U.S. NAVAL RESEARCH LABORATORY

Observations of Ionospheric Magnetic Field Fluctuations with the LWA Interferometer

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Background

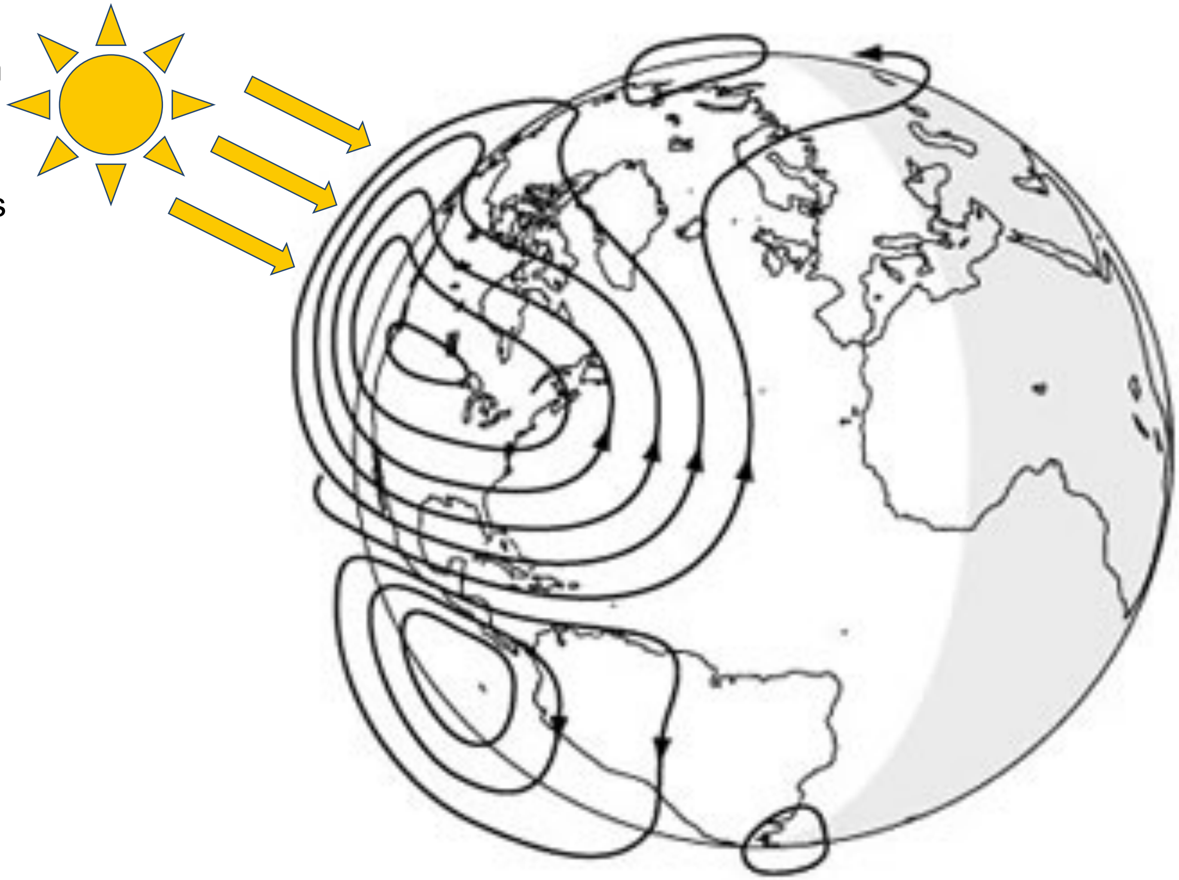
Ionospheric Currents

Solar Quiet (Sq) Currents

- At mid-latitudes, these currents are from the dynamo region where wind pushes ions across magnetic field lines.
- Orientation/intensity of currents changes with the winds, which are mainly driven by solar (diurnal) and lunar (semi-diurnal) tides.
- So, have time-of-day and seasonal dependences.

Magnetic Effects

- These currents cause regular patterns of magnetic field fluctuations (via Ampere's Law) at the level ~50 nT.
- Localized disturbances that disrupt the Sq currents can lead to similarly localized B-field fluctuations.



Ionospheric Currents

Vertically integrated currents

- Dynamo electric field is = ***U***×***B***. If we approximate ionosphere as thin shell, it has a net, "vertically" integrated current density, ***J***, that is this field, multiplied by Pedersen conductivity, σ_P, and integrated along field line.
- Vertically integrated current is perpendicular to field line; gives B-field perturbation perpendicular to nominal field line via Ampere's Law.
- B-field perturbations caused by fluctuations in neutral wind, ***U***, parallel to direction of wind perturbations (vertically integrated).
- Typical conditions near LWA1 give ΔB~0.5 nT for 1 m/s change in neutral wind (within dynamo region).

