General Information

Principal Investigator's Name (Last, First) Scullion, Eamon

Affiliation Northumbria University, UK

Address Pandon Building, Camden Street, Newcastle Upon Tyne, NE1 8ST, UK

Primary Email scullie@tcd.ie

Co-Investigators

Wedemeyer, Sven: University of Oslo, Norway: sven.wedemeyer-bohm@astro.uio.no
Kato, Yoshi: University of Oslo, Norway: yoshiaki.kato@astro.uio.no
Steiner, Oskar: KISP, Germany: steiner@kis.uni-freiburg.de
Rouppe van der Voort, Luc: University of Oslo, Norway: v.d.v.l.rouppe@astro.uio.no
Fedun, Viktor: University of Sheffield, UK: v.fedun@sheffield.ac.uk
Erdelyi, Robert: University of Sheffield, UK: robertus@sheffield.ac.uk
Park, Sung-Hong: National Observatory of Athens, Greece: shpark@noa.gr
Tsiropoula, Georgia: National Observatory of Athens, Greece: georgia@noa.gr
Doyle, John G.: Armagh Observatory, Northern Ireland: jgd@arm.ac.uk
Shelyag, Sergiy: Northumbria Universtiy, UK: sergiy.shelyag@monash.edu

Program Type
Synoptic

2. Science Justification

Title The Multi-Scale Nature of Vorticity in the Solar Atmosphere

Abstract
Vortex motions are present in a wide variety of phenomena and across a range of temporal and spatial scales in the lower solar atmosphere. Current observations at the diffraction limit taken with the best ground-based observatories, allow us to detect the faint signatures of vortex motions, for e.g., in moving magnetic features and whirlpools in the photosphere, as well as, in rapidly evolving type-II spicules and small-scale magnetic tornadoes (aka chromospheric swirls) in the chromosphere and long-lived, large-scale giant tornadoes off-limb. Granulation is thought to drive much of these phenomena, channelling energy outwards into the chromosphere and corona. As a result, vorticity is very much inherent in such a convectively driven system. The widespread, ubiquitous nature of these twisted transients makes them an effective powerhouse of many (if not all) forms of wave propagation, as well as efficient generators of currents, within both quiet and active regions. This indirect impact of vorticity, across a range of scales, could lead to such events having an important contribution to coronal and chromospheric heating, which requires further exploration. Understanding the nature of vorticity directly, at different spatial scales, could lead to new insights in addressing our key question, which is, "*What is the predominant mechanism behind energy dissipation in the solar atmosphere?*" The multi-scaled nature of vorticity implies a possible spectrum of vortex phenomena (beyond simply large-scale or small-scale) in the solar atmosphere, with a resulting energy spectrum. We can explore the

possibility of scaling / power laws (such as Kolmogorov) concerning vorticity and energy budget in vortex motions, through statistically investigating various parameters such as the vortex lifetime, size and rotational velocity distributions. Such scalability (if it exists) will provide a unique insight into the potential dissipative processes taking place in the solar atmosphere.

Keywords

1) Prominence Morphology, Connectivity, and Lifecycles
2) Energy and Magnetic Helicity in Coronal Structures
3) Multilayer Magnetometry and Atmospheric Heating
4) The Chromosphere-Corona Connection

Introduction

This proposal aims to utilise the increased spatial and spectral resolution of DKIST to investigate the detailed physics, within the cross-sections of vortex motions in chromospheric and photospheric magnetic structures, to understand the direct and indirect nature of vorticity in the solar atmosphere and the implications for heating. It is thought that granular-scale vortices, which appear abundantly in a quiet Sun, can be generated by turbulent convection in subsurface layers of the Sun and its interaction with the solar atmosphere (see for e.g., [1-4]). These small-scale vortical flows have caught significant attention in relation to the formation of magnetic or non-magnetic vortex tubes (see for e.g., [7-9]). Vortical flows are complex and in the solar atmosphere exhibit a 3D vector flow field. In principle, horizontal flows from the granule interiors travel towards the downflow regions in the inter-granular lanes and by conservation of net angular momentum a vortex flow forms within the lane. This vortex generation has yet to be confirmed observationally, as it requires a very spatial sampling of individual granules and inter-granular lanes. ~~[8]~~Shelyag et al (2011) investigated the properties of vorticity numerically and in different regimes in the lower solar atmosphere and found that there can exist *non-magnetic* vortices driven by baroclinic motions in the photosphere, as well as, *magnetic* vortices driven by tension in inter-granular magnetic flux concentrations (see Fig. 1 for an example snapshot from 3D Radiative MHD simulations of spiraling streamlines in red in the photosphere / low chromosphere). Granular-driven vortex motions are thought to contribute to the heating of the upper solar atmosphere (e.g., [10,11]). With high-resolution ground-based observatories we are beginning to detect the presence of such vortical motions in the photosphere. ~~[12]~~Bonet et al. (2008) detected so-called whirlpools, through tracing proper motions of bright points in the magnetic network that become engulfed by inter-granular downdrafts. Additionally, ~~[13]~~Manso Sainz et al. (2011) reported very tiny (<0.4 Mm) signatures of swirling motions of internetwork magnetic elements in inter-granular lanes, yet it is expected that vortex motions should exist on smaller scales (< 0.1 Mm).

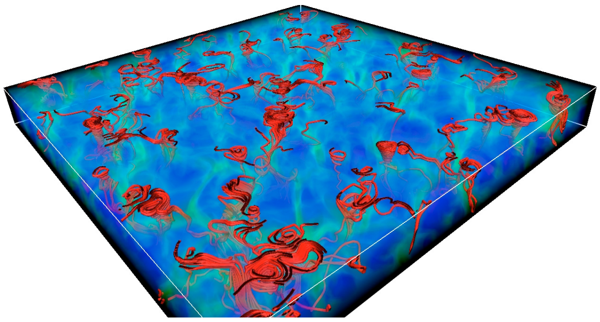

Fig. 1 Advanced 3D numerical simulations reveal spiral structures (red stream lines) in the low solar atmosphere in granular lanes [7].

