Upper-air simulator to evaluate the radiation correction and measurement uncertainty of RS41

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Significance of radiosonde measurement

- Accurate method to monitor the long-term climate change in stratosphere
  - Temperature is the direct index of global warming
- Practical tool to gather climate variables for the weather forecasting in troposphere
- Serve as a Reference to other remote skills such as satellite
- Sounding sites more than 1000 sites
  - National observatories
  - Military bases, etc
  - Institutes & universities for research
Radiosonde meets ...

- High solar irradiance ~ 1360 W/m²
- Low pressure down to a few hPa
- Upward air ventilation +5 m/s
- Low temperature below -70 °C

Requiring accurate test method based on international agreement
Conditions for test method

- Guide to Meteorological Instruments and Methods of Observation (WMO-No.8)
  - Chapter 12, MEASUREMENT OF UPPER-AIR PRESSURE, TEMPERATURE AND HUMIDITY
  - “The calibration methods used by manufacturers should be identified before purchasing radiosondes.”
  - Stability condition of ±0.2 hPa/min for pressure, ±0.25 K/min for temperature and ±1 relative humidity per minute
  - Errors less than ±0.2 hPa for pressure, ±0.1 K for temperature and ±1% relative humidity

There is no detailed descriptions on the implementation of calibration setups/methods
Upper air simulator (UAS) at KRISS

- Radiation correction of temperature sensors
  - Control of temperature, pressure, ventilation, and irradiance
- Calibration of humidity sensors
  - Control of temperature and humidity
Radiation correction setup

- Environmental factors affecting radiation correction
  - Temperature ($T = -70$–$20$ °C) by climate chamber
  - Air pressure ($P = 5$–$500$ hPa) & Ventilation ($v = 4$–$7$ m/s) by sonic nozzles
  - Irradiance ($S_0 = 1000$ W/m$^2$) by solar simulator
Rotation & Tilting of radiosonde

- Simulation of movement of radiosonde in sounding
  - Rotation (5, 10, 15 s) & Boom tilting (27 °)

[Diagram showing normal, rotation, and tilting positions of a radiosonde with labels for irradiation, quartz window, air flow, sensor boom, temperature sensor, and tilt angle.]
Pressure effect

- Convective cooling
  - Radiation correction ($\Delta T_{\text{rad}}$) decreases as air pressure ($P$) increases
  - Air density $\uparrow$ at high $P \rightarrow$ Convective cooling $\uparrow$

\[ \Delta T_{\text{rad}} = A_0(T) + B_0(T) \cdot \log(P) + C_0(T) \cdot [\log(P)]^2 \] for $5 \text{ hPa} \leq P \leq 500 \text{ hPa}$, $S_0 = 980 \text{ W/m}^2$
**Theoretical understanding**

- **Heat transfer calculation**
  - Metal sphere is modelled as a temperature sensor

\[ \alpha S = h(T_s - T_a), \quad h = \frac{k}{D} \left[ 2 + \left( 0.4Re^\frac{1}{2} + 0.06Re^\frac{2}{3} \right) \left( \frac{\mu C_p}{k} \right)^\frac{2}{5} \right] \]

- \( \alpha \) = absorptivity of the metal sphere
- \( S \) = solar irradiance
- \( h \) = heat transfer coefficient
- \( D \) = diameter of the sphere
- \( k \) = thermal conductivity of air
- \( \mu \) = viscosity of air
- \( C_p \) = heat capacity of air
- \( Re = \text{Reynolds number} \ (\rho v D / \mu) \)
- \( \rho \) = density of air
- \( v \) = wind speed

Solar irradiance = 1000 W·m⁻²
Air temperature = \( T_a \)
Wind speed = 5 m·s⁻¹

Metal sphere (Diameter = 1 mm, Temperature = \( T_s \))
Temperature effect

- Radiation from the sensor

\[
T \downarrow \Rightarrow k \text{ (thermal conductivity)} \downarrow \Rightarrow h \downarrow \Rightarrow \Delta T_{\text{rad}}
\]

\[
\alpha S = h(T_s - T_a), \quad h = \frac{k}{D} \left[ 2 + \left( 0.4Re^2 + 0.06Re^{\frac{2}{3}} \right) \left( \frac{\mu C_p}{k} \right)^{\frac{2}{5}} \right]
\]
Estimation of low temperature effect

