Introduction to Solar Resource Assessments

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Outline

- Solar geometry
- Atmospheric transfer and components of solar radiation
- Ground measurements
- Satellite based assessments
- Solar radiation to tilted planes
- Characteristics of solar resources
- Data sources
- GIS analysis

Getting Renewable Energy to Work

Resource mapping

- **Available Resources**

Potentials

- **Technical and economic potentials**
  Which technologies are feasible?

Scenarios

- **Possible capacity development**
  How can they contribute to the national energy system?

Strategies

- **Market introduction**
  How to get them into the market?
  Where to start?

Instruments

- **Political and financial instruments**
  Legislation, incentives

Investments

- **Private investments**

Political + Economic Framework

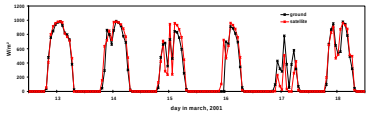
Private investors need resource data for investments

Project Development for Renewable Energy Systems

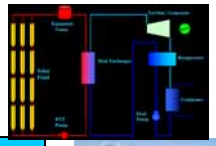
Resources (Atlas)

Project development

Resources (time series)



Engineering



Construction

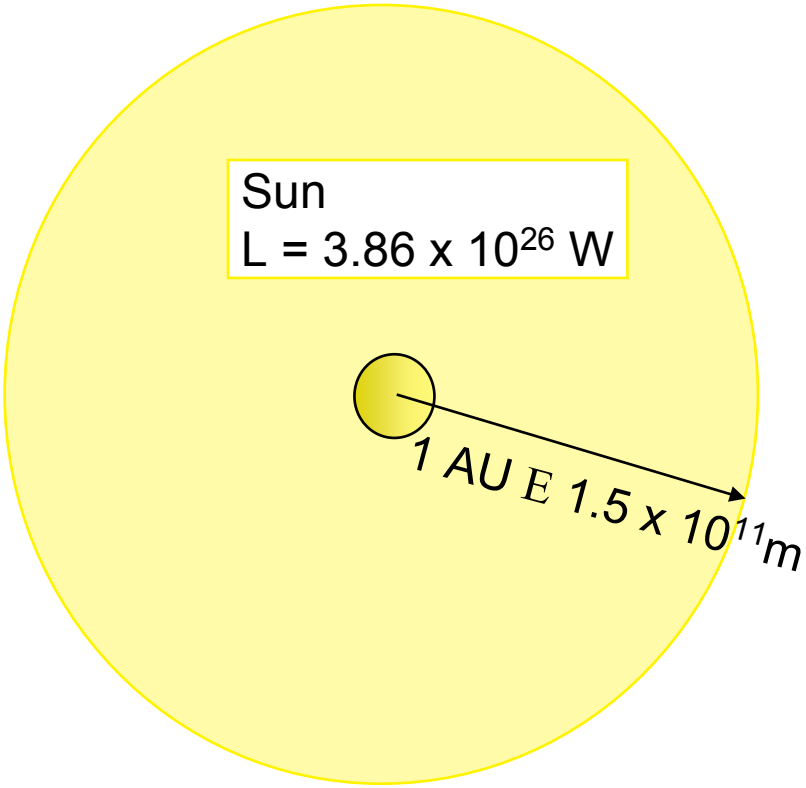
Commissioning

Operation

- Finding suitable sites with high resolution maps and economic evaluations
- Detailed engineering with site specific data with high temporal resolution as input to simulation software

Solar Radiation Basics

Solar Constant



Area of a sphere = $4\pi r^2$

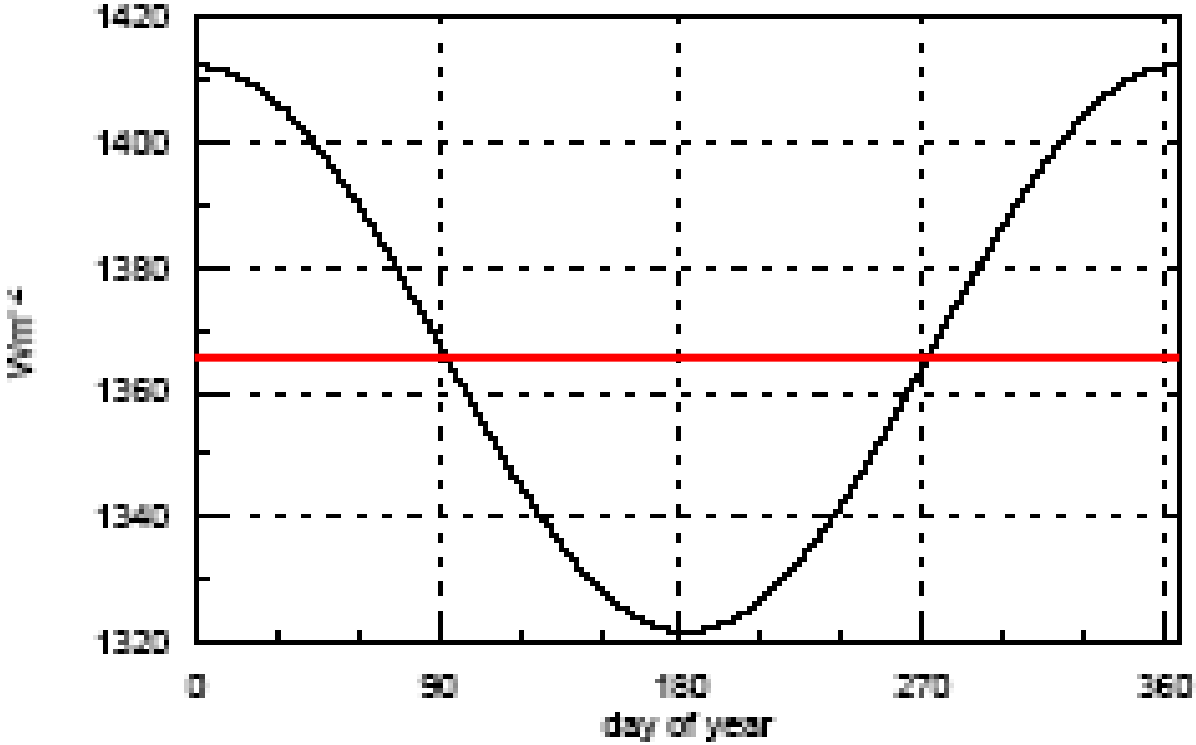
Conservation of energy requires that the total energy flux coming out of the sun must also pass through a sphere at 1 AU.

The energy flux density at 1 AU is

$$\frac{L}{4\pi r^2} = 1367 \frac{W}{m^2}$$

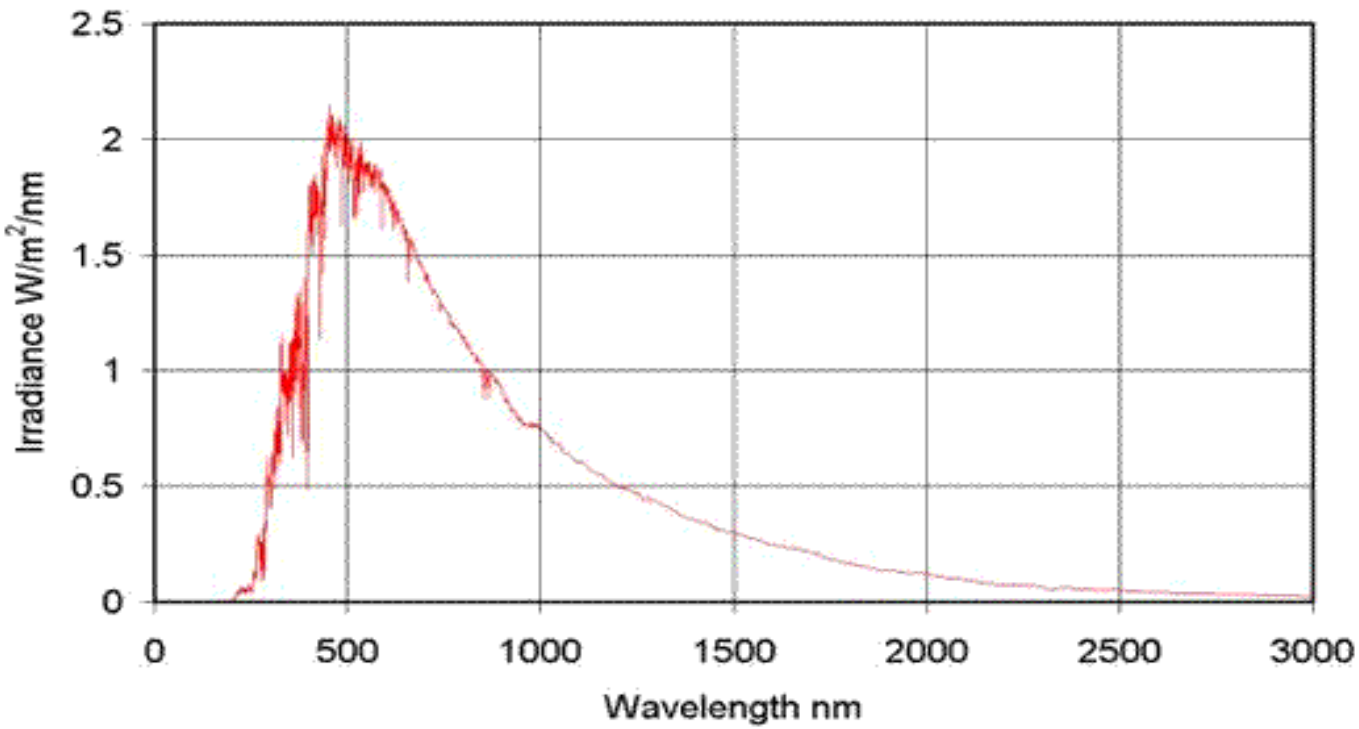
This is the **Solar Constant**.

Variation of the Extraterrestrial Radiation



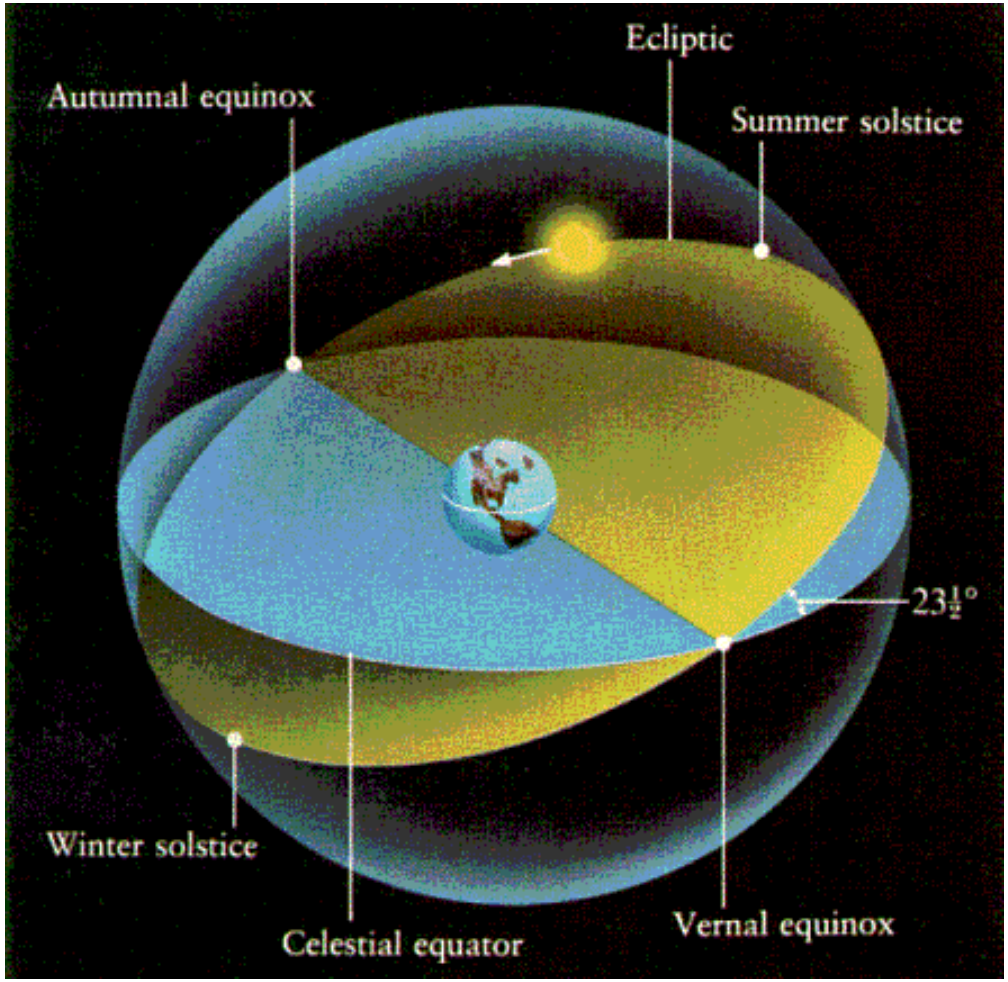
Solar constant = 1367 Wm^{-2}

Extraterrestrial Solar Spectrum

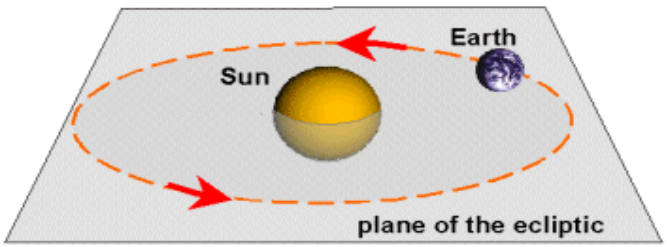


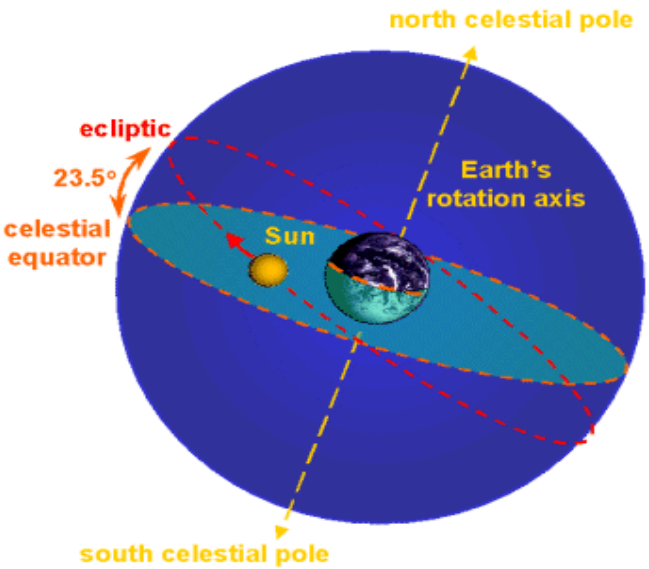
Solar Geometry

Sun – Earth Geometry



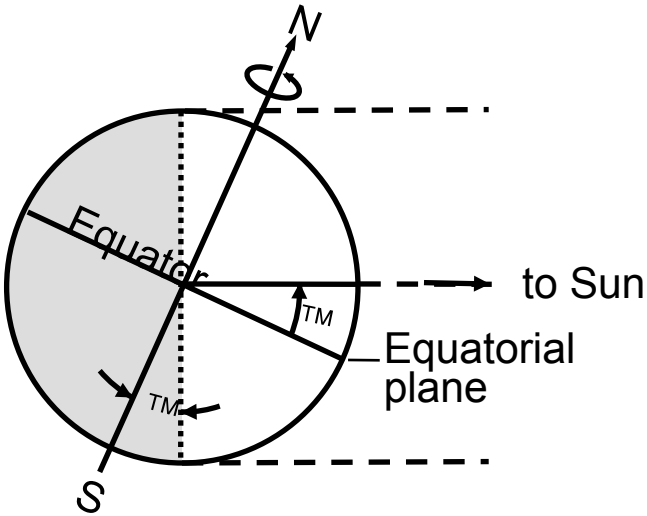
Ecliptic

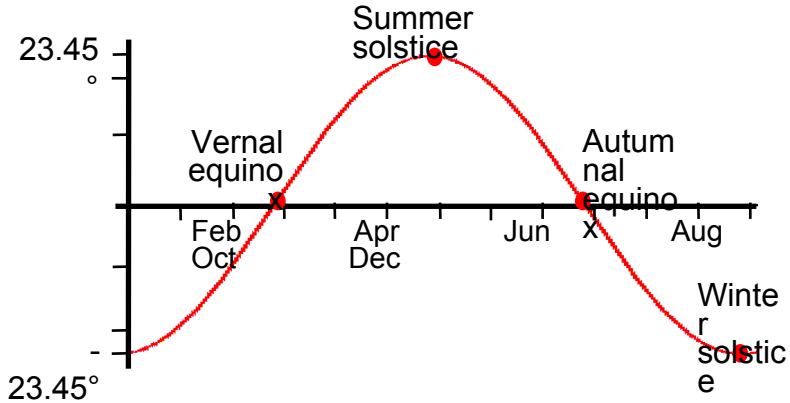




- The ecliptic is the region of sky (of the celestial sphere) through which the Sun appears to move over the course of a year. This apparent motion is caused by the Earth's orbit around the Sun, so the ecliptic corresponds to the projection of the Earth's orbital plane on the celestial sphere. For this reason, the Earth's orbital plane is sometimes called the plane of the ecliptic.
- Due to the tilt of the Earth's rotation axis with respect to its orbital plane, there is an angle of 23.5o between the ecliptic and the celestial equator.

Solar Declination





Declination angle δ = 23.45°

Variation of the declination angle:

$\delta = 23.45 * \sin [360 / 365 * (284 + n)]$

with n = day of the year

(Approximation)

Solar Time

- Daily variations of solar radiation are usually described on the basis of **solar time.**

- Definitions:

  Solar day: Time interval between two sebsequent crossings of the Sun‘s path with the local meridian.

  - length changes from day to day (< 30 sec)
  - mean value: 24h

  Solar noon: Time of the crossing of the Sun‘s path with the local meridian

Solar Time

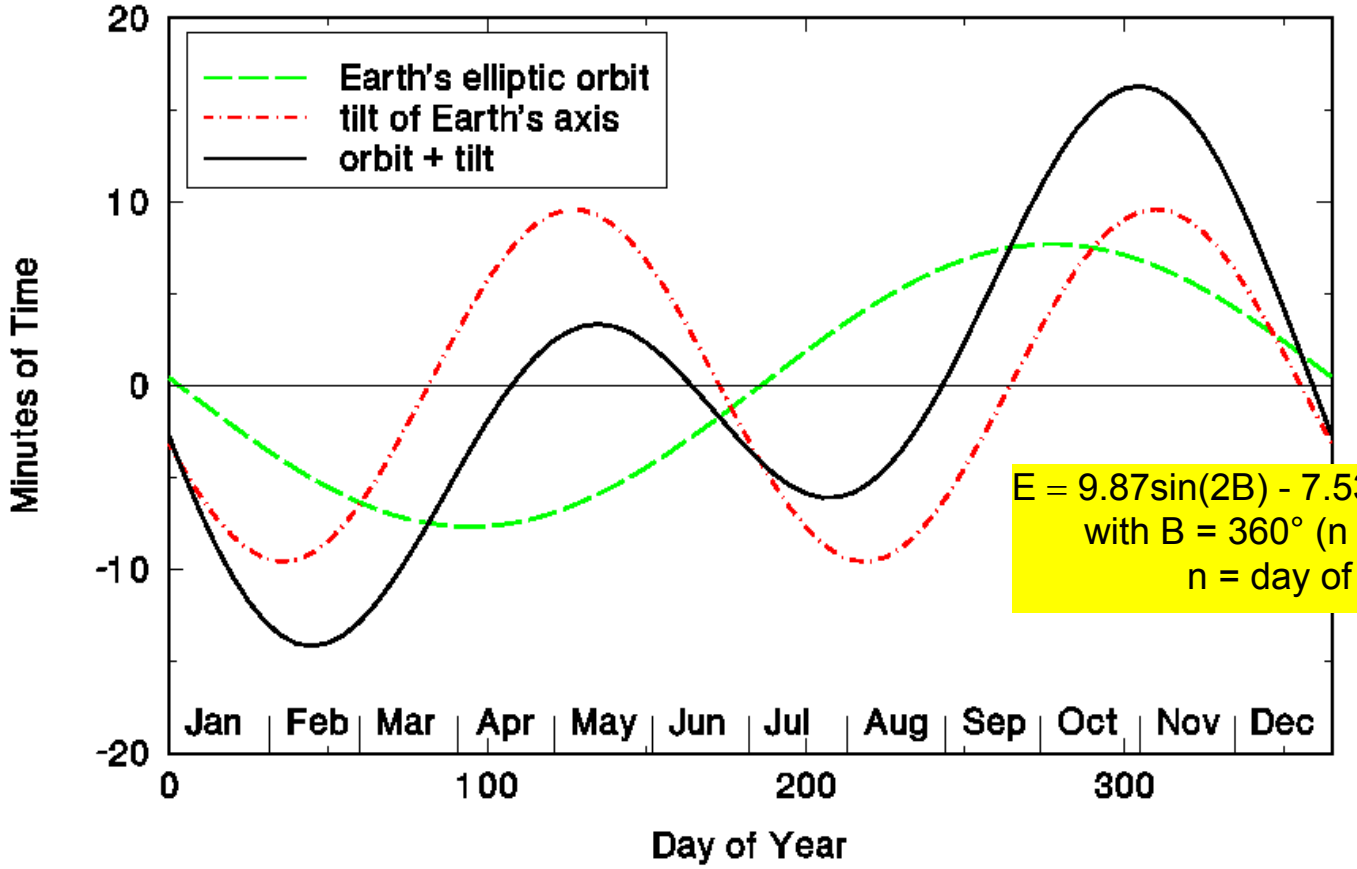
The variation of the solar day length is caused by:

- The elliptical path of the Earth around the Sun
  (Kepler‘s law: Earth sweeps equal areas in equal times)

- The tilt of the Earth‘s axis with respect to the ecliptic plane

Difference between solar time and local mean time
is expressed by Equation of Time

