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Airborne Radiometers to Measure Electromagnetic Radiation in the Earth’s Atmosphere: Mature and Emerging Technologies

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71.1 Introduction

71.1.1 Importance of Airborne Measurements of Electromagnetic Radiation in the Atmosphere

Electromagnetic (EM) radiation is important for many atmospheric and oceanic processes. The solar radiative energy reaching the top of atmosphere (TOA) is the major source of energy feeding weather and climate phenomena on Earth (Sellers, 1965). All biological life depends on the energy provided by solar radiation. Almost every motion of air in the atmosphere or of water in the oceans and numerous chemical processes within the atmosphere are powered by solar radiative energy. If the Sun would hypothetically be switched off, then plants would die within several weeks, and animals would lose food and would die shortly after plants have disappeared. Within about one year, no more higher life would be possible on Earth, and ice and snow would cover the continents. After roughly 15 years, the Earth would be a snowball.

Within the atmosphere and at the Earth’s surface, solar radiation is scattered (redistributed in direction) and absorbed (transformed into other forms of energy, mainly heat or chemical energy). As a result of absorption, the temperatures of the atmospheric components (gases, aerosol particles, clouds) and the Earth’s surface rise.
Earth’s terrestrial radiation is emitted corresponding to the atmospheric and Earth’s surface temperatures and respective emissivities. The radiation emitted by the Earth’s surface is partly reabsorbed and reemitted by the atmospheric components whereby the atmospheric reemission takes place at mostly lower temperatures compared to the Earth’s surface temperature, which causes the atmospheric greenhouse effect; a phenomenon of fundamental importance for life on Earth.

Globally and averaged over long time periods, the climate system is in energetic equilibrium (balanced net radiation, i.e., downward minus upward radiative energy at TOA equals zero) (see Trenberth and Fasullo, 2012). However, on a local and short time scale, there is no such energetic equilibrium. As a result, thermal meridional gradients develop, which are causing compensating dynamic processes, such as atmospheric air motions or oceanic water circulations in the vertical or horizontal directions, thermodynamic processes like evaporation or condensation initiating clouds and precipitation, and chemical reactions. Thus, all processes modifying solar and terrestrial radiation within the atmosphere and at the Earth’s surface are crucial for the energy budget of the global climate systems. For this purpose, airborne measurements of atmospheric EM radiation are of highest importance.

Additionally, airborne observations of EM radiation are fundamental to develop, test, and apply remote sensing techniques to retrieve atmospheric and Earth’s surface properties. In order to characterize the global climate system, satellites comprise an essential tool of observations. All satellite techniques are based on measuring radiative energy in different wavelength ranges. Therefore, the transfer of atmospheric radiative energy through the atmosphere and its interactions with the Earth’s surface needs to be measured by airborne techniques and modeled by radiative transfer simulations in order to interpret the radiation data received by the satellite instruments.

### 71.1.2 Quantitative Description of Electromagnetic Radiation

The following definitions of quantities to describe the atmospheric radiation field follow Wendisch and Yang (2012) and Wendisch et al. (2013).

#### 71.1.2.1 Angular Coordinates

In order to describe direction, spherical polar coordinates are applied. The zenith angle $\theta$ represents the planar angle from local vertical; it is measured in units of radian (rad) or degrees ($^\circ$). Overhead means $\theta = 0$ rad or $0^\circ$ (zenith direction), and the horizon corresponds to $\theta = \pi/2$ rad or $90^\circ$. $\theta = \pi$ rad or $180^\circ$ denotes the nadir direction. Of en instead of the zenith angle, the quantity $\mu = \cos \theta$ is used. The azimuth angle $\varphi$ measures the horizontal angle in units of rad or $^\circ$. $\varphi$ is counted counterclockwise from a reference point such that $0 < \varphi < 2\pi$ rad. Of en, the projection of the direction of the Sun with respect to the horizontal plane is defined as reference. For the direction of the Sun, the subscript “0” is applied.