Science questions to be addressed by DKIST on the nature of photospheric vortex motions are:

1) Can we measure properties of baroclinic motions in the vicinity of magnetic flux concentrations and measure the changes / effect on the magnetic field?
2) What causes the fragmentation of magnetic flux concentrations / bright points?

3) Can we place limits on how many vortices exist in the photosphere at any given time and how many are coupled into the chromosphere and outer solar atmosphere?

Small-scale vortex motions

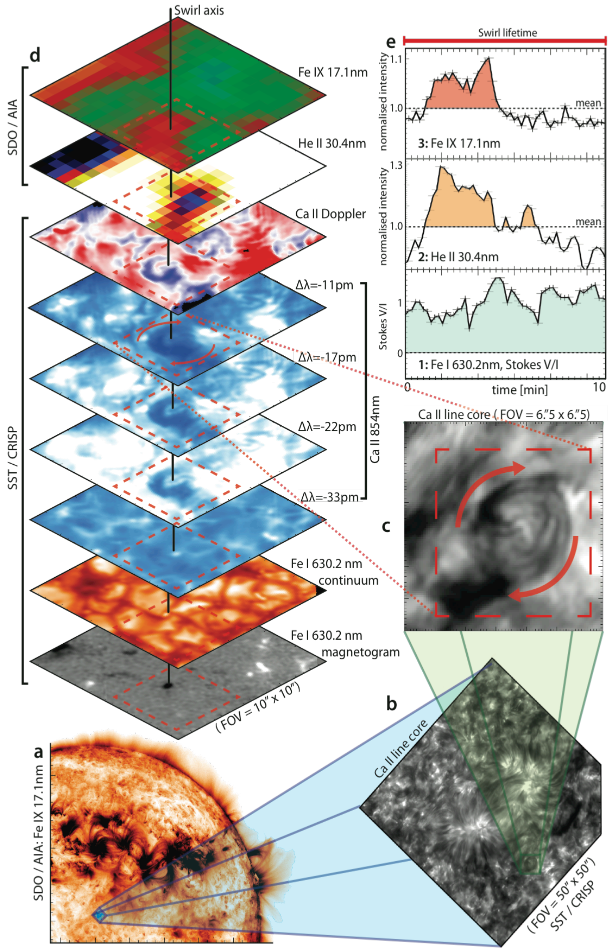

Fig. 2 Observation of a chromospheric swirl as observed by CRISP (SST) in Ca II 854.2 nm spectral images with response in the low corona [16].

~~[14]~~Wedemeyer-Böhm & Rouppe van der Voort (2009) detected dark (absorbing), rotating ring fragments, using high resolution observations from CRISP (CRisp Imaging Spectro-Polarimeter) (SST: [15]), named as small-scale chromospheric swirls have typical cross-sections of 2 arcsec with ring fragments of 0.2-0.5 arcsec and with co-located photospheric bright points (magnetic flux concentrations) close to their swirling centers. With further investigation of such swirls, [16] Wedemeyer-Böhm et al. (2012), demonstrated that vortices in the magnetic flux concentrations can have a significant response in the upper chromosphere and potentially further outwards into the TR / lower corona, where the magnetic vortices in the photosphere can drive the observed chromospheric swirls (aka magnetic tornadoes) (See Fig. 2). It was estimated that the Poynting flux for such small-scale swirling motions is ~440 W/m2 at the upper chromosphere, which would be sufficient for coronal heating to the observed million degree temperatures. It was estimated that there are 3-4 swirls per arcmin at all times and such events lasted for 12 min. +/-4 min. on average, numerically exhibit rotational velocities on the order of 15-20 km/s and observationally 2-5 km/s Doppler shift. Observational confirmation of such rotational velocities in the plane of the swirl (for e.g., through using standard Local Correlation Tracking LCT routines) are inhibited by insufficient spatial resolution with existing ground-based observatories. Recently, ~~[17]~~Park et al. (2015, in prep) detect a corresponding heating signature within the IRIS Mg II h/k spectral profile for a correlated chromospheric swirl, co-observed with CRISP in Hα and Ca II 854.2 nm. The nature of the dissipative mechanism leading to heat exchange between the small-scale swirls and the low corona is yet to be revealed. It is considered that magnetic fields become wound up around flux concentrations leading to rising magneto-acoustic waves which follow the spiraling trajectory, hence, leading to swirls observations [3]. Chromospheric vortex motions are likely to generate a variety of MHD waves considered important for atmospheric heating, such as fast magneto-acoustic / Alfvén / shock waves (see for e.g., [18,19]). ~~[20]~~Kitiashvili et al. (2013) showed in their numerical simulations that small-scale plasma eruptions occur in swirling vortex tubes, which exhibit a complication flow pattern in Doppler space. It is thought that heating through Ohmic dissipation at the edges of magnetic flux concentrations could occur, where acoustic shocks interact with flux concentrations. Or does the non-linear damping of torsional Alfvén waves, generated by the magnetic vortex motions in the chromosphere, result in dissipation at a greater height, in the atmosphere above the chromosphere.

Science questions to be addressed by DKIST on the nature of small-scale swirls are:

1) What are the properties of the magnetic field in the chromosphere within swirls?
2) What waves exist within swirls and how much energy do waves carry?
3) What happens to the vortex driven material as it passes through the upper chromosphere into the TR and low corona?
4) Can we measure the characteristic vortex velocity profile within swirl cross sections and effectively measure their rotational velocities at different heights in the chromosphere?
5) What can swirls tell us about the mass density structure of the chromosphere?