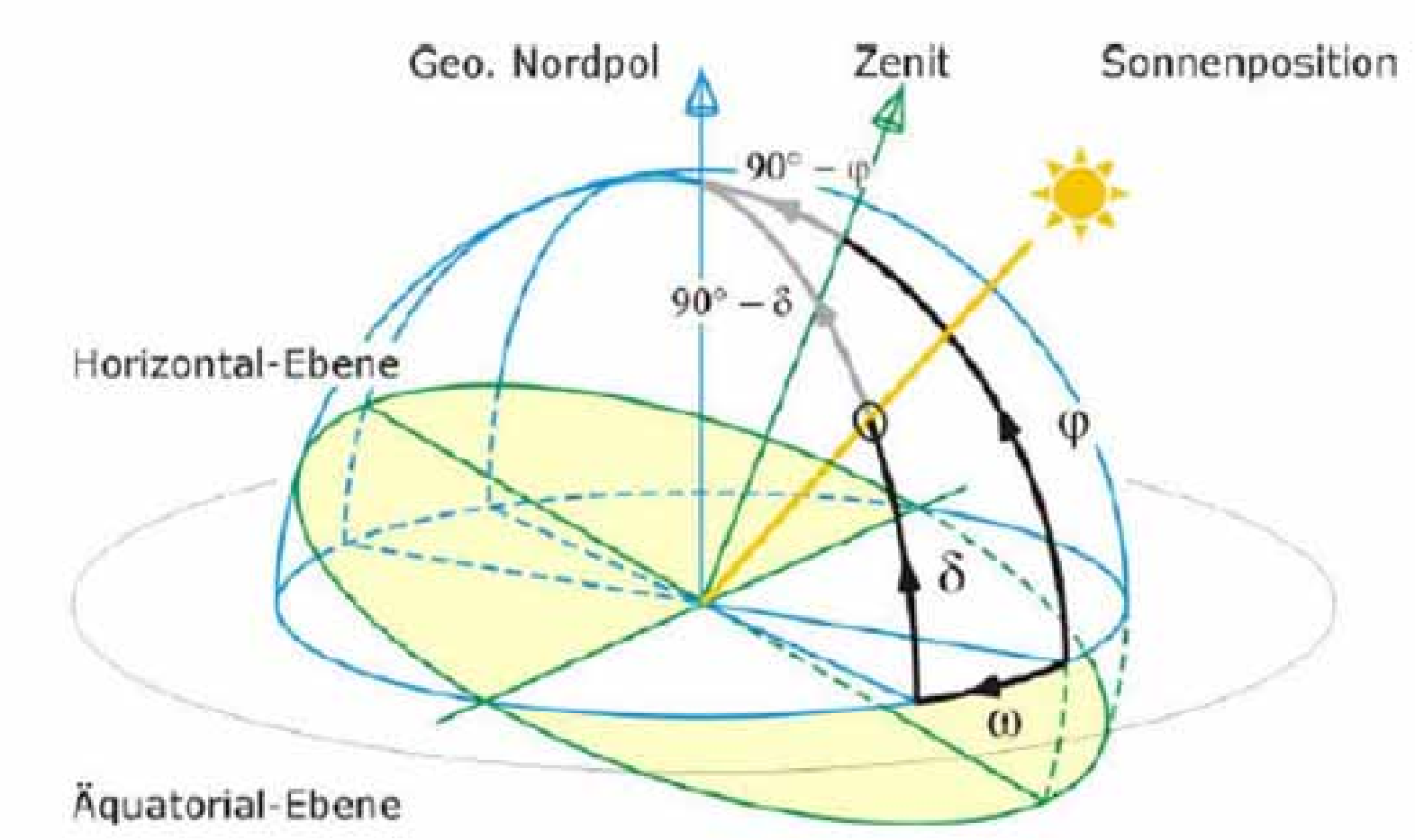
Equation of time



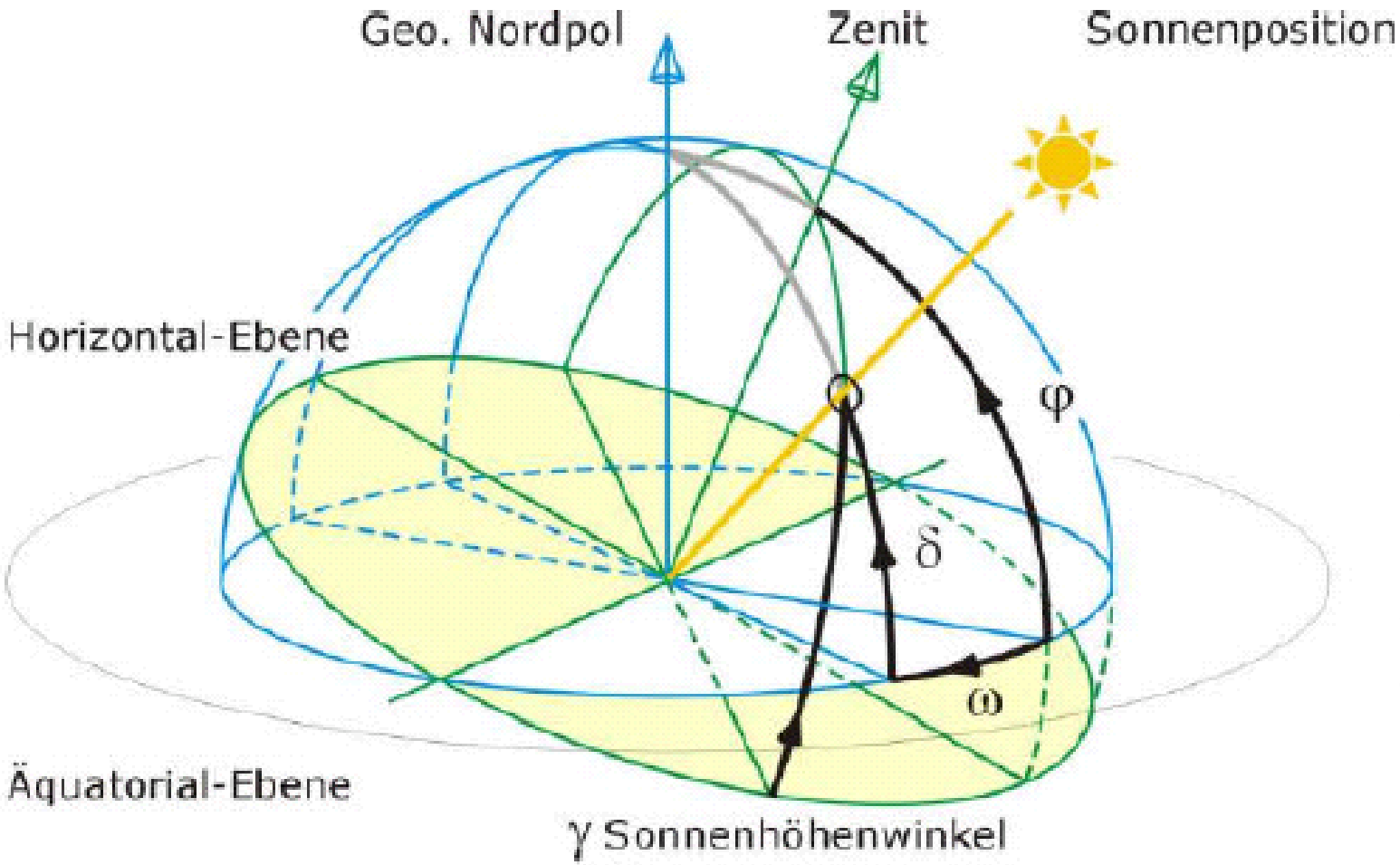
$E = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$
with $B = 360° (n - 81) / 364$ and
n = day of the year

Hour angle

- The **hour angle** ω describes the solar time in trigonometric terms, i.e as an angle.
- ω equals the angular displacement of the Sun from the local meridian due to the rotation of the Earth
- One hour corresponds to an angle of 360°/24h = 15°
- By convention, morning hours are calculated negative, afternoon hours positive. At solar noon, ω=0°.



Quelle Blumberg & Spinnler, 2003



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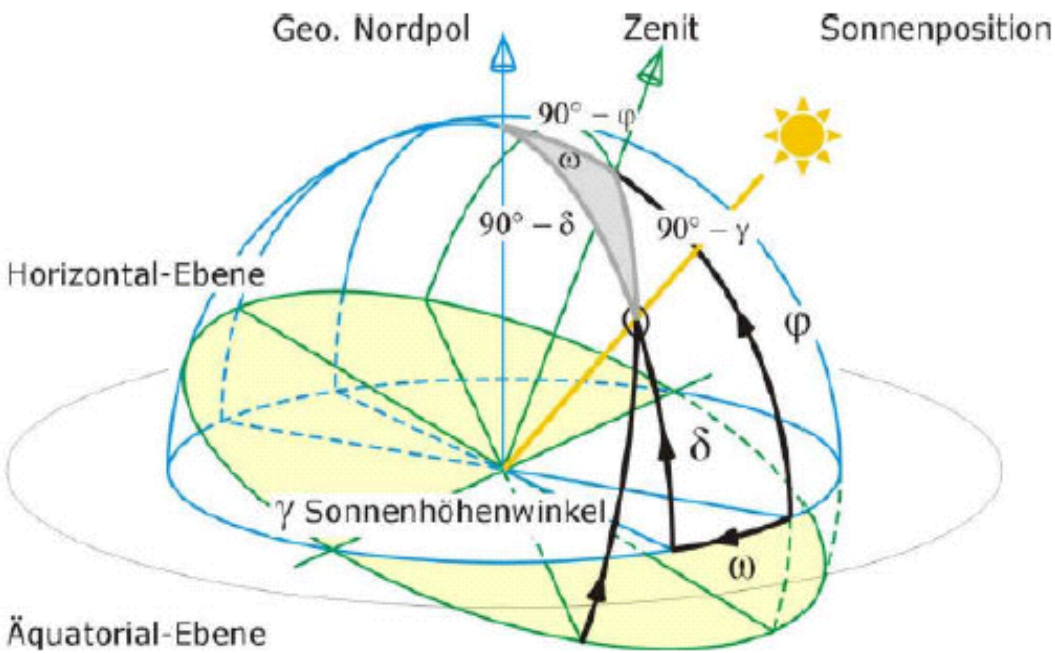
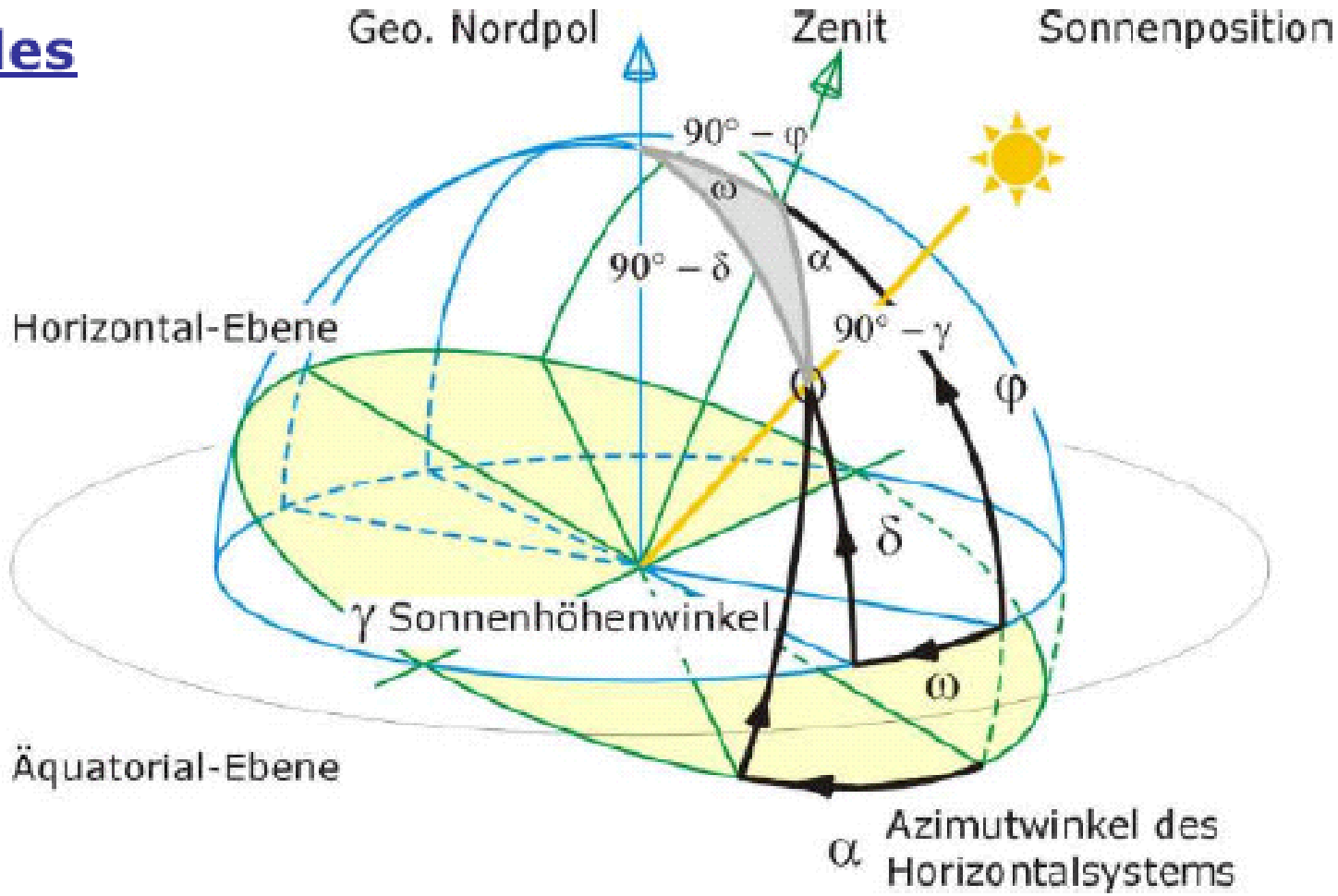


➲ Seitenkosinussatz für sphärische Dreiecke:

$$\cos(90°-\gamma) = \cos(90°-\varphi)\cos(90°-\delta) + \sin(90°-\varphi)\sin(90°-\delta)\cos\omega$$

$$\sin\gamma = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega$$

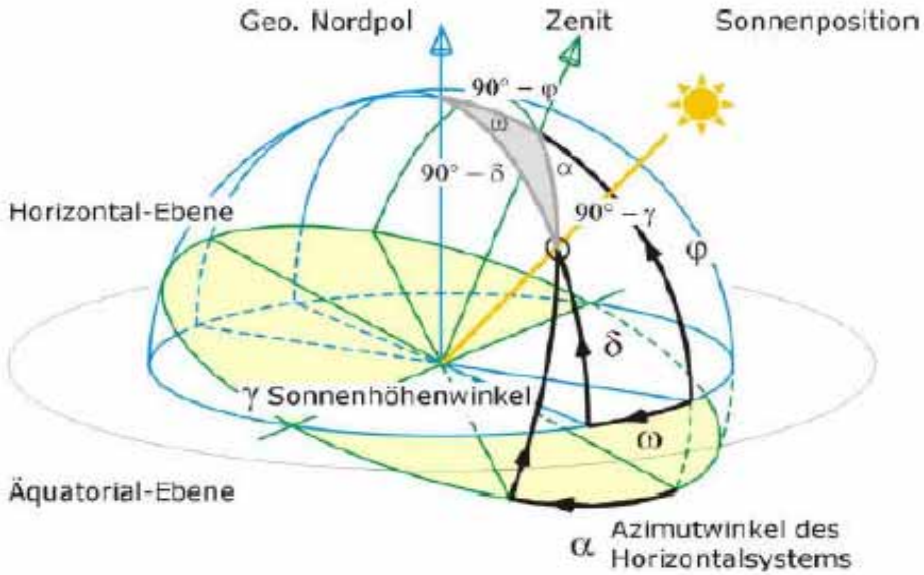
des



Quelle Blumberg & Spinnler, 2003

Der Azimutwinkel α des Horizontalsystems

➲ Seitenkosinussatz für sphärische Dreiecke:



Quelle Blumberg & Spinnler, 2003

$$\cos(90°-\delta) = \cos(90°-\varphi)\cos(90°-\gamma) + \sin(90°-\varphi)\sin(90°-\gamma)\cos(180°-\alpha)$$

$$\sin\delta = \sin\varphi \cdot \sin\gamma - \cos\varphi \cdot \cos\gamma \cdot \cos\alpha$$

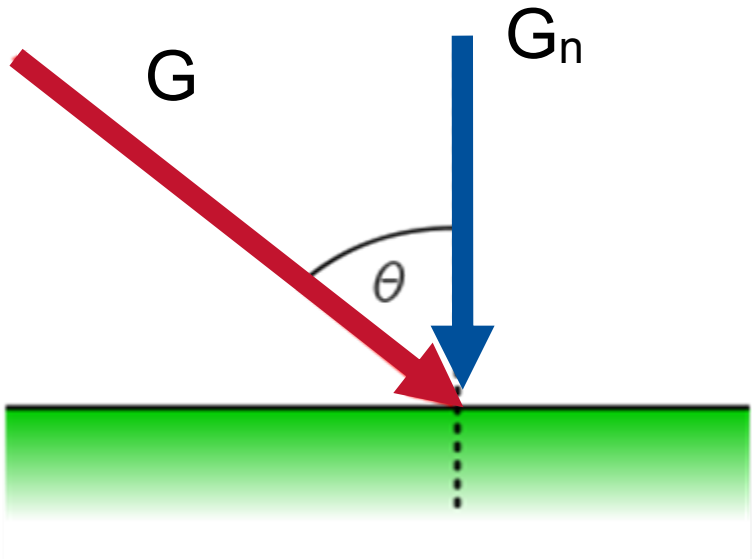
$$\Rightarrow \quad \cos\alpha = \frac{(\sin\varphi \cdot \sin\gamma) - \sin\delta}{\cos\varphi \cdot \cos\gamma}$$

Bsp. 4:

Azimut 24. April, 14:30 Ortszeit

→ ***α = - 40,395°***

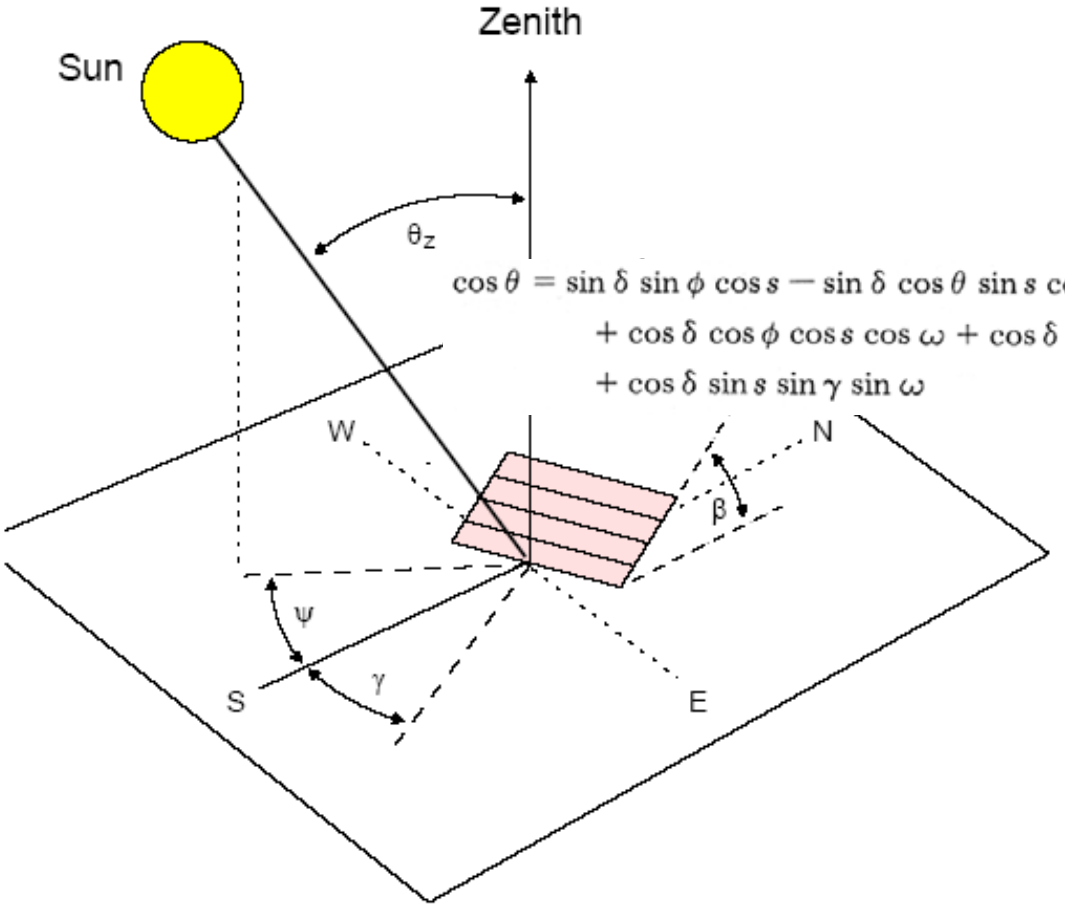
Angle of Incidence



For surfaces not oriented perpendicular to the Sun, the irradiance is given by

$$G = G_n \cos \theta$$

Angle of incidence



$$\cos\theta = \sin\delta\,\sin\phi\,\cos s - \sin\delta\,\cos\theta\,\sin s\,\cos\gamma + \cos\delta\,\cos\phi\,\cos s\,\cos\omega + \cos\delta\,\sin\phi\,\sin s\,\cos\gamma\,\cos\omega + \cos\delta\,\sin s\,\sin\gamma\,\sin\omega$$

with:

latitude Φ

solar declination δ

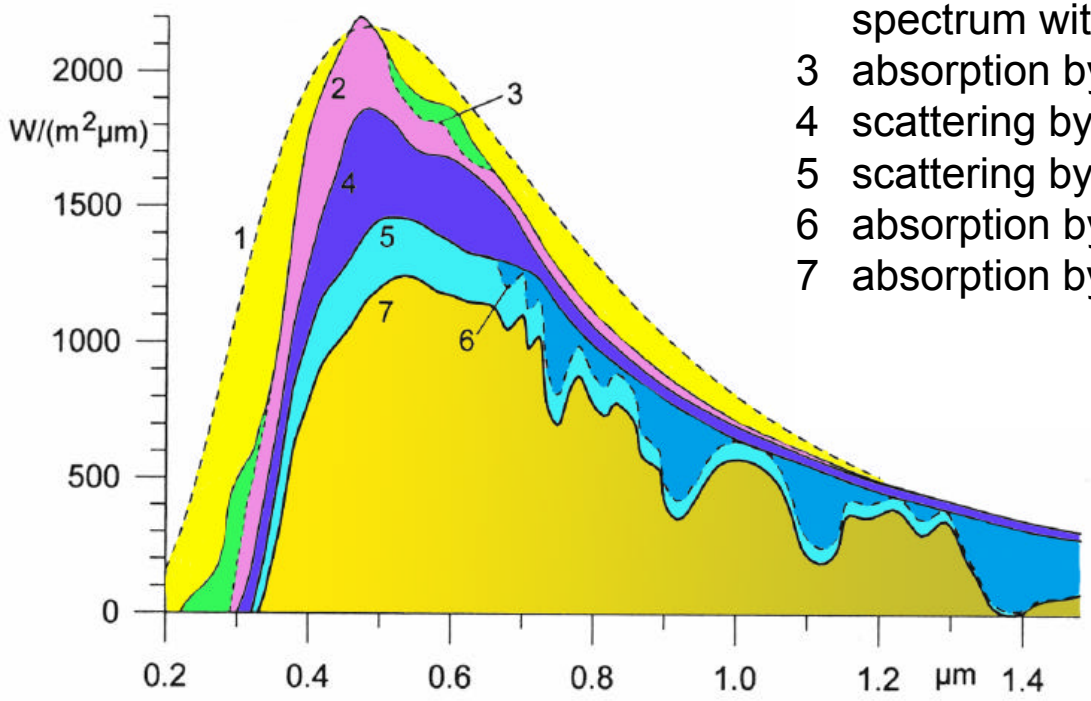
hour angle ω

slope β

surface azimuth γ

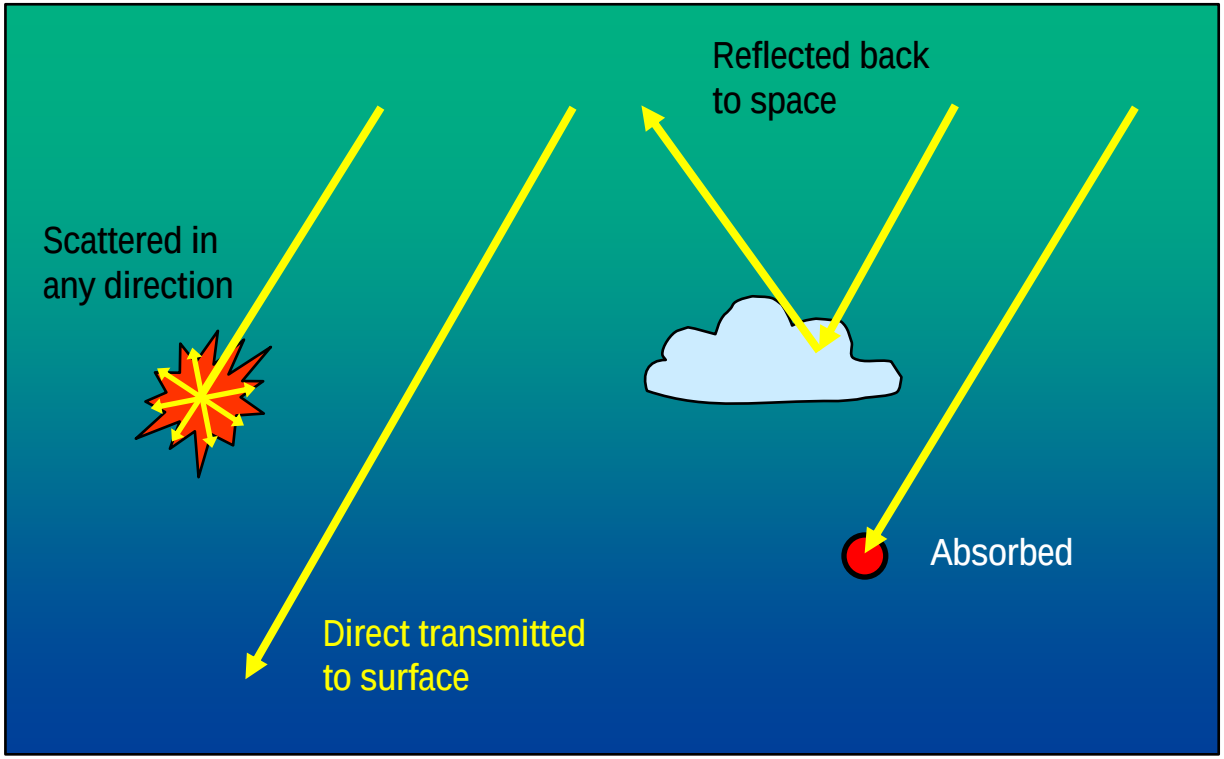
Atmospheric Transfer and Components of solar radiation

Solar Spectrum and Atmospheric influence

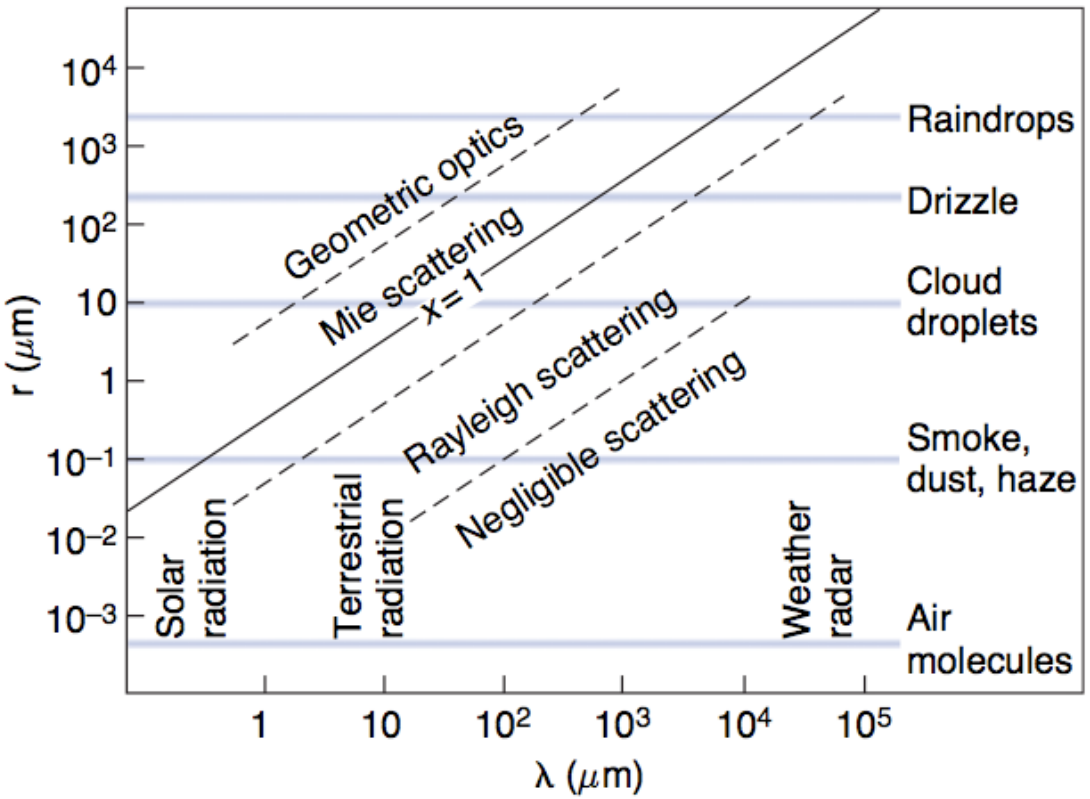


1 Planck curve T=5780 K at mean sun-earth distance
2 extraterrestrial solar spectrum with additional
3 absorption by 0_3
4 scattering by 0_2 und N
5 scattering by aerosols
6 absorption by H_2O vapor
7 absorption by aerosols

Atmospheric Extinction Processes



Scattering Regimes



Dimensionless size parameter $X=2\pi r/\lambda$ as a function of wavelength (λ) of the incident radiation and particle radius r.

Rayleigh and Mie Scattering

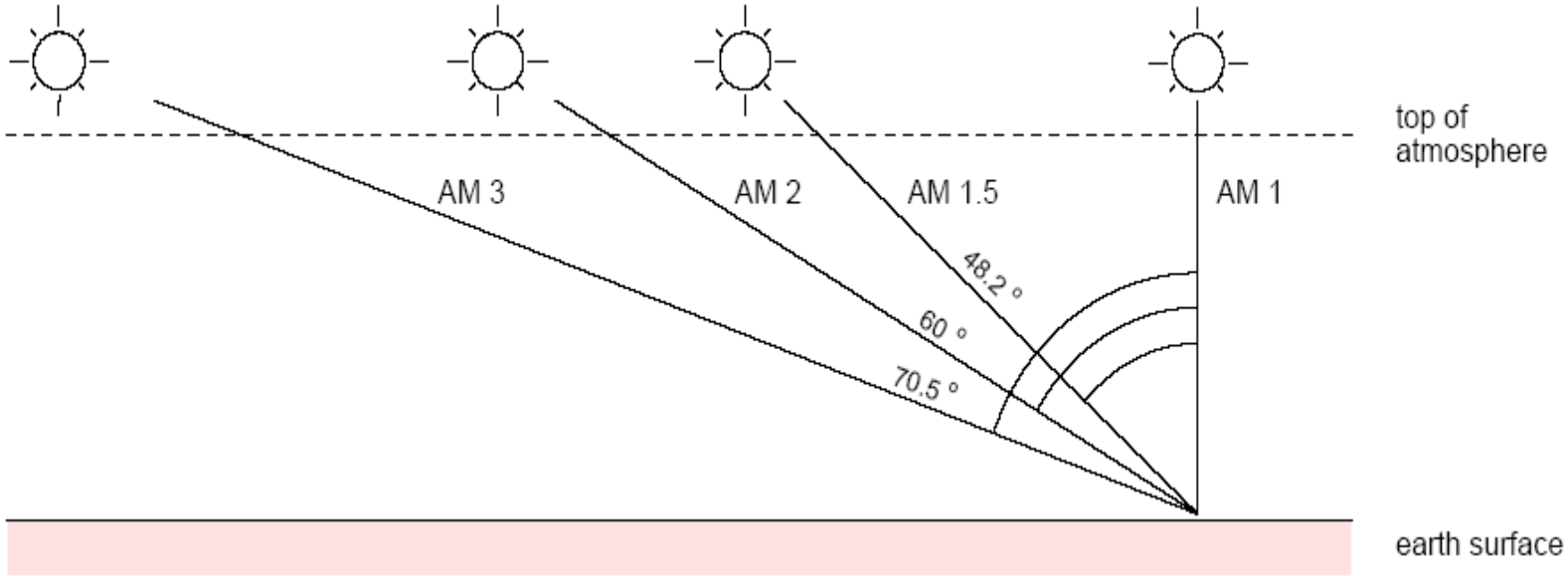
Rayleigh scattering

Mie scttering

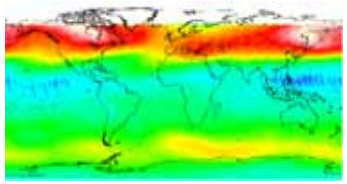
Mie Scattering, larger particles

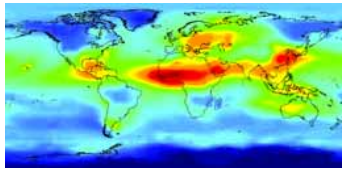
Direction of incident light

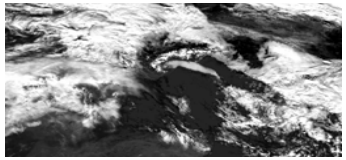
Air Mass

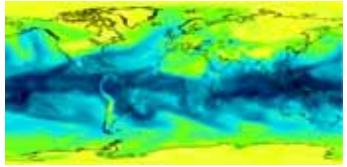


Properties of Solar Radiation









Radiation at the top of atmosphere

Ozone……

Absorption (ca. 1%)

Air molecules……

Rayleigh scattering and absorption (ca. 15%)

Aerosol……

Scatter and Absorption (∅ ca. 15%, max. 100%)

Clouds……

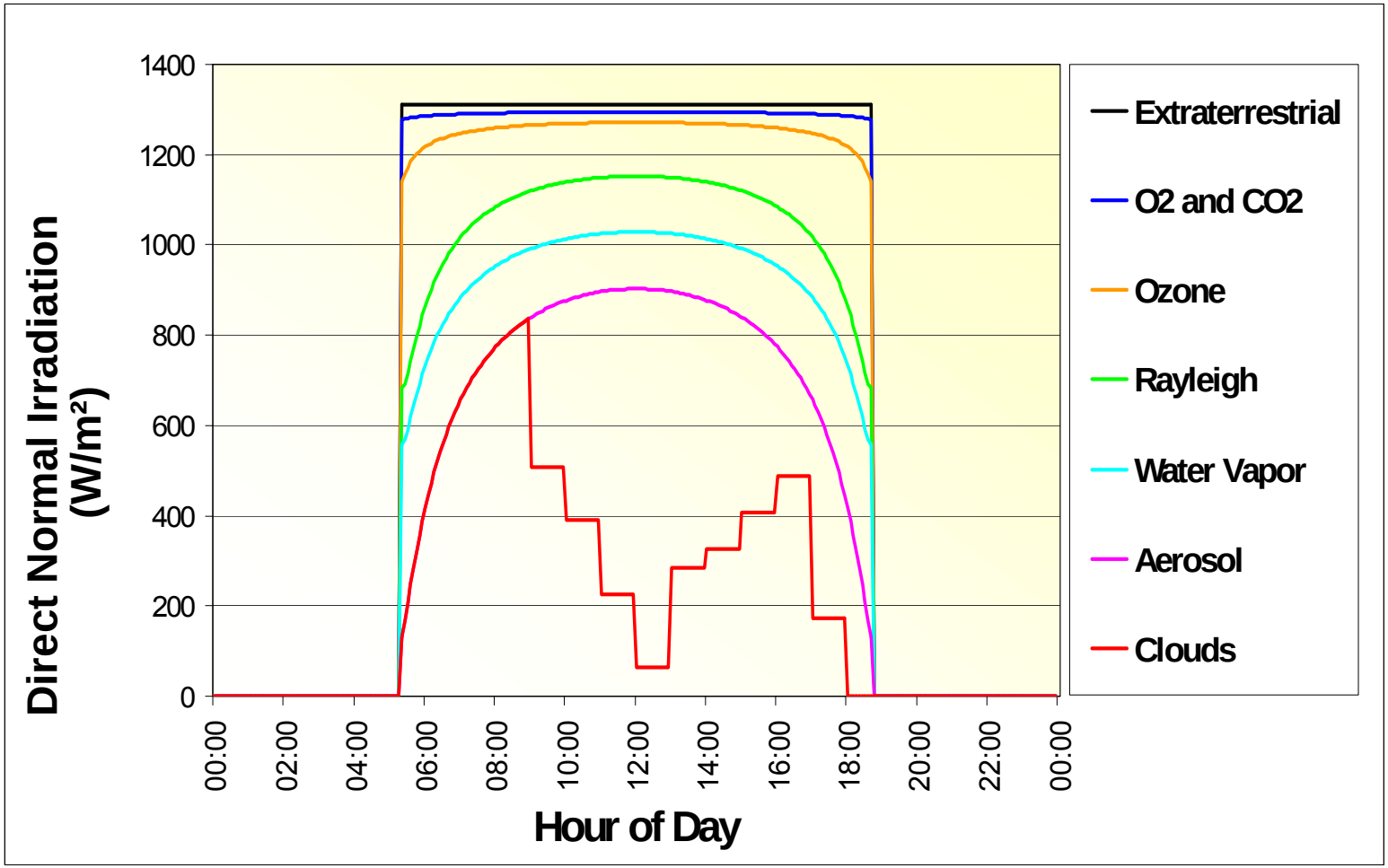
Reflection, Scatter, Absorption (max. 100%)

Water Vapor……

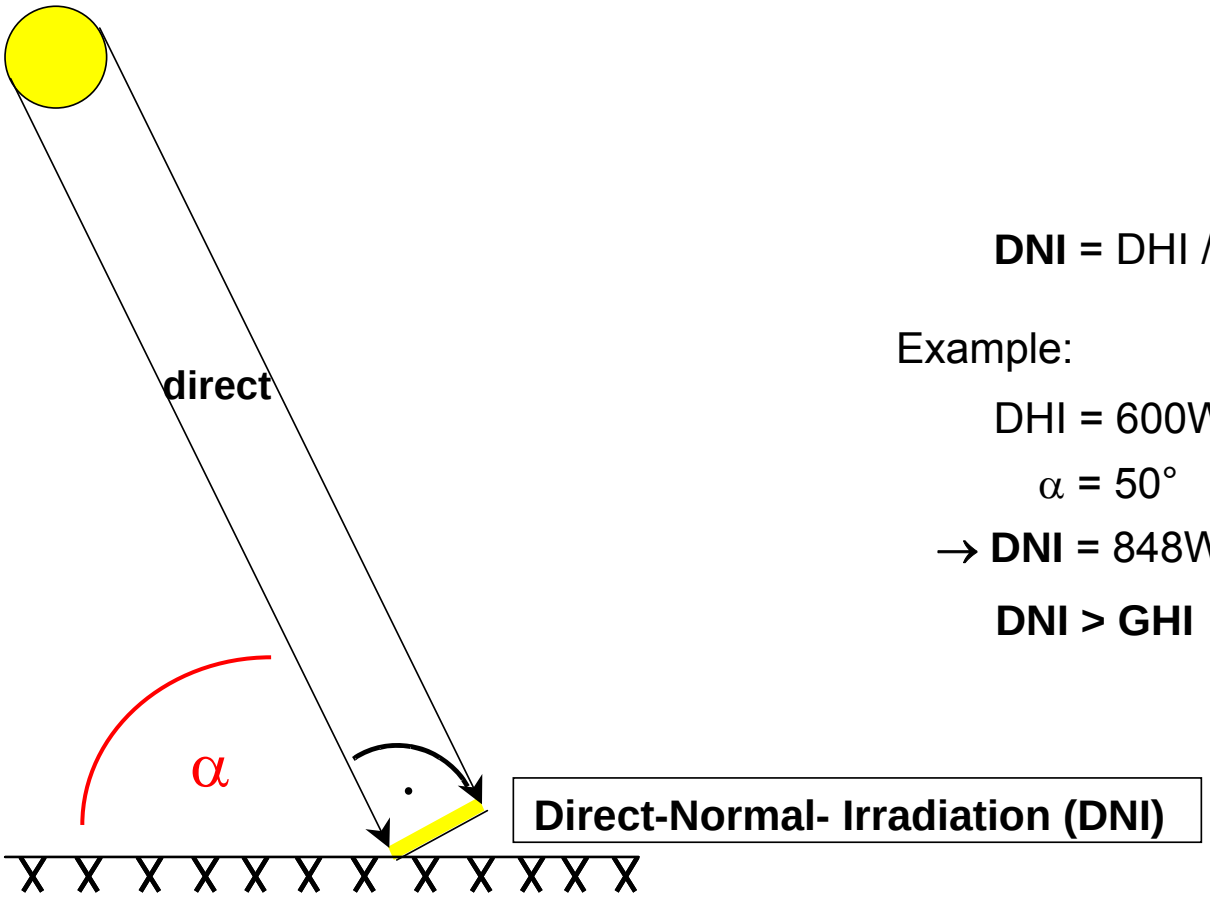
Absorption (ca. 15%)

Direct normal irradiance at ground

Radiative Transfer in the Atmosphere



Direct Normal Irradiation (DNI)



DNI = DHI / sin α

Example:

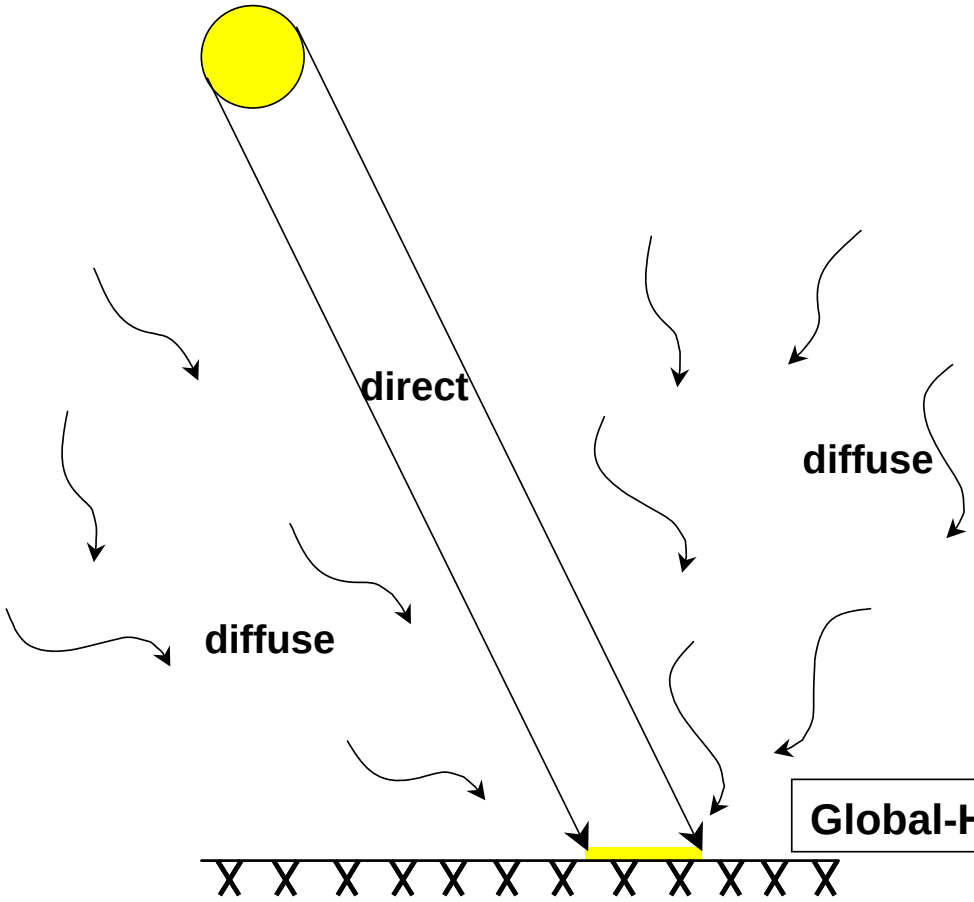
DHI = 600W/m²

α = 50°

→ **DNI** = 848W/m²

DNI > GHI

Global Horizontal Irradiation (GHI)