Current density

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$$ Ampere's Law

Vertically integrated current density

$$\Delta B_{N/S} \approx -\mu_0 J_{E/W} \approx -\mu_0 \int \sigma_p U_{N/S} |\vec{B}| ds$$

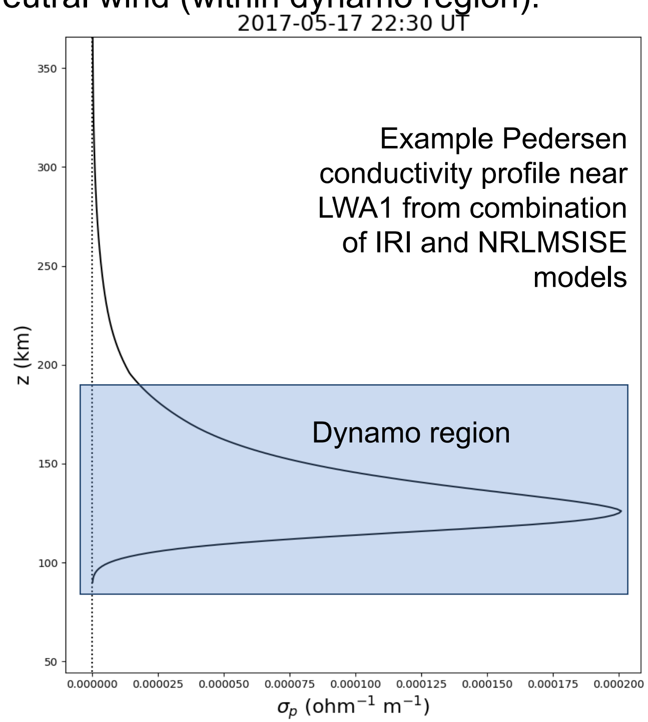
$$\Delta B_{E/W} \approx \mu_0 J_{N/S} \approx \mu_0 \int \sigma_p U_{E/W} |\vec{B}| ds$$

Neutral wind

$$ds \approx \frac{dz}{\sin(I)}$$

Magnetic dip angle

*E/W and N/S refer to magnetic east/west and north/south (perpendicular to ***B***), respectively.