Large-scale vortex motions

Giant tornadoes have been detected in the solar atmosphere since the beginning of high resolution, ground-based solar observatories going as far back as 1868 ~~(~~[21]~~).~~ In the modern era of continuous space-based observations of the Sun, ~~[22]~~Pike & Mason (1998) used the Coronal Diagnostic Spectrometer (CDS), on SOHO, to study the properties of solar tornadoes aka giant tornadoes. These observations suggest that large-scale vortex motions could play an important role in the dynamics of the solar transition region [23,24]. More recently, giant tornadoes were observed in detail with the Atmospheric Imaging Assembly (AIA) onboard SDO. ~~[25]~~Li et al. (2012) detected plasma that moved along spiral paths with an apparent rotation that lasted for more than three hours. ~~[26]~~Wedemeyer et al. (2013) performed a statistical study of giant tornadoes with AIA in the 17.1 nm channel, which exhibited an average lifetime of 20 hours albeit with a large standard deviation. ~~[27]~~Su et al. (2012) suggested that so-called barbs, which appear as dark, extension away from filamentary channels in Hα 656.28 nm are a observational signature of giant tornadoes. Barbs are observed in the Hα spectral line and are known to be rooted in the photosphere and to connect to the horizontal "spine" of a filament in the upper atmosphere (for e.g., [28-30]). Despite the apparent motion in the plane-of-sky observations from high cadence imagers, it is not yet clear whether or not giant tornadoes actually rotate as a vortex about an axis or whether they could exist as flows along helical structures, therefore giving the appearance of vortex motion. In support of this hypothesis, ~~[31]~~Panesar et al. (2013) suggest that giant tornadoes could be caused by the helical magnetic field of a prominence in response to the expansion of the corresponding cavity. However, contrary to this perspective, ~~[32]~~Orozco Suarez et al. (2012) measured Doppler shifts of +/-6 km/s in the adjacent legs of a quiescent hedgerow prominence, which was interpreted as rotation of the structure, around an axis vertical to the solar surface. Furthermore, ~~[27]~~Su et al. (2012) proposed that giant tornadoes could be explained as rotating magnetic structures driven by underlying photospheric vortex flows. ~~[26]~~Wedemeyer et al. (2013) presented supporting observations of a giant tornado, which also exhibited similar opposing Doppler signatures within the legs of a prominence, although with on-average larger Doppler velocities of +/-25 km/s, using high resolution ground-based CRISP observations co-observed with AIA. In agreement, After performing a statistical analysis on giant tornadoes as observed with AIA, they observed tornado groups that grow prior to the eruption of the connected prominence, implying that the large-scale vortex motions may destabilize prominences leading to eruptions. ~~[33]~~Scullion et al. (2015, in prep) also detected opposing Doppler signatures along the spine of a giant tornado at the limb, as observed with both CRISP and AIA with +/-20 km/s Doppler motions, which appeared to last for many days (See Fig. 3 for an observation of a giant tornado).

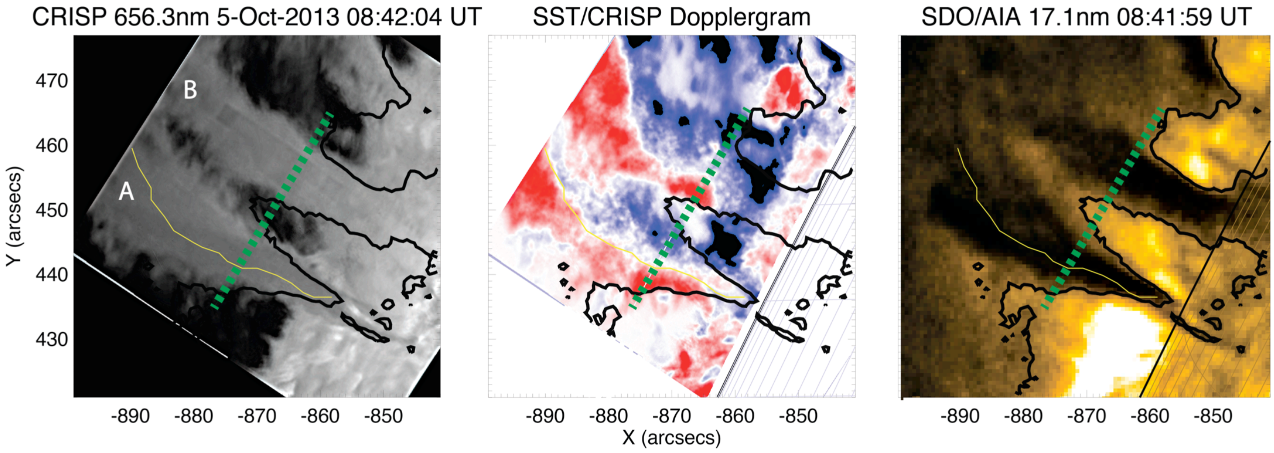

Fig. 3 Observation of a giant tornado at the solar limb as observed with CRISP in Hα (left), Dopplergram (centre) and AIA 17.1nm (right) emission [33].

Science questions to be addressed by DKIST on the nature of small-scale swirls are:

1) Is there a relationship between the size of vortex motions and lifetime of the event?
2) How to small-scale swirls appear at the limb and are they rooted to large-scale vortex motions (such as giant tornadoes in the legs of prominences?
3) Can large-scale vortex motions trigger prominence eruptions?
4) Can we measure the magnetic sub-structure of giant tornadoes in hedgerow prominences?

Goal and Context

Magnetic tension can increase as a result of the rotation of magnetic fields and this process is linked to the formation of solar flares and coronal heating (34). The most prominent and long-standing question in solar physics is, "*What is the origins of coronal heating?*" Today that question should be revised given that we have now discovered an array of phenomena (aside from solar flares in the corona) that are sourced in the chromosphere, which are observed to exhibit rotational / vortical motions on much smaller scales and carry enough energy flux to heat the corona continuously. Examples of prominent events with significant heating potential are type-II spicules (chromospheric jets), magnetic tornadoes (vortex motions) and explosive events (small-scale reconnection). The core problem should be revised, in order to address the extent to which the event can have an impact, with respect to coronal heating. In other words, "*What is the predominant physical mechanism behind energy dissipation in the solar atmosphere?* Is there only local, direct heating or can there be indirect processes leading to heating non-locally?*"* In this proposal, we aim to address this question through exploring the multi-scale nature of vorticity, as a physical mechanism to effectively generate waves (Alfvén, fast/slow magneto-acoustic and body/surface waves) and currents in the solar atmosphere and the possibility of scalability in vortex motions which could provide unique insights into the nature of turbulence in solar plasmas and dissipative processes. We aim to investigate the direct and indirect implications of vorticity with respect to its potential for atmospheric heating, across a broad a range of spatial scales.

The primary objectives that can be investigated with DKIST are:

1) Confirm whether or not giant tornadoes are rotation as a vortex or wave / flow

motions along helical magnetic structures.

