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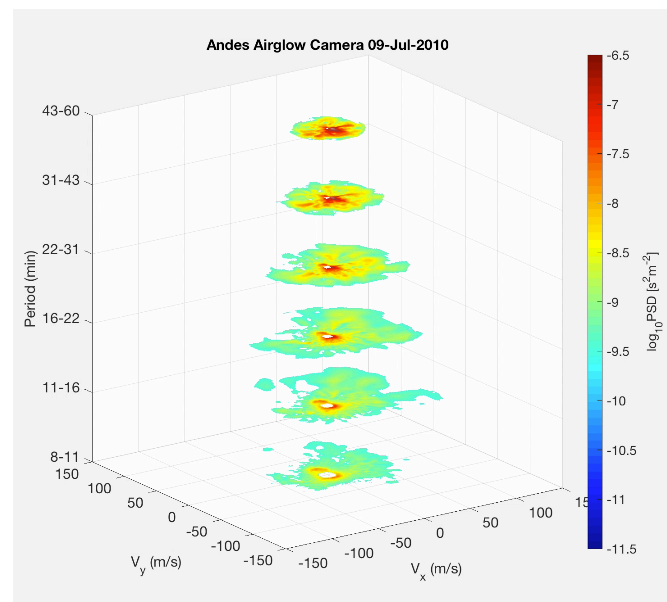
Development of a phase velocity spectral analysis software package (M-transform) for airglow imaging data and its application on atmospheric gravity waves studies



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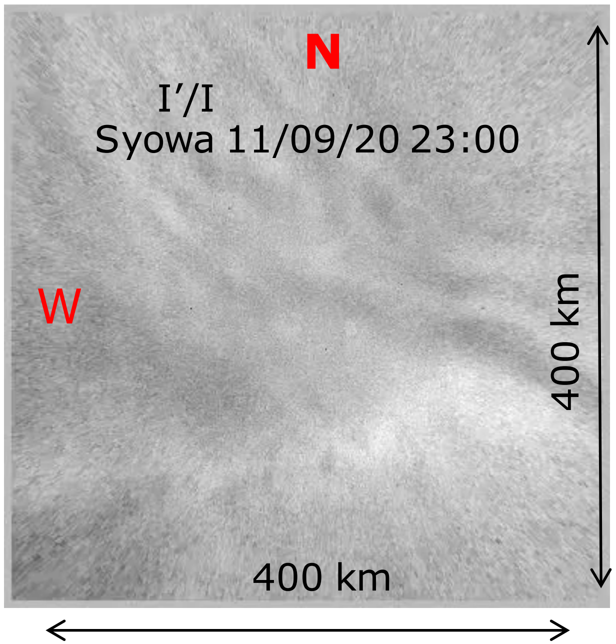
Matsuda Transform (M-Transform)

