ATTITUDE SENSING SYSTEM USING PHOTODETECTORS

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Attitude sensing system

- ✓ Low cost
- ✓ Small size
- ✓ Light weight

Applications

- ✓ Small satellite, Cubesat
- ✓ Unmanned Aerial Vehicle
- ✓ Mars airplane (stabilizing control)

Target

Weight: < 200 g
Size: < W50 × L50 × H40 mm
Resolution: < 0.5 °
Low Cost

	Advantage	Problem
Star Tracker	High Accuracy	High Cost
Sun Sensor	Flexibility	Eclipse

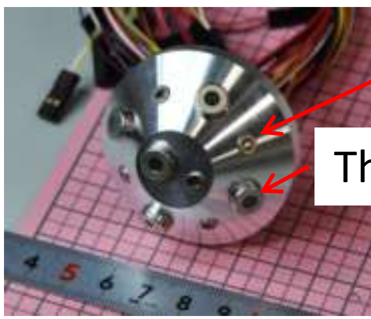
↓

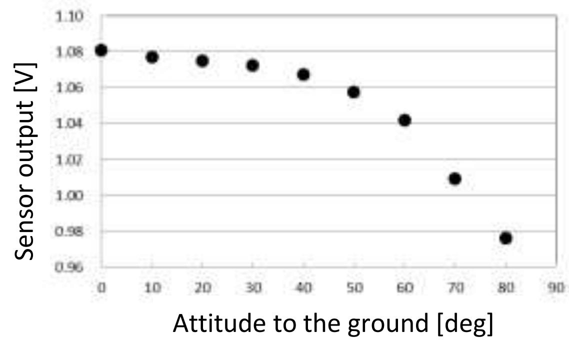
Earth Sensor is suitable for Earth-pointing satellite

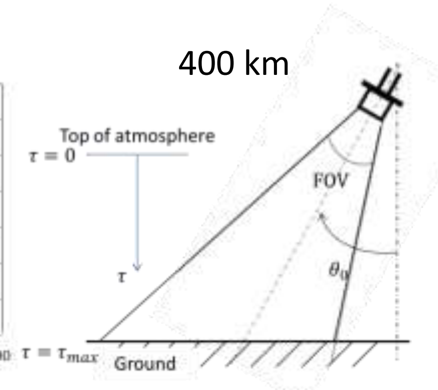
- Attitude sensing system using photodetectors
  - ✓ Several photodetectors are assigned.
  - ✓ Attitude is estimated from the sensor outputs(the sun and the earth).
  - ✓ COTS photodetectors are used.
  - ✓ Precision is improved by the newly proposed method(Virtual sensor method).

Small, light-weight, low cost, acceptable precision

- Engineering model





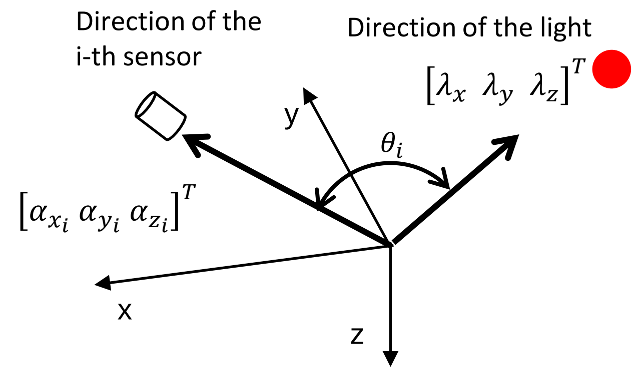


Product	Company	Response range	
Si photodiode S1226-18BK	Hamamatsu Photonics K.K.	320-1000 nm	Sun light
Thermopile sensor HTIA-E	HEIMANN Sensor	Cut on wave length is 5500 nm.	Thermal radiation

Fundamental algorithm

- Direction of the sensor (Known)

$$\alpha_i = [\alpha_{x_i} \quad \alpha_{y_i} \quad \alpha_{z_i}]^T \quad i = 1,2,\dots,r \qquad |\alpha_i| = 1$$

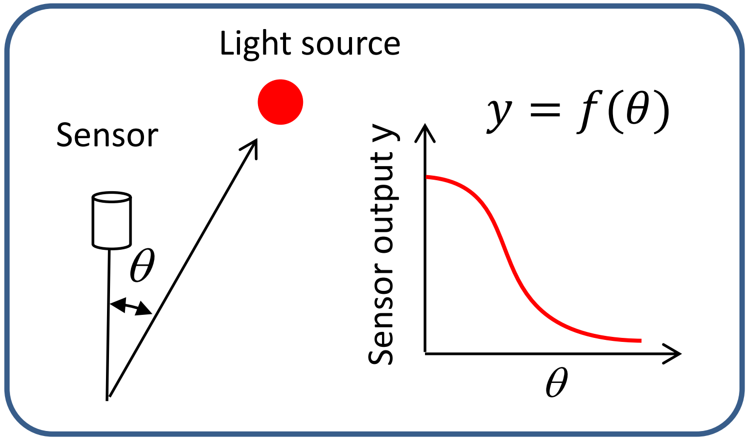


- The estimated angle between the sensor and the light(Known)

$$\hat{\theta}_i = f_i^{-1}(y_i) \qquad i = 1,2,\dots,r$$

- Direction of the light (Unknown)

$$\lambda = [\lambda_x \quad \lambda_y \quad \lambda_z]^T \qquad |\lambda| = 1$$



- $\alpha_i{}^T \cdot \lambda = \cos\hat{\theta}_i \quad (i = 1,\dots,r)$ → Find λ that satisfies this equation for all sensors.

