Problem Set 5

1 A whistler mode chorus event

Obtain and analyze DC and AC wave data for an event, including wave polarization and Poynting flux. A whistler mode chorus event observed by THEMIS, occurred on TH-E (P5) at ~10:00-10:15 UT on 2008-12-15 (referenced in the class notes in Lecture 10, p.5) taken from the paper by Li et al., JGR 2011.

In the overview plots (here and here), E & B wavepower is significant during significant velocity oscillations. A different whistler mode chorus event was observed by MMS on 2019-08-16 at ~09:32:00UT within a flux pileup region shown in Fig. 2 of Fu et al., GRL 2025. MMS overview plot is here. Follow the structure of Hwk05_01.pro (just an example). Work in either IDL or PySPEDAS, for either the THEMIS or the MMS event to:

- Fig. 1. Identify the event in overview plots and point out the wave power related to it
- Fig. 2. Get the Electric Field (Double-Probe) Instruments (EFI) data, remove offsets, show ExB velocity, using E*B=0 approximation
- Fig. 3. Plot on-board computed spectra. Overplot fce, ½ fce
- Fig. 4. Recognize (wave)burst times in the waveforms and plot them and the spectra
- Fig. 5. Introduce E and B and show ground computed spectra (wavelet and Fourier)
- Fig. 6. Rotate into FAC coord's and feed waveforms into wave analysis program. Plot results. Read the section of the relevant paper and explain the role/significance of the whistler waves in their respective setting.
- Fig. 7. Show the Poynting flux for the band-passed signal. Do this is time domain (process time series in real space) and in frequency domain (using the available tools).
  Deliver a report explaining what you did, and your code.

1.1 Identification in overview plots

W. Li, R. M. Thorne, J. Bortnik, Y. Nishimura, and V. Angelopoulos [1]

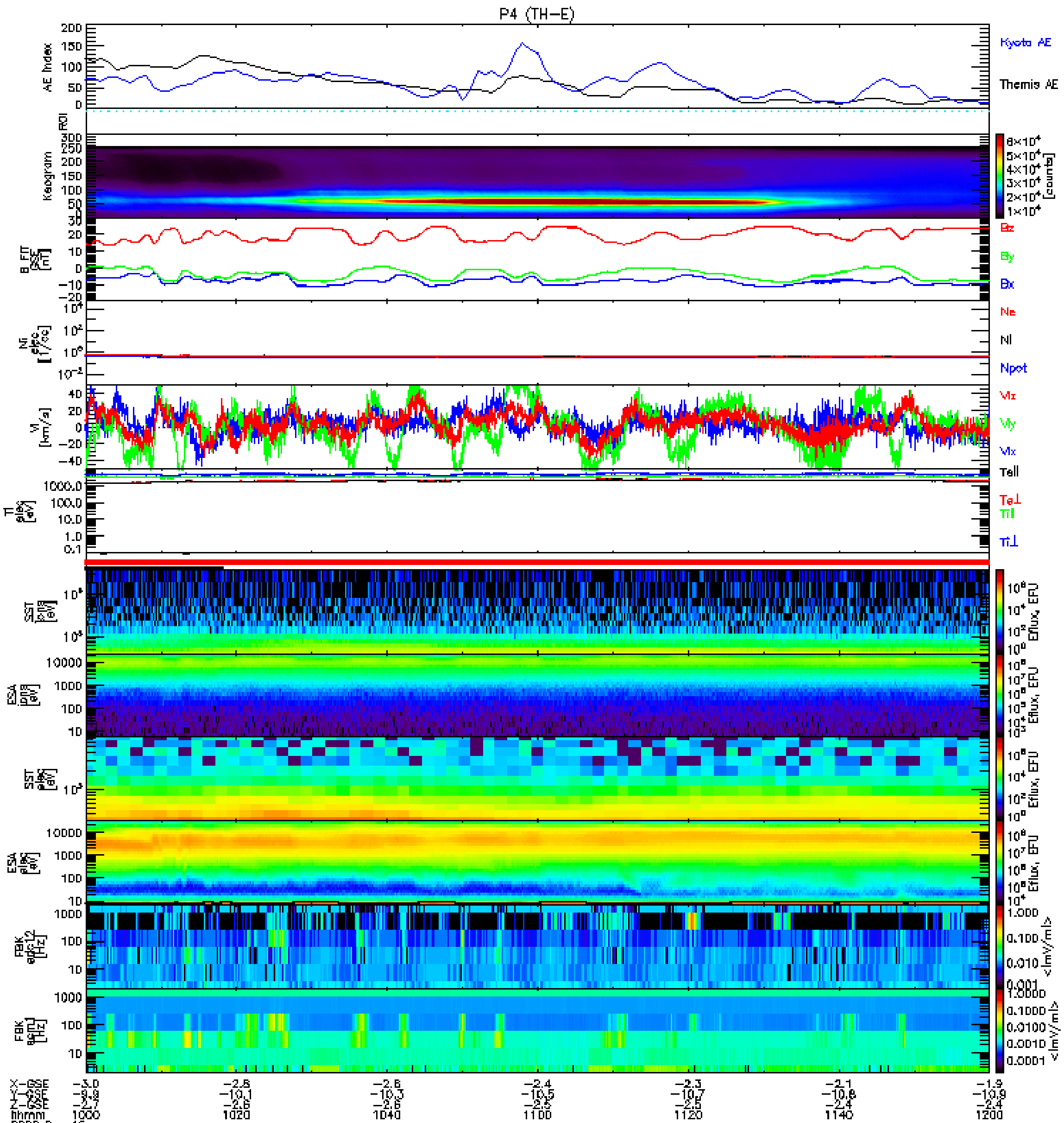


Figure 1: overview summary

We can clearly observe from the overview plot, specifically in the final panel, that the FBK exhibits wave activity within the frequency range of approximately 10–100 Hz. Additionally, it is evident that this wave activity is modulated with a period of roughly 10 seconds.

