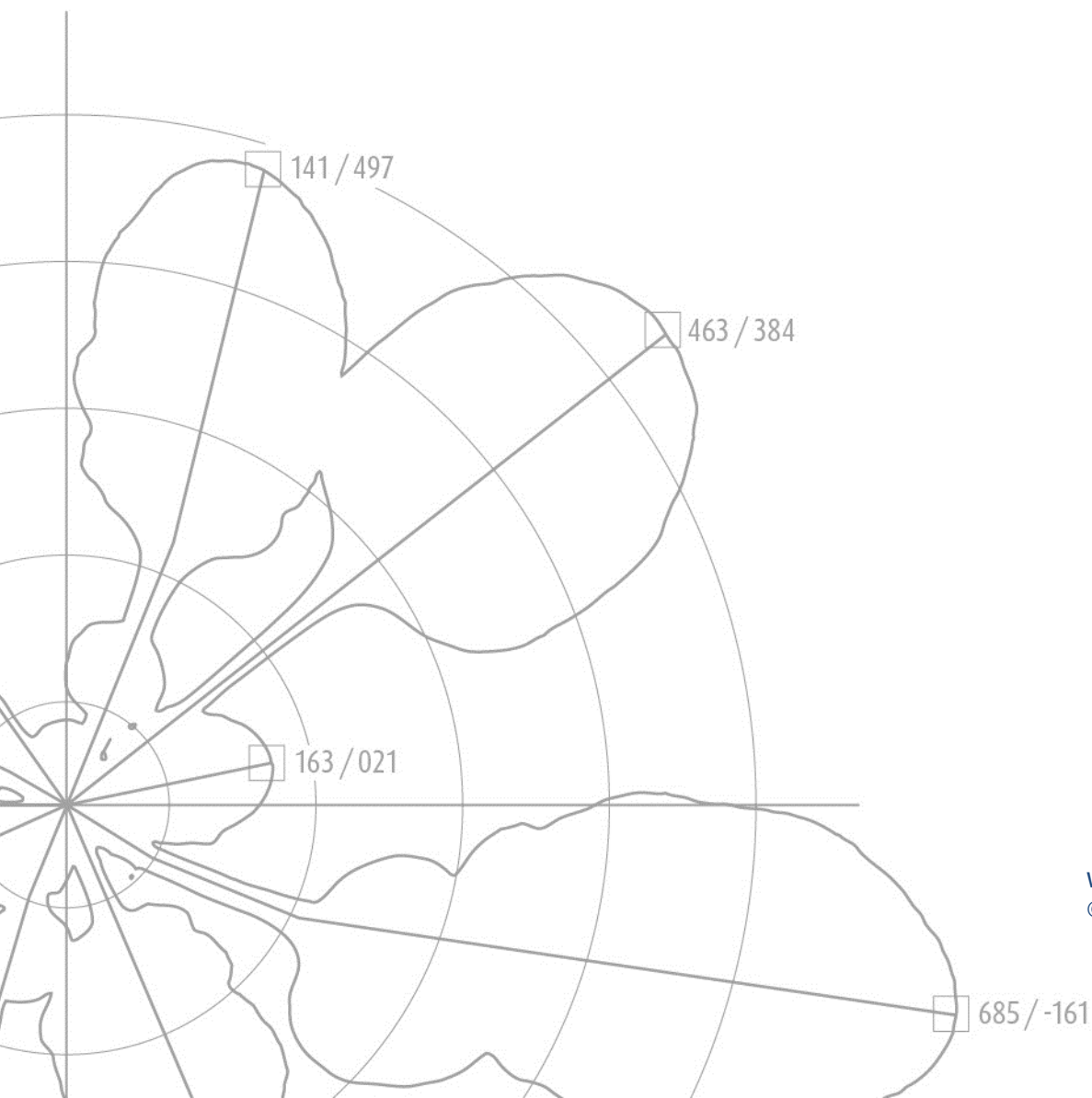




»» 09001-Sensor Accuracy

Sensor documentation for the multi sensor platform

Specification, Manufacturer information and details



Version 1: Monday, 05 September 2016
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Overview:

Sensorbox:

VIS 1
 VIS 2
 PSII
 FLIR
 HS-VNIR
 HS-SWIR
 3D Laser 1
 3D Laser 2
 NDVI
 CropCircle
 PRI
 CO²
 Illumination

Side:

VIS 3
 VIS 4
 VIS 5
 VIS 6
 3D Laser 3
 3D Laser 4
 3D Laser 7
 3D Laser 8

Top:

Thies environmental
 NDVI
 PRI
 PAR
 Spectrometer

Sensor		Calibration		Recalibration		Certification	Test specimen
		calibrated	not calibrated	recalibration by manufacturer	recalibration by customer		
Hyperspec VNIR		X	-	-	-	X	X
Hyperspec SWIR		X	-	-	-	X	X
3D Laserscanner		X	-	-	-	-	X
FLIR IR		X	-	-	-	X	-
VIS RGB		-	X	-	-	-	X
PSII camera		-	X	-	-	-	-
CO ² sensor	TOP	X	-	-	-	X	-
PAR				-	-	-	-
NDVI (Top)		X	-	1.9.2017	-	X	-
PRI (Top)		X	-	1.9.2017	-	X	-
ColorSense / spectrometer		X	-	-	-	-	-
Environmental Sensor / Thies		-	X	-	-	-	-
CropCircle	Sensorbox	-	X	-	-	-	-
NDVI		X	-	1.9.2017	-	X	-
PRI		X	-	1.9.2017	-	X	-



Figure 1: Prosilica GT 3300C color

RGB Camera (Sensorbox)

Manufacturer:

Alliec Vision Technologies GmbH
Taschenweg 2a
07646 Stadtroda
Germany

Model: Prosilica GT 3300C color

Specification:

Interface	IEEE 802.3 1000BASE-T, IEEE 802.3af (PoE)
Resolution	3296 × 2472
Sensor	OnSemi KAI-08051
Sensor type	CCD Progressive
Sensor size	Type 4/3
Cell size	5.5 µm
Lens mount	F-Mount
Max frame rate at full resolution	14.7 fps
ADC	14 bit
On-board	FIFO 128
Output Bit depth	14 (mono) - 12 (color) bit
Mono modes	Mono8, Mono12, Mono12Packed, Mono14
Color modes	YUV YUV411Packed, YUV422Packed, YUV444Packed
Color modes	RGB RGB8Packed, BGR8Packed, RGBA8Packed, BGRA8Packed
Raw modes	BayerGR8, BayerGR12, BayerGR12Packed
General purpose inputs/outputs (GPIOs)	
TTL I/Os	1
Opto-isolated I/Os	1 input, 2 outputs
RS-232	1
Operating temperature	-20°C ... +60°C
Power requirements (DC)	PoE, or 7-25 VDC
Power consumption (@12 V)	6.9 W (PoE) / 5.6 W @ 12 VDC
Mass	314 g
Body dimensions (L × W × H in mm)	121 × 59.7 × 59.7 (including connectors, w/o tripod and lens)
Regulations	CE, FCC Class A, RoHS (2011/65/EU)

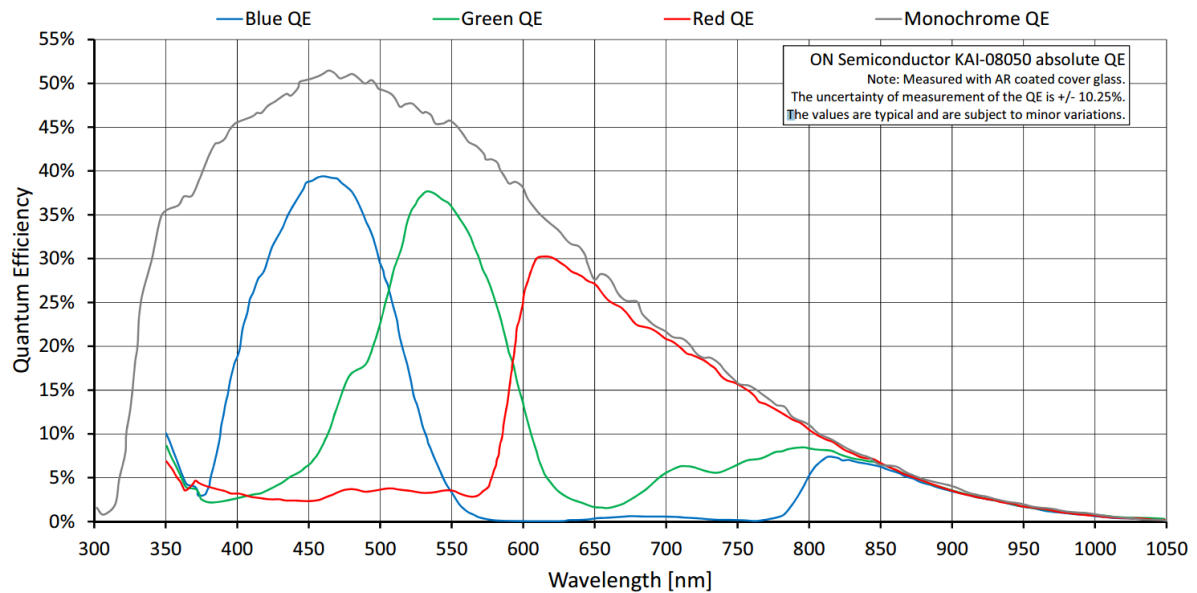
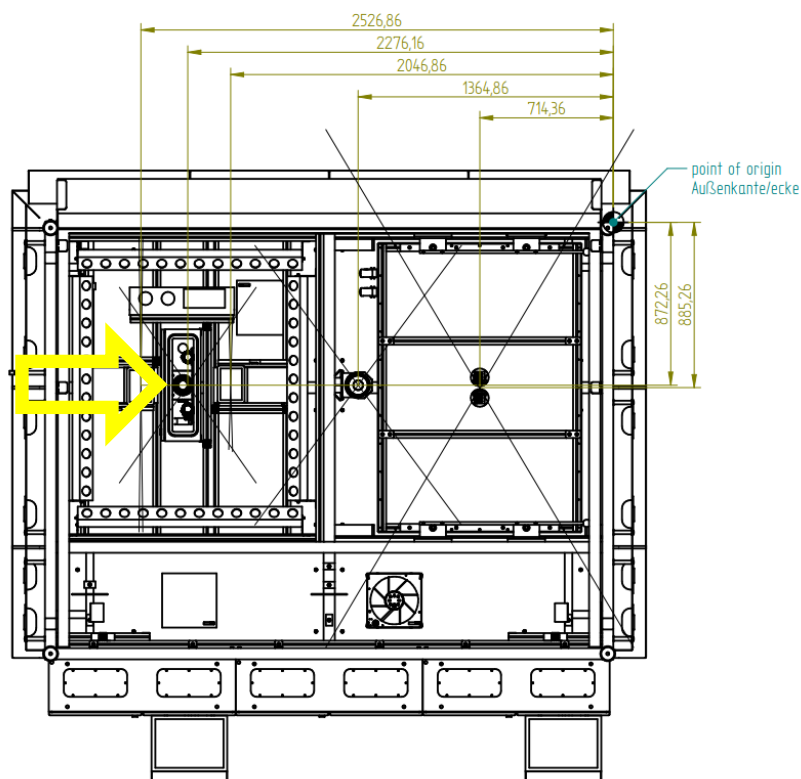
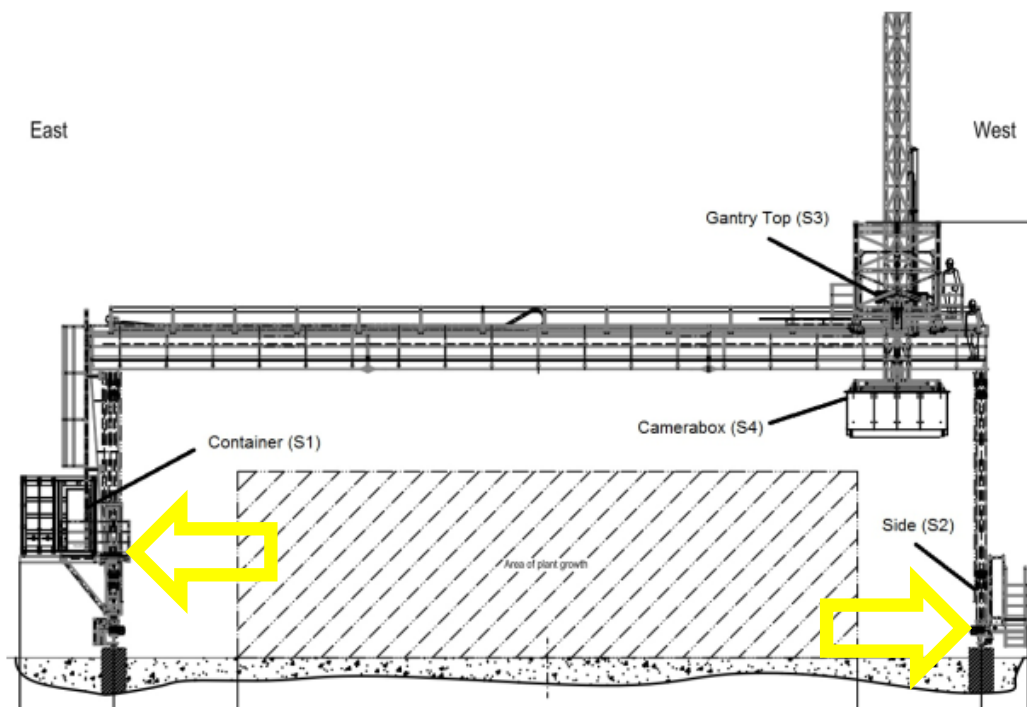


Figure 2: Prosilica GT 3300C color quantum efficiency

Hardware integration:





Test specimen:

Model: Imatest ISO 12233:2014 Edge SFR chart

Manufacturer: Imatest LLC, 4775 Walnut Street, Suite 200, Boulder, CO 80301 USA

Model: X-Rite ColorChecker Classic Spektralfotometer - MSCCC

Manufacturer: X-Rite Europe GmbH, Althardstrasse 70, 8105 Regensburg Schweiz

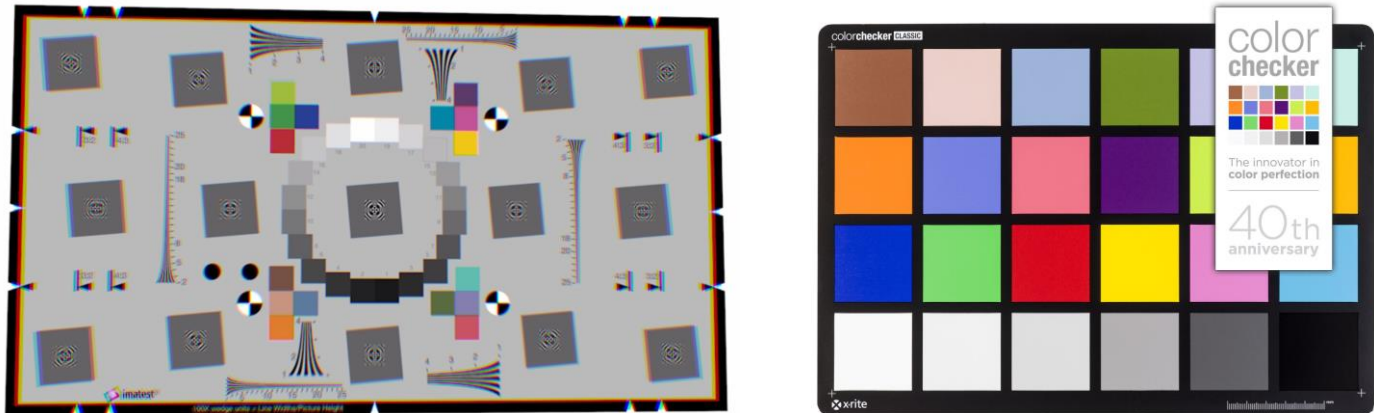


Figure 3: Testchart Imatest ISO 12233:2014 (left) and X-Rite ColorChecker Classic Spektralfotometer - MSCC (right)

Test results & Analysis:

Data acquisition	
	Basis is at least one measurement with every camera / each stereo system
Condition	
	Performed during daylight Artificial light is enabled due to shadowing Test specimen from IMATEST and XRITE as well as a ruler Positioned in the middle of the field of view Distance to test specimen: 2m Number of Iterations: 1X Output: RAW data
Sensor Settings:	
	"sensor_variable_metadata": { "rotate flip type - left": "0", "crosshairs - left": "0", "exposure - left": "2500", "autoexposure - left": "0", "gain - left": "1500", "autogain - left": "0", "gamma - left": "50", "rwhitebalanceratio - left": "170", "bwhitebalanceratio - left": "103", "rotate flip type - right": "0", "crosshairs - right": "0", "exposure - right": "2500",



	<pre>"autoexposure - right": "0", "gain - right": "1500", "autogain - right": "0", "gamma - right": "50", "rwhitebalanceratio - right": "155", "bwhitebalanceratio - right": "110", }</pre>
Analysis	
Sharpness and distortion:	Using the IMATEST software and related test chart a report is generated, which contains , sensor accuracand sensor noise. A rough test on image resolution is obtained from a ruler or a checkerboard in the image.
Color:	Using the IMATEST software and the x-rite color chart a report focusing on color fidelity is generated.
Hot pixels:	Using the IMATEST software and a specific homogeneous test specimen (spectralon) a check for hot pixels is performed. This test is performed at short distance (80cm) such that the spectralon target covers the entire image.
Sensor alignment:	VIS 1 & 2 need to take images (triggering) at the same time. A stopwatch is imaged to calculate the time difference. This test is repeated 10 times. Attention: use a short exposure time. Alignment check. Corresponding points do have <5% deviation regarding the complete pixel size (width / height)

Calibration details:

Not calibrated!

Recalibration:

Not calibrated!

3D Laserscanner (Sensorbox)

Manufacturer:

Fraunhofer-Entwicklungszentrum Röntgentechnik
ein Bereich des Fraunhofer-Instituts für integrierte Schaltungen im IIS
in Kooperation mit Fraunhofer IZFP
Flugplatzstraße 75
90768 Fürth
Germany

Model: Fraunhofer Prototype 2000mW

Specification:

For the 3D data acquisition of plants
Usable during daylight and at direct sun light
Z-axis measurable distance for side-view 3-4m
Measurable width for top-view 0.5m
Measurable depth for all views 0.5m
Working distance (distance between casing / box to the middle of the measurable window) about 2-3m
Resolution for all axis at a scan speed of 10m/s at least 0.5mm

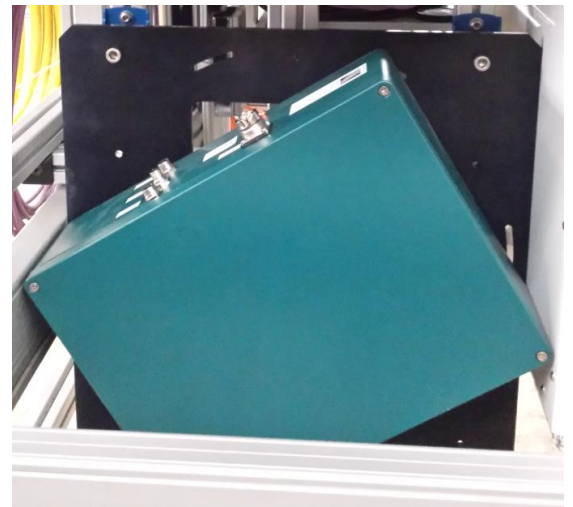
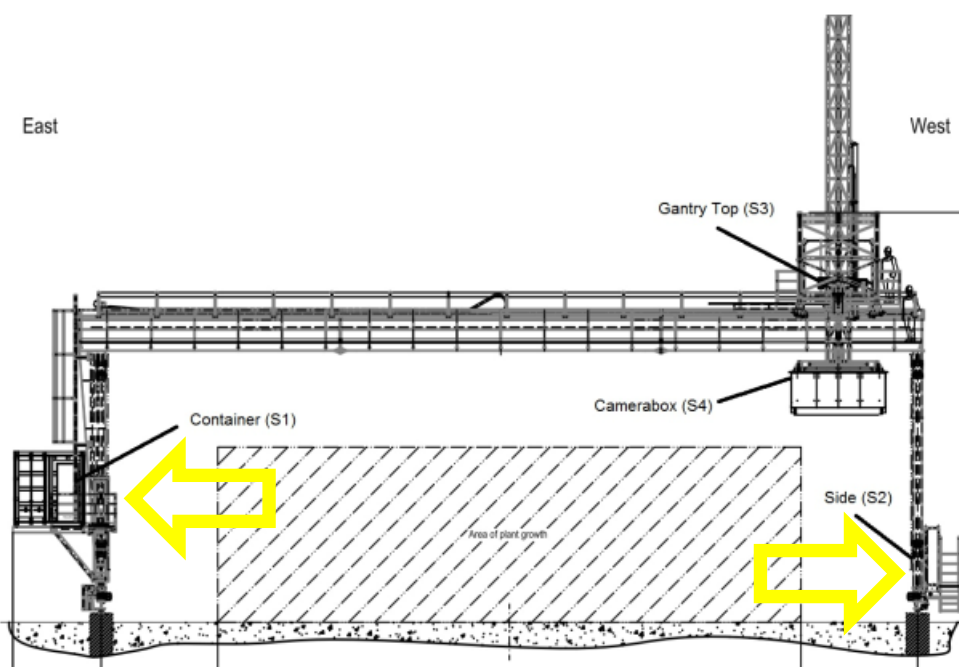
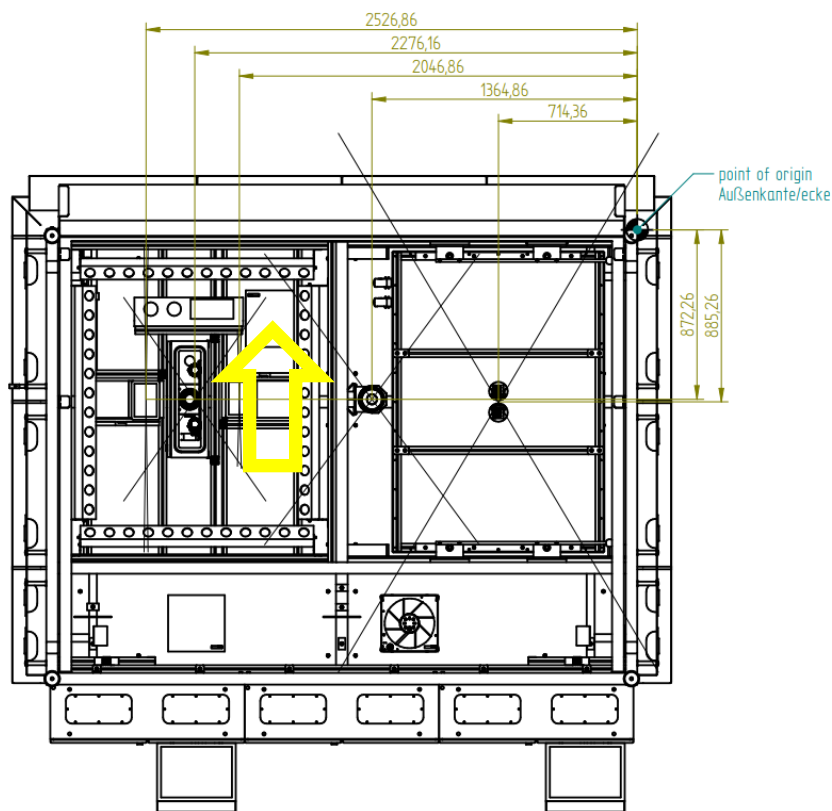


Figure 4: Fraunhofer 3D Laserscanner

Hardware integration:



Test specimen:

There are two test specimen for the calibration of the laser and between the two lasers together. The manufacturers test specimen is used to calibrate the two sensors against each other and to provide a good sensor registration. The second test specimen is provided by LemnaTec and can be used to evaluate the sensor quality regarding plane estimation, resolution and deviation. Specification of the test specimen including a CAD model will be provided additionally to this document.

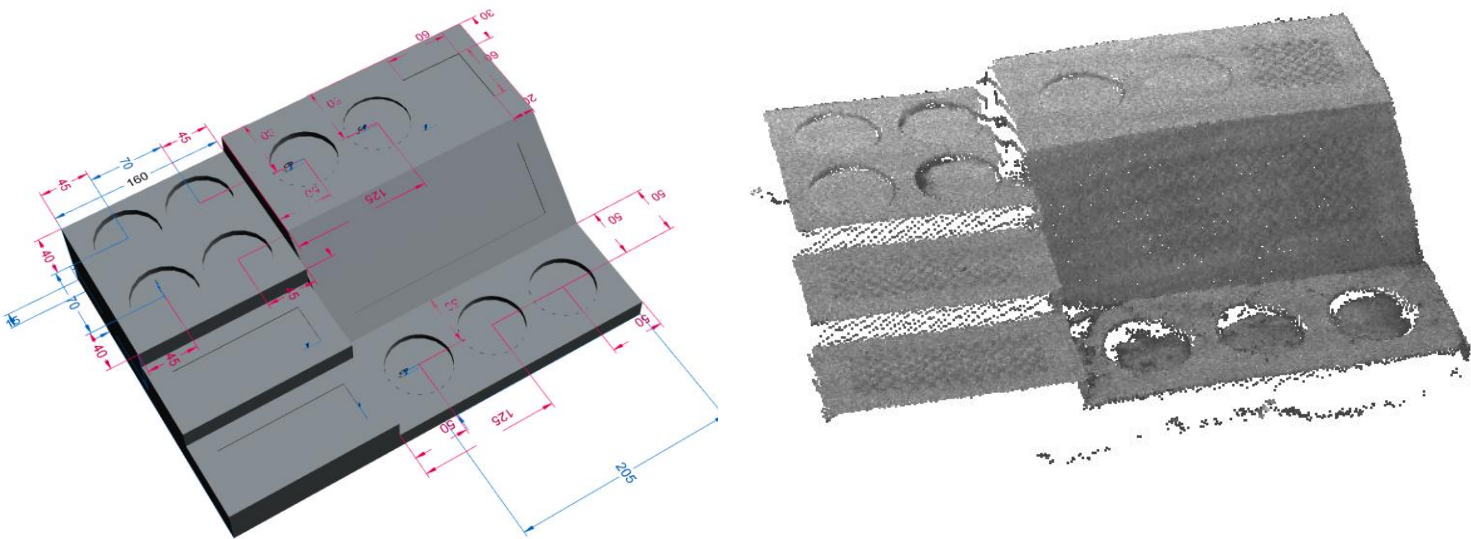


Figure 5: Laserscanner Test specimen



Test results & Analysis:

Data acquisition	
	Basis is at least one measurement with every laserscanner / each stereo laser system
Condition	
	<ul style="list-style-type: none">• Performed during daylight or night as sensor works independent of illumination• Artificial light is disabled• Test specimen from Fraunhofer and LemnaTec• Distance to test specimen: 3-5m• Number of Iterations: 3 times• Speed: 0.1m/s
Sensor Settings	
	<pre>"sensor_variable_metadata": { "current setting Exposure [microS]": "70", "current setting Calculate 3D files": "0", "current setting Laser detection threshold": "512", "current setting Scanlines per output file": "100000", "current setting Scan direction (automatically set at runtime)": "1", "current setting Scan distance (automatically set at runtime) [mm]": "4000", "current setting Scan speed (automatically set at runtime) [microMeter/s]": "100000" }</pre>
Analysis	
Test for accuracy:	Using the described test specimen a plane is fitted to a point cloud area showing point from a plane. Using CloudCompare a freeware point cloud processing software (http://www.danielgm.net/cc/), the deviation in mm within the plane scan is calculated.
Test for stereo measuring:	Using a combined set of laserscans coming from both sensors a plane fitting is performed and analysed.
Test for measurable volume:	Using upper and lower limit of the measurable volume, by adjusting the height of the sensor box, a scan of the known test specimen is performed. The analysis is performed in accordance to the test for accuracy.