2) Identify wave modes (Alfven, magneto-acoustic, body modes) that are sourced to vortex motions on multiple scales in the lower solar atmosphere and determine their energy contribution to coronal heating, with respect to spatial scale.
3) Investigate whether there is any relationship between the vortex size vs. lifetime and vortex size vs. rotational velocity in connecting the physics of giant tornadoes in prominences (or on-disk in filamentary barbs) with small-scale magnetic tornadoes in coronal holes and the quiet Sun on-disk. Is there any power-law relationship i.e. are tornadoes scalable in the solar atmosphere.
4) Determine whether giant tornadoes have origins in photospheric granular vortical motions.
5) Investigate the relationship between giant tornadoes and prominence eruptions.

Expected Data Products

Specify the data products that you expect to obtain in relation to the scientific goal (e.g. you plan to estimate line-of-sight velocities, the strength and geometry of the magnetic field, etc.).

Vortex Dynamics:

In order to investigate vortical motions in the solar atmosphere at multiple scales, we need to evaluate 3D velocity vectors using imaging spectro-polarimetry in a variety of photospheric and chromospheric channels. With imaging we can investigate the plane-of-sky vortical motions in small-scale swirls/tornadoes on-disk in quiet Sun (preferably coronal hole regions) regions. Therefore, the vel-***x*** and vel-***y*** components of vortex motions could be aquired with LCT that will greatly benefit from the high spatial and temporal resolution with the VTF (for chromospheric swirls) and VBI (for photospheric vortex motions in intergranular lanes) instruments. Additionally, with the VTF we can investigate the Doppler component of vortex motions with spectral imaging in Hα and Ca II 854.2 nm (channels where vortex motions have been observed previously). Spectral profiles per pixel will provide the vel-***z*** component within the cross-section of the tornadoes on-disk and rotational velocities in the cross-sections of tornadoes off-limb.

Vortex Structure:

Within both small and large-scale tornadoes it is expected that there will be an increase in magnetic vorticity, as vortical motions evolve. In the photosphere, the magnetic field is frozen into the plasma so the effect of increased non-magnetic vorticity will be present in the granular flow, which will dictate the dynamics of bright-points (at the epicentre of the small-scale tornadoes on-disk) in inter-granular lanes. However, in the transition to predominantly magnetic vorticity in the upper atmosphere we may reveal a change in the dynamics of the vortical flow field as magnetic fields start to dictate the dynamics, especially in giant tornadoes. For this reason we would like to measure the strength and geometry of the magnetic field in both small-scale tornadoes on-disk and in giant tornadoes off-limb. We expect to measure the magnetic field within giant tornadoes for the first time through observations of the chromospheric magnetic field, via full stokes polarimetry in Ca II 854.2 nm (via VTF) together with the spectral slit scanning via VISP. With the VISP we would measure the mass / electron densities (through line ratios) as well as the magnetic field in giant tornadoes that form the legs of prominences off-limb.

For on-disk, small-scale tornadoes in the chromosphere, we would like to measure the magnetic field at two heights using full Stokes polarimetry in Ca II 854.2 nm (scanning via

VTF) as well as in Fe I 630.2 nm (scanning via VTF) for measuring the photospheric magnetic field co-temporally. In the same sequence, we will want line scanning in Hα. The relatively long lifetime of chromospheric swirls means that we do not require extremely high temporal resolution and will prefer deeper spectral imaging to study the structure of the magnetic field in the cross-sections of small-scale tornadoes in the chromosphere. At the same time we will like to use also the VBI instrument to measure the vortical motions of the photosphere below chromospheric tornadoes at the highest possible spatial and temporal resolution to detect the presence of vortex motions around the rooted magnetic flux concentrations.

Data Product Details

Furthermore, please specifically elaborate on each of the following quantities: spatial and spectral resolution, field-of-view, and (if applicable) photometric and polarimetric accuracy and/or precision estimates.

Spatial and Temporal Resolution on-disk (preferably coronal hole / quiet Sun disk centre):

We will require the highest achievable spatial resolution when investigating the vortex motions of the photosphere that are rooted to chromospheric tornadoes. These motions have not been fully investigated around individual bright points and it is expected that the motions will appear within the range of the granulation boundaries (<0.5 Mm). Likewise, we will need to resolve the cross-sections of small-scale tornadoes in the chromosphere, which are observed to have a diameter of 1.5 Mm. In order to resolve these flows within these structures, we will require DKIST observations in the blue channels with VBI at the highest resolution of 0.022 arcsec in 430.5 nm and 0.034 arcsec in Hα. This will enable at least 20 pixel coverage in the cross-sections of inter-granular lanes for identifying vortex motions in the photosphere and allow for a very detailed coverage of the flow field in the chromospheric tornadoes. The 3 x 3 mosaic of the 45 arcsec physical FOV for VBI will provide an extended FOV of 135 x 135 arcsec in a cadence of 27 s after speckle reconstruction. This will enable a robust statistical analysis of vortex motions in the solar atmosphere and investigation of the widespread heating of large-scale structures in the coronal associated with vortex motions in both the photosphere and chromosphere. We can sacrifice on cadence for such a study of chromospheric tornadoes given the expected lifetimes of ~12 minutes. Alternatively, if we optimize for cadence we would like not to use mosaic mode and acquire reconstructed images in 3 s to investigate high frequency wave modes associated with tornadoes on-disk.

Simultaneously, if we use the VTF together with VBI for on-disk then we would like to optimize the diffraction limited spatial resolution of 0.028 arcsec for the VTF with a FOV of 60 arcsec and perform deep spectral scanning of the Hα channel with equidistant spectral sampling between +/-0.1 nm about the Hα line core. The Doppler sensitivity in the red beam with VTF of 75 m/s will enable a very detailed study of magneto-acoustic travelling wave modes in the tornado cross-sections and determination of the velocity profile to confirm the properties of a vortex in the tornadoes. For reduced FOV coordination with VBI we would like to optimize for high cadence imaging of 3 sec so we will limit the VTF scanning to Hα followed by Ca II 854.2 nm at 15 spectral positions in each line, at 3 pm spectral sampling. Likewise, for extended (mosaic) FOV scanning in VBI (with effective cadence of 27 s) we would like to run bursts of 15 point scans in Hα and Ca II per pointing.