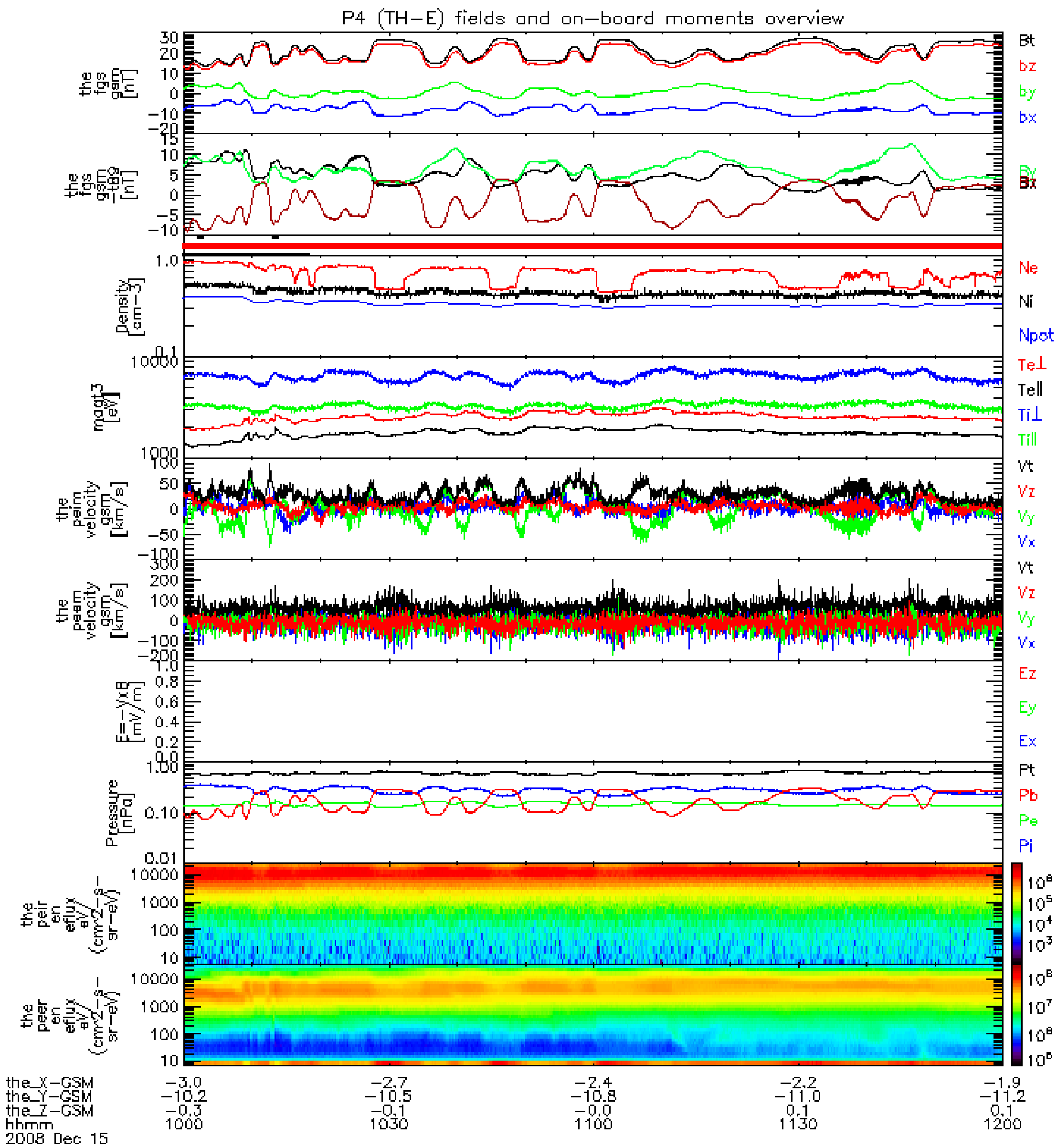


Figure 2: moms summary

Similarly, the pressure, magnetic field, temperature, and electron density measurements also exhibit oscillations with a comparable period.

1.2 Electric field data

Get the Electric Field (Double-Probe) Instruments (EFI) data, remove offsets, show ExB velocity, using E*B=0 approximation

```julia
using Speasy
using CairoMakie
using GLMakie
using Dates
using SpaceTools
using SpaceTools: tplot
using LinearAlgebra
using Statistics
using DimensionalData
using Unitful
using PlasmaFormulary
using SignalAnalysis
using Speasy: get_data
SpaceTools.DEFAULTS.add_title = true
```

```
    CondaPkg Found dependencies: /Users/zijin/.julia/packages/DimensionalData/
M9vEC/CondaPkg.toml
    CondaPkg Found dependencies: /Users/zijin/.julia/dev/Speasy/CondaPkg.toml
    CondaPkg Found dependencies: /Users/zijin/.julia/packages/PythonCall/WMWY0/
CondaPkg.toml
    CondaPkg Found dependencies: /Users/zijin/.julia/dev/PySPEDAS/CondaPkg.toml
    CondaPkg Initialising pixi
                                            │    /Users/zijin/.julia/artifacts/
d2fecc2a9fa3eac2108d3e4d9d155e6ff5dfd0b2/bin/pixi
             │ init
             │ --format pixi
             └ /Users/zijin/projects/beforerr/.CondaPkg
✔ Created /Users/zijin/projects/beforerr/.CondaPkg/pixi.toml
    CondaPkg Wrote /Users/zijin/projects/beforerr/.CondaPkg/pixi.toml
             │ [dependencies]
             │ netcdf4 = "*"
             │ openssl = ">=3, <3.1"
             │ uv = ">=0.4"
             │ xarray = "*"
             │ sqlite = "!=3.49.1"
             │ numpy = "*"
             │
             │     [dependencies.python]
             │     channel = "conda-forge"
             │     build = "*cpython*"
             │     version = ">=3.8,<4"
             │
             │ [project]
             │ name = ".CondaPkg"
             │ platforms = ["osx-arm64"]
             │ channels = ["conda-forge"]
             │ channel-priority = "strict"
```

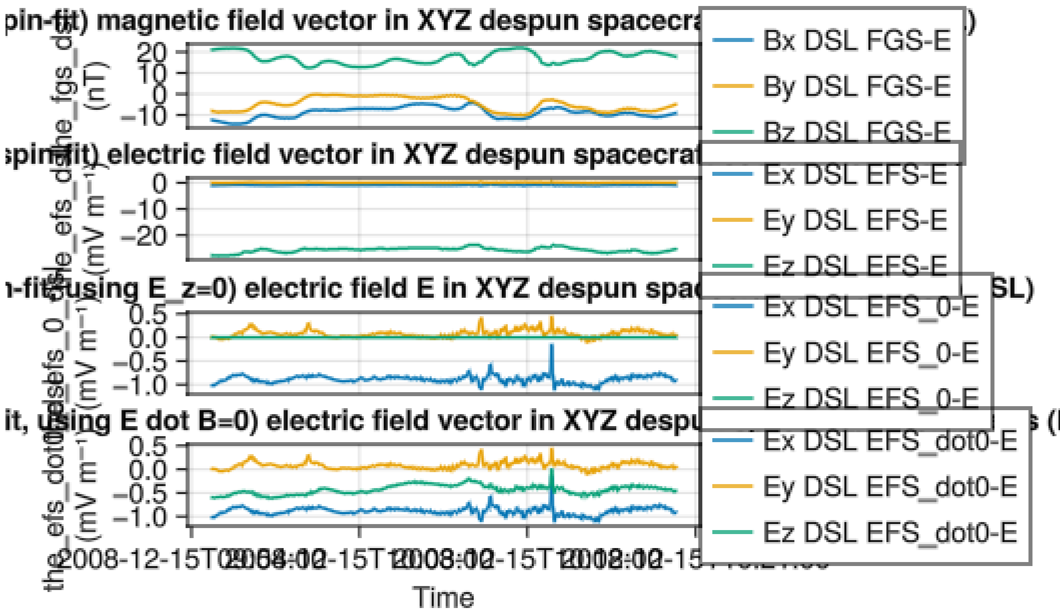
```
              │ description = "automatically generated by CondaPkg.jl"
              │
              │ [pypi-dependencies.speasy]
              │ git = "https://github.com/SciQLop/speasy"
              │
              │ [pypi-dependencies.pyspedas]
              └ git = "https://github.com/spedas/pyspedas"
    CondaPkg Installing packages
                                 │    /Users/zijin/.julia/artifacts/
d2fecc2a9fa3eac2108d3e4d9d155e6ff5dfd0b2/bin/pixi
              │ install
            └ --manifest-path /Users/zijin/projects/beforerr/.CondaPkg/pixi.toml
 WARN Using local manifest /Users/zijin/projects/beforerr/.CondaPkg/pixi.toml
rather than /Users/zijin/projects/beforerr/pyproject.toml from environment
variable `PIXI_PROJECT_MANIFEST`
✔ The default environment has been installed.
```

```
true
```

```
# Define time intervals for the analysis
trange_plus = TimeRange("2008-12-15T09:45:00", "2008-12-15T10:30:00")
trange = TimeRange("2008-12-15T09:55:00", "2008-12-15T10:20:00")
```

```
TimeRange{String, Intervals.Closed, Intervals.Closed}("2008-12-15T09:55:00",
"2008-12-15T10:20:00")
```

```
"""
Reference: [SPEDAS](https://github.com/spedas/bleeding_edge/blob/master/
projects/themis/spacecraft/fields/thm_load_fit.pro)
"""
function thm_load_fit(probe, timerange; vars=("fgs_dsl", "efs_dsl", "efs_0_dsl",
"efs_dot0_dsl"))
    dataset = "TH$(uppercase(probe))_L2_FIT"
    vars = "th$(lowercase(probe))_" .* vars
    ids = "cda/$dataset/" .* vars
    das = DimArray.(get_data(ids, timerange))
    return NamedTuple{Tuple(Symbol.(vars))}(das)
end

data = thm_load_fit("e", trange)

tplot(data)
```