Calibration details:

Stereo laser calibration details:

The stereo calibration raw data is recorded at any time for each camera. This enables a subsequent calibration if a former calibration is defect.

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.



Hyperspectral Camera VNIR (Sensorbox)

Manufacturer:

Headwall Photonics, Inc.
601 River Street
Fitchburg, Massachusetts 01420
USA

Model: 1003C-10147 E-Series

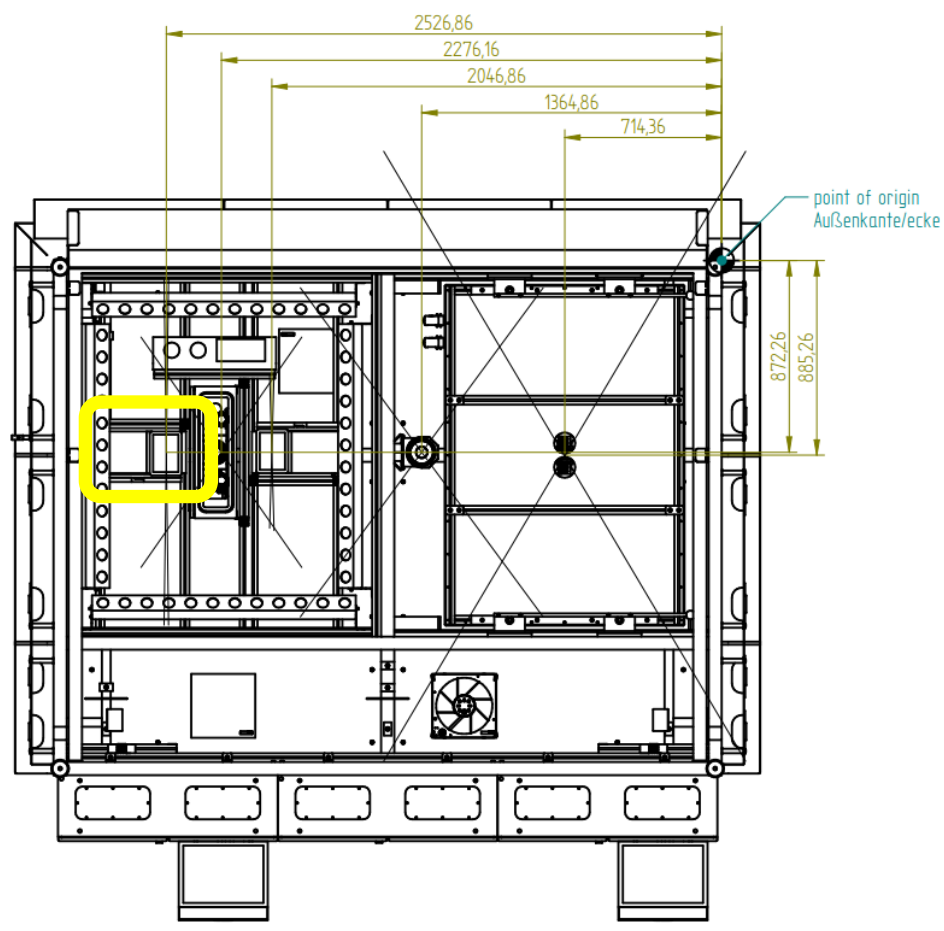
Specification:

Spatial Bands:	1600
Spectral Range:	380-1000nm
Spectral Bands:	923
Dispersion:	0.65 nm/pixel
Pixel pitch:	6.5 microns
Optics manufacturer:	Schneider Kreuznach
Optics name:	Xenoplan
Optics focal length [mm]:	17
Optics focus aperture:	1.4



Figure 6: Headwall VNIR Hyperspec camera

Hardware integration:



Test specimen:

Model: Zenith Polymer diffuse reflectance SG 3156 \approx 95 % 500x500x12 mm (approx. 20x20 inch)
Manufacturer: SphereOptics GmbH, Herrsching, Germany

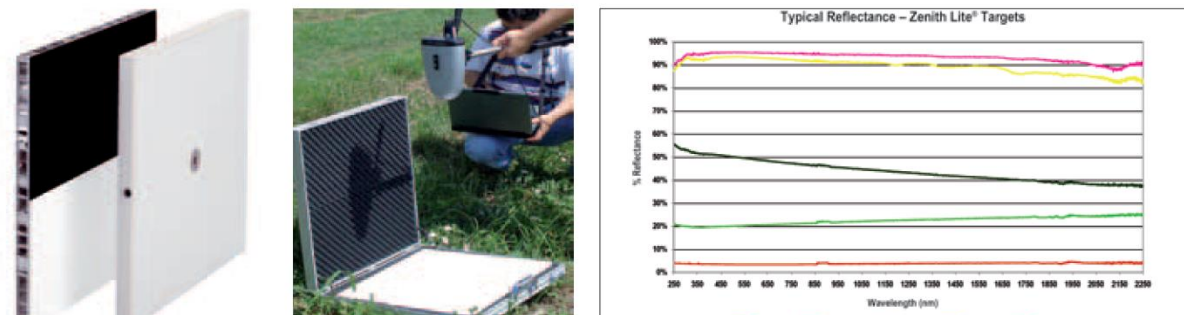


Figure 7: Hyperspectral test specimen

Test results & Analysis:

Data acquisition	
	Basis is one measurement with the sensor
Condition	
	Performed during daylight Artificial light is enabled, 5 min warm-up time for halogen lights Test specimens are a spectralon and a ruler Positioned in the middle of the Field of View Distance to test specimen: 2m Measurement speed: 0.02m/s Number of Iterations: 1X
Sensor Settings:	
	<pre>"sensor_variable_metadata": { "current setting frameperiod": "50", "current setting userotatingmirror": "0", "current setting useexternaltrigger": "0", "current setting exposure": "45", "current setting createdatacube": "0", "current setting speed": "100", "current setting constmirrorpos": "0", }</pre>
Analysis	
Test for homogeneity:	The spectralon target is measured at five positions within the measurable field. Every measurement should result in similar intensity values for the spectralon. If the intensity values are similar (<5%) than the camera is defined to provide homogeneous measurements.
Testing the camera:	Using the test specimen for the RGB camera a complete scan of the test object is acquired. This result is transferred to a standard RGB image and analyzed using ImaTest software as it has been used for the test of the RGB camera. This will provide information about resolution, accuracy and lense distortion. 8 calibrated Spectralon targets (integrated in the 3D test specimen) are measured 10 times. Their measured spectrum is compared to the calibrated spectrum. Both are plotted and compared. The mean error is computed. Both values should not deviate more than 10%.

It is recommended that this unit is tested every six months and to recalibrate the unit if necessary, maybe even earlier than expected.



Calibration details:

Certificate no: CD-1057 Rev A05
 Title: Hyperspec VS Spectrograph Certificate of Compliance
 Serial number: G4-384
 Date of calibration: 11/12/2015

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.

Hyperspectral Camera SWIR (Sensorbox)

Manufacturer:

Headwall Photonics, Inc.
601 River Street
Fitchburg, Massachusetts 01420
USA

Model: 1003A - 10174 (900-2500nm)

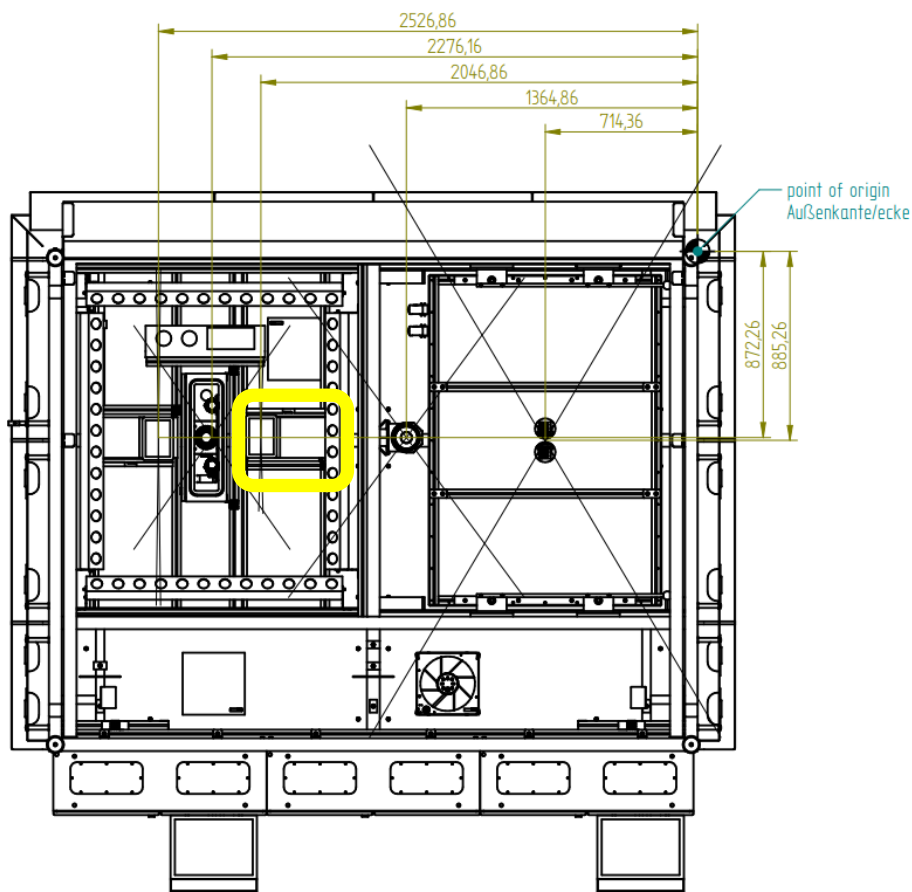
Specification:

Spatial Bands:	384
Spectral Range:	900-2500nm
Spectral Bands:	267
Dispersion:	6 nm/pixel
Pixel pitch:	24 microns
Optics manufacturer:	Stingray optics
Optics name:	SR-1200-030 F/1.3 0.48-2.5µm
Optics focal length [mm]:	25
Optics focus aperture:	2.0



Figure 8: Hyperspectral SWIR camera

Hardware integration:





Test results & Analysis:

Data acquisition	
	Basis is one measurement with the sensor
Condition	
	Performed during daylight Artificial light is enabled, pay attention to the warming of the lights Test specimen is a spectralon well as a ruler Positioned in the middle of the measurable volume Distance to test specimen: 2m Measurement speed: 0.02m/s Number of Iterations: 1X
Sensor Settings:	
	<pre>"sensor_variable_metadata": { "current setting frameperiod": "50", "current setting userotatingmirror": "0", "current setting useexternaltrigger": "1", "current setting exposure": "45", "current setting createdatacube": "0", "current setting speed": "100", "current setting constmirrorpos": "0", }</pre>
Analysis	
Test for plausibility:	Measuring the artificial light, the spectrum of the halogen lamps is recorded and checked for plausibility.

Calibration details:

Certificate no: CD-1057 Rev A05
Title: Hyperspec VS Spectrograph Certificate of Compliance
Serial number: G4-383
Date of calibration: 09/21/2015o

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.



PS II Camera (Sensorbox)

Manufacturer:

LemnaTec GmbH
Pascalstr. 59
52076 Aachen
Germany

Model: LemnaTec PS II Fluorescence Prototype

Specification:

Camera:	
Model and Manufacturer:	AVT Manta G 235b
Interface:	IEEE 802.3 1000BASE-T (no PoE)
Resolution:	1936 × 1216
Sensor type:	CMOS Progressive
Sensor size Type:	1/1.2
Cell size:	5.86 μm
Max frame rate at full resolution:	50 fps
Bit depth:	8 - 12 Bit
Mono modes:	Mono8, Mono12Packed, Mono12
Operating temperature:	+5 °C ... +45 °C
Power consumption:	2.8 W @ 12V

Objective:	
Main Sensor size:	1"
Focal length (mm):	8.0 mm
Iris range (F-stop):	f/1.40 – f/16
Focusing range (m):	0.1000 m
Iris Control:	Manual
Focus Control:	Manual

Resolution	
Center:	120.00 lp/mm
Corner:	80.00 lp/mm
Pixel-Size:	5.00μm
Distortion (TV)	-1.20%
Back focus in air (mm)	11.20 mm
Size	ø57 × 58 mm
Mount	C-mount



Figure 9: LemnaTec PS II camera

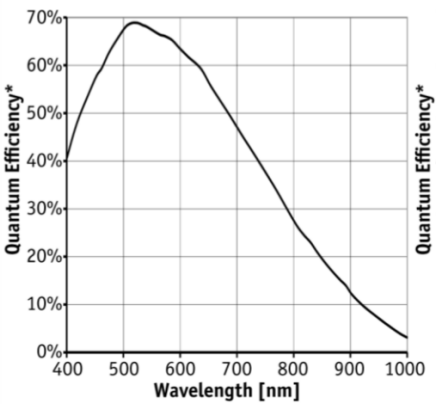


Figure 10: PS II quantum efficiency



Temperature range (°C)	-10°C - +45°C
Filter details:	
Transmission Band 1	Tavg > 93% 690 – 730 nm
Center Wavelength	1 710 nm
Guaranteed Minimum Bandwidth	1 40 nm
FWHM Bandwidth 1 (nominal)	47.5 nm
Blocking Band 1	ODavg > 5 200 – 673 nm
Blocking Band 2	OD > 3.5 741 nm
Blocking Band 3	ODavg > 10 752 – 798 nm (Design specification - measurements are noise-floor limited)
Blocking Band 4	ODavg > 4.5 798 – 925 nm
Blocking Band 5	ODavg > 2 925 – 1100 nm
Angle of Incidence	0 ± 5 degrees
Cone Half-angle	7 degrees
Effective Index	1.77
Transverse Dimensions (Diameter)	21.8 mm
Transverse Tolerance (mounted)	+ 0.0 / – 0.1 mm
Filter Thickness Tolerance (Mounted)	± 0.1 mm
Scratch-Dig	60-40
Substrate Thickness (unmounted)	3.5 mm

LED Lamps

According to the manufacturers datasheet the dominant wavelength (DWL) is in the range of 620 – 630 nm. This specification must be considered more accurate. The dominant wavelength changes due to internal thermal issues in the LED itself within a few milliseconds after switching on. It is stable at 636nm after about 200ms.