Furthermore, the solid angle $\Omega$ is introduced, which is something like “square degrees” and carries the unit of “steradian” (sr). If an observer is situated at the center of a sphere of unit radius, then the total surface area of the sphere is $4\pi$ square radius units. Thus, the total solid angle is defined as $4\pi$ sr. The surface area of one-half of the sphere is $2\pi$ square radius units; the angle is $2\pi$ sr. It holds for the upper and lower hemispheres separately. For the assumed unit sphere with radius of 1 m, the solid angle of 1 sr is bordered by a surface of 1 m$^2$ on the unit sphere. The incremental solid angle $d\Omega$ is defined by:

$$
d\Omega := \sin \theta \, d\theta \, d\varphi = d\mu \, d\varphi = \frac{dA}{a^2},
$$

with $dA$ the enclosed area on the surface of the sphere with radius $a$. Integration over all directions yields $4\pi$ sr:

$$
\iiint_{\mathbb{S}^2} d\Omega = \int_0^{2\pi} \int_0^\pi \sin \theta \, d\theta \, d\varphi = 2\pi \, \pi = 4\pi \text{ sr}.
$$
71.1.2.2 Vertical Coordinate: Optical Depth

We define the vertical spectral optical depth $\tau(\lambda, z)$ at the given wavelength $\lambda$ as a transformed vertical coordinate:

$$\tau(\lambda, z) = \int_{z}^{z_{TOA}} b_{\text{ext}}(\lambda, z') dz'. \quad (71.3)$$

The volume extinction coefficient, $b_{\text{ext}}(\lambda, z)$, quantifies the extinction (sum of absorption and scattering) by atmospheric constituents (gases, aerosol particles, clouds), see Wendisch and Yang (2012). If $\tau$ is used to characterize the extinction properties of a layer, it is called the optical thickness instead of depth.

71.1.2.3 Radiant Energy Quantities

The radiant energy $E_{\text{rad}}$ in units of Joule (J) is the basic quantity to describe the EM radiation field in the atmosphere. It can be measured using first principles. From the differential radiant energy $E_{\text{rad}}$ per time increment $dt$, the radiant energy flux (or radiant power) $\phi$ in units of Watt (W) is derived:

$$\phi(\tau) = \frac{dE_{\text{rad}}}{dt} . \quad (71.4)$$

The radiant energy flux density $F$ (often wrongly quoted as flux) in units of W m$^{-2}$ is given by the incremental radiant flux $d\phi$ per incremental area element $dA$ (with no preferred orientation):

$$F(\tau) = \frac{d\phi}{dA} = \frac{dE_{\text{rad}}}{dt} dA . \quad (71.5)$$

$F$ is a measure of total radiant flux per unit area transported by EM radiation through or deposited on a planar surface A. Finally, the radiancy $I$ in units of W m$^{-2}$ sr$^{-1}$ is defined as:

$$I(\tau, \theta, \phi) = \frac{d\phi}{dA d\Omega} = \frac{d\phi}{\cos \theta dA d\Omega} = \frac{1}{\cos \theta} \frac{dF}{d\Omega} , \quad (71.6)$$

with $dA$, the differential area oriented perpendicularly to the direction of propagation of the EM radiation. The integration of Equation 71.6 over the hemisphere yields the relationship between irradiance and radiancy:

$$F(\tau) = \int_{2\pi} I(\tau, \theta, \phi) \cdot \cos \theta d\Omega . \quad (71.7)$$

In atmospheric applications, the reference unit area is usually defined as horizontal. Therefore, upward $F^\uparrow$ and downward $F^\downarrow$ irradiances are obtained from radiancy $I$ by applying Equations 71.7 and 71.1:

$$F^\uparrow(\tau) = \int_{\pi/2}^{2\pi} \int_{0}^{\pi} I(\tau, \theta, \phi) \cdot \cos \theta \sin \theta d\theta d\phi , \quad (71.8)$$

and

$$F^\downarrow(\tau) = \int_{\pi/2}^{2\pi} \int_{0}^{\pi} I(\tau, \theta, \phi) \cdot \cos \theta \sin \theta d\theta d\phi . \quad (71.9)$$
The dimensionless albedo $\alpha$ is the ratio of upward to downward irradiance:

$$\alpha(\tau) = \frac{F^+}{F^-}. \tag{71.10}$$

Actinic flux density $F_{\text{act}}$, sometimes called average intensity, is the integral of radiance over solid angle:

$$F_{\text{act}}(\tau) = \int_{0}^{2\pi} \int_{0}^{\pi} I(\tau, \theta, \phi) \cdot \sin \theta \, d\theta \, d\phi. \tag{71.11}$$