Matsuda et al., 2014

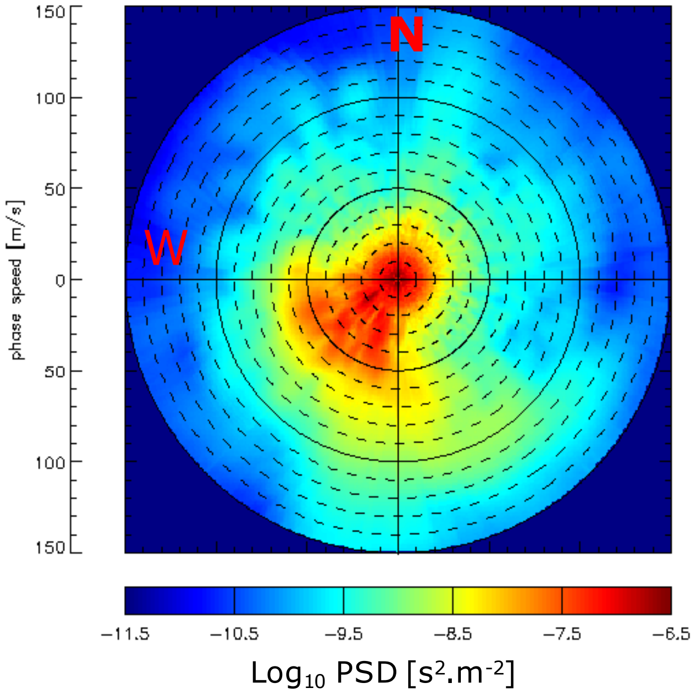
$F_1(x, y, t)$



$F_3(k, l, \omega)$

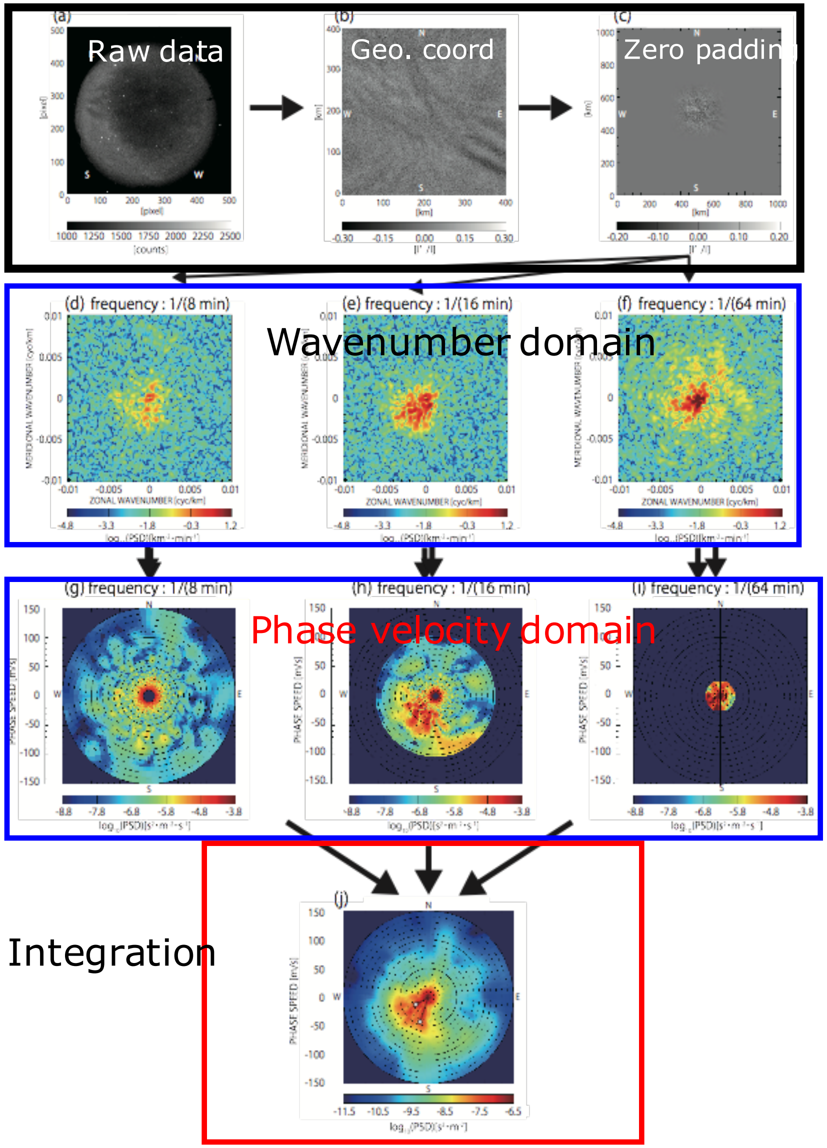
3D FFT

$F_4(v_x, v_y)$



Transform airglow intensity data to power spectrum in horizontal phase velocity domain.

How does it work?



$$v_x = \frac{\omega k}{k^2 + l^2}$$

$$v_y = \frac{\omega l}{k^2 + l^2}$$

Image preprocessing
$F_0(\theta, \phi, t) \rightarrow F_1(x, y, t)$

Coble et al., 1998

3D FFT
$F_1(x, y, t) \rightarrow F_2(k, l, \omega)$

Matsuda et al., 2014

Wave number to phase speed domain

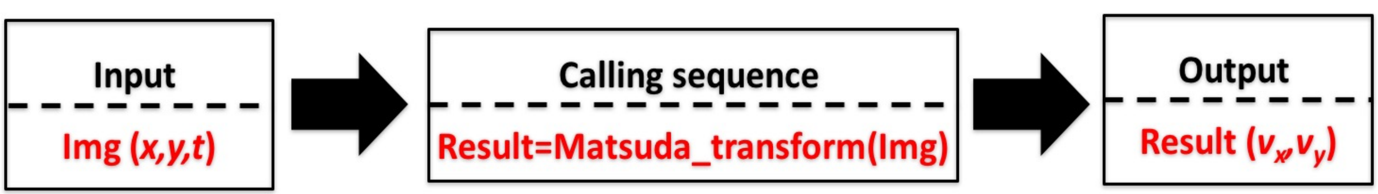
$F_2(k, l, \omega) \rightarrow F_3(v_x, v_y, \omega)$

Integration over frequency
$F_3(v_x, v_y, \omega) \rightarrow F_4(v_x, v_y)$

M-Transform Software

Table 1. Description of M-transform function on IDL.

Program description	
Name	Matsuda_transform
Purpose	Calculate horizontal phase velocity spectra from airglow intensity image data using 3-D FFT
Calling sequence	Result=Matsuda_transform(Img)
Inputs	Img: time series of 2-D airglow data in geographic coordinates (x, y, t)
Input keywords	(a) dx, dy, dt: image resolution in x (m), y (m), and time (s) (b) LH_min, LH_max: minimum and maximum horizontal wavelength (m) to be processed (c) T_min, T_max: minimum and maximum wave period (s) to be processed (d) Vp_min, Vp_max: minimum and maximum horizontal phase speed ($\mathrm{m\,s^{-1}}$) to be calculated (e) zpx, zpy, zpt: dimension of the zero-padded image size in x, y, and t to improve the intervals of k, l, and ω (f) min1, max1: minimum and maximum phase velocity spectra to be plotted (g) Interpolation: select interpolation method
Outputs	2-D phase velocity spectra (v_x, v_y)
Remarks	Requires equal sampling interval time resolution (dt)