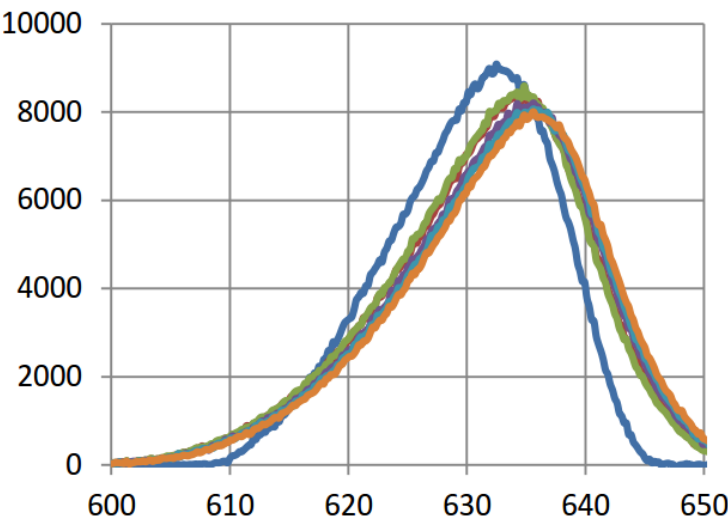
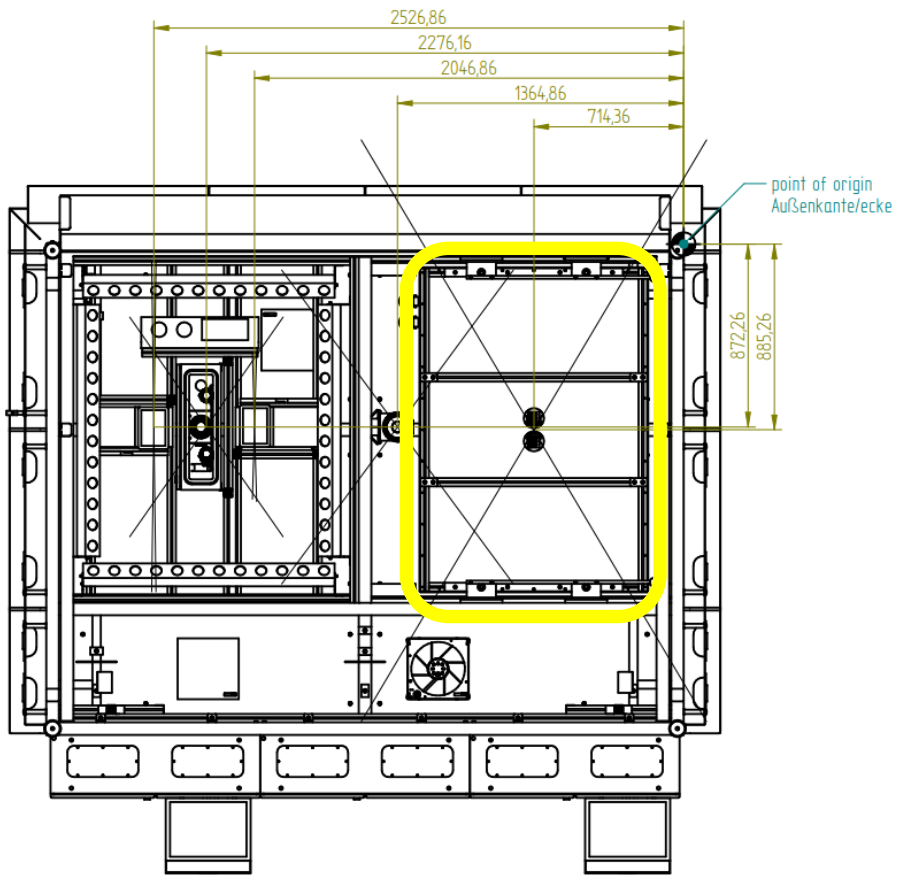


Figure 11: LED Lamps Intensity showing wavelength (x-axis) and intensity in counts (y-axis)

Hardware integration:



Test specimen:

Model: Fluorescence tile
Manufacturer: PhenoVation B.V., Droevendaalsesteeg 1, 6708PB Wageningen, The Netherlands



Figure 12: Fluorescence test specimen



Test results & Analysis:

Data acquisition	
	Basis is one measurement with the sensor
Condition	
	Performed during night Artificial light is disabled Test specimen is a Fluorescence PSII target Positioned in the middle of the measurable volume Distance to test specimen: 0.8m Number of Iterations: 1X
Sensor Settings:	
	<pre>"sensor_variable_metadata": { "current setting rotate flip type": "0", "current setting crosshairs": "0", "current setting exposure": "28", "current setting gain": "3000", "current setting gamma": "100", "current setting ledcurrent": "60" }</pre>
Analysis	
Testing the fluorescence:	Measure above ground and above plants. For the plants a result > 0.75 is expected for the calculation of FV/FM and for the ground a value close to zero. Use different flash intensities for the testing.
Testing for homogeneity	Test for homogeneity illumination. By using five different positions of the camera - test specimen layout we can check the illumination distribution within the image.

Calibration details:

Recalibration:

Infrared Imager (Sensorbox)

Manufacturer:

FLIR Systems, Inc.
27700 SW Parkway Ave.
Wilsonville, OR 97070
USA

Model: FLIR A615 (640x480 @50Hz, 25°lense)

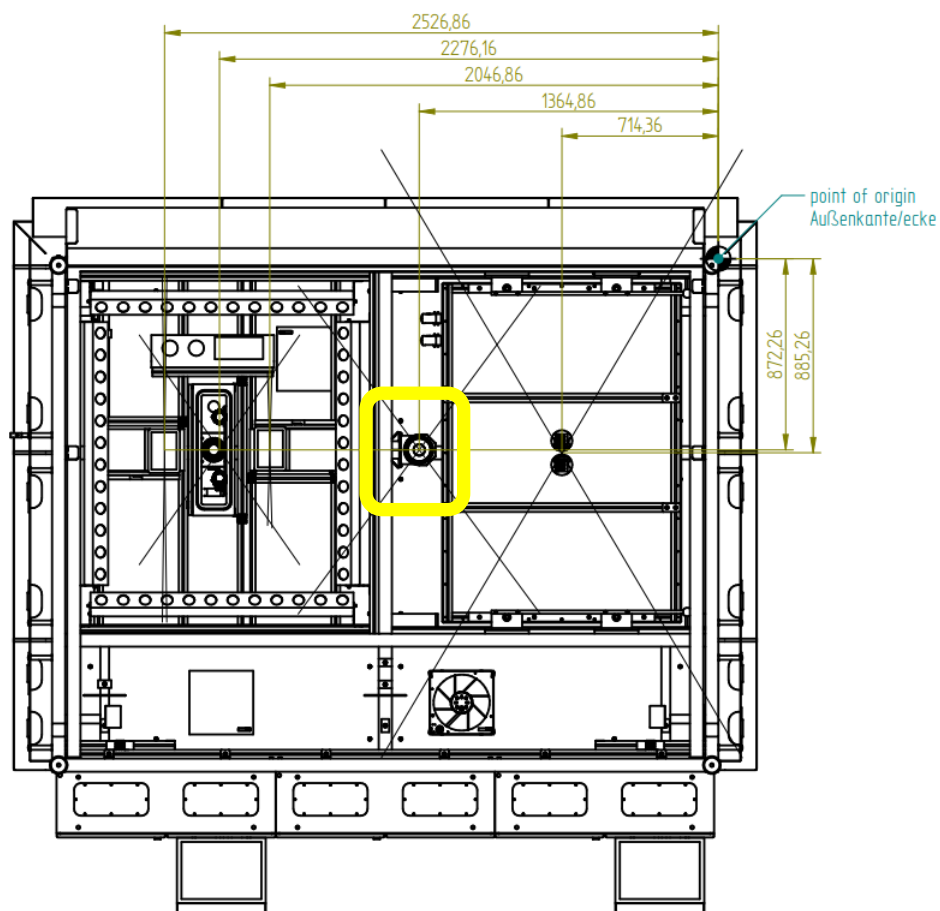
Specification:

IR resolution:	640 x 480
Thermal sensitivity:	< 0.05°C @ +30°C (+86°F) / 50 mK
Spectral range:	7.5-14 µm
F-number:	1.0
Spectral range:	7.5-14 µm
Detector pitch:	17 µm
Object temperature range:	-40°C to +150°C (-40°F to +302°F)
Accuracy:	±2°C (±3.6°F) or ±2% of reading
Emissivity correction:	Variable from 0.01 to 1.0
Lense:	T197914; IR lens, f=41.3 mm (15°) with case



Figure 13: Thermal camera / FLIR camera

Hardware integration:





Test results & Analysis:

Data acquisition	
	Basis is one measurement with the sensor
Condition	
	Performed during daylight Artificial light is disabled Test specimen is a black body cavity radiator specimen The reference sensor is an external thermal sensor. Positioned in the middle of the measurable volume Distance to test specimen: 2m Number of Iterations: 1X
Sensor Settings:	
	<pre>"sensor_variable_metadata": { "current setting AutoFocus": "1", "current setting Manual focal length [cm]": "200", }</pre>
Analysis	
Analysis	A correlation between IR output and thermal sensor is calculated as 1:1 correlation plot Mean average relative error is calculated and is expected to be less than 5%..

Calibration details:

Certificate no: -
Serial number: 55003076
Model number: FLIR A615
Date of calibration: 09/24/2015

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.



CROP CIRCLE (Sensorbox)



Figure 14: Crop Circle sensor

Manufacturer:

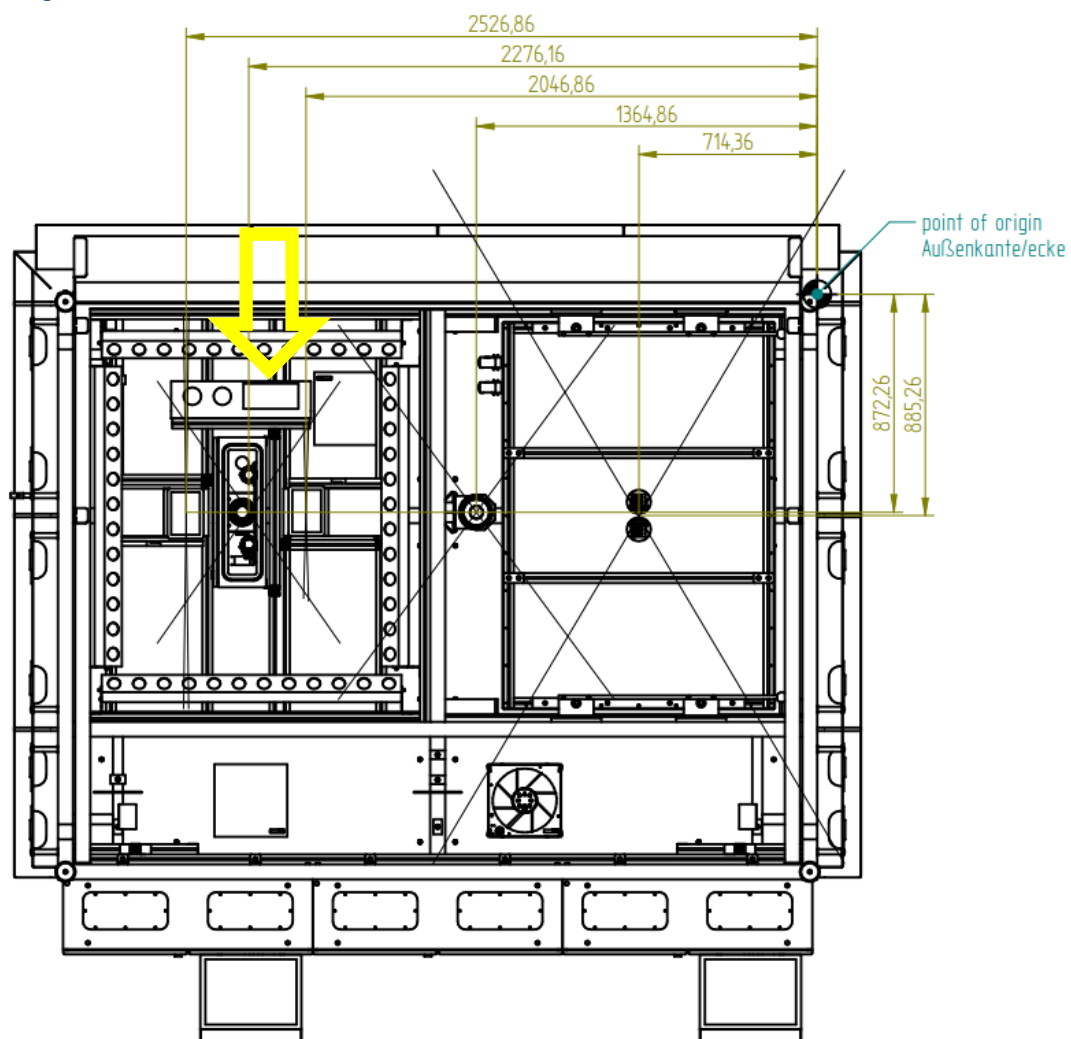
CropCircle: HollandScientific
Holland Scientific, Inc.
6001 South 58th Street
Suite D
Lincoln, NE 68516
USA

Model: Crop Circle ACS-430 Active Crop Canopy Sensor

Specification:

Sensor-to-Canopy Range:	Typically 10 in (25 cm) to >72 in (183 cm)
Field-of-View:	~30 degrees by ~14 degrees
Active Light Source:	Modulated polychromatic LED array
Photodetection:	Three channel silicon photodiode array with spectral range of 320 nm to 1100 nm
Optical Measurement Bands: 670 nm, 730nm and 775nm	
Enclosure:	Injection molded polycarbonate
Environmental:	IP68 for dust and water resistance
Weight:	0.94 lb. (430 gm)
Sensor Mount:	(2) ¼ - 20 threaded holes in base of sensor spaced 1.25 in (3.18 cm)
Dimensions:	Width 3.5 in (8.9 cm), Length 7.9 in (20.1 cm), Height 1.9 in (4.8 cm)
Serial/Power Connector:	Four pin male Eurofast type, O-ring sealed
Sample Output Rate:	Programmable for 1 sample per second to 20 samples per second; Factory default 10 samples per second
Operating Range: 0 to 50 °C	
Communication Interface:	RS-485 multidrop (bidirectional communication);
RS-232 (autosend, output only)	
RS-232 Serial Communication: 76800, no parity, 8 data bits, 1 stop bit	
Power:	9 to 17V DC @ ~350 mA
EMC Certifications: C-Tick, CE	

Hardware integration:



Test results & Analysis:

<u>Data acquisition</u>	
	Basis is one measurements with the sensor
<u>Condition</u>	
	<p>Performed during daylight or night</p> <p>Artificial light is disabled</p> <p>No test specimen is used.</p> <p>Test scans were performed for vegetation and soil.</p> <p>Positioned in the middle of the measurable volume</p> <p>Distance to test specimen: 2m</p> <p>Number of Iterations: 1X</p>
<u>Sensor Settings:</u>	
	Factory settings (see calibration certificate)
<u>Analysis</u>	
Test for accuracy:	Manufacturer proposes a measurement over vegetation and soil. The wavelengths 670,730 & 780 nm were checked against an external spectrometer measurement.

