Evaluation of Optical Flow Based Methods for Temporal Satellite Imagery

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Introduction and Motivation

- Optical Flow (OF) is defined as the "distributions of apparent velocities of movement of brightness patterns in an image" (*Horn and Schunck 1981*).
- OF retrievals are enabled for most cloud and water-vapor motions by the Geostationary Operational Environmental Satellite (GOES)-R Advanced Baseline Imager (ABI) spatial and temporal resolutions (**Fig. 1a**).
- Dense (every image pixel) OF retrievals enable temporal interpolation of CONUS imagery and accurate estimations of winds from cloud motions.
- Accurate temporal interpolation provides unprecedented proxy fine temporal resolution imagery over much larger domains than native ABI alone. (**Fig. 1b**)
- Temporal interpolation also improves image compositing algorithms which blend imagery from multiple instruments scanning at different times,
- This study aims to find the best approaches for computing OF to render the most accurate temporal interpolation outputs.

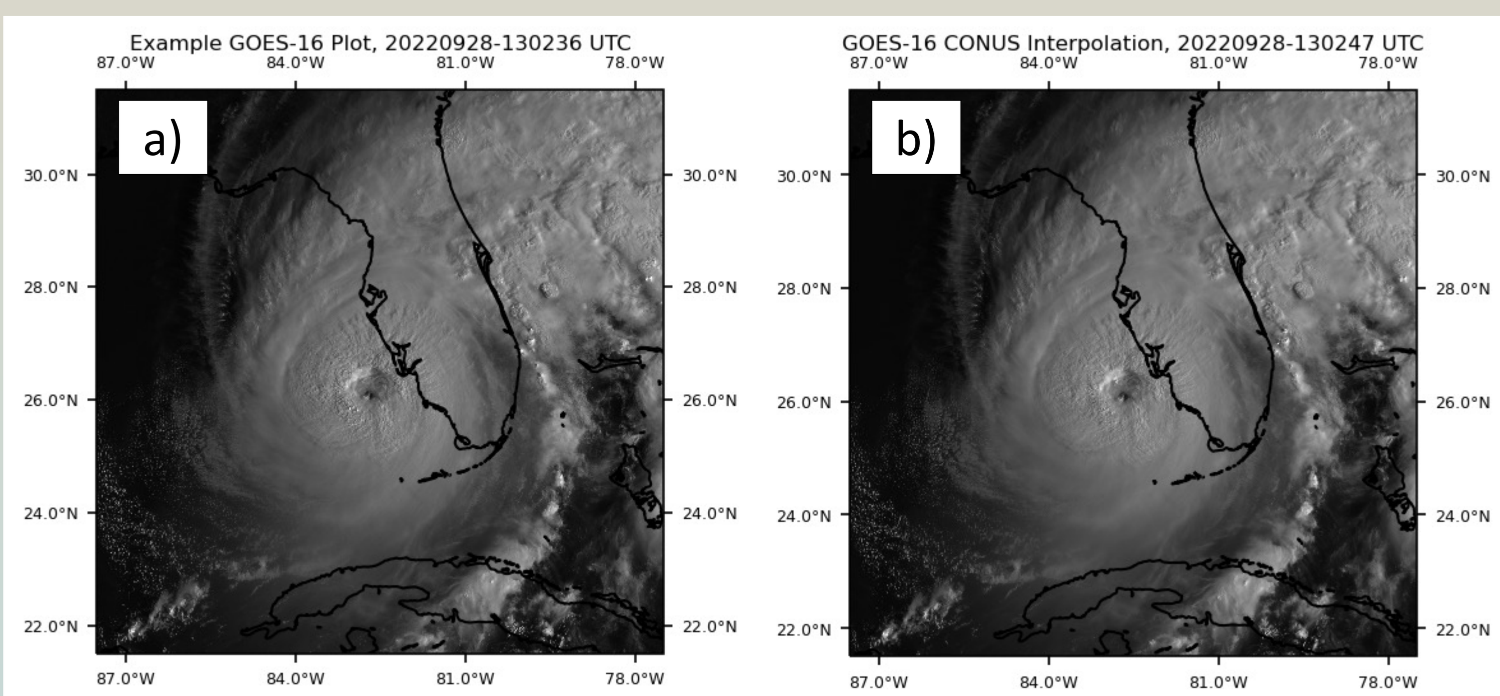
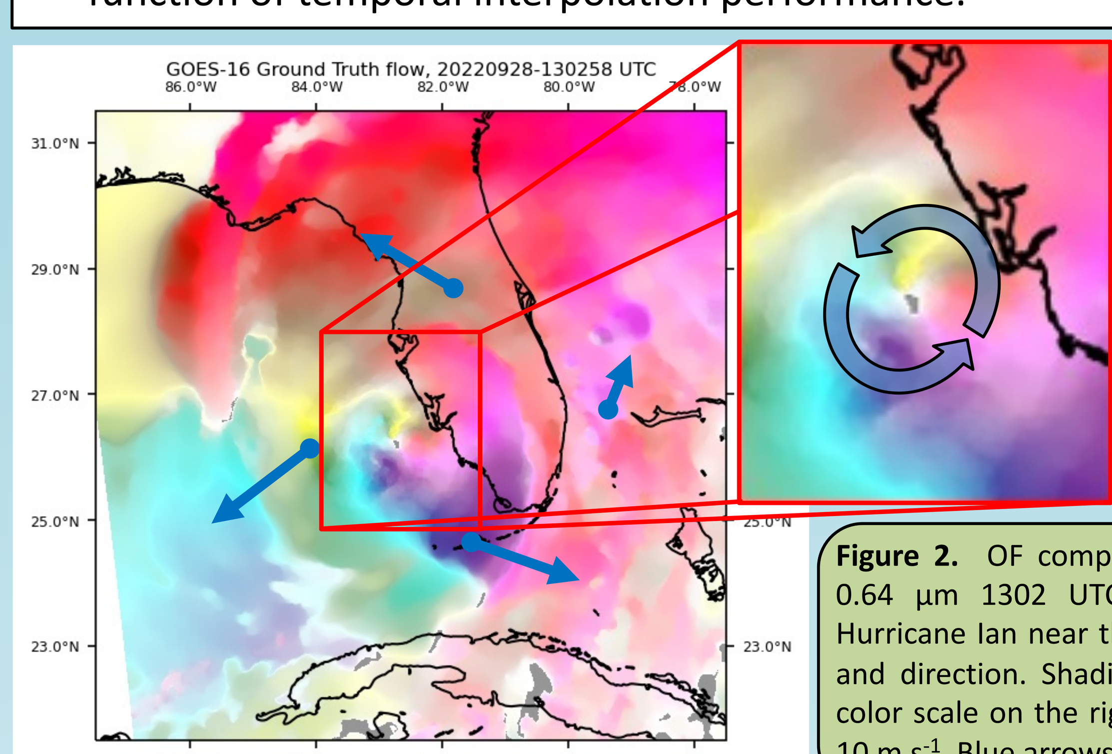


