Observations of Spatiotemporally local Structure in the Thermosphere over Alaska

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Motivation

Earth's thermosphere spans the atmospheric region between the mesopause temperature minimum at 90 km altitude and the collisionless Exosphere, which begins at about 500km altitude. Physically important qualities of the thermosphere inlcude a positive temperature gradient with increasing altitude, very high kinematic viscosity, and a density low enough to allow constituents to stratify according to their mass-dependent scale-heights. These qualities should, in theory, lead to very stable dynamics, characterized by laminar flows that are absent of convective overturning, turbulence, sharp shears, or local-scale (<100 km) flow structures. However, embedded within the thermosphere are ionized constituents known collectively as the ionosphere. Generally less than 1% of the night-time thermosphere is ionized - but, at high latitudes, this component is strongly driven by electric fields of magnetospheric origin that are capable of depositing substantial energy and momentum at small spatio-temporal scales. Although these collocated systems have disparate concentrations and primary drivers, they have been shown to be coupled, often referenced together as the Ionosphere-Thermosphere (I-T) system. The net result is that the coupled I-T is an open and externally driven system that exhibits complex and highly varied behavior (Schunk et al. [6]). Thus when evaluating the thermosphere, we must consider effects (and drivers) of the ionosphere as well as typical neutral atmospheric drivers (such as diurnal heating).

The climatological behavior of the thermosphere has been modeled on synoptic scales with success, but spatio-temporally local events remain poorly understood. Here we present observations of spatio-temporally local events over Alaska during the JETS sounding rocket launch on the night of March 2, 2017. Applying a novel geophysical inversion technique, derived in part from the work of Harding et al. [5], to a dense network of all-sky viewing Fabry-Perot Interferometers, alongside optical imagers accompanied by a sounding rocket launch from Poker Flat Research Range, we present observations of spatio-temporally local behaviour in the auroral zone neutral winds and offer observational evidence of neutral jets from auroral arcs.

Instrumentation

Primary instrumentation used was a network of all-sky viewing Fabry-Perot Interferometers (FPIs). The all-sky FPI has been described by Conde & Smith [1, 2, 3] and Conde et al. [4]. An all-sky lens maps a zenith-centered field of view spanning around 75^o half-angle in the object space through an interference filter and etalon, with output optics then forming a sharp image onto a 512 x 512 pixel EMCCD camera. The etalon transmits around 6 interference orders. Techniques described by Conde [2] are used to divide the field of view into 115 sub-regions, termed zones, and to derive an independent spectrum from each such region. The spectra are fitted as described by Conde [4] to produce line of sight (LOS) winds (see figure 1). For the night of March 2, 2017 the SDI network recorded both 630nm "red" spectra and 558nm "green" spectra over Toolik Lake, Poker Flat, and Eagle, Alaska.

