identified by comparing it with optical images [red dot ellipse in Fig. 1(a)]. The overall pattern of interferograms represents a very long fringe wavelength, reflecting a smooth water surface in the wetland environments. Tilted fringe patterns of both interferograms show low gradient water surfaces from the northern to southwestern part of the Everglades wetland rather than the residual orbital fringe. It is interesting that the coherence of the interferometric pair (>0.61) on August 31, 2015, was higher than that of the other pair (>0.4) acquired on August 26, 2015, although the difference in the perpendicular baseline was only 78.6 m. Several severe signal attenuation patched were detected in the amplitude image of August 26, 2015 [dark areas, marked by red arrows in Fig. 2(a)]. These patched reflect atmospheric phenomenon, because they do not appear in the August 31, 2015 image [see Fig. 2(f)]. According to their diffusive shape, they very likely related to thick cloud conditions. A detailed topographic variation could be retrieved by the small height of ambiguities, which might not be achieved in a typical satellite orbit configuration.

Scatter plots were displayed using hourly water level measurements at the stage stations to evaluate and calibrate the extracted absolute water level [see Fig. 3(a) and (b)]. We assumed that: 1) there is a single offset between two measurements (water level at stage stations = water level from the TanDEM-X + offset) and 2) the low coherent phase disturbed by volume scattering in the vegetated area could not contain water surface level information. The scatter plots showed an excellent correlation (degree of determination >0.96), and the estimated offsets were -3.17 and -3.39 m, respectively. However, some stage measurements, marked in red in Fig. 1(b), were excluded as outliers based on coherence criteria (<0.3). Most outliers were located at stage stations in relatively heavily vegetated areas or artificial levees. A validation analysis using a root mean square error (RMSE) estimator shows sub-meter accuracy (0.66–0.77 m).

We also compared the extracted absolute water level maps with the EDEN spatially continuous maps, which were interpolated using daily median value of the stage station water level measurements [see Fig. 2(d) and (i)]. The comparison indicates that both water level maps show similar patterns, although they have significantly different height variation. While the TanDEM-X-derived maps range from 0 to 4 m [see Fig. 2(c) and (h)], the EDEN maps are in the range of 0–2.2 m [see Fig. 2(d) and (i)]. The residual maps between the InSAR-derived and the EDEN interpolated water surface maps show deviation up to 2.5 m [see Fig 2(e) and (j)].

VI. CONCLUSION AND DISCUSSION

The TanDEM-X bistatic SAR interferometric observations with large perpendicular and zero temporal baselines collected during the science phase enabled the successful extraction of absolute water level maps that cannot be generated using a conventional repeat-pass interferometric pair. The small height of ambiguity, which is inversely proportional to the perpendicular baseline, provides spatially detailed water level maps. We evaluated two TanDEM-X observations over the Everglades wetland in South Florida, USA. Coherence was degraded because of severe volume decorrelation in vegetated areas. However, higher coherence (>0.7) was maintained in herbaceous wetland where we observed phase differences related to the water level, which is the topographic height in the solid earth, owing to double-bounce scattering. The validation results using hourly water level measurements from the EDEN showed excellent agreement (degree of determination > 0.95) between the derived absolute water levels and the stage station measurements [see Fig. 3(a) and (b)]. The uncertainty analysis using the RMSE estimator reveals the range of 0.66–0.77 m. Note that RMSE level of the result in this study has been improved compared with previous operational TanDEM-X DEM assessment over the woody wetland ($\sim$1.81 m RMSE level, [16]).

Even though the EDEN water surface map was interpolated by daily median water level from nearly 300 stage stations, there is deviation with the InSAR-derived absolute water level. To assess the EDEN water surface map, we compared the water levels between stage stations and the surface maps. The comparison show good correlations between the stage and EDEN interpolated water level values [linear trend–red lines in Fig. 3(c) and (d)]. However, because the slope of the regression line is not 1 (black line), the EDEN interpolated values have systematic variation from 0 to 2 m, causing large RMSE level from 14.66 to 18.26 m at the single offset fit model [see Fig. 3(c) and (d)]. We suspect that the systematic discrepancy ($\sim$1.7 of the gradient) between the measured and interpolated values reflects interpolation errors possibly caused by the limited number of stage stations in a coarse-resolution grid.