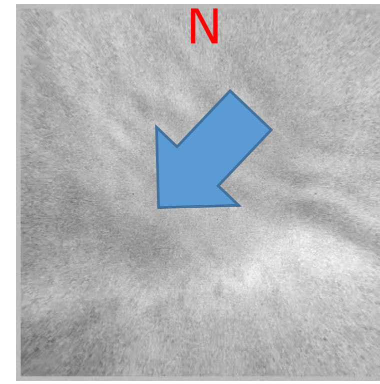


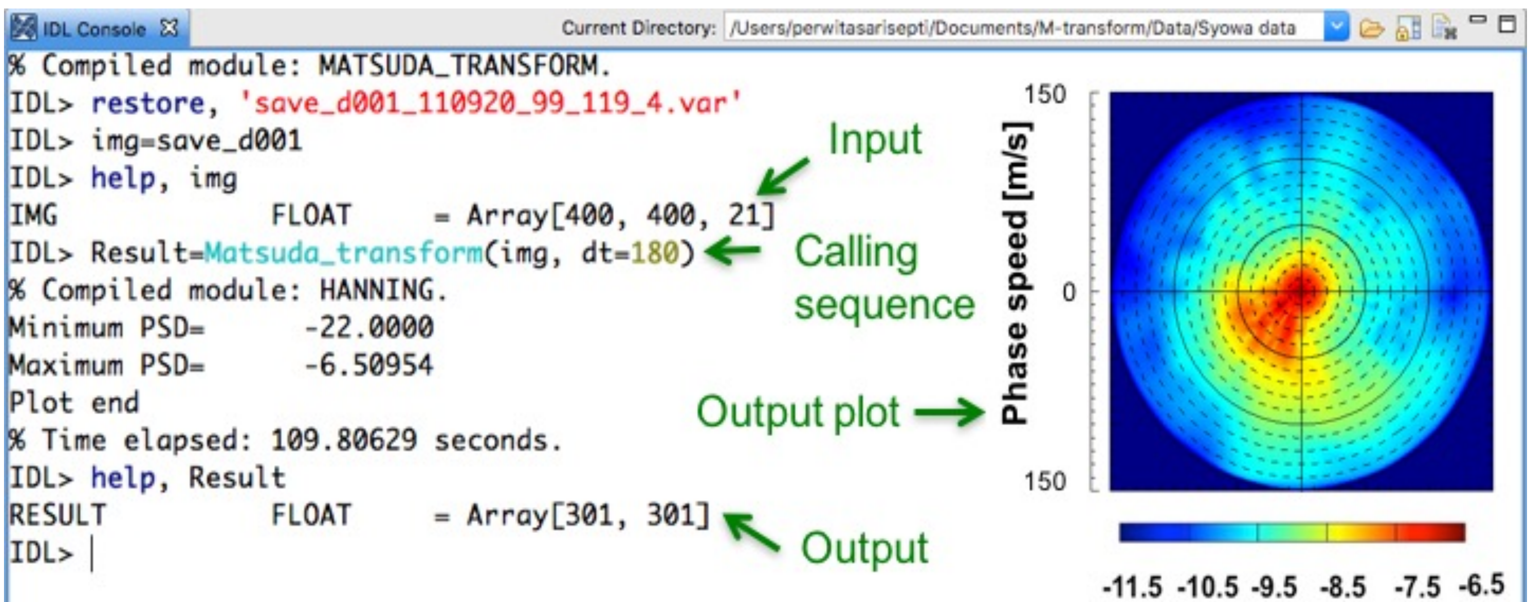
How to use?

Airglow intensity data at Syowa station 11/09/20 23:00-06:00

Input=airglow image (400 x 400 km, number of image= 21)
Keywords:
dt=180 (image resolution=3 minutes)
LH= default (5-100 km)
T= default (8-60 min)
Vp= default (0-150 m/s)

Airglow data (*x*,*y*,*t*)





Performance Analysis

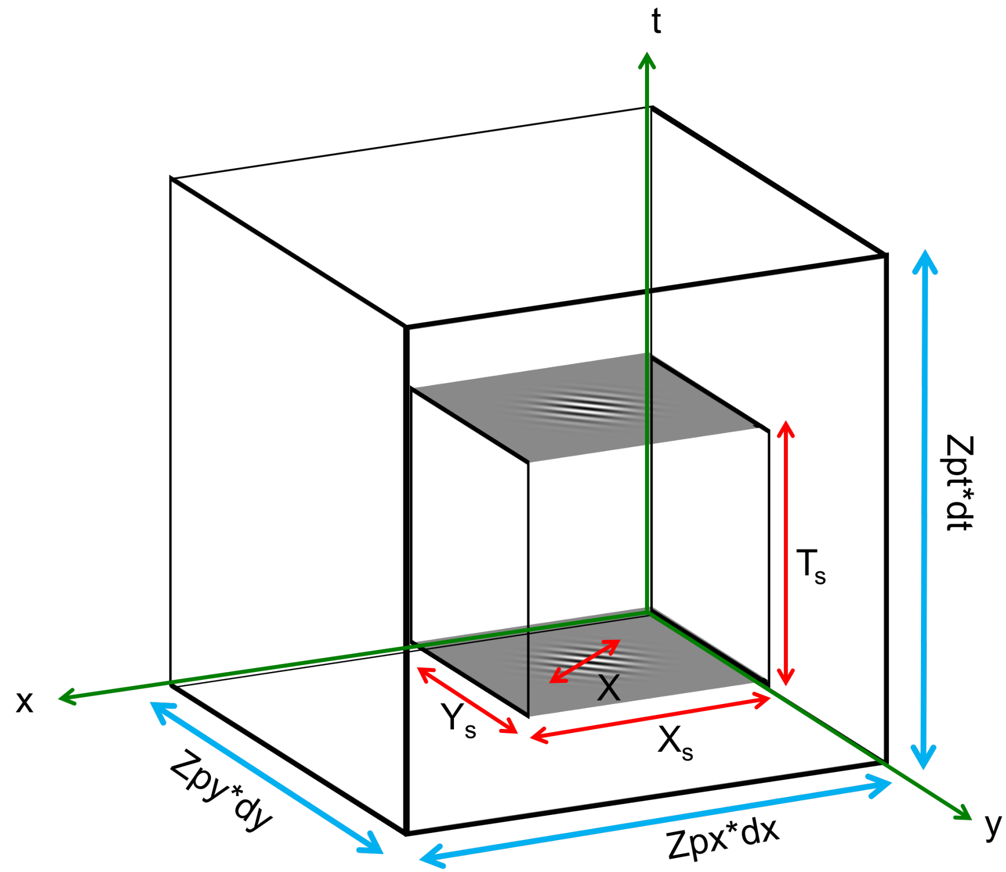
We examine the performance of this function by running several simulations:

- Changing the wave packet size (*X*) and wave duration (*T*) using test data:

1. Case 1: *c* constant (40 m/s), τ and *LH* vary (τ=8, 15, 30 min).
2. Case 2: *c* constant, *X* varies (FWHM=50, 100, 200 km).
3. Case 3: *c* constant (40 m/s), *T* varies (30, 60, 120 min).