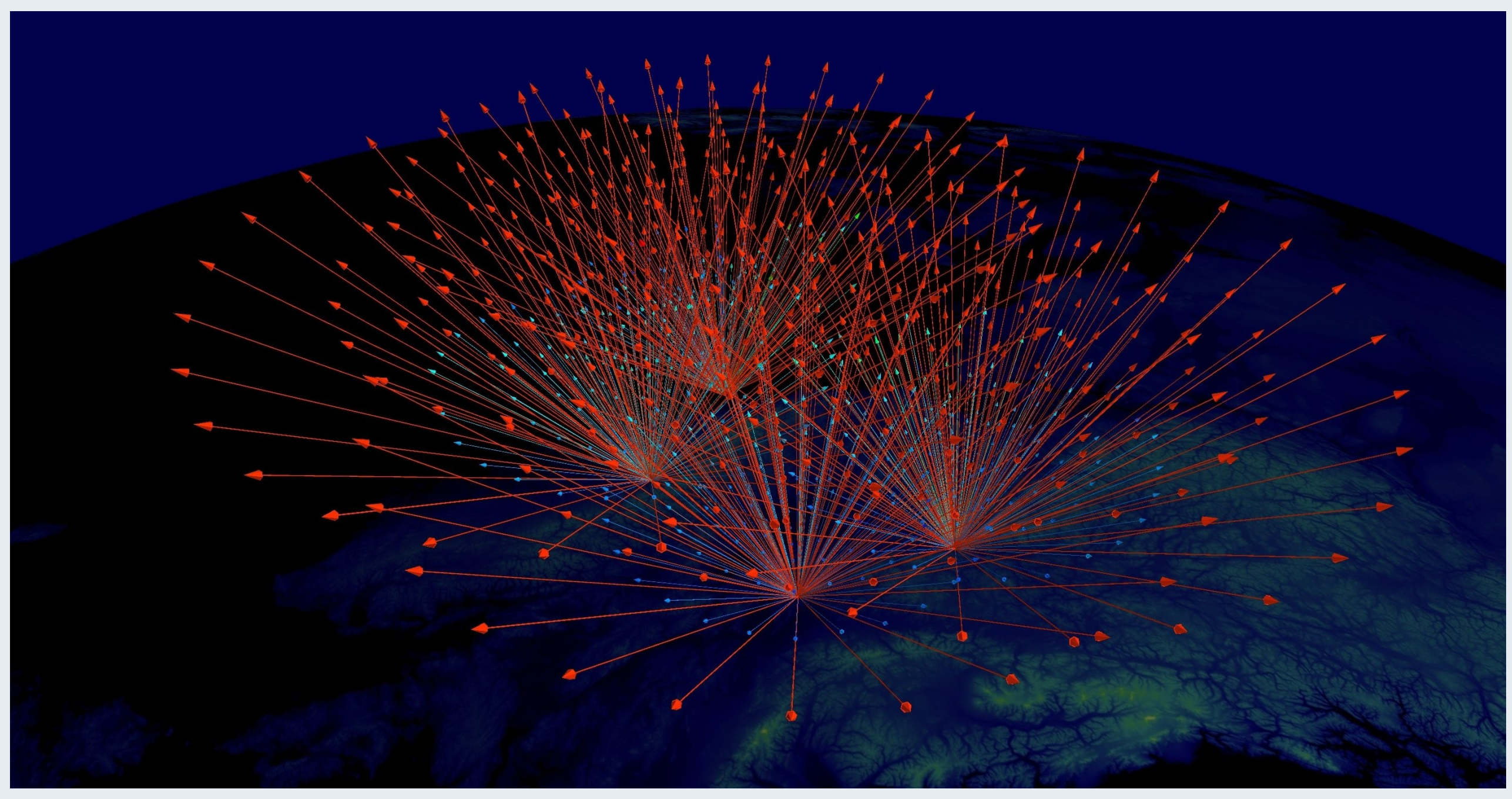

Figure 1:A 3D plot of the available look directions the full Alaskan FPI network can present. Red vectors represent 6300Å spectra while teal vectors represent height-corrected 5577Å spectra. Spectra are observed in series, while look directions are observed in parallel. For any given night a subset of these look directions may be available due to weather or other technical difficulties.

The night of March 2nd, 2017 was chosen for investigation due to high levels of auroral activity, the array of optical remote sensing equipment available, and the successful execution of the JETS sounding rocket mission. At approximately 0545 the dual sounding rocket "Neutral Jets in Auroral Arcs" (JETS) mission was conducted at Poker Flat Research Range (PFRR) with suite of on-board instrumentation and a Trimethylaluminum (TMA) sub-payload tracer release. Via the TMA tracers the local horizontal wind profile of the thermosphere was observed. The spatiotemporal extent of the TMA profile is limited for our purposes (roughly one cubic kilometer) but is absolutely calibrated and serves as the ground truth for neutral winds at the given location, so long as the assumption that the TMA travels with the winds is correct (it is widely considered correct). This TMA profile serves as a basis for validation of our methods of inferring wind fields on this night.

Finally, a suite of optical imagers across the state of Alaska were active. The Poker Flat all-sky imager was used to observe auroral arcs for this night.