Figure 1. GOES-16 0.64 µm visible imagery from a) the GOES-16 1-min mesosector (truth data) shown with b) the temporal interpolation output using optical flow from the 5-min CONUS sector over Hurricane Ian making landfall on 28 Sept 2022 at 1302 UTC off the coast of Florida.

Methods for Interpolation

- This study uses the OF Code for Atmospheric motion vector, Tracking, and Nowcasting Experiments (OCTANE), which solves for OF from two input image frames using a variational approach (Optimal estimation; Apke et al. 2022)
- The variational approach renders brightness motions which track consistent features in brightness and brightness gradient values across the frames, using surrounding motion estimates in the absence of texture. (**Fig. 2**)
- Once OF is retrieved, we interpolate 5-min imagery to 30-sec using image warping techniques (Baker et al. 2011).
- OCTANE has tunable settings for OF smoothness (Alpha or α) and adherence to tracking consistent brightness gradients (Lambda or λ) which we will study as a function of temporal interpolation performance.



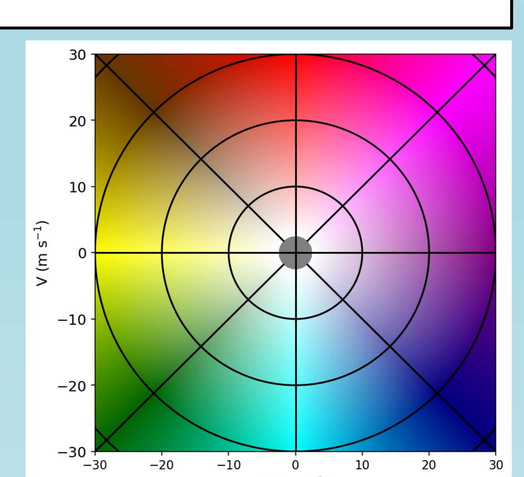


Figure 2. OF computed from the GOES-16 mesosector 0.64 µm 1302 UTC imagery on 28 Sept 2022 over Hurricane Ian near the coast of Florida, shaded by speed and direction. Shading for optical flow is shown in the color scale on the right, with circles at speed intervals of 10 m s^{-1}. Blue arrows indicate local OF motions.