- Aliasing effect analysis.
- Zero padding size analysis
- Noise sensitivity analysis

Simulation Set Up

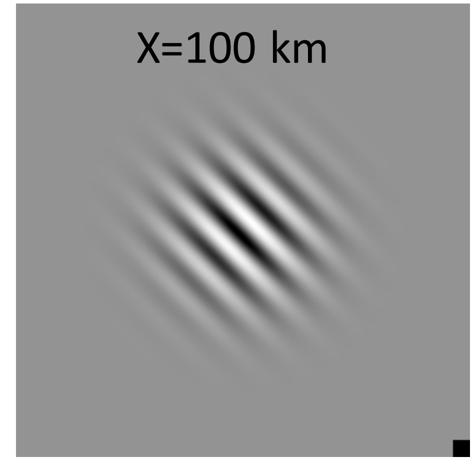


$$y = A(sin(wavenumx * Xs + wavenumy * Ys) - \omega * Ts)$$

$$wavenumberx = \frac{2\pi}{LH}\cos(\frac{2\pi}{\theta})$$

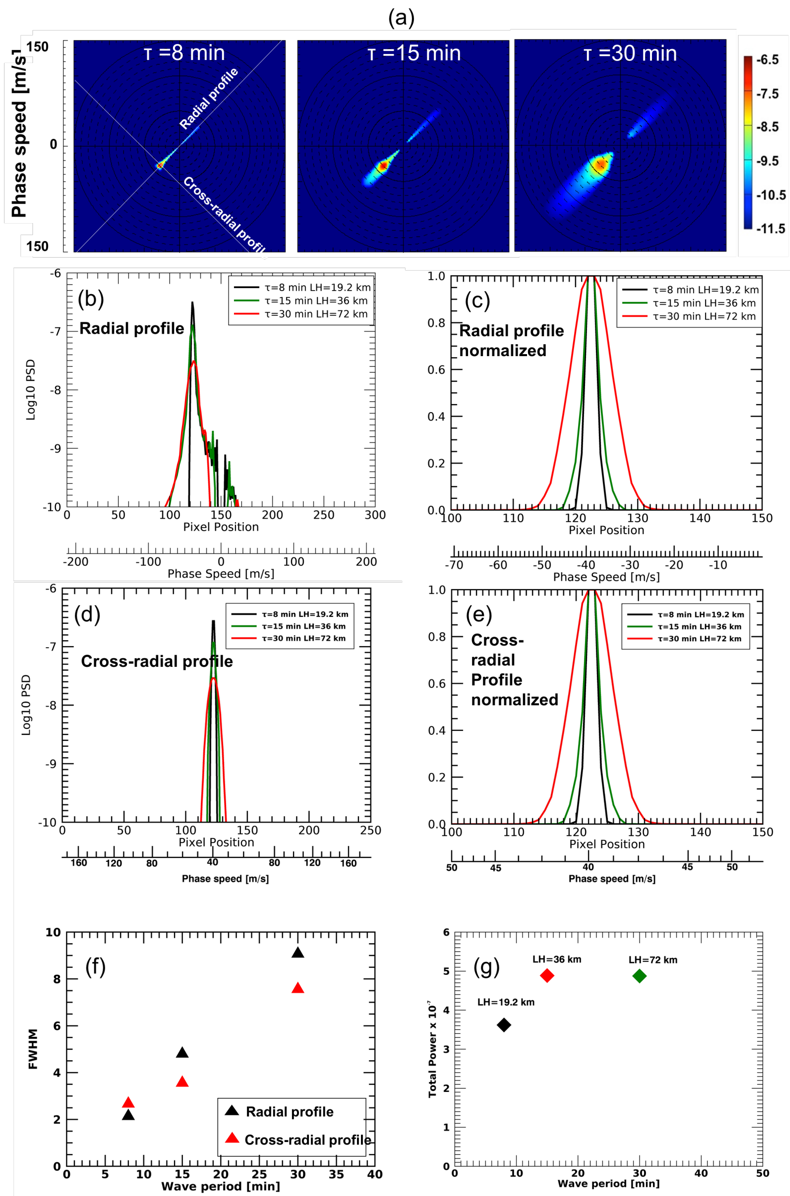
$$wavenumbery = \frac{2\pi}{LH}\sin(\frac{2\pi}{\theta})$$

$$\omega = 2\pi/\tau$$



- X, Y, T = Size of wave packet size in horizontal, meridional and temporal direction
- Xs, Ys, Ts = Size of airglow image in x (km, y (km) and time (second)
- *Zpx, Zpy, Zpt* = Zero padding size

Case 1: Different wave period and horizontal wavelength



$$y = A(sin(wavenumx * Xs + wavenumy * Ys) - \omega * Ts)$$

$$wavenumberx = \frac{2\pi}{LH}\cos\left(\frac{2\pi}{\theta}\right)$$

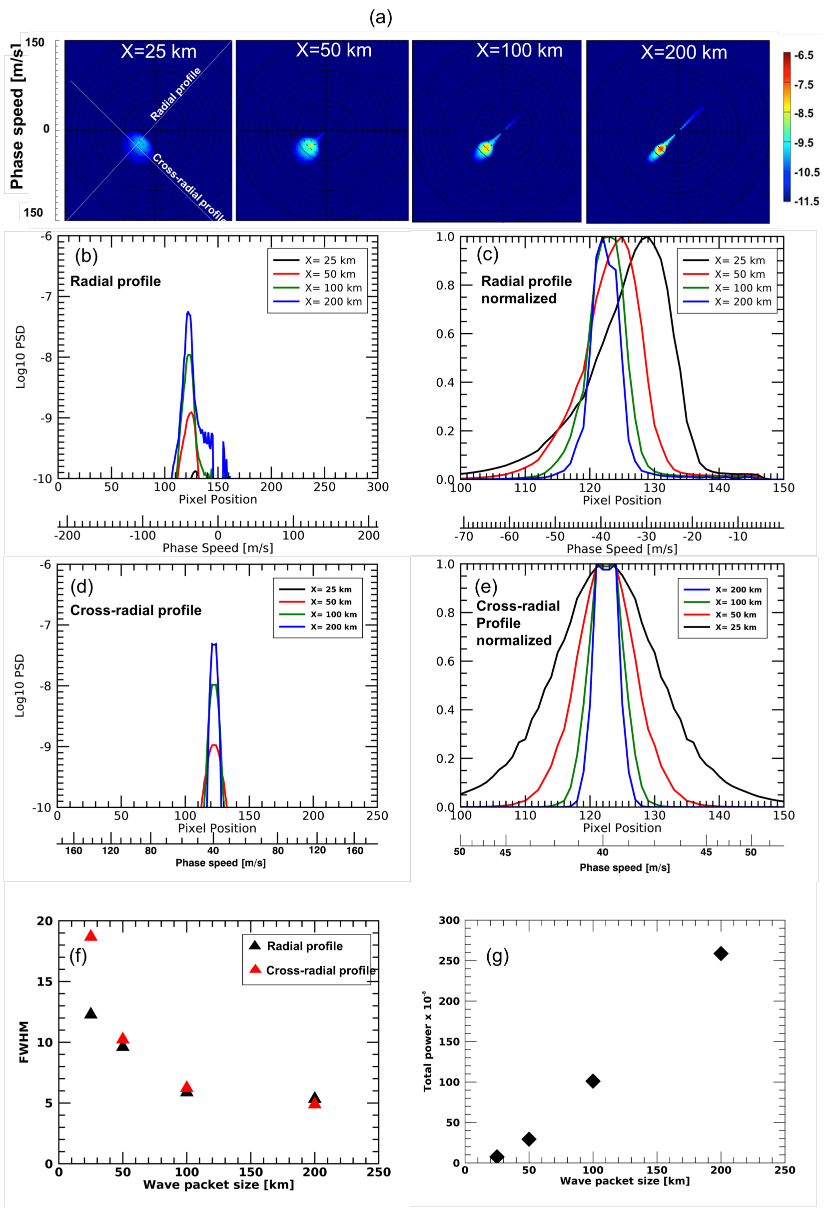
$$wavenumbery = \frac{2\pi}{LH}\sin\left(\frac{2\pi}{\theta}\right)$$