【Optimization problem】

$$minimize\ J \qquad J = |A\hat{\lambda} - \beta|, \qquad |\hat{\lambda}| = 1$$

$$A = [\alpha_1 \quad \cdots \quad \alpha_r]^T$$

$$\beta = [\cos\hat{\theta}_1 \quad \cdots \quad \cos\hat{\theta}_r]^T$$

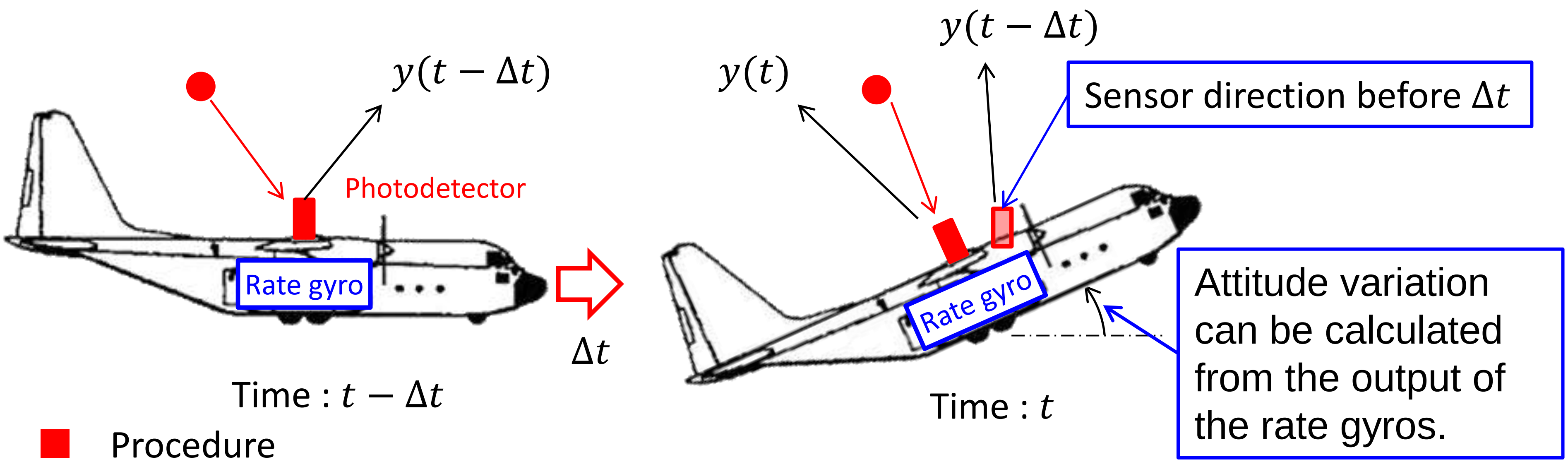
Many sensors are desired

- ✓ Reduction of noise
- ✓ Light should be in the detecting area of some of sensors.

Heavy weight

Virtual sensor method

The performance can be improved without increase of number of sensor.



Procedure

1. Attitude variation for Δt is calculated from the outputs of the rate gyros.
2. The directions of the virtual sensor associated with present body axes are determined.
3. The present sensor outputs and the virtual sensor outputs are used to obtain the airplane attitude.

- ✓ The number of the virtual sensors can be increased arbitrarily as far as the airplane attitude varies.
- ✓ Precise coordinate transformation matrix is necessary to obtain the virtual sensor's direction.

- The direction of the virtual sensor associated with present body axes

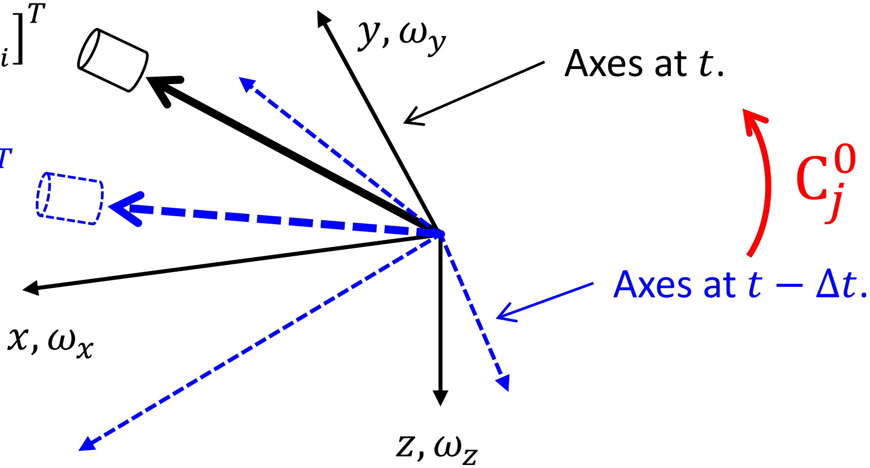
Present sensor

$\alpha_i = [\alpha_{x_i}\ \alpha_{y_i}\ \alpha_{z_i}]^T$

Past sensor(Virtual sensor)

$\alpha_i^{(j)} = [\alpha_{x_i}^{(j)}\ \ \alpha_{y_i}^{(j)}\ \ \alpha_{z_i}^{(j)}]^T$

The direction of the virtual sensor
with the present body axes.



$$\alpha_i^{(j)}(t) = C_j^0(t)\alpha_i$$

Coordinate at $t-\Delta t_i$ ➡ Coordinate at t Transformation matrix

Rate of airplane : $[\omega_x(t)\quad \omega_y(t)\quad \omega_z(t)]^T$

$$C_A^B(t) = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad \dot{C}_A^B(t) = \begin{bmatrix} a_{21}\omega_z - a_{31}\omega_y & a_{22}\omega_z - a_{32}\omega_y & a_{23}\omega_z - a_{33}\omega_y \\ a_{31}\omega_x - a_{11}\omega_z & a_{32}\omega_x - a_{12}\omega_z & a_{33}\omega_x - a_{13}\omega_z \\ a_{11}\omega_y - a_{21}\omega_x & a_{12}\omega_y - a_{22}\omega_x & a_{13}\omega_y - a_{23}\omega_x \end{bmatrix}$$

The coordinate transformation matrix can be
determined using integration of the rate gyro outputs.

Radiosonde

GPS radiosonde is an upper-atmosphere sounding instrument for meteorological measurement.
(CO_2, wind velocity, pressure, temperature and humidity)

→ Operation test of attitude sensing system

Multiple Choices of Interfaces
8 ports for A/D, serial ports, abundant interfaces for additional sensors

Only 150g Weight with Batteries Included
Design of lightweight and low density offers lower risks due to ground fall

Easy Preflight Preparation Work
Lithium batteries enable the radiosonde preparation much easier.

