Protocol for measuring light transmission of horticultural screens

Gert-Jan Swinkels, Silke Hemming, Vida Mohammadkhani, Jim van Ruijven
Wageningen UR Greenhouse Horticulture

Rapport GTB-1252

Abstract
The light transmission is an important property for horticultural screens. For energy screens in particular, an accurate measurement of the light transmission is important because these screens are often used during the day, in the winter period when radiation is limited. For shading screens the shading factor is an important factor. To enable a fair comparison between horticultural screens Wageningen UR in collaboration with screen producers Ludvig Svensson, Novavert and Bonar, developed a new protocol for measuring the transmission of horticultural screens. The protocol is based on the earlier developed protocol for measuring the light transmission of greenhouse covering materials, which was developed by TNO and Wageningen UR. The protocol covers the measurement of the transmission of horticultural screens for photosynthetically active radiation (PAR) in terms of hemispherical transmission. The scope of the protocol is limited to transparent screens with hemisferical transmittance greater than 10% and does not include the measurement of blackout screens. The protocol is regarded as the standard by the parties involved. The transmission measured can serve as a basis for comparing horticultural screens and can be used in calculating the performance of greenhouses.

Wageningen UR Greenhouse Horticulture

Address : P.O. Box 644, 6700 AP Wageningen, the Netherlands
Tel. : +31 317 - 48 60 01
Fax : +31 317 - 41 80 94
E-mail : greenhousehorticulture@wur.nl
Internet : www.greenhousehorticulture.wur.nl

Inhoudsopgave

1 Introduction

Light is the energy source for plant growth. Solar radiance is sustainable and free and therefore the most favourable source of light in greenhouse crop production. Plant growth and with it the economical production depend strongly on the (daily) light sum at plant level. Therefore knowing the light transmission of the greenhouse covers and screens is important when considering building a new greenhouse. For energy screens in particular, an accurate measurement of the light transmission is important because these screens are often used during the day, in the winter period when radiation is limited. For shading screens the light transmission (shading factor) is an important factor for plant growth.

For greenhouse covering materials, a standard for measuring light transmission which is used traditionally is the Dutch norm NEN 2675 (NEN 2675, 1990). This norm describes a method for measuring the PAR transmission of standard float glass for normal incidence (parallel to the normal of the surface) and is primarily intended for product comparison. For the optical performance in greenhouses however, the hemispherical transmission is a more important factor than the perpendicular transmission, especially at Northern latitudes. Here diffuse light dominates the global radiation, up to 80% in winter. Moreover, since the last 5 years, a large variety of new covering materials with improved thermal insulation, light transmission and diffusing properties has been developed. For these materials, often with coatings, the relation between the normal and hemispherical transmission is not straightforward which makes the NEN 2675 inappropriate. To enable a fair comparison between greenhouse covering materials, TNO and Wageningen UR developed a new protocol for measuring the transmission of greenhouse covering materials (Ruigrok, 2008).

Before the publication of this document, no standard protocol was available for measuring the light transmission of shading and energy screens used in greenhouse horticulture. Different screen manufacturers and research institutes used different methods, which made a comparison of light transmission values for growers and industrial partners difficult. For that reason the standard protocol for measuring the light transmittance of horticultural screens, described in this document, was developed in co-operation with relevant screen manufacturers.

Because measuring the transmittance of covering materials has many similarities with horticultural screens the screen protocol is based on the protocol for measuring covering materials. Screens are often inhomogeneous materials composed from different materials such as plastic, aluminium. They are three-dimensional structures influencing light transmission paths through the material. Depending on the screen type the patterns is relatively large which requires relatively large samples for transmission measurements.

The measurement protocol for horticultural screens has been developed in cooperation with:
- Bonar (bonartf.com)
- Ludvig Svensson (svenssonglobal.com)
- Novavert (novavert.com)

2 Scope

This protocol covers the measurement of the transmission of horticultural screens for photosynthetically active radiation (PAR) in terms of hemispherical transmission. The scope of the protocol is limited to transparent screens with hemisferical transmittance greater than 10% and does not include the measurement of blackout screens. The protocol is regarded as the standard by the parties involved. The transmission measured can serve as a basis for comparing horticultural screens and can be used in calculating the performance of greenhouses. This protocol does not address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this protocol to establish appropriate safety and health practices.

3 Terminology

Hemispherical light
Light coming from a hemisphere over the observer or target and which is distributed equally over the hemisphere surface.

The hemispherical transmission (Them)
The total transmission for hemispherical light.

Single beam substitution error
The systematic, predictable, and non-random error inherent in single beam integrating spheres measuring reflectance or transmittance

Light intensity
The value for each wavelength (range) measured by the detector

Angle of incidence
The angle of incidence (AOI) is the angle between a beam incident on a surface and the line perpendicular to the surface at the point of incidence, called the normal.

4 Equipment

The equipment shall consist of a light source, lens system and, integrating sphere and detector.

4.1 Light source

The light source must produce light in the wavelength range of 400 - 700 nm or broader. If the light source is connected to an unstable grid, a stabilised power supply must be used. With a system of lenses, which may have a limited influence on the spectral range, the output beam must be parallel with a divergence of 3° at maximum. The beam spot must be homogeneous as much as possible without imaging the filament of arc. The beam must be able to incident from angles in the range of 0° to 80°. This can be achieved with a system of lenses and/or mirrors. The accuracy of the angles must be calibrated with a calibration sample with known angular transmittance.