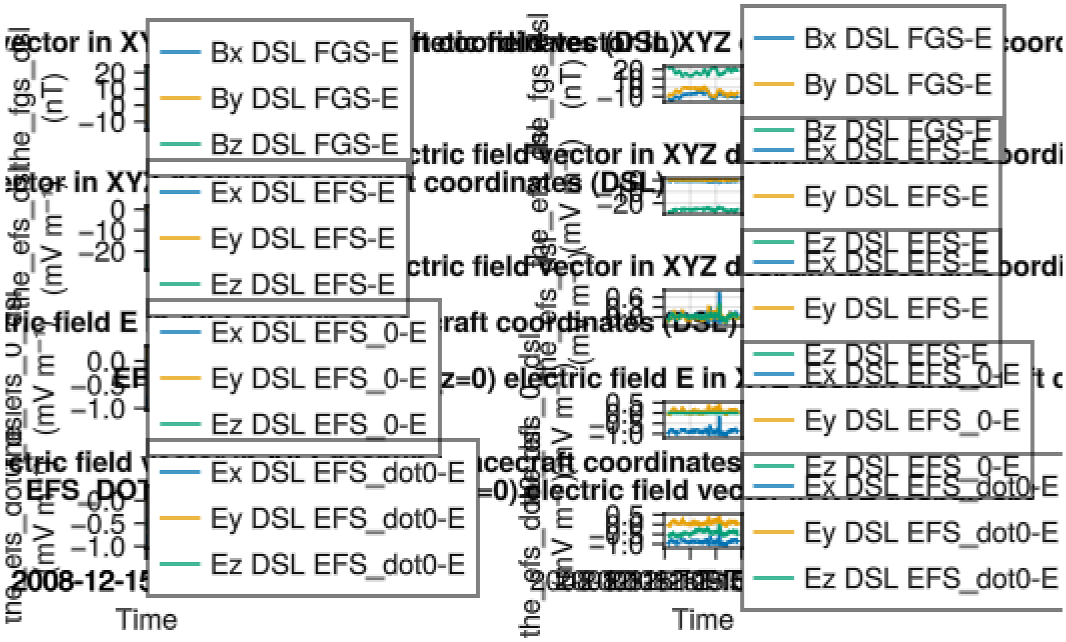


Here's the Julia equivalent of the provided IDL code for removing offsets and calculating electric field components:

```
# Get Ez (dsl) and ExB
let B = data.the_fgs_dsl, E = data.the_efs_dsl, angle = 20.0  # degrees
    # First get Ex/y offsets
    println("Select 2 times (Start/Stop) for obtaining Ex, Ey offsets")
    trange4offset = ["2008-12-15T10:30:00", "2008-12-15T10:40:00"]

    data_offset = thm_load_fit("e", trange4offset)
    Eoffsets = tmean(data_offset.the_efs_dsl)
    @info "Eoffsets" Eoffsets.data

    # Set angle threshold
    tanangle = tan(angle * π / 180.0)

    # Calculate the condition for each data point
    B = B[DimSelectors(E)]
    bxy_magnitude = sqrt.(B[:, 1] .^ 2 + B[:, 2] .^ 2)
    angle_condition = abs.(B[:, 3] ./ bxy_magnitude) .>= tanangle
    igood = findall(angle_condition)
    ibad = findall(.!angle_condition)
    janygood = length(igood)
    janybad = length(ibad)
    @info "janygood" janygood
    @info "janybad" janybad
    # Apply offsets to Ex and Ey components
```

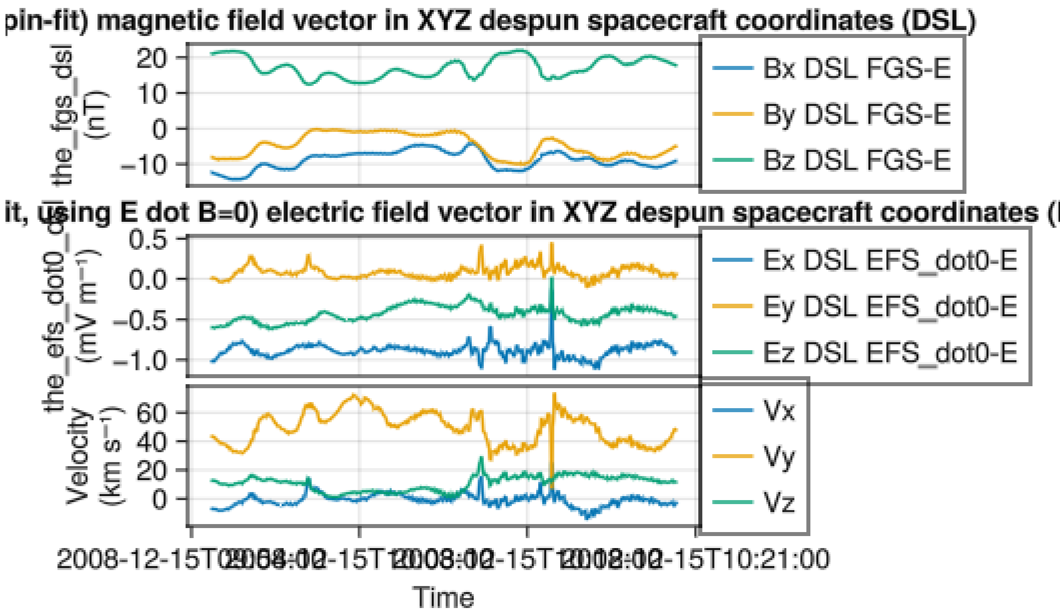
```
    E_corrected = deepcopy(E)
    E_corrected[:, 1] .-= Eoffsets[1]
    E_corrected[:, 2] .-= Eoffsets[2]

    # Set bad data points to NaN
    if janybad >= 1
        for i in ibad
            E_corrected[i, :] .= NaN
        end
    end

    if janygood < 1
        println("*****WARNING: NO GOOD 3D ExB data")
    else
        for i in igood
            E_corrected[i, 3] =
                -(E_corrected[i, 1] * B[i, 1] +
                  E_corrected[i, 2] * B[i, 2]) /
                B[i, 3]
        end
    end

    f = Figure()
    tplot(f[1, 1], data_offset)
            tplot(f[1,   2:4],   [B,   E,   E_corrected,   data.the_efs_0_dsl,
data.the_efs_dot0_dsl])
    f
end
```

```
Select 2 times (Start/Stop) for obtaining Ex, Ey offsets
┌ Info: Eoffsets
│   Eoffsets.data =
│    1×3 Matrix{Quantity{Float32, ? ? ?⁻¹ ?⁻³, Unitful.FreeUnits{(m⁻¹, mV),
? ? ?⁻¹ ?⁻³, nothing}}}:
└     -0.90413 mV m⁻¹  0.0725118 mV m⁻¹  -25.9938 mV m⁻¹
┌ Warning: (DimensionalData.Dimensions.Dim{:the_efs_dsl},) dims were not found
in object.
└ @ DimensionalData.Dimensions ~/.julia/packages/DimensionalData/M9vEC/src/
Dimensions/primitives.jl:844
┌ Info: janygood
└   janygood = 489
┌ Info: janybad
└   janybad = 0
```



In the left panel, we present the data utilized for the offset analysis. In the right panel, arranged sequentially from top to bottom, we display the magnetic field data, the electric field data, the electric field data corrected using our offset analysis, and finally, the corresponding electric field data extracted from the L2 dataset `efs_0_dsl` and `efs_dot0_dsl`.

```
let E = data.the_efs_dot0_dsl, B = data.the_fgs_dsl
    B_int = tinterp(B, E)
    V = tcross(E, B_int) ./ tdot(B_int, B_int) .|> u"km/s"
    V = modify_meta(V, long_name="Velocity", labels=("Vx", "Vy", "Vz"))
    tplot([B, E, V])
end
```



Computed $V = E \times B / B^2$ is shown in the last panel.

1.3 On-board computed spectra

Plot on-board computed spectra. Overplot fce, ½ fce

```
function thm_load_fbk(probe, timerange; vars=("fb_edc12", "fb_scm1"))
    dataset = "TH$(uppercase(probe))_L2_FBK"
    vars = "th$(lowercase(probe))_" .* vars
    ids = "cda/$dataset/" .* vars
    DimArray.(get_data(ids, timerange))
end

thm_fb_edc12, thm_fb_scm1 = thm_load_fbk("e", trange) .|>
SpaceTools.set_colorrange
```

```
[ Info: Cannot parse unit <|mV/m|>
[ Info: Cannot parse unit <|nT|>
```

