GONIOMETERS

Goniometry is the science of measuring angles. The instruments used to perform this task are called goniometers. They provide an accurate reference system for angular-dependent measurements in a wide field of applications. In their most elementary form, goniometers have existed for many hundreds of years. Recently, they have assumed an extra role as powerful high-precision and computer-controlled systems capable of positioning an infinite variety of emitters, detectors, and targets in any combination and permutation of geometrical configurations. Their field of application has widened as the need for more precise information from an ever-increasing number of high-precision emitters and detectors has grown and, above all, because the large amount of information generated in the process can now be rapidly and automatically acquired, stored, processed, and analyzed. From a simple hand-held device for the measurement of angles, the goniometer has also become the heart of many of the most sophisticated and intelligent analytical tools available to mankind. Goniometers today find numerous new applications in research and industry, from the traditional fields of medicine and materials analyses to the more recent fields of remote sensing and space applications. At the same time, they remain the basic element in a large number of precise mechanical positioning systems.

HISTORICAL BACKGROUND

Considering the fact that traditional navigational instruments such as astrolabes, quadrants, octants, and sextants are all examples of goniometers, we can see that the goniometer is one of the oldest scientific instruments known to mankind. The original astrolabe was a hand-held astronomical instrument used by ancient Greeks and others to measure the height above the horizon of celestial bodies. Another version of this was the marine astrolabe, a simple wooden or brass graduated disk used for measuring the angle of the sun or a star from the horizon in order to obtain one's position in terms of degrees of latitude above the equator. The quadrant, a graduated quarter circle with a suspended plumb bob, was another example of a goniometer used to assist in determining latitude by alignment with the sun or a star, typically the Pole Star.

An improved version of the quadrant was Hadley's octant in 1731, which incorporated the use of a mirror to bring the object viewed into coincidence with another. From the inclination of the mirror, a measurement of the angle between the two objects could be obtained. The octant was in time superseded by an improved goniometric instrument, the sextant, which along with the compass has remained the basis of marine navigation until recent times.

In other sciences, such as mineralogy, improvements were also being made to the goniometer. One of the first references to be found on the subject is that of Carangeot's contact goniometer (1), which was used by mineralogists to compare large crystals of different development by measuring the interfacial angles. It consisted of two flat steel bars pivoted together like a pair of scissors. The angle between the bars was read from a graduated semicircle with a precision of about a half degree. The contact goniometer was mainly used for large dull crystals that did not yield reflections. For the study of the mor-

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phology of smaller crystals, Wollaston's reflecting goniometer in 1809 was a considerable improvement on the contact goniometer, enabling more precise measurements to be taken. This was a simple, cheap, and portable instrument that affected the interpretation of the structure of crystals and had a great influence on the science of mineralogy.

This type of goniometer was followed by the two-circle or theodolite goniometer in 1876, which was a combination of the vertical- and horizontal-circle types. This eliminated the need to mount and readjust the crystal for each series of measurements.

Another important event in the history of goniometers and their role in crystallography took place in 1912 when von Laue showed that diffraction of X rays occurred when they were passed through a suitably oriented crystal. At the same time, he effectively established that X rays have very short wavelengths and that crystals have their atoms arranged in a regular structure. This was followed shortly by the experiments of Bragg in 1912, which gave further important insights into the nature of X rays. These pioneering experiments led to the development of the X-ray goniometer, which used X rays instead of visible light as the source and an ionization chamber instead of a telescope as the detector and which was designed to measure angles between the atomic planes within crystals.

Reflectivity measurements of different kinds of surfaces have been made for various purposes in the field of astronomy from the turn of the nineteenth century using goniometric systems. The earlier studies mainly concerned the overall photometric behavior of materials. These measurements are still important today because they were made usually in a more systematic way than more recent ones.

As a result of satellite navigation systems, the role of one type of goniometer—the sextant—has lost some importance, although it still remains an essential marine navigational instrument. Thanks to earth-observation satellites, a new type of goniometer has been developed for remote sensing applications during the last few decades because of the need for a more complete characterization on the angular reflectance characteristics of natural and man-made surfaces. This is partially achieved today with the help of custom-built and generally large-scale goniometers capable of observing relatively large target areas, covering one to several tens of square meters.

APPLICATION FIELDS

Today, goniometers are found in a large number of traditional and new application fields. In navigation they are intensively used for direction finding. The direction of a radio transmitter can be rapidly and precisely obtained by measuring the angle of maximum intensity of the transmitted signal with respect to a fixed point. This technique is used in the electronic goniometer or direction-finding receiver, which can be mounted in a fixed or mobile station and is used to measure the direction of propagation of electromagnetic waves. The electronic goniometer can take a variety of forms but is a basic element in most direction-finding antenna array systems in navigation.

In surveying, the theodolite, a very accurate goniometric instrument, allows the precise measurement of angles, both vertically and horizontally. It is usually mounted on an accurately graduated horizontal circle and consists of a telescope and an alidade with a graduated vertical circle. The optical theodolite uses horizontal and vertical circles graduated on glass. Another version of the instrument used in terrestrial photogrammetry is the photo-theodolite consisting of a combined theodolite and camera. The electronic tachymeter or tacheometer is another example of a goniometer mainly used in large-scale topographic surveys and designed for the rapid determination from a single observation of horizontal angles and zenith distances. Trigonometric heighting, electronic distance measurement, traversing, contouring, and detail surveys are just some of the applications of electronic tacheometry.

Goniometers have also many medical uses. In anthropology and chirurgy, goniometric devices are used to measure the various angles of the skull and other bones. These are often in the form of hand-held goniometers used to measure the range of motion and the angle of joints in the human body (e.g., to monitor knee joint angle or movements of fingers about knuckle joints). Measurements of these angles also provide important information for analysis of changes in posture and movement of the human body during space flight. In certain eye diseases, it is necessary to measure the anterior chamber angle formed by the iris with respect to the rear face of the cornea. This is performed by means of another goniometric device—the gonioscope.