Magnetic field measurements in Ca II 854.2 nm and Fe I 630.2 nm with VTF:

We would like to an observation sequence with the VBI which involves measuring high cadence, high spectral spatial sampling of the photosphere in 430.5 nm (blue channel) and chromosphere (in Hα) together with a magnetic field measurement at two heights with VTF. The magnetic field sensitivity of the 40 Gauss in the longitudinal and 200 Gauss in the transversal magnetic field in Fe I 630.2 nm and Ca II 854.2 nm using 16 accumulations at 25 ms exposures per LC state for 24 positions (with 30 mÅ spectral sampling) in the line scans. [35]Kato et al. (2015, in prep) has measure the statistical properties of magnetic tornadoes in the chromosphere using 3D radiative MHD simulations and determines that at 50 Gauss magnetic field in the initial atmosphere they maximize the number of detectable vortex motions. A spectral range of +/-0.03 nm about the lines cores will be sufficient for recovering the Stokes profiles of both lines and at a SNR of >650, we will be sensitive to such weak magnetic fields in the longitudinal direction. Weak transverse magnetic fields of approx. 200 Gauss are detectable with the VTF at this polarimetric sensitivity, which will enable unique insights into the magnetic sub-structure of small-scale and large-scale vortex motions. This spectral resolution across a broad spectral range will enable a satisfactory application of magnetic field inversions in the post-reconstruction to determine the magnetic field vectors within the FOV of the tornadoes in the photosphere and chromosphere simultaneously.

Spectral and Temporal Resolution off-limb

In order to investigate large-scale vortex motions in giant tornadoes we will prefer to observe deep scans in Hα and Ca II 854.2 nm off-limb, without polarimetry. The lifetime of giant tornadoes is sufficient to allow for a long cadence and deep spectral scans in order to recover meaningful Doppler velocity measurements in the cross-sections of the tornadoes. We would like to combine these VISP spectral scanning measurements to investigate the mass density properties of giant tornadoes and the magnetic field in the legs of prominences, using the Hanle effect. VISP will be highly effective in studying prominence sub-structure and off-limb activity with 120 x 120 arcsec FOV at 0.07 arcsec spatial resolution in 3 spectral lines simultaneously. Ideally we will want to investigate the connectivity between giant tornadoes and prominences using the Sr I 460.73 nm triplet line for measuring magnetic fields in the giant tornadoes with the Hanle Effect, the He I D 587.59 nm prominence line and the Na I D2 and D1 line ratios (i.e. 589.0 & 589.59 nm) for density diagnostics..

Data Analysis Methods

Please describe the methods you intend to apply to the proposed observations to pursue your science goal(s) (e.g. you plan to use a bisector analysis or a center-of-gravity method to estimate line-of-sight velocities, or you plan to apply an inversion to derive the magnetic field strength and the magnetic field geometry, etc.).

With respect to the spectral scans in in Hα and Ca II 854.2 nm, as well as, full Stokes spectro-polarimetric scans in Fe I 630.2 nm from the VTF, we will apply a reduction pipeline to perform MOMFBD reconstructions to the data after processing [36,37]. We would therefore like to obtain the raw data files from the VTF measurements concerning the flats, darks and pinholes in the calibration of the instruments prior to the observing run. We have experience and access to the necessary computational facilities in order to apply MOMFBD reconstructions. We have sufficient experience in this process through applying the method to CRISP observations from the SST, which is very similar to the VTF. After post-processing of VTF data and acquiring the speckle reconstructed VBI data, most techniques will be based on manipulation of the monochromatic intensity images (in particular with the VBI data) and exploiting time-series analysis, e.g., Fourier, Wavelet, Multi-scale, LCT, feature tracking etc. We will apply a bisector analysis to determine the Doppler velocities within the spectral images from the VTF and perform multi-Gaussian component line fitting analysis to determine other parameters such at the thermal velocity per pixel from the spectral lines obtained with VTF. We will reconstruct the Stokes I, Q, U, V profiles (observed as 4 modulation states) from the full Stokes scans in 630.2 nm and 854.2 nm using the NICOLE, SIR and / or Centre Of Gravity (COG) algorithms (some of which are available within SolarSoft in IDL) in order to model the properties of the magnetic field vectors (transverse and Longitudinal components) per pixel and measure Doppler motions in the photosphere. We will then construct the resulting data cubes from VBI and VTF into a format suitable for visualization and inspection with the widely used CRISPEX software [38]. This will enable a fast approach to arriving at new and interesting science results given the wide range of data products that will be made available.

Image Upload

You may upload a PDF, JPG or PNG file in support of your Science Use Case.

Figures 1, 2 and 3 are uploaded with this proposal.

3. Observation Specifics

Observing Strategy

Please provide a detailed description of how the observations should be obtained in sequence.

SEQ 1: Small-scale vortex motions on-disk – reduced FOV

VBI – BLUE (45 x 45 arcsec), 393.3 nm + G-Band 430.5 nm + 450.4 nm + 486.1 nm
Cadence = 3.2 s cadence per detector / spectral line

Together with:

VTF - Hα scanning (60 x 60 arcsec FOV), 11 spectral positions (5 on either side of line core, spectral range +/-0.1 nm, spectral sampling 200 mÅ), 8 accumulations per position (for reconstructions), 25 ms exposure time, 1 modulation state = 3 s cadence
+
Ca II 854.2 nm scanning (60 x 60 arcsec FOV), 11 spectral positions (5 on either side of line core, spectral range +/-0.1 nm, spectral sampling 100 mÅ for 4 positions on both sides of the line core then 1 far wing positions at 0.1 nm in both wings), 1 modulation state = 3 s
effective cadence **=** 3.0+3.0+0.6 (FP tuning time = 0.3) = 6.6 s

SEQ 2: Small-scale vortex motions on-disk – large FOV

VBI – BLUE Same as SEQ 1 with 3 x 3 mosaic for 27 s cadence
VBI – RED (69 x 69 arcsec), Hα + 668.4 nm + 705.4 nm + 854.2 nm
= 3.2 s per spectral line / detector