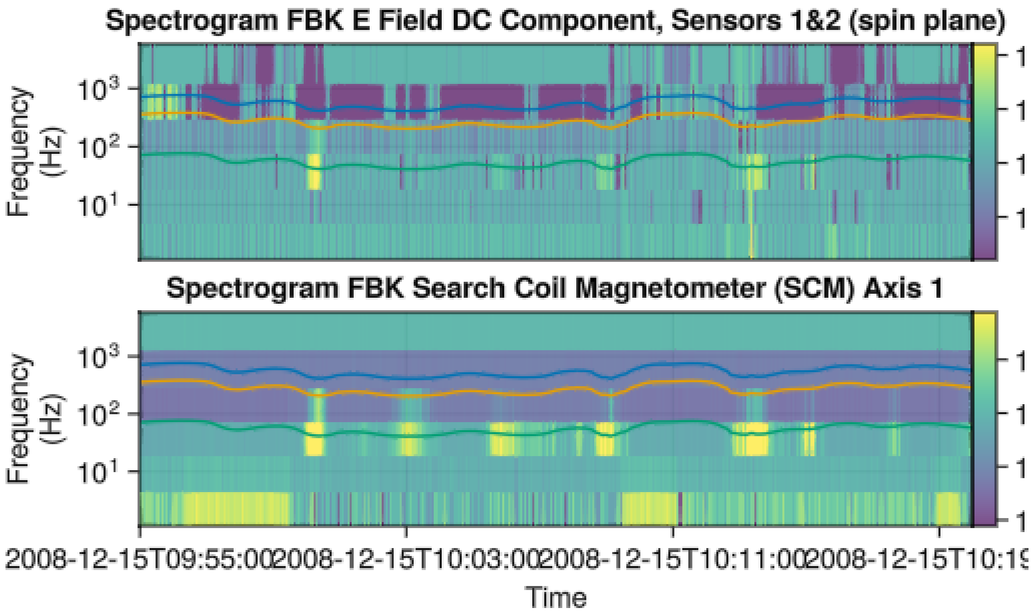
```
2-element Vector{DimMatrix{Float32, D, Tuple{}, Matrix{Float32}, Symbol,
Dict{Any, Any}} where D<:Tuple}:
 Float32[0.014709114 0.0073833982 … 0.012690215 0.01730484; 0.014709114
0.020304345 … 0.009229247 0.01730484; … ; 0.014709114 0.0 … 0.008075591
0.01730484; 0.0 0.0 … 0.013843872 0.020765807]
```

```
  Float32[0.0032959487  0.00077439536  …  0.003418021  0.0085832;  0.0032959487
0.00077439536  …  0.0028839551  0.009536888;  …  ;  0.0032959487  0.00082780194  …
0.0023498894 0.0014305334; 0.00343328 0.00082780194 … 0.0024567025 0.0071526663]
```

The three lines in Figures represent 1 fce (blue), 0.5 fce (orange), and 0.1 fce (green).

```
let B = tnorm(data.the_fgs_dsl)
    fce = gyrofrequency.(B, :e) .|> ω2f
    fce = modify_meta(fce, scale=log10) ./ 1u"Hz"
    f = tplot([thm_fb_edc12, thm_fb_scm1]; add_title=true, alpha=0.7)
    tplot_panel!.(f.axes, Ref([fce, fce / 2, fce / 10]))
    f
end
```

```
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
```



`ffw_16_eac34` and `ffp_16_eac34` `ffp_16_scm3` data are not available for this event.

```
function thm_load_fft(probe, timerange; vars=("ffw_16_eac34", "ffp_16_eac34",
"ffp_16_scm3"))
    dataset = "TH$(uppercase(probe))_L2_FFT"
    vars = "th$(lowercase(probe))_" .* vars
    ids = "cda/$dataset/" .* vars
    DimArray.(get_data(ids, timerange))
end

fft_tvars = [
    "cda/THE_L2_FFT/the_ffp_16_eac34",
    "cda/THE_L2_FFT/the_ffp_16_scm3",
    "cda/THE_L2_FFT/the_ffw_16_eac34",
    "cda/THE_L2_FFT/the_ffw_16_scm3",
]

fft_data = get_data.(fft_tvars, trange)
all(ismissing.(fft_data)) && @warn "Data not available"
```

```
Non compliant ISTP file: trying to load the_ffp_16_eac34_yaxis_vary as support
data for the_ffp_16_eac34 but it is absent from the file
Non compliant ISTP file: trying to load the_ffp_16_scm3_yaxis_vary as support
data for the_ffp_16_scm3 but it is absent from the file
Non compliant ISTP file: trying to load the_ffw_16_eac34_yaxis_vary as support
data for the_ffw_16_eac34 but it is absent from the file
```

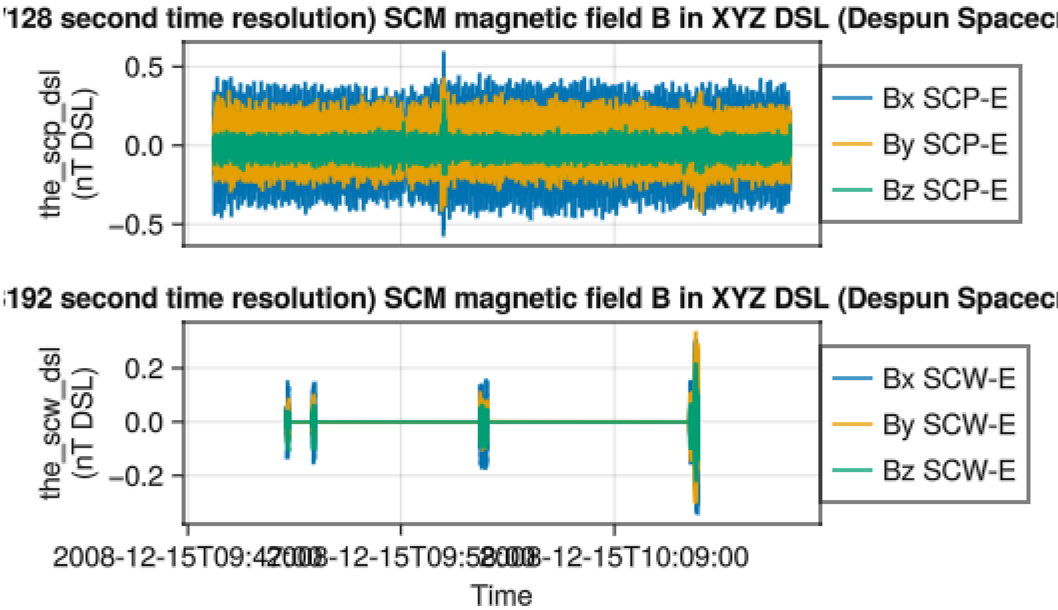
```
Non compliant ISTP file: trying to load the_ffw_16_scm3_yaxis_vary as support
data for the_ffw_16_scm3 but it is absent from the file
Non compliant ISTP file: swapping DEPEND_0 with DEPEND_TIME for the_ffw_16_scm3,
if you think this is a bug report it here: https://github.com/SciQLop/PyISTP/
issues
┌ Warning: Data not available
└ @ Main.Notebook ~/projects/beforerr/docs/courses/epss261/homework/ps5.qmd:193
```

1.4 Waveburst and spectra

Recognize (wave)burst times in the waveforms and plot them and the spectra.

```
tvars = [
    "cda/THE_L2_SCM/the_scp_dsl",
    "cda/THE_L2_SCM/the_scw_dsl",
]

thm_scp_dsl, thm_scw_dsl = get_data.(tvars, trange_plus) .|> DimArray
f = Figure()
tplot(f[1, 1], [thm_scp_dsl, thm_scw_dsl])
f
```

```
[ Info: Cannot parse unit nT*DSL
[ Info: Cannot parse unit nT*DSL
[ Info: Resampling array of size (228865, 3) along dimension 1 from 228865 to
6070 points
[ Info: Resampling array of size (391173, 3) along dimension 1 from 391173 to
6070 points
```