4.2 Integrating sphere

An Integrating sphere (also known as Ulbricht sphere) is an optical component consisting of a hollow spherical cavity with its interior covered with a diffuse white reflective coating, with small holes for entrance and exit ports. Its relevant property is a uniform scattering or diffusing effect. Light rays incident on any point on the inner surface are, by multiple scattering reflections, distributed equally to all other points. The effects of the original direction of light are minimized. An integrating sphere may be thought of as a diffuser which preserves power but destroys spatial information. It is typically used with some light source and a detector for optical power measurement.
Usually a detector is placed directly, or via fiber optics, on the sphere's surface. The amount of incident light which reaches the detector, is governed by the laws of probability. In a small integrating sphere, a photon will have to take a certain number of bounces before it reaches the detector. In a larger sphere system, however, statistics dictate that a photon will have to take more bounces than were required in the smaller integrating sphere to reach the same detector. In the larger sphere, since more "bounces" are required, the photon must undergo many more interactions with the sphere wall and, therefore, is more likely to be absorbed before it actually reaches the detector. Thus, a large integrating sphere acts as an attenuator of signal and is inherently less efficient than a small sphere. A rule of thumb, all other factors being equal, is that the relative attenuation is roughly equal to the square of the ratio between two sphere diameters (Labsphere Inc. Application Note No. 03).

It is important that the optical sensor is shielded from direct light from the light source or scattered from the sample. In theory, an integrating sphere should have no disturbances inside the sphere. In practice, the port dimensions should not exceed 5% of the inner sphere surface and components like baffles should be minimized.
The size of the sphere largely determines the accuracy of the measurement. The light intensity will decrease strongly with the diameter which makes measurements especially in the NIR range complicated. As a consequence, thick materials, materials with a large surface structure and materials with strong light scattering properties require a relatively large sphere in order to allow a large sample port.

Figure 1. Integrating sphere (source: www.labsphere.com/)

4.3 Detector

For measuring the spectral light intensity inside the sphere a spectrometer system is used. Professional spectrometer systems often use a monochromator which generally consists of entrance slit, collimator, a dispersive element, such as a grating or prism, focusing optics and detector which receives only a narrow portion of the spectrum. The spectrum is scanned by rotating the grating. With the development of micro-electronics in the field of multi-element optical detectors, low cost scanners, such as device (CCD) cameras have become available and as a result the CCD spectrometer. Together with low absorption silica fibers developed for communication technology, the light intensity in the UV-, VIS- and NIR-range can be measured simultaneously and fast which makes *e.g.* fluorescence measurements possible.

It is important that the detector's field of view does not include the sample port while, this would introduce a measurement error. To prevent this, a baffle is placed near the detector and prevents a direct view on the sample port (Figure 2.). Baffles are typically coated with the same material as the integrating sphere wall.

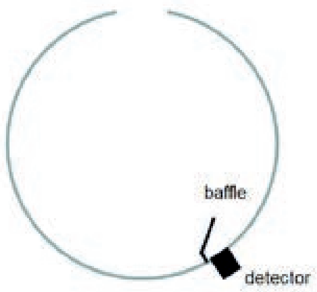


Figure 2. Integrating sphere with detector located in the sphere wall and protected by a baffle from first order light rays

5 Measurement principles

5.1 Single beam and double beam system

There are two major principles of transmission measurement: single beam and double beam. A double beam system compares the light intensity between two light paths, one path containing a reference sample and the other the test sample. A single beam system measures the relative light intensity of the beam before and after a test sample is inserted. Although comparison measurements from double beam instruments are easier and more stable, single beam instruments can have a larger dynamic range and are optically simpler and more compact.

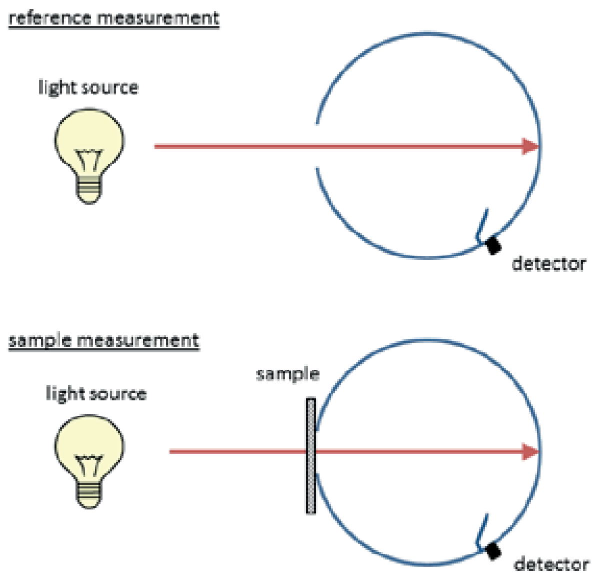


Figure 3. Singe beam system: the transmission is determined by measuring the relative light intensity of the beam before and after the sample is inserted. Because of the higher internal sphere reflectance during the sample measurement the measured transmission is overestimated dependent on the port size.