$$\omega = 2\pi/\tau$$

c= 40 m/s
LH= 30 km
τ= 8, 15, 30 min
Ts=120 min
Xs=400 km
dT=1 min
Ts_min= 3dT
θ = 225 deg
(0=eastward)

- The longer the period, the wider the spectrum.
- i.e. The smaller number of cycle causes the wider spectrum.
- The total power difference is ~30%.

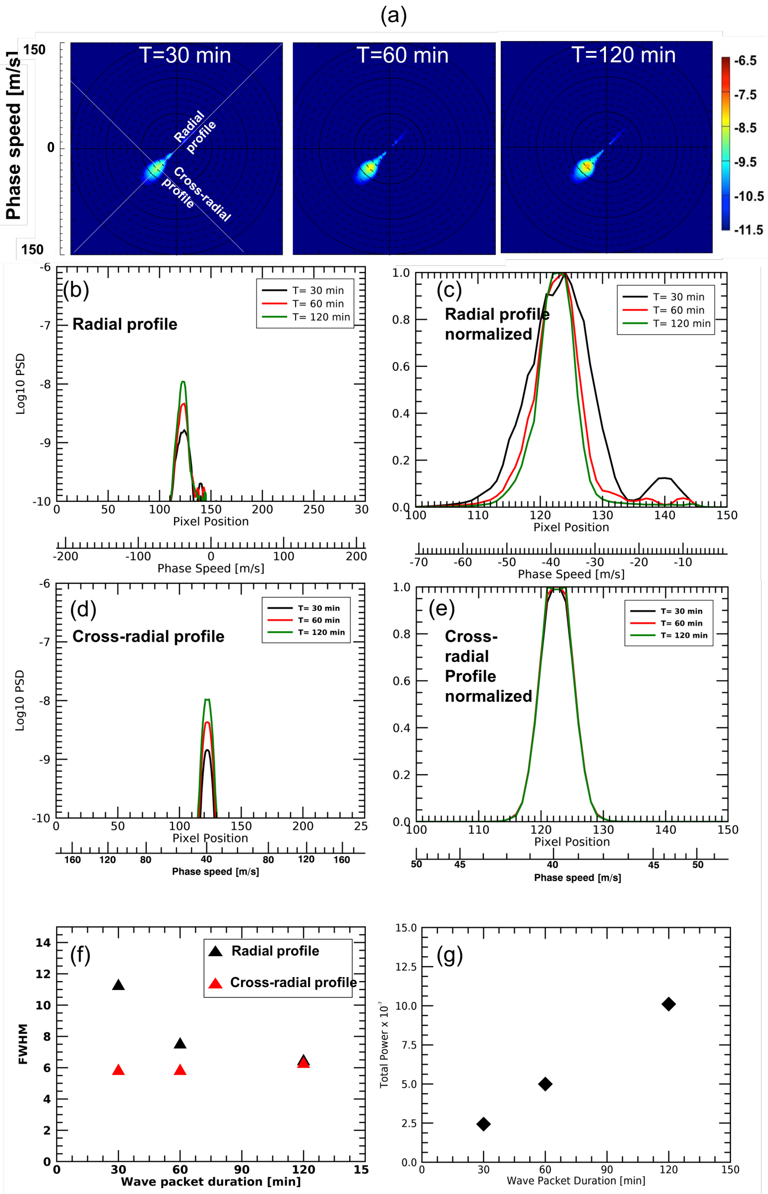
Case 2: Different Wave Packet Size (X)



c= 40 m/s
LH= 30 km
τ= 12.5 min
X=25, 50, 100, 200 km
Ts=120 min
Xs=400 km
dT=1 min
Ts_min= 3dT
θ = 225 deg (0=eastward)

- The bigger the wave packet size (X), the sharper the spectrum
- Total power increases ~4x when X increases 2x.

