Retrieval of Temperature Profiles using Radio Acoustic Sounding System (RASS) with the Equatorial Atmosphere Radar (EAR) in West Sumatra, Indonesia

Ina Juaeni[1], Hiraku Tabata[2], Noersomadi[2,1], Halimurrahman[1], Hiroyuki Hashiguchi[2] and Toshitaka Tsuda[2]

1: National Institute of Aeronautics and Space (LAPAN), Indonesia
2: Research Institute for Sustainable Humanosphere (RISH), Kyoto University

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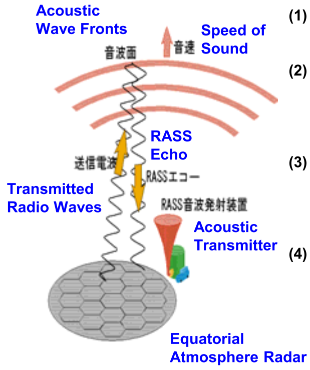
We carried out eight campaign observations in 2016, testing the performance of EAR-RASS.
We intensively analyzed the RASS results from August 29 to September 3, 2016, when radiosondes were launched 12 times from the EAR site.

RASS (Radio Acoustic Sounding System)



(1) To emit sound pulse by a high-power acoustic transmitter
(2) Refractive index fluctuations are produced due to density perturbations caused by sound waves
(3) To detect scattered echo from acoustic wave fronts (RASS echo), and to determine Doppler shift (sound speed)
(4) From a relation; temperature ∝ (sound speed)², a temperature profile is obtained.

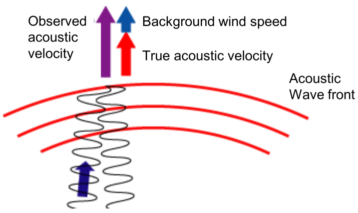
RASS Observations

advection by wind

$$C_a = C_s + v$$

$$T_v = \left(\frac{C_a - v}{K_d}\right)^2$$

C_a: Apparent sound speed
C_s: True sound speed
v: Wind speed
T_v: Virtual temperature (K)
K_d=20.047



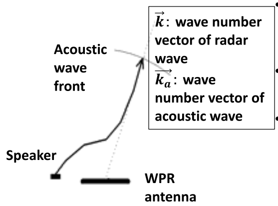
Bragg condition

Bragg condition of RASS：

$$2\vec{k} = \vec{k_a}$$

$$(1):\quad 2\left|\vec{k}\right| = \left|\vec{k_a}\right|$$

$$(2):\quad \vec{k} // \vec{k_a}$$



$\vec{k}$: wave number vector of radar wave
$\vec{k_a}$: wave number vector of acoustic wave

Condition (1)

Because the temperature decreases along altitude, we need to select appropriate acoustic frequency that satisfies the condition (1).

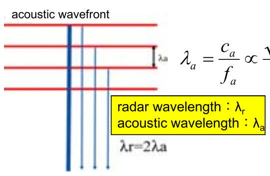
We employ the FM chirped signal that sweeps from 85 to 115 Hz to cover up to 20 km.

Condition (2)

- As the acoustic propagation is affected by the background wind velocity and temperature, $\vec{k_a}$ varies accordingly.
- We apply a ray-tracing technique to know the variation of $\vec{k_a}$.
- Antenna beam is steered into appropriate direction, considering the results of the ray-tracing

Bragg condition to obtain strong RASS echoes

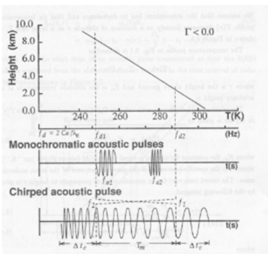
Bragg condition



$$\lambda_a = \frac{c_a}{f_a} \propto \frac{\sqrt{T_v}}{f_a}$$

radar wavelength：λ_r
acoustic wavelength：λ_a

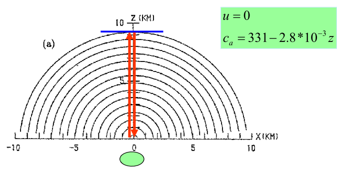
$\lambda_r = 2\lambda_a$

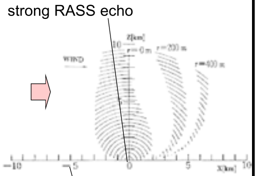


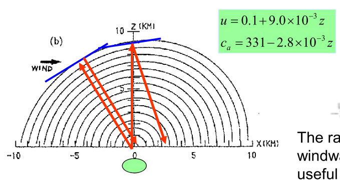
FM-chirped sound is used to satisfy the Bragg condition in a wide height range