Like irradiance, actinic flux density has units of $W \, m^{-2}$. It represents the energy flux on a unit sphere, normalized by the cross section of the sphere, and therefore is related to flux divergence.

Irradiance ($F$), radiance ($I$), and actinic flux density ($F_{\text{act}}$) can be either spectral or band-integrated (broadband) quantities. For example, the spectral flux density $F_\lambda$ is the irradiance per unit wavelength interval indicated by the subscript $\lambda$ ($\lambda$ itself is the symbol for wavelength). As a result, the units of a spectral radiant energy quantity contain an additional term $nm^{-1}$. The band-integrated flux density $F(\lambda_1, \lambda_2)$ includes radiant energy contributions from wavelengths within an interval $(\lambda_1, \lambda_2)$. Here, we concentrate on spectral irradiance, radiance, and actinic flux density measurements from aircraft.

Irradiance and radiance may be divided into the contributions from scattering (diffuse) and direct transmission (direct) indicated by the subscripts “dif” and “dir,” respectively (Wendisch et al., 2013). The sum of both corresponds to the total irradiance or radiance with the subscript “tot.” For example, for the total irradiance, we obtain:

$$F_{\text{tot}} = F_{\text{dir}} + F_{\text{dif}}. \tag{71.12}$$

### 71.1.3 Solar and Terrestrial Spectra

The important spectral range for the application of airborne measurements of EM radiation in energy budget and remote sensing studies covers wavelengths between 0.3 and 100 $\mu$m. Generally, two subranges may be distinguished: The solar spectrum spans from 0.2 to 5 $\mu$m, and the terrestrial wavelength range covers wavelengths larger than 5 $\mu$m. The thermal infrared (IR) usually refers to wavelengths between 5 and 50 $\mu$m. Furthermore, the ultraviolet (UV, 10–370 nm wavelength) and microwave (MW, 0.3 mm–30 cm) spectral ranges are specified. The MW range corresponds to a frequency range of 1000–1 GHz. Frequency $\nu$ or wavenumber $\tilde{\nu}$ is sometimes used alternatively to wavelength $\lambda$. They are defined by:

$$\lambda = \frac{c}{\nu}. \tag{71.13}$$

With the speed of light in a vacuum, $c$ is given by:

$$c = 2.997925 \times 10^8 \, m \, s^{-1}. \tag{71.14}$$

The wavenumber is defined as:

$$\tilde{\nu} = \frac{1}{\lambda}. \tag{71.15}$$
71.2 Airborne Radiometers

In general, radiometers measure radiant energy $E_{rad}$ directly or quantities derived from $E_{rad}$, such as radiance or irradiance. These are called radiometric quantities in the following text. A comprehensive overview of airborne radiometers including issues and future challenges is given in Chapter 7 of Wendisch and Brenguier (2013).
71.2.1 Instruments for Broadband Solar Radiation Measurements (Broadband Radiometers)

Instruments that measure broadband solar irradiance are often called pyranometers or broadband radiometers. Mostly, the total irradiance is measured with pyranometers; however, there are also versions that may separate direct and diffuse irradiance (Valero et al., 1989; Pilewskie and Valero, 1993). Examples of pyranometers widely used in airborne applications are those manufactured by Kipp & Zonen (http://www.kippzonen.com/) and Eppley (the Eppley Laboratory, Inc., http://www.eppleylab.com/). Here, we describe the pyranometer manufactured by Kipp & Zonen and the total ultraviolet radiometer (TUVR) from Eppley. Furthermore, pyroelectric radiometers are in use.