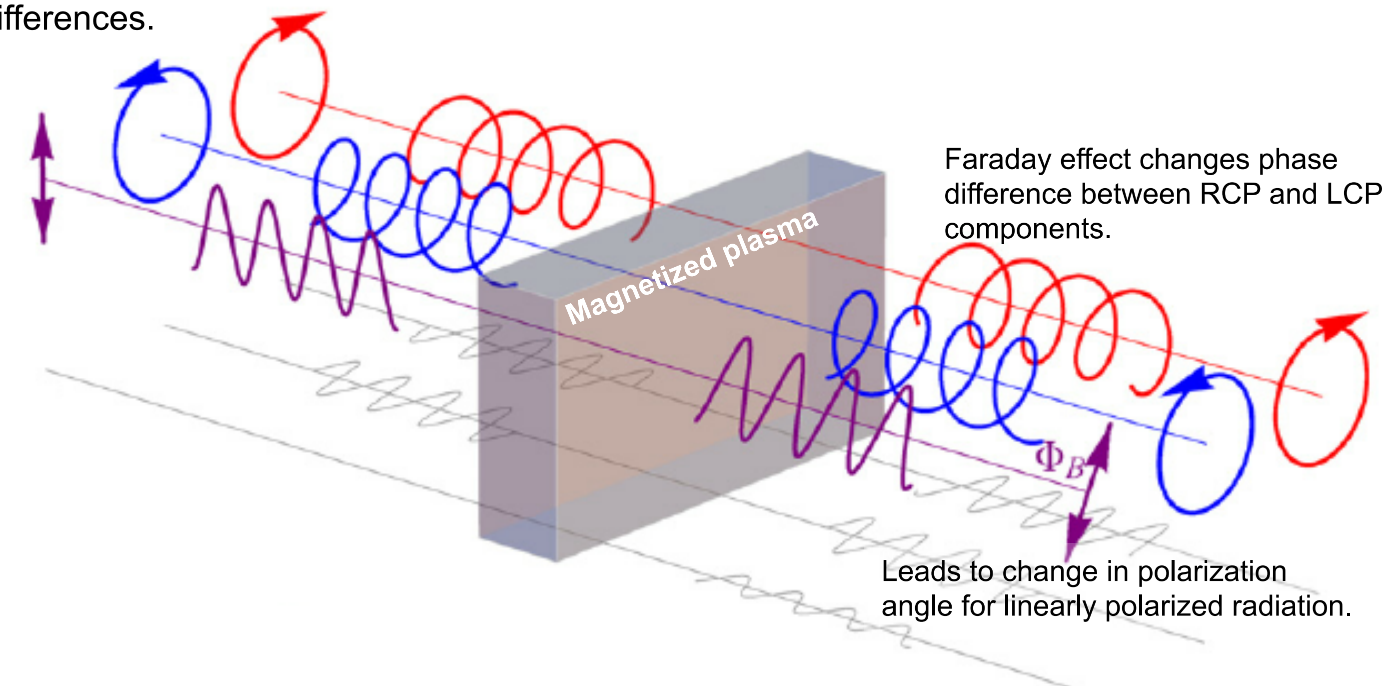


Magnetic Field Remote Sensing

Faraday Effect

Faraday Rotation

- Faraday rotation used for decades to remotely study magnetic fields in far away, magnetoionic plasmas (e.g., solar corona, AGN jets, radio galaxy lobes, galaxy cluster halos).
- Uses rotation of polarization vector of linearly polarized radiation passing through magnetized plasma.
- But, what if you don't have a linearly polarized source? Ionospheric Faraday effect is relatively weak at frequencies where cosmic sources tend to be linearly polarized. Satellite beacons tend to be circularly polarized and at higher frequencies.
- You can measure differential Faraday effect between two locations with an un-polarized source by comparing RCP and LCP phase differences.



Interferometric Measurements

Differential Faraday Effect

Baseline Phases

- For low-frequency, un-polarized cosmic source, phase on a single baseline consists of:

$$\phi_{RR} = \phi_{source} + \phi_{instrument} + \phi_{noise} + n2\pi + \Delta TEC \frac{A_1}{\upsilon} \quad \text{radians}$$

$$\phi_{RR} - \phi_{LL} = \Delta RM \frac{A_2}{\upsilon^2} \quad \text{radians}$$

$$RM = \int B_{\parallel} n_e \, dl \approx B_{\parallel}(z = h'F) TEC \quad \text{TECU Tesla}$$

$$\Delta RM \approx \Delta B_{\parallel} \langle TEC \rangle + \Delta TEC \langle B_{\parallel} \rangle \quad \text{TECU Tesla}$$

Peak height of ionosphere F-region ($h'F$)

$\Delta B_{\parallel}$: WHAT WE'RE AFTER

$\langle TEC \rangle$: Can estimate from GPS-based TEC maps produced by JPL

ΔTEC: Measure from RR baseline phase. CAVEAT: This will contain some residual contribution from source/instrument that will corrupt $\Delta B_{\parallel}$ estimate

$\langle B_{\parallel} \rangle$: Can calculate from model of Earth's B-field

A_1 = 8436 MHz TECU^{-1}

$A_2 = 1.57\times10^6$ TECU^{-1} Tesla^{-1} MHz^2

Can use difference between RR and LL phases with other measurements to estimate difference in line-of-sight magnetic field between array elements with unpolarized source.

The LWA Interferometer/Magnetometer

LWA1 ★ LWA-SV

LWA Program LH015

- Once a week, observing two bright sources with two beams and two tunings (9.8 MHz bandwidth each) simultaneously with LWA1 and LWA-SV. Observe for two hours at a time straddling mean transit time for the two sources to minimize polarization leakage (elevation > 45°).
- Recorded voltages are cross-correlated (J. Dowell) with 1s integrations and 256 channels per tuning. Data converted to RR, LL, RL, and LR during correlation and written out in FITS-IDI format. (Note: within these, LWA1 = antenna 51; LWA-SV = antenna 52.)
- Data are read in and processed with custom python script that:

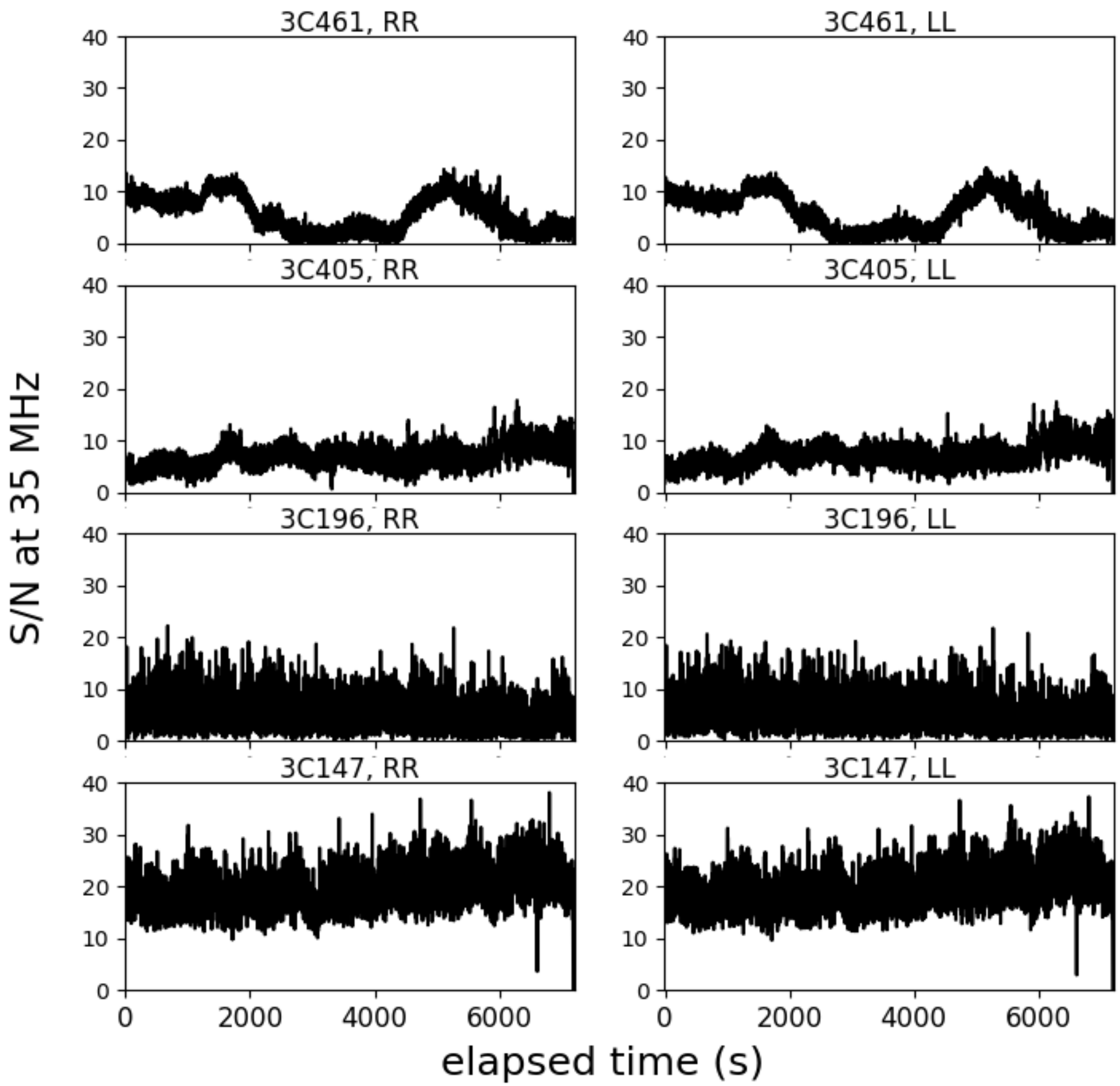
1. Does some additional flagging (using median absolute deviation of visibility amplitudes per channel).
2. Averages over all channels (with outer channels trimmed) to make “channel 0” visibilities.
3. (Optional) Smooths channel 0 visibilities with Gaussian window to increase S/N.
4. Extracts RR phases, unwraps them, and converts to ΔTEC.
5. Computes difference in RR and LL phases by computing the phase of $V_{RR}V^*_{LL}$ (no need to unwrap) and converts to ΔRM.
6. Computes background $B_{||}$ for z=300 km and subtracts product of this and ΔTEC from ΔRM; the mean of these residuals is then set to zero to (partially) account for source/instrumental corruption of ΔTEC.
7. Computes (slant) TEC from JPL maps and divides this into ΔRM residuals from previous step to yield estimate of $\Delta B_{||}$. (Note: Uses getIONEX from RMmextract python package by M. Mevius; JPL maps obtained from cddis.nasa.gov/gnss/products/ionex.)

LH015 Observations

Sources

Long Baseline Makes Source Selection Tricky

- Need S/N>5 to unwrap phases without artifacts; requires relatively bright sources. But, LWA1*LWA-SV baseline is about 75 km long; many bright sources are well resolved at LWA frequencies.
- Started out using Cas A/Cyg A. Found that only Cyg A was consistently useful and only at 35 MHz.
- Have recently tried 3C196/3C147 with great success, especially with 3C147. However, last few observations hampered by RFI; switching back to Cyg A has temporarily fixed this (not sure why).