Together with:

VTF – Intermittent busts of Ca II 8542 scanning at 1 modulation (LC) state we will have a scan of full Stokes polarimetry (magnetic field measurements) in Ca II 854.2 nm scanning (60 x 60 arcsec FOV), 8 accumulations per spectral position per LC state, 4 modulation states, 13 spectral positions (1 core + 6 positions on either side of line core, spectral range +/-0.1 nm, spectral sampling 50 mÅ for 5 positions on with side of the line core then 1 far wing positions at 0.09 nm and 0.1 nm in both wings) = 13 s cadence
+
Full Stokes polarimetry (magnetic field measurements) in Fe I 630.2 nm using the same spectral sampling but the far wing spectral positions should be at 0.04 nm and 0.05 nm in both wings. = 13 s cadence
effective cadence **=** 26 s

This polarimetric scan in 854.2 nm and 630.2 nm should get performed once every 10 min in the observation sequence.

SEQ 3: Large-scale vortex motions off-limb – VTF & VISP

VTF - Scanning in 769.9 nm scanning (60 x 60 arcsec FOV), 11 spectral positions (5 on either side of line core, spectral range +/-0.05 nm, spectral sampling 100 mÅ), 8 accumulations per position (for reconstructions), 25 ms exposure time, 1 modulation state, cadence = 3 s cadence
+
Scanning Ca II 854.2 nm scanning (60 x 60 arcsec FOV), 11 spectral positions (5 on either side of line core, spectral range +/-0.1 nm, spectral sampling 100 mÅ for 4 positions on with side of the line core then 1 far wing positions at 0.1 nm in both wings), 1 modulation state, cadence = 3 s
+
Scanning in 866.22 nm (60 x 60 arcsec FOV), 11 spectral positions (5 on either side of line core, spectral range +/-0.05 nm, spectral sampling 100 mÅ), 8 accumulations per position (for reconstructions), 25 ms exposure time, 1 modulation state, cadence = 3 s
giving
effective cadence **=** 3.0+3.0+3.0+0.3 (FP tuning time 0.1) = 9.3 s

Together with:

VISP - 120x120 arcsec FOV, 0.07 arcsec spatial resolution, 3 spectral lines simultaneously using the Sr I 460.73 nm for measuring magnetic fields with the Hanle Effect, + He I D 587.59 nm prominence line + Na I D2 and Na I D1 line ratios (i.e. 589.0 & 589.59 nm) + Hα **=** 3 min cadence

SEQ 4: multi-scale vortex motions on-disk (multi-wavelength) - VBI & VTF & DL-NIRSP

VBI BLUE – Calcium K 393.3 nm + G-Band 430.5 nm + 450.4 nm + 486.1 nm
Cadence = 3.2 sec cadence per detector / spectral line

Together with:
VTF – Hα 656.28 nm: 75 wavelength points, 1 modulation state per spectral line, 8 accumulations, 25 ms, 30 mÅ spectral sampling from core out to

-/+1110 mÅ on both sides of line core.
Cadence = 20.3 sec
OR
Ca II 854.2 nm: 61 wavelength points, 1 modulation state per spectral line, 8 accumulations, 25 ms, 30 mÅ spectral sampling from core out to
-/+900 mÅ on both sides of line core.
Cadence = 16.5 sec

Together with:
DL-NIRSP –I prefer 5 slit sampling (120 x 120 FOV) and high res mode at 0.03 arcsec spatial sampling (at 900 nm). From 2.4 x 1.8 arcsec IFU unit FOV, with mosaicking. Spectral sampling includes Fe XIII 1075.0 nm and 1080.0 nm for electron density diagnostics.

SEQ 5: multi-scale vortex motions off-limb (Deep scan)– VTF & DL-NIRSP

VTF – Hα: 75 wavelength points, 1 modulation state per spectral line, 8 accumulations, 25 ms, 30 mÅ spectral sampling from core out to
-/+1110 mÅ on both sides of line core.
Cadence = 20.3 sec
OR
Ca II 854.2 nm: 61 wavelength points, 1 modulation state per spectral line, 8 accumulations, 25 ms, 30 mÅ spectral sampling from core out to
-/+900 mÅ on both sides of line core.
Cadence = 16.5 sec

Together with:
DL-NIRSP –I prefer 5 slit sampling (120 x 120 FOV) and high res mode at 0.03 arcsec spatial sampling (at 900 nm). From 2.4 x 1.8 arcsec IFU unit FOV, with mosaicking. Spectral sampling includes Fe XIII 1075.0 nm and 1080.0 nm for electron density diagnostics.

SEQ 6: multi-scale vortex motions on-disk (Magnetic Fields)– VBI & DL-NIRSP
VBI BLUE – Calcium K 393.3 nm + G-Band 430.5 nm + 450.4 nm + 486.1 nm
Cadence = 3.2 sec cadence per detector / spectral line

Together with:
DL-NIRSP – Fe I 630.2 nm (full stokes polarimetry) + Hα 656.28 nm + 854.2 nm (full stokes polarimetry). For DL-NIRSP I prefer 5 slit sampling and high res mode at 0.03 arcsec spatial sampling (at 900 nm). Magnetic field at two heights together with high res. photospheric vortex motions.
Cadence = 3 min

Observing Coordination

In case the observations require coordination with another facility, please elaborate on the details of the planned coordination.

No coordinated observations required although we will aim to run coordinate campaigns independently with IRIS and the SST.

Observing Condition Specifics: Seeing

Good

Observing Condition Specifics: Sky Clarity

1) SEQ1, SEQ2(a,b), SEQ4 & SEQ6: On-disk (disk center or within 20 degrees of disk center) for photospheric and small-scale vortex motions in preferably quiet Sun and coronal hole atmospheres.
2) SEQ3 & SEQ5: Off-limb (quiet Sun) for large-scale vortex motions such as giant tornadoes which appear within the legs of (hedgerow) prominences.

4. Target Specifics
Type of Target(s)

Quiet Sun
Coronal hole
Filament
Prominence

Target Specifics

Please provide a detailed description of the solar target(s).