Observations

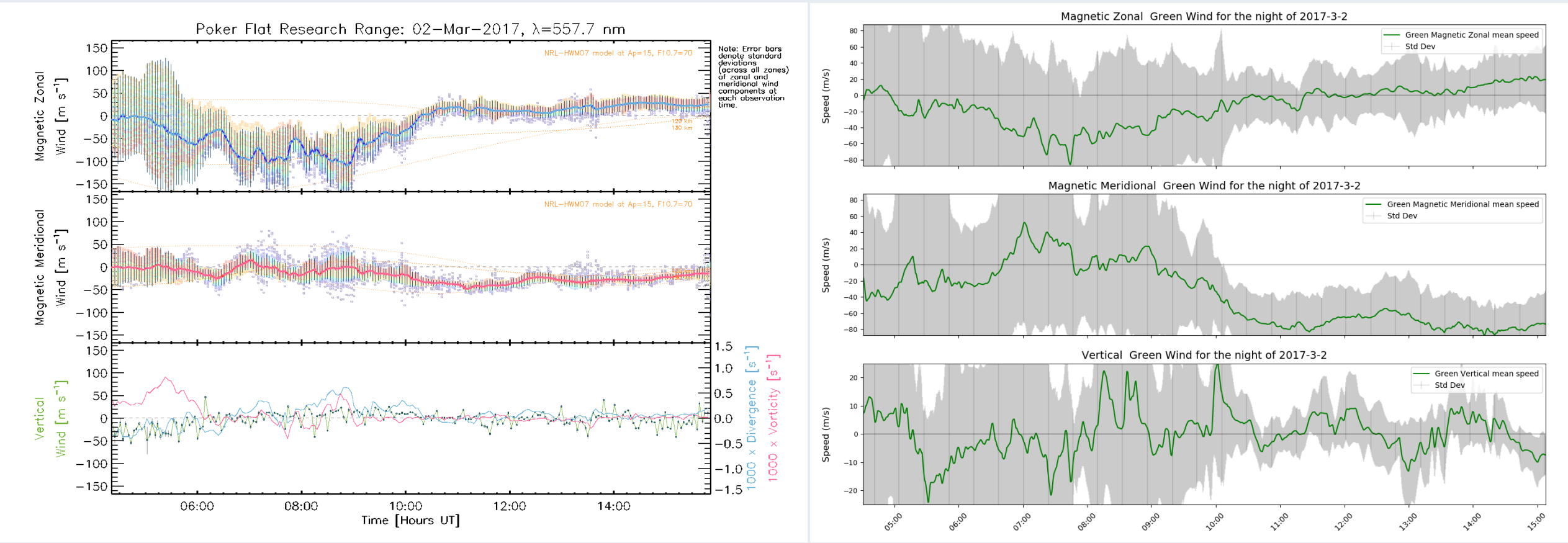

Figure 2:Left: Monostatic wind summary for green-line 5577Å FPI spectra LOS observations from Poker Flat developed by Professor Mark Conde and retrieved from `http://sdi_server.gi.alaska.edu/sdiweb/` on June 9, 2019. Right: Geophysical inversion summary winds for green-line 5577Å combined Poker Flat, Eagle, and Toolik Field Station LOS observations. The raw data used to produce the left summaries is a subset of the raw data used to produce the right summaries.