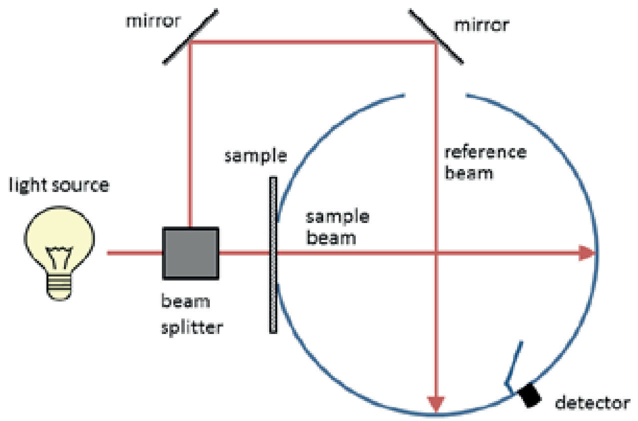


Figure 4. Double beam system: the transmission is determined by comparing the light intensity between two light paths, one path through an open port (air) and the other the sample. Although comparison measurements from double beam instruments are easier and more stable, single beam instruments can have a larger dynamic range and are optically simpler and more compact.

Single beam measurements are less accurate due to a measurement error which is caused by an increased sphere reflectance when the sample is placed. This error, called the single beam substitution error, is the systematic, predictable, and non-random error inherent in single beam integrating spheres measuring reflectance or transmittance (Labsphere Inc., Appl. Note no. 01). In single beam transmittance measurements the measured transmittance is usually higher when the sample is present since an open port (which has zero reflectance when viewed from inside the sphere) is typically used as a reference. In double beam systems, the sample and reference beam each 'see' the same sphere. There is an active comparison between intensities with both sample and reference in place, thus there is no substitution error. The gravity of this error is dependent on the port size and reflection value of the sample.

The substitution error can be determined by measuring the sphere's internal reflectance with an without the sample in place. This is done by measuring the ratio between light intensities with open port and with the sample in place. Because this measurement will correct the changed internal reflectance of the sphere when placing the sample, the sphere must be illuminated from the inside with one ore more light sources with a strongly diverging beam to prevent hot spots on the sphere wall.

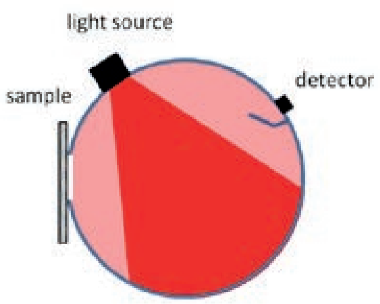


Figure 5. Measuring the single beam substitution error by using an internal light source which illuminates the sphere from the inside and measuring the intensity ratio between an open port and the sample in place.

5.2 Critical dimensions

For transmission measurements the basic rule is that all incident light, falling within the sample port area, must be captured by the integrating sphere after having passed through the sample as transmitted light. Regarding beam spot size there are two options: the beam spot size must be either smaller or larger than the sample port size. A larger beam is favourable but should only be used if the divergence is limited. With a smaller beam spot size it is important that the combination of sample port, material thickness and beam spot size is such that all transmitted light is captured by the integrating sphere. With light scattering materials, loss off light can occur due to scattering and refracting of the light (Figure 6.). This loss will increase with higher angles of incidence. With specular non scattering samples light loss can occur due to inter-reflection at off-normal incident light (Figure 7.).

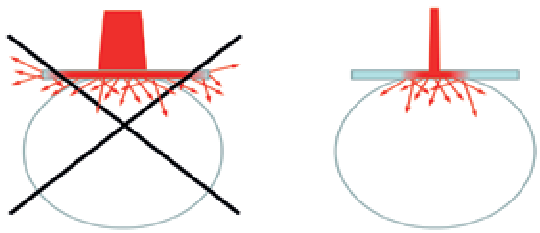


Figure 6. Using a smaller beam, the beam spot must be small enough to prevent light loss due to scattering when measuring light scattering materials.

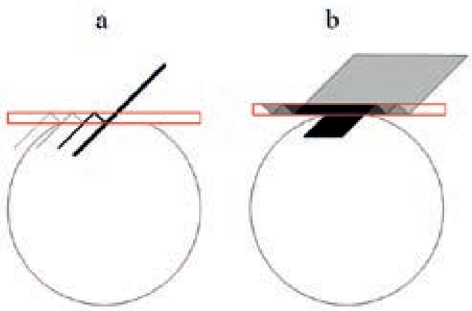


Figure 7. Using a smaller beam is not always possible. A fraction of the transmitted light is lost due to inter-reflection inside the specular sample (a). With a beam spot larger than the sample port, light loss due to inter-reflected light on the left of the sample port is compensated by the inter-reflected light on the right of the sample (b).

The sample must always be larger than the sample port and large enough to prevent light losses though the sides (Figure 7.) and sides which are in the light path (Figure 8.)