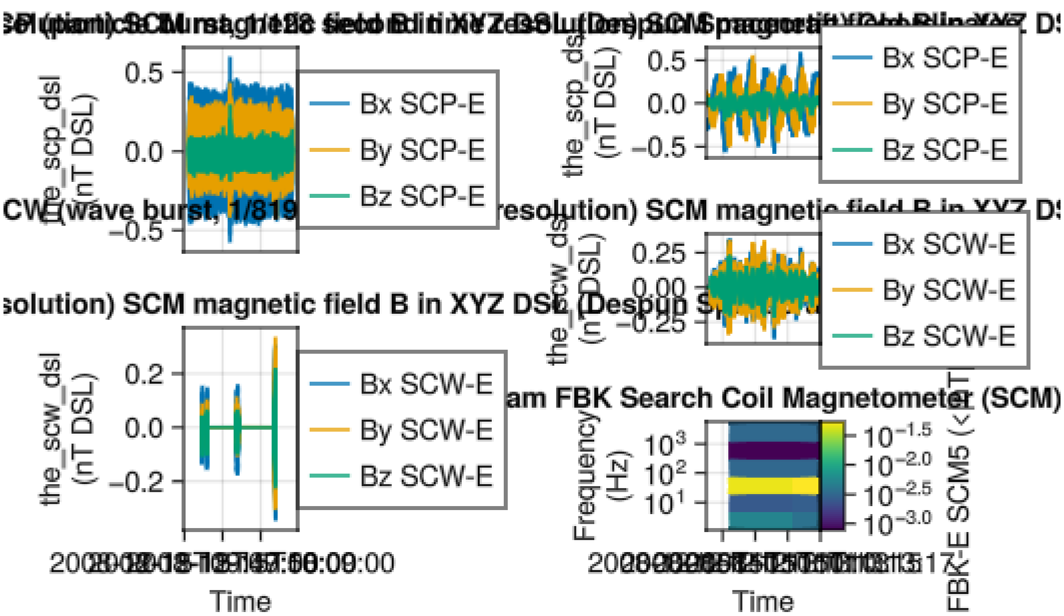


We see a waveburst around 2008-12-15T10:13:10.

```
tvars_wb = [
    "cda/THE_L2_SCM/the_scp_dsl",
    "cda/THE_L2_SCM/the_scw_dsl",
    "cda/THE_L2_FBK/the_fb_scm1",
]
trange_wb = TimeRange("2008-12-15T10:13:10", "2008-12-15T10:13:20")
trange_wb_s = TimeRange("2008-12-15T10:13:10", "2008-12-15T10:13:17")
data_wb = get_data.(tvars_wb, trange_wb) .|> DimArray
tplot(f[1, 2], data_wb)
tlims!(trange_wb_s)
```

```
[ Info: Cannot parse unit nT*DSL
[ Info: Cannot parse unit nT*DSL
[ Info: Cannot parse unit <|nT|>
[ Info: Resampling array of size (63403, 3) along dimension 1 from 63403 to 6070
points
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
┌ Warning: Automatically using edge for Makie because transform == log10 and the
```

```
first edge is negative
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/methods.jl:40
```



1.5 Ground computed spectra

Introduce E and B and show ground computed spectra (wavelet and Fourier)

```
using PySPEDAS.Projects
thm_efi_ds = themis.efi(trange, level="l1", probe="e")
thm_efw = DimArray(thm_efi_ds.the_efw)
```

Loading `efw` data using `PySPEDAS` is somehow quite slow, instead we define a configuration file and load the `efw` data from the SPDF.

```
{yaml}
the_efw_l1:
  inventory_path: spdf/THEMIS/THE/L1/EFW
  master_cdf: https://spdf.gsfc.nasa.gov/pub/data/themis/the/l1/efw/2021/the_l1_efw_20210102_v01.cdf
  split_frequency: daily
  split_rule: regular
  url_pattern: https://spdf.gsfc.nasa.gov/pub/data/themis/the/l1/efw/{Y}/the_l1_efw_{Y}{M:02d}{D:02d}_v\d+.cdf
  use_file_list: true
```

```
the_efw_l1_index =
speasy.inventories.data_tree.archive.spdf.THEMIS.THE.L1.EFW.the_efw_l1
tvars = [
    "cda/THE_L2_FGM/the_fgs_gsm",
    "cda/THE_L2_FGM/the_fgh_gsm",
    "cda/THE_L2_SCM/the_scp_dsl",
    "cda/THE_L2_SCM/the_scw_dsl"
]
thm_fgs_gsm, thm_fgh_gsm, thm_scp_dsl, thm_scw_dsl = get_data(tvars,
trange_plus) .|> DimArray
```

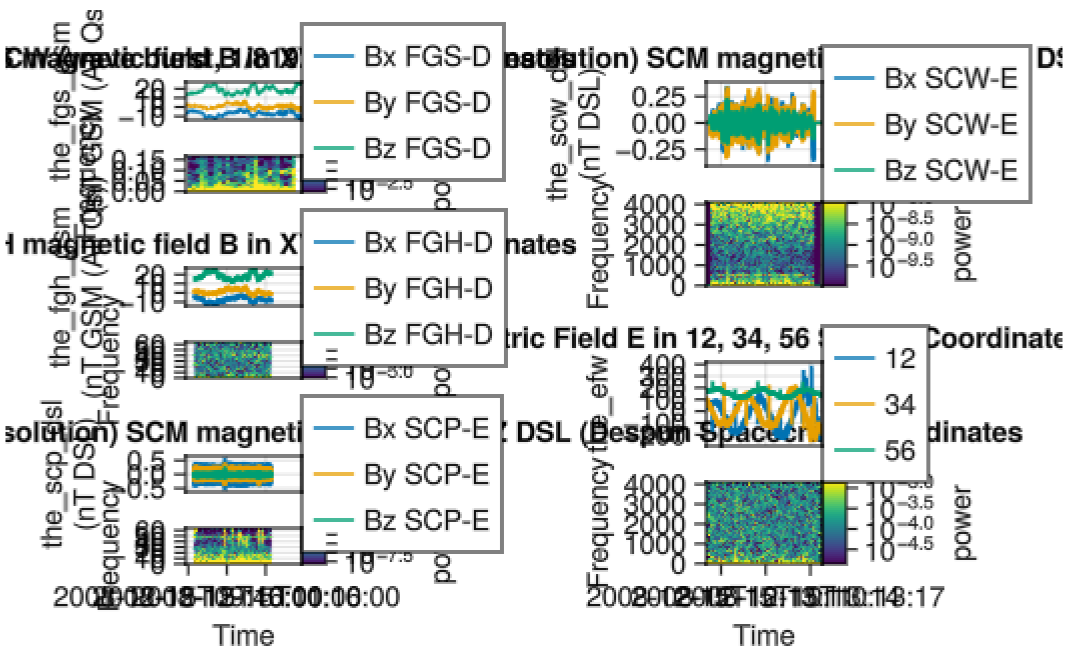
```
[ Info: Cannot parse unit nT*GSM*(All*Qs)
[ Info: Cannot parse unit nT*GSM*(All*Qs)
[ Info: Cannot parse unit nT*DSL
[ Info: Cannot parse unit nT*DSL
```

```
4-element Vector{DimMatrix{Float32, D, Tuple{}, Matrix{Float32}, Symbol,
Dict{Any, Any}} where D<:Tuple}:
  Float32[-6.884452 2.770554 13.2441; -6.8816504 2.699388 13.368085; … ;
-10.854679 -2.0566497 25.193708; -11.012929 -1.8605247 25.144516]
  Float32[-4.202244 1.5139444 15.179175; -4.1365685 1.664007 15.140432; … ;
-8.527703 -0.975849 22.252335; -8.648017 -1.0026835 22.07751]
 Float32[-7.3053866f-6 -1.8908788f-5 -2.836187f-5; -7.3053866f-6 -1.8908788f-5
-2.836187f-5; … ; 4.3625614f-6 5.230054f-6 -9.406129f-6; 4.3625614f-6
5.230054f-6 -9.406129f-6]
   Float32[-0.000119733224 0.00037838318 -0.00024678188; -0.000119733224
0.00037838318 -0.00024678188; … ; 0.0017912713 -0.0006972916 0.0004022404;
0.0017912713 -0.0006972916 0.0004022404]
```

```
thm_fgs_gsm_z_dpwrspc = SpaceTools.pspectrum(thm_fgs_gsm[:, 3]; nfft=64) |>
SpaceTools.set_colorrange
thm_scp_dsl_z_dpwrspc = SpaceTools.pspectrum(thm_scp_dsl[:, 3]; nfft=512) |>
SpaceTools.set_colorrange
thm_fgh_gsm_z_dpwrspc = SpaceTools.pspectrum(thm_fgh_gsm[:, 3]) |>
SpaceTools.set_colorrange

tvars_wb = [
    the_efw_l1_index.the_efw,
    "cda/THE_L2_SCM/the_scw_dsl"
]

thm_efw, thm_scw_dsl = get_data.(tvars_wb, trange_wb) .|> DimArray

thm_scw_dsl_z_dpwrspc = SpaceTools.pspectrum(thm_scw_dsl[:, 3]) |>
SpaceTools.set_colorrange
thm_efw_z_dpwrspc = SpaceTools.pspectrum(thm_efw[:, 3]) |>
```

```
SpaceTools.set_colorrange

f = Figure()
tplot(f[1, 1], [
    thm_fgs_gsm, thm_fgs_gsm_z_dpwrspc,
    thm_fgh_gsm, thm_fgh_gsm_z_dpwrspc,
    thm_scp_dsl, thm_scp_dsl_z_dpwrspc,
])

tplot(f[1, 2], [
    thm_scw_dsl, thm_scw_dsl_z_dpwrspc,
    thm_efw, thm_efw_z_dpwrspc,
])
```

```
┌ Warning: Time resolution is is not approximately constant (relerr ≈
510.99292220984336)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
511.99292220984336)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Cannot parse unit
[ Info: Cannot parse unit nT*DSL
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Resampling array of size (228864, 3) along dimension 1 from 228864 to
6070 points
[ Info: Resampling array of size (228865, 3) along dimension 1 from 228865 to
6070 points
[ Info: Resampling array of size (63403, 3) along dimension 1 from 63403 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to
6070 points
```



During the interval when we have wavebursts, the whistle wave is clearly identifiable in the SCP data. However, in the higher-frequency data product, it becomes difficult to discern any distinct signatures within the spectrogram.