In industry, goniometers have innumerable applications. To analyze the light distributions of different compact fluorescent lamps, for example, goniophotometers with automated control and data acquisition systems are used. These measure the angular distribution of light emanating from various lighting fixtures. Goniometers have been used in projection photometry where the angular characteristics of search lights and projectors (e.g., cone angles) are measured and analyzed and for the photometric calibration of light sources including the infrared region (2). Goniophotometric measurements are used to quantify light interactions with coated surfaces (e.g., to study the reflectance of metallic finishes in the automobile industry and to improve colorant formulation and shading). In the paper industry, goniometers have been used to provide the necessary scattering characteristics of cellulose fibers and pigments used in papers. Goniometers are also used in the test and calibration of angular dividing equipment. In general, they have helped to develop a better physical understanding of the complex problem of color and the appearance of coatings in industry.

In military use, goniometric compasses have been extensively employed for topographic measurements and for aiming artillery fire.

In science, goniometer systems play a vital role in a large number of disciplines. Three representative examples (advanced material science, astronomy, and remote sensing) are presented in some detail here.

ADVANCED MATERIAL SCIENCE

X-ray diffraction is probably the best known and most appropriate method of determining the crystalline structure of solid materials. It is used for a variety of structures, and even though it is particularly simple in the case of well-crystallized inorganic solids as a "fingerprinting" method for phase analysis, it can also be applied to a wide variety of more complicated organic molecules and to nanocrystalline or amorphous

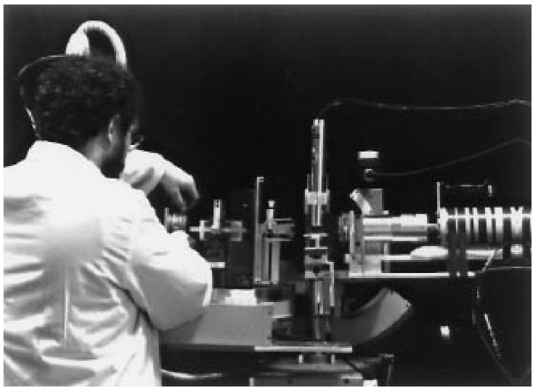

Figure 1. An X-ray diffraction goniometer at Joint Research Centre, Ispra, Italy.

materials. In addition to the crystalline structure, X-ray diffraction can reveal information on stress, crystallite size distribution, preferred orientation, and texture.

Highly accurate goniometers are an essential part of X-ray diffraction systems (Fig. 1). The most common experimental configuration for polycrystalline materials consists of an X ray beam passing precisely over the axis of a perfectly concentric dual goniometer system, each goniometer having a precision of better than 0.001°, and in many cases, especially in research, some orders of magnitude better than this. The sample is then moved by an angle θ, and the detector by precisely 2θ. The Bragg condition for diffraction peaks to appear is

$$n\lambda = 2d \sin\theta$$

where n is an integer and d is an interplanar spacing present in the material. The intensity of the peaks depends on several factors and in some cases may be zero. The diffracted intensity plotted against 2θ in a *diffractogram* may then be analyzed either by reference to a database of fingerprint spectra or, in the case of new crystalline structures, by comparison to simulated spectra generated by appropriate computer programs using postulated structures. Of course, there are many other experimental arrangements (e.g., for single-crystal analysis or for stress determination) and methods of analyzing or treating diffraction spectra to extract the appropriate information.

At the Institute for Advanced Materials of the Joint Research Centre, Ispra, Italy, a special system has been constructed for the structural analysis of very thin films. Instead of both goniometers being scanned during a measurement, the incident beam impinges on the sample at a very low incident angle, typically from 0.2° to 1.0°. Only the detector (2θ) goniometer is scanned, and special optics ensure that a good angular resolution is maintained. This glancing angle geometry renders the diffraction measurement much more sensitive to the surface of the specimen under examination. Additionally, in order to optimize the signal-to-noise ratio, the distances from x ray source to sample and from sample to detector have been minimized, a high-precision variable slit system to define the incident beam dimensions is used, and a solid-state detector is employed to isolate the desired wavelength without the use of filters or a monochromator and to reduce the background count rate to a minimum. The system may also be used for x ray reflectivity measurements, which can provide highly accurate information about the thickness of thin films, as well as their density and interfacial roughness, by monitoring the specularly reflected X ray intensity as a function of angle of incidence (3).

Many versions of horizontal and vertical goniometers with microprocessor control units have been designed for X ray powder diffraction measurements, phase analysis, and stress and texture analysis. Stand-alone operation of the diffractometers is often possible, thereby reducing the risk of human error. Automated sample spinning is also implemented in some systems to compensate for surface effects and nonrandom crystal orientations.

ASTRONOMY

Various kinds of goniometers have been devised by astronomers mainly for the measurement of the angular reflectance of planetary surfaces. Reflectance measurements of natural surfaces were not started in earnest until the 1960s with the advent of space exploration. Toward the end of the 19th century, however, Kononoviz (4) had started to measure the *surface reflectance* (i.e., the ratio of the light scattered from a surface to the light incident on the surface) of various surfaces on the Earth using a large range of angles. Ångstrom (5) also made a series of measurements on natural surfaces with various angles of incidence and reflectance. The measured surface materials were mainly different surface types of water, sand, and vegetation.

Albedo measurements were also accomplished later by Kulebakin (6) and Kimball and Hand (7). The main purpose of the studies was to establish a measure (usually the reflectivity) for different kinds of scattering media. Kulebakin made systematic measurements of natural and artificial surfaces using a rudimental form of goniometer. His study focused on the simulation of the overall roughness of natural surfaces such as snow, sand, and vegetation, and some man-made surfaces, which were made from cardboard. Kulebakin's work was the first attempt to accomplish the parametrization of the scattering phenomena of surface materials from laboratory measurements. In addition, Kimball and Hand demonstrated for the first time the importance of surface roughness on the backscattering of light properties. They also included in their study natural surfaces such as water and snow. Measurements were made with the help of an airplane and the sun was used as the illumination source.