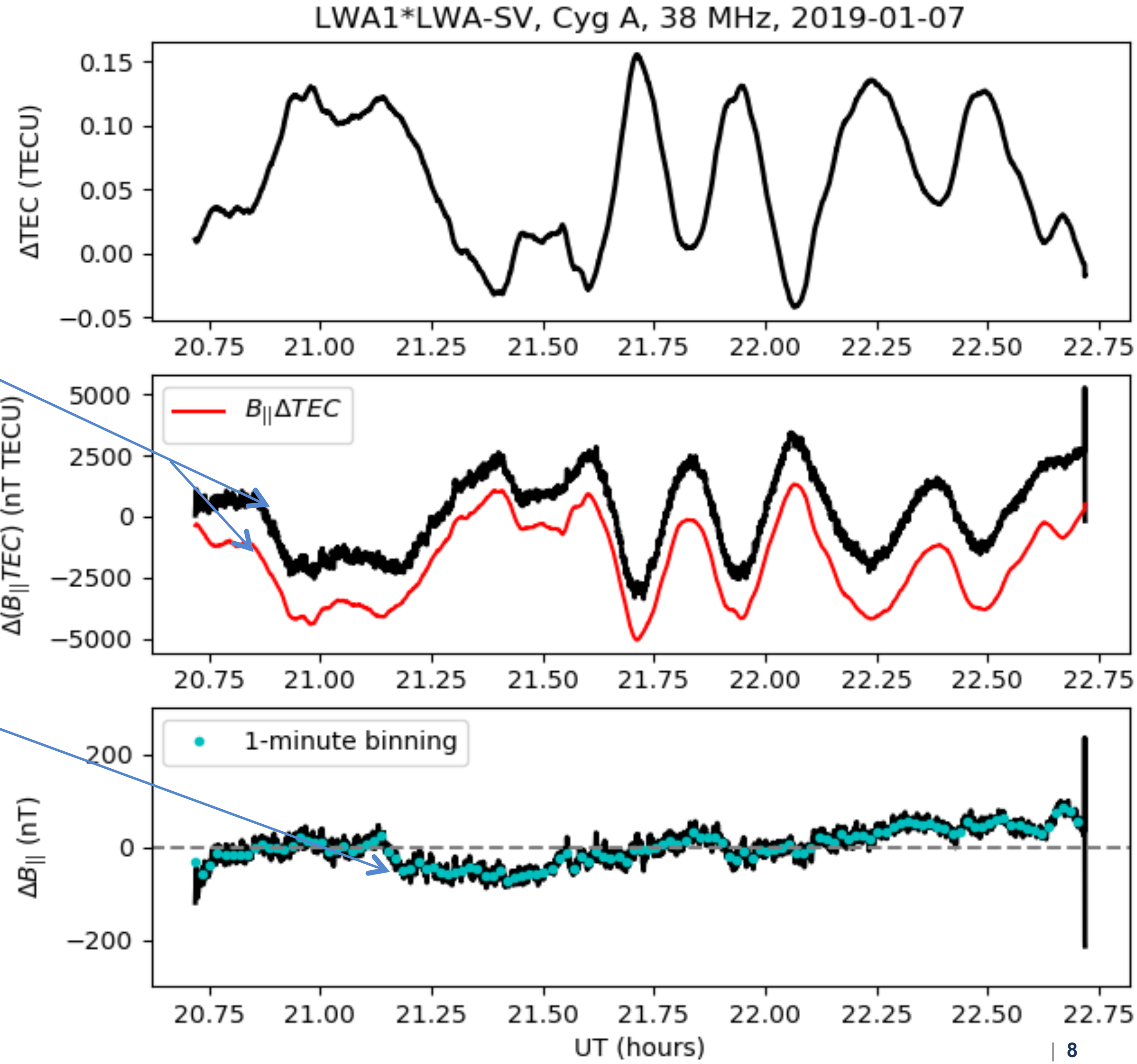


LH015 Observations

Example Collection

First Cyg A Dataset

- Figure to the right shows steps in $\Delta B_{||}$ estimation. Here, visibilities smoothed with 10s window to increase S/N.
- Bulk offset between curves in middle panel from instrumental contribution to ΔTEC measurement.
- Slow/general upward trend in final $\Delta B_{||}$ (bottom panel) due mostly to residual source contamination of ΔTEC measurement, but "wiggles" of tens of nT are real.
- Could remove source contribution with good, high resolution model of Cyg A at 35 MHz.