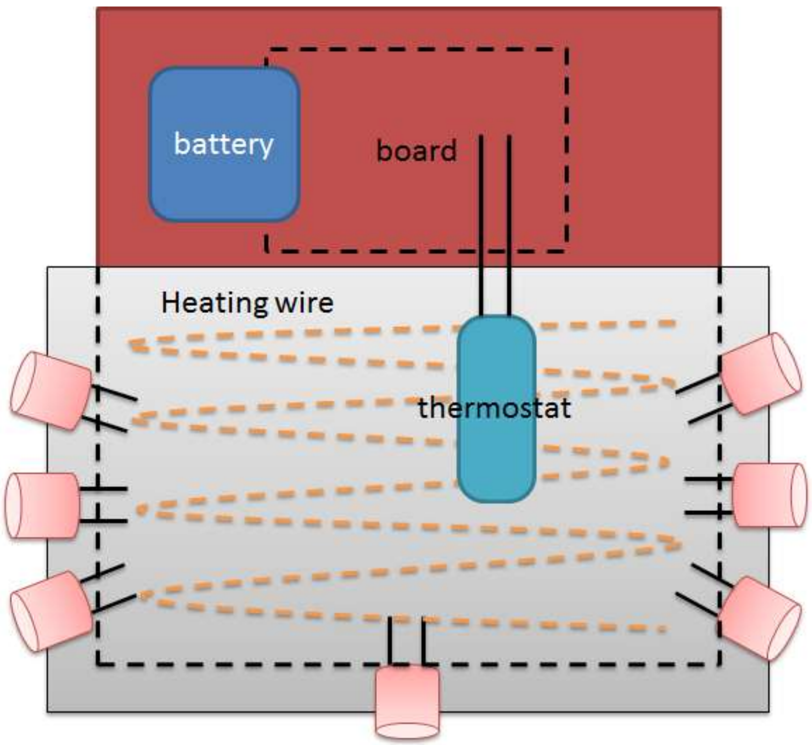
CO_2 Radiosonde

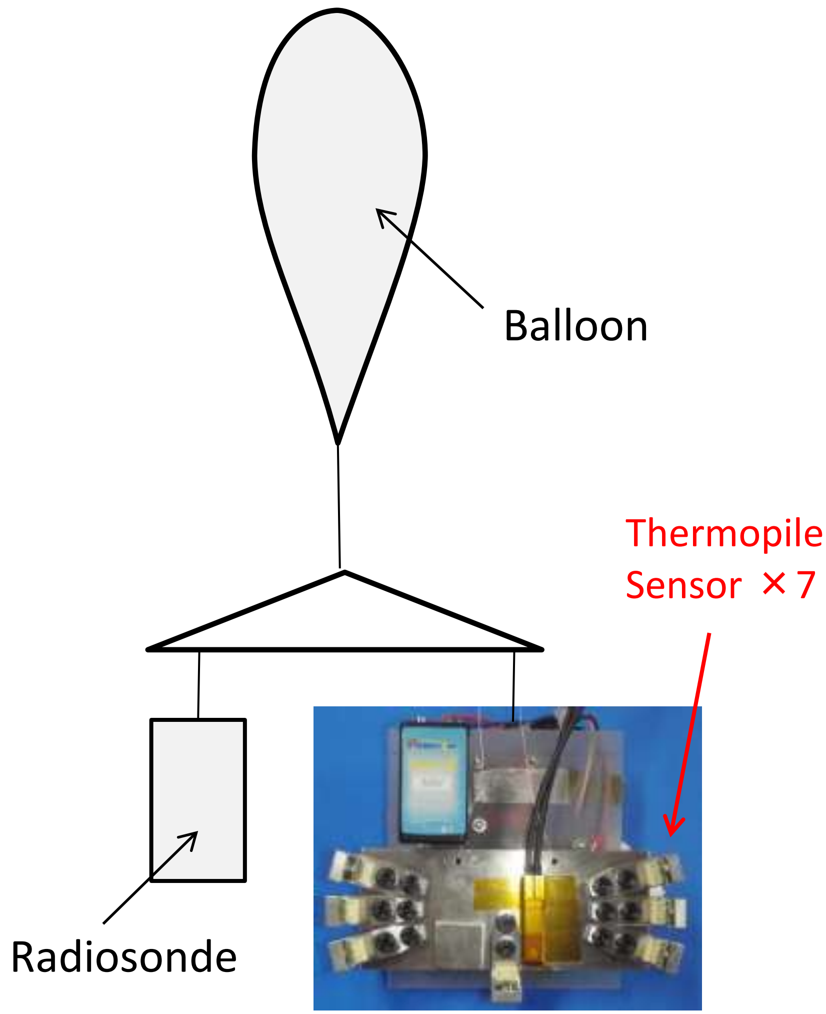
Please visit following site for detail.
http://www.meisei.co.jp/english/

MEISEI

- Purpose of experiment
  - ✓ Demonstration of attitude sensing system using thermopile sensor.
  - ✓ Evaluation of the accuracy
  - ✓ Demonstration of virtual sensor algorithm

- Experiment configuration





Experiment will be performed on Oct. or Nov.

Conclusions

- Main results

1. GNC system of the Mars airplane was proposed.
2. Attitude sensing system and algorithm using photodetector was constructed.
3. Virtual sensor method was proposed.
4. COTS can be applied.

- Future works

1. Experiments in the real environments
2. Validation with flight testing

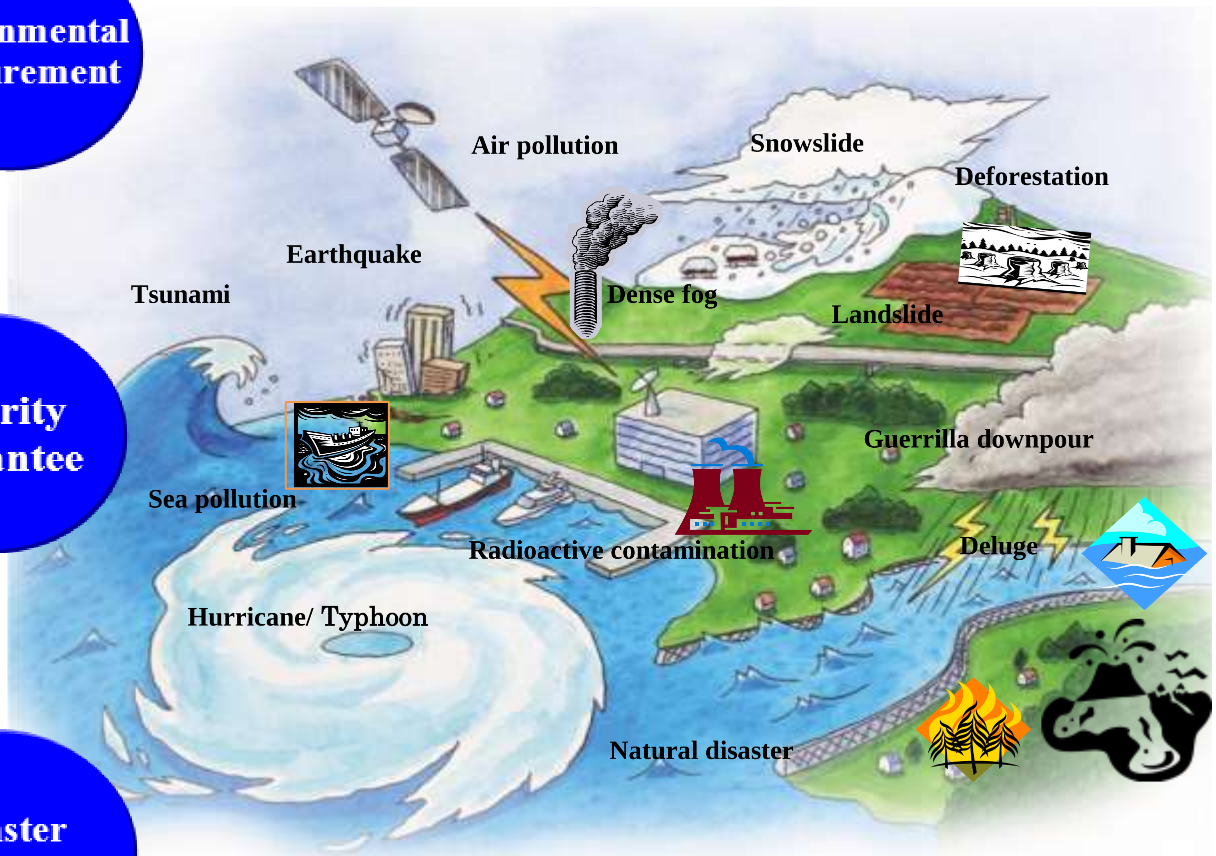
BACKUP

Applications to satellite

Environmental Measurement

Security guarantee

Disaster monitoring



Calculation of the Radiant flux density

$$F_\kappa(\tau) = \pi \int_{\theta_0}^{\theta_0 - \frac{\mathrm{FOV}}{2}} I_\kappa(\tau, \theta) \cos(\theta - \theta_0) \sin(\theta - \theta_0)\, d\theta$$
$$+ \pi \int_{\theta_0}^{\theta_0 + \frac{\mathrm{FOV}}{2}} I_\kappa(\tau, \theta) \cos(\theta - \theta_0) \sin(\theta - \theta_0)\, d\theta$$

