InSAR-based hydrology of the Everglades, South Florida

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ABSTRACT

New space-based observations of South Florida reveal spatially detailed, quantitative images of water levels in the Everglades, the focus of the largest wetlands restoration project yet attempted. The new data capture dynamic water level topography, providing the first three-dimensional regional-scale picture of wetland sheet flow. We observe localized radial sheet flow in addition to well-known southward unidirectional sheet flow. Our study shows that space-based hydrological observations can provide critical information for monitoring, understanding and managing wetland sheet flow, and contribute to wetland restoration.

1 INTRODUCTION

The Everglades region in south Florida (Fig. 1a) is a unique ecological environment. It is a gently sloping surface flow that drains Lake Okeechobee southwards into the Gulf of Mexico. The combination of abundant water and sub-tropical climate results in a wide diversity of flora and fauna. Anthropogenic changes in the past 50 years, mainly for water supply, agricultural development and flood control purposes, have disrupted natural water flow and severely impacted the regional ecosystem. Currently, Everglades flow is controlled by a series of hydraulic control structures to prevent flooding and regulate flow rates, but which also suppress natural water level fluctuations, essential for supporting the fragile wetland ecosystem. This controlled Everglades environment provides a large-scale laboratory for monitoring and modeling wetland surface flow. Enhanced modeling capabilities and understanding of the Everglades hydrological system are essential for the Everglades restoration project, which is the largest and most expensive (multi-billion dollar) wetland restoration project yet attempted.

The Everglades are currently monitored by a network of stage (water level), meteorological, hydrogeologic, and water quality control stations, providing daily average estimates of water level, rainfall and other key hydrologic parameters. Monitoring is conducted by the South Florida Water Management District (SFWMD), United State Geological Survey (USGS), and the Everglades National Park (ENP). Due to the limited number of stations (station spacing ~ 10 km) and their distribution, mainly along existing structures, the current data can constrain regional scale models, such as the 2 x 2 mile2 South Florida Water Management Model (SFWMM), but lack the spatial density for more detailed models.

In this study, we use new space-based hydrologic observations of water levels in the Everglades, with spatial resolution (~30 x 30 m2) more than two orders of magnitude higher than the existing ground network. The observations are derived from Synthetic Aperture Radar (SAR) data acquired by low earth-orbiting satellite, processed using interferometric methods [1]. Alsdorf et al. [2] demonstrated that interferometric processing of L-band SAR data (wavelength 24 cm) acquired at different times is suitable to detect water level variations in wetlands with emergent vegetation (measurement accuracy 3-6 cm). The radar pulse is backscattered twice (“double-bounce” [3]), from the water surface and vegetation (Fig. 1b). A change in water level between the two acquisitions results in a change in travel distance for the radar signal (range change), which is recorded as a phase change in the interferogram. By integrating the space-based observation of relative water-level changes with the stage data, we are capable of translating the InSAR observations into actual water level heights and derive the inferred hydrologic flow.

2 InSAR OF THE EVERGLADES

Our data consists of three SAR passes over South Florida acquired by the Japan Earth Resources Satellite (JERS-1) in 1994 (1994/6/24, 1994/8/9, and 1994/12/19), at the beginning, middle, and end of the local wet season (June-November). The JERS-1 operated a L-band SAR during 1992-1998 with frequency 1.275 GHz, 75-km swath, and 18-m resolution. We calculated 3 interferograms, spanning 44 days (June-August), 132 days (August-December), and 176 days (June-December) covering the rural Everglades and urban Miami-Fort Lauderdale (Fig. 1a). The interferogram
calculations include phase unwrapping, but not topography phase removal, because the south Florida topography is flat. The interferograms’ baselines are in the range of 214-647 m.

The June-August interferogram shows very high interferometric coherence, in both rural and urban areas, and allows the following observations: (1) Significant elevation changes occur in the controlled-flow regions (within the white box in the upper half of Fig. 1b). (2) Discontinuities occur across man-made structures (canals, levees, and roads), and (3) Elevation changes in Miami-Ft. Lauderdale metropolitan area are small. The fringes in the urban area show patterns of small (~1 km diameter) subsidence "bulls-eyes" that occur at known well-field locations where ground water pumping occurs. The high pumping rate temporarily lowering the water table and leading to elastic deformation in the vicinity of the well head [4]. The two other interferograms, spanning longer periods, have lower coherence. We applied a spatial filter, improving the interferogram quality with some degradation in horizontal resolution (100x100 to 300x300 m²), still significantly better than any available terrestrial monitoring technique.