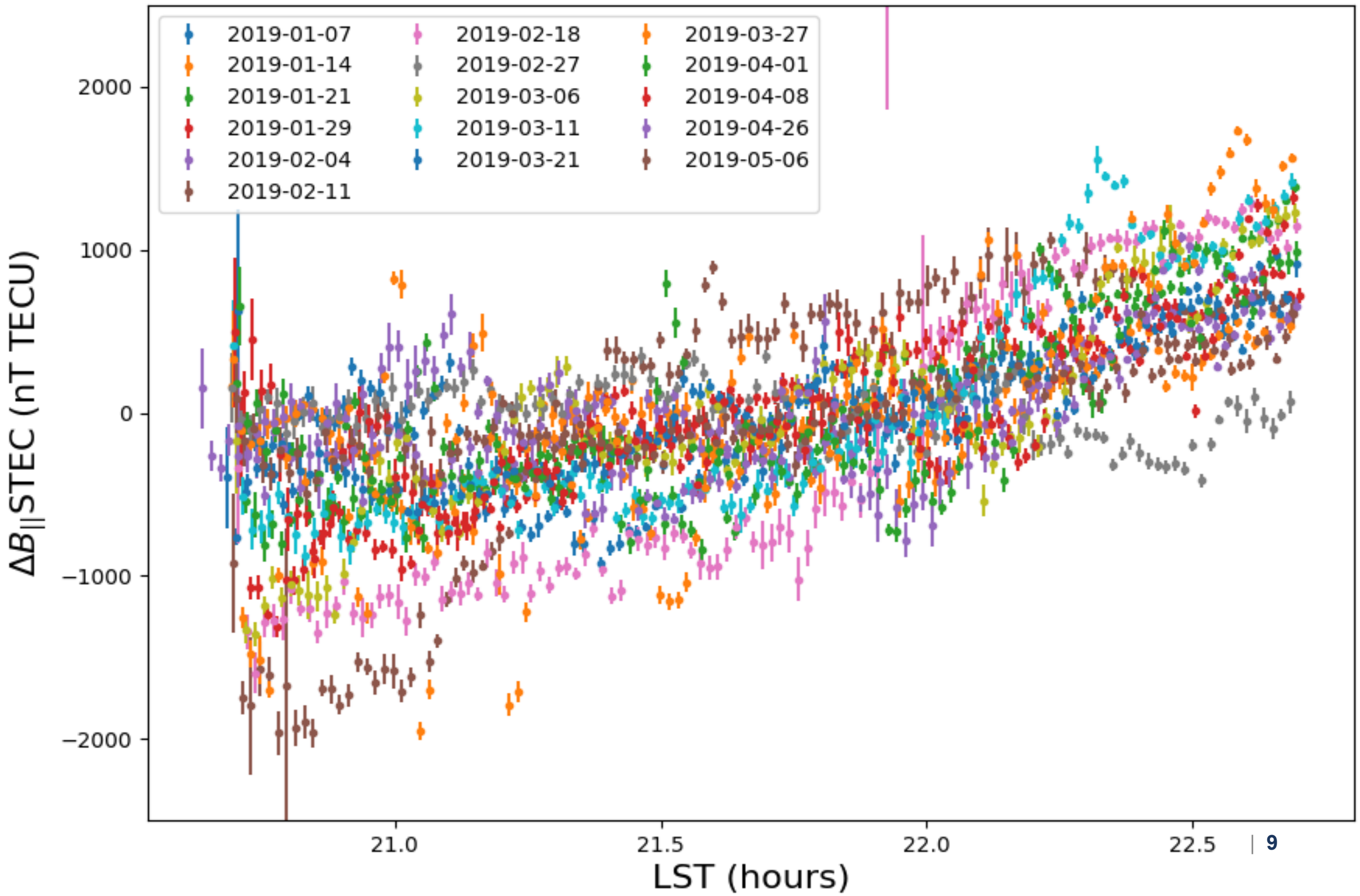


LH015 Observations

Four Months of Observing Cyg A

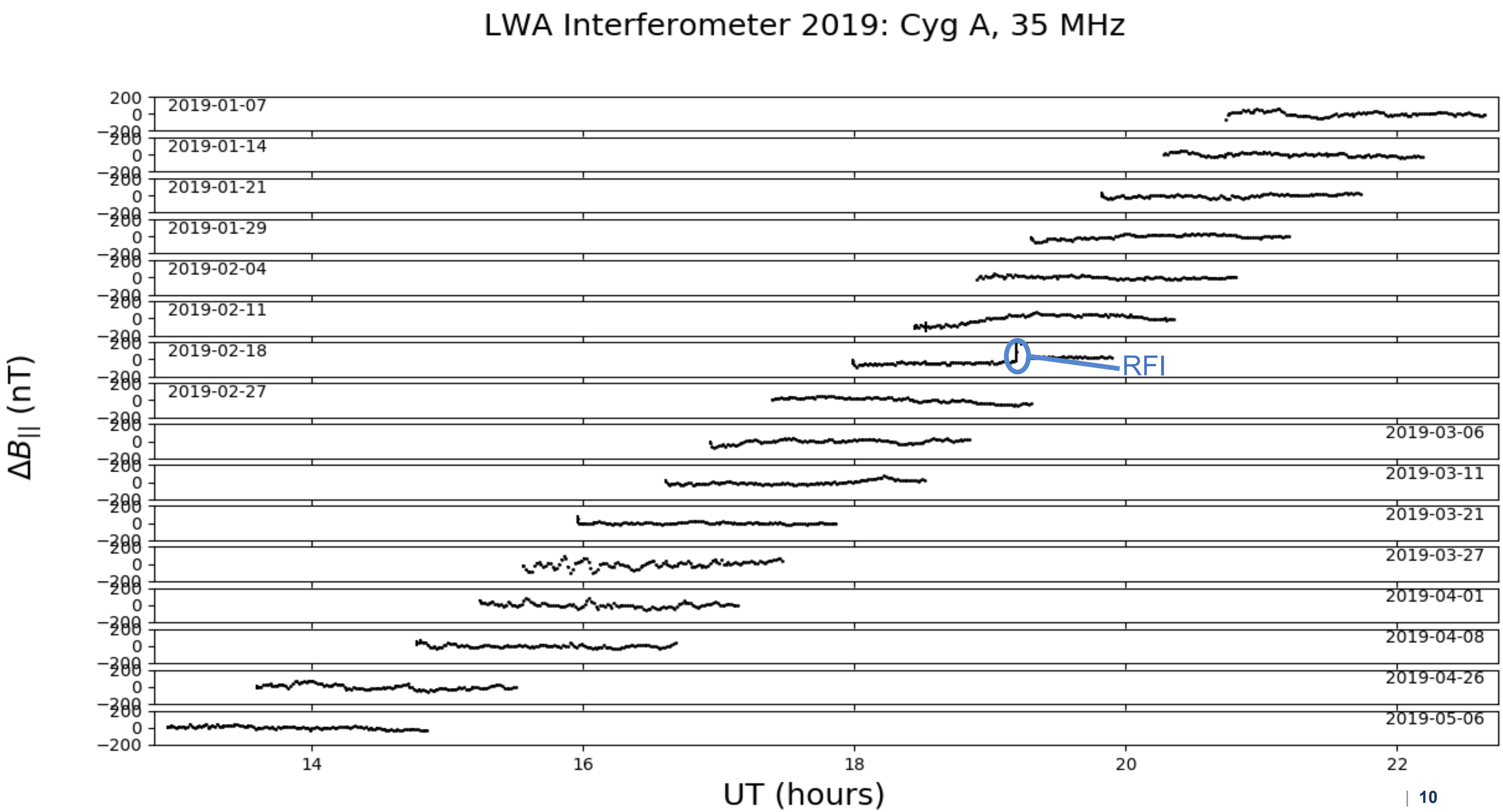
A Trend Emerges

- Contamination from source within TEC measurement shows up in the estimate of $\Delta B_{||} \times$STEC.
- In the absence of a detailed model, can use the fact that we observe at the same LST every time and the fact that the source phase will repeat with LST.
- Remove the median trend versus LST from the data, then divide by STEC (from JPL maps) to get final $\Delta B_{||}$ estimates.