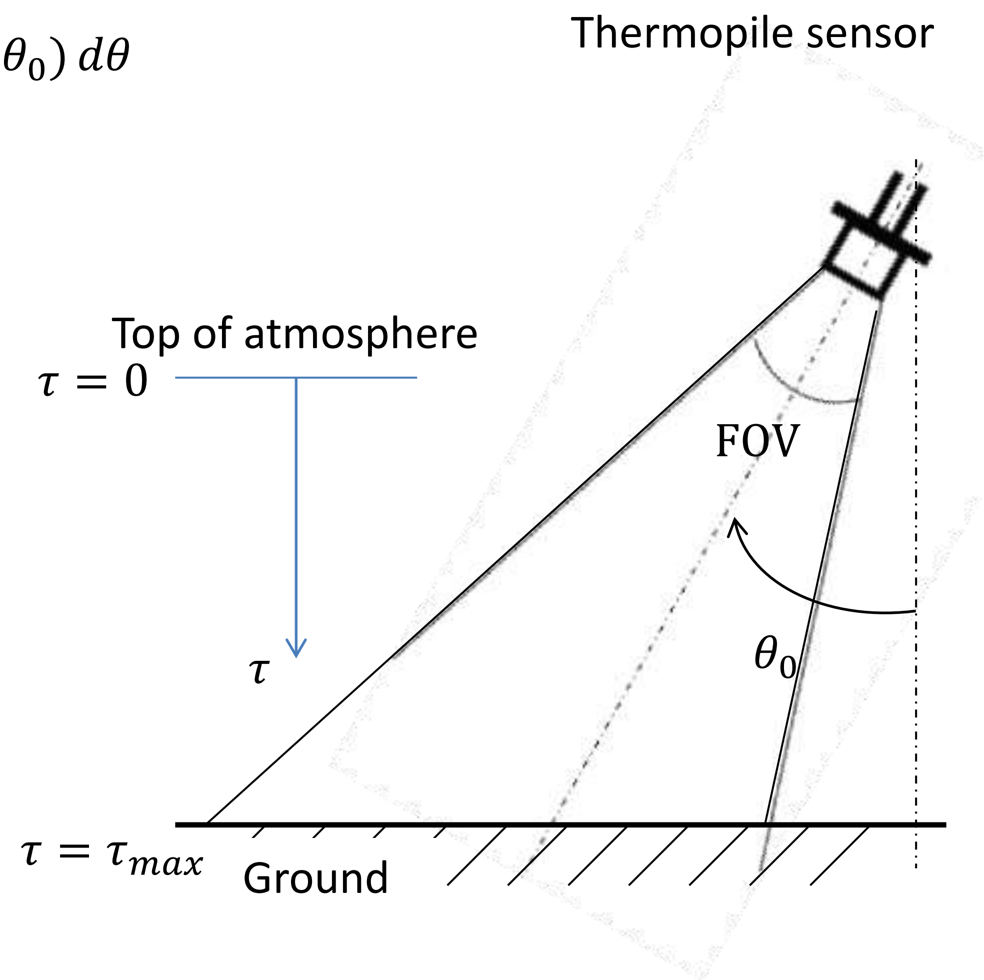
$F_\kappa(\tau)$: Radiant flux density of wavenumber

$I_\kappa(\tau, \theta)$: Upward radiance of wavenumber

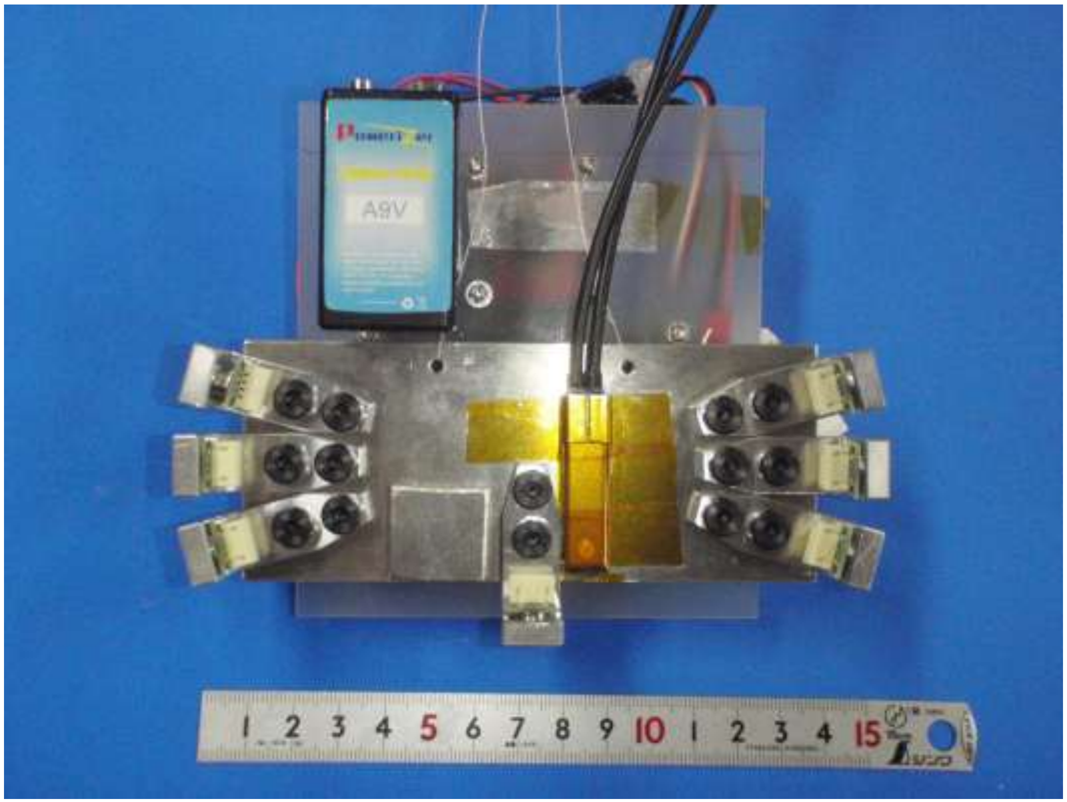
τ : Optical thickness FOV : Field of view