**Fig. 1:** (a) RADARSAT-1 ScanSAR image of Florida showing location of study area (RADARSAT data © Canadian Space Agency / Agence spatiale canadienne 2002. Processed by CSTARS and distributed by RADARSAT International). (b) Cartoon illustrating the double-bounce radar signal return in vegetated aquatic environments. The red ray bounces twice and returns to the satellite, whereas the black ray bounces once and scattered away. (c) JERS L-band interferogram of the eastern south Florida area showing phase differences occurring during 44 days (1994/6/26-1994/8/9). Each color cycle represents 15.1 cm of elevation change (See color scale in Fig. 2).
The observed lateral phase changes (colors in Fig. 2b) might be attributed to lateral variation of atmospheric water, in addition to surface displacement. Atmospheric effects would appear as random shapes with fuzzy boundaries, similar to clouds [5]. The fuzzy small patched of phase changes in the urban area well correlates with well fields and, hence, are attributed to anthropogenic changes. The larger phase change patterns occur in the rural Everglades region and are truncated along straight lines associated with man-made structures. Thus, we attribute the observed phase changes purely to surface displacements. Each phase cycle ($2\pi$) corresponds to 12 cm of displacement in the radar line-of-sight, corresponding to 15.1 cm of vertical displacement [6]. Lateral phase changes in the urban area reflect vertical displacements of the solid surface. Over wetland environments, the observed phase changes reflect water level or vegetation changes. Assuming the latter are small they correspond to water level changes.

Fig. 2: L-band backscatter amplitude and interferograms of the Water Conservation Areas (WCA) 1, 2A, and 2B (location in Fig. 1c). (a) Amplitude (brightness) variations represent radar backscatter, which depends on the surface dielectric properties and surface orientation with respect to the satellite. The small, elongated white areas in the WCAs are vegetated tree islands ($10^2$), aligned along regional flow direction. Large white areas in 2A and 2B are dense vegetated areas. (b) 176-day (June-December) interferogram, (c) 132-day (August-December) interferogram, and (d) 44-day (June-August) interferogram. The interferograms show (i) the largest water level changes occurred in area 2A (up to 1 m – 7 cycles in (c)) and smaller scale ones in areas 1 and 2B. (ii) The pattern of water level change is unidirectional in the eastern section of area 2A and radial in the western part. In the northern section of area 2B the water level change is characterized by 3 bulls-eye radial patterns (b and c).
3 INSAR DETECTED WATER LEVEL CHANGES

The most significant elevation changes occur in the northern section of the interferogram, across man-made structures, known as Water Conservation Areas (WCA) 1, 2A, and 2B. Fig. 2 shows both the L-band backscatter amplitude and interferograms for the three time spans. The amplitude (brightness) variations (Fig. 2a) represent the radar scatter, which depends on the surface dielectric properties and surface orientation with respect to the satellite. The small, elongated white areas are vegetated tree islands aligned along the long-term regional flow direction. The large white areas in areas 2A and 2B are dense vegetated areas. The pattern of water level change is unidirectional in the eastern section of area 2A and radial in the western part. In the northern section of area 2B the water level change is characterized by 3 radial (“bulls eye”) patterns (b and c). The interferometric phase (Fig. 2b, 2c and 2d) show water level changes in area 2A; the change direction and amount vary. The change in Fig. 2b indicates water level decrease towards the NE by about 60 cm (4 cycles), in Fig. 2c a NE decrease of about 105 cm (7 cycles), and in Fig. 2d an increase by 45 cm (3 cycles with opposite color scheme), which agrees with the difference between (2b) and (2c).

Fig. 3 shows the June-December water level changes in areas 1, 2A, 2B and their surroundings. Because InSAR measures relative changes within each area, but not between the areas, we assigned in each area the lowest change level to zero. The most significant water level changes occur in the eastern section of area 2A, where the level changes can be described by a series of NWN-ESE almost parallel contours. The water level changes are illustrated in a profile perpendicular to water level contours in the eastern part of area 2 (white lines in Fig. 3a). The profile (solid blue line in Fig. 3b) shows a southward increase in the water level change in all areas. The overall gradient and shorter wavelength variations vary from one area to the other. The highest gradient is in area 2A, whereas in area 2B high gradient occurs only near the levee and further south the gradient in water level change is very small.

