Studying and Correcting for Ionospheric Effects in OVRO-LWA Images

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Abstract

The Owens Valley Radio Observatory's Long Wavelength Array (OVRO-LWA) images the entire visible night sky at low frequencies (from 15 MHz to 85 MHz) at up to once every 10 seconds (Anderson, M. M., et al., 2019). However, the measurements made are imperfect due to the refraction of radio waves caused by the ionosphere. Correcting for refractive shifts is critical to producing accurate all-sky maps, which helps to facilitate the search for transient radio signals produced by exoplanets, coronal mass ejections, stellar explosions, neutron star mergers, etc. The existing Fits_Warp dewarping algorithm introduced by Hurley-Walker & Hancock is implemented and verified as a baseline. We also introduce a new approach based on optical flow to directly infer pixel offsets representing refractive shifts in an image. By computing flow between real OVRO-LWA images and theoretical sky models, we are able to smoothly de-warp radio images at a variety of frequencies. Computing flow between different sub-bands in the same image produces similar results. This approach can be extended to extrapolate to out-of-band frequencies and/or infer ionospheric electron densities in the atmosphere. The models are evaluated on their effectiveness, computational efficiency, and applicability to real-world data.

Background

As explained above, the goal of this project is to correct for the refractive effects of the ionosphere on radio waves measured by the OVRO-LWA. An important physical property is that the magnitude of refraction increases at lower frequencies, while its direction depends on the physical structure of the ionosphere. In general, we expect refractive effects to shift sources away from the zenith angle in a radio image since we can assume that the ionosphere is approximately a flat slab sitting in between the Earth and outer space. However, there are also time-varying structures in the ionosphere which produce refractive shifts that can evolve on the time-scale of minutes. The latter will be referred to as absolute TEC (total electron content), and the former as relative TEC.

In 2018, a method was introduced for reducing ionospheric effects in the image domain (Hurley-Walker & Hancock, 2018). The algorithm, named Fits_Warp, performs crossmatching between a reference catalog of radio sources and the sources within an image before interpolating between the sparse set of pixel offsets in order to dewarp the input image. Essentially, it uses the prior knowledge of existing radio sources in order to estimate and correct for the refractive shifts caused by the ionosphere. According to the paper, performing this dewarping can reduce the separation between source positions and their true sky positions by an order of magnitude, from the order of 100 arcseconds to 10 arcseconds on average (Hurley-Walker & Hancock, 2018).

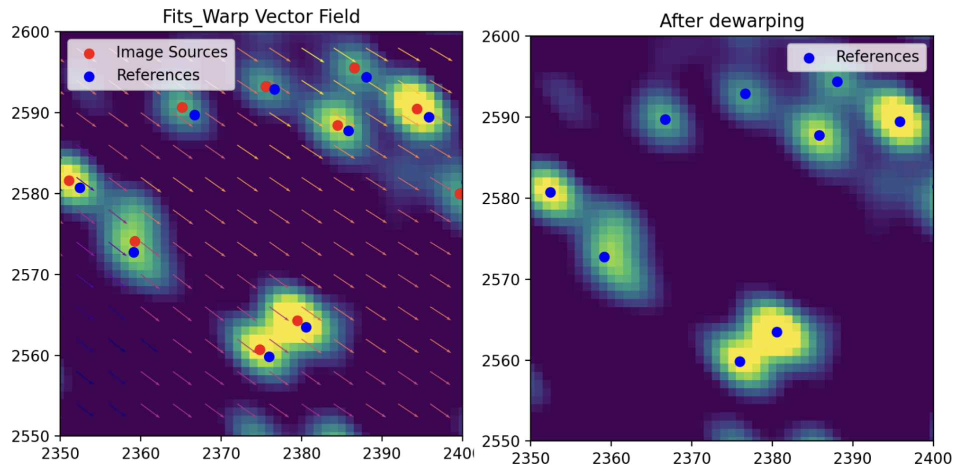

Figure 1. A small cutout demonstrating the fits_warp algorithm on a real OVRO-LWA image. As can be seen, the image sources are matched with references, which is then used to generate a vector field to dewarp the image.