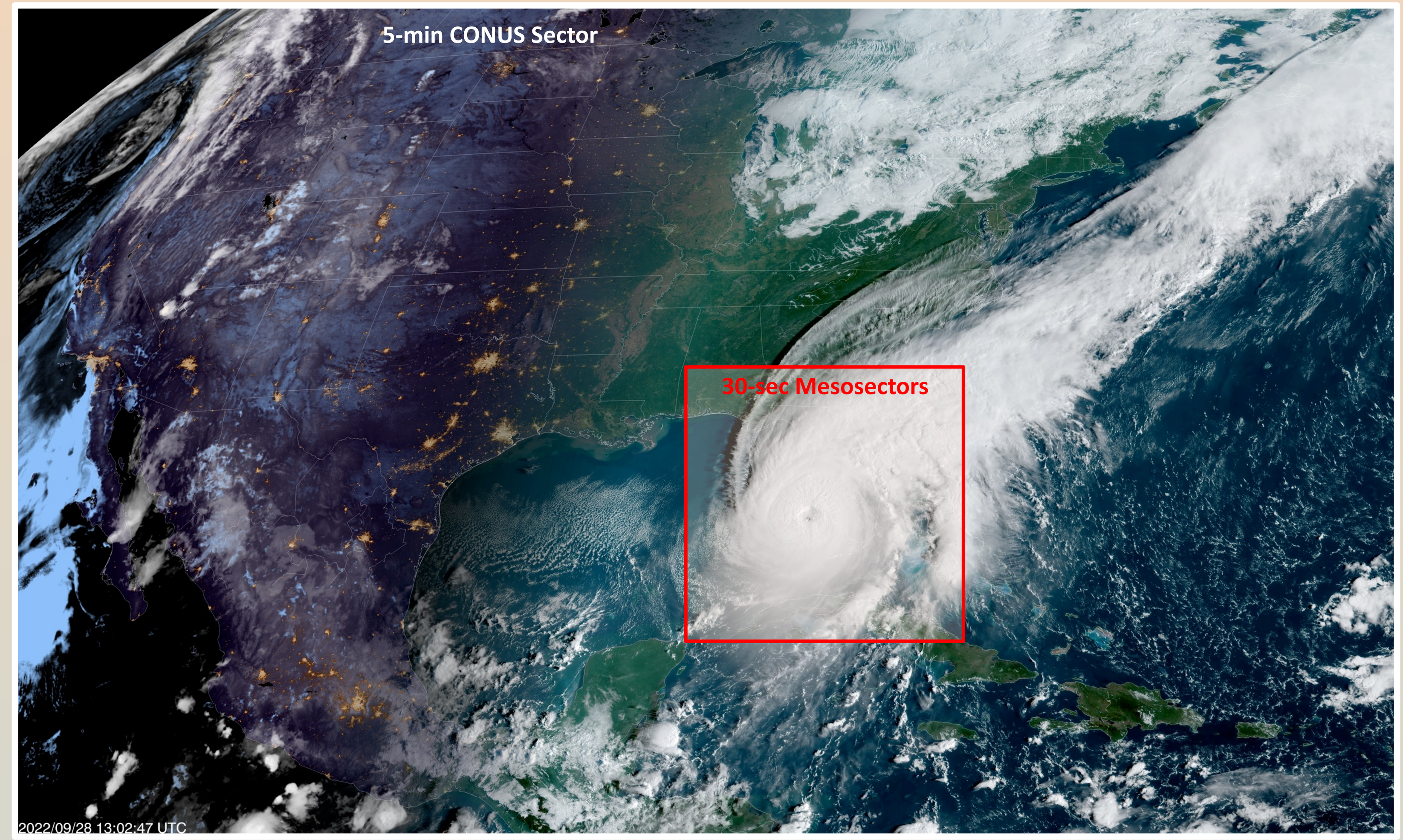


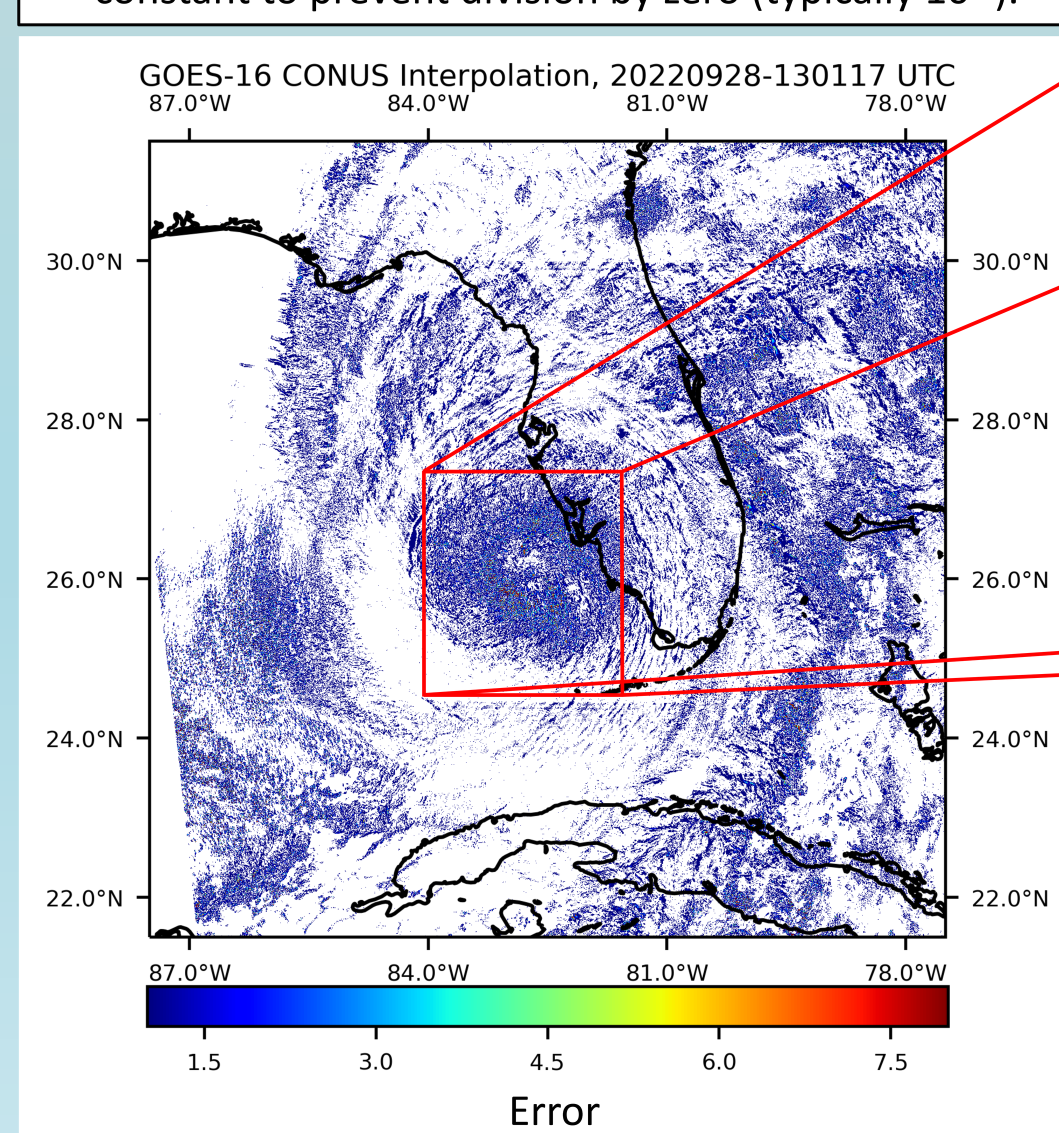
Figure 3. GOES-16 GeoColor CONUS imagery on 28 Sept 2022 at 130247 UTC. The red box shows the overlapping mesosectors which provide provide Ground Truth for temporal interpolation.