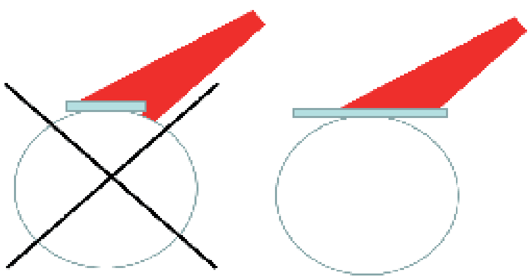


Figure 8. The sample must be large enough to prevent illumination of the sides

Normally the decrease of transmittance per degree increases at higher angles of incidence. This means that for high angles of incidence the accuracy of the angle must be high: at 1° deviation the measurement error will be up to 3%. This means also that a (slightly) divergent beam will cause considerable deviation at high angles of incidence.

The illuminated area of the sample should be large enough to cover patterns or structures in the material. In other words, the measurement result must be independent on which part of the material is illuminated. As a rule of thumb at least 10 repeating structures should be illuminated. To be sure, the measurement must be repeated with the sample in different positions until the standard deviation of the repetitions lies within the desired measurement error.

For structures or patterns which repeat not equally in all orientations the transmission should be measured for different orientations of the sample (Figure 9.). The overall transmission can be calculated as the plain average of all orientations.

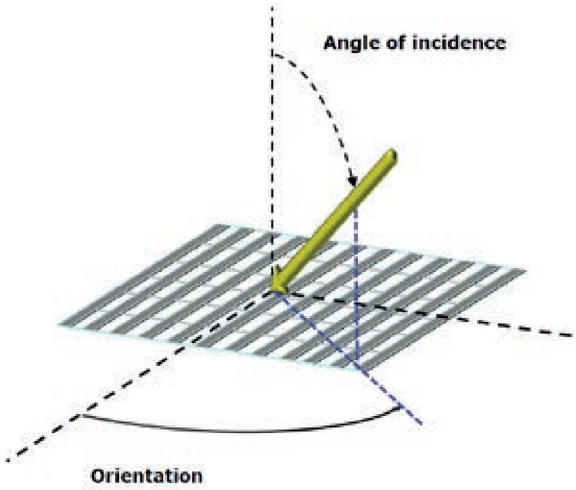


Figure 9. For structures or patterns which repeat not equally in all orientations, like straps, the transmission should be measured for both 0° and 90° orientations of the sample.

6 Protocols

6.1 Direct transmission

The angle of incidence (AOI) is the angle between a beam incident on a surface and the line perpendicular to the surface at the point of incidence, called the normal. The direct transmission for an AOI of x (Tx) is defined as the transmission of light which incidents on the material under an AOI of x.

A light source as described in chapter 4.1 is used to illuminate the sample port of an integrating sphere (chapter 4.2). The detector (chapter 4.3) is situated at the inner wall of the sphere and is protected from direct light by a baffle. The dimensions of the beam spot, integrating sphere and sample port must meet the criteria of chapter 5.2.

Either a single beam or double beam system method can be chosen.

Single beam measurement

In case of a single beam system the measurement must start with the determination of the single beam substitution correction as described in chapter 5.1. Then the spectral light intensity is measured with an open port (I_{ref}) and with the sample in place (I_{sam}). The spectral transmission factor for a specific wavelength and angle of incidence is calculated as:

$$T_{\lambda,\phi} = \frac{I_{sam,\lambda}}{I_{ref,\lambda}} \times \frac{R_{ref,\lambda}}{R_{sam,\lambda}} \qquad (1)$$

With :

$T_{\lambda,\Phi}$	Transmission factor [-]
$I_{sam,\lambda}$	Intensity when sample in place and transmittance beam [counts]
$I_{ref,\lambda}$	Intensity at an open port and transmittance beam [counts]
$R_{sam,\lambda}$	Intensity when sample in place and internal reflectance light source [counts]
$R_{ref,\lambda}$	Intensity at an open port and internal reflectance light source [counts]
Φ	Angle of incidence [°]
λ	Wavelength [nm]

Double beam measurement

In case of a double beam system the measurement must start with a calibration measurement ("zeroing") in order to determine the difference between the two ports. This is done by measuring the intensity in the sphere when the open reference port and open sample port are illuminated one by one. Then, the sample is placed on the sample port and the intensities are measured again. The spectral transmission factor for a specific wavelength and angle of incidence is calculated as:

$$T_{\lambda,\phi} = \frac{I_{samportSam,\lambda}}{I_{refportSam,\lambda}} \times \frac{I_{refportref,\lambda}}{I_{samportref,\lambda}} \qquad (2)$$

With :

$T_{\lambda,\Phi}$	Transmission factor [-]
$I_{samportSam,\lambda}$	Intensity with illuminated sample port and sample in place [counts]
$I_{refportSam,\lambda}$	Intensity with illuminated open sample port [counts]
$I_{samportRef,\lambda}$	Intensity with illuminated reference port and sample in place [counts]
$I_{refportRef,\lambda}$	Intensity with illuminated open reference port [counts]
Φ	Angle of incidence [°]
λ	Wavelength [nm]

The integral transmission factor (mean) is calculated by weighted averaging in the photosynthetically active radiation (PAR), which goes from 400 to 700 nm. It is calculated as:

$$T_{\phi} = \frac{\int_{400nm}^{700nm} D_{\lambda} \cdot S_{\lambda} \cdot \tau_{\lambda}}{\int_{400nm}^{700nm} D_{\lambda} \cdot S_{\lambda}} \qquad (3)$$

With :

T_{θ}	Transmission factor for angle of incidence θ [-]
D_{λ}	Relative spectral energy density of solar radiation [-]
S_{λ}	Relative spectral plant response [-]
τ_{λ}	Spectral transmission factor [-]
λ	Wavelength [nm]

Values of D_{λ} and S_{λ} can be combined into one value A_{λ} which is given in the table below:

Table 1. Spectral values of D_λ and S_λ combined into A_λ according to Dutch NEN2675 norm for determination of the light transmission of greenhouse glass.