Calibration details:

Recalibration:

NDVI (Sensorbox)

(633.0nm & 800.7nm)

Manufacturer:

Skye Instruments Ltd
21, Ddale Enterprise Park
Llandrindad Wells
Powyr LD1 6DF
United Kingdom

Model: SKR 1860NDA

Specification:

Range: 4 channels individually chosen at time of ordering between 400-2400 nm. Bandwidths from 5nm to several 100 nm

Construction: Plain anodised aluminium housing Cosine correcting head for incident. Waterproof rating IP65, fully weatherproof. Regular maintenance required to keep light collecting surfaces clean and free from obstruction, e.g. dust, moisture, algae etc

Filters: Metal interference and/or glass depending on wavelengths & bandwidths chosen, to military spec.

Detector: Silicon photodiode

Cable: Screened military specification. 3m. Standard length.

Temperature Range: -35 to +75 °C

Humidity Range: 0-100%

Output: SKR 1860D/ND - current output (nA) which varies with filters used.

Power supply: SKR 1860D/ND not required

Linearity: Better than 0.2% of scaled range.

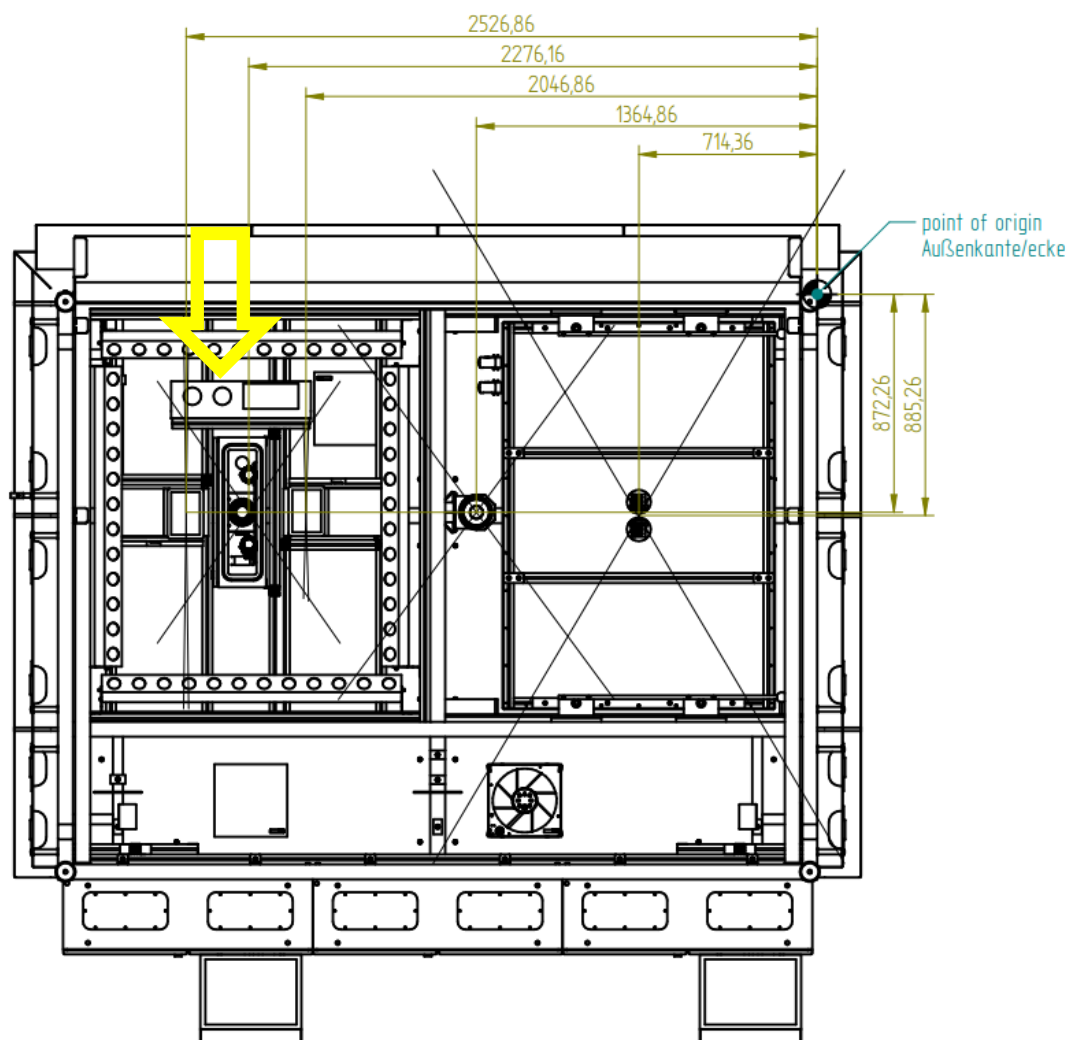
Response Time: SKR 1860D/ND - typically less than 100 nanoseconds.

Mounting: M6 x 7mm tapped hole in base. Sensor supplied with M6 x 16mm screw + 4x 1.5mm washers to suit panel thicknesses of 3-10mm



Figure 15: NDVI Sensor

Hardware integration:





Test results & Analysis:

Data acquisition	
	Basis are multiple (10-30) measurements with the sensor
Condition	
	Performed during daylight Artificial light is disabled Test scans were performed using the homogeneous spectralon, an area of grass and soil Positioned in the middle of the measurable volume Distance to test specimen: 2m Number of Iterations: 10-30X Reference data is coming from an external spectrometer measuring the same homogeneous ground data.
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows the correlation between these two sensors. RMSE and MAPE are not possible as we compare measurements of different aperture angle and different spectral resolution

Calibration details:

Certificate no: 1860NDA / 115 / 0915
Serial number: SKR 1860ND / A 45951
Date of calibration: 01/09/2015
Lamp reference: SK5
Calibration typically better than 5%. Note that this error is to some dependant on bandwidth - wide Bandwidths will be less subject to error than very low bandwidth channels.

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.

NDVI (Top)

(633.2nm & 799.7nm)

Manufacturer:

Skye Instruments Ltd
21, Ddale Enterprise Park
Llandrindad Wells
Powyr LD1 6DF
United Kingdom

Model: SKR 1860NDA



Figure 16: NDVI Sensor

Specification:

Range: 4 channels individually chosen at time of ordering between 400-2400 nm. Bandwidths from 5nm to several 100 nm

Construction: Plain anodised aluminium housing Cosine correcting head for incident. Waterproof rating IP65, fully weatherproof. Regular maintenance required to keep light collecting surfaces clean and free from obstruction, e.g. dust, moisture, algae etc

Filters: Metal interference and/or glass depending on wavelengths & bandwidths chosen, to military spec.

Detector: Silicon photodiode

Cable: Screened military specification. 3m. Standard length.

Temperature Range: -35 to +75 °C

Humidity Range: 0-100%

Output: SKR 1860D/ND - current output (nA) which varies with filters used.

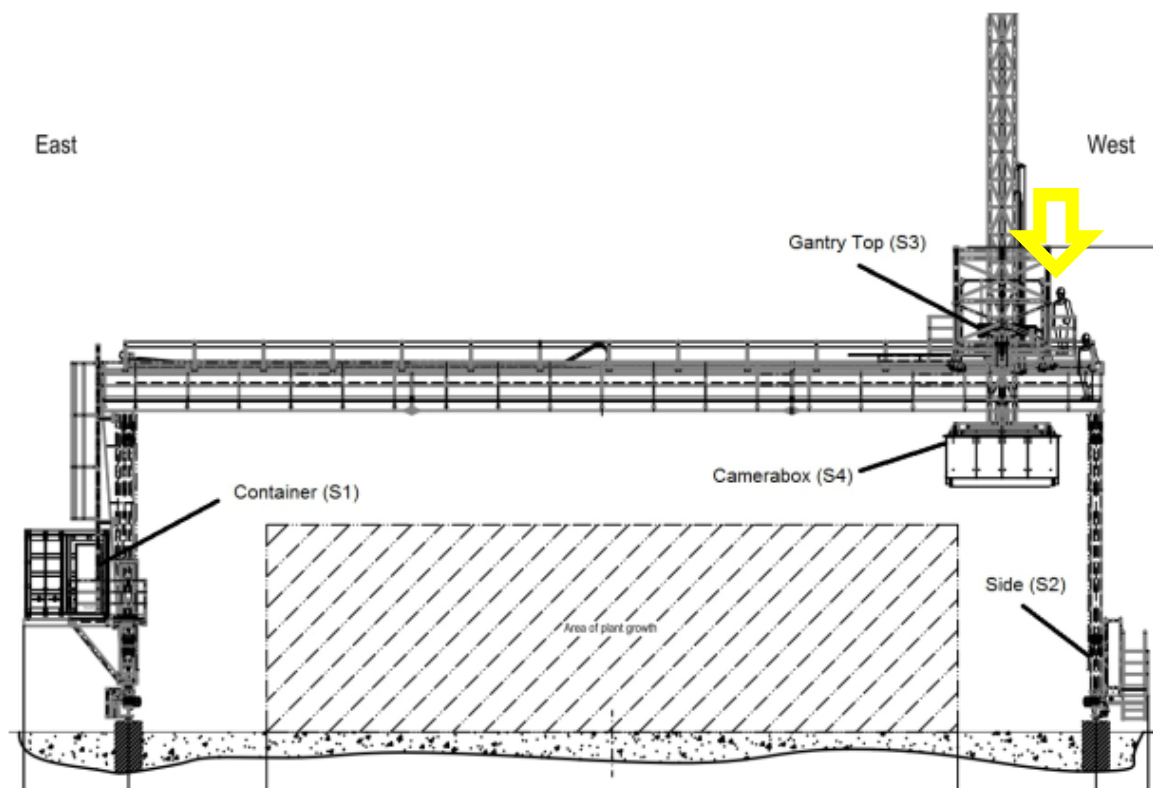
Power supply: SKR 1860D/ND not required

Linearity: Better than 0.2% of scaled range.

Response Time: SKR 1860D/ND - typically less than 100 nanoseconds.

Mounting: M6 x 7mm tapped hole in base. Sensor supplied with M6 x 16mm screw + 4x 1.5mm washers to suit panel thicknesses of 3-10mm

Hardware integration:

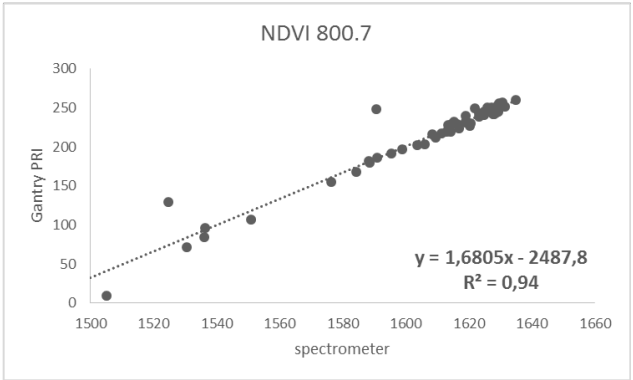
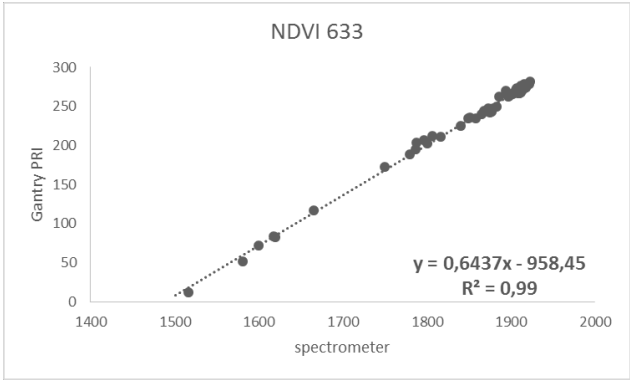




Test results & Analysis:

Data acquisition	
	Basis are multiple measurements with the sensor between June and July 2016
Condition	
	Performed during daylight Artificial light is disabled Number of Iterations: 10-30X Reference data is coming from the gantry spectrometer
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows the correlation between these two sensors. RMSE and MAPE are not possible as we compare measurements of different aperture angle and different spectral resolution

NDVI 633			NDVI 800,7		
R ²	Limit	Unit	R ²	Limit	Unit
0,99	0,7	degrees	0,94	0,7	μmol/sm ²



Calibration details:

Certificate no: 1860NDA / 117 / 0915
Serial number: SKR 1860ND / A 45952
Date of calibration: 01/09/2015
Lamp reference: SK5
Calibration typically better than 5%. Note that this error is to some dependant on bandwidth - wide Bandwidths will be less subject to error than very low bandwidth channels.

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.