Methods for Performance Evaluation

- This study uses OF and subsequent interpolations from the red band (0.64 µm) reflectance factor imagery, which has the finest spatial resolution on the ABI (~0.5 km at nadir), normalized from values of 0 to 255.
- To evaluate performance, we compared interpolated data from the CONUS sector to a case study containing overlapping 30-sec refresh mesosectors (considered Ground Truth; GT) from 1300 → 1400 UTC (e.g. **Fig. 3**).
- The OCTANE weights for brightness gradient constancy (λ) and the smoothness constraint (α) were varied to determine optimal values for the least error.
- Evaluation follows Baker et. al. (2011) metrics for the Gradient-Normalized Root Mean Squared error (*NE*).

$$NE = \sqrt{\frac{1}{N}\sum_{(x,y)} \frac{(I(x,y) - I_{GT}(x,y))^2}{\|\nabla I_{GT}(x,y)\|^2 + \epsilon}}$$

- In this equation, *N* denotes the total number of pixels, and ϵ is a small numerical constant to prevent division by zero (typically 10^{-6}).



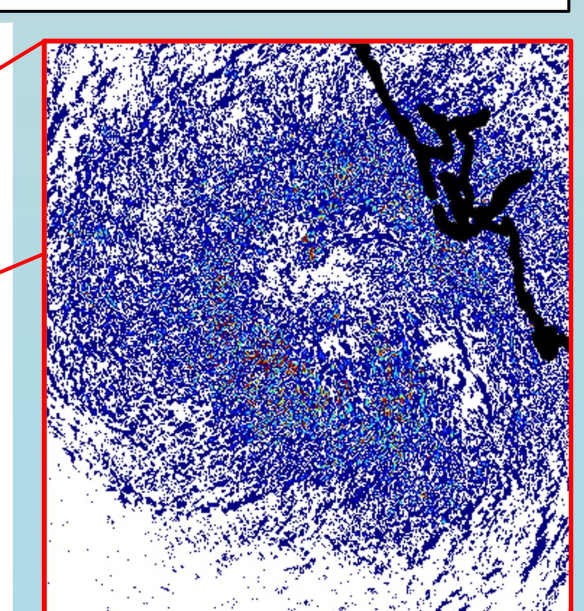


Figure 4. The Gradient-normalized Squared Error of the CONUS temporal interpolation at 1302 UTC on 28 Sept 2022 over Hurricane Ian, with hotter colors indicating higher error values.

Results

- Large errors are found around the eyewall of Hurricane Ian due to strong rotation and occlusions of brightness features. (**Fig. 4**)
- Larger errors are also observed in regions with thin cirrus and low texture.
- Error is also found near the scan lines at ~25° and ~30° latitude.
- Preliminary tests over the hour determined that a value of $\alpha = 17$ and $\lambda = 3$ optimize OF temporal interpolation in this case (**Fig. 5**).
- Large ranges of α $(15 < \alpha < 27)$ and λ $(1.5 < \lambda < 3.0)$ provide a range of acceptably low errors.
- Early experiments at different times highlight that there may be some variability in the exact values of α and λ that optimized temporal interpolation (not shown).