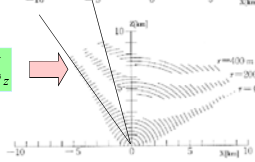
Modulation of acoustic wave front by wind

Effective area to detect strong RASS echo

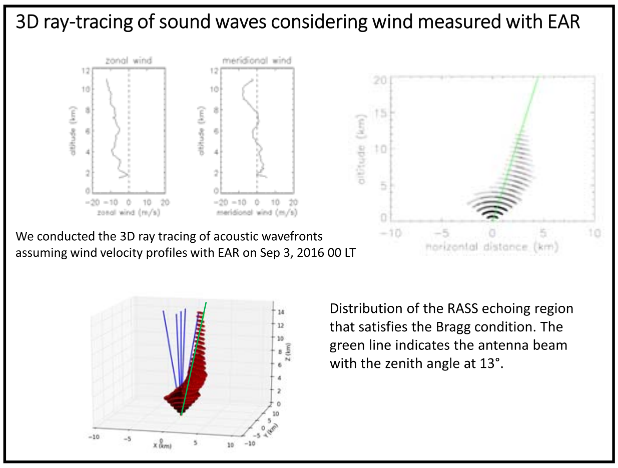


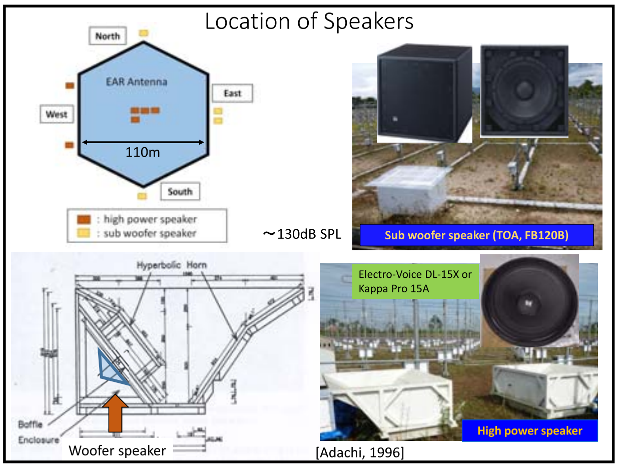


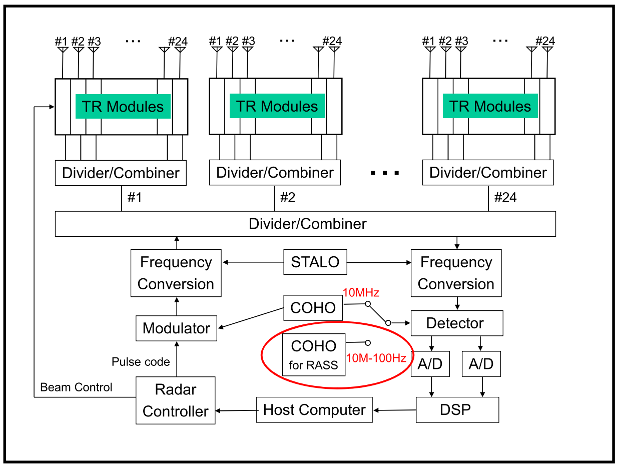


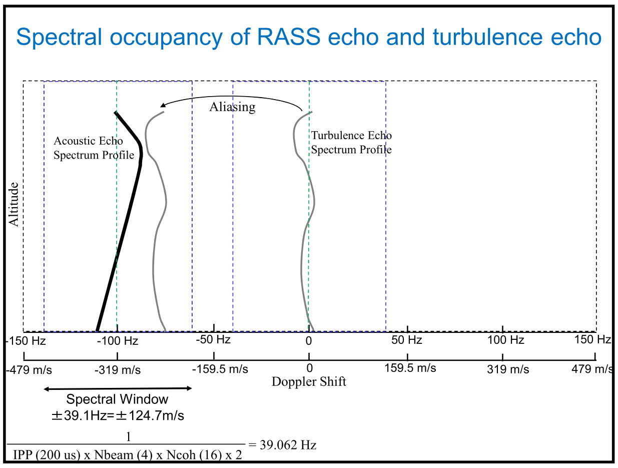


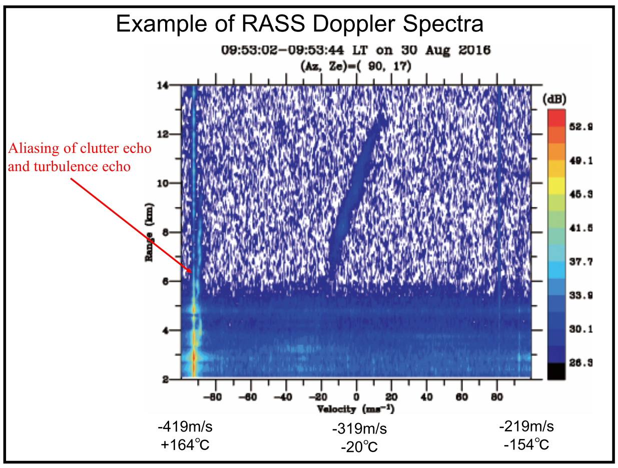
The radar beam direction steering to windward and windward acoustic source is useful to detect RASS echo at high altitude.

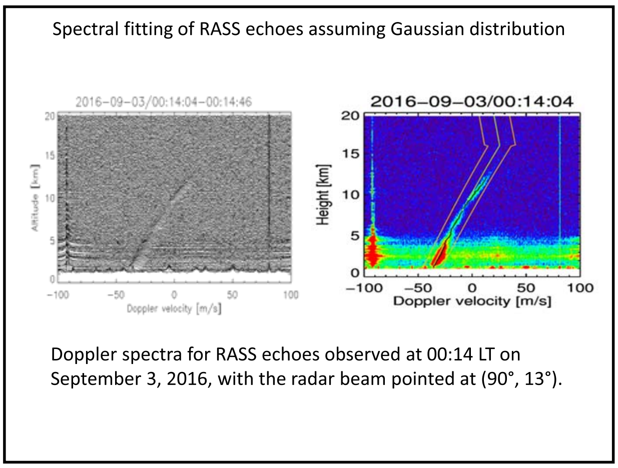

3D ray-tracing of sound waves considering wind measured with EAR
zonal wind
meridional wind
altitude (km)
zonal wind (m/s)
meridional wind (m/s)
altitude (km)
horizontal distance (km)
We conducted the 3D ray tracing of acoustic wavefronts assuming wind velocity profiles with EAR on Sep 3, 2016 00 LT
Distribution of the RASS echoing region that satisfies the Bragg condition. The green line indicates the antenna beam with the zenith angle at 13°.


Location of Speakers
North
EAR Antenna
West
East
110m
South
: high power speaker
: sub woofer speaker
～130dB SPL
Sub woofer speaker (TOA, FB120B)
Hyperbolic Horn
Baffle
Enclosure
Woofer speaker
Electro-Voice DL-15X or Kappa Pro 15A
High power speaker