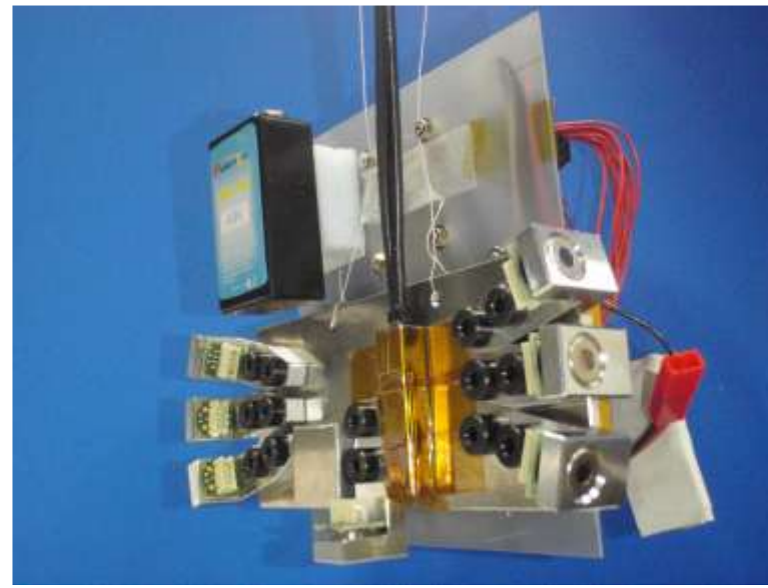
θ_0 : Attitude of sensor θ : Zenith angle

κ : Wave number

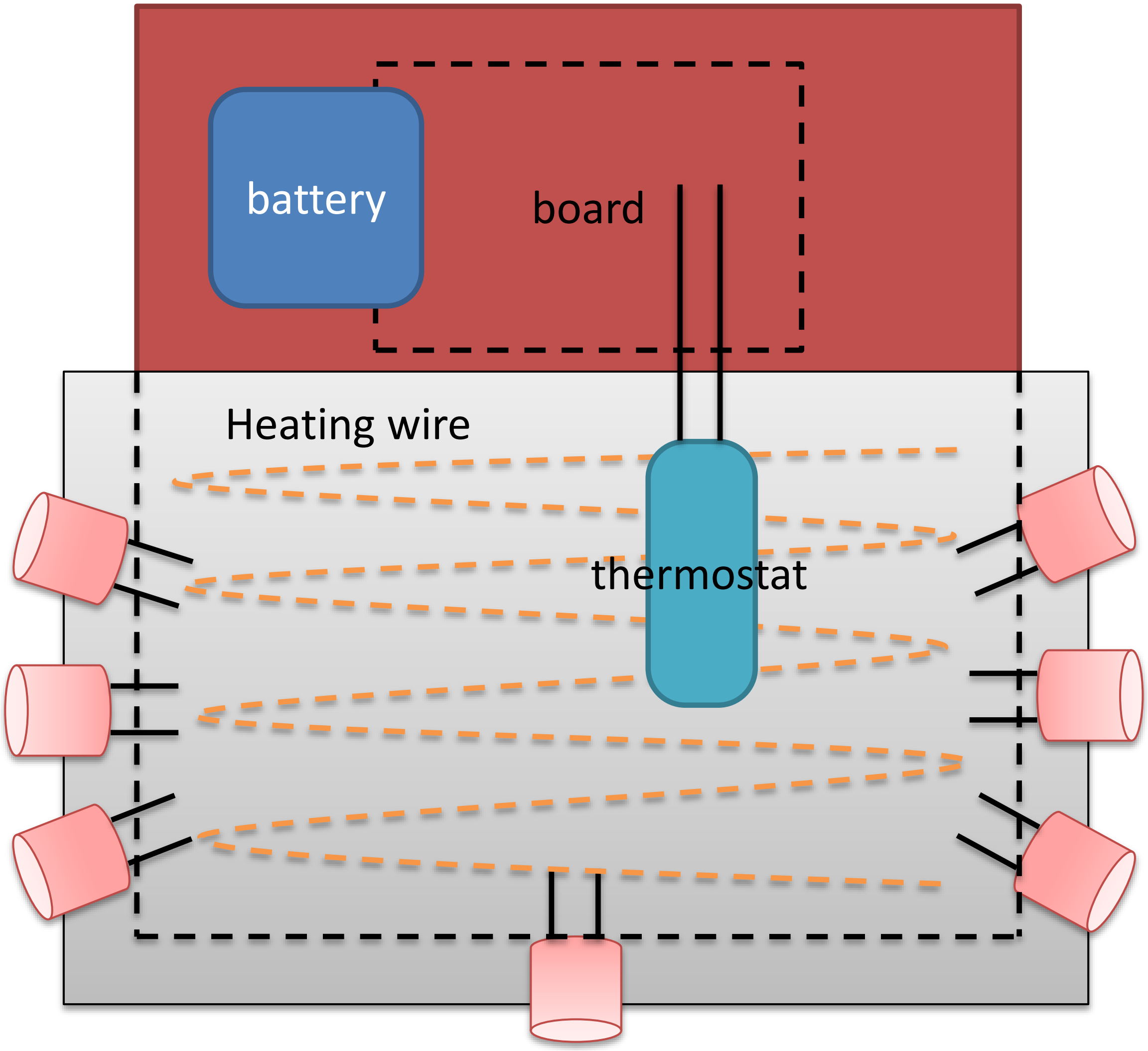


- Plane-parallel atmosphere
- Mid-Latitude summer atmosphere
- temperature of the ground : 305K