The pyranometer is the most common type of instrument to measure broadband solar irradiances from an aircraft, for example, Wendisch and Keil (1999). It has a circular multijunction thermopile of the plated (copper–constantan, hot and cold junction) wire wound type (Coulson, 1975). The sensitivity of the thermopile is in the range of 10 μV/(W m⁻²); therefore, the signal needs electronic magnification in order to be logged. The temperature sensed by the detector is nearly linear with the flux density of incident radiation. The pyranometer manufactured by Kipp & Zonen is supplied with a pair of concentric hemispheres of Schott optical glass (see Figure 71.2). The inner dome is transparent to wavelengths in the range of 0.285–2.8 μm. The outer dome can be replaced by Schott glass hemispherical filters, which transmit within specified bandwidths. The outer dome is for mechanical protection of the inner dome. Furthermore, the air between the domes assures thermal insulation of the inner dome, which is then not heated by incoming solar radiation preventing emission due to solar heating. The response time of the pyranometer is in the range of 1 s. One of the advantages of the pyranometer is its mechanical robustness, which makes it well suited for airborne use. The largest problem of the pyranometer is the fact that temperature changes of the surrounding air also influence the housing and thus the temperature of the cold thermopile sensor. To mitigate this problem, thermocompensation is implemented in the pyranometer.

The Eppley TUVR measures broadband irradiance within the wavelength range from 0.295 to 0.385 μm (broadband UV) (see Wendisch et al., 1996; Wendisch and Keil, 1999). It utilizes a hermetically sealed selenium barrier-layer cell (photocell), which is protected by a quartz window. A specially designed Teflon diffuser reduces the radiant flux to acceptable levels and assures close adherence to the Lambert cosine law corresponding to Equation 71.7. An encapsulated narrow band-pass (interference) filter limits the spectral response of the photocell to the UV.

![Diagram of a pyranometer](image)

**FIGURE 71.2** The Kipp & Zonen pyranometer. (Reprinted with permission from Kipp & Zonen, CMP Series Pyranometer Instruction Manual, The Netherlands, 2010.)

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Pyroelectric solar radiometers use the temperature dependence of electric polarization in a pyroelectric crystal (Geist and Blevin, 1973; Valero et al., 1982; Hengstberger, 1989). If the temperature is changed, then the lattice spacing in the crystal also changes, which causes a change in the electric polarization of the crystal and consequently leads to a charging of the crystal surface generating a current that is used as a measure of the radiant energy. Thus, these sensors need a change in temperature to generate a signal. Therefore, they need to be equipped with a chopper, which, however, causes mechanical problems in aircraft installation. The major advantage of this type of radiometer is its fast response time (>100 Hz).

71.2.2 Spectroradiometers to Measure Spectral Solar Radiation

Spectral radiometers (also called spectroradiometers) measure radiometric quantities in narrow spectral bands as a function of wavelength. In this way, spectroradiometers allow more detailed insights into the nature of solar radiation as can be achieved by broadband radiometers.

71.2.2.1 Spectral Solar Irradiance and Radiance (Spectroradiometers)

Typically, solar spectroradiometers consist of four components (Shetter and Müller, 1999; Wendisch et al., 2001; Pilewskie et al., 2003): the optical inlet, fiber optics, spectrometer (including detector), and electronics with data acquisition.

The optical inlet (fore optic) comprises either a hemispheric light collector for irradiance or a telescope for radiance observations. The hemispheric light collector is a diffuse element that transmits or reflects radiant energy flux (power) proportional to the cosine of the angle of the incident light, corresponding to Equation 71.7. For the diffuse, usually scattering hemispheric light collector based on transmission, mostly, materials like ashed opal, Teflon, or Delrin are applied. Because scattering is wavelength dependent and mostly drops in the near IR, instead of transmitting hemispheric light collectors, an integrating sphere (using highly reflective Spectralon) can be applied (Crowther, 1997; Kindel et al., 2010).

Optical fibers transmit the light from the optical inlet (either hemispheric light collector or telescope) into the entrance slit of a spectrometer (monochromator including the detector). The wavelength dispersion within the spectrometer is often realized by gratings; sometimes also prisms or circular fiber wheels are applied. The detector elements include photovoltaic and photoconductive devices, photomultiplier tubes (PM Ts), photodiode, or charge-coupled device (CCD) arrays.