1) SEQ1, SEQ2, SEQ4 & SEQ6: This target is ideal for looking at small-scale vortex motions whilst minimizing the projection effects in order to study the cross-sections of tornadoes to identify vorticity and propagating wave modes. Hence, we require photospheric and small-scale vortex motions in preferably quiet Sun and coronal hole atmospheres where there is no overlying structures in the corona. The target should be free of active regions or trailing plage.
2) SEQ3 & SEQ5: We can best detect giant tornadoes off-limb with good contrast for measuring LOS Doppler velocities. The prominence target is useful for detecting large-scale vortex motions, such as giant tornadoes, which appear within their legs, such as in hedgerow prominences.

Number of Targets
(e.g. when a center-to-limb variation is intended)

One target is required in SEQ1 and SEQ3. For SEQ2, we will run a 3x3 mosaic with the VBI. The centre of the 3x3 grid should be centred close to the disk centre (within 20 degrees).

Position(s) on Sun
Specify the position of the target(s) on the Sun in +/- [x,y] arcsec from disk center.

For out disk centre observations we will want to point the telescope no further than 20 degrees (LAT,LON) from the [0,0] disk centre. For our off-limb observations we would like to centre of the FOV to be pointed at the solar limb so that a portion of the FOV is off-limb and some part on-disk where there may be some bright / contrasting feature to track. This may be beneficial to ensure stable locking of the AO whilst observing.

Time on each Target
Please enter Minimum, then Optimum, in minutes.

We will expect a minimum of 15 minutes (given the lifetime of small-scale vortex motions) and an optimum of 30 minutes to detect interesting evolutions in giant tornadoes. We would hope for up to 1 hour observing runs.

5. Instrument Specifics

Instrument Set Definition

For detailed information on the instruments capabilities please visit the DKIST Instrumentation and Coudé configuration web-pages. Please select all applicable from the listed choices. PLEASE NOTE that the Cryo-NIRSP cannot be operated with any other instruments.

SEQ 1: VBI-BLUE + VTF – optimized cadence for small-scale vortex
SEQ 2a: VBI-RED + VBI-BLUE – highest resolution of photosphere & chromosphere and large FOV (for statistics)
SEQ2b: SEQ2a + VTF (intermittently – can this be done on mosaic mode in all pointings?)
SEQ 3: VTF + VISP – optimized cadence large-scale vortex dynamics.
SEQ 4: VBI + VTF + DL-NIRSP – deep spectral study of swirls.
SEQ 5: VTF + DL-NIRSP – electron density and deep 656.3 scan.
SEQ 6: VBI + DL-NIRSP – magnetic fields at two heights.

Filter Sequence & Spectral Lines
For each instrument selected, please enter the filter sequence and spectral lines.

See detailed description of spectral line sequencing within "Observing Strategy" for SEQ1, SEQ2 and SEQ3.

Scanning FOV
If you chose ViSP or either NIRSP, please enter the scanning field of view.

For SEQ3-6, we use VISP or DL-NIRSP together with VTF, which should have a 120x120 arcsec FOV centered on the limb and co-pointing with VTF for off-limb prominence observations to detect giant tornadoes. Context images should be made prior to and post observing to ensure co-pointing of the VISP with other observatories.

Coudé Configuration
Copy here the output of the beam-splitter IDL tool.

SEQUENCE 1:
```
[CL2a CL2 CL3a CL3] sequence: BS-680 BS-555 BS-950 Mir1
ViSP gets NO light
VBI/B gets light in the range of [380.00000, 530.00000] nm
successful    : VBI/B       393.30000
```

```
successful    : VBI/B      430.50000
successful    : VBI/B      450.40000
successful    : VBI/B      486.10000
VBI/R gets light in the range of [1000.0000, 2500.0000] nm
VTF gets light in the range of [580.00000, 900.00000] nm
successful    : VTF      656.28000
successful    : VTF      854.20000
DL-NIRSP gets NO light
successful diagnostics = 6
```

SEQUENCE 2a:

```
[CL2a CL2 CL3a CL3] sequence: BS-680 BS-555 BS-465 BS-950
ViSP gets NO light
VBI/B gets light in the range of [380.00000, 530.00000] nm
successful    : VBI/B      393.30000
successful    : VBI/B      430.50000
successful    : VBI/B      450.40000
successful    : VBI/B      486.10000
VBI/R gets light in the range of [580.00000, 900.00000] nm
successful    : VBI/R      656.30000
successful    : VBI/R      668.40000
successful    : VBI/R      705.40000
successful    : VBI/R      854.20000
VTF gets NO light
DL-NIRSP gets light in the range of [1000.0000, 2500.0000] nm
successful diagnostics = 8
```

SEQUENCE 2b (intermittent with SEQUENCE 2a):

```
[CL2a CL2 CL3a CL3] sequence: BS-465 BS-555 BS-950 Mir1
ViSP gets light in the range of [490.00000, 530.00000] nm
VBI/B gets light in the range of [380.00000, 440.00000] nm
VBI/R gets light in the range of [1000.0000, 2500.0000] nm
VTF gets light in the range of [580.00000, 900.00000] nm
successful    : VTF      630.20000
successful    : VTF      854.20000
DL-NIRSP gets NO light
```

SEQUENCE 3:

```
[CL2a CL2 CL3a CL3] sequence: Win1 BS-680 BS-950 Mir1
ViSP gets light in the range of [380.00000, 660.00000] nm
successful    : ViSP      460.73000
successful    : ViSP      587.59000
successful    : ViSP      589.00000
successful    : ViSP      589.59000
successful    : ViSP      656.28000
VBI/B gets NO light
VBI/R gets light in the range of [1000.0000, 2500.0000] nm
VTF gets light in the range of [700.00000, 900.00000] nm
successful    : VTF      769.90000
successful    : VTF      866.22000
successful    : VTF      854.20000
DL-NIRSP gets NO light
successful diagnostics = 8
```