However, one fundamental issue with Fits_Warp is that its effectiveness is limited by the quality of the cross-matching and source detection. It is very difficult to avoid false cross-matches, and this is addressed by Fits_Warp by simply smoothing over all of the offsets. In addition, the reference catalog used can affect the matching - if the reference sources are much denser than the image sources, then it is more likely that each image source is matched to a reference that is close to it but not associated with that source (thus producing false positives). As a result, we cut off the reference sources at a certain flux level, but this meant that some of the image sources did not have a corresponding reference, also resulting in false matches. We believe that some of these issues can be side-stepped by working purely in the image domain instead of explicitly performing source detection and cross-matching. We can treat image-plane correction as an inverse problem where we try to learn the pixel-wise shifts that transform the true sky into the measured image. Since the LWA measures the night sky at multiple frequencies, we can theoretically take the all-sky maps at different frequencies and use this information to infer the direction and magnitude of refractive shifts due to the dependence of refraction on frequency. Thus, if we can compute a smooth warp between two radio images at different frequencies, then we should be able to invert/scale this warp and apply it to one of the original maps, correcting for refractive shifts.

Luckily, it turns out that this task (identifying pixel offsets between two images) is an existing problem in computer vision research known as optical flow, and there is an extensive literature on the subject. To summarize, there are classical techniques which define an energy function that depends on the quality of the computed flow, along with a numerical algorithm to optimize the energy function (typically some sort of convex optimization). Recently, there have also been deep learning-based approaches that use convolutional neural networks and a variety of ideas from computer vision to predict flow fields between frames of videos. We chose to use the Brox optical flow algorithm, which is a classical model that reduces the problem of optical flow to solving a system of linear equations (Brox et al., 2004). This model makes assumptions such as smoothness of flow and brightness constancy, which we believe align well with the domain of radio images. Additionally, a CUDA-accelerated implementation of Brox optical flow exists in OpenCV, which can compute flows over pairs of 4096x4096 images in approximately 60 milliseconds each (Bradski, 2000).

Approach

The first way we can use optical flow is to estimate flow between a real LWA image and a theoretical model of the sky. We generate theoretical sky images by plotting reference sources as points (delta functions) on a grid representing the sky before convolving it with the point source function (PSF) of the telescope. To improve the quality of the flow computed, we pre-processed pairs of images to bring the overall brightness levels of their pixels closer to each other. This was done by first zeroing pixels within 10 degrees of the horizon (due to radio interference), matching the histograms of both images with each other, clipping pixel values outside of the 50th to 99th quantiles, and then normalizing pixels to the range [0, 1]. Additionally, both images can be blurred using a gaussian kernel of 3-5 pixels to enforce a smoothness prior on the computed flow. After all of the preprocessing, the pair of images is passed into the Brox optical flow model to generate the flow. The parameters used during experimentation ranged from alpha=1, gamma=150 to alpha=0.45, gamma=90, depending on the smoothness desired. A scale_factor=0.7 was used regardless. We visualized the shifts by letting color represent the direction of the shift and the brightness correspond to the magnitude of the shift, as seen in the figure below. Then, the shifts were applied to the original LWA image, causing sources to shift closer to where they are located in the theoretical image, therefore correcting for refractive effects.