GHI = DHI + DIF

Example:

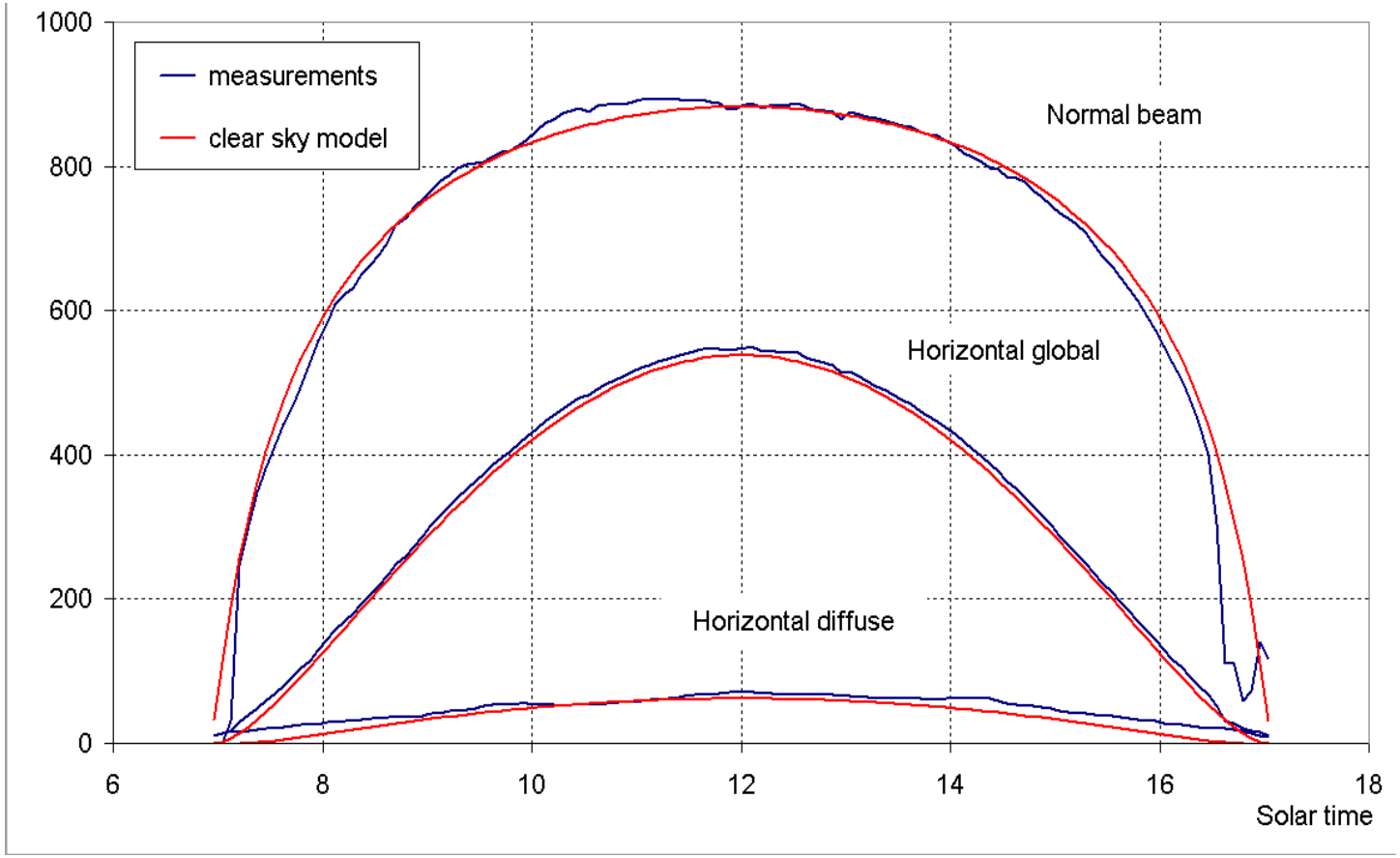
DHI = 600W/m²

DIF = 150W/m²

→ **GHI** = 750W/m²

Global-Horizontal-Irradiation (GHI)

Clear sky


1000
800
600
400
200
0
6
8
10
12
14
16
18
Solar time
measurements
clear sky model
Normal beam
Horizontal global
Horizontal diffuse

Clearness Index

The clearness index k_T is a more general measure of the radiation that is transmitted through the atmosphere (transmittance).

It relates the radiation incident on the earth's surface to the extraterrestrial radiation:

$k_T = G / G_o$

Note, that there is still a significant influence of the air mass through increased extinction with increased path length even for constant atmospheric situations.

The monthly average clearness index generally varies from about 0.3 to about 0.8.

Optical Depth

Optical Depth (or Optical Thickness) δ : Dimensionless line integral of the extinction coefficient along any path in a medium.

For the volume extinction coefficient τ has the dimension of length^{-1} (area per volume).

Physical interpretation:

length of a path in units of the mean free path (in an uniform medium)

Aerosol optical Depth (AOD)

- quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere
- not directly measurable; retrieval from ground-based observations of atmospheric spectral transmission by sunphotometers
- The solar irradiance I at a given wavelength can be expressed as

  $$I = I_0 \exp(-m\delta)$$

  with I_0 the extraterrestrial solar irradiance, m the air mass and δ the total optical depth.
- The total optical depth δ at a given wavelength is composed of several components such as scattering by gas molecules, δR (Rayleigh scattering), extinction by aerosol particles, δA, absorption of trace gases, δG, like ozone, and possible cloud contamination. Thus, the AOD can be obtained from the total optical depth by subtracting modelled estimates of the other components:
- $AOD = \delta A = \delta - \delta R - \delta G$

Atmospheric Turbidity

- **Linke turbidity factor T_L**: Measure of optical depth of the atmosphere due to aerosol particles and water vapour relative to a dry and clean atmosphere: $T_L = \delta(m_r) / \delta_{Rayl}(m_r)$
- Interpretation: Number of clean and dry atmospheres necessary to get the same extinction effect as that produced by the actual atmosphere
- T_L depends on the optical depth of the clean and dry atmosphere which is very sensitive to the air mass AM (or m_r). Therefore, T_L depends on AM, and consequently, on solar elevation.
- T_L generally lies between 2.0 (for a clean and dry atmosphere) and 6.0 (for a humid and polluted atmosphere). A complete clean and dry atmosphere (‘Rayleigh atmosphere‘) gives the value TL=1.

Clear sky modeling

Simple broadband clear sky model for direct and diffuse irradiance (Bird)

Basic equations:

$$I_{dir} = I_o (\cos \theta) \ (0.9662) \ \tau_{Rayl} \ \tau_{O3} \ \tau_{MolAbs} \ \tau_{H2O} \ \tau_{Aer}$$

$$I_{atm\_sc} = I_o (\cos \theta) \ (0.79) \ \tau_{O3} \ \tau_{H2O} \ \tau_{MolAbs} \ \tau_{H2O} \ \tau_{AerAbs}$$

$$[0.5 (1- \tau_{Rayl}) + B_a (1- \tau_{AerSc})] / 1 - m + (m)^{1.02}$$

$$Ig = (I_{dir} + I_{atm\_sc}) / (1-r_g r_s)$$

with I_o: extraterrestrial irradiance

τ : atmospheric transmittances

Clear Sky Index

- The clear sky index k_T* is a more general measure of the radiation that is transmitted through the atmosphere (transmittance).
- It relates the radiation incident on the earth's surface to the radiation in the clear sky case
- $k_T^* = G / G_{clear}$
- As such, the clear sky index is independent on solar geometry and should be free of influence of the atmospheric path length. As clear sky models are not perfect, there is some influence left.
- The clear sky index varies from almost 0 to about 1.1. Values above one are possible, if the sky is clearer than then model expects or in broken cloud situations where reflections from cloud add to the radiation at the ground.

Ground Measurements

Instruments

- **Absolute Cavity Pyrheliometer**
  A self-calibrating, electrical-substitution, view- limited thermopile radiometer the aperture of which is maintained normal to the sun's beam radiation.

- **Pyrheliometer**
  Same as an absolute cavity except that it is not self-calibrating; i.e., a view-limited radiometer the aperture of which is maintained normal to the sun's beam component.

- **Pyranometer**
  A radiometer used to measure all radiation incident on its flat receiver from a 2-pi steradians hemisphere.

Solar radiation instruments

direct irradiance

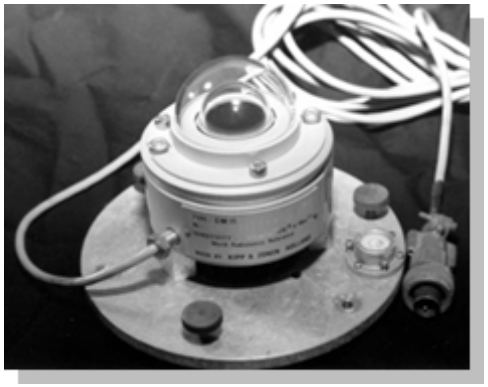
- absolute cavity radiometer (current world reference of calibration, used to transfer calibration from the Word Radiation Reference in Davos to working phyherliometers)
- field pyrheliometer
- Field of view usually 5°
- combined measurement uncertainty: 1%*
- rotating shadowband pyranometer uncertainty: 2%

*target accuracy of Baseline Surface Radiation Network (BSRN)

Solar radiation instruments

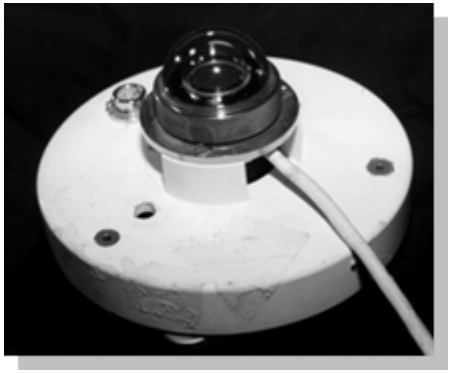
- Most pyranometers use a thermopile as means of converting solar irradiance into an electrical signal.
- Conversion of temperature difference between hot and cold junctions of the thermopile to electrical voltage (~40 μV C^{-1} jct^{-1}).
- Advantage: Thermopile is spectrally neutral across the entire solar spectrum (domes may have spectral dependencies)
- Disadvantage: Output is temperature dependent and the instruments must ‘create’ a cold junction.
- Three primary types of instruments:
  - Black and White
  - Non-temperature compensated (Single and double domed)
  - Temperature compensated (Single and double domed)
- uncertainty: 2%* – 5% (*target accuracy of Baseline Surface Radiation Network (BSRN))

Pyranometer Types



K & Z CM11
(double dome, temperature compensated)

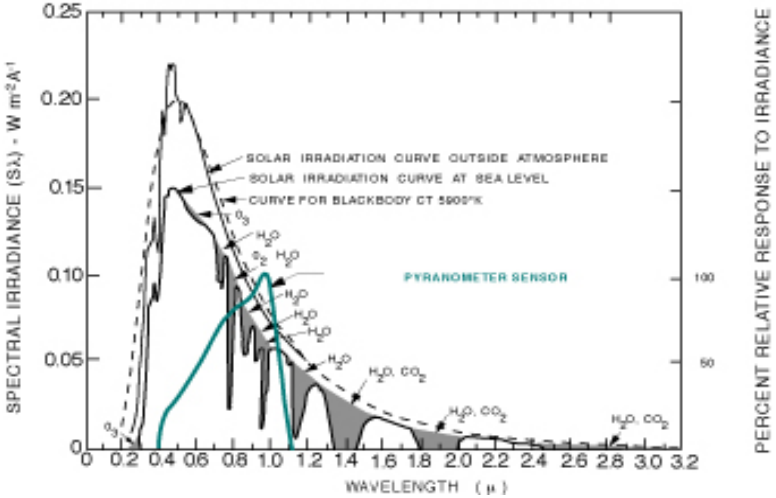
EKO Black & White (single dome)



K & Z CM5
(single dome, non-temperature compensated)

Photoelectric Pyranometers

- Spectral response is non-linear and does not match solar spectrum.
- General calibrations are through comparison with pyranometers, therefore there are spectral mismatch problems.
  must be used in the same lighting conditions as those under which it was calibrated.
- Pyranometer sensors are calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions. Typical error under these conditions is ±5%.
- Similar problems arise when using sensors calibrated in one climate regime and used in a different regime.



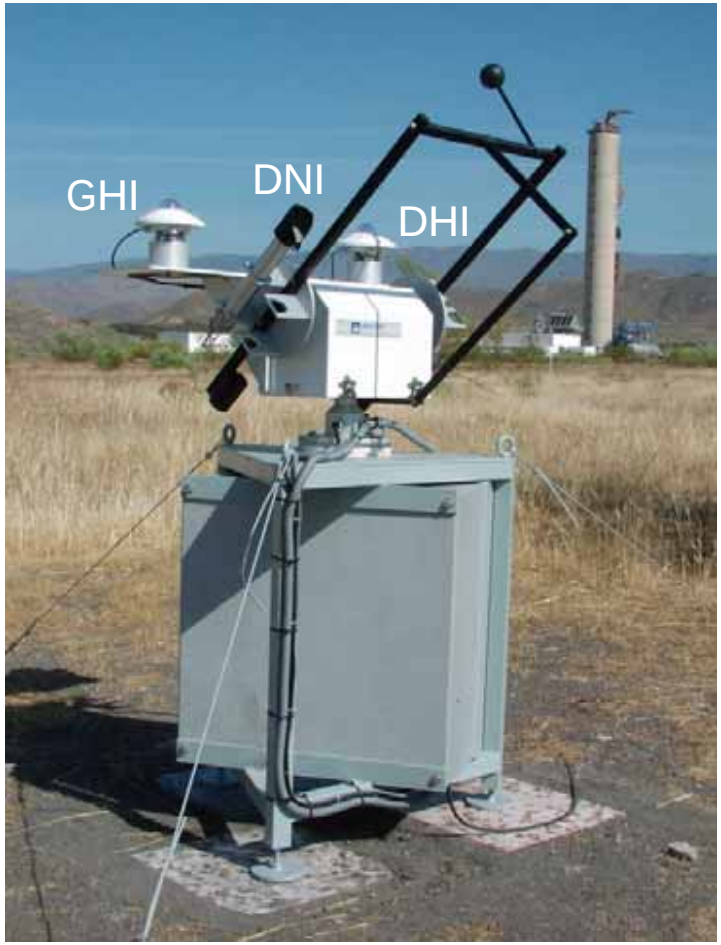
Solar radiation instruments

diffuse irradiance

- shaded pyranometers
  - pyranometer with shading ring
  - pyranometer with shading disc and sun tracking device
- uncertainty: 4%*- 8%

*target accuracy of Baseline Surface Radiation Network (BSRN)

Precise sensors *(also for calibration of RSP)*:



Thermal sensors:
pyranometer and pyrheliometer, precise 2-axis tracking

Advantage:

+ high accuracy

+ separate GHI, DNI and DHI sensors
(cross-check through redundant measurements)

Disadvantages:

- high acquisition and O&M costs

- high susceptibility for soiling

- high power supply

Instrumentation for unattended abroad sites:

Rotating Shadowband Pyranometer (RSP)

Sensor: Si photodiode

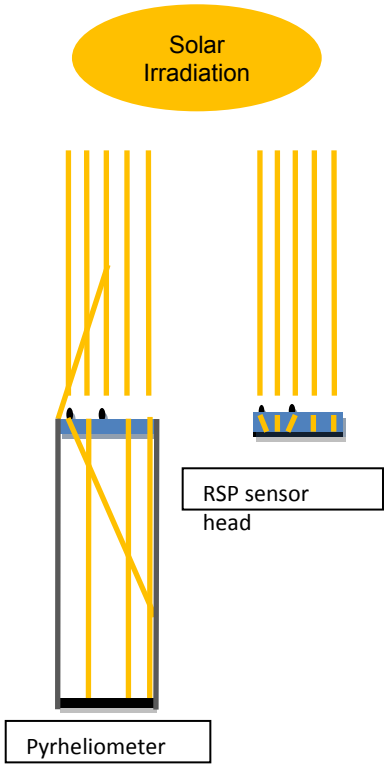
Advantages:

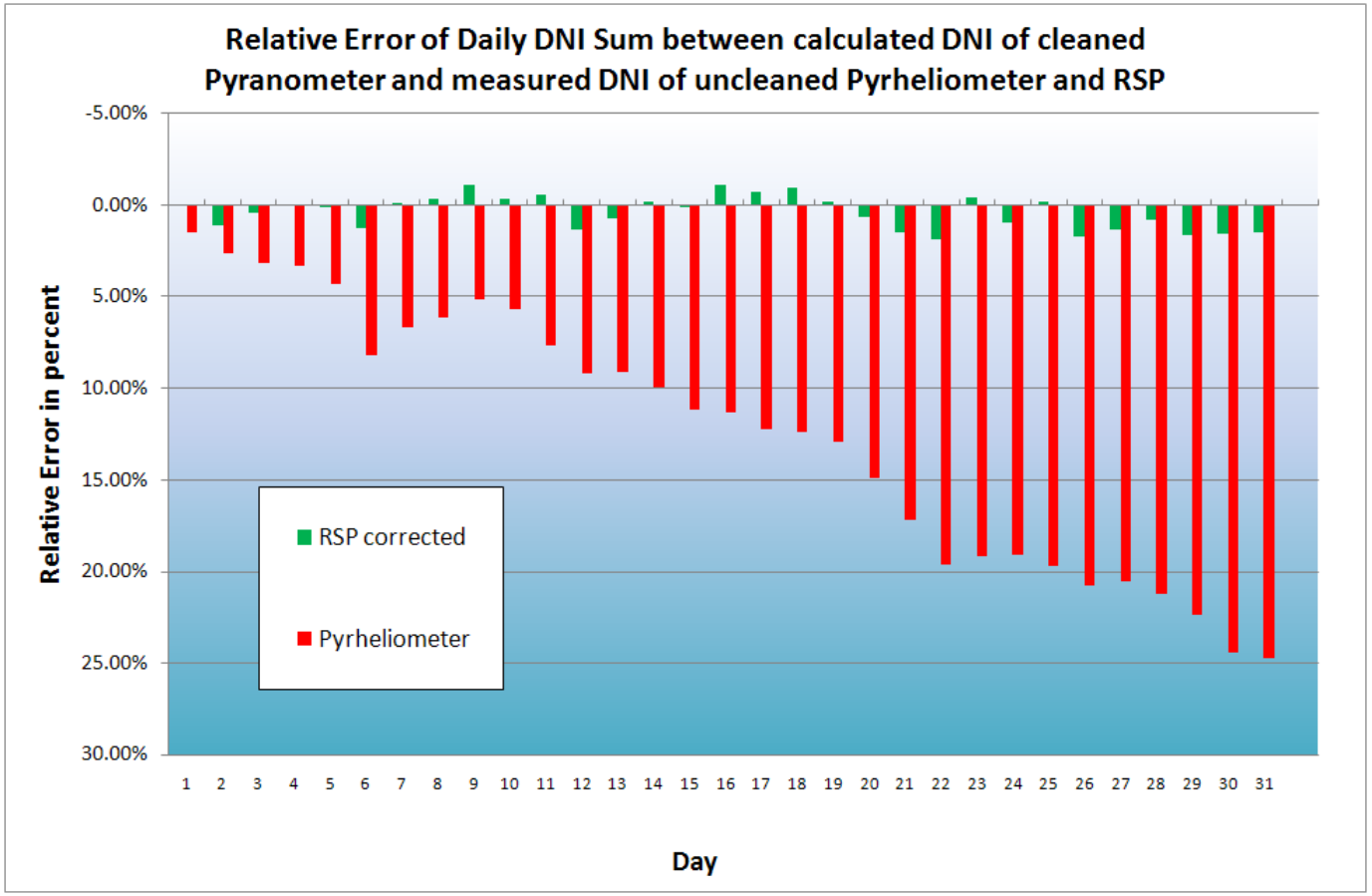
+ fairly acquisition costs
+ small maintenance costs
+ low susceptibility for soiling
+ low power supply

Disadvantage:

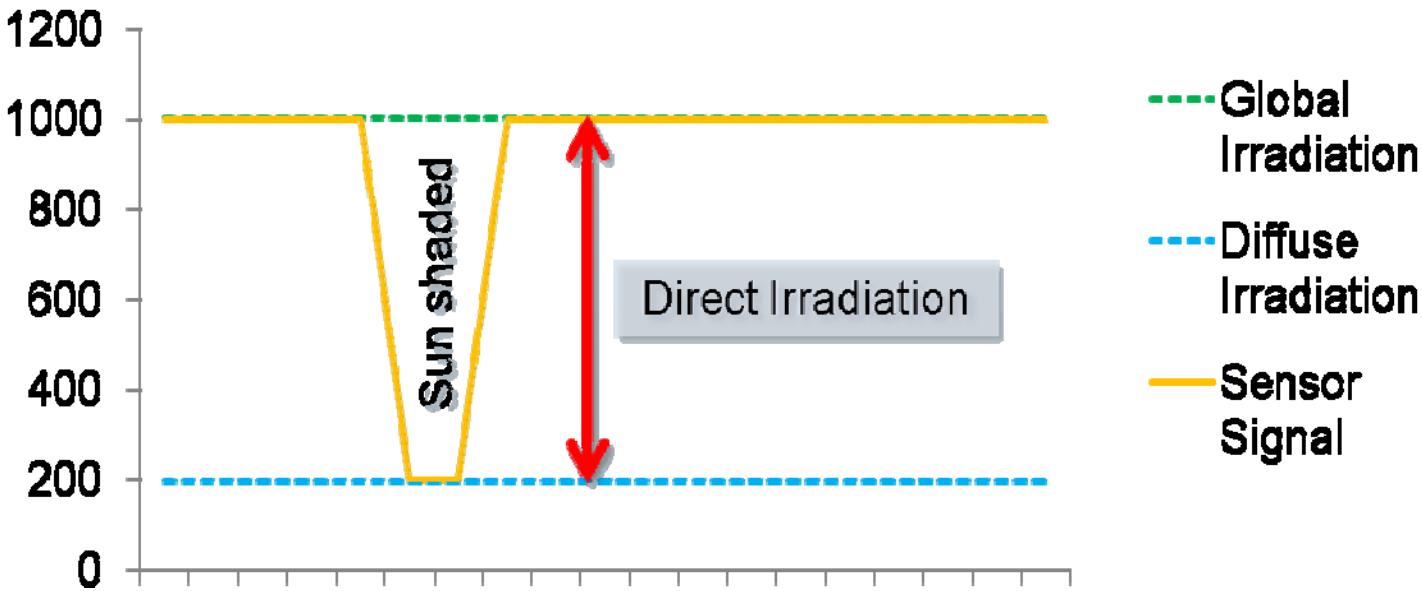
- special correction for good accuracy necessary *(established by DLR)*

Soiling – Why pyrheliometers don´t meet the need

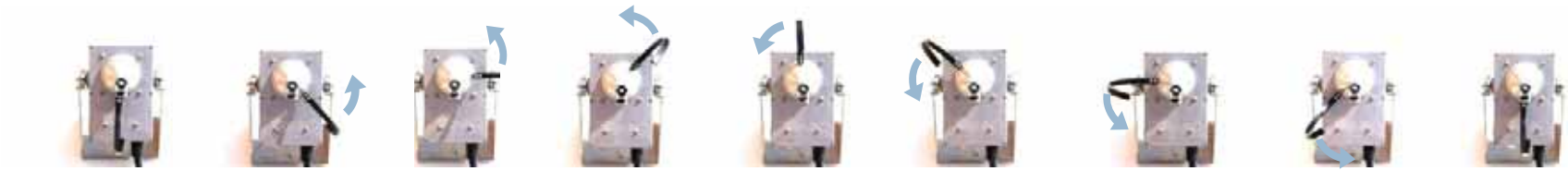




RSP – Principle of Measurement



Simplified sensor signal during shadow band rotation, which takes place once per minute and lasts about 1.5 seconds per rotation.