Observations

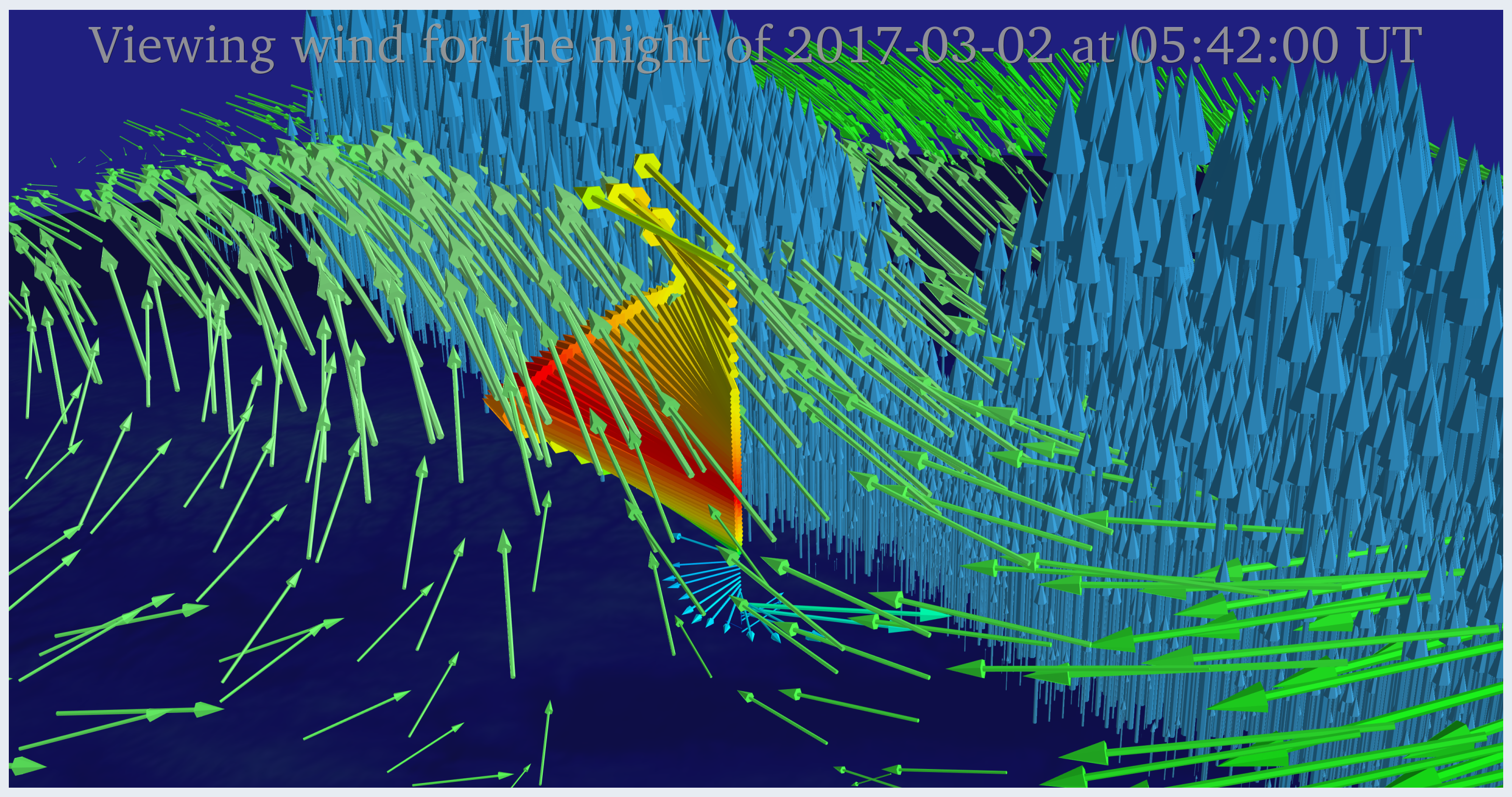

Figure 3:The up-leg of the JETS rocket launch wind profile is displayed with JET colormap according to vector magnitude. A log-intensity plot in the form of vertical vectors of the Poker Flat all-sky imager is displayed at an assumed 120km altitude with blue colormapping. Green-spectra geophysically inverted winds are presented as a vector field at 135km altitude. The scene is angled approximately in-line with the rocket profile winds (bearing 305 degrees geographic)