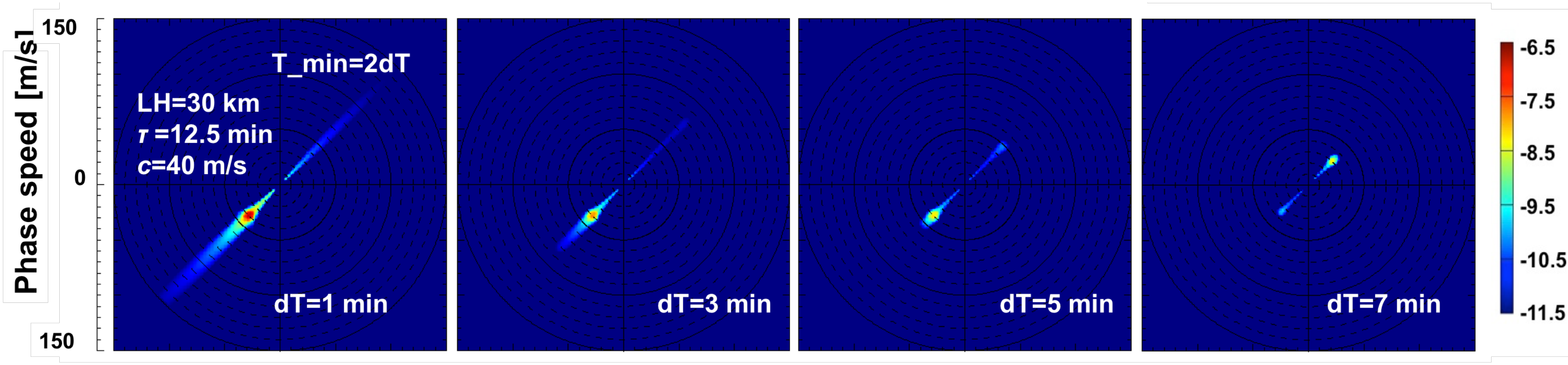
Case 3: Different Wave Packet Duration (T)



c= 40 m/s
LH= 30 km
τ= 12.5 min
X= 100 km
T=30, 60, 120 min
Xs=400 km
dT=1 min
Ts_min= 3dT
θ = 225 deg (0=eastward)

- The longer the duration of wave packet, the spectrum becomes sharper.
- Total power increases by ~2x when T increases by 2x.

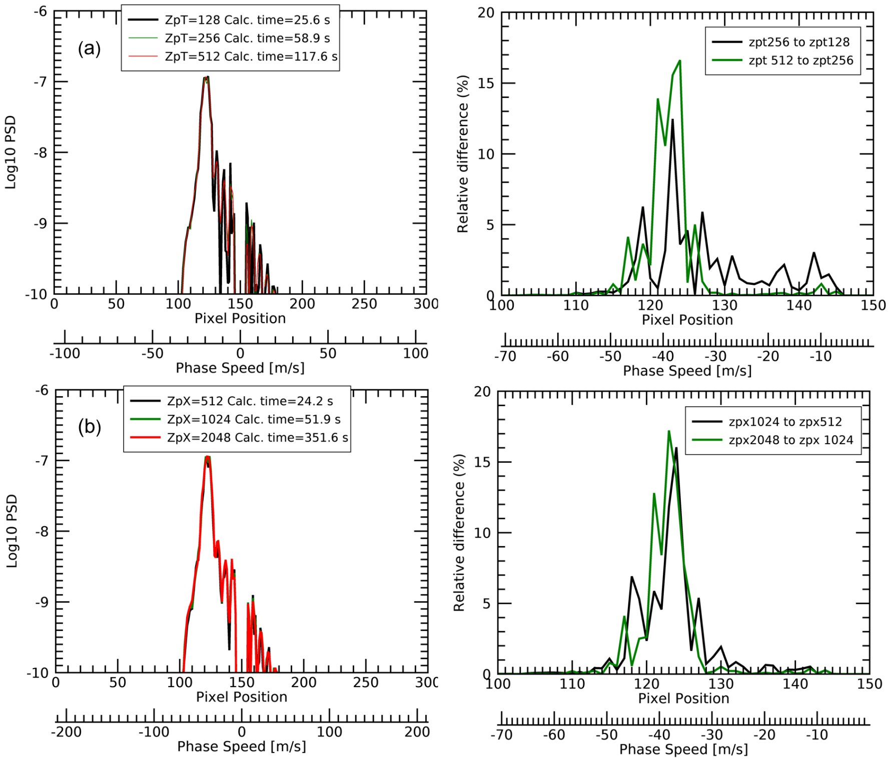
Aliasing Effect/Mirror artifact



c= 40 m/s
LH= 30 km
τ= 12.5 min
dt=1, 3, 5, 7 min
T=120 min
Xs=400 km
dT=1 min
Ts_min= 2dT
θ = 225 deg (0=eastward)

- When the target frequency is lower than but close to the Nyquist frequency, the aliasing effect still appeared.
- It is recommended to use at least **Ts_min=3dT**

Zero Padding Size Effect



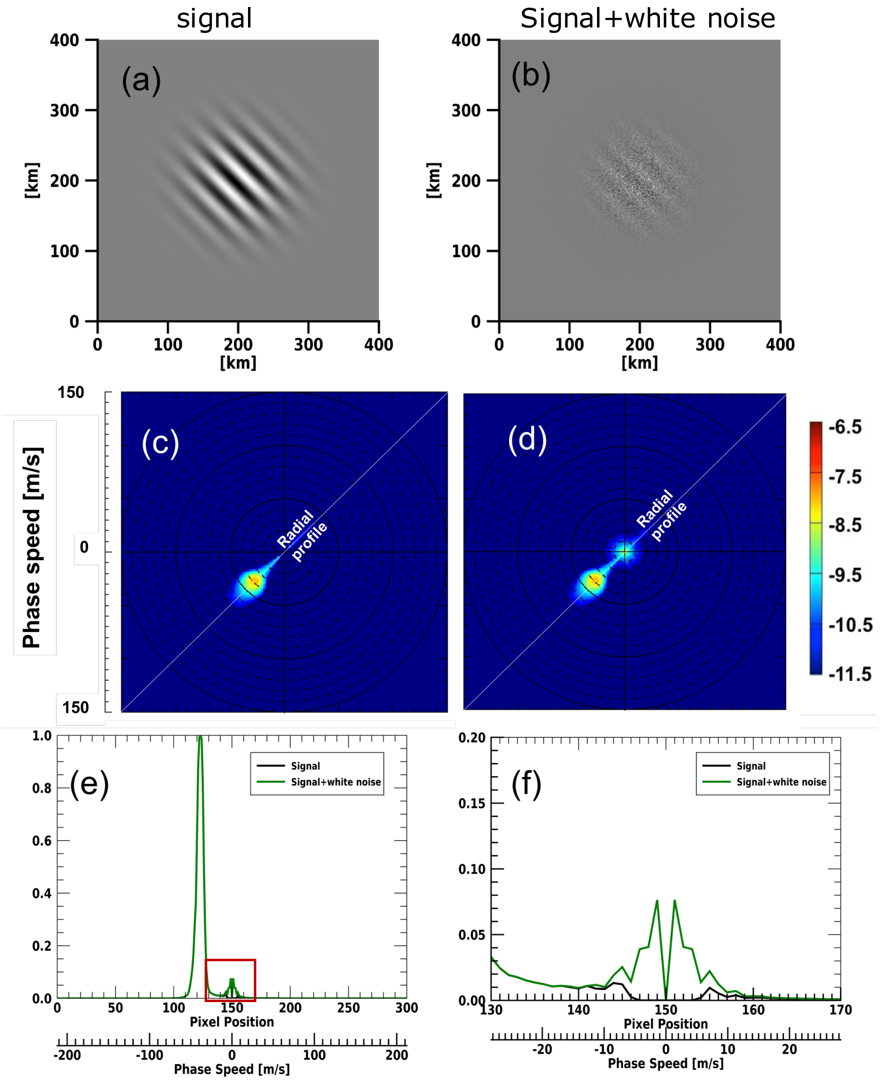
a)Zpx= 512, 1024 and 2048
b)Zpt= 128, 256 and 512