LH015 Observations

Final $\Delta B_{||}$ Time Series, Jan. 7 through May 6

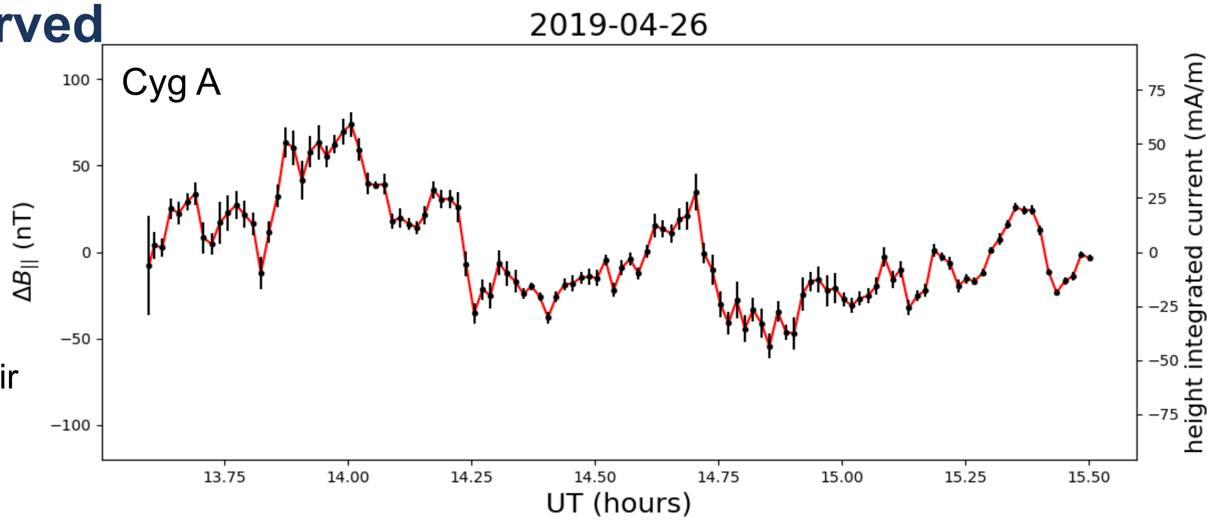


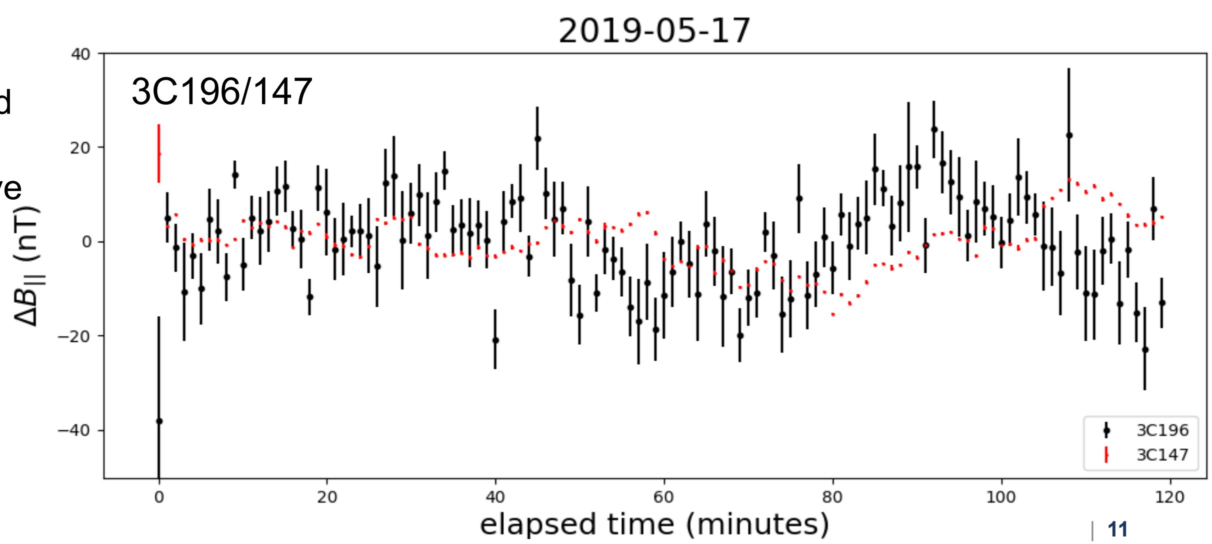
Magnetic Disturbances

Various Fluctuations Observed

Amplitudes Range from a few to ~50 nT

- Recall that a fluctuation in neutral wind of roughly 2 m/s can generate B-field fluctuation of 1 nT.
- Therefore, some disturbances could be linked to gravity waves.
- First observation with 3C196/3C147 pair consistent with this.
- Shows wavelike pattern toward both sources, but with 15-20 minute lag. Pierce-points at z=300 km separated by ~140 km, almost entirely in longitude (3C147 farther east).
- Could be gravity wave moving eastward at ~130 m/s, or more slowly toward the northeast or southeast. Appears to have long period of ~50 minutes, implying mostly vertical propagation (buoyancy period is ~10 minutes).
- Amplitude of ~15 nT requires neutral wind fluctuations of roughly 30 m/s on scales comparable to 75 km baseline; reasonable if speed closer to ~50 m/s.





Summary and Future Plans

LH015 Succeeding and Still Going

Results

- Have completed and analyzed 24 observing runs so far.
- Have developed algorithms for data processing and extracting $\Delta B_{||}$ time series from the observations.
- Have found evidences of several instances of $\Delta B_{||}$ fluctuations with amplitudes of 10s of nT; could be tied to gravity wave-driven fluctuations in the thermospheric neutral wind.
- $\Delta B_{||}$ fluctuations roughly consistent with levels of B-field fluctuations within magnetometer data from the DMSP satellites in LEO at ~800 km altitude.

Plans for 2019

- Will continue once per week cadence of observations for the rest of 2019. Will hopefully resolve RFI issue with 3C196/3C147 and resume observing that pair to look for new candidate wavelike disturbances like that observed on May 17.
- Will continue to refine processing methods to better handle bursts of RFI and streamline pipeline.
- Will further explore possibility of gravity waves being the chief driver of observed $\Delta B_{||}$ fluctuations, including the development of a model combining NRLMSISE and IRI models with models of gravity wave propagation. Will also include additional datasets with concurrent information regarding gravity wave drivers (e.g., wind flow over mountains, shear within jet streams).
- Will obtain publicly available TLEs for DMSP satellites to predict LWA flyovers and schedule observations during those to help validate interferometer-based $\Delta B_{||}$ measurements.