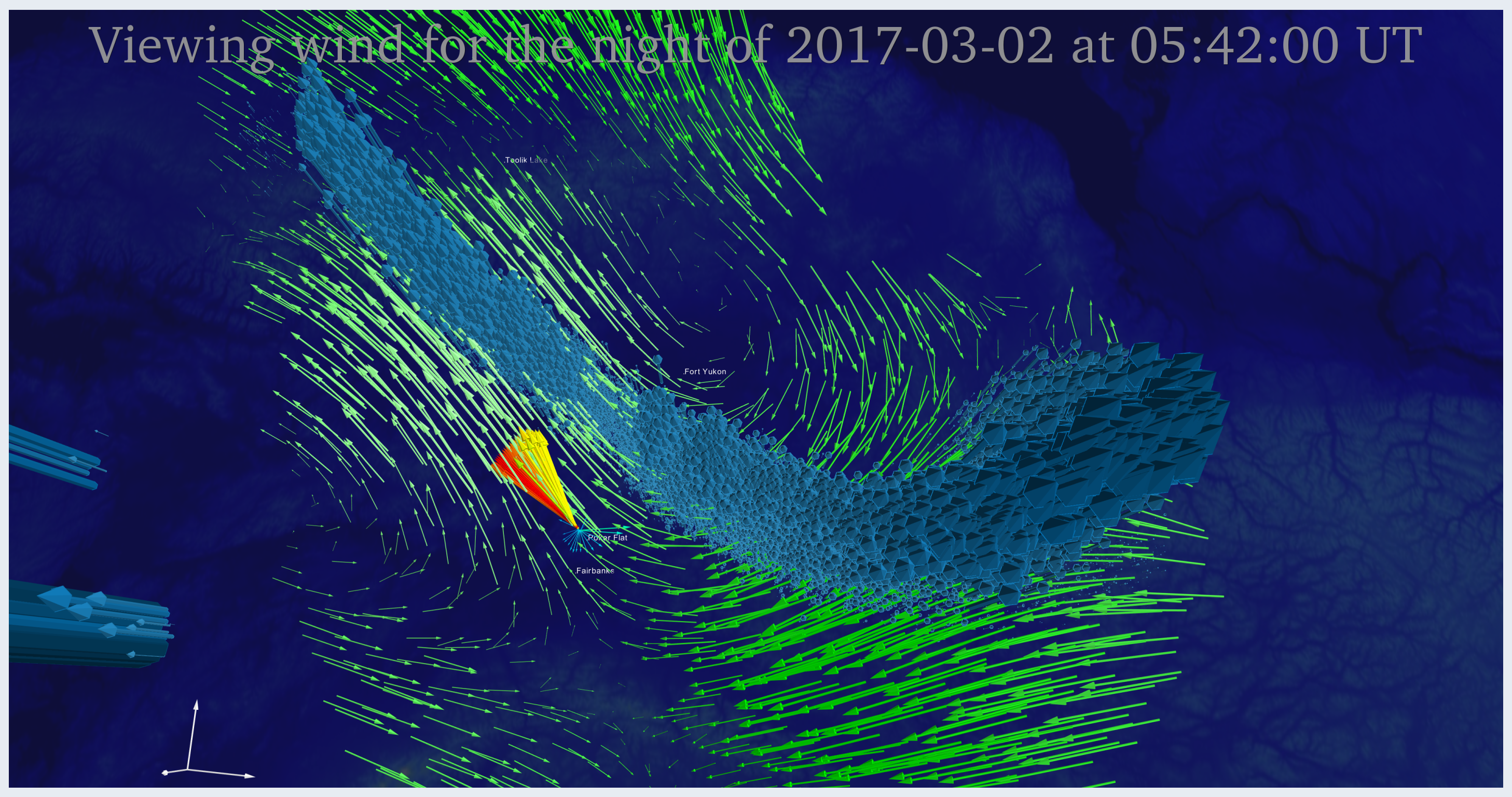

Figure 4:Overhead view of same scene as figure 3. Geographic North is up the page vertically. Winds can be seen following the path of the aurora in an apparent neutral jet. A white 200 m/s reference vector can be seen lower-left.