SEQUENCE 4:

```
[CL2a CL2 CL3a CL3] sequence: BS-680 BS-555 Mir1 BS-950
ViSP gets NO light
VBI/B gets light in the range of [380.00000, 530.00000] nm
successful    : VBI/B       393.30000
successful    : VBI/B       430.50000
successful    : VBI/B       450.40000
successful    : VBI/B       486.10000
VBI/R gets NO light
VTF gets light in the range of [580.00000, 900.00000] nm
successful    : VTF       656.30000
successful    : VTF       854.20000
DL-NIRSP gets light in the range of [1000.0000, 2500.0000] nm
successful    : DL-NIRSP       1075.0000
successful    : DL-NIRSP       1080.0000
```

SEQUENCE 5:

```
[CL2a CL2 CL3a CL3] sequence: BS-465 BS-555 Mir1 BS-950
ViSP gets light in the range of [490.00000, 530.00000] nm
VBI/B gets light in the range of [380.00000, 440.00000] nm
VBI/R gets NO light
VTF gets light in the range of [580.00000, 900.00000] nm
successful    : VTF       656.30000
successful    : VTF       854.20000
DL-NIRSP gets light in the range of [1000.0000, 2500.0000] nm
successful    : DL-NIRSP       1075.0000
successful    : DL-NIRSP       1080.0000
successful diagnostics = 4
```

SEQUENCE 6:

```
[CL2a CL2 CL3a CL3] sequence: BS-680 BS-555 BS-465 Win1
ViSP gets NO light
VBI/B gets light in the range of [380.00000, 530.00000] nm
successful    : VBI/B       393.30000
successful    : VBI/B       430.50000
successful    : VBI/B       450.40000
successful    : VBI/B       486.10000
VBI/R gets NO light
VTF gets NO light
DL-NIRSP gets light in the range of [580.00000, 900.00000] nm
successful    : DL-NIRSP       630.20000
successful    : DL-NIRSP       656.28000
successful    : DL-NIRSP       854.20000
successful diagnostics = 7
```

6. References
References

[1] Nordlund, A . Solar convection. Sol. Phys. 100, 209–235 (1985).
[2] Stein, R. F., & Nordlund, Å. 2000, Sol. Phys., 192, 91
[3] Carlsson, M.; Hansteen, V. H.; Gudiksen, B. V., 2010, Memorie della Societa Astronomica Italiana, v.81, p.582
[4] Steiner, O. et al., 2010, Astrophys. J. 723, L180–L184
[5] Kitiashvili, I. N., Kosovichev, A. G., Mansour, N. N., Lele, S. K., &Wray, A. A. 2012a, Phys. Scr, 86, 018403
[6] Moll, R., Cameron, R. & Schussler, M. Vortices in simulations of solar surface convection. Astron. Astrophys. 533, A126 (2011).

[7] Shelyag, S., Keys, P., Mathioudakis, M., & Keenan, F. P. 2011, A&A, 526, A5
[8] Kitiashvili, I. N., Kosovichev, A. G.,Mansour, N. N., &Wray, A. A. 2012b, ApJ, 751, L21
[9] Sturrock, P. A., & Uchida, Y. 1981, ApJ, 246, 331
[10] Zirker, J. B. 1993, Sol. Phys., 147, 47
[11] Bonet, J. A.,Márquez, I., Sánchez Almeida, J., Cabello, I., & Domingo, V. 2008, ApJ, 687, L131
[12] Manso Sainz, R., Martínez González, M. J., & Asensio Ramos, A. 2011, A&A, 531, L9
[13] Wedemeyer-Böhm, S., & Rouppe van der Voort, L. 2009, A&A, 507, L9
[14] Scharmer, G. B., Bjelksjo, K., Korhonen, T. K., Lindberg, B., & Petterson, B. 2003a, Proc. SPIE, 4853, 341
[15] Wedemeyer-Böhm, S., Scullion, E., Steiner, O., et al. 2012, Nature, 486, 505
[16] S. H. Park, G. Tsiropoula, I. Kontogiannis, K. Tziotziou, E. Scullion, and J.G. Doyle, 2015, "First simultaneous SST and IRIS observations of consecutive small-scale vortex events in the quiet Sun", A&A, submitted
[17] Fedun, V., Shelyag, S., Verth, G.,Mathioudakis, M., & Erdélyi, R. 2011, Annales Geophysicae, 29, 1029
[18] Kitiashvili, I. N., Kosovichev, A. G., Mansour, N. N., & Wray, A. A. 2011, ApJ, 727, L50
[19] Kitiashvili, I. N., Kosovichev, A. G., Lele, S. K.,Mansour, N. N., &Wray, A. A. 2013, ApJ, 770, 37
[20] Żollner, F. 1869, AN, 74, 269
[21] Pike, C. D., & Mason, H. E. 1998, SoPh, 182, 333
[22] Pike, C. D., & Harrison, R. A. 1997, SoPh, 175, 457
[23] Banerjee, D., O'Shea, E., & Doyle, J. G. 2000, A&A, 355, 1152
[24] Li, X., Morgan, H., Leonard, D., & Jeska, L. 2012, ApJL, 752, L22
[25] Wedemeyer}, S., Scullion, E., Rouppe van der Voort, L, Bosnjak, A., Antolin, P., 2013, ApJ, 774, 123
[26] Su, Y., Wang, T., Veronig, A., Temmer, M., & Gan, W. 2012, ApJL, 756, L41
[27] Zirker, J. B., Engvold, O., & Martin, S. F. 1998,Natur, 396, 440
[28] Martin, S. F. 1998, SoPh, 182, 107
[29] Li, L., & Zhang, J. 2013, SoPh, 282, 147
[30] Panesar, N. K., Innes, D. E., Tiwari, S. K., & Low, B. C. 2013, A&A, 549, A105
[31] Orozco Súarez, D., Asensio Ramos, A., & Trujillo Bueno, J. 2012, ApJL, 761, L25
[32] Scullion, E. et al. (2015, in prep)
[33] Parker, E. N. 1983, ApJ, 264, 642
[34] Kato, Y. et al. (2015, in prep)
[35] van Noort, M., Rouppe van der Voort, L., & Löfdahl, M. G. 2005, Sol. Phys., 228, 191
[36] de la Cruz Rodríguez, J., Löfdahl, M. G., Sütterlin, P., Hillberg, T., & Rouppe van der Voort, L. 2015, A&A, 573, A40
[37] Vissers, G. & Rouppe van der Voort, L. 2012, ApJ, 750, 22