Wavelength [nm]	A_λ	Wavelength [nm]	A_λ
400	47.28	560	80.00
410	53.59	570	78.44
420	56.06	580	79.37
430	53.25	590	74.75
440	65.91	600	77.15
450	75.22	610	78.08
460	77.42	620	77.68
470	77.12	630	74.96
480	79.49	640	76.54
490	76.17	650	74.31
500	78.11	660	75.63
510	78.54	670	78.75
520	77.84	680	76.04
530	81.54	690	68.72
540	80.54	700	71.61
550	81.75		

The total measurement uncertainty for the spectral and mean transmission factors depends on whether a single beam or double beam system is used.
For a single beam system without substitution error correction the theoretical accuracy at normal incidence depends on the sample port fraction. To achieve an accuracy of ±2% for the investigated screen types, the port fraction should not exceed 0.2%. Regarding the fact that the neccesary surface for fine structures must be at least 50 mm diameter, the corresponding diameter of the sphere is over 700 mm. For course or multilayered structures the port diameter should be much larger.
When correcting the substitution error the measurement error must be below 2% for normal incidence.
With a double beam system an accuracy of ±1% at normal incidence should be possible for the screens tested for this protocol (Table 3.). For thick or multi-layered screens, or screen with coarse structures the accuracy will be lower.

For non-normal angles of incidence the dimensions of beam spot, sample and sample port will increasingly influence the accuracy.
In all cases the accuracy must specified by the authority responsible for the measurement.

6.2 Hemispherical transmission

The hemispherical transmission (T_{hem}) is defined as the total transmission for hemispherical incident light, which is light that is incident from all directions and is distributed equally over the hemisphere surface. With respect to the angle of incidence (AOI), the majority of the light is coming from 45° and goes to zero towards 0° and 90° AOI.

There are 2 ways to measure the T_{hem}:

- Generating hemispherical light with a half sphere
- Numerical integration of the direct transmission for 0° to 90° AOI.

Because measuring under different AOI's is assumed to be easier than creating a uniform illuminated half hemisphere, the protocol for hemispherical transmission requires an angular measurement. For non-clear samples, the measured angles of incidence should be at least 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70° and 60°. For clear samples 0°, 15°, 30°, 45°, 60° and 75° should be sufficient.
In all cases spline interpolation should be used to fit a smooth piecewise-defined polynomial function through the measured values. T_{hem} is then calculated by numerical integration of the direct transmission values for every 1° according to:

$$T_{HEM} = \frac{\int_{0}^{2pi} \int_{0}^{pi/2} T(\phi,\theta) I(\phi,\theta) \sin(\theta)\cos(\theta) d\theta d\phi}{\int_{0}^{2pi} \int_{0}^{pi/2} I(\phi,\theta) \sin(\theta)\cos(\theta) d\theta d\phi} \qquad (4)$$

Where:

ϕ	Azimuth angle (horizontal plane)
θ	Angle of incidence
T	Angular transmittance

$I(\phi, \theta)$ Distribution function, in this case according to the "standard uniform sky" (I = 1), uniform luminance that does not change with altitude and azimuth.

The hemispherical transmittance is based on the direct transmittance between 0 - 90°. Because the accuracy drops with an increasing angle of incidence, the accuracy will be less than the accuracy for direct transmittance and is theoretically the weighted average of the angular accuracies.

When correcting the substitution error the measurement error must be below ±3%.
With a double beam system an accuracy of ±1.5% should be possible for the screens tested for this protocol. For thick or multi-layered screens, or screen with coarse structures the accuracy will be lower.

In all cases the accuracy must specified by the authority which performs the measurement.

Literature

Dutch Norm Institute NEN, 1990.
NEN 2675: Greenhouse glass - Determination of the light transmission, www.nen.nl.

Ruigrok, J., Swinkels, G.L.A.M, 2008.
Lichtmeetprotocol kasdekmaterialen. TNO-rapport 034-DTM-2010-03385.

Wikipedia 2012,
Integrating sphere, http://en.wikipedia.org/wiki/Integrating_sphere (optional description).

Labsphere Inc. Application Note No. 01. *Methods for single beam substitution error correction for Integrating Sphere Reflectance Spectroscopy Accessories.* www.labsphere.com.

Labsphere Inc. Application Note No. 03. February 1998.
Choosing the Right Sphere Size for Your Application.