[Adachi, 1996]


#1 #2 #3 ··· #24
TR Modules
Divider/Combiner
#1
#2
#24
Divider/Combiner
Frequency Conversion
STALO
Frequency Conversion
10MHz
COHO
Modulator
Detector
COHO for RASS
10M-100Hz
A/D
A/D
Pulse code
Beam Control
Radar Controller
Host Computer
DSP

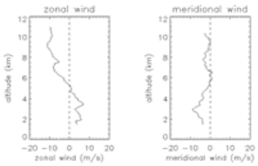

Spectral occupancy of RASS echo and turbulence echo
Aliasing
Acoustic Echo Spectrum Profile
Turbulence Echo Spectrum Profile
Altitude
-150 Hz
-100 Hz
-50 Hz
0
50 Hz
100 Hz
150 Hz
-479 m/s
-319 m/s
-159.5 m/s
0
159.5 m/s
319 m/s
479 m/s
Doppler Shift
Spectral Window
±39.1Hz=±124.7m/s
1 / IPP (200 us) x Nbeam (4) x Ncoh (16) x 2 = 39.062 Hz

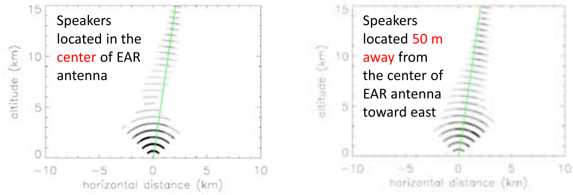

Example of RASS Doppler Spectra
09:53:02–09:53:44 LT on 30 Aug 2016
(Az, Ze)=(90, 17)
Aliasing of clutter echo and turbulence echo
Range (km)
Velocity (ms⁻¹)
(dB)
-419m/s
+164℃
-319m/s
-20℃
-219m/s
-154℃


Spectral fitting of RASS echoes assuming Gaussian distribution
2016-09-03/00:14:04-00:14:46
Altitude [km]
Doppler velocity [m/s]
2016–09–03/00:14:04
Height [km]
Doppler velocity [m/s]
Doppler spectra for RASS echoes observed at 00:14 LT on September 3, 2016, with the radar beam pointed at (90°, 13°).