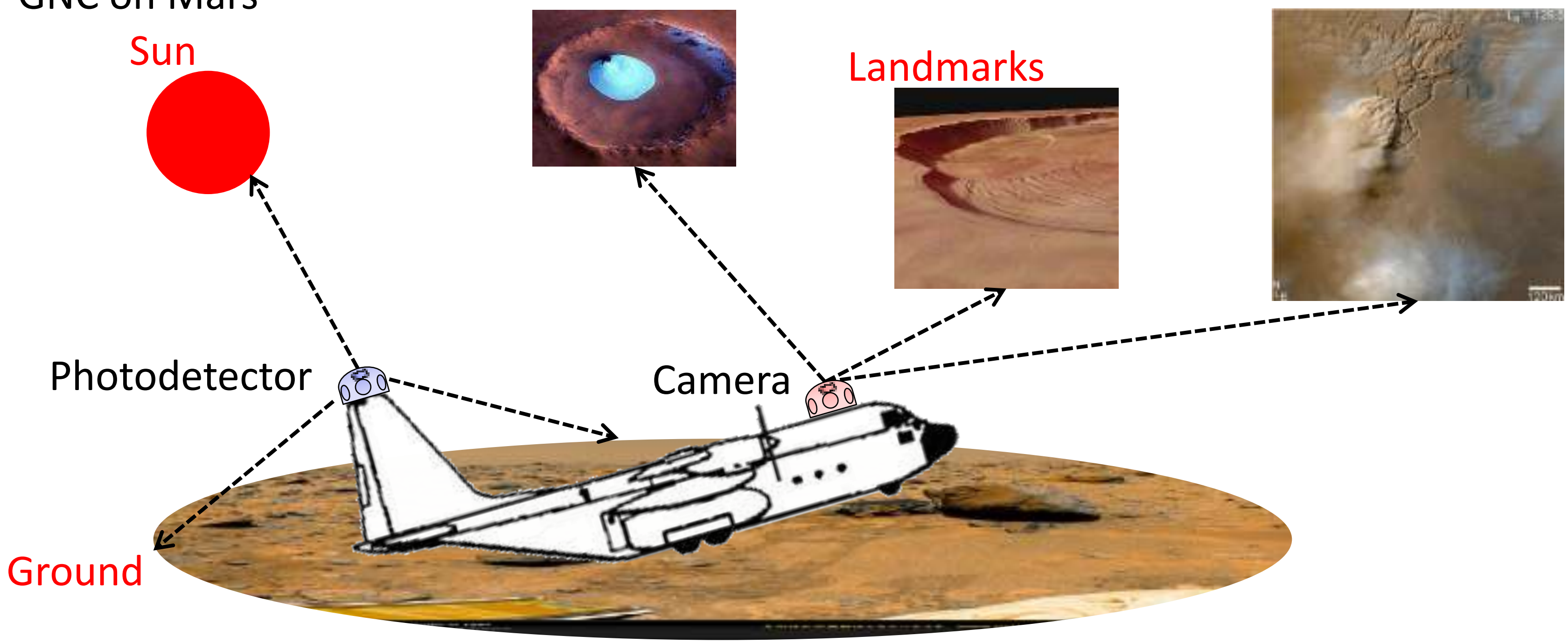
325 g



Thermopile sensor

GNC System of the Mars Airplane

- GNC on Mars

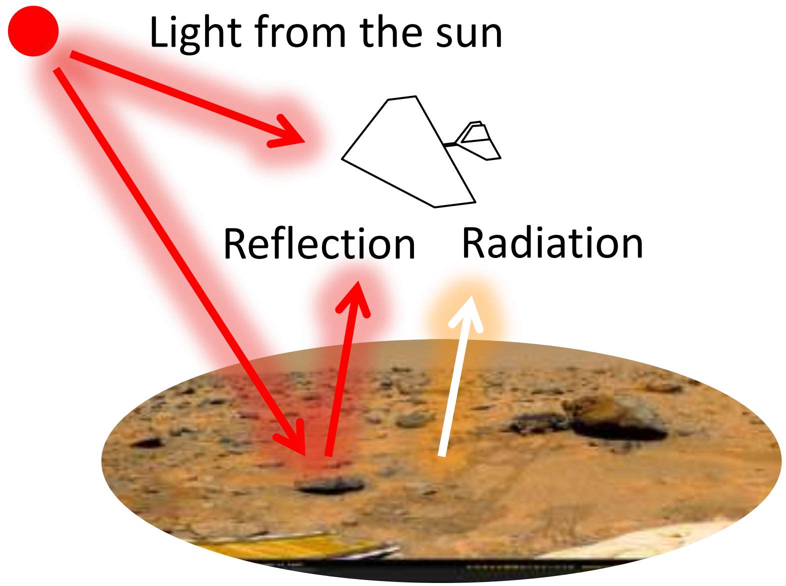


- Attitude sensing system (Stabilizing control)
  - ✓ Airplane attitude is detected from the direction to the sun and ground.
  - ✓ Weight : 150g

- Positioning system (Navigation and guidance)
  - ✓ The airplane position is estimated from the visual image and landmark of database.
  - ✓ Weight : 70g

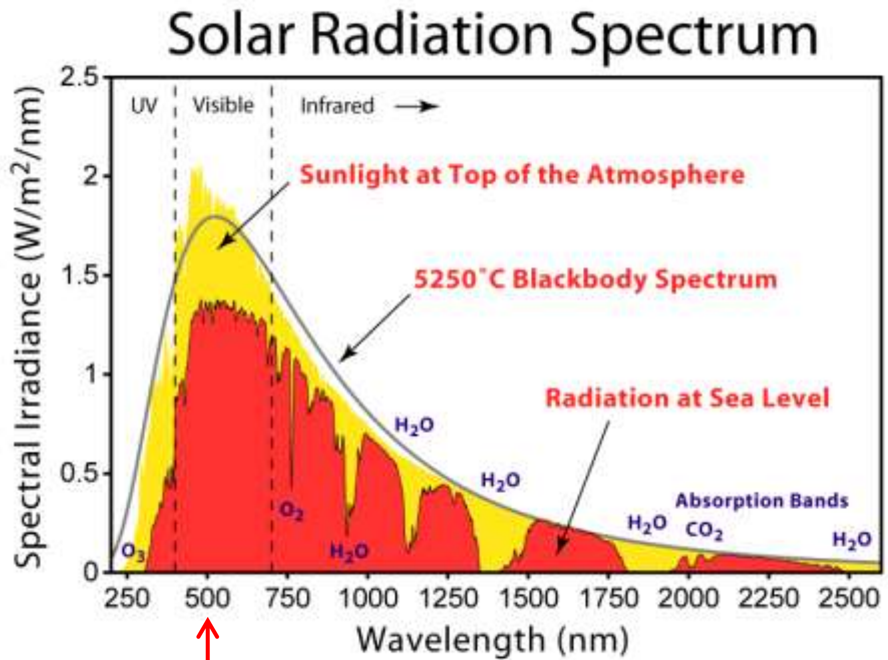
- Rate gyros, ADS and altitude sensor are used by stabilizing controller.
- Pressure sensor isn’t precise.
- Magnetic direction sensor isn’t available.

Sensor of Attitude Sensing System



※The albedo of Mars is approximately 0.15.

http://en.wikipedia.org/wiki/File:Solar_Spectrum.png



The peak wave length is 500 nm.

The wave length of the thermal radiation is 14000nm.

The temperature of Mars surface is 210K

λ_{max}=2.898 × 10^{-5}/210=14μm=14000nm

- ✓ Thermopile sensor can detect the thermal radiation from the ground.
  → The direction to the ground
- ✓ Photodiode can detect light from the sun.
  → The direction to the sun

The photodetectors with different response ranges are used.
The sun light and the thermal radiation are detected separately.