Appendix I Determination of the single beam substitution error

Measurement device
On base of the measurement protocol for greenhouse covering materials Wageningen UR Greenhouse Horticulture developed a device for measuring the angular and hemispherical transmission of transparent materials (Figure x). The device is able to measure according to the single beam principle as well as double beam principle and can handle relatively large samples like greenhouse covering materials and screens.

A 2000W fixed xenon light source generates a parallel beam along the optical and mechanical axis of a rotatable arm for angular illumination of the sample. A micro lens array is put in the light path to create a uniform spot. A divergent lens together with a beam splitter create two separate beams for the reference port and sample port. With shutters which block both ports separately, both ports can be illuminated alternately. Both the intensities of the light source (for correction fluctuations in source intensity) and sphere are guided to a CCD spectrometer with optical fiber cables.
In the range of 350 to 2000 nm the device measures the total transmission for angles of incidence from 0° up to 80° (direct transmission). From these, the total transmission for hemispherical incident light (hemispherical transmission) is calculated.

The device is specially developed for measuring thick and multi-layer materials and large materials over which cannot be cut, like tempered or structured glass panes.

Accuracy measurements of glass
For clear specular materials the total measurement uncertainty of a transmission measurement under normal incidence is ±0.002 which is according to the NEN 2675. For most other materials, as well as the hemispherical transmission measurement, an accuracy of ±0.005 is achieved. This applies to both the spectral values and the (weighted) mean value. For extreme materials like weave structures, elastic and multi-layer materials, the measurement uncertainty will be higher. The measurement uncertainty for haze measurements is ±0.01.

In order to validate the output, reference measurements are carried out with a Perkin Elmer Lambda 950 system with the UL270 integrating sphere accessory, which is specially designed for measuring light-diffusing materials. The results (Table 1) show an accuracy for specular samples which meets the NEN 2675 and are well within the specified range of ±0.005 for diffuse samples.

Table 2. Comparison of the normal transmission for a specular and diffuse samples, measured on a Perkin Elmer system with UL270 integrating sphere accessory and the device of Wageningen UR.

Sample	Method	PE UL270	Transvision
Standard float glass	NEN 2675	0.902 ±0.002	0.902 ±0.002
Prismatic glass 1	TNO-WUR	0.920[*)]	0.921 ±0.005
Prismatic glass 2	TNO-WUR	0.969[*)]	0.966 ±0.005
Rolled glass 1	TNO-WUR	0.967[*)]	0.964 ±0.005
Rolled glass 2	TNO-WUR	0.944[*)]	0.942 ±0.005

