Supplementary Material

Figures S1 and S2 detail the workflow for our methodology. Figure S1 describes the processing of raw data into the various rasters. Figure S2 describes how we gathered our training data, created a machine learning classifier, classified our testing data, and validated the results.
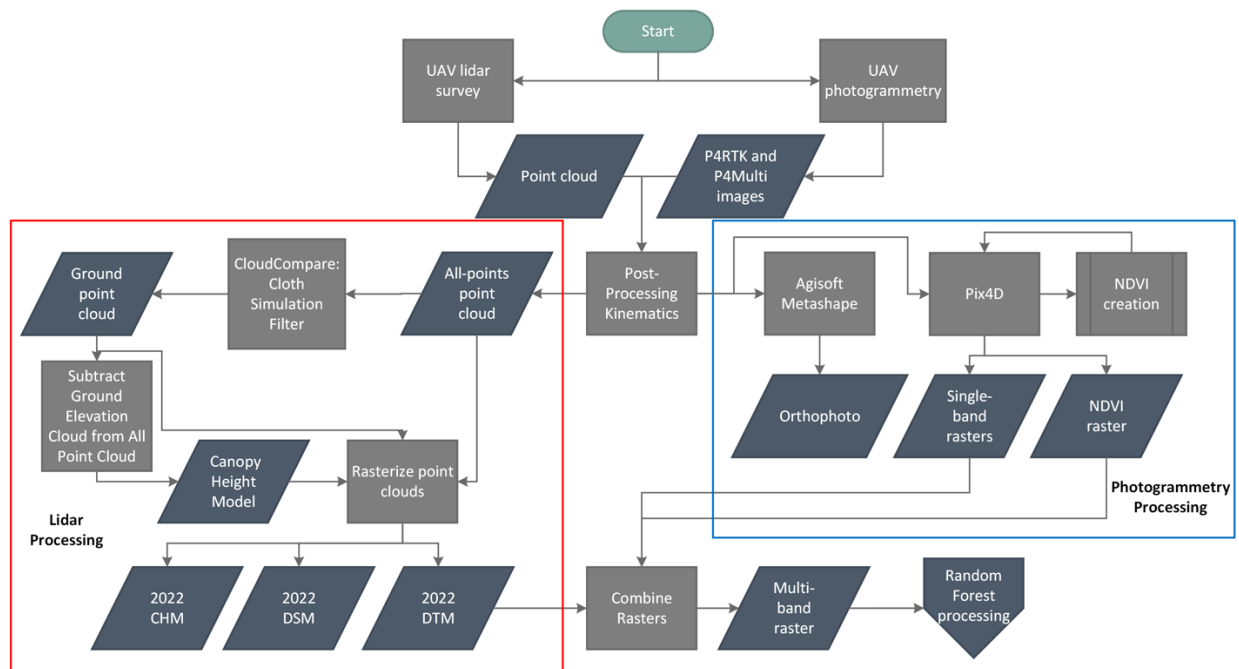

Figure S1. Workflow for processing the LiDAR and photogrammetry surveys to create a multi-band raster.
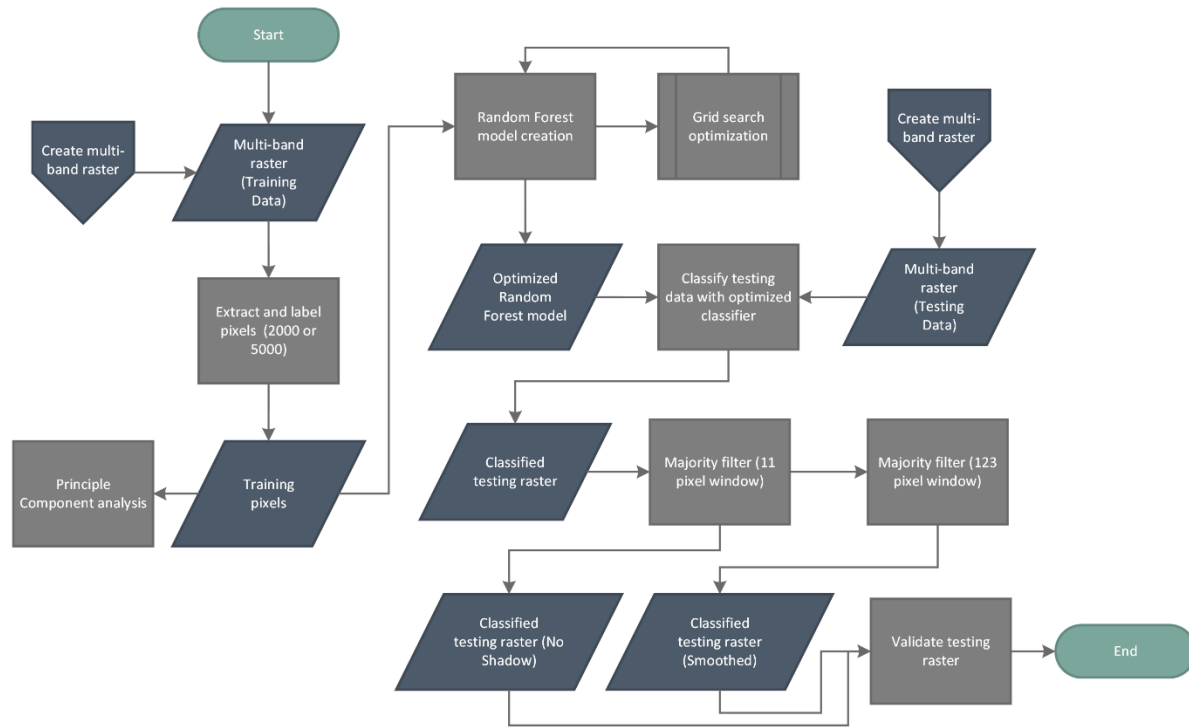
Figure S2. Workflow for the random forest classification. The segment titled 'Create multi-band raster' comprises the workflow described in Figure S1.