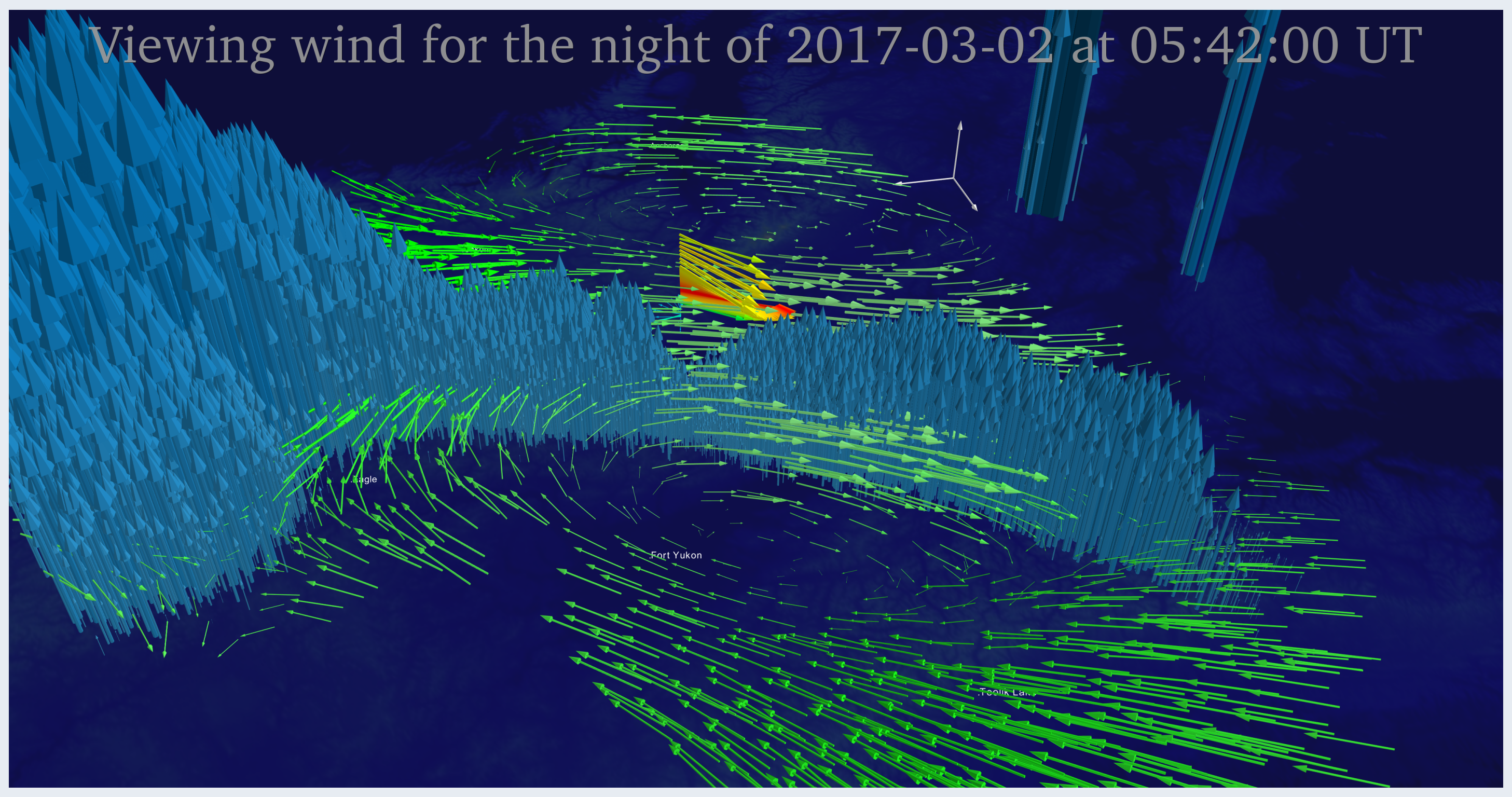

Figure 5:Magnetic northerly view of same scene as 3. Local structure forms magnetically pole-ward of the auroral arc. Winds at the northern and south edge of observation exhibiting more typical diurnal flow patterns. A white 200 m/s reference vector can be seen upper-right.