Solar spectroradiometers require careful calibration with regard to radiant power, as well as angular and spectral response. More details can be found in Wendisch and Brenguier (2013), Chapter 7.

71.2.2.2 Spectral Actinic Radiation

The major purpose of measuring spectral actinic flux density from aircraft is to determine the photolysis frequencies \( J \) by integrating (over wavelength) the product of spectral actinic flux density, absorption cross section of the molecular species to be photolyzed, and the quantum yield of the photoproduct. \( J \) in units of \( \text{s}^{-1} \) is given by:

\[
J(\lambda \to B) = \int_0^\infty \sigma_\lambda(\lambda, T, p) \cdot \phi_\lambda(\lambda, T, p) \cdot F'_{\text{act},\lambda} \, d\lambda, \quad (71.16)
\]

where

- \( \sigma_\lambda \) is the absorption cross section of the molecular species \( \lambda \) in units of \( \text{cm}^2 \)
- \( \phi_\lambda \) is the quantum yield of the photoproduct \( B \) (dimensionless)
- \( T \) is the air temperature
- \( p \) is the atmospheric pressure

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Note that in Equation 71.16, the quantity $F'$ (spectral photon actinic flux density) is introduced instead of the spectral actinic flux density, $F_{\text{act,}\lambda}$ is defined in Equation 71.11. $F_{\text{act,}\lambda}'$ must be converted to the corresponding spectral photon actinic flux density $F'$ applying the following relation:

$$F_{\text{act,}\lambda}' = \frac{\lambda}{h \cdot c} \times 10^{-13} F_{\text{act,}\lambda},$$

(71.17)

where

- $\lambda$ is given in units of nm
- $F_{\text{act,}\lambda}$ is given in units of W m$^{-2}$ nm$^{-1}$
- $F_{\text{act,}\lambda}'$ is given in units of cm$^{-2}$ nm$^{-1}$ s$^{-1}$

Two types of instruments are applied: actinic spectroradiometers and filter radiometers. Both types are described by Hofzumahaus (2006).

71.2.2.2.1 Actinic Spectroradiometers

The main setup of the spectroradiometers for actinic radiation measurements is similar to that of a spectroradiometer for irradiance measurements, except that the optical inlet has an isotropic angular response. Mainly two separate $2\pi$ optical inlets are used (one for the upper, the other for the lower hemisphere). There are two kinds of spectroradiometer for actinic radiation measurements: (a) scanning double monochromators (Shetter and Müller, 1999) and (b) single monochromators (Jäkel et al., 2005):

a. Scanning double monochromators select one wavelength band by a fixed grating position, while a second moving diffraction grating is scanning the fixed wavelength range with high spectral resolution. The spectral radiation is directed onto the detector (PMT) by moving the diffraction grating. Scanning double monochromators have the advantages of low stray light contribution and high sensitivity in the UV spectral range. However, the disadvantages in particular for airborne operation are that the wavelength scanning is time-consuming (in the order of several seconds up to minutes) and that the mechanical stability during aircraft operation is not guaranteed.

b. Therefore, in recent years, more and more single-monochromator spectroradiometers have been applied for airborne research to measure spectral actinic flux density. The multichannel spectrometer (MCS) has a photodiode array (PDA) or CCD detectors. The advantages of the single-monochromator approach are the fast time resolution of the spectra (one spectrum in less than 1 s) and the mechanical stability because of the fixed grating (no moving grating). The disadvantages are the relatively high stray light contribution (problems in the UV) and the lower sensitivity in the UV compared to scanning-monochromators with PMT detector.