- Empirical formula based on experiment
- Estimation of $\Delta T_{\text{rad}}$ at cold temperatures using $\Delta T_{\text{rad}}$ at 20 °C

\[
\frac{\Delta T_{\text{rad}}}{\Delta T_{\text{rad,20}}} \times 100 \% = D(T) \cdot P + E(T) , \quad D(T) = d_0 \cdot T + d_1 \quad \text{and} \quad E(T) = e_0 \cdot T + e_1
\]
Ventilation effect

- Convective cooling

\[ \Delta T_{\text{rad}} \downarrow \]

\[ \Delta T_{\text{rad}} = A_0(T) + B_0(T) \cdot \log(P) + C_0(T) \cdot [\log(P)]^2 - 0.027 \cdot (v-5) \]

for \( 5 \text{ hPa} \leq P \leq 500 \text{ hPa}, S_0 = 980 \text{ W} \cdot \text{m}^{-2} \)

Laser Doppler Velocimetry

Reference: 4.67 m\text{s}^{-1} (550 hPa)
Measurement mean: 4.63 m\text{s}^{-1}
Irradiance effect

- Heating by solar irradiance
  - $\Delta T_{\text{rad}}$ is proportional to $S$

\[-h(T_s - T_a) - \sigma \varepsilon (T_s^4 - T_a^4) + \alpha S = 0\]

(Proportional to $S$)

$T_s - T_a = \frac{\alpha S}{h}$


$\Delta T_{\text{rad}} = \frac{S}{S_0} \times [A_0(T) + B_0(T) \cdot \log(P) + C_0(T) \cdot [\log(P)]^2 - 0.027 \cdot (v-5)]$

for $5 \text{ hPa} \leq P \leq 500 \text{ hPa}$, $S_0 = 980 \text{ W} \cdot \text{m}^{-2}$
Rotation of radiosonde

- Simulating rotation motion of radiosonde in sounding
  - Oscillation of $\triangle T_{\text{rad}}$

Oscillation of $\triangle T_{\text{rad}}$ can be averaged out by fittings or treated as uncertainty.
Radiosonde tilting

- Simulating solar elevation angle
- Calculation of $\Delta T_{\text{rad}}$ in proportion to effective irradiance

$$\Delta T_{\text{rad}} = \left(\frac{S_{\text{eff}}}{S_0}\right) \times \left[A_0(T) + B_0(T) \cdot \log(P) + C_0(T) \cdot \left(\log(P)\right)^2 - 0.027 \cdot (v-5)\right]$$

for 5 hPa $\leq$ $P$ $\leq$ 500 hPa, $S_0$ = 980 W·m$^{-2}$
Effective irradiance to sensor

- Solar angle $\alpha$, Azimuthal angle $\varphi$, & Boom tilti angle $\theta$
  - Effective irradiance (mean over rotation angle, $\varphi$)

$$S_{\text{eff}} = S_{\text{dir}} \cdot \left( \frac{A_{\text{eff}}}{A_0} \right)$$

$$S_{\text{eff}} = S_{\text{dir}} \cdot \left| \cos \alpha \cos \theta \cos \varphi - \sin \theta \sin \alpha \right|$$
Radiation correction

UAS (KRISS) vs. Manufacturer (Vaisala)

$\Delta T_{\text{rad UAS}} < \Delta T_{\text{rad Vaisala}}$

Tilt angle = 45° & Solar angle = 45°

$\Delta T_{\text{rad UAS}} < \Delta T_{\text{rad Vaisala}}$ by 0.5–0.7 °C at −70 °C & 5 hPa with $S = 1360 \text{ W} \cdot \text{m}^{-2}$ & $\alpha = 45–90^\circ$

$\Delta T_{\text{rad UAS}} < \Delta T_{\text{rad Vaisala}}$ by 0.04–0.4 °C at −70 °C & 5 hPa with $S = 1360+400 \text{ W} \cdot \text{m}^{-2}$ & $\alpha = 45–90^\circ$
Uncertainty