Solar Millennium Meteostations

Measurements

- All relevant meteorological data for CSP in 1-10 min intervals
  - Direct Normal Irradiation (DNI)
  - Global Horizontal Irradiation (GHI)
  - Diffuse Horizontal Irradiation (DHI)
  - Temperature
  - Relative Humidity
  - Wind speed
  - Wind direction
  - Atmospheric pressure or others on request

Solar Millennium Meteostations

Main Features

- Fully automated measurement and data acquisition at arbitrary remote sites
- Automated daily data transfer via mobile communication network
- Autarkic power supply by solar panel and battery
- Minimal maintenance effort
- Rugged station for tough climatic conditions
- Certified Quality:
  - One by one radiation sensor calibration by German Aerospace Center (DLR)
  - Standard deviation in radiation ~4% (individually determined by DLR)
  - Sophisticated correction formulas developed in cooperation with DLR

Radiometer Characteristics

- **Calibration Stability**
  can it maintain a calibration over a long period of time?
- **Cosine response**
  are the optics of a quality that the signal output is independent of solar elevation?
- **Temperature stability**
  will a given input provide the same output voltage independent of temperature?
- **Spectral Quality**
  is the instrument spectrally flat across the solar spectrum so that it responds linearly to changes in the solar spectrum?
- **Tilt**
  does the instrument behave the same when tilted?

Calibration

International calibration methods

- Pyranometer and pyrheliometer calibration scales are traced to the World Radiometric Reference (WRR) (maintained by the World Radiation centre (WRC) in Davos, Switzerland)
- WRC maintains the World Standard Group (WSG), and thus the World Radiometric reference (WRR), with the highest possible stability and to provide the highest possible world-wide homogeneity for solar irradiance measurements.

Calibration – World Radiometric Reference

- measurement standard representing the SI unit of irradiance
- introduced to ensure world-wide homogeneity of solar radiation measurements
- in use since 1980determined from the weighted mean of the measurements of a group of 15 absolute cavity radiometers which have been fully characterized
- Currently, the WSG is composed of 6 instruments: PMO-2, PMO-5, CROM-2L, PACRAD-3, TMI-67814 and HF-18748.
- estimated accuracy of 0.3%
- mandatory use introduced by WMO in its statutes in 1979

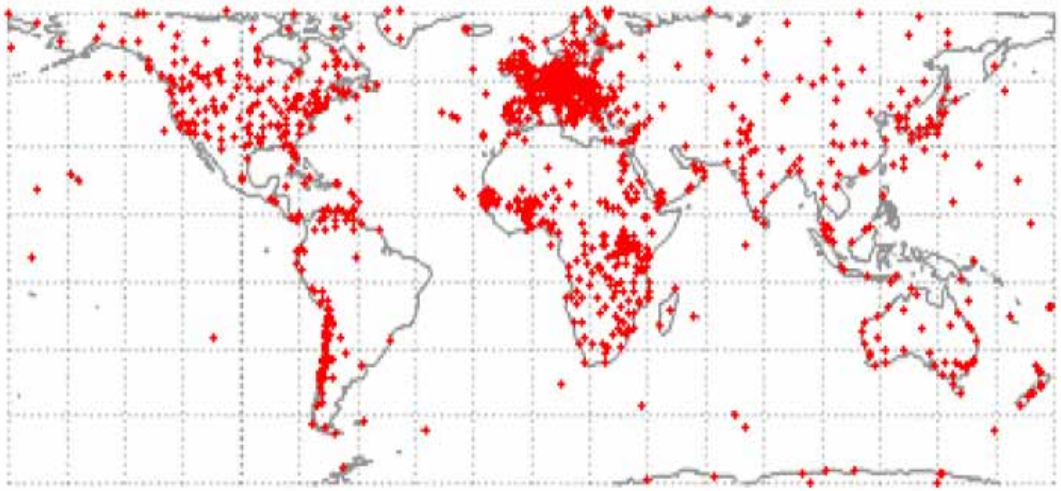
Availability of ground measured data

long term measurements at meteorological stations

- National Meteorological offices
- World radiometric Network (by World Meteorological Organisation)
- Baseline Surface Radiation Network

World radiometric network

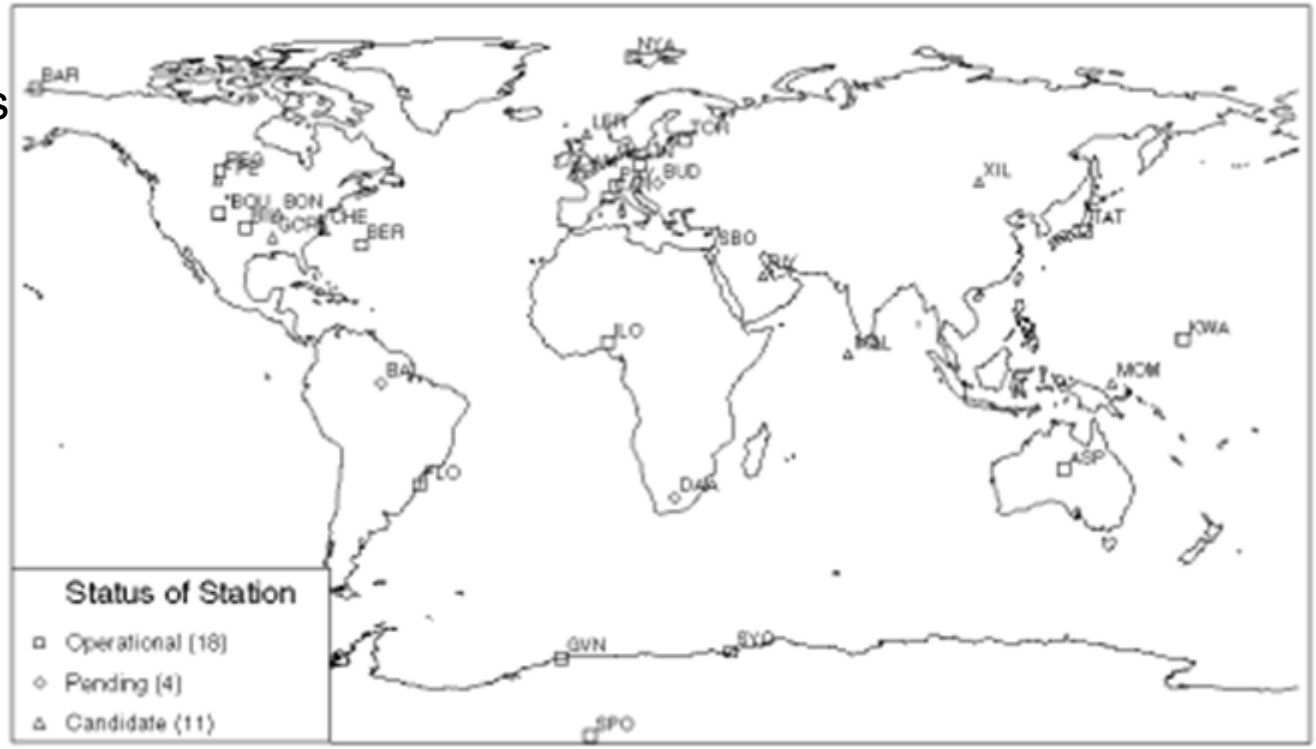
- global irradiance & sunshine duration
- ca. 1200 stations
- monthly or daily values



World Radiometric network 1966- 1993
(source: WRDC/WMO, Cros et al. , 2004)

Baseline surface radiation network

- high quality measurements
- global, direct, diffuse
- minute values



Resource products based on ground measured data

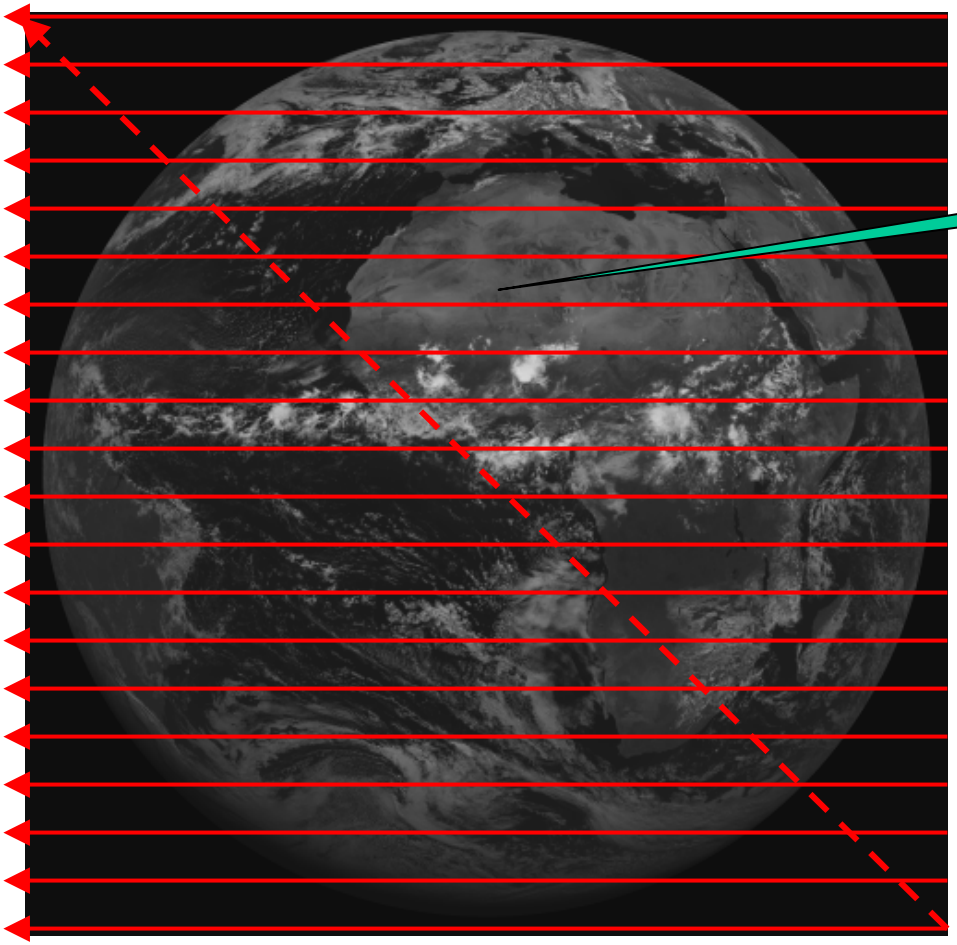
- **spatial interpolation techniques** to derive maps and site specific data
- **stochastic models or average daily profiles**
  to derive values with high temporal resolution
  (daily,hourly or minute values)
- **statistical global to beam models** to derive DNI

Satellite based assessments

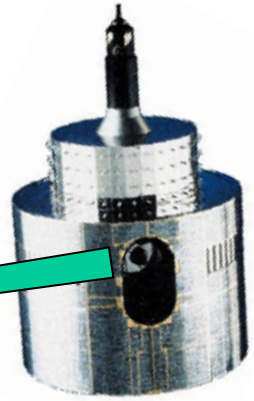
How two derive irradiance data from satellites

- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour

Das Meteosat System – Image recording

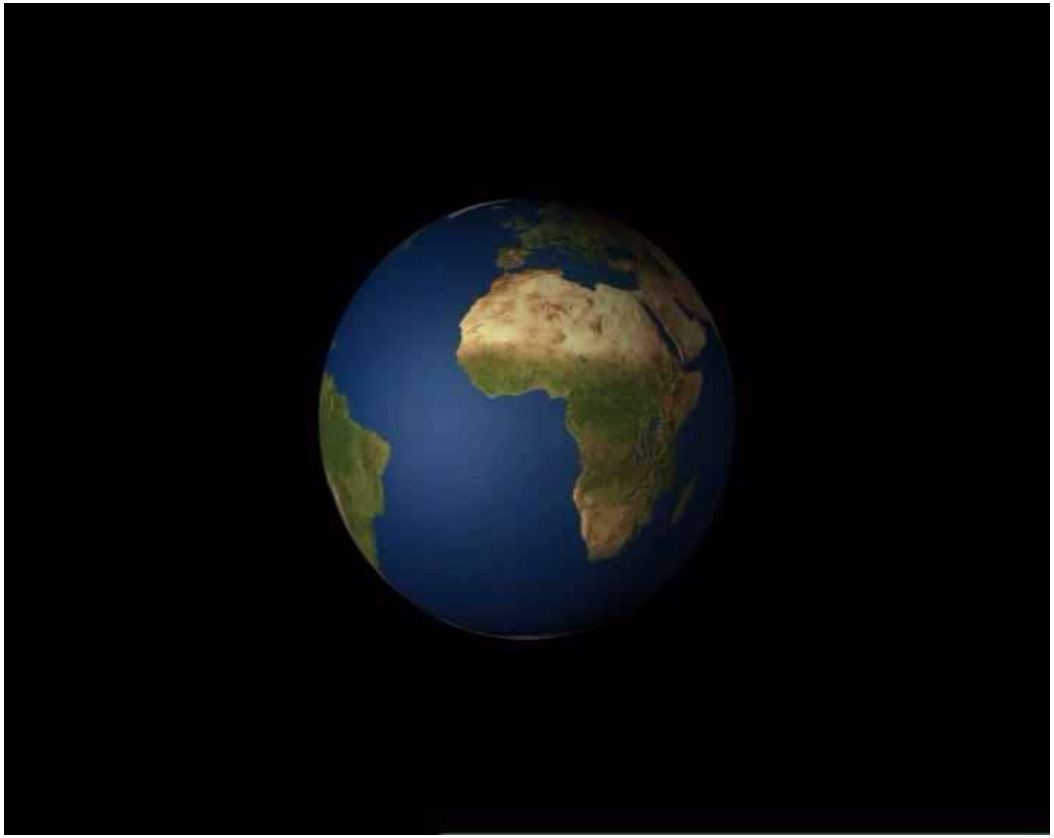


Scan



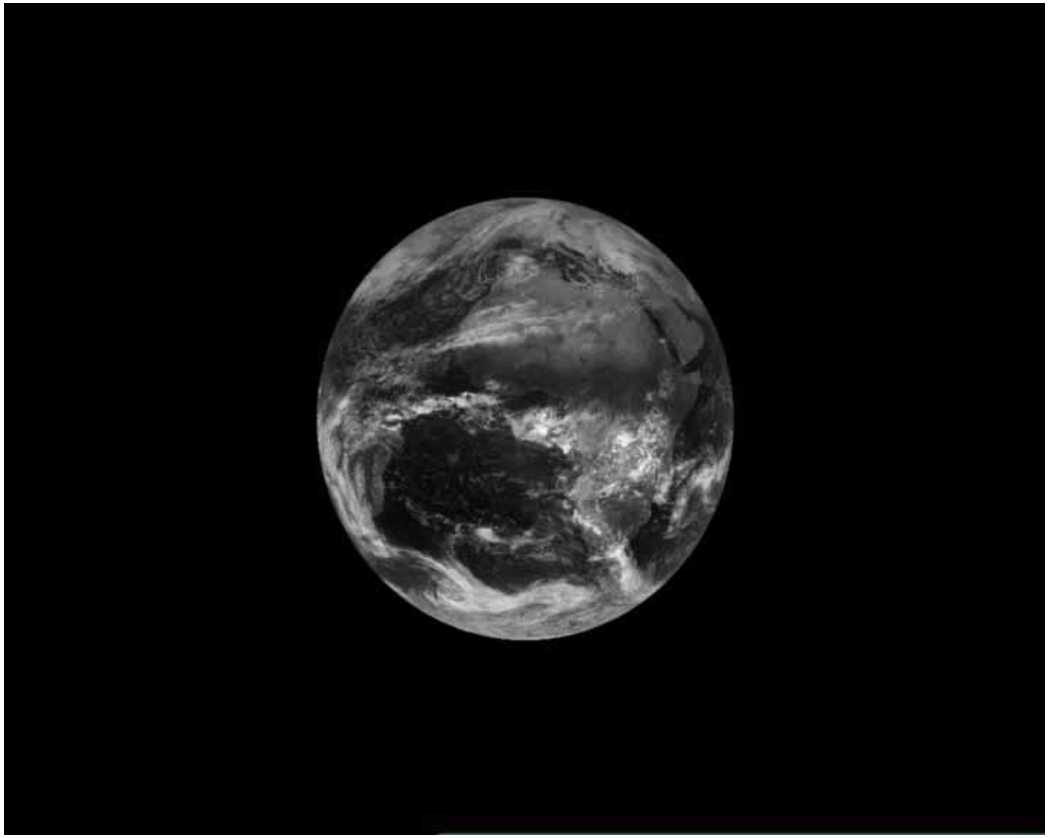
- The satellite rotates at 100 rpm
- Line by line scanning of the earth from south to north
- Pixels by sampling of the analog sensor signal
- Field of view of the sensor e.g. in Europe 3 x 4 km due to geometric distortion

How two derive irradiance data from satellites



- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible …

How two derive irradiance data from satellites



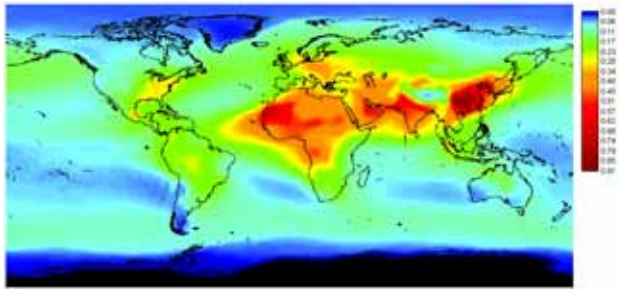
- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible and infra red spectrum

How two derive irradiance data from satellites

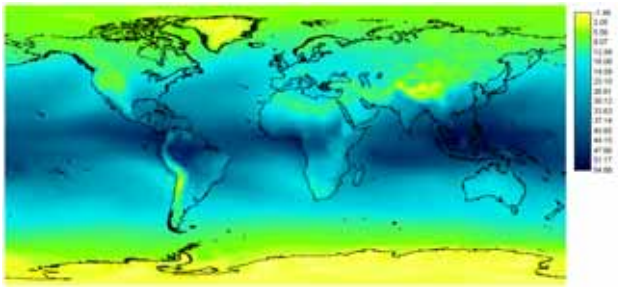
- The Meteosat satellite is located in a geostationary orbit
- The satellite scans the earth line by line every half hour
- The earth is scanned in the visible and infra red spectrum
- A cloud index is composed from the two channels

Clear sky Model input data

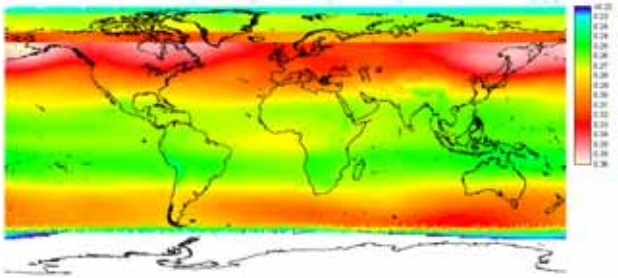
- Aerosol optical thickness
  GACP Resolution 4°x5°, monthly climatology
  MATCH Resolution 1.9°x1.9°, daily climatology



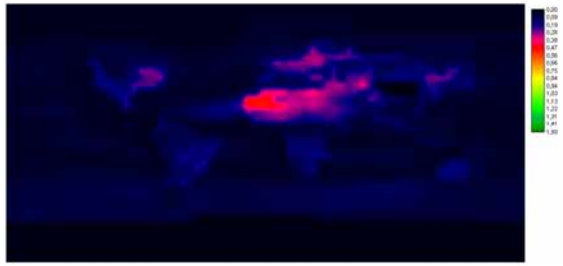
- Water Vapor: NCAR/NCEP Reanalysis
  Resolution 1.125°x1.125°, daily values