- MacBook Pro: dual core 2.8 GHz Intel Core i7 processor with 4 MB cache size and 16 GB memory, while the program was single-threaded.
- No significant differences in profile.

✓Calculation time ~ proportional with the number of zero padding
Zpx= 0.5 x default → 0.5 x decrease
Zpx= 2 x default → ~4-5 x increase
Zpt= 0.5 x default → 0.5 x decrease
Zpx= 2 x default → ~2 x increase

- It should be noted that bigger zero padding give finer frequency resolution.

Noise Sensitifity Analysis

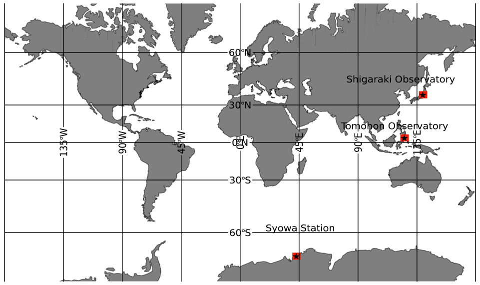


c= 40 m/s
LH= 30 km
τ= 12.5 min
dt=1, 3, 5, 7 min
T=120 min
Xs=400 km
dT=1 min
Ts_min= 2dT
θ = 225 deg (0=eastward)

- PSD enhancement caused by the white noise can be seen around 0-10 m/s in the phase spectra density and radial profile
- it is recommended to exclude the spectrum between **0-20 m/s** when the data is contaminated by noise.

Application: Comparison of gravity wave propagation directions at three different latitudes

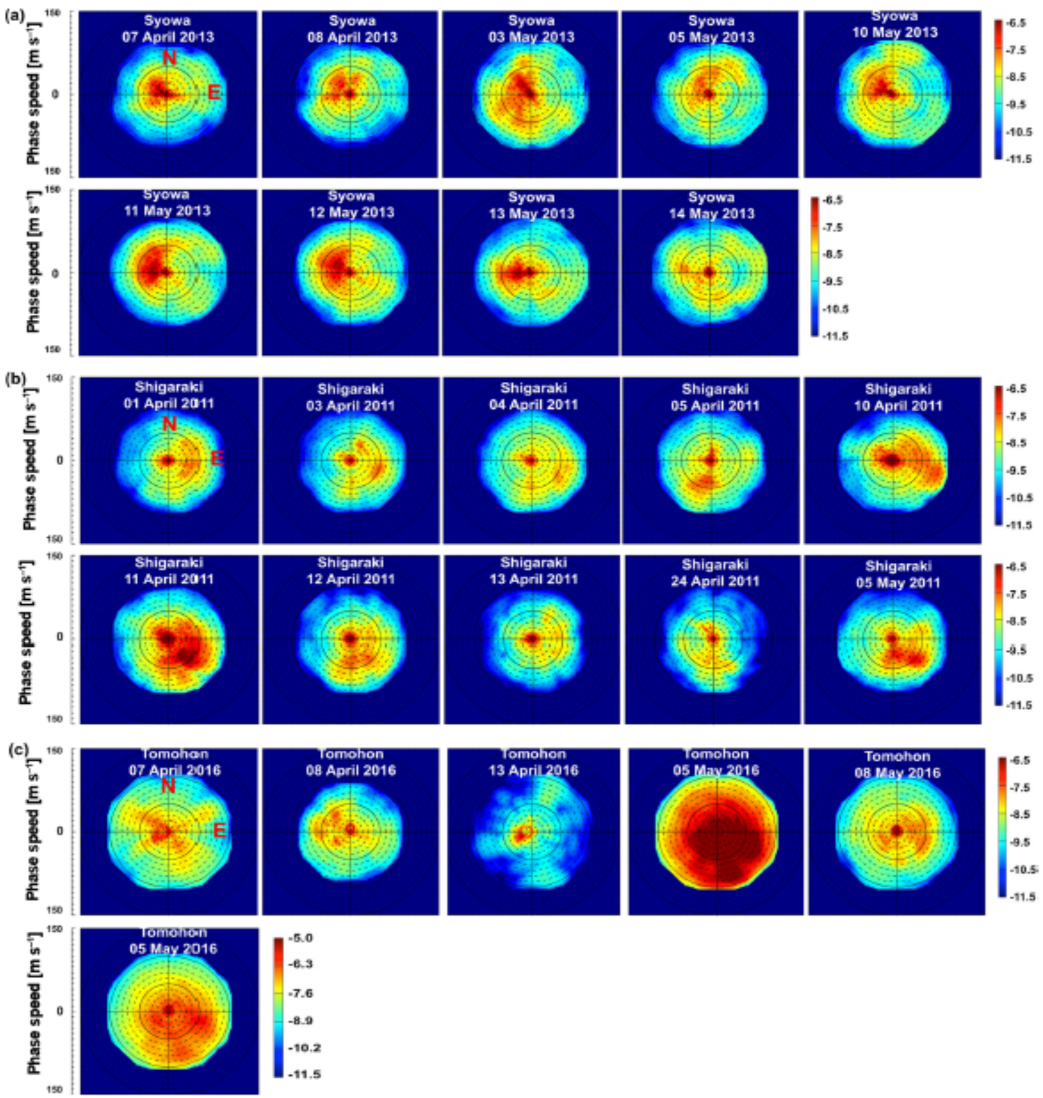
Station name (country)	Syowa (Antarctic)	Shigaraki (Japan)	Tomohon (Indonesia)
Location	69° S, 40° E	35° N, 136° E	1° N, 122° E
Institution	National Institute of Polar Research (NIPR)	Nagoya University	National Institute of Aeronautics and Space (LAPAN)
Airglow emission	Na (589.6 nm)	OI (557.7 nm)	OI (557.7 nm)
Sampling interval (dt) (min)	1	5.5	2.5
Image size (km)	400 × 400	400 × 400	400 × 400
Minimum wave period (T_min) (min)	16.5	16.5	16.5
Maximum wave period (T_max) (min)	60	60	60