The most important studies of light scattering by surface materials were accomplished by Oetking (8) and Hapke and van Horn (9), who made extensive goniometric measurements of snow, rocks, and different kinds of powders. These works were the basis of the theoretical explanation of the scattering properties of the surface of the Moon. The study of Hapke and van Horn concentrated mainly on the Moon's photometric properties, whereas Oetking made systematic photometry of various kinds of powders with a selection of particle sizes. Oetking focused on the comparison of laboratory measurements and the reflectance of different parts of the Moon. His goniometer was capable of measuring phase angles of less than 1°, but operated in the principal plane only. The device was table mounted, with a constantly positioned 75 W Zenon arc lamp as light source and the detector, a photomultiplier, at the end of a rod. At the other end was a corotating sample tray with a mirror above it inclined at 45°. Because the detector was placed under another semitransparent mirror at 45°, it was also possible to measure samples at zero phase angle. Oetking measured extensively phase curves of different types of rocks, aluminum oxide, magnesium oxide, magnesium carbonate, small spheres, and even granulated sugar. The particle sizes were accurately measured, making this set of measurements an excellent example of a controlled and repeatable experiment.

The measurements of snow surfaces by Knowles Middleton and Mungall (10) have been important in explaining the photometric results of the bright and icy objects of the solar system. The aim of this study was to investigate the specular reflection of different kinds of snow surfaces. The smallest detectable angle was 5°. Thus the opposition spike could not be detected. They concluded that below an angle of incidence of 45° diffuse reflection dominates for most of the snow surface. With angles greater than that, the specular reflection is more profound.

Instruments for these types of goniometric measurements were usually made according to the purpose of the study so there was no standard way to build the instrumentation. This is still the case, as we shall see later in the section dealing with the remote sensing applications of goniometers. Sometimes, the instruments were portable [e.g., Knowles Middleton and Mungall, (10)], whereas others were fixed in the laboratory. The original aim of the studies may have been rather restricted, and so the instruments are far from multipurpose. Also for most instruments, the financing seems to have been rather low, and therefore they were generally suited only for restricted purposes in a limited time.

Goniometric measurements by van Diggelen (11) were of great importance in understanding the reflection of the particulate surface of the Moon. The aim of the measurements was to compare the reflectivity of the Moon to terrestrial volcanic ash samples.

Egan (12) made extensive goniometric measurements of porous materials. The main purpose of his study was to understand the polarimetric properties of materials, particularly from Mars. The importance of his work is in establishing the albedo-polarization rule of the dark particulate surfaces, which is a useful tool in determining the radiometric sizes of atmosphereless objects. The method is based on the dependence of a negative polarization of the surface porosity of the object. This relationship is one of the major methods to determine the albedos of asteroids. The goniometer designed by Egan used two fixed photometers at viewing angles of 0° and 60°. The collimated light source could be rotated. The phase angles were limited to a range of 40° to 130°. Egan used tilted mirrors to produce polarization of light.

Other researchers have measured the polarization of a variety of targets in the principal plane using a goniometer with 1.2 m arm and a rotating Glan-prism to have an effective way to measure the degree of polarization (13). These basic studies of planetary materials have been successfully continued using a goniometer designed at Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) of Berlin, Germany (14), which was used mainly to support space missions such as NASA's *Mars Pathfinder*.

Another interesting device used to measure the backscattering range of small phase angles is a type of microscopic goniometer (15). The measurements were used as a reference during the introduction of the coherent backscattering mechanism. The goniometer applied can reach all possible angles including the backscattering direction. This device has been deployed for the comparison of the scattering of bright materials with the observations of bright (icy) solar system moons. Recently, Piironen et al. (16) have published a series of goniometric measurements of snow at very small phase angles. The results show that the degree of backscattering depends on the type and amount of impurities in the snow.

Small particle goniometers have been widely used for basic research in the Free University of Amsterdam (17). Their instrument is based in the flowing particle stream and can measure the full Muller matrix (18). The Muller matrix explains the conditions of light scattering including polarization and directional information and is an extension of the Stokes four-element vector to a 4×4 matrix. Stokes parameters are used to describe the polarization of electromagnetic radiation. The activity has been recently concentrated on the study of micron- and submicron-sized particles of silt and algae in water. Another ingenious goniometer for small particle scattering measurements is designed by Sasse in DLR, Stuttgart, Germany (Fig. 2). The device uses fiber optics to measure the full half circle of scattering angles at the same time of a single particle inside an electrostatic levitator (19). This instrument has been used for scattering measurements of fluidized bed particles for improved solar power plants and meteoritic particles in the size range from a few tens to a few hundreds of micrometers.

REMOTE SENSING

Most of the earth's surfaces reflect varying amounts of electromagnetic radiation in different directions. Unless a surface is reflecting isotropically, any change of the viewing or illumination directions has an impact on the spectral reflectance signature in remote sensing imagery. Varying illumination angles are caused by changes in the latitudinal coordinates in a global remote sensing data set or by seasonal and diurnal effects in a multitemporal approach. Viewing angle geometry is influenced by topographical effects, by the extent of the sensor's field-of-view, or by actively changing the view direction in pointable sensors. To make correct measurements of the

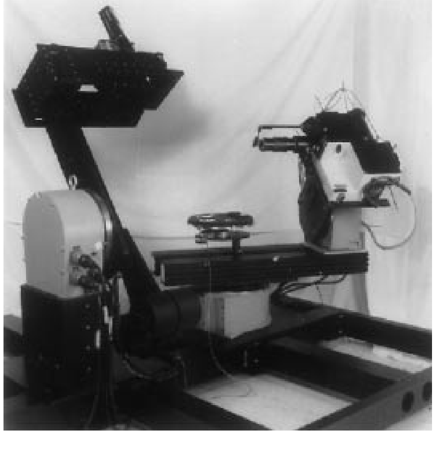

Figure 2. A small particle goniometer at DLR, Stuttgart, Germany.