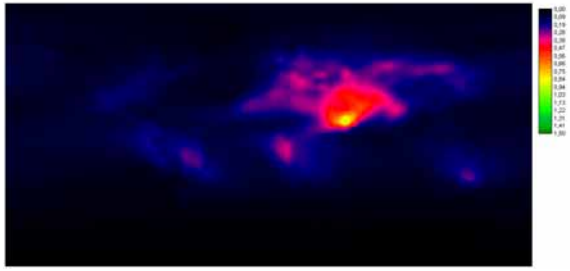
- Ozone: TOMS sensor
  Resolution 1.25°x1.25°, monthly values



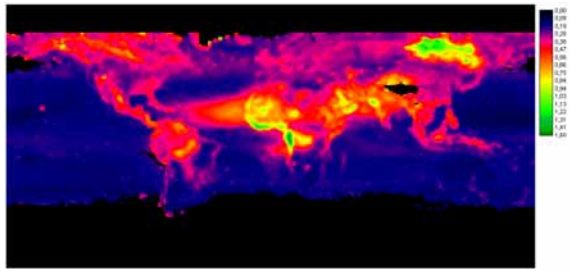
Uncertainty in Aerosols



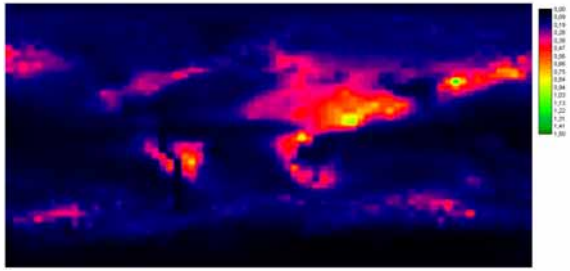
GADS



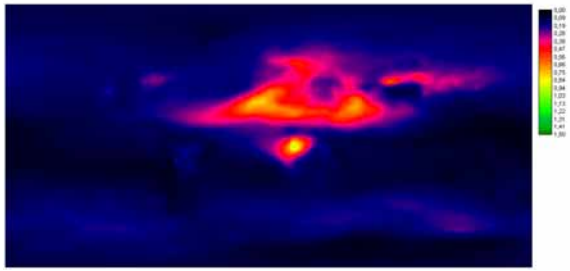
NASA GISS v1 / GACP



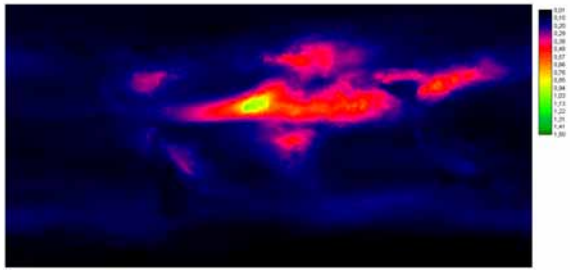
Toms



NASA GISS v2 1990

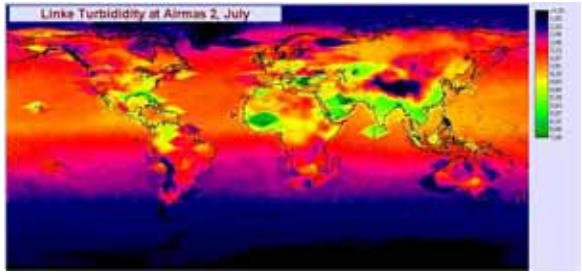


GOCART



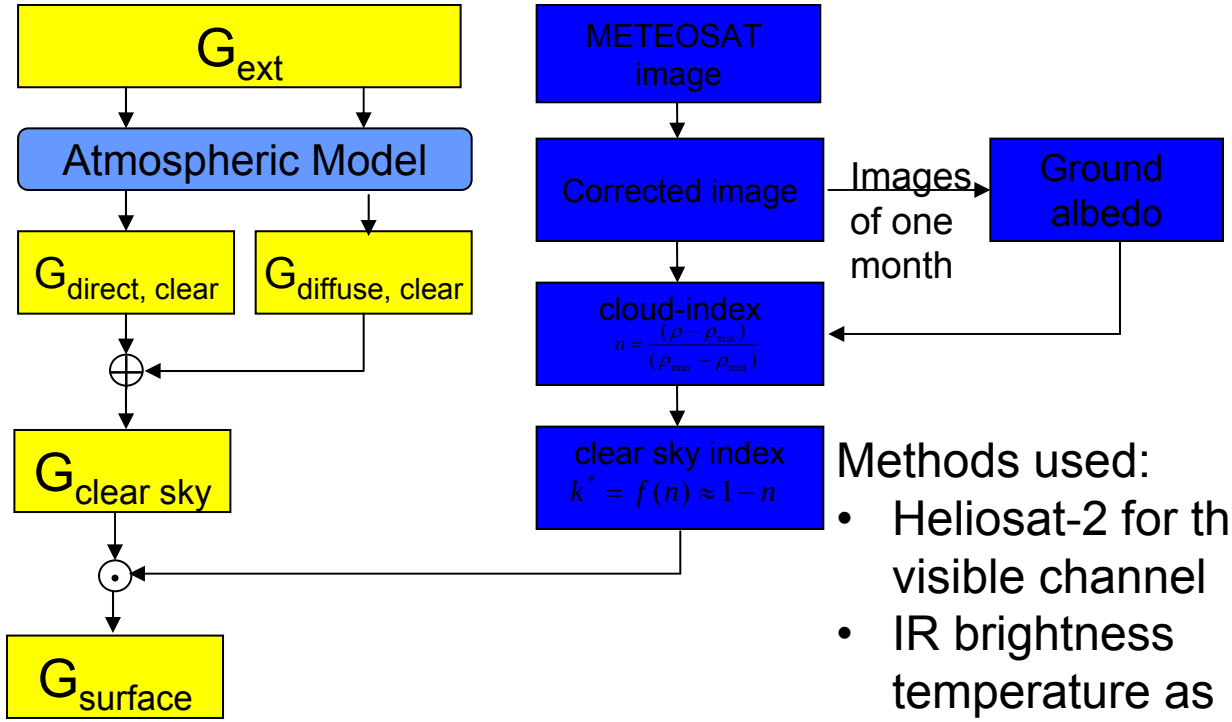
AeroCom

- All graphs are for July
- Scales are the same! (0 – 1.5)
- Large differences in Aerosol values and distribution



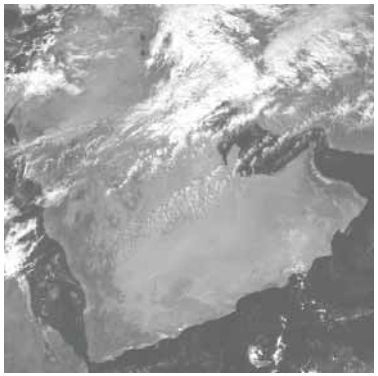
Linke Turbidity

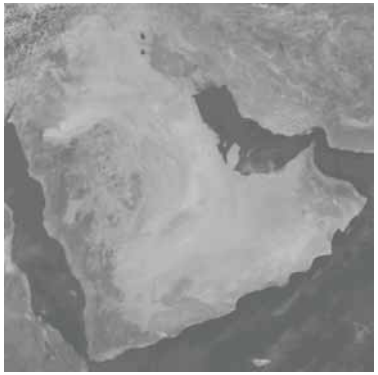
Calculation of solar radiation from remote sensing

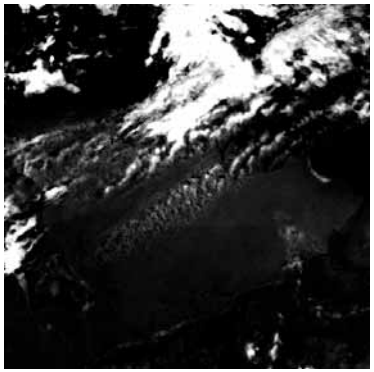


Methods used:

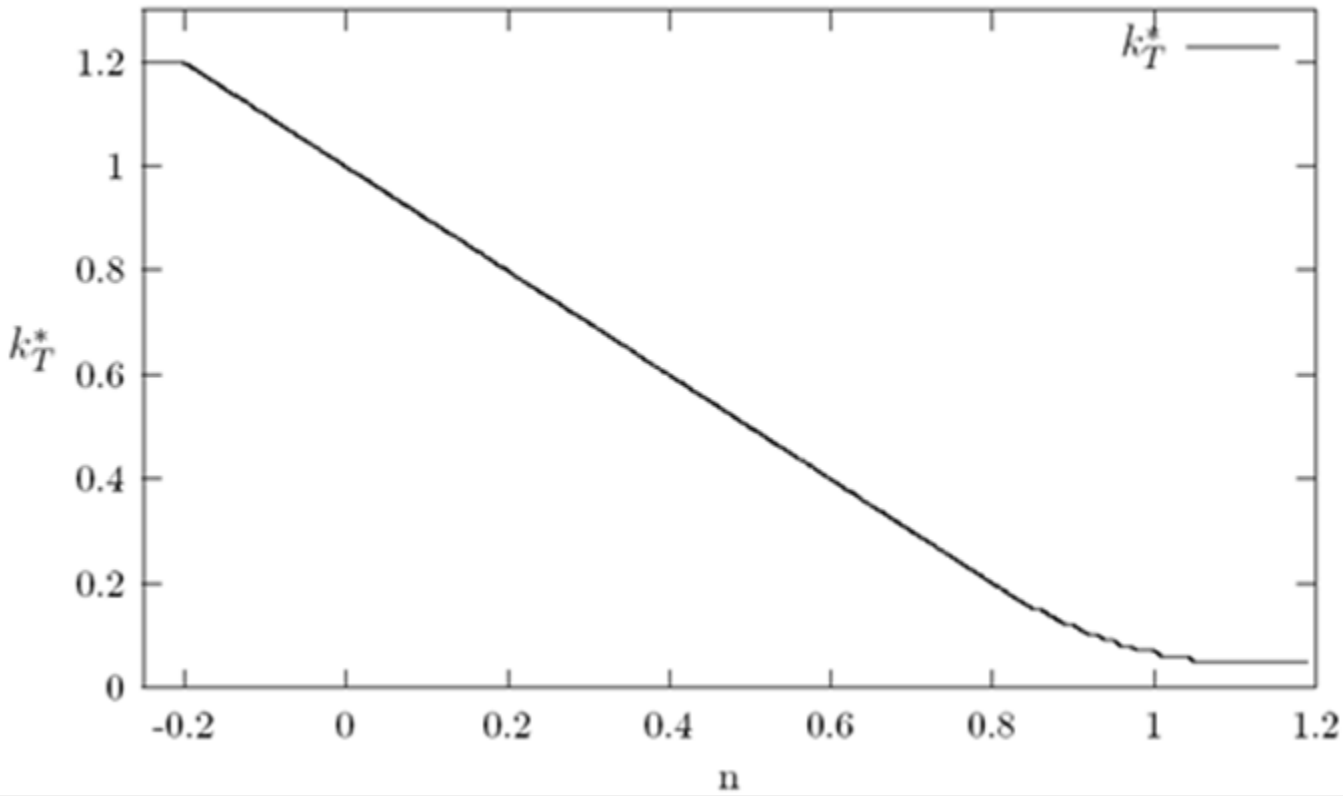
- Heliosat-2 for the visible channel
- IR brightness temperature as indicator for high cirrus clouds (T < -30°C, DNI = 0)



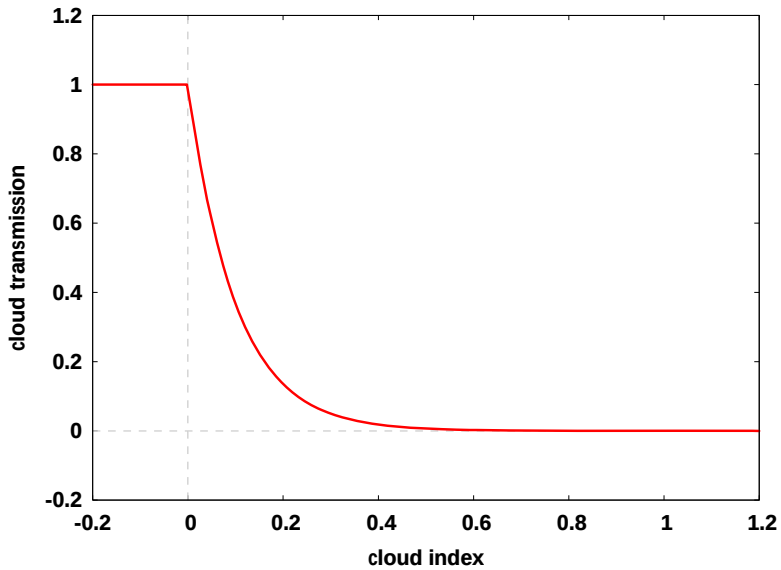


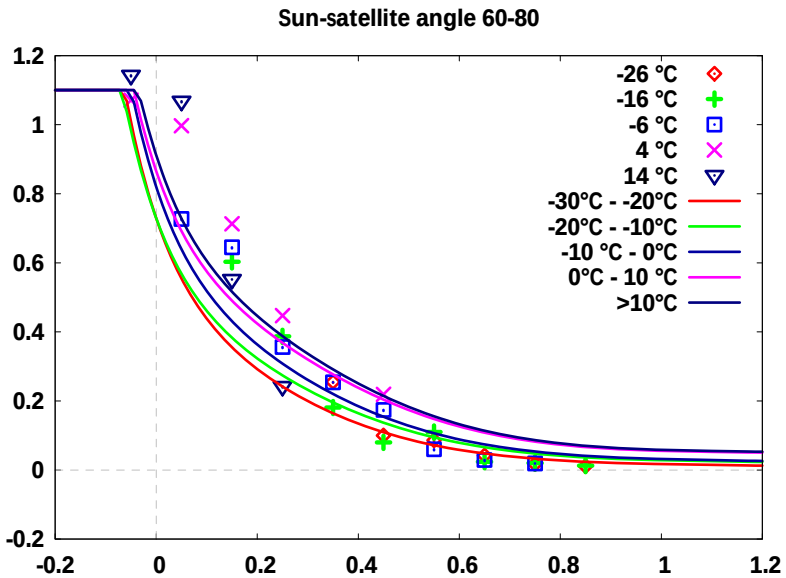


Cloud Transmission for GHI



Cloud Transmission for DNI



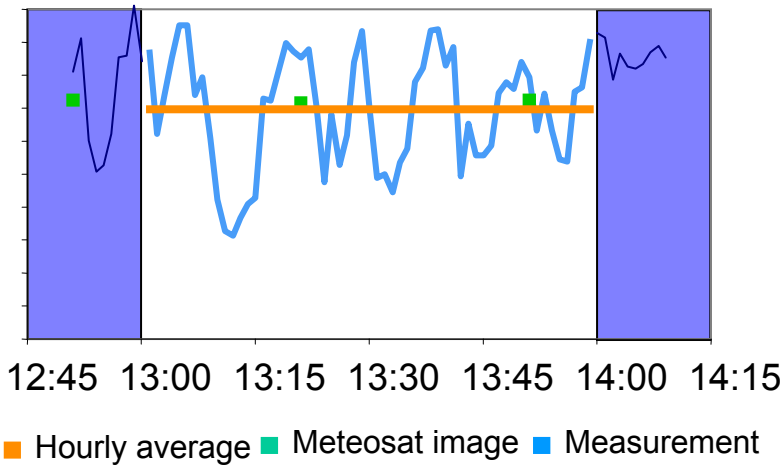


Simple function $\tau = e^{-10*ci}$

Complex functions:
Different exp. function for various viewing angles and brightness temperatures

Comparing ground and satellite data: time scales

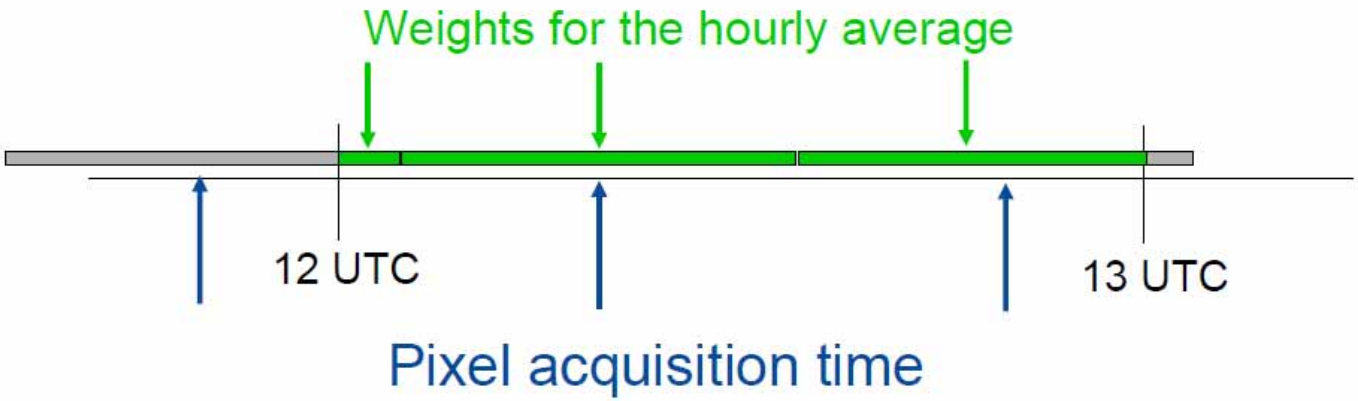
Hi-res satellite pixel in Europe



- Ground measurements are typically pin point measurements which are temporally integrated
- Satellite measurements are instantaneous spatial averages
- Hourly values are calculated from temporal and spatial averaging (cloud movement)

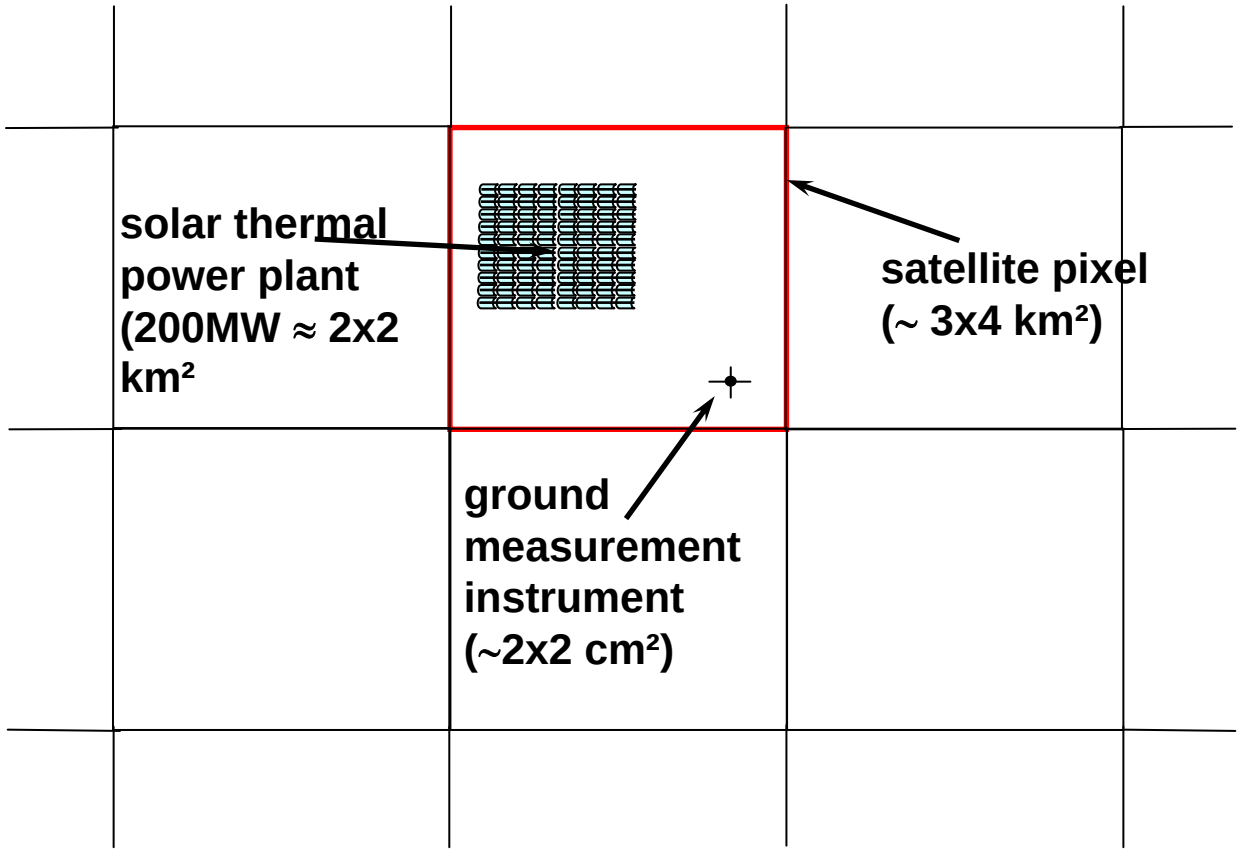
Constrution of hourly averages from satellite images