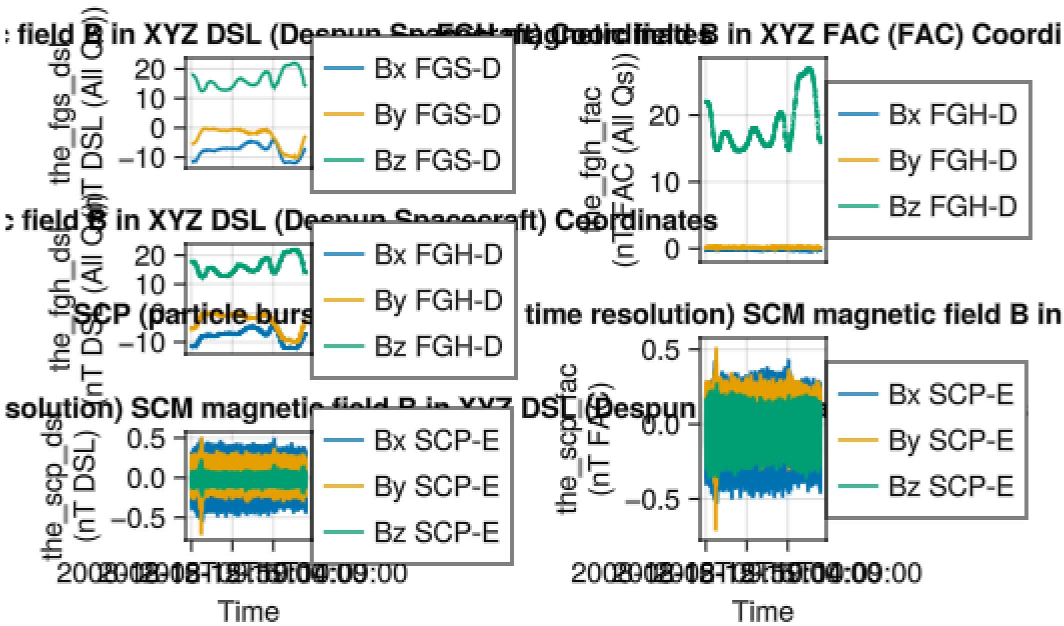
1.6 FAC coordinate

> Rotate into FAC coord's and feed waveforms into wave analysis program. Plot results. Read the section of the relevant paper and explain the role/significance of the whistler waves in their respective setting.

```
tvars = [
    "cda/THE_L2_FGM/the_fgs_dsl",
    "cda/THE_L2_FGM/the_fgh_dsl",
    "cda/THE_L2_SCM/the_scp_dsl",
]
_trange = ["2008-12-15T09:59", "2008-12-15T10:13"]

thm_fgs_dsl, thm_fgh_dsl, thm_scp_dsl = Speasy.get_data(tvars, _trange) .|>
DimArray

fac_mats = tfac_mat(thm_fgs_dsl)
thm_scp_fac = select_rotate(thm_scp_dsl, fac_mats, "FAC")
thm_fgh_fac = select_rotate(thm_fgh_dsl, fac_mats, "FAC")

f = Figure()
```

```julia
tplot(f[1, 1], [
    thm_fgs_dsl,
    thm_fgh_dsl,
    thm_scp_dsl,
])
tplot(f[1, 2], [
    thm_fgh_fac,
    thm_scp_fac,
])
```

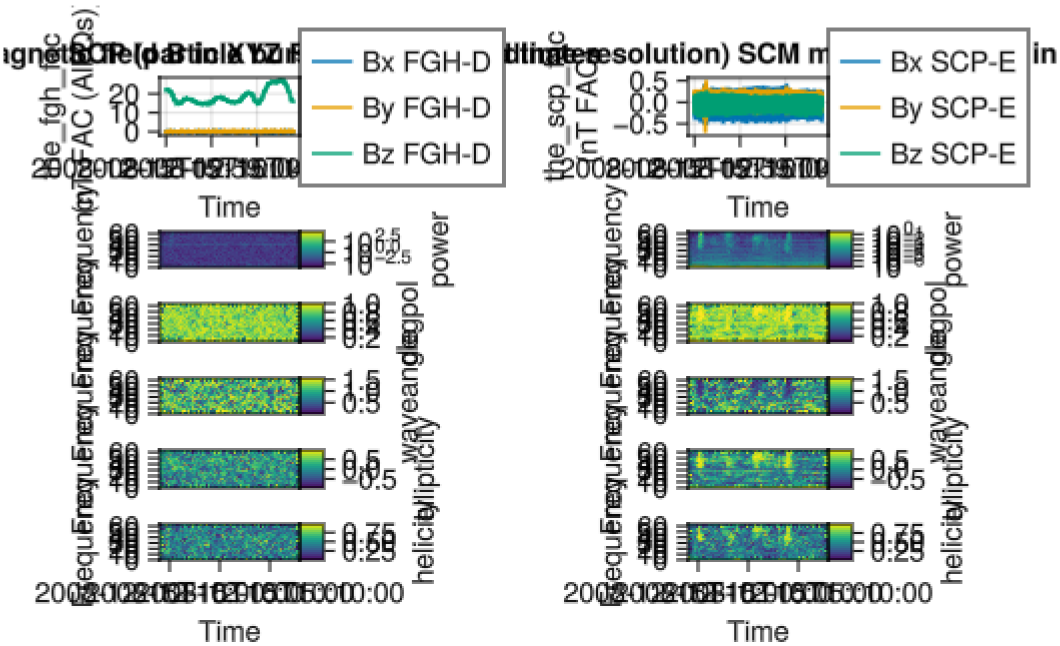
```
[ Info: Cannot parse unit nT*DSL*(All*Qs)
[ Info: Cannot parse unit nT*DSL*(All*Qs)
[ Info: Cannot parse unit nT*DSL
┌ Warning: (DimensionalData.Dimensions.Dim{:the_scp_dsl},) dims were not found
in object.
└  @  DimensionalData.Dimensions  ~/.julia/packages/DimensionalData/M9vEC/src/
Dimensions/primitives.jl:844
┌ Warning: (DimensionalData.Dimensions.Dim{:the_fgh_dsl},) dims were not found
in object.
└  @  DimensionalData.Dimensions  ~/.julia/packages/DimensionalData/M9vEC/src/
Dimensions/primitives.jl:844
[ Info: Resampling array of size (107008, 3) along dimension 1 from 107008 to
6070 points
[ Info: Resampling array of size (107520, 3) along dimension 1 from 107520 to
6070 points
[ Info: Resampling array of size (107008, 3) along dimension 1 from 107008 to
6070 points
[ Info: Resampling array of size (107520, 3) along dimension 1 from 107520 to
6070 points
```



1.6.a Wave polarization analysis

```
f = Figure(;)
tplot(f[1, 1], thm_fgh_fac)
tplot(f[2:6, 1], twavpol(thm_fgh_fac))
tplot(f[1, 2], thm_scp_fac)
tplot(f[2:6, 2], twavpol(thm_scp_fac))
```

```
[ Info: Resampling array of size (107008, 3) along dimension 1 from 107008 to
6070 points
┌ Warning: Time resolution is is not approximately constant (relerr ≈
511.99292220984336)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Resampling array of size (107520, 3) along dimension 1 from 107520 to
6070 points
```



Compressional pulsations are associated with modulations of resonant electron fluxes and chorus intensity.