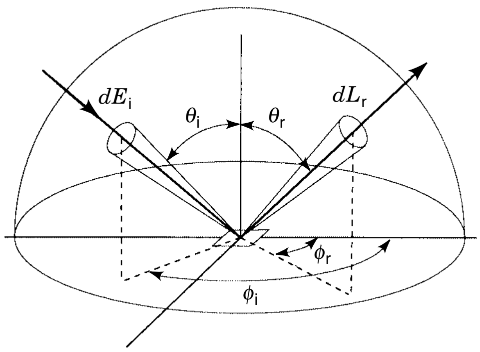

Figure 3. Concept and parameters of BRDF.

total reflected flux, the earth's surface must be observed from many directions using air- or satellite-borne detectors. The directional reflectance characteristics or the amount of solar radiation scattered from a surface in a given direction provides important information about the surface characteristics. Many earth-observation satellite instruments today look only vertically downward at the earth's surface, but in the near future a highly increased amount of data from sensors with off-nadir capability will become available primarily from NASA's space-borne sensor MISR (20). In order to apply remote sensing data to land use change and ecologically relevant studies within NASA's Earth Science Enterprise and other programs, bidirectional ground reference data must be widely available. A wide variety of bidirectional reflectance models have already been designed to use the multidirectional information effectively with these remote sensing data. However, there is still a lack of bidirectional ground reference data to adequately validate the remotely sensed data and the various models.

Reflectance, BRF, and BRDF

Bidirectional reflectance factor (BRF) and bidirectional reflectance distribution function (BRDF) are the key parameters addressed in goniometric measurements of reflected radiance. The bidirectional reflectance factor R is the ratio of radiant flux $d\Phi_r$ reflected from a target to the flux $d\Phi_{rid}$ reflected from a lossless isotropic (lambertian) surface for a given illumination-viewing geometry (θ_i, ϕ_i; θ_r, ϕ_r) and wavelength (λ):

$$R(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = d\Phi_r/d\Phi_{rid} \qquad \text{(dimensionless)}$$

The bidirectional reflectance distribution function f_r as defined by Nicodemus et al. (21) is the fraction of the radiance L[$\mathrm{W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}}$] of the incident irradiance E_i[$\mathrm{W \cdot m^{-2} \cdot nm^{-1}}$] from direction θ_i, ϕ_i reflected into a specific direction θ_r, ϕ_r (Fig. 3):

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)}{dE_i(\theta_i, \phi_i; \lambda)} \qquad (\mathrm{sr}^{-1})$$

Assuming isotropic irradiance and BRDF within designated solid angles, R and f_r are interrelated by

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = \frac{R(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)}{\pi}$$

It might be confusing that BRDF is not defined as a ratio of equal units although dL_r and dE_i are both clearly directional quantities. The reason is found in the diffuse reflection that causes the small, but finite incident radiant flux to be reflected in infinitesimally small parts in all directions over the hemisphere. It seems appropriate therefore to produce a dimensionless quantity only when all "parts" of dL_r reflected over the hemisphere have been integrated before taking the ratio of dL_r to dE_i. This however contradicts the bidirectional concept of the BRDF.

Both R and f_r are intrinsic properties of the reflecting surface and are mainly driven by the reflection properties of the material, the surface structure, multiple scattering, and mutual shadowing effects. Because of the directionality, BRF and BRDF expose values between 0 and infinity. Values over 1 are achieved in peak reflectance directions such as the specular spot of a metallic surface, where the reflected flux in a single direction is much higher than the flux reflected from a corresponding ideal diffuse (lambertian) reflector. Hemispherical reflectance ρ, however, only exposes values between 0 and 1, as a result of the conservation of energy. ρ is defined as the ratio of total hemispherical incident Φ_i and reflected Φ_r radiant flux:

$$\rho = \frac{\Phi_r}{\Phi_i}$$

For most natural and man-made surfaces bidirectional reflectance factors vary significantly for different view and illumination angles. Only very few, highly homogeneous and fine-structured objects like gypsum sand or reference panel material expose nearly lambertian (i.e., completely diffuse reflectance characteristics). Vegetation surfaces for example show a strong backscatter component with a peak reflectance in the direction of illumination, called hot spot (Fig. 4). Mirroring surfaces like metals and some natural surfaces, such as ice and weathered snow, expose distinctive high-reflectance values in the forward scatter direction related to the specular spot. Other materials like concrete exhibit a mix-

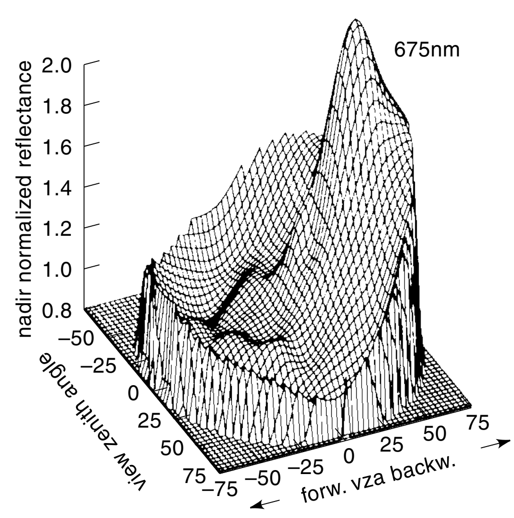

Figure 4. BRDF of a grass lawn at 675 nm wavelength acquired with the FIGOS field goniometer under 35° sun zenith angle.

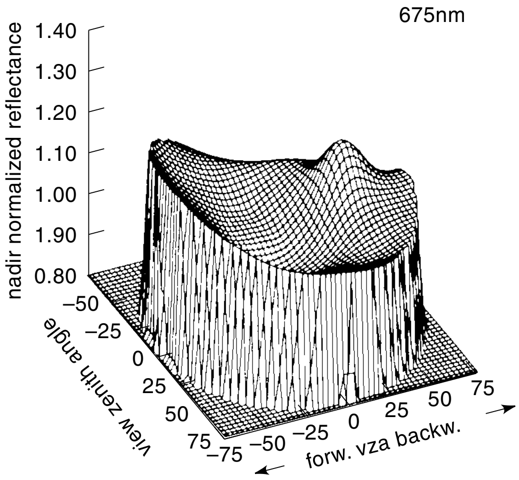

Figure 5. BRDF of a concrete slab at 675 nm wavelength acquired with the EGO laboratory goniometer under 35° illumination zenith angle.

ture of forward and backscattering components (Fig. 5). In general, BRDF effects are most prominent in the principal plane where the source of illumination, sensor, and target surface are aligned in one plane. In the plane perpendicular to the principal plane, bidirectional effects are least pronounced.