[*)] Accuracy for non-specular materials is not specified

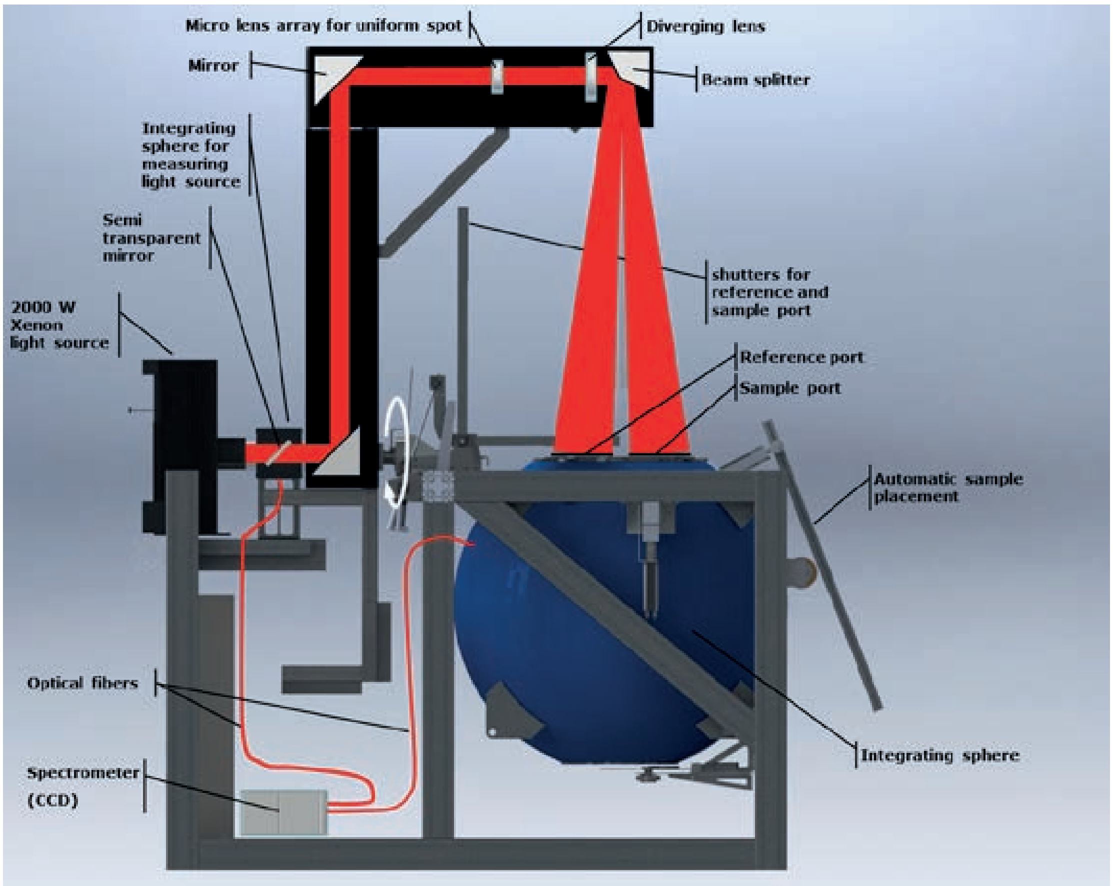


Figure 10. Schematic overview of the Transvision measuring device. A 2000W fixed xenon light source generates a parallel beam along the optical an mechanical axis of a rotatable arm for angular illumination of the sample. With a micro lens, divergent lens and beam splitter the 170 mm reference and sample ports are alternately illuminated with a uniform spot by means of shutters. Both the intensities of the light source (correction for fluctuations in source intensity) and sphere are guided to a CCD spectrometer with fiber cables.

Port size and accuracy of screens

The port fraction is the fraction of port area divided by the total area of the inner sphere wall. In order to determine the relation between the port fraction and the single beam substitution error a series of measurements have been carried out with different port sizes. Since the single beam substitution error relates to the internal sphere reflection, the error is independent on the angle of incidence. For this reason, it will suffice to determine the error on base of perpendicular transmission measurements only.

Table 3. shows an overview of different screen types selected for determining the port size and accuracy of transmittance measurements. The results are shown in Table 4. .

Table 3. Screen types used for determination of the single beam substitution error

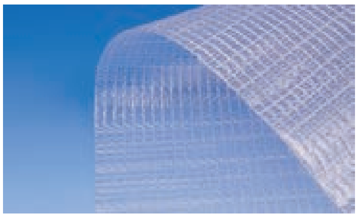
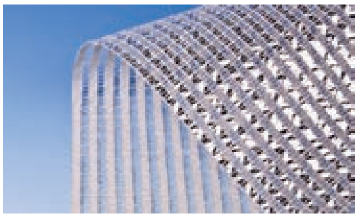
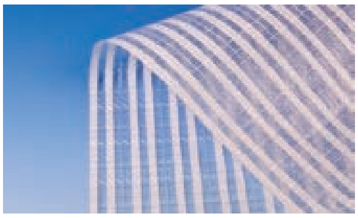
Manufacturer	Screen type	
Bonar TF	Phormitex, Lumina 500	
Bonar TF	Phormitex clear	
Bonar TF	PH77	
Ludvig Svensson	XLS 10 Ultra Plus	
Ludvig Svensson	XLS 15 Revolux	
Ludvig Svensson	XLS 40 Harmony Revolux	
Novavert	SHS 15 Transparent	
Novavert	SHS 10 Antifire B1	
Novavert	TREVIRA CS (B1+M1) fire ret.	

Table 4. Single beam normal transmittance for different port sizes and the corresponding double beam values.

	Normal transmittance [%]				Hemispherical transmittance [%]
	Single beam, port fraction [%]			Double beam	Double beam
	3.6	0.81	0.16		
Standard glass (90.2%)	98.3	94.8	91.3	90.4	82.5
Coated glass (77.8%)	83.5	80.5	78.2	77.7	69.5
Phormitex, Lumina 500	73.6	57.2	51.0	50.2	46.2
Phormitex clear	100.9	90.2	85.7	84.6	73.0
PH77	36.9	26.8	23.0		
XLS 10 Ultra Plus	97.4	85.1	80.2	80.0	68.4
XLS 15 Revolux	56.6	44.6	39.8	38.9	33.9
XLS 40 Harmony Revolux	70.7	53.2	46.8		
SHS 15 Transparent	94.6	81.9	76.1	74.4	65.4
SHS 10 Antifire B1	96.7	83.1	77.4	76.8	67.7
TREVIRA CS (B1+M1) fire ret.					

To determine the relation between port fraction and single beam substitution error, a linear curve is fitted through the measured values at different port sizes. This is done for each sample. According to the results, the substitution error increases with an increasing reflectance of the sample (Figure 11. and Figure 12.).