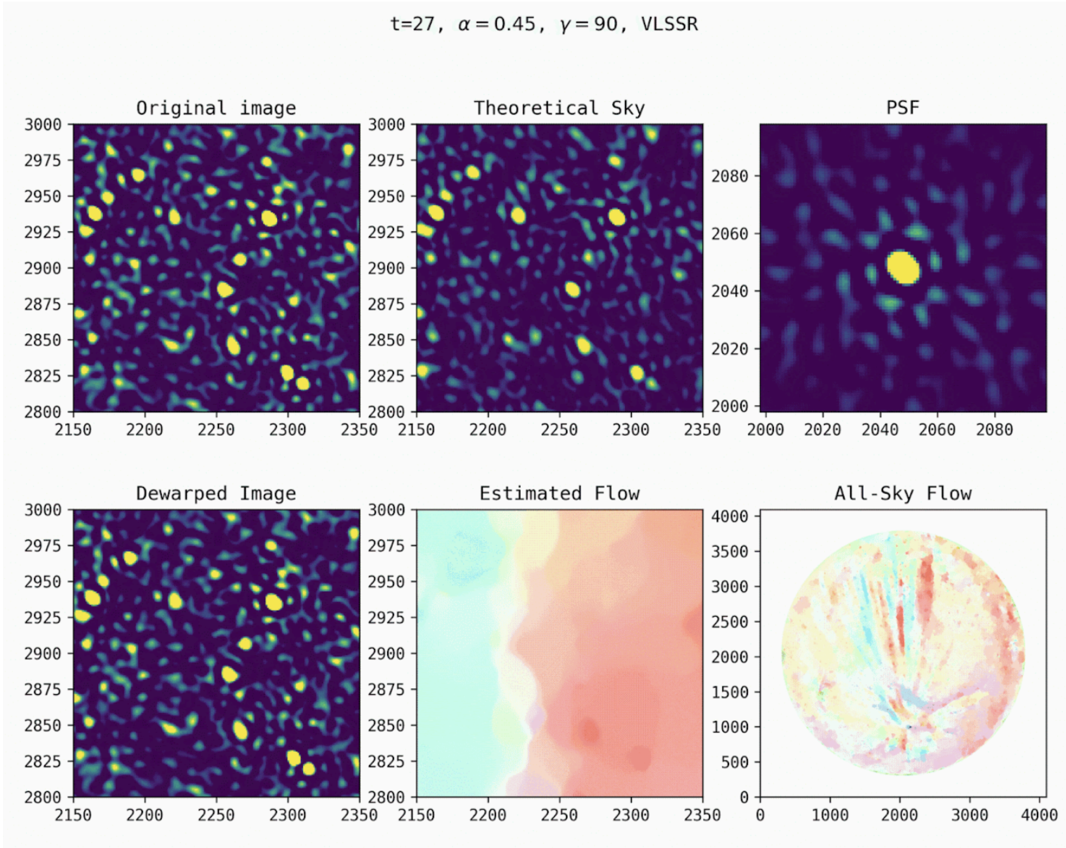

Figure 2. A grid of images demonstrating the process of computing flow between an image and its theoretical counterpart. We see that this flow can be used to dewarp the original image. Furthermore, there appears to be a coherent structure to the flow throughout the entire sky, which reflects the structure of electron columns in the ionosphere.

Furthermore, this method works at multiple frequencies, and it is even possible to perform linear regression in order to fit a refractive law to the observed shifts. We computed flow at one low frequency and one high frequency before interpolating to a medium-frequency flow. Applying this flow to the mid-frequency image then resulted in a similar de-warp than to if the flow were computed directly.