BRF and BRDF can only be approximated and not actually measured because by definition an infinitesimally small sensor field-of-view would be required. In practice, BRDF values are derived from goniometric measurements by dividing radiances L measured with a small aperture radiometer by the hemispherical irradiance E_i determined from calibrated reference panels. BRF values are likewise obtained by the ratio of fluxes $d\Phi_r$ and $d\Phi_{rid}$ measured in small solid angles with a goniometer-mounted radiometer. For a full characterization of a BRDF, an infinite number of measurements would be required. For practical reasons, only a limited number of sample points are measured over the hemisphere, which in most cases are regularly spaced with the help of a goniometer. The BRDF is then derived from these sample points using various modeling techniques.

Spectral Ranges

Most of the goniometric measurements in the optical domain have been performed in the reflecting part of the spectrum between 300 and 2500 nm (e.g., EGO, FIGOS, and PARABOLA, which are described later). In the thermal infrared region relatively few data have been acquired using goniometric devices for remote-sensing applications. Thermal infrared studies revealed a rather high dependence of measured infrared temperatures on view zenith angles. Sun-illuminated parts of a plant canopy were found to be considerably warmer than the shaded components. Kimes et al. (22) found temperature differences as great as 13°C when changing the view zenith angle from 0° to 80° which were a function of canopy structure and vertical temperature distribution. Leaf temperature measurements by infrared emission at different detection angles have also been made using the FEBO spectrogoniometer (2). Goniometers have also been used in the past with Light Detection and Ranging (LIDAR) systems at the Joint Research Centre, Ispra, for the remote sensing of air pollution and in particular for the mapping of smoke plumes (23). Another unique goniometer system installed at the Joint Research Centre, Ispra, is the EMSL facility, which operates in the Radio Detection and Ranging (RADAR) domain and is described in more detail later.

Goniospectroscopy

With the tremendous increase of spectral bands in remote sensing devices in recent years, a need for hyperspectral ground reference data has arisen. Most of the BRDF data sets available today however lack a high spectral resolution. Only recently have hyperspectral BRDF data, acquired with the EGO and FIGOS goniometers, been analyzed (24). In these studies, a strong wavelength dependence of BRDF effects was found for vegetation canopies, mainly caused by multiple scattering effects as a function of leaf optical properties. The wavelength dependency is best observed in an erectophile (i.e., vertically structured vegetation surface such as a grass lawn), which exposes strong BRDF effects resulting from the gap structure of the canopy. Multiple scattering is particularly strong in the highly reflecting near-infrared range, and to a certain degree in the green part of the spectrum, and equalizes effectively the hard contrast between shaded and sunlit canopy particles. In the blue and red chlorophyll absorption bands, however, multiple scattering is low, and the canopy heterogeneity becomes dominant. As a consequence, the BRDF characteristics of a vegetation canopy are more isotropic in the near-infrared and the green range than in the blue and red range. Similar effects can also be observed in the mid-infrared range.

EXAMPLES OF GONIOMETERS USED IN REMOTE SENSING

Both laboratory (25) and field goniometers (26) have been developed and deployed for remote sensing applications, mainly addressing the reflecting range of the electromagnetic spectrum between 300 nm and 2500 nm. Out of the many goniometric systems recently developed, four significant state-of-the art examples (EGO, FIGOS, PARABOLA, and EMSL) are described here.

EGO

The European Goniometric Facility (EGO) is operated by the Space Applications Institute of the Joint Research Centre, Ispra, Italy. It was constructed and assembled under custom design in a specialized workshop equipped with machinery to build and work large circular rails and arcs with a precision of 0.1 mm (27). The laboratory-based system allows the independent positioning of a light source and a detector anywhere on a 2 m radius hemisphere centered on a target, allowing bidirectional reflectance measurements under controlled laboratory conditions. To reduce light scattering, the goniometer is painted black, and accommodated in a special black laboratory featuring light-absorbing rubber floor material. The main support structure is made from a strong 10 cm double T angle iron. It consists of two horizontal circular rails of 4.4 m and 4.8 m diameter on which two vertical arcs, mounted on motor-

Figure 6. The EGO goniometer installed at JRC, Ispra, Italy.

ized sleds, rotate (Fig. 6). The outer arc supports the light source, and the inner arc holds the detector. In its most recent configuration, both arcs cover 90° on the vertical plane. The system is mechanically centered on the ceiling and the floor of the laboratory and weighs about 700 kg. Each arc supports a mobile sled that can displace a detector and a light source of up to 15 kg weight each. The vertical arcs are mounted 240 mm out of axis in such a way that both the source and the detector can reach the zenithal position and that a minimal distance between the source and the detector can be achieved. Another important characteristic is that the origin of the arcs, corresponding to the horizontal plane crossing the center of the hemisphere, is 280 mm above the mechanical plate on which the target is placed, thus allowing measurements at grazing angles. Microswitches and user-set software limits prevent rotation of the arcs beyond certain points, thus reducing the risk of mechanical damage resulting from collision.