UAV-Photogrammetry PPK

In UAV photogrammetry, the use of an RTK (Real-Time Kinematic) tracked drone is often advertised as a way to decrease or eliminate the need for Ground Control Points (GCPs). Although this technique can indeed lead to more precise and faster output from SfM (Structure from Motion) software, it can lead to unwanted bias and distortion in the output models. Figure S3 compares the elevations along the paved road at our test site between the ground-based total station elevation survey (black line) and the SfM model using UAV flight height from the RTK data (green line). This figure shows that the SfM model is higher at the southern end of the survey than it should be with respect to the ground-based total station survey. This figure also shows that using PPK (Post-Processing Kinematic) solutions (blue line) for the UAV position and then using these new positions as camera locations in the SfM processing, almost completely removes this bias.
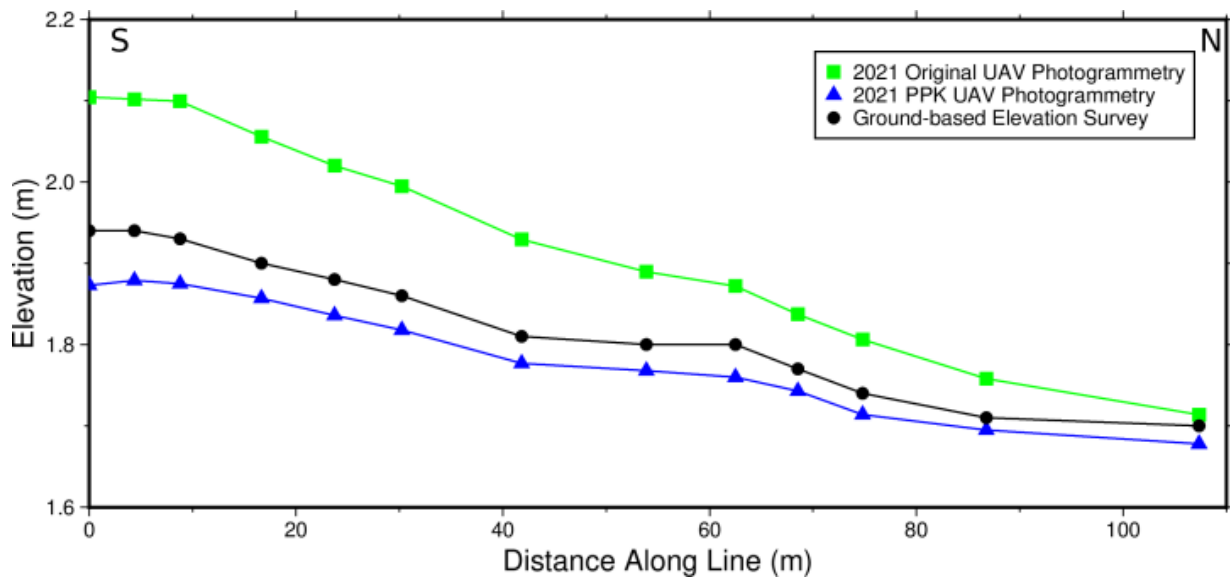
Figure S3. Comparison of modeled DEM derived from RTK (green squares) and PPK (blue triangles) UAV positioning with ground-based total station elevation survey ('Ground Truth') along the paved road at Fort De Soto (black circles). Point locations correspond to the white points in Figure 5

Figure S4 (left) shows that the camera positions fed to the SfM software by the RTK system describe a flat surface above the ground that only varies by about ±3 cm. In contrast, the PPK position (center) indicates that the flight path has a domed structure with lines at the north and southern ends of the surveyed area significantly lower (>5cm) than the expected flight path. For each flight line the difference between the expected flight path and real height above ground increases by a few cm as the lines move away from the GNSS base station on the ground. This behavior may reflect the fact that during the turn between flight lines GNSS signal lock can be lost, resulting in fewer tracking data for the next line. Multipath may also increase during the turn, resulting in noisier data and loss of lock.