PRI (Sensorbox)

(531.0nm & 569.3nm)

Manufacturer:

Skye Instruments Ltd
21, Ddale Enterprise Park
Llandrindad Wells
Powyr LD1 6DF
United Kingdom

Model: SKR 1860NDA

Specification:

Range: 4 channels individually chosen at time of ordering between 400-2400 nm. Bandwidths from 5nm to several 100 nm

Construction: Plain anodised aluminium housing Cosine correcting head for incident. Waterproof rating IP65, fully weatherproof. Regular maintenance required to keep light collecting surfaces clean and free from obstruction, e.g. dust, moisture, algae etc

Filters: Metal interference and/or glass depending on wavelengths & bandwidths chosen, to military spec.

Detector: Silicon photodiode

Cable: Screened military specification. 3m. Standard length.

Temperature Range: -35 to +75 °C

Humidity Range: 0-100%

Output: SKR 1860D/ND - current output (nA) which varies with filters used.

Power supply: SKR 1860D/ND not required

Linearity: Better than 0.2% of scaled range.

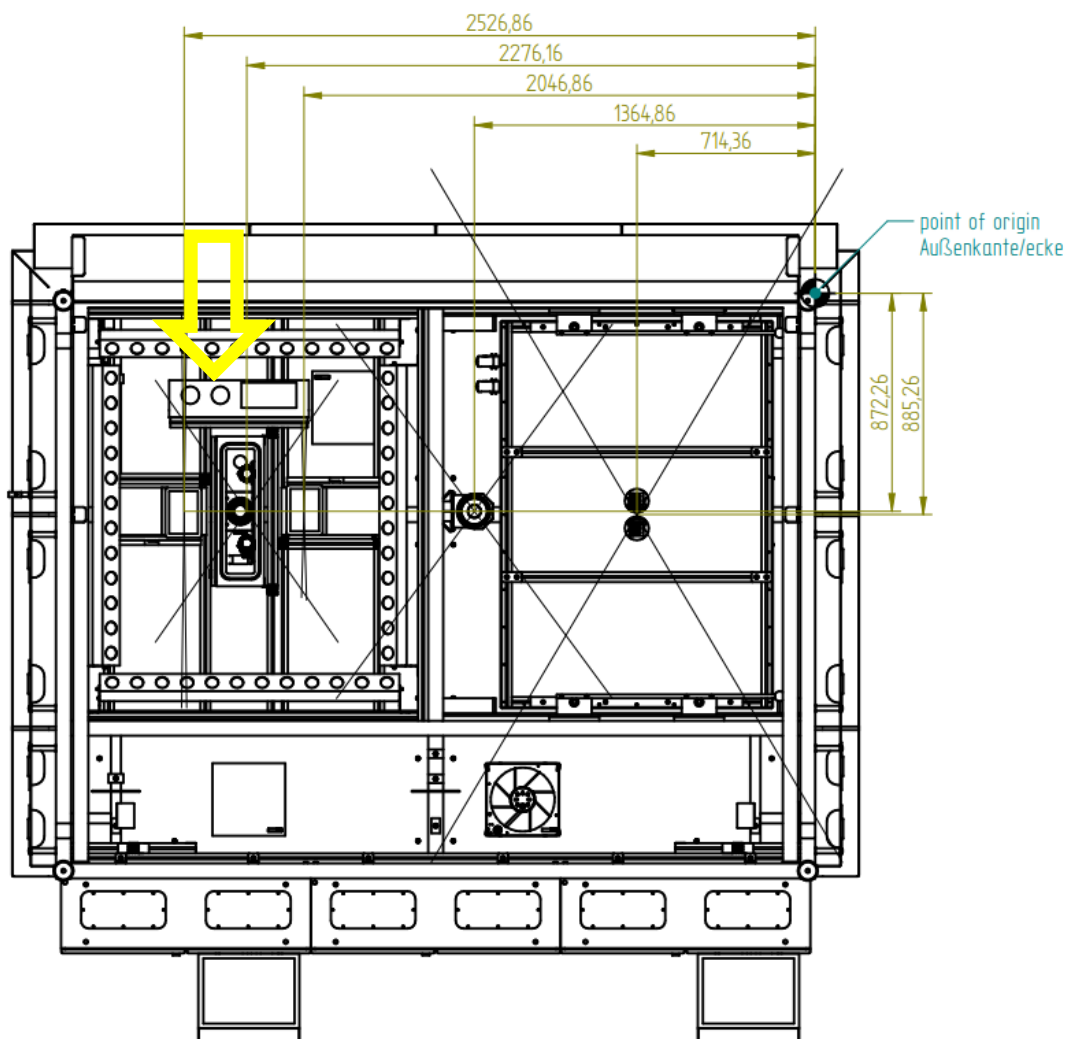
Response Time: SKR 1860D/ND - typically less than 100 nanoseconds.

Mounting: M6 x 7mm tapped hole in base. Sensor supplied with M6 x 16mm screw + 4x 1.5mm washers to suit panel thicknesses of 3-10mm



Figure 17: PRI Sensor

Hardware integration:





Test results & Analysis:

Data acquisition	
	Basis are multiple (10-30) measurements with the sensor
Condition	
	Performed during daylight Artificial light is disabled Test scans were performed using the homogeneous spectralon, an area of grass and soil Positioned in the middle of the measurable volume Distance to test specimen: 2m Number of Iterations: 10-30X Reference data is coming from an external spectrometer measuring the same homogeneous ground data.
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows the correlation between these two sensors. RMSE and MAPE are not possible as we compare measurements of different aperture angle and different spectral resolution

Calibration details:

Certificate no: 1860NDA / 115 / 0915
Serial number: SKR 1860ND / A 45954
Date of calibration: 01/09/2015
Lamp reference: SK5
Calibration typically better than 5%. Note that this error is to some dependant on bandwidth - wide Bandwidths will be less subject to error than very low bandwidth channels.

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.

PRI (Top)

(531.2nm & 568.9nm)

Manufacturer:

Skye Instruments Ltd
21, Ddale Enterprise Park
Llandrindad Wells
Powyr LD1 6DF
United Kingdom

Model: SKR 1860NDA

Specification:

Range: 4 channels individually chosen at time of ordering between 400-2400 nm. Bandwidths from 5nm to several 100 nm

Construction: Plain anodised aluminium housing Cosine correcting head for incident. Waterproof rating IP65, fully weatherproof. Regular maintenance required to keep light collecting surfaces clean and free from obstruction, e.g. dust, moisture, algae etc

Filters: Metal interference and/or glass depending on wavelengths & bandwidths chosen, to military spec.

Detector: Silicon photodiode

Cable: Screened military specification. 3m. Standard length.

Temperature Range: -35 to +75 °C

Humidity Range: 0-100%

Output: SKR 1860D/ND - current output (nA) which varies with filters used.

Power supply: SKR 1860D/ND not required

Linearity: Better than 0.2% of scaled range.

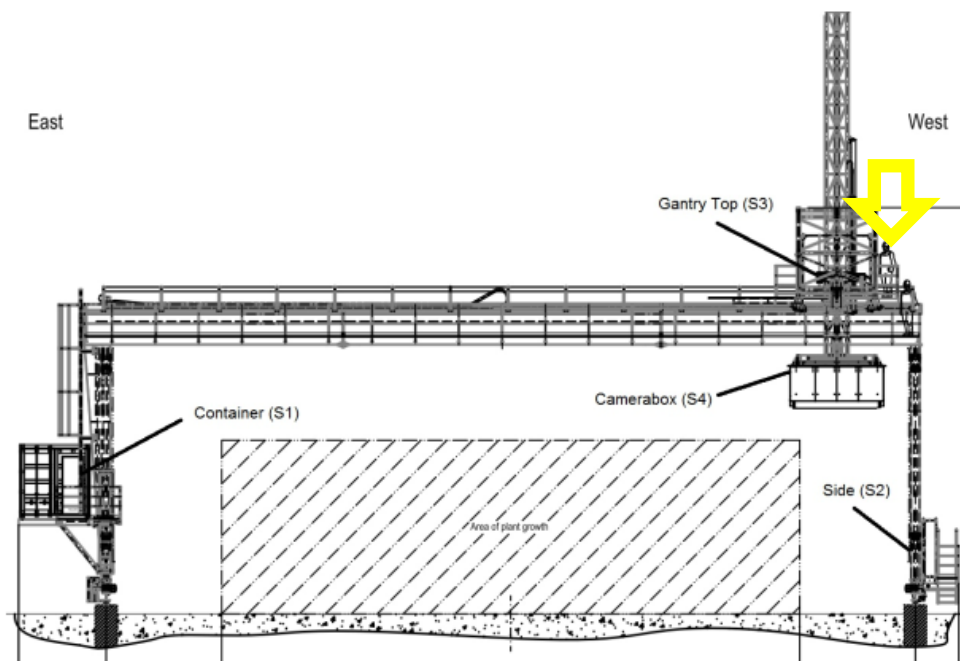
Response Time: SKR 1860D/ND - typically less than 100 nanoseconds.

Mounting: M6 x 7mm tapped hole in base. Sensor supplied with M6 x 16mm screw + 4x 1.5mm washers to suit panel thicknesses of 3-10mm



Figure 18: PRI Sensor

Hardware integration:

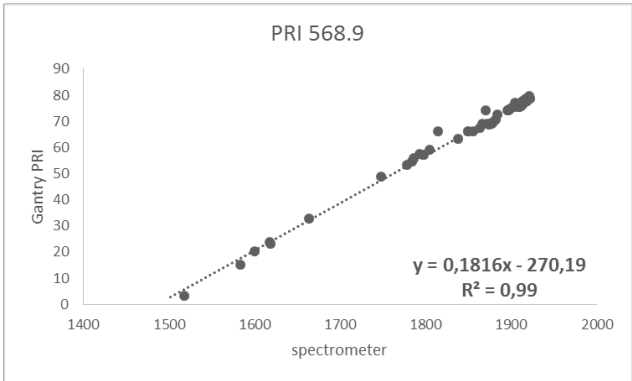
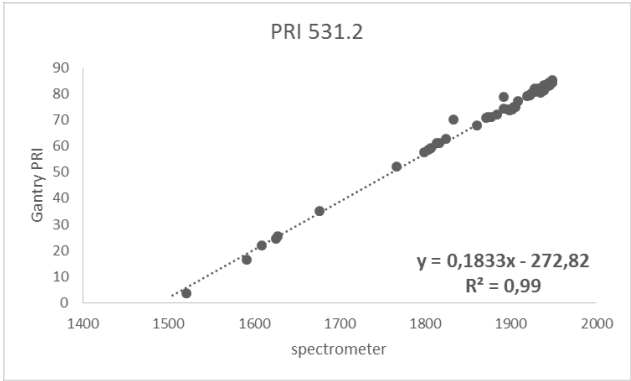




Test results & Analysis:

Data acquisition	
	Basis are multiple measurements with the sensor between June and July 2016
Condition	
	Performed during daylight Artificial light is disabled Number of Iterations: 10-30X Reference data is coming from the gantry spectrometer
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows the correlation between these two sensors. RMSE and MAPE are not possible as we compare measurements of different aperture angle and different spectral resolution

PRI 531.2			PRI 568.9		
R²	Limit	Unit	R²	Limit	Unit
0.99	0.7	°C	0.99	0.7	m/s



Calibration details:

Certificate no: 1860NDA / 117 / 0915
Serial number: SKR 1860ND / A 45953
Date of calibration: 01/09/2015
Lamp reference: SK5

Calibration typically better than 5%. Note that this error is to some dependant on bandwidth - wide Bandwidths will be less subject to error than very low bandwidth channels.



Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.



Figure 19: CO₂ sensor

CO₂

Manufacturer:

Vaisala GmbH - Germany North
Monitoring Systems, Data Loggers, Measurement Instruments & Services for Validated En
Notkestraße 11
D-22607 Hamburg
Germany

Model: GMP343 Carbon dioxide probe

Specification:

Measurement range options	0 ... 1000 ppm, 0 ... 2000 ppm, 0 ... 3000 ppm, 0 ... 4000 ppm, 0 ... 5000 ppm, 0 ... 2 %
Accuracy (excluding noise) at 25 °C (77 °F) and 1013 hPa after factory calibration with 0.5 % accurate gases with different range options	0 ... 1000 ppm ±(3 ppm + 1 % of reading) 0 ... 2000 ppm - 0 ... 2 %* ±(5 ppm + 2 % of reading)

*Accuracy below 200 ppm CO₂ not specified for 2 % range option

Noise (repeatability) at 370 ppm CO ₂	with no output averaging ±3 ppm CO ₂ with 30 s output averaging ±1 ppm CO ₂
--	--

Effect on accuracy with temperature compensation:

CO ₂ range options	0 ... 1000 ppm 0 ... 2 000 - 5000 ppm	0 ... 2 %
Temperature °C (°F)	Accuracy (% of reading)	
+10 ... +40 (+50 ... +104) ±1	±1	±2
+40 ... +60 (+104 ... +140) ±2	±3	±4
-40 ... +10 (-40 ... +50) ±3	±3	±5

For readings below 200 ppm CO₂ ±5 ppm CO₂. Temperature compensation is performed by an integrated Pt1000 element.