The EGO goniometer is equipped with an automated high-precision target tilt and rotation platform that can tilt and rotate targets with a precision better than 0.001°. The target can be rotated on a full circle, whereas the tilting is limited to an arc of 60° at a velocity of ~0.2°/s. This capability, although exceeding most remote sensing requirements, can be used for instance for targets with a row structure or for those where the specular reflecting component is of particular interest. The targets, which can be up to 1 m × 1 m in dimensions and can weigh up to 7 kg to 8 kg, are precisely positioned by means of small HeNe lasers. The four angular movements of the detector and the light source are realized by precision stepping motors with a resolution of 0.01° and an angular positioning accuracy of ±0.1°. Each stepping motor is equipped with an encoder. The angular velocity on the azimuth rail is 1°/s and on the zenith arcs 0.5°/s. All movements of detector, light source, and platform are controlled by a PC-based custom designed EGO monitoring system software, which is able to handle all experimental and measurement data. The control unit can be operated in manual or batch modes, allowing automated performance of bidirectional reflectance measurements. Two color charge-coupled device (CCD) TV cameras help to capture the experiment set up for future reference. Some of the currently available spectroradiometers used as detectors are the GER IRIS, Spectron Engineering SE590, and the ASD FieldSpec-FR. The system is also equipped with a high-resolution CCD camera. A series of calibrated polytetrafluorethylene (PTFE) panels are available as reference standards being very close to the ideal white diffuse lambertian reflector. Depending on the experiment purpose, various lasers and voltage-stabilized halogen lamps can be used as light sources. It is also planned to use natural light as an illumination source in the future thus enhancing the potential of the EGO goniometer. This versatile facility is currently being used by several European research groups involved in remote sensing applications.

FIGOS

The RSL Field-Goniometer System (FIGOS) was built by Willy Sandmeier at Fa. Lehner & Co AG, Gränichen, Switzerland, in cooperation with the Remote Sensing Laboratories (RSL) at the University of Zurich, Switzerland (28). The planning and construction required about 700 working hours. FIGOS is a transportable field goniometer that is operated with a PC-controlled GER-3700 spectroradiometer covering the spectrum between 400 nm and 2500 nm in 704 bands with a resolution of 1.5 nm (400 nm to 1050 nm) and 8.4 nm (1050 nm to 2500 nm), respectively. FIGOS consists of three major parts: a zenith arc, an azimuth rail of 2 m radius each, and a motorized sled with the spectroradiometer mounted (Fig. 7). FIGOS allows the acquisition of hyperspectral BRDF data under natural light conditions for a wide field of applications such as providing ground reference data for pointable remote sensing devices and BRDF model validation efforts. The technical design and the dimensions are similar to the EGO goniometer, but all parts are made of black-coated aluminum resulting in a total weight of only 230 kg. The complete goniometer system is stored and transported on a trailer with a specifically designed interior, allowing fast and convenient access to a field site. The construction of the zenith arc follows the technique used for cranes providing a high stability in spite of the rather small weight of 48 kg. If transported, the zenith arc is separated into two parts. The azimuth rail is mounted on sockets forming a circle. It weighs about 150 kg altogether. For transportation, the rail and its base are split into four quarters. Mounting of the zenith arc is provided by sleds interconnected on the azimuth rail and allowing a full 360° rotation. The ball-bearing of the wagons embrace the azimuth rail in a way that the zenith arc is tightly fixed even on sloped terrain. A support linking the center of the zenith arc with the azimuth rail serves as a further stabilization and

Figure 7. The FIGOS field goniometer in action in Zurich, Switzerland.

helps to guide the cables. Similar to the EGO goniometer, the zenith arc is mounted eccentrically on the azimuth rail to prevent it from shadowing the target when measuring in the solar principal plane. Freely placable labels on the zenith arc allow for an automated positioning of the spectroradiometer.

The sled with the spectroradiometer mounted is driven by a 24 V dc braking motor, and a precision chain serves as a guideway for the $\frac{3}{8}$ in. cogwheel. The motor velocity is set to 2.5°/s. By default the labels are set every 15° resulting in 11 measurements with zenith angles ranging from −75° to +75°. It is also possible to drive the sled-motor manually from a remote control unit to any desired position on the zenith arc. The positioning precision on the zenith arc is within ±0.2°. The geometric precision of the zenith arc is referenced with the help of a laser moving over the zenith arc on plane ground. The deviation of the laser spot, representing the center of the sensor's field-of-view, shows values within ±3.5 cm. It is introduced by mechanical problems in bending the aluminum profiles. The roundness of the zenith arc is nearly perfect showing deviations of the laser spot from the center within ±1 cm between −60° and +60°. The azimuth view angle is given by a scale engraved in the azimuth basement. In its current configuration, the zenith arc is positioned manually with the help of a pointer and a brake fixing the position of the zenith arc. The azimuth arc is almost perfectly round. A laser spot pointing vertically from the center of the zenith arc on the ground moves less than ±1 cm when the zenith arc is rotated. By default, an increment of 30° is set on the azimuth arc resulting in 6 measurement profiles, each containing 11 measurements on the zenith arc. Thus to cover the full hemisphere, 66 measurements of the target surface are needed. In addition, a Spectralon reference panel is used to determine irradiance conditions during data acquisition. A full hemisphere is covered in approximately 15 min. About 90 min are needed for the set-up of the goniometer with a team of two people.

PARABOLA

The Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere (PARABOLA) is a rotating head radiometer consisting of three primary units—the sensor head, data recording unit, and a power pack. It was designed and constructed by NASA to enable fast and effective in situ measurements of bidirectional reflectance (29). The original instrument features three spectral bands (0.65 μm to 0.67 μm, 0.81 μm to 0.84 μm, 1.62 μm to 1.69 μm), and an upgraded, commercially available version (Sensit Technologies, Portland, ND) consists of seven channels in the visible and near-infrared range. The sensor elements are mounted within a motorized two-axis rotating head, which scans almost the complete sky- and ground hemispheres in 15° instantaneous field-of-view sectors (respectively 5° for the upgraded PARABOLA version) in only 11 s (Fig. 8). To document the target observed, a nadir-looking camera with a wide field-of-view lens is mounted next to the radiometer head. The roll axis scan rate provides contiguous swaths at the nadir/zenith positions, and progressively increasing overlap at other elevation angles away from the nadir/zenith position. A timing wheel optical sensor triggers concurrent electronic sampling of the voltage outputs from the detectors along the roll axis. The angular positioning accuracy is estimated to be