71.2.2.2.2 Filter Radiometers for Actinic Radiation

Filter radiometers are designed such that the spectral response of the interference filters is close to the spectral shape of the product of the quantum yield $\phi_A$ of a specific species A and the absorption cross section $\sigma_B$. Widely used are filter radiometers for the photolysis of NO$_2$ and ozone (Junkermann, 1994; Volz-Tomas et al., 1996; Früh et al., 2000). The input optics (optical inlet) consists of a series of frosted hemispherical quartz domes that act as a diffuser with nearly isotropic response similar to the inlets of the actinic spectroradiometers. The photons are transferred by a pair of optical filters and detected by a photodiode. Ideally, the signal is directly proportional to $J$; in reality, however, the spectral response matches not exactly the spectral relative shape of the product $\phi_A \cdot \sigma_B$. Actually, the accuracy of filter radiometers is temperature-dependent and sensitive to changes of the solar zenith angle and the total ozone column.

71.2.2.3 Direct Solar Radiation

Airborne measurements of direct solar radiation are performed to derive the optical thickness of major atmospheric constituents, mostly aerosol particles (see Equation 71.3). The optical thickness of aerosol
particles comprises one of the important input parameters for radiative transfer simulations. In general, Sun photometers are applied for this type of measurements. The direct portion of solar irradiance is measured by restricting the field of view of the instrument to the solar disc, that is, to 0.5° angular width of the Sun using a cylindrical tube (Gershun tube). Interference filters are applied for wavelength separation and photodiodes for detection. An automated drive mechanism finds and tracks the Sun (Matsumoto et al., 1987; Russell et al., 1993). Sometimes handheld Sun photometers are being used; however, the data quality in this case is not always sufficient (Porter et al., 2007). For calibration, the so-called Langley method is employed where the extraterrestrial spectral irradiance is obtained by extrapolating irradiance measurements during rising or setting Sun to a zero air mass, that is, to TOA (Langley, 1903).

71.2.3 Leveling Issues

A typical airborne irradiance sensor (broadband or spectral) is fixed with the fuselage of the aircraft. Therefore, it moves with respect to the Earth-fixed coordinate systems due to attitude changes of the aircraft during flight. However, atmospheric applications of irradiance (i.e., flux density) strictly refer to a horizontal receiving plane. If the sensor receiving plane is out of horizontal level, serious deviations compared to measurements with a horizontal sensor plane may arise (Wendisch et al., 2001). To correct for misalignments, either a software postprocessing procedure or an active, mechanical leveling of the sensor heads during the flight is required.

71.2.3.1 Software Postprocessing Correction

The following technique holds for the direct portion of solar radiation only. Although this software, past-flight procedure is not optimal, it is widely used to correct for horizontal misalignment of irradiance sensors, because the active leveling technique is technically challenging and expensive. To correct the irradiance measurements for airplane attitude deviations from the horizon, the following equation is applied (Bannehr and Schwiesow, 1993):

\[
k = \frac{\sin h_0}{\cos h_0 \sin \phi \sin (\rho_0 - \psi) - \cos h_0 \sin \Theta \cos (\rho_0 - \psi) + \sin h_0 \cos \Theta \cos \phi},
\]

with the solar altitude angle \( h_0 = \pi - \theta_0 \); \( \theta_0 \) and \( \rho_0 \) are the solar zenith distance angle and the solar azimuth angles, respectively. The aircraft attitude angles (no index) are given as \( \psi \), the true heading of the aircraft with respect to the Earth-fixed coordinate system, \( \Theta \) being the aircraft pitch angle and \( \phi \) representing the aircraft roll angle. The formula does not consider for effects, in case the radiometer is not level with the aircraft-fixed horizontal plane.

71.2.3.2 Active Horizontal Stabilization of Sensor Heads

An active and fast horizontal stabilization technique has been developed by Wendisch et al. (2001) and Bucholtz et al. (2008). The technical challenge is to precisely measure the roll and pitch angles on an accelerated platform (aircraft) and to use these measurements to compensate for aircraft attitude changes in real time with desired final adjustment accuracy better than ±0.2°. To achieve these demands, an active horizontal stabilization involves two parts: (a) an accurate aircraft roll and pitch angle measurement unit and (b) an active horizontal mechanical adjustment system:

a. Usual inclination sensors measure the tilt of a coordinate system with respect to the Earth’s gravity vector. On accelerated platforms like an aircraft, this technique does not work because the sensor cannot distinguish between the Earth’s gravity and the acceleration vector of the moving platform. In this case, a so-called artificial horizon (AHZ) has to be applied. The AHZ consists of three linear servo-acceleration sensors, which deliver the aircraft velocity and position with respect to the inertial Earth-fixed coordinate system by integration of the lateral acceleration measurements and three fiber optical gyros, which measure angular rates also with respect to the inertial Earth-fixed frame. From these data, the aircraft attitude angles (i.e., roll and pitch) are derived. However, the measurements
of the acceleration sensors as well as of the fiber optical gyroscopes are affected by temporal drifts due to sensor errors and electronic noise. These drifts are compensated by using supporting information from a Global Positioning System (GPS). The combined AHZ and GPS data are processed, and the resulting accurate position and attitude data are stored on a first data acquisition system.

b. The processor unit transfers analog output signals of the roll and pitch angles to a personal computer. This drives (after amplification) two separate 2D tilt stages, which are connected with the optical inlet systems of the radiation sensors, that is, cardianally mounted. Each of the two separate 2D tilt stages consists of two servomotors (servos), which realize the horizontal adjustment of the optical inlets. Additionally, the measured attitude data from the combined AHZ-GPS system and the signals to drive the servos are stored on a second data acquisition system.

### 71.2.4 Techniques to Measure Terrestrial Radiation

#### 71.2.4.1 Broadband Thermal IR Irradiance

Terrestrial radiation can be measured with an IR thermometer or a pyrgeometer, for example, Eppley precision IR radiometer (PIR) or Kipp & Zonen pyrgeometers. The measurement principle for the pyrgeometer is based on the exchange of energy between hotter and cooler objects (Foot, 1986; Philipona et al., 1995). Assuming that the instrument is one of the objects, the instrument absorbs or emits energy if it is cooler or warmer than the object that is being sensed. A pyrgeometer is used to measure, hemispherically, the exchange of terrestrial radiation between a horizontal blackened surface (the detector) and the target viewed (i.e., the sky or the ground). The PIR has the same circular multijunction thermopile detector as the pyranometer, which is used as a method of transducing the terrestrial radiation flux into an electric response. The inner silicon dome is coated with a vacuum-deposited interference filter. Radiation at wavelengths from 0.3 to 0.4 μm to approximately 50 μm is transmitted into the sensor. The amount of radiation in the visible spectrum 0.3-4.0 μm is not significant; absorption and reemission effects are small and are compensated for in the calibration.

#### 71.2.4.2 Spectral Thermal IR Irradiance

These instruments are composed of three major parts: the optical system, a detector, and a signal processing system (electronics and data acquisition). Furthermore, calibration targets are required that are usually a hot and cold black-body target. An optical window transmits the radiation from the outside atmosphere into the instrument's optics and to the detector. Zinc selenide (ZnSe) is a common material that has a fairly flat spectral response and transmits radiation across a wide spectral range. The filter selects wavelengths; it consists of a narrow band-pass highly transmissive material. Some instruments have individual filters in front of a detector; others use a filter wheel to rotate a selection of filters in front of the detector. The light hits the detector (thermal or quantum). Thermal detectors convert the absorbed radiative energy into thermal energy. Most thermal detectors do not require cooling but have slow response times and poor detection capability. Quantum detectors usually are faster but often require cooling.

### 71.2.5 Microwave Radiometers

The MW spectral range of terrestrial EM radiation is characterized by a typically high transmissivity of the atmosphere (>80% below 40 GHz), which allows the retrieval of surface properties by downward looking MW radiometers from aircraft. Because wavelengths are large compared to atmospheric particles, scattering of EM radiation can be ignored for most applications in the MW spectral range. This simplifies the respective equations of the radiative transfers significantly.

Some examples of scanning airborne MW radiometers are given here. The conical scanning millimeter-wave imaging radiometer (CoSSIR) (Wang et al., 2007) has a fixed angle of incidence and a vertical
axis of rotation. The polarimetric scanning radiometer (PSR) (Stankov et al., 2008) allows both cross-track and conical scanning. Similarly, the microwave airborne radiometer scanning system (M ARSS) (McGrath and Hewison, 2001) is operated in an external pod.