We have developed a high-performance wave polarization program implemented in Julia, achieving a significant speedup of approximately 100 times compared to its Python counterpart. Furthermore, our implementation is more generalizable, extending the original program's capabilities to accommodate data in n dimensions. The program is accessible via the following link:

- https://beforerr.github.io/SpaceTools.jl/dev/explanations/waves/
- https://beforerr.github.io/SpaceTools.jl/dev/validation/pyspedas/

Core part is attached in the appendix.

1.7 Poynting flux

- thm_crib_poynting_flux.pro
- thm_efi_clean_efw.pro

From top to bottom, we present the original data, the cleaned data with spikes removed, and the filtered data.

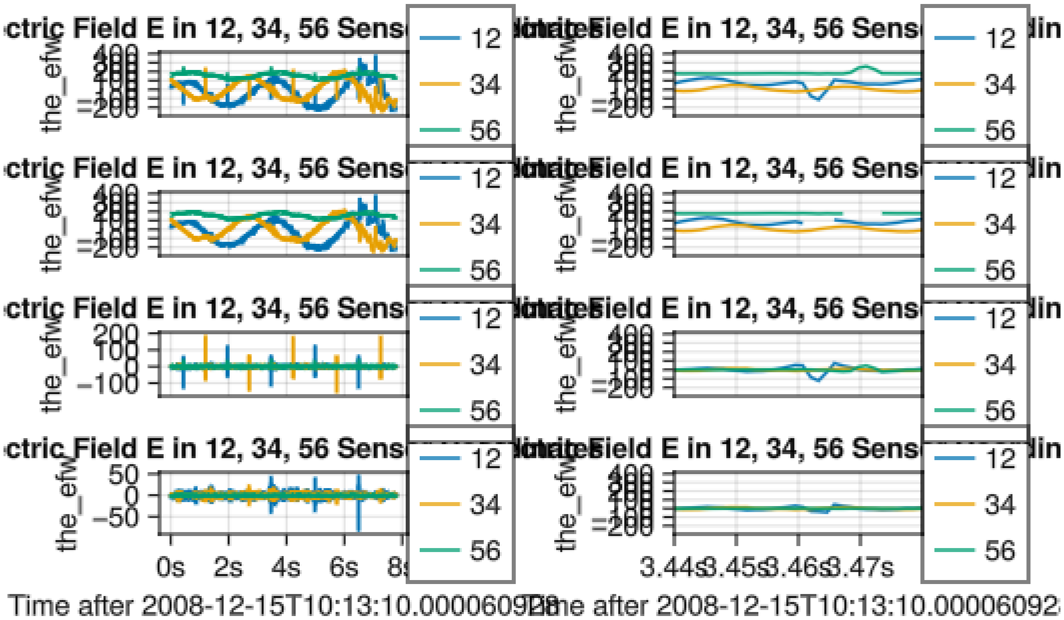
The right panel provides a magnified view of the data presented in the left panel

We can see that removing spikes is essential for the accuracy of the filtered data.

```
begin
    E = tclip(thm_efw, trange_wb) |> standardize
    E_clean = replace_outliers(E; window=128)
    E_sm = tfilter(E, 64u"Hz")
```

```julia
    E_clean_sm = tfilter(tinterp_nans(E_clean), 64u"Hz")

    tvars = [E, E_clean, E_sm, E_clean_sm] .|> timeshift
    f = Figure()
    tplot(f[1, 1], tvars)
    fa2 = tplot(f[1, 2], tvars; link_yaxes=true)
    tlims!.(fa2.axes, 3.44u"s", 3.48u"s")
    f
end
```

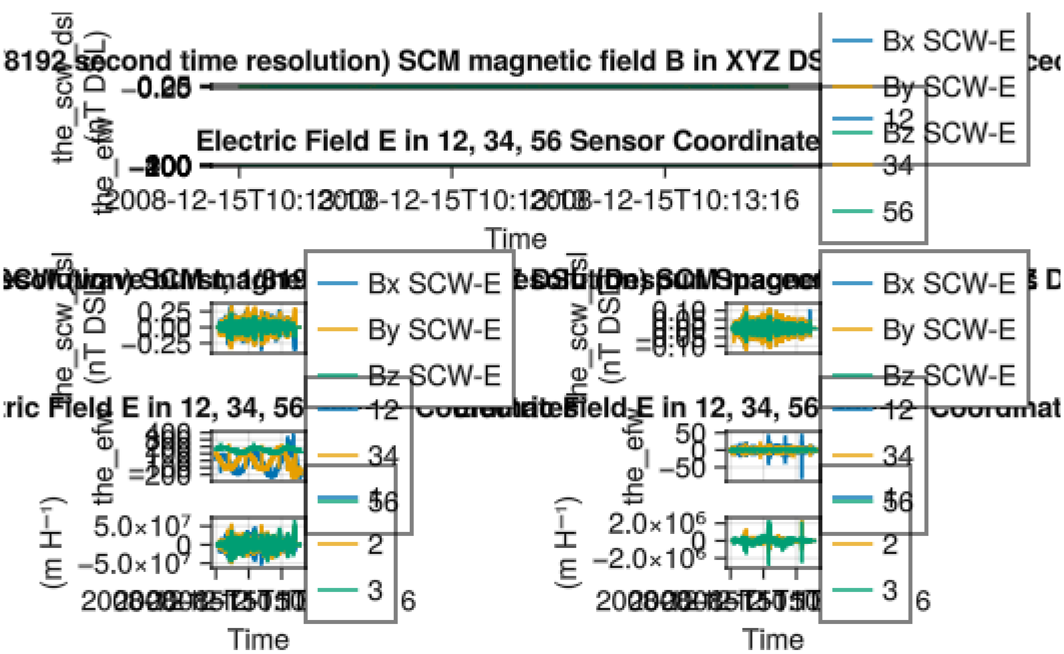
```
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to
6070 points
```



```
Poynting_vector(E, B) = tcross(E, B) ./ Unitful.μ0

begin
    B = tclip(thm_scw_dsl, trange_wb)
    E = tclip(thm_efw, trange_wb) |> standardize
    B = B[DimSelectors(E; selectors=Near())]

    E_clean = replace_outliers(E; window=128)
    B_sm = tfilter(B, 64u"Hz")
    E_clean_sm = tfilter(tinterp_nans(E_clean), 64u"Hz")

    S = Poynting_vector(B, E)
    S_sm = Poynting_vector(B_sm, E_clean_sm)

    f = Figure()
    tplot(f[1, 1:2], [thm_scw_dsl, thm_efw])
    tplot(f[2:4, 1], [B, E, S])
    tplot(f[2:4, 2], [B_sm, E_clean_sm, S_sm])
    f
end
```

```
┌ Warning: (DimensionalData.Dimensions.Dim{:the_efw},) dims were not found in
object.
└  @  DimensionalData.Dimensions  ~/.julia/packages/DimensionalData/M9vEC/src/
Dimensions/primitives.jl:844
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 1.0)
```

```
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 1.0)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈
0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Resampling array of size (63403, 3) along dimension 1 from 63403 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to 6070
points
[ Info: Resampling array of size (63915, 3) along dimension 1 from 63915 to
6070 points
```