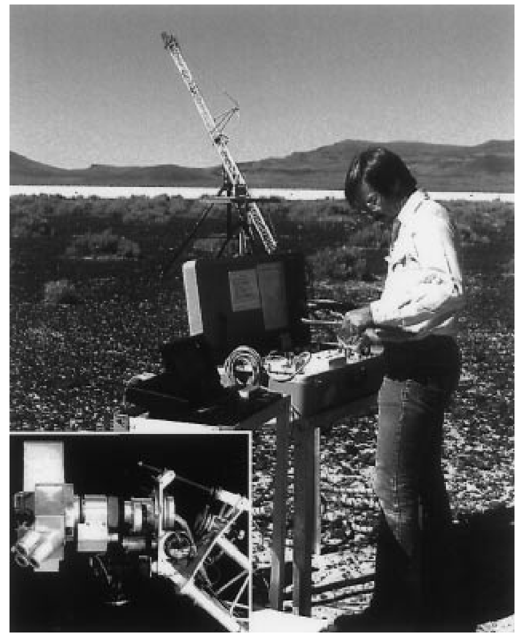

Figure 8. The PARABOLA instrument deployed in the field.

±0.5° as a result of wind and other factors. Unlike EGO and FIGOS, targets are scanned in a continuous helical pattern rather than focusing on a specific spot. To reduce effects of spatial inhomogeneity, the system can be moved within a site, acquiring multiple replicates which are subsequently averaged. The height of the radiometer above the canopy surface is adjusted to accommodate the heterogeneity of the target and provide representative sampling. The primary mounting device for the 4 kg radiometer head is a lightweight, collapsible boom apparatus consisting of an aluminum triangular truss that decouples as four 2 m long sections. It can be deployed using a variety of mounting platforms including tripods, large van booms, pick-up trucks, and even tower trams and hot-air balloons. All operations of the PARABOLA system are remotely controlled by PC-based software. Data have been collected over a wide variety of surfaces and have been intensively used in the BRDF community.

EMSL

In the microwave range of the electromagnetic spectrum, the European Microwave Signature Laboratory (EMSL), also installed at the Joint Research Centre at Ispra, Italy, is another example of a state-of-the-art goniometric facility that provides unique opportunities in terms of measurement capabilities and data processing (30). The laboratory is mainly devoted to polarimetric radar measurements aimed at complementing air- and spaceborne remote sensing experiments by providing stable and reproducible environmental conditions and flexible operational modes for well-controlled experiments. Although designed to serve researchers and users in the field of land-oriented remote sensing tasks, the laboratory can be efficiently used in many different research fields as well as for industrial applications. The overall structure is formed by the conjunction of a hemispherical and a cylindrical part, both with a radius of 10 m. The height of the chamber is 15 m so that the center of the hemisphere is located 5 m above the chamber floor. In the gap between the two parts, a circular rail is mounted where two sleds carrying the radar antennas can move independently. The object under test is transported inside the chamber through a large door (5 m wide and 8 m high) by means of a target positioner moving on a linear rail. The same system allows the rotational positioning of the object inside the chamber before and during the microwave measurements with a precision of $\pm 0.05°$. Both the electromechanical components and the microwave measurement system are remotely controlled by a computer.

Field Versus Laboratory Measurements

Laboratory goniometers such as EGO and field instruments such as FIGOS and PARABOLA have nearly complementary advantages and disadvantages. Field measurements suffer from an instable irradiance resulting from changing atmospheric conditions and sun positions. But they allow us to measure targets in situ and in vivo under natural light conditions and are therefore generally better suited for remote-sensing applications than indoor measurements. In a laboratory, targets are either man-made or separated from their natural habitat and can suffer from water and temperature stress introduced by the intense laboratory irradiance. Additionally, the light intensity is usually lower than in the field leading to lower signal-to-noise ratios than in the field. Compared to sun light, laboratory irradiance is often highly heterogeneous and nonparallel and may suffer from voltage variations too. Furthermore, the spectral characteristics of the irradiance differ significantly from the solar spectrum. Major advantages of laboratory measurements, however, are the control over the light source position, the nearly complete lack of diffuse irradiance, and the ability to produce data sets in very high angular resolutions. Because of their application in an indoor environment, they are constructed much more sturdily and therefore are more precise than the lightweight field instruments. Thus, calibration procedures, sensitivity analysis, and controlled model validation efforts are generally easier to perform in a laboratory, and remote-sensing ground reference data are more adequately acquired in goniometric field campaigns. The complete calibration of a large-scale goniometer is usually a very time consuming and tedious task however, and the results are rarely entirely satisfactory (31).

CONCLUSIONS

Geometrical optics have been of great interest during the last two millenia since visual phenomena have been man's most important contact with the physical world. Goniometers, in various forms, have played a very important role in the study of these phenomena. This has recently expanded with the development of sophisticated sensors operating in other regions of the electromagnetic spectrum and by the addition of powerful computerized control systems. Intelligent robots with goniometric positioning capabilities may become commonplace in the near future and replace many of the traditional forms of goniometers. In remote sensing, goniometric measurements and modeling of bidirectional reflectance data will become increasingly important with the advent of NASA's Earth Observing System (EOS) platforms and other satellites with multidirectional viewing capability. The potential of multiangular data to derive biogeophysical parameters from remotely sensed imagery is still under study. Spectral libraries of bidirectional reflectance measurements of natural and man-made surfaces are only recently being set up and will become of significant importance for remote sensing and other applications. There is considerable hope that goniometric measurements from ground, air and space will contribute to a better understanding of the earth's biosphere and give insight into global change issues such as the global carbon balance issue. In astronomy, goniometric measurements of particles and particulate surfaces also have been essential in developing models and theories of light scattering from the planetary bodies and will continue to play an important role in the years to come.