Location of Acoustic Speakers

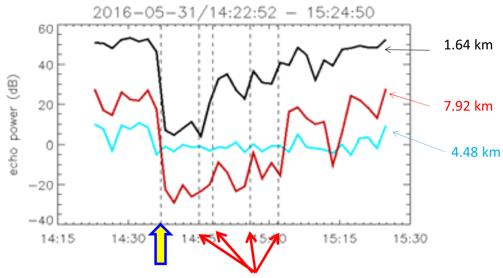
wind velocity profiles observed with EAR at 14:30 LT on May 31, 2016.





Cross sections of the ray-tracing results with an azimuth angle of 60° assuming wind velocity profiles on May 31, 2016 at 14:30 LT

RASS echo power at selected altitudes

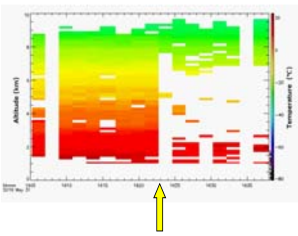


All speakers were turned off at 14.37 LT

Center speakers were turned on one by one at 14:45, 14:48, 14:56, and 15:02 LT

Operation of the speakers was changed at the timing of the vertical dashed lines.

Time and height variations of the temperature observed with EAR-RASS from 16:05 to 16:38 LT on May 31, 2016.



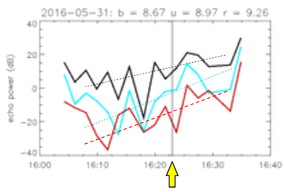
Sweep range of the FM-chirped acoustic signals was changed at 16:23 LT from **90-115 Hz** to **90-100 Hz**

We expected the increase of RASS echo to be:

$$10 \log \left(\frac{25}{10}\right)^2 \approx 8 \text{ dB}$$

90 Hz ⇔ 287 m/s ⇔ 205 K (-68 ℃)
100 Hz ⇔ 319 m/s ⇔ 253 K (-20 ℃)
115 Hz ⇔ 367 m/s ⇔ 335 K (+62 ℃)

RASS echo intensity at selected altitudes

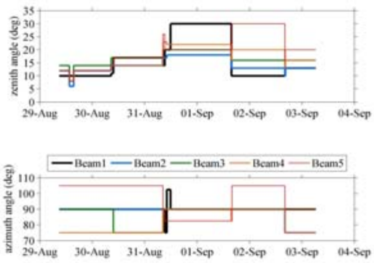


Black : 8.67 km, 10.2 dB to 17.8 dB (**7.6 dB**)

Blue : 8.97 km, -7.9 dB to 8.6 dB (16.5 dB)

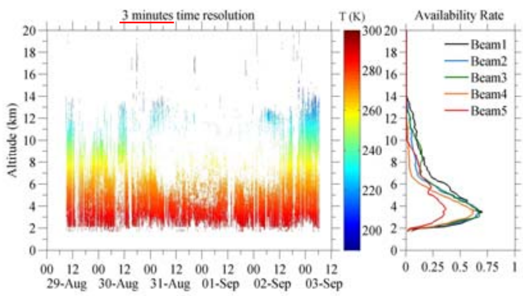
Red : 9.26 km, -16.9 dB to -2.9 dB (14.0 dB)

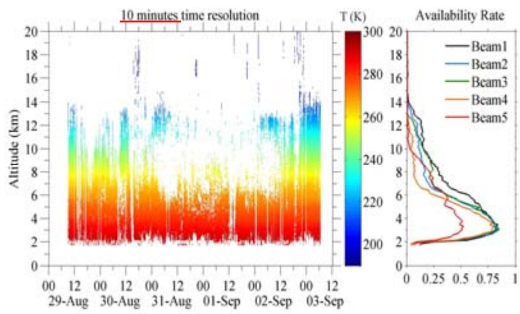
EAR-RASS observation from Aug 29, 2016 to Sep 3, 2016



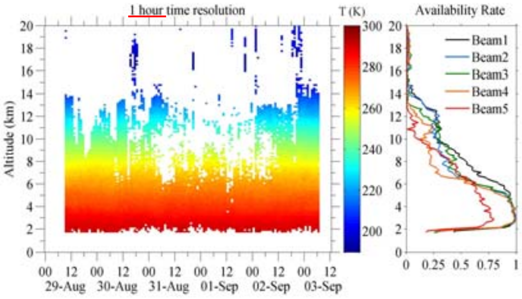
Variation of zenith and azimuth angles.