Although the TanDEM-X bistatic mode observation might be the only tool to extract a 2-D water level map with high

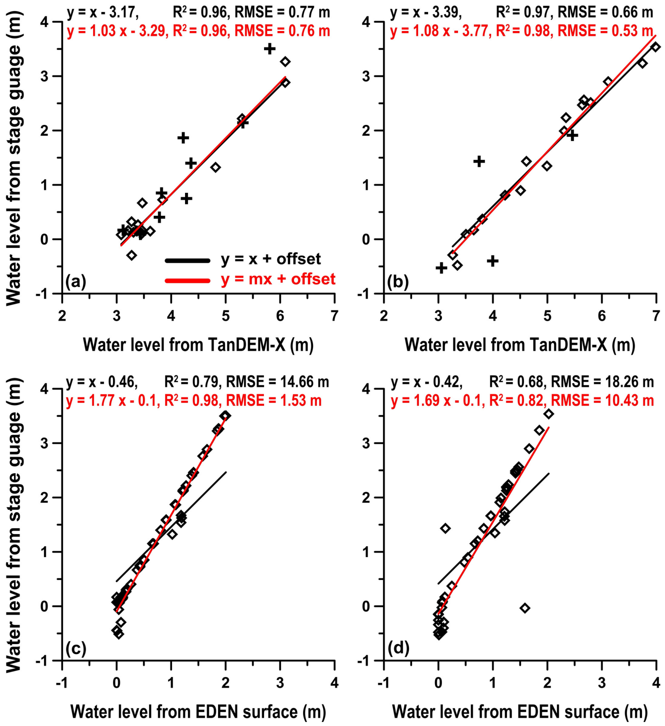

Fig. 3. Calibration plots of the absolute water level maps in (a) August 26, 2015 and (b) August 31, 2015. Assuming that there is a single offset between two observations ($y = x+$ offset), the estimated offsets between InSAR and stage station observations were used to adjust the derived water level instead of reference points. The black solid-line plots show excellent agreement (degree of determination > 0.95), and the estimated RMSE is 0.77 and 0.66 m, respectively. The symbol "+" marks outliers omitted from the calibration offset calculations because of mostly low coherence. The red line's best-fit plots show a very similar linear pattern with a single offset fit model. A best-fit in black solid-line and a single offset fit in red is displayed to compare hourly water level stage station measurements with interpolated EDEN surface map using daily stage station data in (c) August 26, 2015 and (d) August 31, 2015. Although both measurements show a good correlation (degree of determination of 0.68–0.79), systematic gradients ($\sim$1.7) causing worse RMSE level ranges from 14.66 to 18.26 m have been estimated. Thus a single offset fit model shows a divergent pattern to a best-fit model.

spatial resolution in wetland, practical hydrological applications might be limited. The science phase, which was a campaign mode for testing new technology, was not operational. Thus, the large perpendicular baseline during the science phase is very useful for achieving the height of ambiguity. However, severe volume scattering from its geometric configuration prohibits high coherence in calculating the water level in wetland with woody and dense vegetation. Because the longer-wavelength SAR signal benefits from maintaining coherence in the wetland area, a constellation SAR mission such as TanDEM-L could be a beneficial resource for absolute water level extraction from space-based observations. Although the height of ambiguity should undoubtedly decrease at longer wavelengths, the volume decorrelation in multiple scattered vegetated areas can be reduced [17]. As a result, more coherence phase information on the water surface can be retrieved. A multitemporal absolute water level map can help to better understand hydrology of water flow in wetland environments for conservation and restoration purposes.

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