Fig. 3: (a) InSAR-based water level change map for the June-December time interval of areas 1, 2A and 2B. Red triangles mark the location of stage stations and the white line marks the water level profile location, drawn perpendicular to water level contours. The characters (A, C and D) and (digits 4, 5 and 6) mark gate locations, presented in Table 1. (b, c, and d) Comparison between the zero-offset InSAR and the stage data calculated separately for each area. The bracket values in (c) are obtained after removing two outliers (located above the dashed line). (e) Comparison between InSAR and stage water level changes along the profile. Stage data observed in the center of areas 1 and 2A are projected onto the profile. The vertical dashed lines mark the location of levees separating between the conservation areas. The corrected InSAR curve (dashed line) is calculated from a least-square adjustment.
In order to validate and calibrate our InSAR technique, we compared the InSAR observations with stage data (red triangles in Fig. 3a) collected by the South Florida Water Management District’s DBHYDRO hydrologic database. The stage data consist of daily average level above the NGVD29 datum. We use these data to calculate water level differences between the two acquisition dates. Comparison between the InSAR and stage data shows excellent agreement for each of the three water conservation areas (Fig. 3b, 3c and 3d). The InSAR values are calculated from the nearest pixels to the stage station. Unfortunately, most of the stage stations are located along the levees, where the InSAR data is less reliable due to edge effect of the spatial filter. The InSAR-based water level changes reflect a wider area and in some cases are a few hundreds meter away from the actual location of the stage stations. The calculated offset and rms in area 2A (Fig. 3c) are strongly biased by two outliers. Fig. 3c shows the estimated offset and rms difference with (11.3 cm rms) and without (5.1 cm rms) these outliers. Area 2B has a small number of stage measurements with limited geographic distribution, but nevertheless shows reasonable agreement between the two date sets (8.0 cm rms). We conducted the same least-square analysis with the other two interferograms (June-August and August-December), which yields very similar rms values, and conclude that the precision of the InSAR water level change measurements is ~5 cm. It also allows us to compute and correct the datum offset between stage and InSAR data, which were set arbitrarily to zero value at the lowest level in each area (Fig. 3e).

4 FROM WATER LEVEL CHANGES TO WATER LEVELS

The new space-based observations provide, with very high spatial resolution, water level changes in the Everglades occurring over 44, 136 and 176 day time intervals (Fig. 3, 4a and 4b). Because these time intervals are long compared to the duration of natural and man-made water level changes in the Everglades (days to several weeks), the observed water level changes represents the differences between two states and not a continuous process. Fig. 4c and 4d present stage elevations during the three observation periods. The December InSAR observation occurred during a period of negligible water flow across the conservation areas (Table 1), resulting in almost flat water levels in the three areas (red lines in Fig. 4c and 4d). By using the December stage data as a reference level, we calculate the June and August water levels along the profiles (blue lines), which agree well with the available stage data for the two time periods. The InSAR observations thus provide important details of water level changes in the entire study area not available by the stage data. Fig. 4e and 4f show the corresponding June and August water levels.

![Figure 4](https://example.com/fig4.png)

**Fig. 4:** (a) Water level changes along the profile in Fig. 3c, showing corrected InSAR curve and stage data for June-December time interval. Vertical dashed lines mark location of levees separating the WCAs. (b) Water level changes for the August-December time interval. (c) June and December water levels along the profile. Based on the December stage data (red squares) and gate information (Table 1), we assume flat water level in each area (red lines). The June water level (blue line) is obtained by subtracting the corrected InSAR curve from the assumed flat December level. The calculated June curve fits well with the stage data. (d) August and December water levels following the same procedure as in (c). (e) Three-dimensional illustration of the June water levels, calculated by subtracting the corrected InSAR data from the assumed flat December levels, for the entire studied area. (f) Three-dimensional illustration of the August water levels.
The InSAR observations represent snapshots of dynamic water topography during the June and August observations, dominated by gate operations (Table 1, Fig. 3), allowing water to flow from area 1 to 2A and from 2A to 2B. Using the gate flow information, the following details can be observed and explained, illustrative of how InSAR data can enhance gate operations to better mimic natural flow conditions: (1) The observed difference across area 2A is significantly higher in August than June because of August’s higher flow rate across the S-10 gates. (2) The shape of the lowest water level change along the 1-2A levee is long and linear in August (Fig. 3b) and shorter in June because gate S-10D was closed during the June observation period. (3) Both maps show three small bull-eye patterns in the north of area 2B, reflecting low flow rates across gates 145, 146 and 147. (iv) The “bulls-eye” patterns are not observed in the June-August interferogram (Fig. 2d), reflecting the existence of similar dynamic topography both in June and August caused by similar flow rates across the same gates.

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The rates are in CFS (cubic feet per second). The data was collected by the SFWMD at the gates feeding and draining area 1A. (Data source: DBHYDRO). The symbol indicates the gate location in Figure 3a.

5 CONCLUSIONS

L-band InSAR can measure water levels in the Everglades and other wetlands with high spatial resolution and a vertical precision of ~ 5 cm. These data can be used in an operational sense to better understand the flow regime, and can also yield high-resolution estimates of important physical flow properties, e.g. flow friction. These in turn can be used to spatially and temporally characterize the distribution of resistance to flow (surface roughness) associated with different types of soil, vegetation coverage and land use, and better manage these important wetland environments.

6 REFERENCES