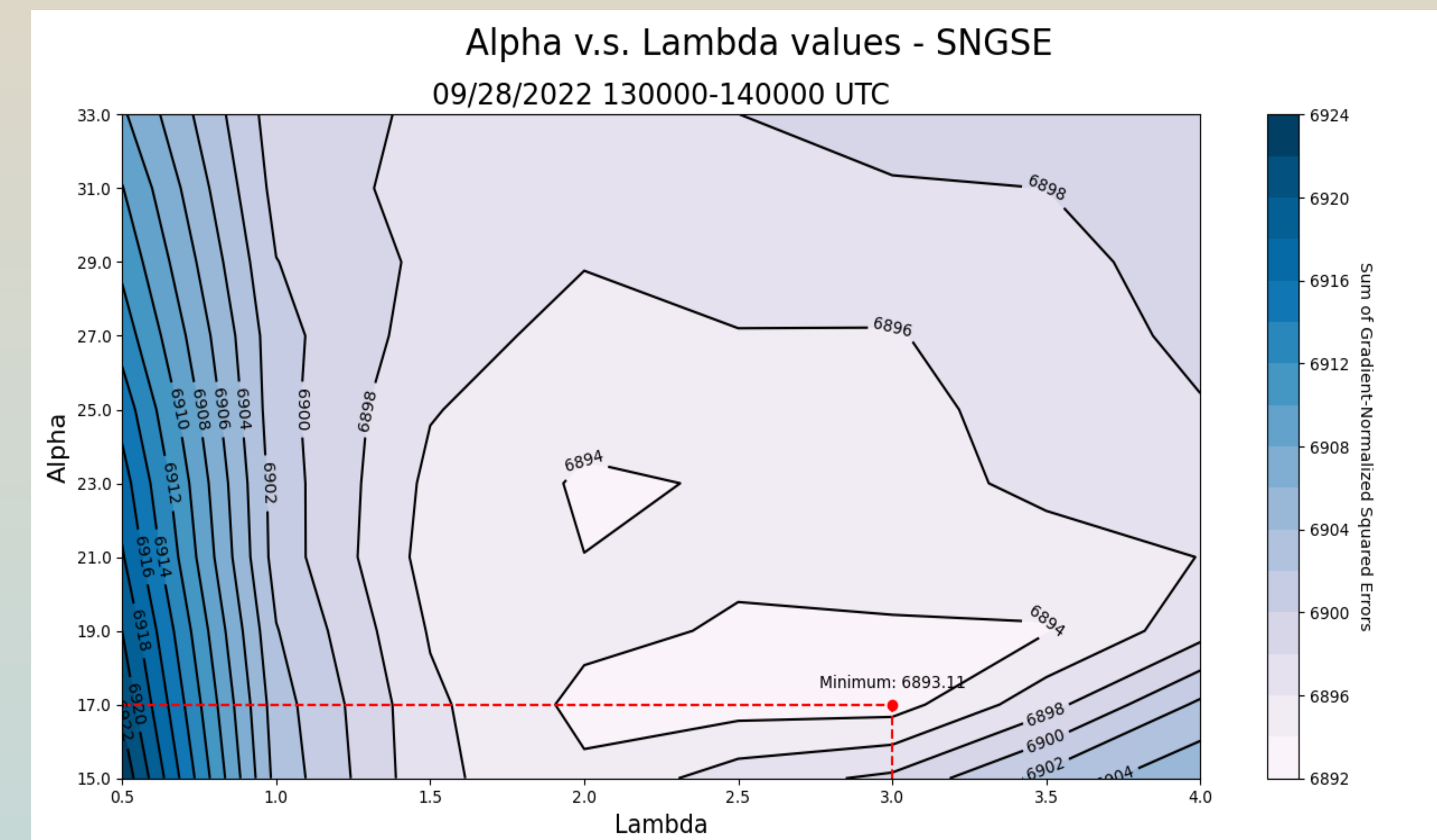


Figure 5. Gradient Normalized Root Mean Squared Error plotted for various brightness gradient and smoothness constraint weights at 1302 UTC 28 Sept 2022. For this specific case, the minimum error occurs at α=17 and λ=3. Sharp increase in errors are seen where the smoothness constraint α<15 and the gradient constancy weight λ<1.5.

Conclusions and Future Work

- Using Hurricane Ian as a sample, it is possible to find parameters for OCTANE that minimize temporal interpolation error.
- Optimal settings for temporal interpolation were smoother than OF for 1-min 0.64 µm wind retrievals (alpha =5, lambda =1; e.g. Apke et al. 2022).
- This analysis used ABI channel 2: future analysis will include all GeoColor ABI channels (1,2,3,7, and 13).
- Similar analysis will also be performed over several new case studies containing a wide variety of meteorological phenomena, cloud motions, and image textures.
- Analysis of performance as a function of cloud type and motion is of interest to reduce image artifacts and enhance understandings of uncertainties
- Future analysis of performance will also be evaluated at full-disk 10-min temporal resolution imagery, which is commonly used for image compositing applications.
- The constraint ∈ can be tuned to mitigate large error contributions of very small gradients in the imagery.

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Citations:
Apke, J. M., Y.-J. Noh, and K. Bedka, 2022: Comparison of Optical Flow Derivation Techniques for Retrieving Tropospheric Winds from Satellite Image Sequences. *Journal of Atmospheric and Oceanic Technology*, **39**, 2005–2021, https://doi.org/10.1175/JTECH-D-22-0057.1.
Baker, S., D. Scharstein, J. P. Lewis, S. Roth, M. J. Black, and R. Szeliski, 2011: A Database and Evaluation Methodology for Optical Flow. *Int J Comput Vis*, **92**, 1–31, https://doi.org/10.1007/s11263-010-0390-2.