Syowa station: 9 clear-nights (April-May 2013)
Shigaraki : 10 clear-nights (April-May 2011)
Tomohon : 5 clear-nights (April-May 2016)

(***Perwitasari et al.*, 2018)**

Day-to-day variation of 2D phase velocity spectra



Syowa:

- The day-to-day variation of the phase velocity spectrum at the Syowa Station is **smaller** and the propagation direction is mainly **westward**.

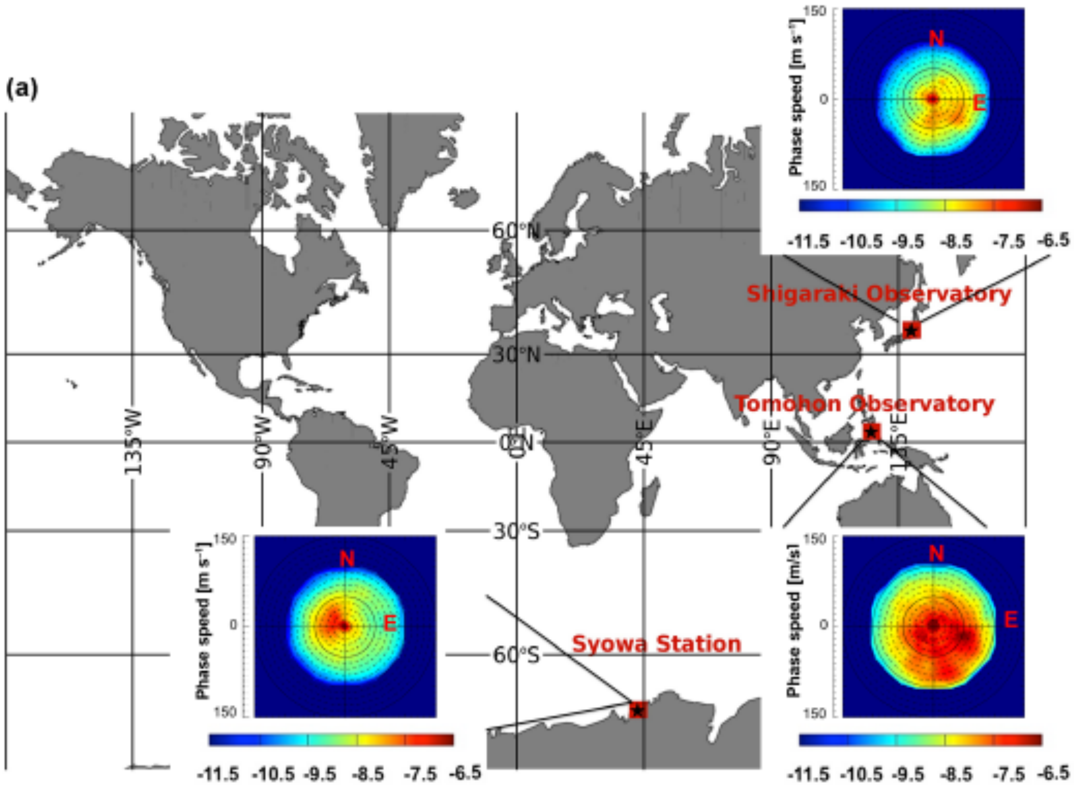
Shigaraki:

- The day-to-day variation of the horizontal propagation direction is **larger** than that at the Syowa Station.

Tomohon:

- The day to day variation of the nightly power spectrum magnitude is remarkable, which indicates ***the intermittency of atmospheric gravity waves*** (AGWs).

Average day-to-day variation of the 2D phase velocity spectrum



Syowa:

- Shows that the dominant propagation is **westward** with a phase **speed <50 m/s.**

Shigaraki:

- Shows **east/southeastward** dominant propagation with a phase speed of up to ~80 m/s.

Tomohon:

- The day-to-day variation in Tomohon is too strong to discuss average characteristics; however, a phase speed of up to ~100 m/s and faster is observed.

Summary and Future Works

- We developed a user-friendly IDL function based on *Matsuda et al.*'s (2014) 3D FFT method for airglow data analysis.
- This function can calculate big amount of data with reasonable execution time.
- Several simulations have been done to examine the performance analysis of this new function.
- This new function was applied to airglow imaging obtained from April–May of selected years at three different latitudes: Syowa Station (69°S, 40°E), Shigaraki (35°N, 136°E), and Tomohon (1°N, 122°E), run by different groups.
- We demonstrated the distinct difference of the GW propagation characteristics at three different latitudes based on the phase velocity spectra.
- **If you are interested in using our program, please do not hesitate to contact us.**