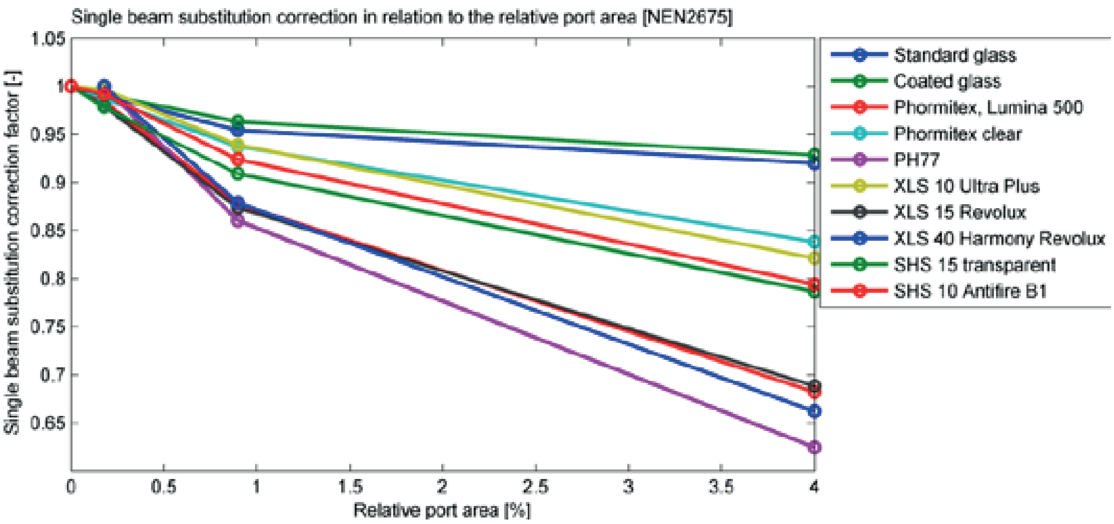


Figure 11. Measured values of the single beam substitution correction factor of different materials in relation to the relative port area between 0 and 4%

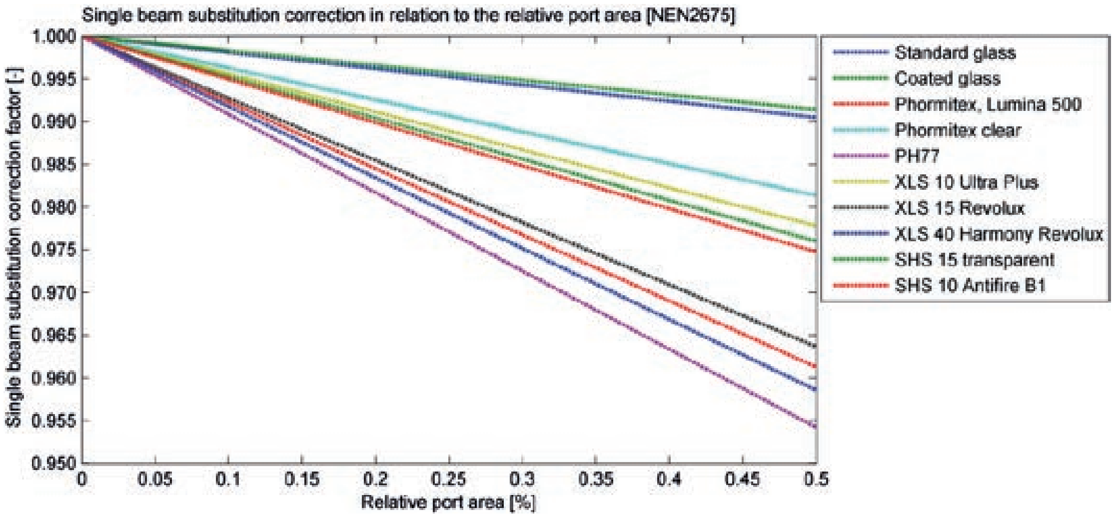


Figure 12. Fitted single beam substitution correction of different materials in relation to the relative port area between 0 and 0.5%. According to this the relative port area should not exceed 0.5% to keep the substitution error below 5%.

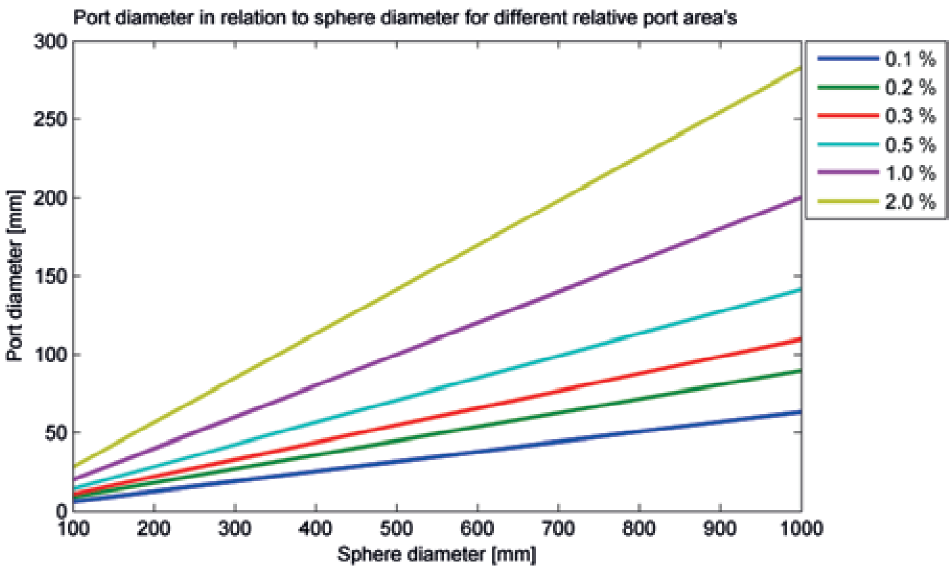


Figure 13. Port diameter in relation to sphere diameter for different relative port area's in.

From the results a basic rule of thumb can be applied, which implies that for single beam measurements on horticultural screens, the port fraction should not exceed 0.5% to reach an accuracy of ±5%.

In Figure 13. the relation between port diameter and sphere diameter is shown. According to this an 350 mm integrating sphere is required to keep the substitution error below 5% with a sample port of 50 mm.

Projectnummer: 3242137800