Uncertainty of radiation correction, $U(\Delta T_{\text{rad}})$

<table>
<thead>
<tr>
<th>Uncertainty factor</th>
<th>Condition</th>
<th>Unit</th>
<th>Standard uncertainty ($k = 1$)</th>
<th>Contribution to uncertainty of radiation correction ($k = 2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>-67</td>
<td>°C</td>
<td>0.028</td>
<td>0.000 °C</td>
</tr>
<tr>
<td>$P$</td>
<td>5</td>
<td>hPa</td>
<td>0.01</td>
<td>0.000 °C</td>
</tr>
<tr>
<td>$v$</td>
<td>5</td>
<td>m·s$^{-1}$</td>
<td>0.058</td>
<td>0.004 °C</td>
</tr>
<tr>
<td>$S$</td>
<td>980</td>
<td>W·m$^{-2}$</td>
<td>30.5</td>
<td>0.062 °C</td>
</tr>
<tr>
<td>Rotation</td>
<td>24</td>
<td>°·s$^{-1}$</td>
<td>-</td>
<td>0.035 °C</td>
</tr>
<tr>
<td>Tilting</td>
<td>27</td>
<td>°</td>
<td>-</td>
<td>0.052 °C</td>
</tr>
<tr>
<td>Fitting error</td>
<td>-0.024 – 0.04</td>
<td>°C</td>
<td>0.023</td>
<td>0.046 °C</td>
</tr>
</tbody>
</table>

Expanded uncertainty of radiation correction ($k = 2$), $U(\Delta T_{\text{rad}})$

0.100 °C

Uncertainty of corrected temperature, $U(T_{\text{cor}})$

$U(T_{\text{cor}})^2 = U(T_{\text{raw}})^2 + U(\Delta T_{\text{rad}})^2$

<table>
<thead>
<tr>
<th>Uncertainty factor</th>
<th>Uncertainty ($k = 2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded uncertainty for the radiation correction at 1360 W·m$^{-2}$, $U(\Delta T_{\text{rad}})$</td>
<td>0.138 °C</td>
</tr>
<tr>
<td>Calibration of RS41 temperature sensor (Vaisala), $U(T_{\text{raw}})$</td>
<td>0.100 °C</td>
</tr>
<tr>
<td>Expanded uncertainty in the corrected temperature, $U(T_{\text{cor}})$</td>
<td>0.170 °C</td>
</tr>
</tbody>
</table>

Scaled to 1360 W·m$^{-2}$
Radiation correction with irradiance measurement

- **Dual thermistor radiosonde (DTR)**

**Parameterization of** $S$ & $\Delta T_{\text{rad}}$ **with** $T_B - T_W$, $T$, $P$, $v$ in UAS

<table>
<thead>
<tr>
<th>Daytime</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td></td>
</tr>
</tbody>
</table>

**Daytime**

- **$T_B - T_W$**
  - **0.5 ~ 2.5 °C**
- **Irradiance calculation**
- **Correction value**
  - **0.1 ~ 0.8 °C**

Dual thermistor radiosonde will be presented by Dr. Yong-Gyoo Kim (KRISS)
Summary

- Upper air simulator for radiation correction of radiosonde
  - Temperature (-70–20 °C), Pressure (5–500 hPa), Ventilation (4–7 m/s), & Irradiance (1000 W/m²)
  - Radiosonde rotation (5, 10, 15 s) & Boom tilting (0–27 °)
  - Radiation correction as a function of $T$, $P$, $v$, $S$ and solar angle
  - $\Delta T_{\text{rad,UAS}} < \Delta T_{\text{rad,Vaisala}}$ by max. 0.04–0.4 °C with $\alpha = 45–90$ °
  - Uncertainty of radiation correction, $U(\Delta T_{\text{rad}}) = 0.14$ °C
  - Uncertainty of corrected temperature, $U(T_{\text{cor}}) = 0.17$ °C
  - Uncertainty of soundings should be added to $U(T_{\text{cor}})$
  - Any type of radiosonde can be tested using the UAS at KRISS
Thank you for your attention

More discussions to sangwook@kriss.re.kr