BIBLIOGRAPHY

1. A. Carangeot, Goniomètre ou mesure-angle, *Observations sur la physique, sur l'histoire naturelle et sur les arts,* No. 22, March 1783, pp. 193–197.
2. P. Mazzinghi et al., A new narrow angle spectrogoniometer for the measurement of bidirectional reflectance, *Proc. IGARSS'95,* Florence, Italy, 1995, pp. 2075–2077.
3. P. Gibson, Thin films: X-ray characterization, R. W. Cahn (ed.), *Encyclopedia Materials Science and Engineering, Supplementary Vol. 2,* New York: Pergamon Press, 1990, pp. 1328–1332.
4. A. Kononoviz, Determination of the albedo of white cardboard independent of Lamberts' photometric calculations, *Zapiski Matematizesko Otdela Novorossiskaya Obschestva Estestvoist pytatelei,* No. 2, 1882.
5. A. Ångstrom, The albedo of various surfaces of ground, *Geografiska Annalen,* 1925, pp. 323–342.
6. V. Kulebakin, Reflection of light from terrestrial surfaces, *Trudy Gosudarstvemnogo Experimentalnoge Elektrotechischenskogo Instituta,* **17**: 5–29, 1926.
7. H. Kimball and I. Hand, Reflectivity of different kinds of surfaces, *Monthly Weather Rev.,* **58**: 280–282, 1930.
8. P. Oetking, Photometric studies of diffusely reflecting surfaces with applications to the brightness of the moon, *J. Geophys. Res.,* **71**: 2505–2513, 1966.
9. B. Hapke and H. van Horn, Photometric studies of complex surfaces with application to the moon, *J. Geophys. Res.,* **68**: 4545–4570, 1963.
10. W. Knowles Middleton and A. Mungall, The luminous directional reflectance of snow, *J. Opt. Soc. Am.,* **42**: 572–579, 1952.
11. J. van Diggelen, *Photometric Properties of Lunar Crater Floors,* Ph.D. Thesis NASA technical translation to English, NASA F-209, Utrecht Observatory, 1963.
12. W. Egan, Polarimetric and photometric simulation of the martian surface, *Icarus,* **10**: 223–227, 1969.
13. B. Zellner et al., The asteroid albedo scale. I. Laboratory polarimetry of meteorites, *Proc. Lunar Sci. Conf.,* **8**: 1091–1110, 1977.
14. A. Oehler, *Experimentelle und theoretische Untersuchung der goniospektrometrischen Eigenschaften regolithartiger Materialen in den Spektralbereichen UV, VIS, und NIR,* Ph.D. Thesis, Deutsche Forschungsanstalt für Luft- und Raumfahrt, Köln, Germany, 1996.
15. B. Buratti et al., Spectrogoniometer for measuring planetary surface materials at small phase angles, *Appl. Opt.,* **27**: 161–165, 1988.
16. J. Piironen et al., Backscattering of light by snow: Field measurements, *Proc. ENAMORS Workshop in Tuusula,* Sept. 1997, (in press), pp. 17–19.
17. F. Kuik, P. Stammes, and J. Hovenier, Experimental determination of scattering matrices of water droplets and quartz particles, *Appl. Opt.,* **30**: 4872–4881, 1991.

18. A. Hunt and D. Huffman, A new polarization-modulated light scattering instrument, *Rev. Sci. Instrum.,* **44** (12): 1753, 1973.

19. C. Sasse and J. Peltoniemi, Angular scattering measurements and calculations of rough spherically shaped carbon particles, *Opt. Sci. and Sci. Instr.,* SPIE's 40th Annual Meeting, San Diego, July 9–14, 1995.

20. D. Diner et al., A Multi-angle imaging spectro-radiometer for terrestrial remote sensing from the earth observing system, *Int. J. Imaging Syst. Technol.,* **3**: 92–107, 1991.

21. F. Nicodemus et al., Geometrical considerations and nomenclature for reflectance, *National Bur. Standards Monograph,* vol. 160, 1977.

22. D. Kimes et al., View angle effects in the radiometric measurement of plant canopy temperatures, *Remote Sens. Environ.,* **10**: 273–284, 1980.

23. R. Benoit, A. Pedrini, and L. Stanchi, The electronics associated with a LIDAR system for remote sensing of air pollution, *Proc. 2nd Ispra Nuclear Electronics Symposium,* 1975, p. 237.

24. St. Sandmeier et al., Physical mechanisms in hyperspectral BRDF-data of grass and watercress, *Remote Sens. Environ.,* 1998, in press.

25. D. Gibbs et al., Automated measurement of polarized bidirectional reflectance, *Remote Sens. Environ.,* **43**: 97–114, 1993.

26. R. Jackson et al., Bidirectional measurements of surface reflectance for view angle corrections of oblique imagery, *Remote Sens. Environ.,* **32**: 189–202, 1990.

27. C. Koechler et al., The European Optical Goniometric Facility: Technical description and first experiments on spectral unmixing, *Proc. IGARSS'94,* Pasadena, 1994, pp. 2375–2377.

28. St. Sandmeier et al., Acquisition of bidirectional reflectance data using the Swiss field-goniometer system (FIGOS), *Proc. EARSeL Symp.,* Basel, Switzerland, Balkema Publ. NL, 1995, pp. 55–61.

29. D. Deering, Field measurements of bidirectional reflectance, in G. Asrar (ed.), *Theory and Applications of Optical Remote Sensing,* New York: Wiley, 1989, pp. 14–65.

30. A. Sieber, The European Microwave Signature Laboratory, *EARSeL Adv. Remote Sens.,* **2** (1): 195–204, 1993.

31. I. Solheim et al., Calibration and Characterization of Data from the European Goniometric Facility (EGO), Report EUR 17268 EN, 1997.

Reading List

J. C. Stover, *Optical Scattering,* New York: McGraw-Hill, 1990.

B. Hosgood
J. Piironen
G. Andreoli
C. Koechler
Space Applications Institute
St. Sandmeier
University of Zurich

GPS. See Aircraft navigation.
GRAMMARS. See Automata theory.
GRAPHICAL ANALYSIS. See Data visualization.
GRAPHICAL PROGRAMMING. See Visual programming.
GRAPHICAL SOLUTIONS. See Smith chart.