Effect on accuracy with pressure compensation:

CO ₂ range options	0 ... 1000 ppm	0 ... 2000 - 2 %
Pressure (hPa)	Accuracy (% of reading)	
900 ... 1050	±0.5	±1
700 ... 1300	±1	±2

Warm-up time
full accuracy ±0.5 % 10 min
full accuracy 30 min



Operating Environment

Temperature	
operating	-40 ... +60 °C (-40 ... +140 °F)
storage	-40 ... +70 °C (-40 ... 158 °F)
Pressure	
compensated range	700 ... 1300 hPa
operating	<5 bar
Gas flow for flow-through model	0 ... 10 liters/min
Electromagnetic compatibility	EN61326, Generic Environment

Inputs and outputs

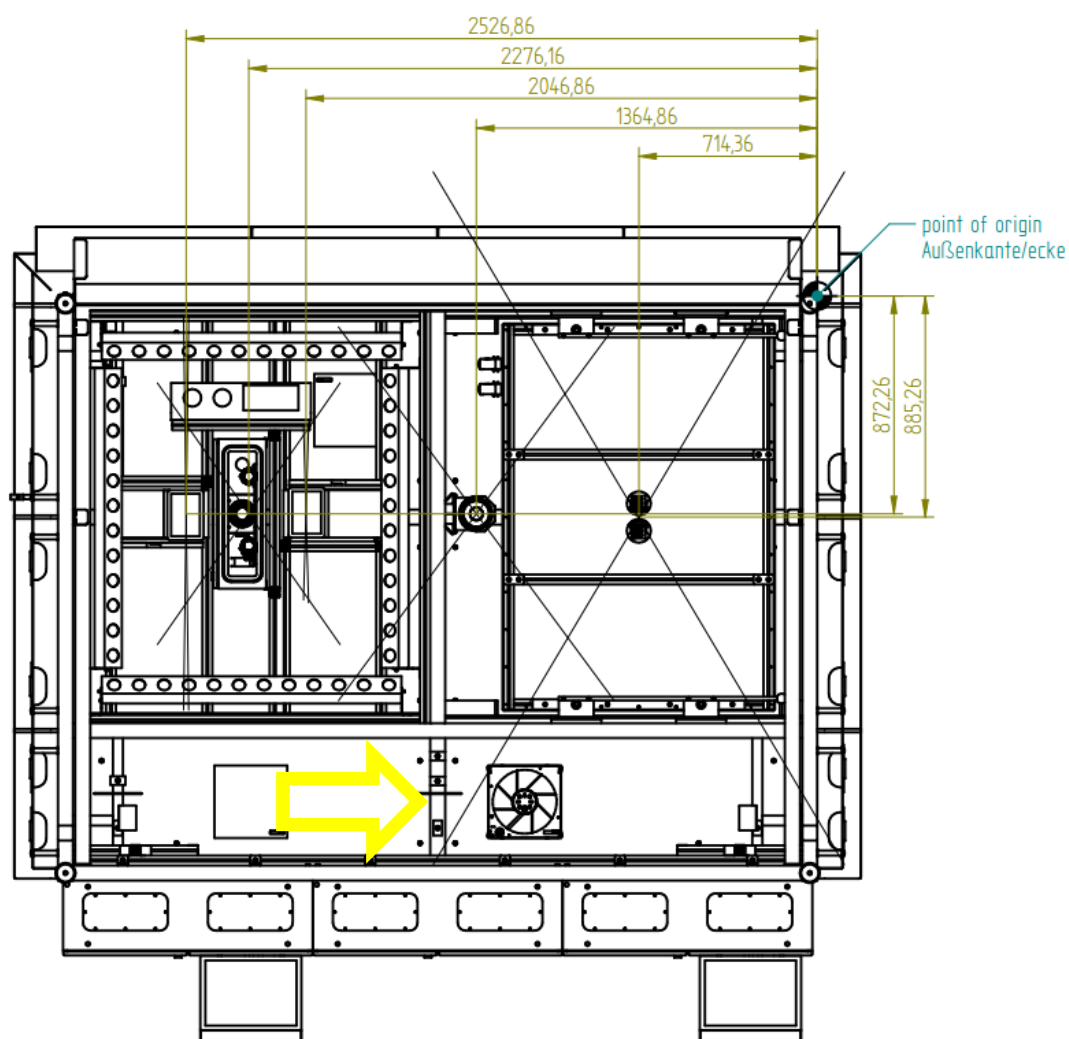
Operating voltage	11 ... 36 VDC
Power consumption	
without optics heating	<1 W
with optics heating	<3.5 W
ANALOG OUTPUTS	
Current output	
range	4 ... 20 mA
resolution	14 bits
max. load	800 Ohm @ 24 VDC, 150 Ohm @ 10 VDC
Voltage output	
range	0 ... 2.5 V, 0 ... 5 V
resolution	14 bits (13 bits with 0 ... 2.5 V)
min. load	5 kOhm
DIGITAL OUTPUTS	RS485, RS232

Materials

Housing	anodized aluminium
Filter cover	PC
IP classification	<1 W
Housing (cable attached)	IP67
Diffusion filter (weather protection)	IP65
Diffusion filter (sintered PTFE)	IP66
Cable connector type	8-pin M12
Weight (probe only)	360 g

For further information, read the applicable sensor documentation provided by LemnaTec.

Hardware integration:





Test results and Analysis:

<u>Data acquisition</u>	
	Basis is one measurement with the sensor
<u>Condition</u>	
	Performed during daylight Artificial light is disabled Number of Iterations: 1X
<u>Sensor Settings:</u>	
	Factory settings (see calibration certificate)
<u>Analysis</u>	
Test for plausibility:	Shut down ventilation, use nitrogen to measure zero line or alternatively breath out into the sensor for peak, start ventilation again. There should be a plausible zero line and a plausible amplitude.

Calibration details:

Certificate no: H32-15340016
Serial number: L3420008
Date of calibration: August 18. 2015

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.

PAR Sensor

Manufacturer:

Apogee Instruments, Inc.
721 W 1800 N
Logan, UT 84321, USA

Model: SQ 214

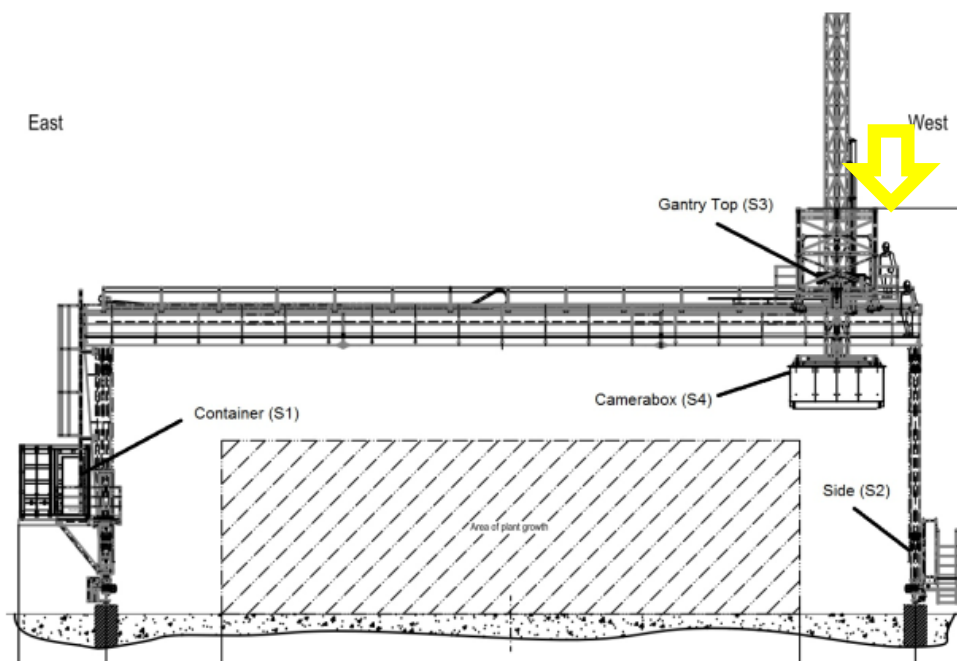
Specification:

Power supply:	5-36 V DC with a maximum current drain of 22 mA (2 mA quiescent current drain)
Output sensitivity:	0.0064 mA per $\mu\text{mol m}^{-2} \text{s}^{-1}$
Calibration Factor:	156.0 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV
Calibration Uncertainty:	+/- 5%
Measurement Repeatability:	less than 1%
Long-term Drift:	less than 2% per year
Non-linearity:	less than 1 % (up to 2500 $\mu\text{mol m}^{-2} \text{s}^{-1}$; maximum PPF measurement is 2500 $\mu\text{mol m}^{-2} \text{s}^{-1}$)
Response time:	less than 1ms
Field of view:	180°
Spectral Range:	410 – 655nm (wavelengths where response is greater than 50% of maximum)
Directional Cosine Response:	0.06 ± 0.06 % per C
Temperature Response:	+/- 5 % at 75° zenith angle
Operating Environment:	-40 to 70 C; 0 to 100 % relative humidity; can be submerged in water up to depths of 30 m
Dimensions:	24 mm diameter; 28 mm height
Mass:	140g (with 5m of lead wire)
Cable:	5 m of shielded, twisted-pair wire; additional cable available in multiples of 5 m; santoprene rubber jacket (high water resistance, high UV stability, flexibility in cold conditions); pigtail lead wires



Figure 20: PAR sensor

Hardware integration:

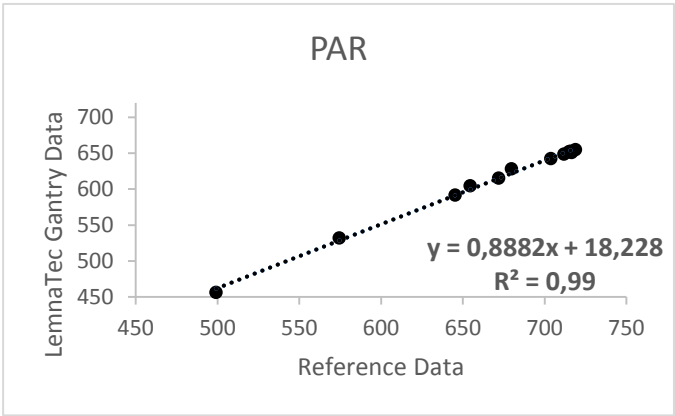


as shown in Operating Manual



Test results & Analysis:

Data acquisition	
	Basis are twelve measurements with the sensor between June and July 2016
Condition	
	Performed during daylight Artificial light is disabled Number of Iterations: 10-30X Reference data is coming from an external weather station
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows three different error measurements to classify the sensor accuracy (R ² , RMSE & MAPE)



PAR			
RMSE	Limit	MAPE	Limit
56,38	150	-0,09	5%
R ²	Limit	Unit	
1,00	0,7	µmol/sm ²	

Calibration details:

.....

Recalibration:

.....



Thies Weather station:

Manufacturer:

Adolf Thies GmbH & CO. KG
Hauptstraße 76
Box 3536+3541
37083 Göttingen
Germany

Model: Clima Sensor US NHTFB



Figure 21: Thies environmental sensor

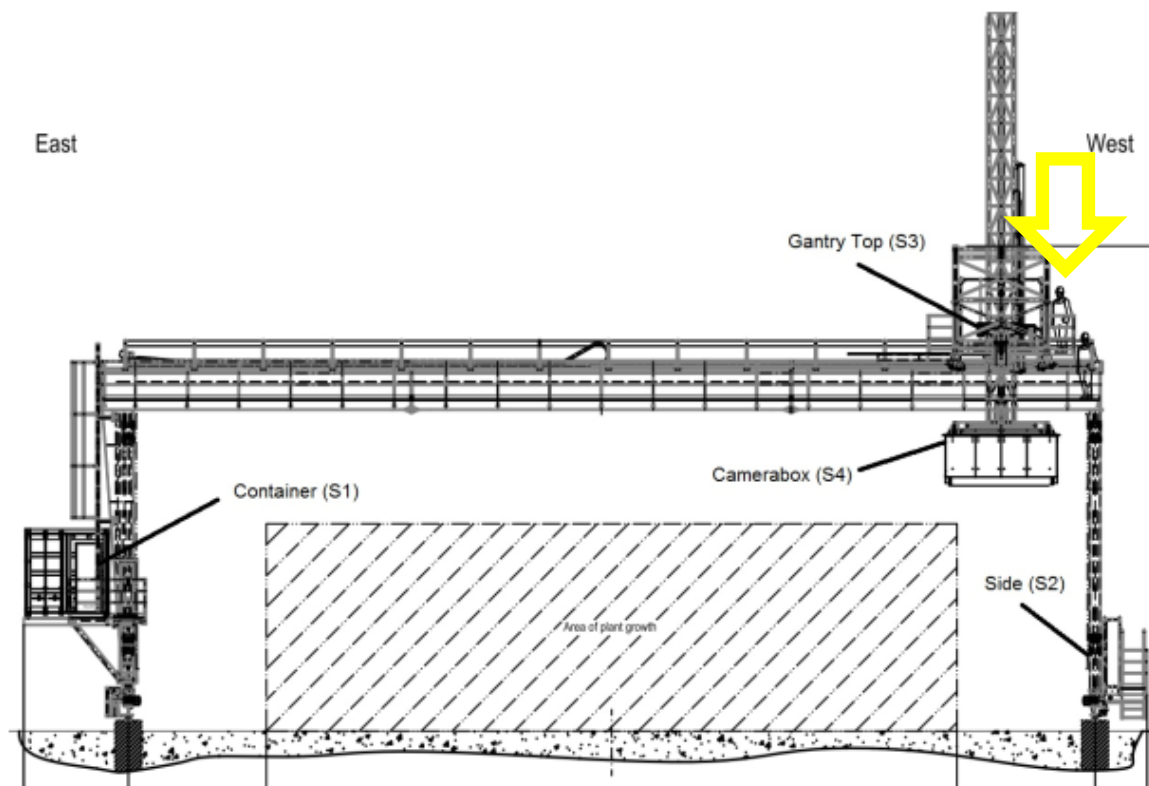
Specification:

Wind speed	Measuring range	0.01 m/s...60 m/s
		Scaling of analogue output freely selectable
	Accuracy	≤ 5 m/s ± 0.3 m/s (rms - mean over 360°)
		5...60m/s: ± 3 % of measured value (rms -mean over 360°)
Wind direction	Resolution	0.1 m/s: in telegrams 1, 2, 3, 5, 6
		0.01 m/s: in telegram 14
	Measuring range	0...360°
	Accuracy	± 2.0° with WS > 2 m/s
Virtual temperature	Resolution	1°: in telegrams 1, 2, 3, 4, 6
		0.1°: in telegrams 5, 14
	Measuring range	-40°C ...+80°C
	Accuracy	± 0.5 K
Air temperature	Resolution	0.1 K
	Measuring range	-40°C ...+80°C
	Accuracy	± 0.3 K @ 25°C, ± 1.0 K above -40°C ...+80°C
	Resolution	0.1 K
Air humidity, relative	Long-term stability	< 0.04 K per year
	Measuring range	0% ...100% relative humidity
	Accuracy	± 1.8% of 10% ...90%, ± 3.0% of 0% ...100%
	Long-term stability	< 0.5% per year
Air pressure	Resolution	0.1%
	Measuring range	300 hPa ...1100 hPa
	Accuracy	± 0.25 hPa at +10...+35°C
		± 1 hPa at -20...+60°C
Brightness	Resolution	0.1 hPa
	Long-term stability	< ± 1 hPa per year
	Measuring range	1 lux ...150 klux
	Accuracy	0,3% of relative measured value
Precipitation	Resolution	approx. 0,3% of measuring value
	Measuring ranges:	
	Intensities	0.001 mm/h ... 999 mm/h
	Resolution intensity	0.001 mm/h
	Daily total	0.01 mm ... 999 mm
	Resolution daily total	0.01 mm
	Droplet size	0.25 mm to 5.0mm, large as hail
	Accuracy with precipitation	with 95% of the precipitations deviations less than 15% compared with Thies Laser Precipitation Monitor (Reference)
	Type of precipitation	Rain, snow, sleet, ice crystals, hail



Data output digital	Interface	RS 485 / RS 422
		Electrically isolated from supply
	Baud rate	1200, 2400, 4800, 9600, 19200, 38400, 57600, 115200, 230400, 460800, 921600 selectable
	Output	Instantaneous values, sliding means from 100 msec to 2 min in increments of 100 msec freely selectable
	Output rate	One per 10 msec to one per 60 seconds in increments of 1 msec freely selectable
Data output analogue	Protocol	ASCII- Thies-Format and MODBUS RTU
	Electrical outputs	0... 10 V
		Electrically isolated from supply
		Permissible burden on voltage output: $\geq 2000\Omega$
	Output	Instantaneous values, sliding means from 100 msec to 2 min in increments of 100 msec freely selectable
General	Output rate	Update rate 10 msec
	Resolution	16 bit
	Internal measuring rate	Wind: up to 1000 propagation time measurements per second, up to 250 complete measuring sequences/second incl. calculations
		Temperature, humidity, pressure, precipitation, brightness: updated 1x a second
	Bus mode	Bus mode with up to 99 devices possible
Operating voltage	Firmware update	Firmware update in full duplex mode via RS422
	Temperature range	Operating temperature -30 ... +70°C
		Storage temperature -55 ... +80°C
	Supply without cover heating	6V...40 V DC or 10...28 V AC 50Hz / 60Hz typ. 50 mA @ 24V
	Supply with cover heating	24 V AC/DC $\pm 15\%$, 25 VA typically @ 24 V nominal (execution only 4.9200.00.00x, 4.9202.00.00x)
Housing	Type of protection	IP 67 (when mounted correctly, see section "Preparation for operation")
	4.92xx.xx.xxx	Plastic: LEXAN (polycarbonate, UV-stabilised) impact and weather-resistant
	Mounting	e.g. on mast tube R1½" (Ø 48.3 mm)
	Type of connection	19-pin plug connection
	Weight	approx. 900g (full version)

Hardware integration:

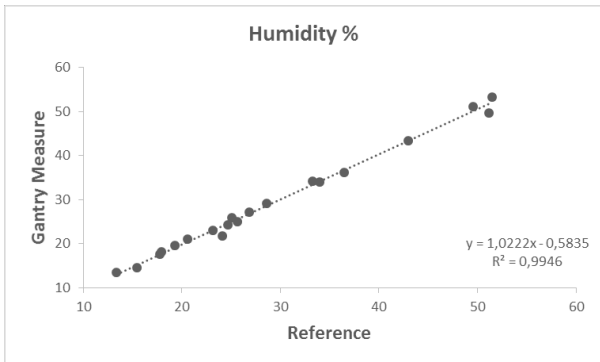
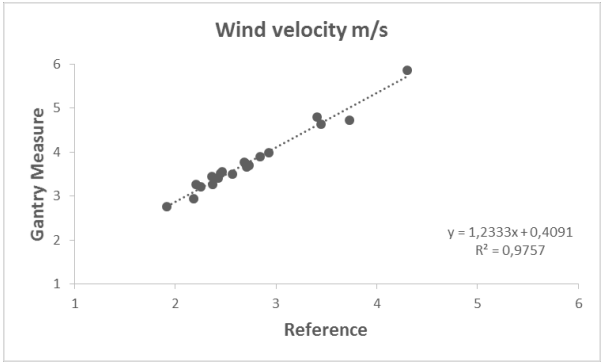
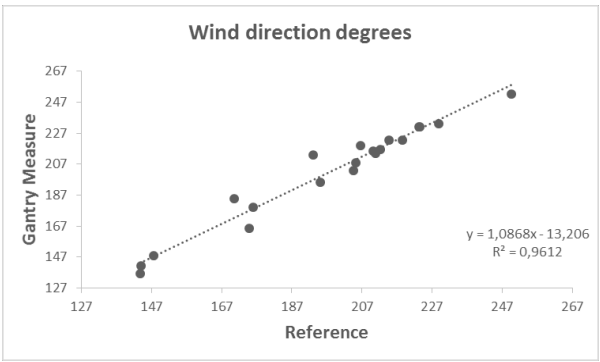
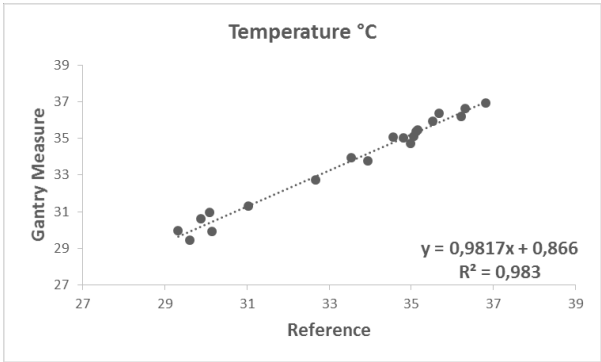




Test results & Analysis:

Data acquisition	
	Basis are twelve measurement with the sensor between June and July 2016
Condition	
	Performed during daylight Artificial light is disabled Number of Iterations: 10-30X Reference data is coming from an external weather station
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows three different error measurements to classify the sensor accuracy (R ² , RMSE & MAPE)

Temperature				Wind Velocity				Wind Direction				Humidity			
RMSE	Limit	MAPE	Limit	RMSE	Limit	MAPE	Limit	RMSE	Limit	MAPE	Limit	RMSE	Limit	MAPE	Limit
0,24	5°	0,00	5%	1,09	5m/s	-0,38	5%	5,860	45	-0,01	5%	0,58	25	-0,01	5%
R ²	Limit	Unit		R ²	Limit	Unit		R ²	Limit	Unit		R ²	Limit	Unit	
0,99	0,7	°C		0,98	0,7	m/s		0,97	0,7	degrees		1,00	0,7	%	





Calibration details:

Is not calibrated!

Recalibration:

Is not calibrated!



Spectrometer

Manufacturer:

Ocean Optics
830 Douglas Ave.
Dunedin, FL 34698
USA

Model: S05673

Specification:

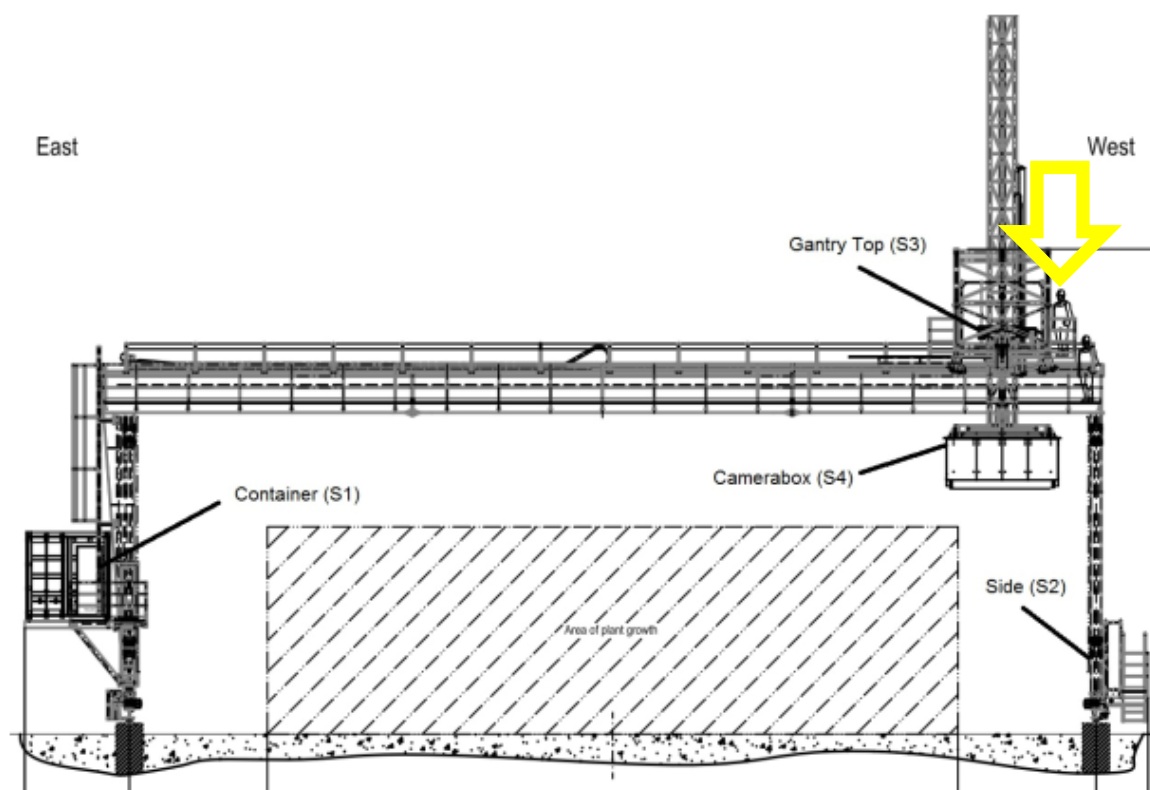
Specifications		Criteria
Absolute Maximum Ratings:	Vcc	+ 5.5 VDC
	Voltage on any pin	Vcc
Physical Specifications:	Physical Dimensions	40 mm x 42 mm x 24 mm
	Weight	60 g
Power		5V supply < 500mA inrush, 150mA average current
Spectrometer:	Design	Asymmetric crossed Czerny-Turner
	Focal length	28 mm
	Input fiber connector	SMA 905 -- See Warning on next page
	Grating	600g/mm
		10, 25, 50, 100, or 200 µm slits (In the absence of a slit, the fiber acts as the entrance slit)
	Entrance Slit	
	Detector	ELIS1024, 1024 pixel linear CMOS, 7.8 x 125µm pixels
	Hot Pixels ¹	Typically 0 – 5 ; 20 maximum
	Detector Sensitivity	6.74V/lux-sec typical (555nm)
	Range	
Spectroscopic:	VIS	350 – 800 nm
	NIR	650 – 1100 nm
	UV	190 – 650 nm
	Pixel Well Depth	800k e-
	Average linearity	< +/- 1% from 15-95% full scale (2500 - 14000 counts net)
	Corrected linearity	< +/- 0.5% from 15-95% full scale (2500 - 14000 counts net)
	Uncorrected linearity	+/-5% from 5-95% full scale (2500 - 14000 counts net)
	Integration Time	10 µs – 10 s
	Dynamic Range	5 x 109 (system, 10s max. integration), ~4600 single acquisition
	Signal-to-Noise Ratio	>1500:1 (maximum signal)
	Readout Noise	≤3 counts rms
	Dark Current	~150 counts/sec at 60°C; ~50 counts/sec at 35°C
	Fixed Pattern Noise (Normal Mode) ²	± 3 counts
	Resolution (FWHM)	
	Typical	1nm (10µm slit), 1.5nm (25µm slit), 6nm (100µm slit), 12nm

¹ Hot pixels at 1 ms integration time are defined as those that are barely outside the range 1500 ± 3 counts; at 2 s: <1300 counts. See the online [glossary](#) definition of a hot pixel.

² Fixed pattern noise (Raw Mode) is ~100 counts up to 300ms integration time

Maximum	(200µm slit)
A/D Resolution	2.0nm (10µm slit), 2.5nm (25µm slit), 8nm (100µm slit), 16nm (200µm slit)
Wavelength Temperature Stability	(200µm slit)
Spectrometer Channels	14 bits
Baseline Drift	0.06 pixel/°C
Unit-to-unit repeatability	One ± 3 counts ³ ± 25%
Environmental Conditions:	
Temperature	-30° to +70° C Storage & 0° to +50° C Operation; 10° C change/hour ramp
Humidity	0% - 90% noncondensing
Interfaces:	
USB	USB 2.0, 12 Mbps
RS-232	3-wire RS-232 (Tx, Rx, ground), scan rate of ~5 scans per second at 460K Baud; Communications is N81 with support for hardware (RTS/CTS) handshaking (with firmware version 0043 and later) and no support for software flow control; Default baud rate 9600; +/- 5V

Hardware integration:



WARNING

³ Baseline Drift auto-corrected for temperature, in Normal mode operation (other than dark current contribution, which should only be significant for integration time >300 ms)



Use only precision connectors that meet IES specification standard 60874 when connecting a fiber to the STS. Ferrule lengths that are out of specification can destroy the STS.

Note
For typical integration times and normal ambient temperatures, it should only be necessary to perform a single dark scan after startup at a given integration time.

Test results & Analysis:

Data acquisition	
	Basis are multiple measurements with the sensor
Condition	
	Performed during daylight Artificial light is disabled Number of Iterations: 10-30X Reference data is coming from an external spectrometer station. Reference data is coming from an external spectrometer. Both spectrometers face into the same direction to the top.
Sensor Settings:	
	Factory settings (see calibration certificate)
Analysis	
Test for accuracy:	Analysis shows three different error measurements to classify the sensor accuracy (R ² , RMSE & MAPE)

Calibration details:

Certificate no: 18732
Serial number: S05673
Model number: STS-VIS-L-50-400-SMA
Date of calibration: 08/06/2015

Recalibration:

It is recommended that this unit is recalibrated within two years of the above calibration date.