The beam width should be limited to a few degrees. Therefore, the antenna size becomes relatively large (up to 0.5 m for <10 GHz), which often proves to be a limiting factor for the operation on a smaller aircraft. Flight altitude and antenna beam width determine the spatial resolution of the observations of the Earth’s surface. For example, for a flight altitude of 6 km and a beam width of 8°, the spatial resolution at the surface of the Earth is about 2 km.

MW radiometers need to significantly amplify the signal received at the antenna. Low-noise amplifiers (LNAs) are available for frequencies up to about 100 GHz.

71.3 Examples of Applications

71.3.1 Airborne Surface Albedo Measurements

The albedo $\alpha$ in general is defined as the ratio of upward and downward irradiance (see Equation 71.10) at any altitude in the atmosphere. It is a nonlinear function of the vertical coordinate $r$; it is wavelength-dependent and a function of the underlying atmospheric and ground properties. The spectral surface albedo at the ground is the spectral albedo at the Earth’s surface, which constitutes a major input function for radiative transfer simulations. Surface albedo cannot be measured representatively at the ground. Also, it cannot be directly derived from aircraft measurements of $\alpha$, because scattering and absorption processes in the atmospheric layer between the aircraft and the Earth’s surface also influence the signal measured at the aircraft altitude. To correct for this so-called atmospheric masking, a nonlinear retrieval procedure has been developed by Wendisch et al. (2004) and applied over different terrains. Figure 71.3 shows some exemplary results of surface albedo measurements over water, desert, ice, and vegetation corrected for atmospheric masking by using the method of Wendisch et al. (2004). Different spectral features become obvious from Figure 71.3. Generally, low values of surface albedo are observed over water; ice surfaces exhibit high surface albedo values. The typical vegetation step around 750 nm wavelengths dominates the surface albedo spectra over planted surfaces.

![Figure 71.3: Different surface albedo spectra for various surface conditions. (Adapted from Wendisch, M. and Yang, P.: Theory of Atmospheric Radiative Transfer—A Comprehensive Introduction. Weinheim, Germany. 2012. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reprinted with permission; Courtesy of E. Bierwirth.)](image-url)
71.3.2 Impact of Crystal Shape in Cirrus on Thermal IR Irradiance

Examples of airborne pyrgeometer measurements along straight, horizontal flight paths are plotted in Figure 71.4 as open squares with horizontal lines indicating the standard deviation during the flight leg. The curve notation indicating the assumed crystal shape is given in Table 71.1.

Figure 71.4a and c show that the cirrus decreases the upward broadband thermal IR irradiance above its base height, compared to the cloudless atmosphere (greenhouse effect of cirrus). The strength...
of this decrease depends on the altitude of the cirrus (i.e., its temperature) and its optical thickness. The height (temperature) dependence is because the cirrus emits less thermal IR radiation in colder environment (higher altitude). Below the cloud, there are no effects of the assumed crystal habit on the upward thermal IR irradiances. Above the cloud base, there are significant shape-related effects on upward irradiance in the cirrus case of small optical thickness. An outgoing longwave radiation (OLR) bias is seen in the difference in calculated and measured upward terrestrial irradiance in Figures 71.4a. Most probably this OLR bias is caused by the neglect of horizontal cirrus inhomogeneities. The effect is most significant for semitransparent cirrus (low optical thickness), which is located in the cold upper troposphere. For the low (warm), optically thick cirrus observed on July 23, 2002, there is no such OLR bias.

Figure 71.4b and d demonstrate that the cirrus generally increases the downward broadband thermal IR irradiance below its top height, compared to the cloudless atmosphere. This is because (due to its emission) the cirrus constitutes an additional source of thermal IR radiation, which adds to the cloud-free atmosphere emission. The cirrus has almost no impact on the downward broadband thermal IR irradiance reaching the surface; the emission source (cirrus) is too far away from the surface. The impact of crystal shape on atmospheric radiant energy budget simulations is concluded to be important for the high, optically thin cirrus only.

References