Basic experiment 1

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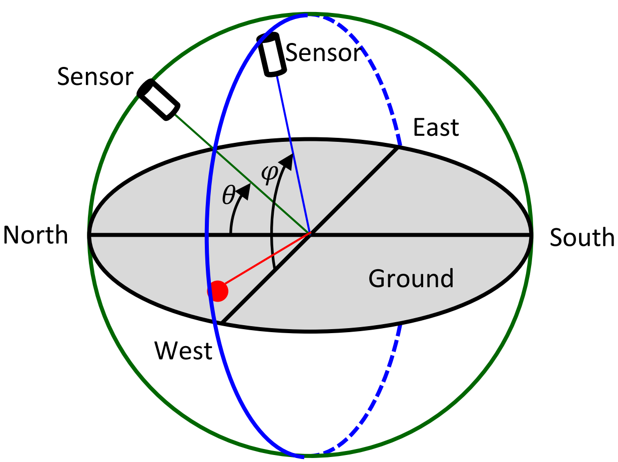
Used sensors

Product	Company	Response range	
Si photodiode S1226-18BK	Hamamatsu Photonics K.K.	320-1000 nm	Sun light
Thermopile sensor HTIA-E	HEIMANN Sensor	Cut on wave length is 5500 nm.	Thermal radiation

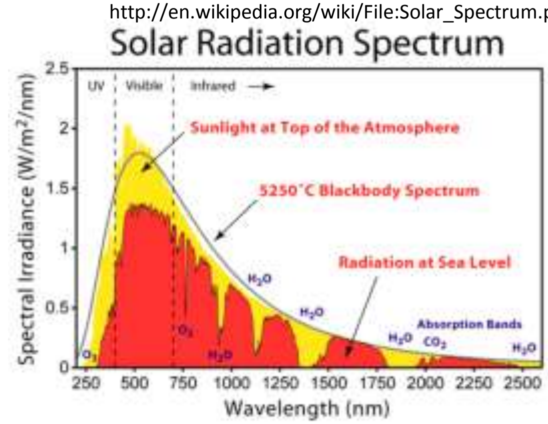
Experiments

- ✓ 1.2 m from the ground
- ✓ The direction of the sensor was changed in 10° increments and sensor outputs were recorded.
  ① W→top→E→bottom→W, ② N→top→S→bottom→N
- ✓ Daytime and night
- ✓ Daytime: sun light and thermal radiation Night : thermal radiation



The sun's altitude was approximately 10° , and its azimuth angle was approximately 270° .

http://en.wikipedia.org/wiki/File:Solar_Spectrum.png



Photodiode

Thermopile 5500nm ~

Peak of thermal radiation=14000nm

Experimental results

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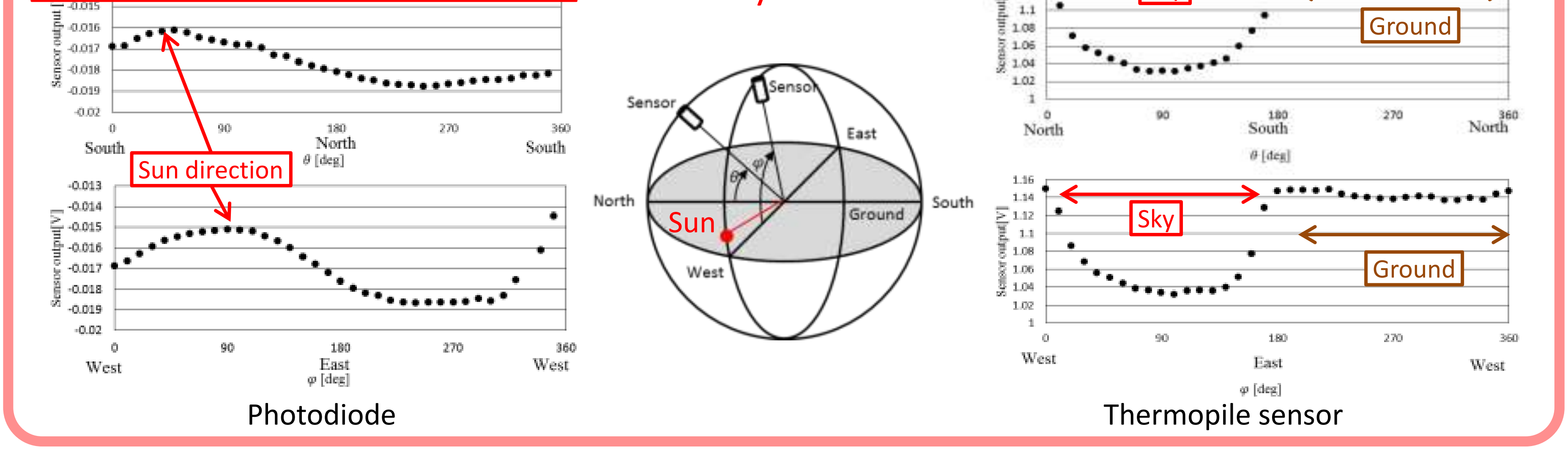
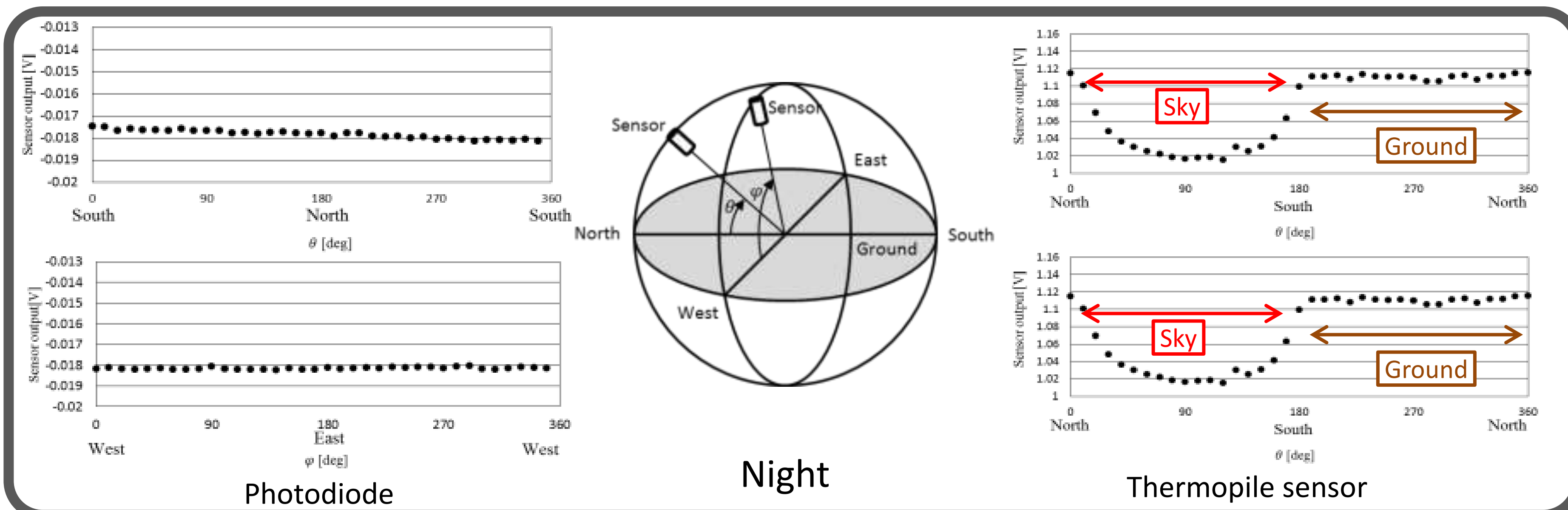
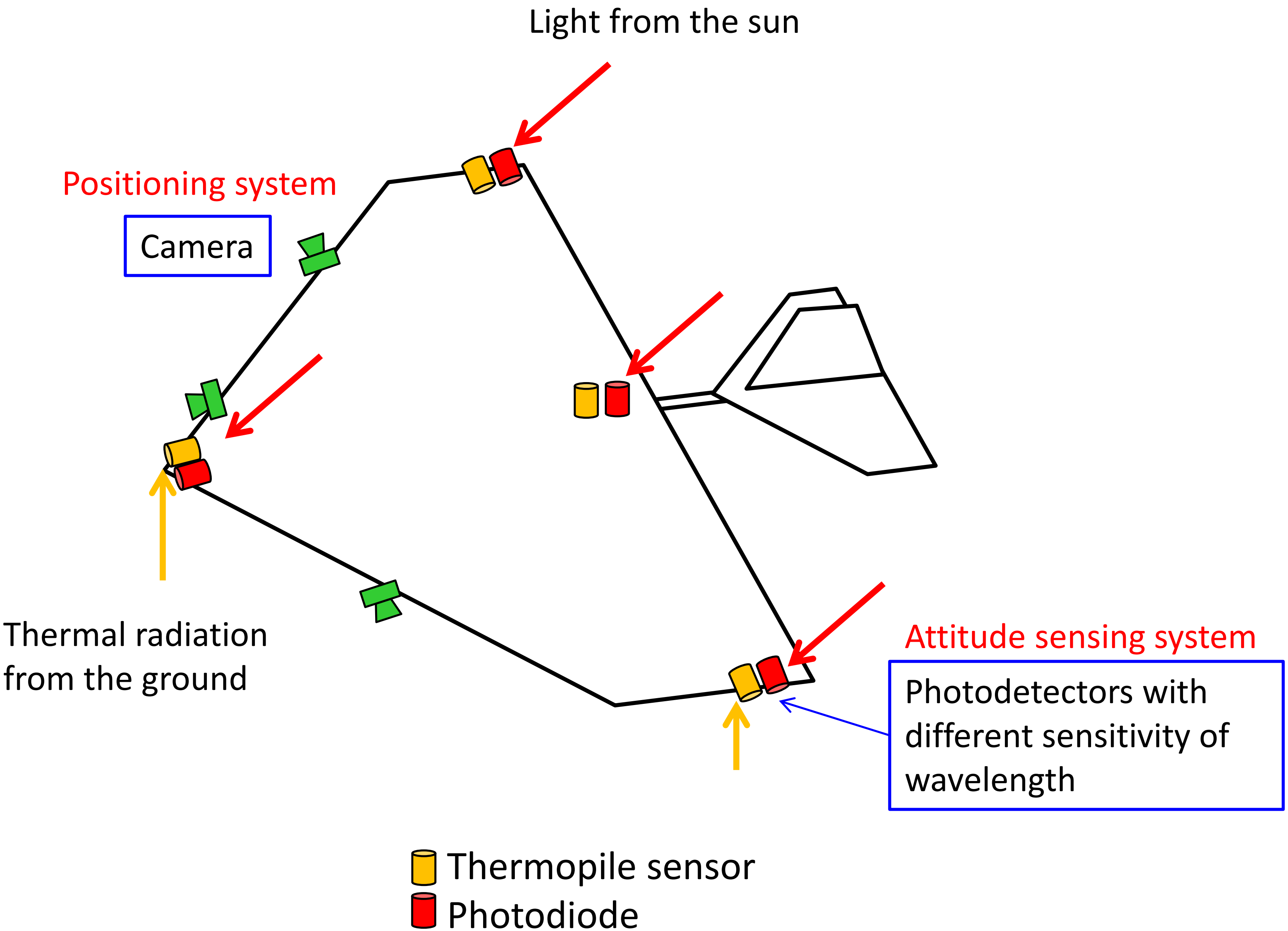
Output is affected by the scattering of the cloud and reflection from the ground