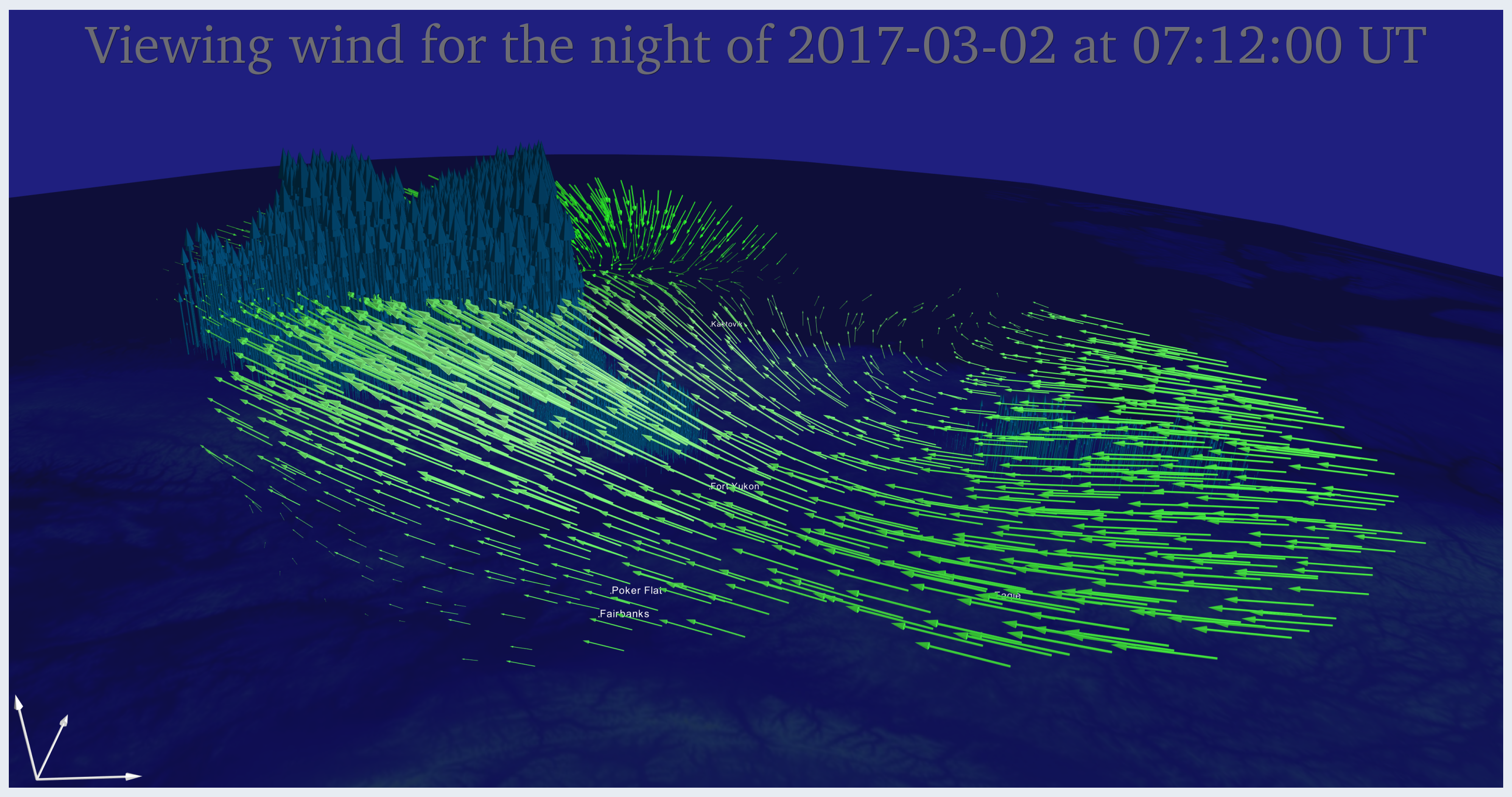

Figure 6:Slant view 90 minutes after the up-leg wind profile was established by the JETS rocket, looking geographic north. Time is 0712UTC. Winds have relaxed with much more regular structure than in figure 4, although auroral activity is still present, accompanied by dynamic winds, at the northern edge of observation. A white 200 m/s reference vector can be seen lower-left.

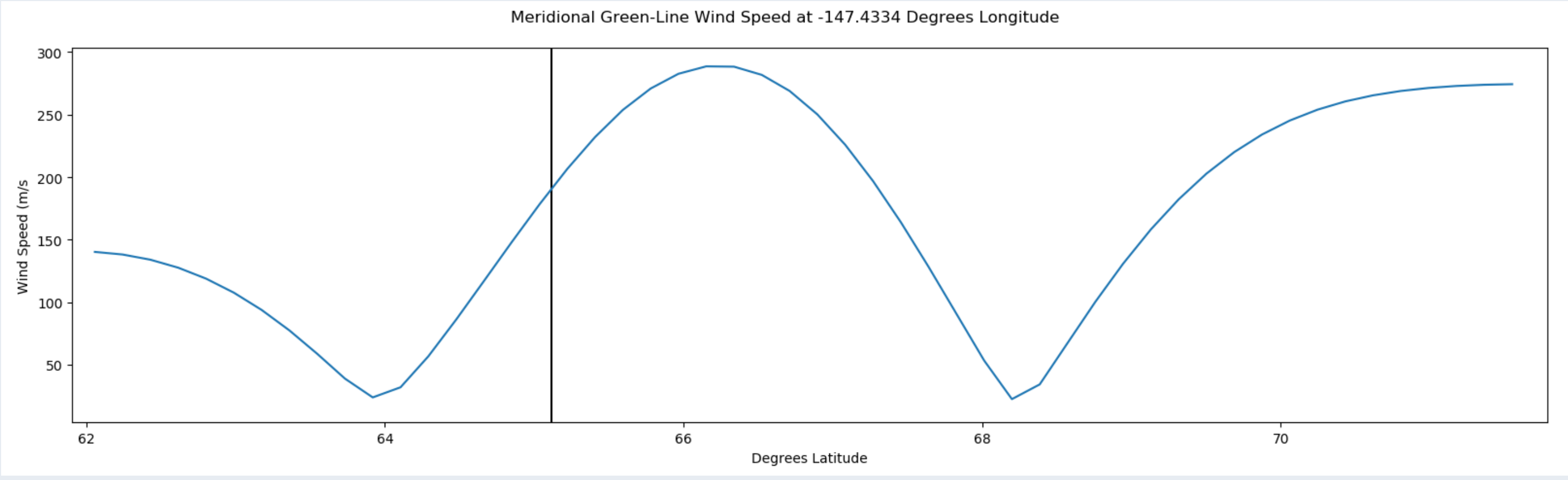

Figure 7:A line plot meridional slice of the green-line neutral wind speed at the longitude of the up-leg JETS TMA wind profile. A vertical black line has been used to indicate the latitude of the up-leg TMA wind profile.