The observed differences between the RTK-calculated UAV position and the real (PPK) UAV position, and particularly the doming shape of the real flight path, map a bias into the modeled DEM when using RTK UAV positions.
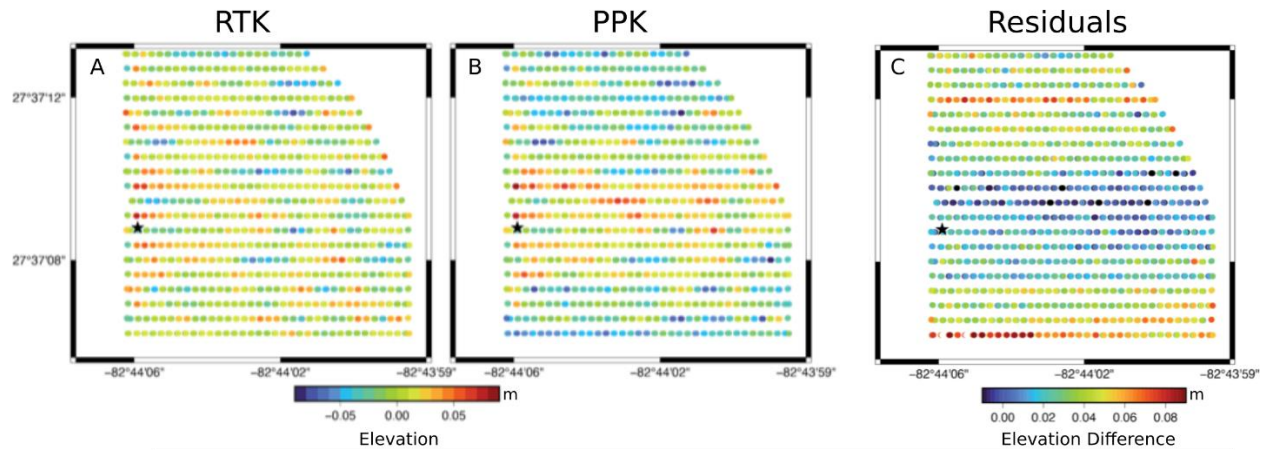
Figure S4. A: UAV position and elevation (in meters with respect to expected flight path above ground) with only RTK showing a constant offset away from the RTK base. B: UAV position and elevation after PPK processing. C: The difference between RTK minus PPK. The black star shows the location of the RTK base.

The PPK solutions for UAV position were done utilizing only the GNSS data collected by the drone and the ground base station. The ground station collected data for more than 2 h and its position was computed using both the OPUS service provided by the National Geodetic Survey (https://geodesy.noaa.gov/OPUS/) and the FPRN service provided by the Florida Department of Transportation (https://www.fdot.gov/geospatial/fprn.shtm). These two approaches gave results that were equivalent within uncertainties. Tropospheric delay was then computed solving for the base station position in PPP mode using RTKlib version 2.4.2 [65]. The RINEX files collected by the base station and the UAV were then processed as kinematic solutions in double difference mode using RTKlib with final GNSS orbits and clocks from CODEs [66] in ITRF2014 reference frame. Our data processing used the VMF1 tropospheric mapping function [68] and the second-order ionosphere correction from the JPL IONEX files (https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html).

In our view, PPK solutions are critical to minimize distortions and achieve accurate georeferencing when a limited number of GCPs are available. This approach includes deciding which orbit estimates will be used for the PPK solution. There is a trade-off between waiting for final processed orbit estimates (2 weeks or more after real-time, 3D RMS accuracy ~2.5cm) or processing the data sooner with lower accuracy orbit estimates. Rapid orbits are available the next day, with ~3.5 cm accuracy, or ultra-rapid with less than 2 h latency and similar accuracy [67]. This choice can be tailored to the specific needs of the project. In some cases, data may need to be processed twice.

Additional GCPs, particularly for areas far away from the base station, are probably the best way to avoid biases due to fly path distortion. However, this may introduce logistical challenges in the field. Whenever possible, UAV positions should be calculated using PPK solutions and DEM products created from those improved UAV positions.