- The hourly irradiance values are calculated by a weighted average



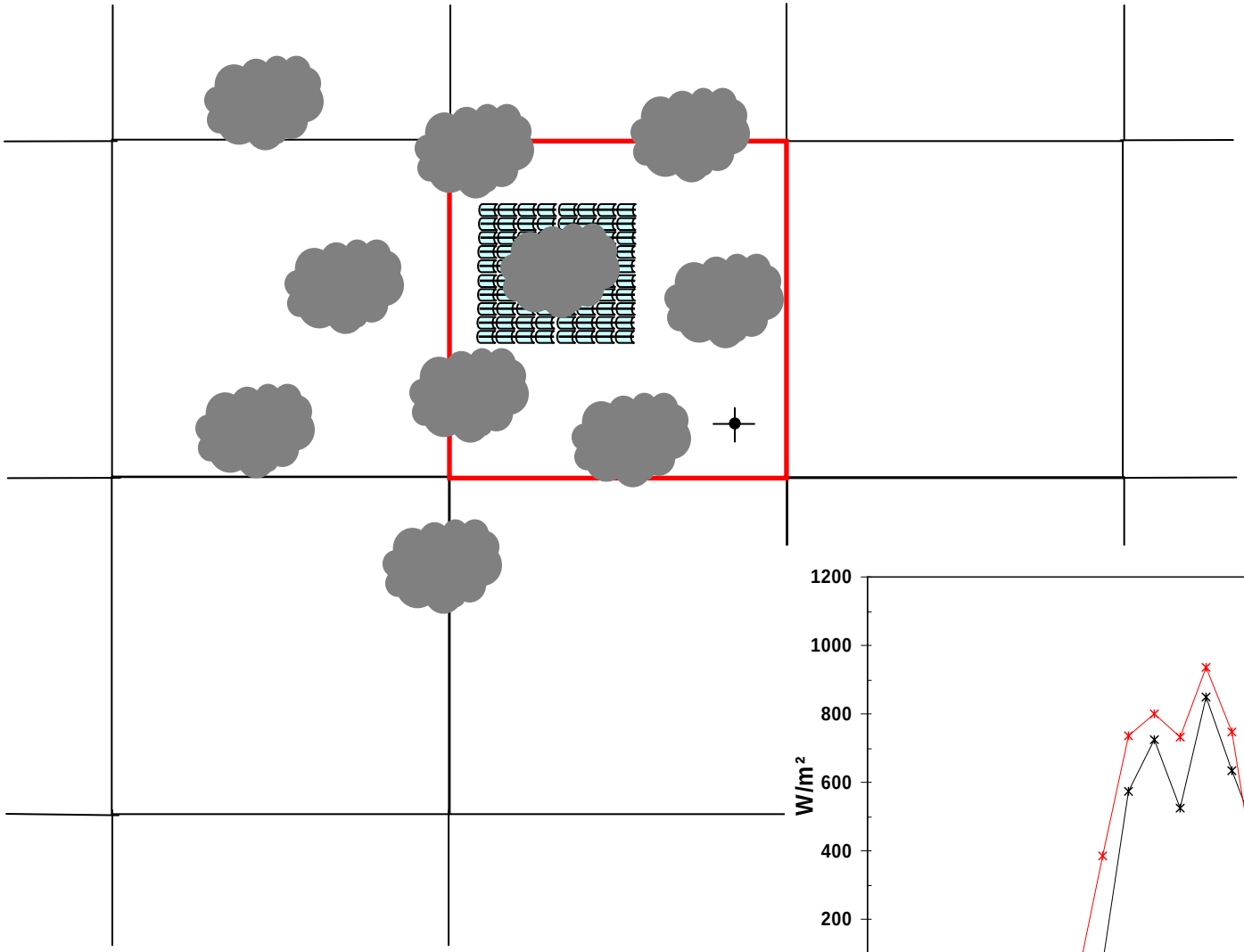
- full scan : 3 images per hour

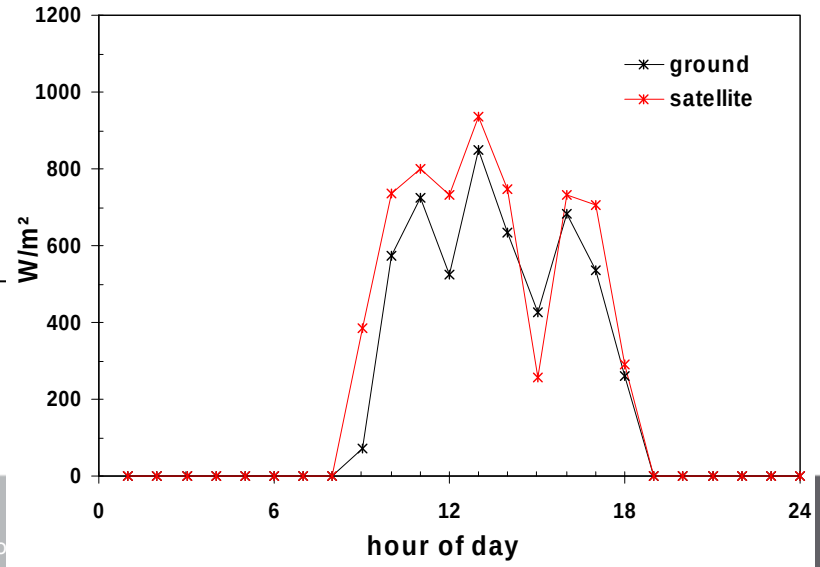
Comparing ground and satellite data: “sensor size”



Comparison with ground measurements and accuracy

general difficulties: *point versus area* and *time integrated versus area integrated*

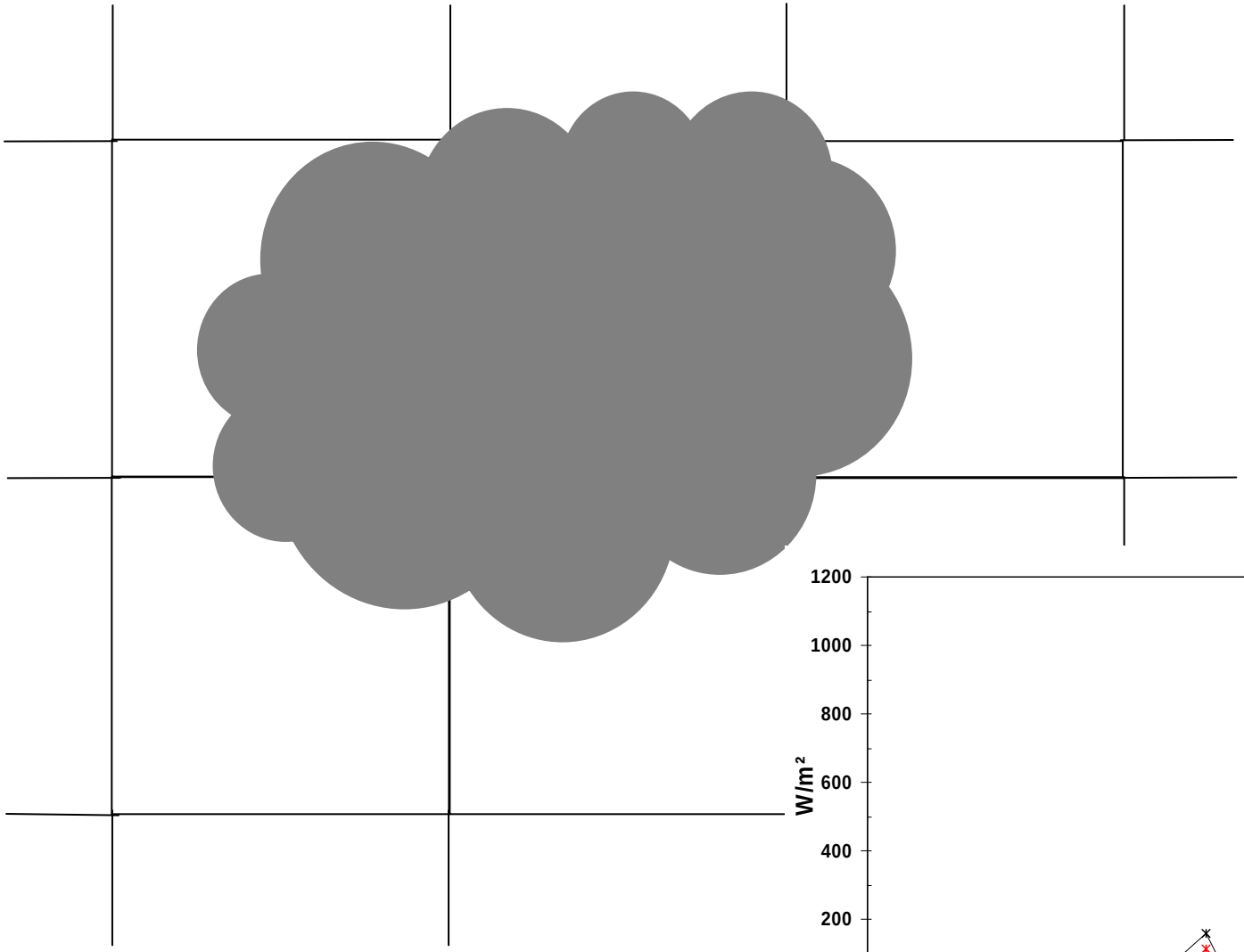


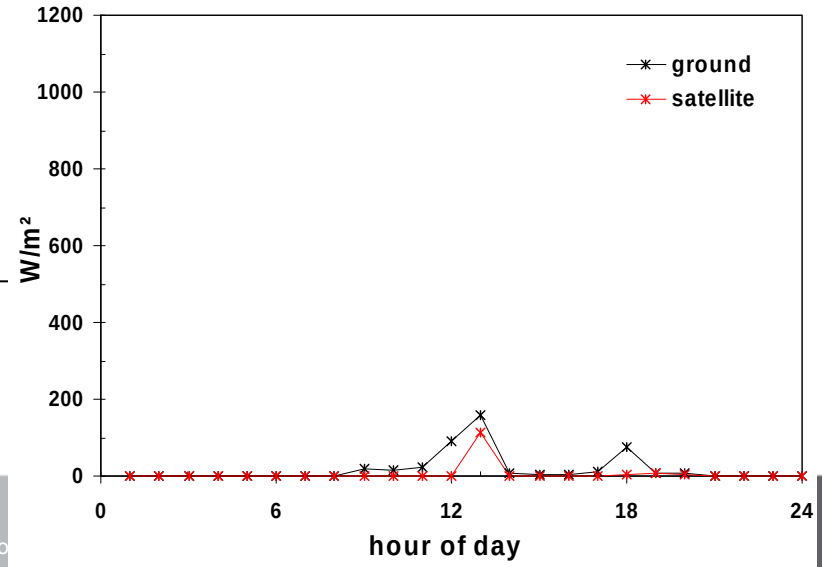


DNI time serie for 1.11.2001, Almería
Partially cloudy conditions, cumulus humilis

Comparison with ground measurements and accuracy

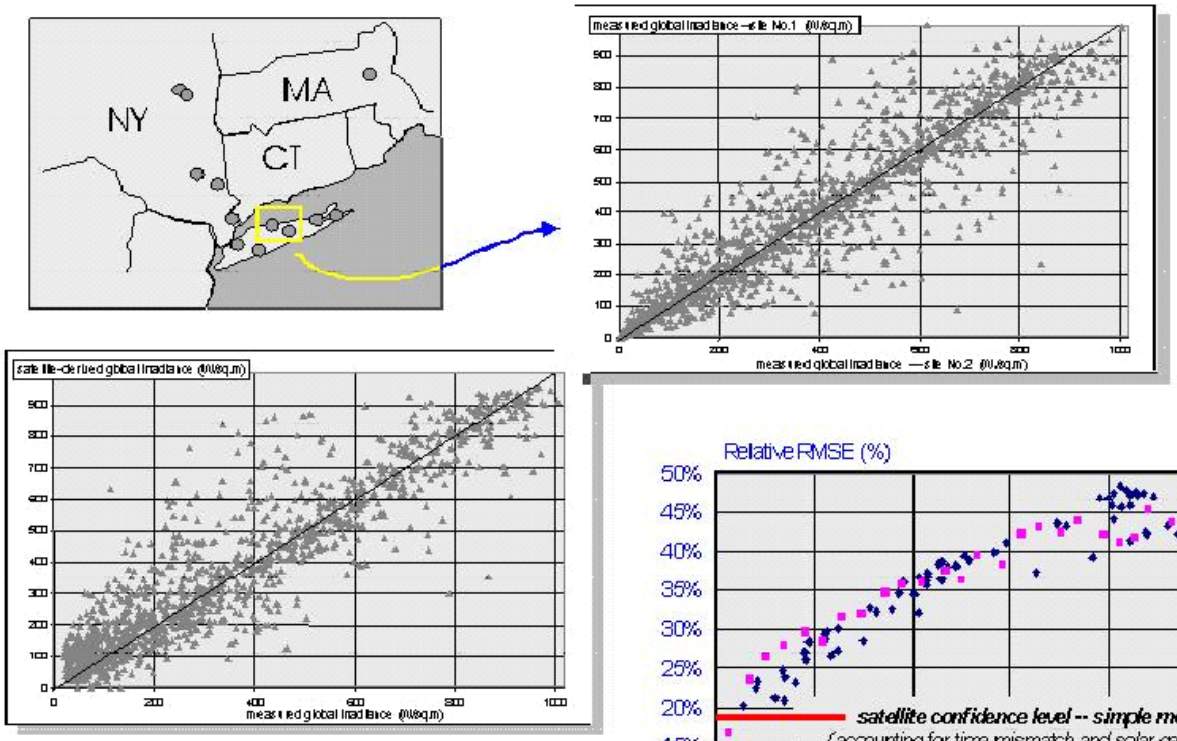
general difficulties: *point versus area* and *time integrated versus area integrated*

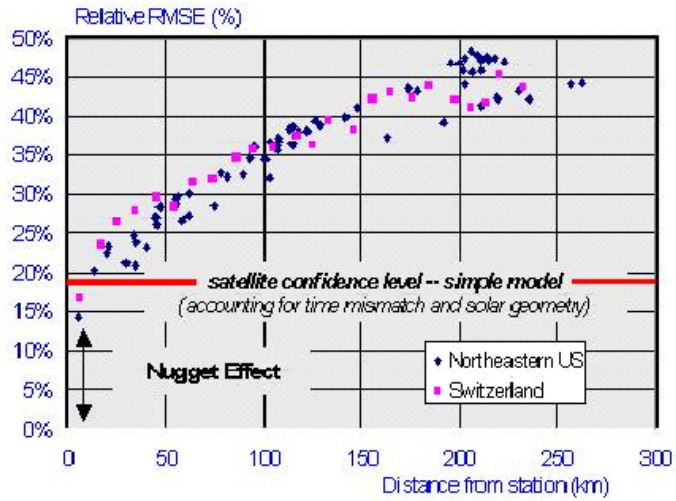




DNI time serie for 30.4.2000, Almería
overcast conditions, strato cumulus

Satellite data and nearest neighbour stations

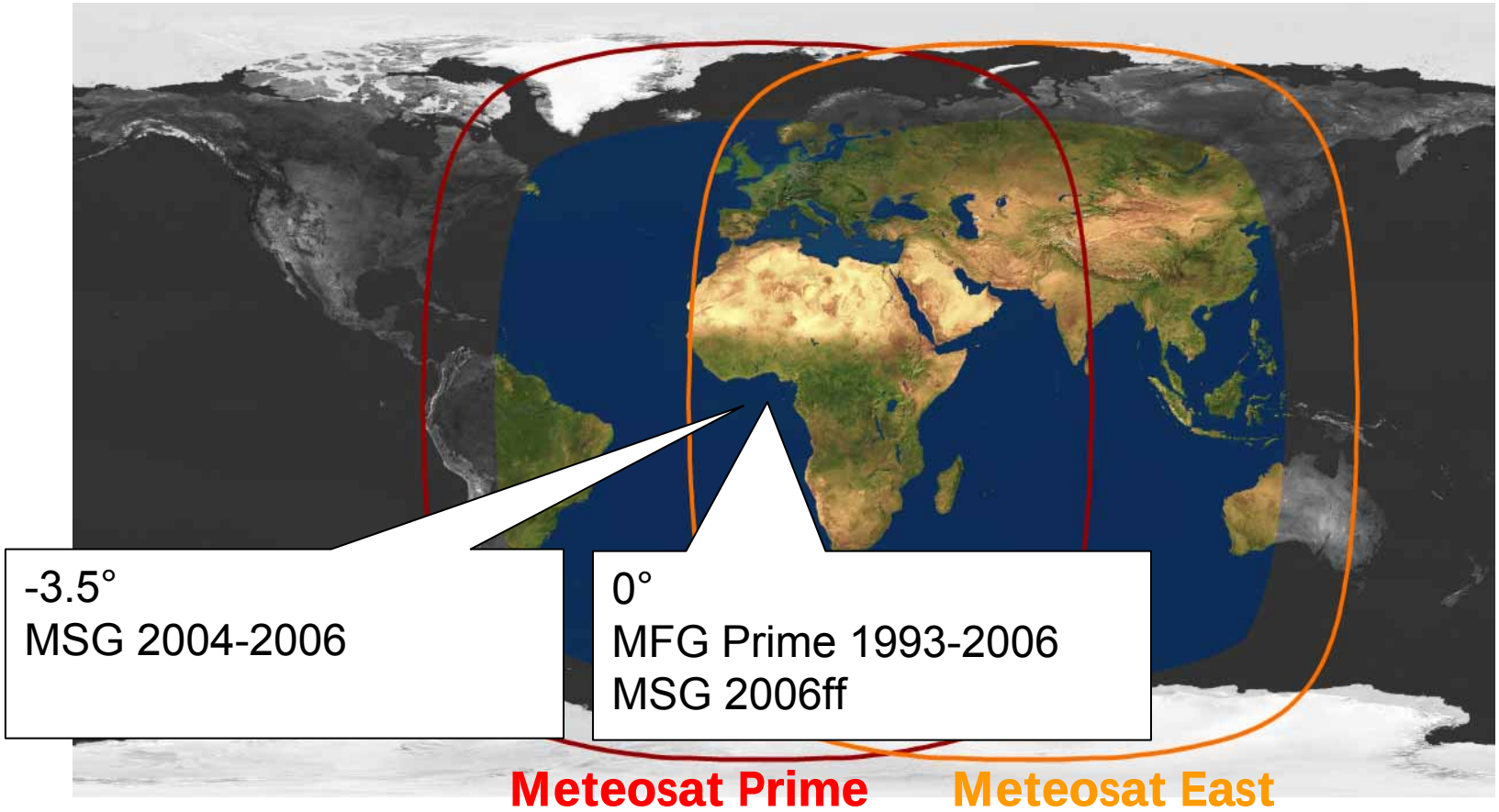




- Satellite derived data fit better to a selected site than ground measurements from a site farther than 25 km away.

Perez et al., ASRC

Meteosat Positions

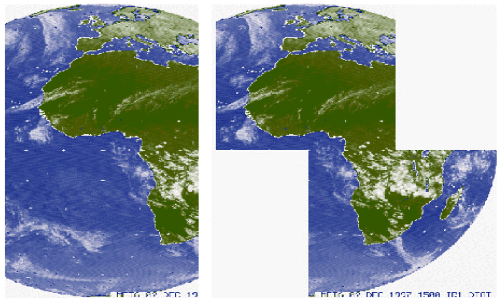


Comparision First und Second Generation

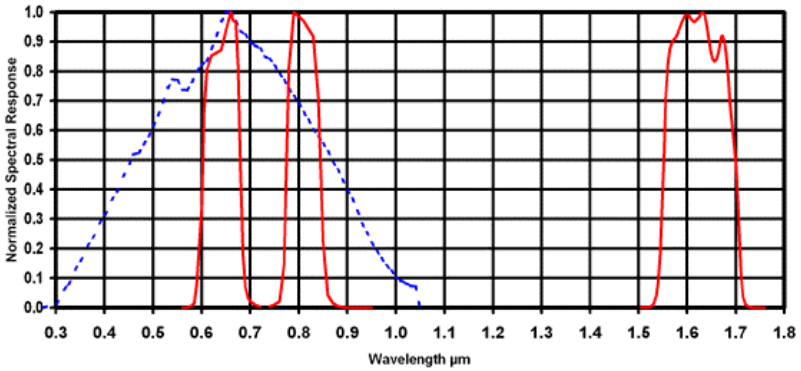
	1st Generation (MOP)	2nd Generation (MSG)
Radiometric	8 bit	10 bit
Spatial (VIS - HRV)	2.5 km	1 km
Spatial (all other)	5 km	3 km
Temporal	30 min	15 min
Spectral	3 channels	12 channels

Necessary changes in MSG Processing

- MSG does not have a full disc broadband vis channel. The HRV channel is due to the split coverage difficult to use.
- Two narrowband channels at 0.6 and 0.8 µm can be use to create a pseudo broadband channel We apply a method by Cros / Albuisson / Wald (2005).