Light from the sun
Positioning system
Camera
Thermal radiation
from the ground
Attitude sensing system
Photodetectors with
different sensitivity of
wavelength
Thermopile sensor
Photodiode

Numerical example 1

Conditions

✓ Two sensors are assigned.

$$\alpha_i = [\cos\gamma_i \quad \sin\gamma_i]^T, \quad \gamma_1 = 0°, \quad \gamma_2 = 90°$$

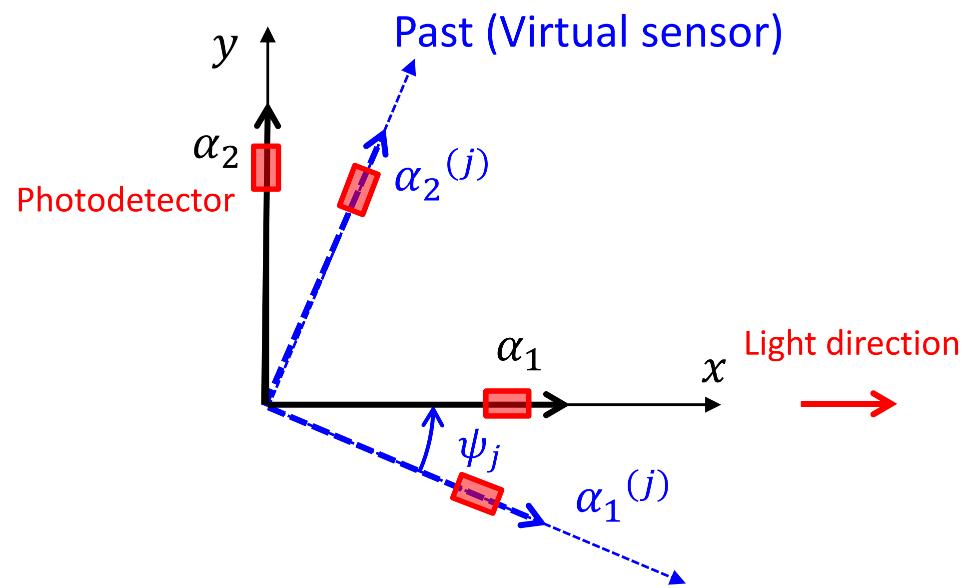
✓ The angle between the past axes and present axes is defined as:

$$\psi_j = \frac{10\pi}{180} \times j \ (\text{rad}), \qquad j = 0,1,\ldots,m$$ (m : The numbers of the used virtual sensor set)

✓ The estimated angle between the sensor direction and the light direction contains the measurement noise $w_i^{(j)}$.

$$\hat{\theta}_i^{(j)} = \gamma_i - \psi_j + w_i^{(j)}$$

Gaussian white noise with the mean of 0 and the standard deviation of 5 ° .



- Results

Estimation errors of the light direction were calculated with the variation of the number of the virtual sensor set. (Average of the 1000 times results)

Estimation error

Number of the virtual sensor set	0	1	2	3	4	5
Average of the estimation error (°)	3.97	2.73	2.10	1.62	1.38	1.21

✓ The method is precise when the number of the virtual sensor is large.

✓ Preciseness depends on the measurement error of the photodetector and the rate gyro.