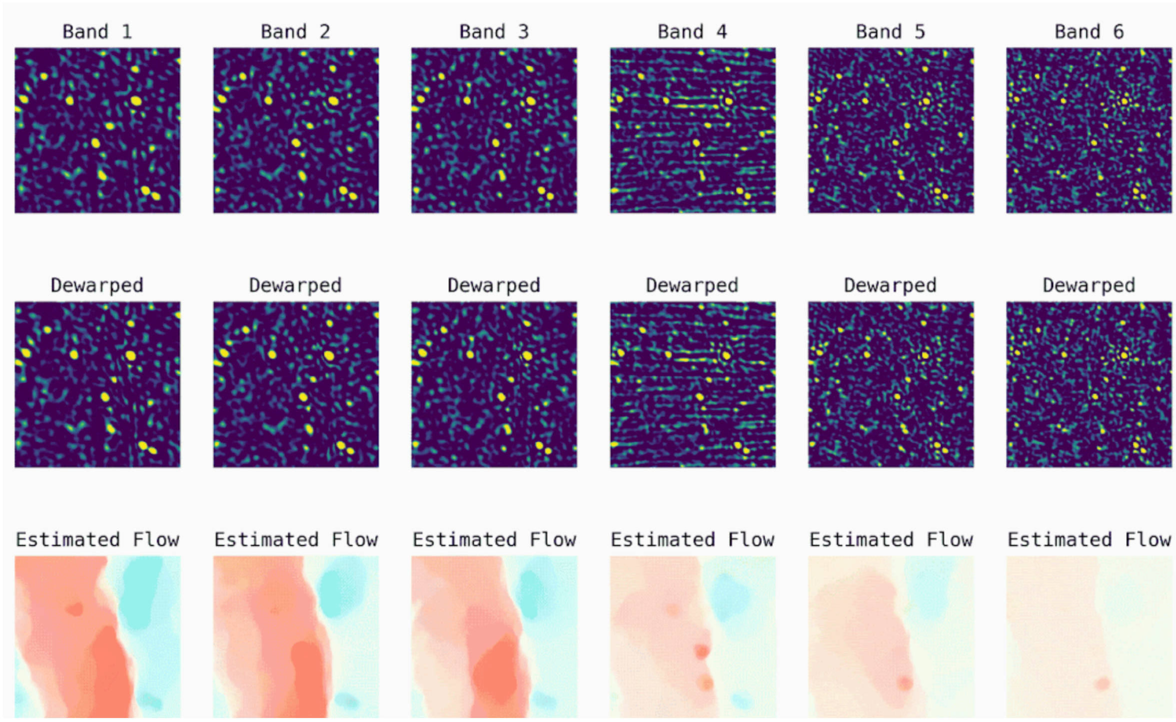

Figure 3. The flows computed independently across multiple sub-bands, starting with the lowest frequency on the left going to the highest on the right. Note that the color scale is identical on each flow plot, and so the lighter colors from left to right suggest that the magnitude of refraction decreases with increasing frequency, which we know to be true.

A second way of utilizing optical flow is matching between the same radio image but at different frequencies. One major issue is that the PSF actually varies in size between images of the different frequencies. However, we can correct for this by applying a gaussian filter to both images, causing the PSFs to widen to the same size. For the LWA images, we use a filter width varying from 0px to 5px based on the difference in beam size between different frequencies. The flow can then be computed using the previous method, with similar results (see Figure 4). The main difference is that the computed flow has a decreased magnitude, which is expected. Theoretically speaking, the flow direction should be correlated with the effect of refraction.

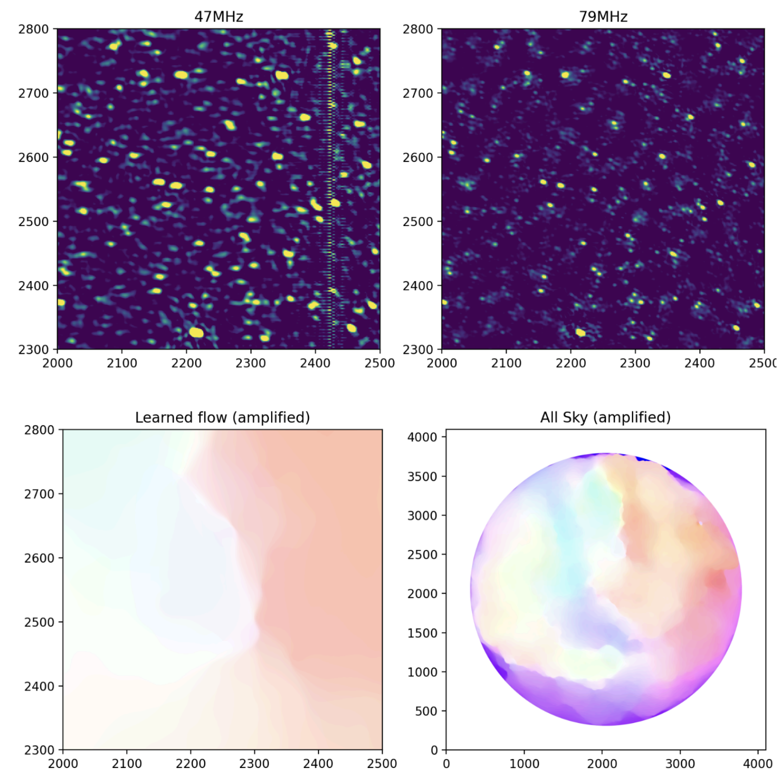

Figure 4. The result of computing flow between different sub-bands of the same image. At first glance, there appears to be little information to be gleaned from the two images, but after correcting for differences in PSF and computing flow, we see that there is in fact an underlying signal caused by refraction.

Conclusion

In general, we see that optical flow is a powerful tool that can identify and correct for ionospheric refraction. By computing flow between images, we can extract the underlying information they carry in regards to the direction and magnitude of refraction. Additionally, the efficient implementation of the Brox optical flow means that it can be used to de-warp images in near real-time. However, there is still a lot of area for further research. The main next step is using a quantitative metric to evaluate the quality of the estimated flow fields. At the moment, the main results are very qualitative. Additionally, another important direction is verifying if the estimated flow fields are actually representative of the physical phenomenon of refraction. For example, there might be small variations in the flow fields that are caused by image artifacts or issues with the theoretical sky, not the ionosphere itself. Plus, it is important to ensure certain invariants, like preservation of flux before and after warping. It may be also possible to incorporate the physical law of refraction into the optical flow model itself, though that would likely require a significant amount of work (and may not produce results that are any better than simply performing linear regression after the fact, as shown above).

References

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