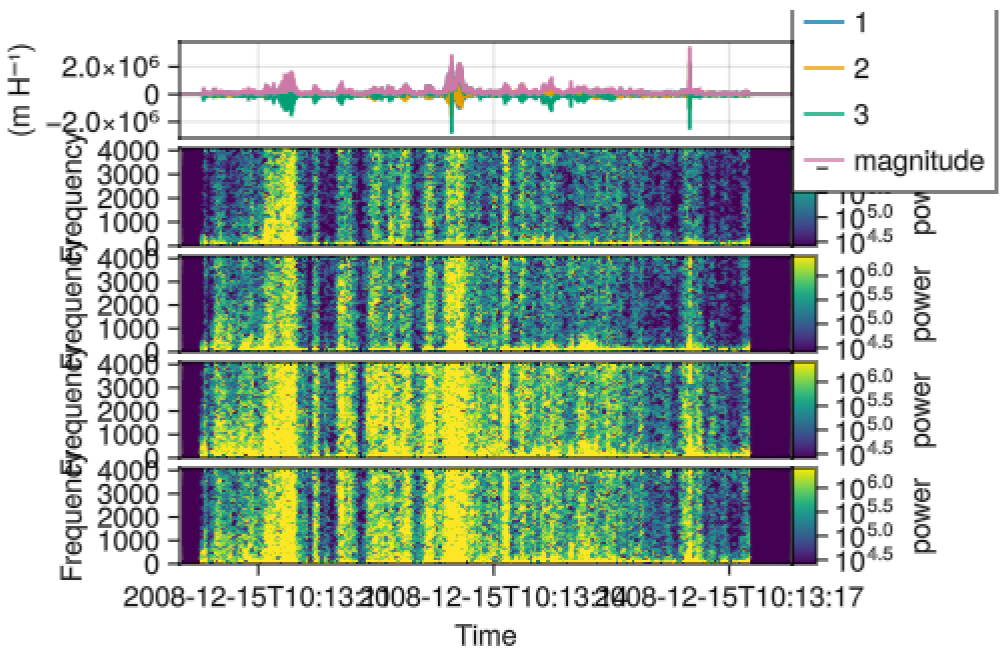


1.7.a Frequency-Domain Calculation of Poynting Flux

From top to bottom, the panels show the Poynting flux and its corresponding frequency spectra in the x, y, z directions and magnitude, respectively.

```
let S = tnorm_combine(S_sm)
    S_dpwrspc = pspectrum(S; nfft=512) |> SpaceTools.set_colorrange
    f = tplot([
        S,
        eachslice(S_dpwrspc; dims=Y())...
    ])
end
```

```
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
┌ Warning: Time resolution is is not approximately constant (relerr ≈ 0.0020964360587002098)
└ @ SpaceTools ~/.julia/dev/SpaceTools/src/timeseries.jl:23
[ Info: Resampling array of size (63915, 4) along dimension 1 from 63915 to 6070 points
```



2 Appendix

Core codes is pasted here for reference (which is readable to some extent:).

```
"""
    spectral_matrix(X, window)
"""
function spectral_matrix(X::AbstractMatrix, window::AbstractVector=ones(size(X,
1)))
    n_samples, n = size(X)

    # Apply the window to each component
    Xw = X .* window

    # Compute FFTs and normalize
    Xf = fft(Xw, 1) ./ sqrt(n_samples)

    # Only keep the positive frequencies
    Nfreq = div(n_samples, 2)
    Xf = Xf[1:Nfreq, :]

    S = Array{ComplexF64,3}(undef, Nfreq, n, n)
    for i in 1:n, j in 1:n
        @. S[:, i, j] = Xf[:, i] * conj(Xf[:, j])
    end

    return S
end

"""
    wavpol(ct, X; nfft=256, noverlap=nfft÷2, bin_freq=3)

Perform polarization analysis of `n`-component time series data.

Assumes the data are in a right-handed, field-aligned coordinate system
(with Z along the ambient magnetic field).

For each FFT window (with specified overlap), the routine:
  1. Computes the FFT and constructs the spectral matrix ``S(f)``.
  2. Applies frequency smoothing using a window (of length `bin_freq`).
  3. Computes the wave power, degree of polarization, wave normal angle,
     ellipticity, and helicity.

# Returns
A tuple: where each parameter (except `freqline`) is an array with one row per
FFT window.
"""
function wavpol(ct, X; nfft=256, noverlap=div(nfft, 2), bin_freq=3)
    # Ensure the smoothing window length is odd.
```

```
    iseven(bin_freq) && (bin_freq += 1)

    N = size(X, 1)
    samp_freq = samplingrate(ct)
    Nfreq = div(nfft, 2)
    fs = (samp_freq / nfft) * (0:(Nfreq-1))

    # Define the number of FFT windows and times (center time of each window)
    nsteps = floor(Int, (N - nfft) / noverlap) + 1
    times = similar(ct, nsteps)

    # Define the FFT window (here a smooth window similar to Hanning)
    window = 0.08 .+ 0.46 .* (1 .- cos.(2π .* (0:(nfft-1)) ./ nfft))
    half = div(nfft, 2)
    # Use a Hamming window for frequency smoothing.
    smooth_win = 0.54 .- 0.46 * cos.(2π .* (0:(bin_freq-1)) ./ (bin_freq - 1))
    smooth_win = smooth_win / sum(smooth_win)

    # Preallocate arrays for the results.
    power = zeros(Float64, nsteps, Nfreq)
    degpol = zeros(Float64, nsteps, Nfreq)
    waveangle = zeros(Float64, nsteps, Nfreq)
    ellipticity = zeros(Float64, nsteps, Nfreq)
    helicity = zeros(Float64, nsteps, Nfreq)

    # Process each FFT window.
    Threads.@threads for j in 1:nsteps
        start_idx = 1 + (j - 1) * noverlap
        end_idx = start_idx + nfft - 1
        if end_idx > N
            continue
        end
        S = spectral_matrix(@view(X[start_idx:end_idx, :]), window)
        S_smooth = smooth_spectral_matrix(S, smooth_win)
        params = compute_polarization_parameters(S_smooth)

        # Store the results.
        power[j, :] = params.power
        degpol[j, :] = params.degpol
        waveangle[j, :] = params.waveangle
        ellipticity[j, :] = params.ellipticity
        helicity[j, :] = params.helicity
        times[j] = ct[start_idx+half] # Set the times at the center of the FFT
window.
    end
    return (; times, fs, power, degpol, waveangle, ellipticity, helicity)
end
```

```julia
function wpol_helicity(S::AbstractMatrix{ComplexF64}, waveangle::Number)
    # Preallocate arrays for 3 polarization components
    helicity_comps = zeros(Float64, 3)
    ellip_comps = zeros(Float64, 3)

    for comp in 1:3
        # Build state vector λ_u for this polarization component
        alph = sqrt(real(S[comp, comp]))
        alph == 0.0 && continue
        if comp == 1
            lam_u = [
                alph,
                (real(S[1, 2]) / alph) + im * (-imag(S[1, 2]) / alph),
                (real(S[1, 3]) / alph) + im * (-imag(S[1, 3]) / alph)
            ]
        elseif comp == 2
            lam_u = [
                (real(S[2, 1]) / alph) + im * (-imag(S[2, 1]) / alph),
                alph,
                (real(S[2, 3]) / alph) + im * (-imag(S[2, 3]) / alph)
            ]
        else
            lam_u = [
                (real(S[3, 1]) / alph) + im * (-imag(S[3, 1]) / alph),
                (real(S[3, 2]) / alph) + im * (-imag(S[3, 2]) / alph),
                alph
            ]
        end

        # Compute the phase rotation (gammay) for this state vector
        lam_y = phase_factor(lam_u) * lam_u

        # Helicity: ratio of the norm of the imaginary part to the real part
        norm_real = norm(real(lam_y))
        norm_imag = norm(imag(lam_y))
        helicity_comps[comp] = (norm_imag != 0) ? norm_imag / norm_real : NaN

        # For ellipticity, use only the first two components
        u1 = lam_y[1]
        u2 = lam_y[2]

        # TODO: why there is no 2 in front of uppere?
        uppere = imag(u1) * real(u1) + imag(u2) * real(u2)
        lowere = (-imag(u1)^2 + real(u1)^2 - imag(u2)^2 + real(u2)^2)
        gammarot = atan(uppere, lowere)
        lam_urot = exp(-1im * 0.5 * gammarot) * [u1, u2]

        num = norm(imag(lam_urot))
```

```
        den = norm(real(lam_urot))
        ellip_val = (den != 0) ? num / den : NaN
         # Adjust sign using the off-diagonal of ematspec and the wave normal
angle
        sign_factor = sign(imag(S[1, 2]) * sin(waveangle))
        ellip_comps[comp] = ellip_val * sign_factor
    end

    # Average the three computed values
    helicity = mean(helicity_comps)
    ellipticity = mean(ellip_comps)

    return helicity, ellipticity
end
```

3 References

Search Coil Magnetometer (SCM) science data

- WB waveforms (scw) [8192 S/s]
- https://themis.igpp.ucla.edu/scm_dataflow.shtml

Electric Field Instruments (EFI) science data

- PB waveforms (efp, vap) [128 S/s; Allocation ~ 1.2h]
- WB waveforms (efw, vaw) [8192 S/s; Allocation ~ 43s]
- https://themis.ssl.berkeley.edu/instrument_efi.shtml

Bibliography

[1] W. Li, R. M. Thorne, J. Bortnik, Y. Nishimura, and V. Angelopoulos, “Modulation of Whistler Mode Chorus Waves: 1. Role of Compressional Pc4–5 Pulsations,” *Journal of Geophysical Research: Space Physics*, vol. 116, no. A6, 2011, doi: 10.1029/2010JA016312.