Geophysical Inversion Inference

The Geophysical inversion technique that has been used applies a piece-wise-modified Tikhonov Regularization to a geometric transformation forward model for the LOS observations. As this method has not been rigorously validated in this context, we must first assess its validity against other data and methods for this night and time of observation.

Considering other methods of inference from LOS observations, the method of geophysical inversion, on average, is shown to be in general agreement with the monostatic-fit technique used by Conde et al. (see figure 2) for the night of March 2, 2017. Overall behavior is consistent with what is expected on synoptic scales with both techniques.

Figure 3 illustrates the horizontal wind profile produced by the Tri-Methyl-Aluminum (TMA) tracers released with the up-leg of the JETS sounding rocket (derived by Miguel Larsen, Clemson University). MSIS-based estimates for the emission altitude is 135km. At 134.6km altitude the up-leg TMA-derived wind speed was $u = -227.6ms^{-1}, v = 274.7ms^{-1}$, zonal and meridional respectively, resulting in an angle of 129.6 degrees from east and wind speed of $356.7ms^{-1}$. The geophysical inversion derived wind field, spatially interpolated by radial basis function, observed a wind speed of $u = -109.5ms^{-1}, v = 147.7ms^{-1}$, resulting in an angle of 126.5 degrees from east and wind speed of $191ms^{-1}$.

The disparity between the angles of wind, 3.1 degrees, is considered not statistically significant. The differences in wind magnitude however is almost exactly double with the geophysical inverse winds under-reporting winds by half. As figures 3,4 show there is a very dynamic situation surrounding the sounding rocket's position in space and time, with winds converging nearby. It is very likely that the lower geophysical inversion wind speed is a result of multiple averaging effects. The TMA wind profile is spatially very local at about 1 cubic kilometer of volume, while the FPI is averaging winds on order of 500km^2. Additionally the applied regularization smooths winds considering the nearby values, reducing overall wind magnitudes in areas of convergence. With an understanding of the difference in precision, we progress forward with the geophysical winds.

Results

With the above considerations we now present figures 4,5 as observance of local structure in the thermosphere. Figure 4 shows an overhead view (orientated to geographic north) of the green-line winds (green vectors) inferred by geophysical inversion. The blue vectors are a log-intensity plot of an all-sky imager present at Poker Flat Research Range (imager data provided by Don Hampton, retrieved from `http://optics.gi.alaska.edu` on June 9th, 2019). The JET colormapped vectors centered over Poker Flat are the TMA wind profile from the up-leg of the JETS sounding rocket.

At 0542 the neutral winds are observed to be traveling magnetically westward in the regions with high auroral brightness as observed by the Poker Flat all-sky imager. Winds for this time are also observed traveling magnetically eastward away from regions of high auroral brightness (see figures 4,5). In between these regions is a transient area of highly dynamic winds. A wind speed enhancement is observed within the larger region of auroral brightness (see figure 7) and an attenuation of wind speed appears at outer auroral boundary.

In the region immediately magnetically pole-ward of the auroral arc sheers can readily be observed (see figure 5) as the neutral winds "bend back" on themselves over a span of <100km. Approximately overhead of Toolik Field Station observations of shears are at the resolving capability of the FPI network at this location, 50km. Wind speeds changing by $> 1m/s$ per kilometer are observed.

Magnetically equatorward of the auroral arc (see figure 4) neutral winds can be observed traveling westerly from the south-western edge and easterly from the south-eastern edge, finding a convergence approximately 250km magnetically south of the auroral arc.

These features present at 0542 are largely diminished 90 minutes later (see figure 6). Based on these observations we hypothesize that a neutral jet formed coincident with the observed auroral arc, driven by mechanisms therein, and established structures that were spatially localized to the auroal arc, and temporally localized to the substorm that created it.

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Acknowledgments

This research has been made possible through grants from National Auronotics and Space Administration (NASA) and the National Science Foundation (NSF). Specifically:

> This work was supported by NASA award number NNX16AL87G, "Neutral Jets in Auroral Arcs," via a subcontract to the University of Alaska from GSFC.
>
> This work was supported by NSF award number 1452333, "CEDAR: High-resolution Multistatic Mapping of Small-Scale Flow Structures in Earth's Auroral Thermosphere."

The research presented here is built on work from numerous scientists from several disciplines. Without the support of these many organizations and researchers this work would not be possible.