Time variations of EAR-RASS mean temperature from five beams

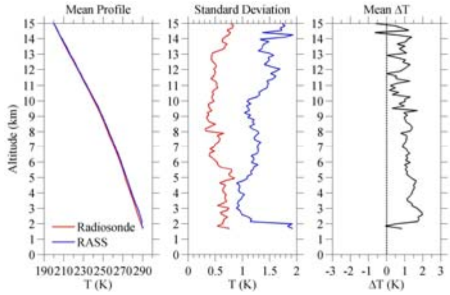




The availability rate at 2-6 km is about 50-80% and up to 14 km about 10%.

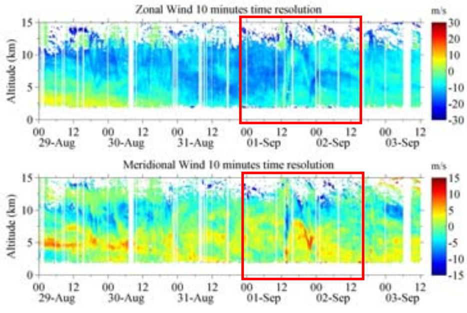


Comparison of the EAR-RASS temperature profile and radiosonde results



Averaged of 10 min resolution EAR-RASS results (**blue**) and the mean of 12 radiosonde results (**red**) from August 29 to September 3, 2016.

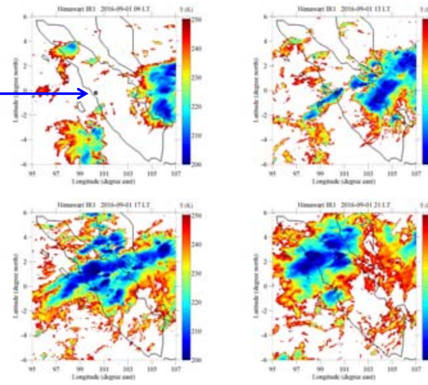
Disturbance event on Sep 1, 2016



Time and height variations of the eastward (top) and northward (bottom) wind velocity observed with the standard five-beam method with EAR from August 29 to September 3, 2016.

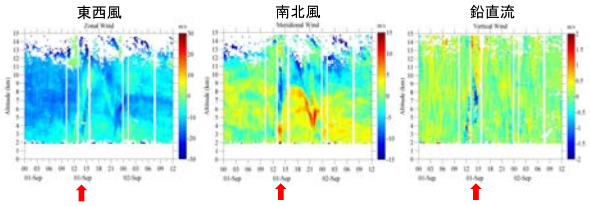
Satellite images at 09, 13, 17 and 21 LT on September 1, 2016.

Location of EAR

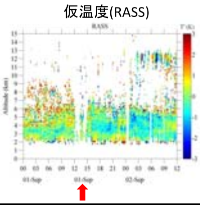


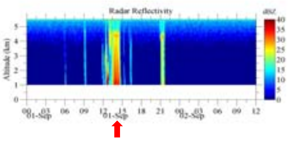
Enlarged plot of wind components observed with EAR, RASS temperature profiles, and MRR radar reflectivity from 00 LT Sep 1 to 12 LT Sep 2, 2016.

東西風 南北風 鉛直流



仮温度(RASS)





Micro Rain Radar observation

Concluding remarks

- We carried out EAR-RASS observations during 2016 and examined the Bragg condition of RASS echoes.
- We adopted the 3-D ray tracing of acoustic waves for determining the appropriate antenna directions for obtaining RASS echoes.
- We investigated the acoustic sources, including the location of speakers and the sweep frequency range of the FM-chirped acoustic signals. The speakers located in the center of the EAR antenna were most effective, but speakers outside the antenna were also useful for obtaining the RASS echoes in the lower altitudes when the wind velocity became large.
- The RASS temperature with 10-min resolution was determined at 2–6 km with 50–80% availability, and up to about 14 km with about 10% availability.
- The standard deviation from the mean temperature difference was about 0.4 K.
- We found a few interesting meteorological disturbances that occurred between August 30 and September 1, 2016. A preliminary report was presented on the behavior of the wind velocity and temperature variations in association with the rain data and satellite images on September 1.