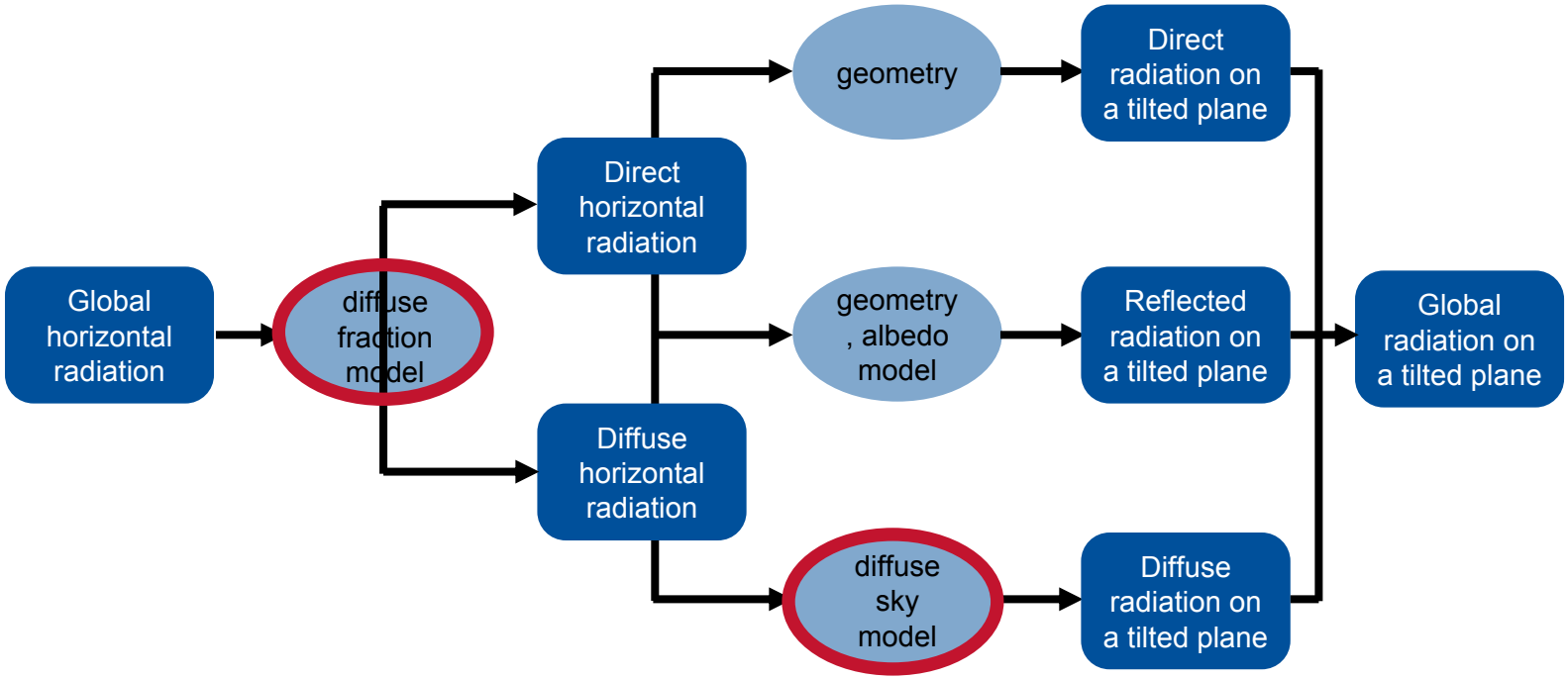
HRV Coverage



Spectral sensitivity

Solar radiation to tilted planes

Solar radiation on a tilted plane

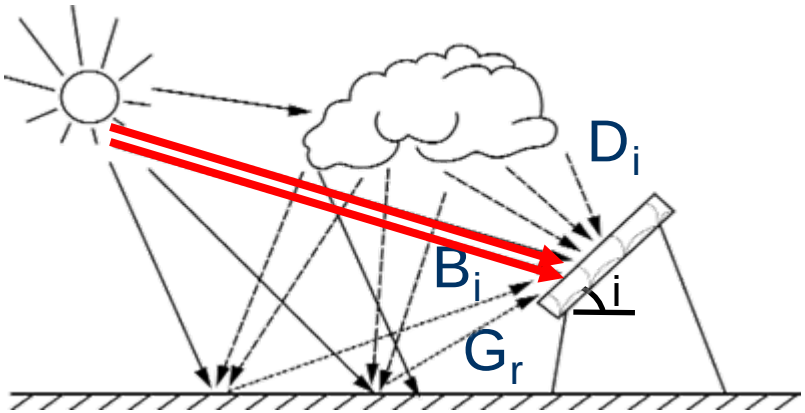


Direct radiation on a tilted plane

$$G_{bt} = G_{bn} \cos\theta$$

$$\text{With}: G_b = G_{bn} \cos\theta_z$$

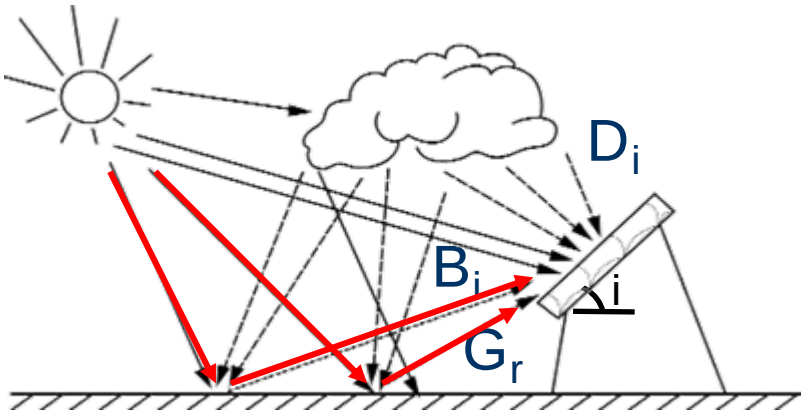
$$G_{bt} = G_b \frac{\cos\theta}{\cos\theta_z}$$



this is often referred as the geometric factor R_b

Radiation reflected from ground

$$G_{rt} = G\rho \frac{1-\cos\beta}{2}$$



for isotropic ground reflectance ρ

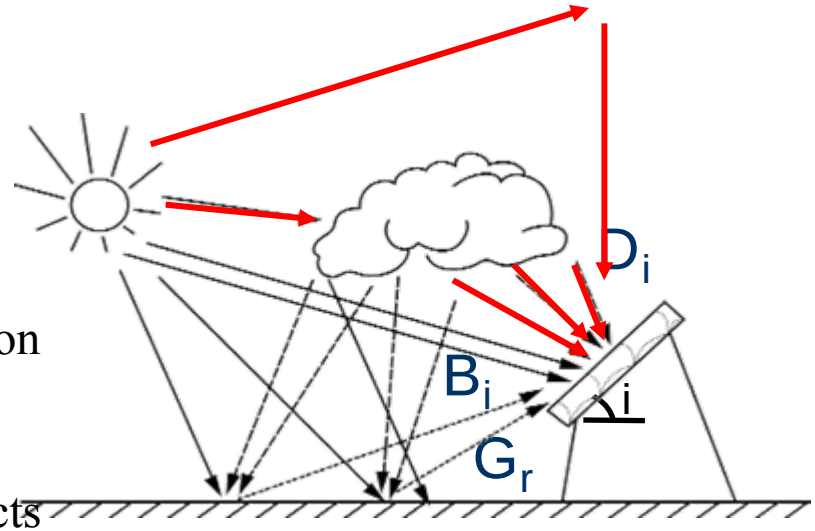
Diffuse radiation to a tilted plane

$$G_{dt} = G_d \frac{(1+\cos\beta)}{2} \quad M_x M_y$$

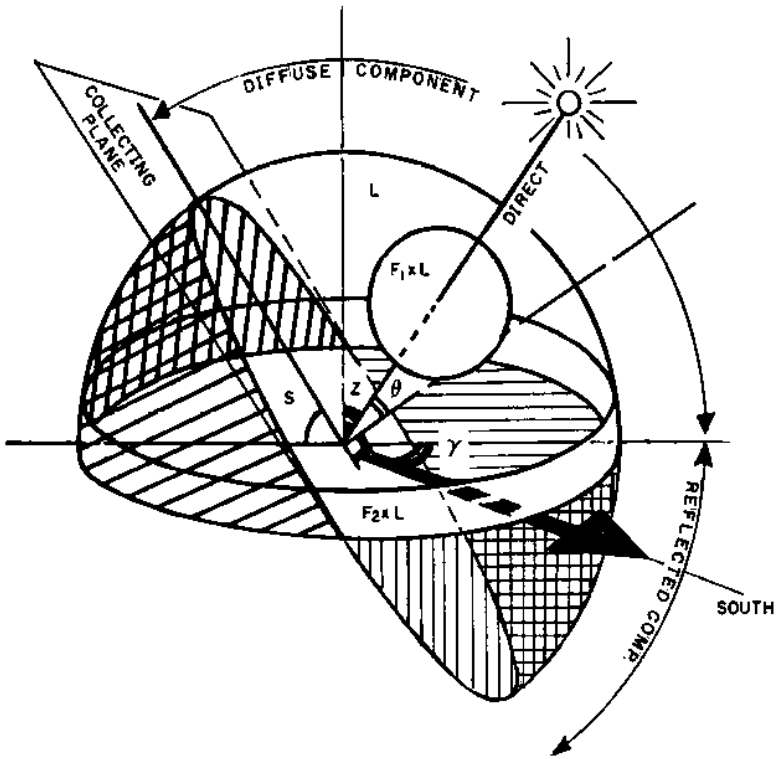
Liu - Jordon

Temps / Coulson
Klucher

anisotroic effects



Radiation on a titled plane – more complex – Perez Model



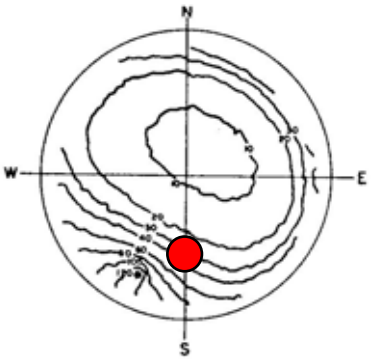
- Representation of the three radiation components seen by a tilted plane (direct, diffuse and reflected) and representation of the sky dome used in the Perez algorithm.
- Sky radiance is respectively equal to L, F_1L, and F_2L for the main, the circumsolar, and the horizon zone.
- Highly empirical approach!

Splitting Global in the components Diffuse + Direct

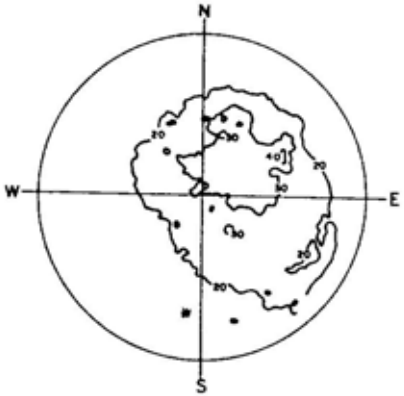
- Calculation of radiation on tilted planes needs diffuse fraction
- but: depends heavily on empirical tuning
- depending on considered time scale
- nonlinear!
- mainly related with: clearness index (global irradiance), solar elevation, turbidity, hour-to-hour-variability, surface albedo
- important: proper probability distribution of diffuse fraction

Isotropic versus non Isotrotropic diffuse radiation

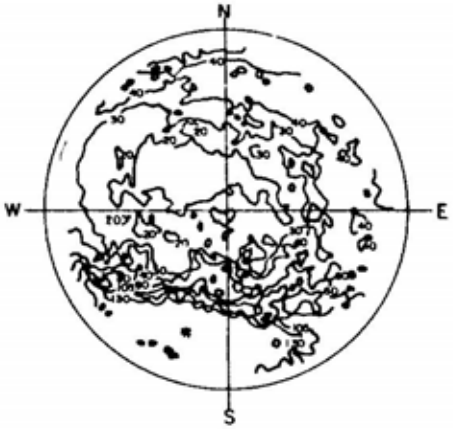
- Circumsolar
- Horizon Brightening



Clear sky

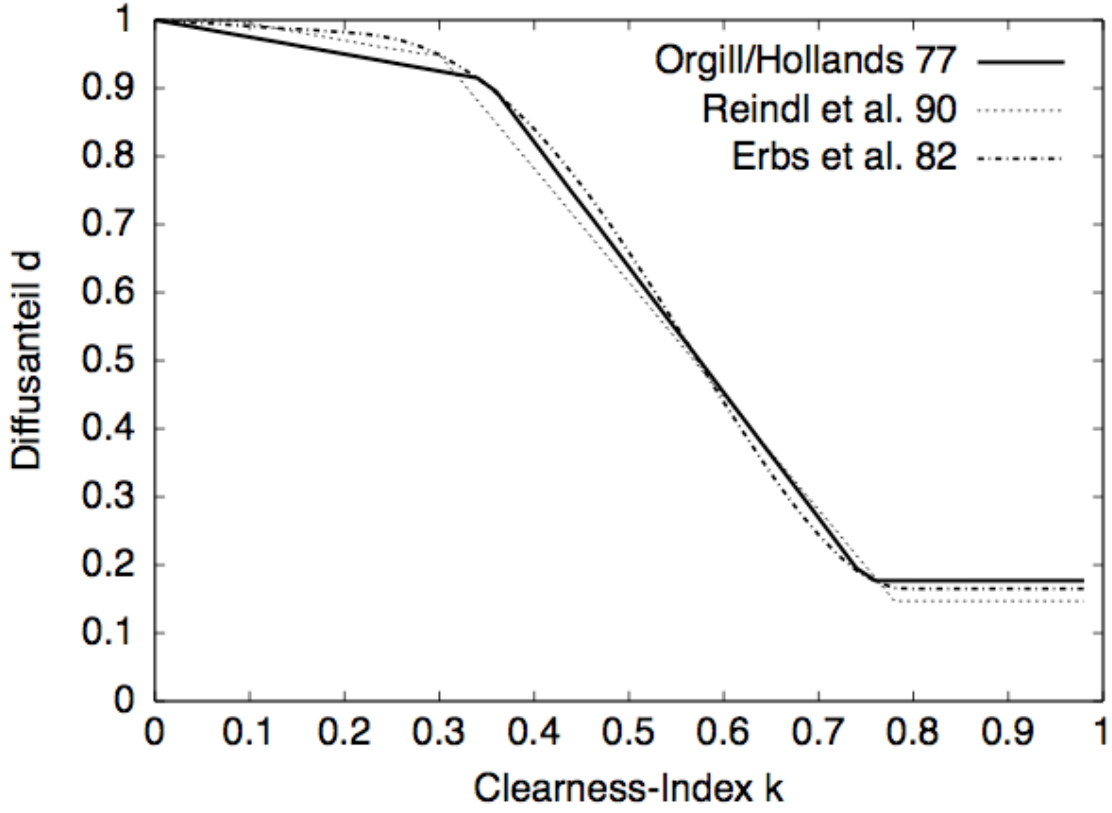


Cloudy sky



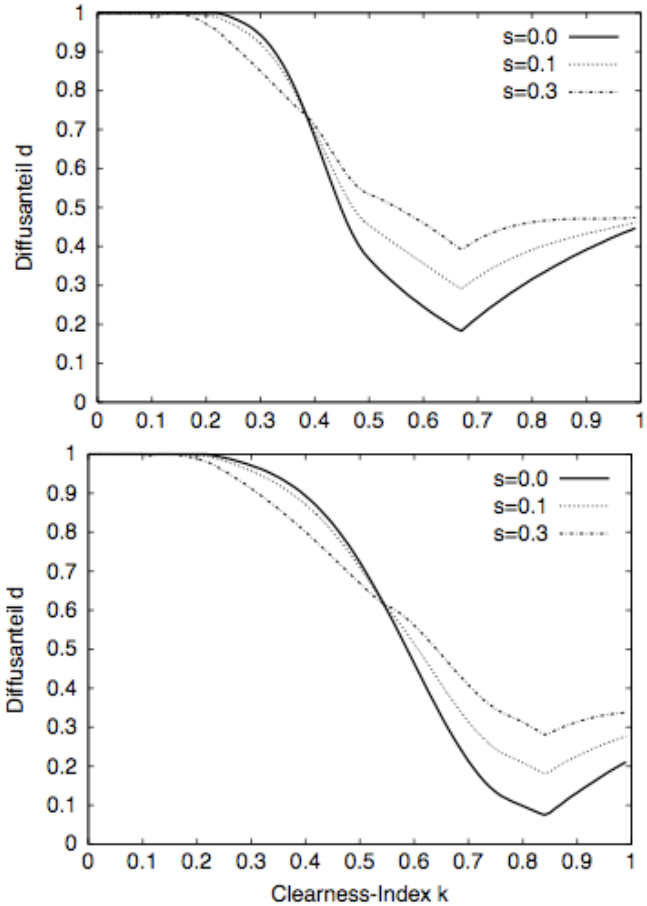
Intermediate sky
(broken cloudiness)

Diffuse fraction models



- Simple models based only on clear-sky index kt
- piecewise linear function with threshold values for clear (k_c) and cloudy (k_0) skies

Diffuse fraction – more complex

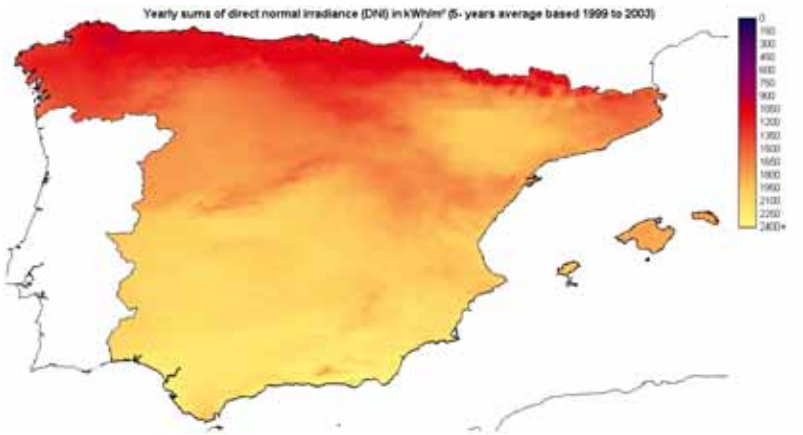


- Skartveit/Olseth model (1997)
- adding effects of increasing diffuse irradiance by reflecting clouds depending on variability index s and solar altitude (i.e., 90° - solar zenith):
- 10° (top),
- 50° (bottom)

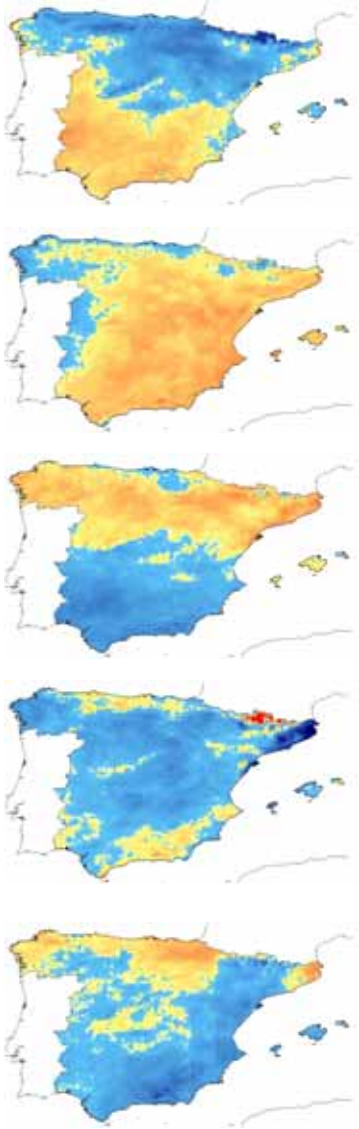
Characteristics of Resource Assessments

Inter annual variability

- Strong inter annual and regional variations



Average of the direct normal irradiance from 1999-2003



1999

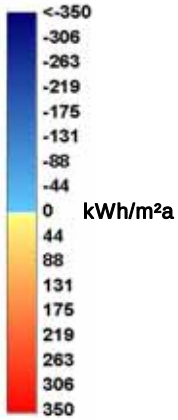
2000

2001

2002

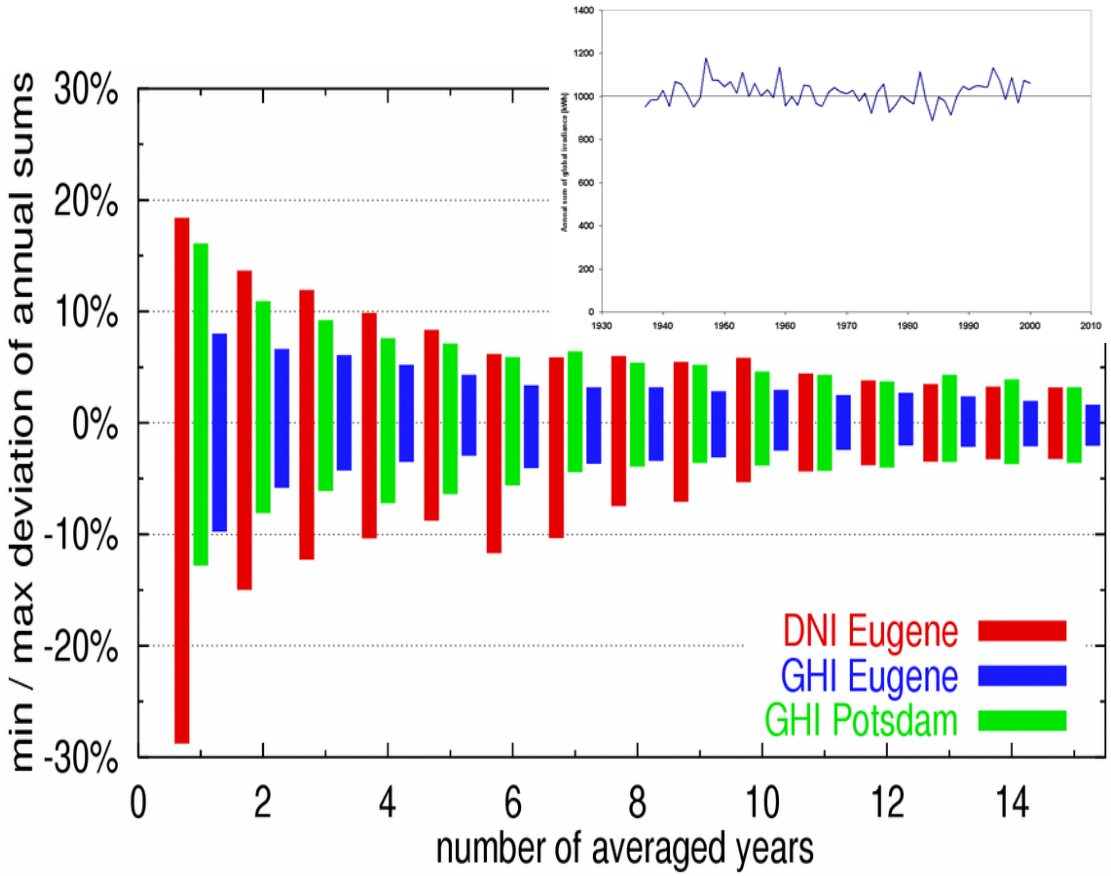
2003

deviation to mean



Long-term variability of solar irradiance

- 7 to 10 years of measurement to get long-term mean within 5%



Ground measurements vs. satellite derived data

Ground measurements

Advantages

+ high accuracy *(depending on sensors)*
+ high time resolution

Disadvantages

- high costs for installation and O&M
- soiling of the sensors
- sometimes sensor failure
- no possibility to gain data of the past

Satellite data

Advantages

+ spatial resolution
+ long-term data *(more than 20 years)*
+ effectively no failures
+ no soiling
+ no ground site necessary
+ low costs

Disadvantages

- lower time resolution
- low accuracy at high time resolution

Combining Ground and Satellite Assessments

- Satellite data
  - Long term average
  - Year to year variability
  - Regional assessment

- Ground data
  - Site specific
  - High temporal resolution possible
    (up to 1 min to model transient effects)
  - Good distribution function

Matching Ground and Satellite Data

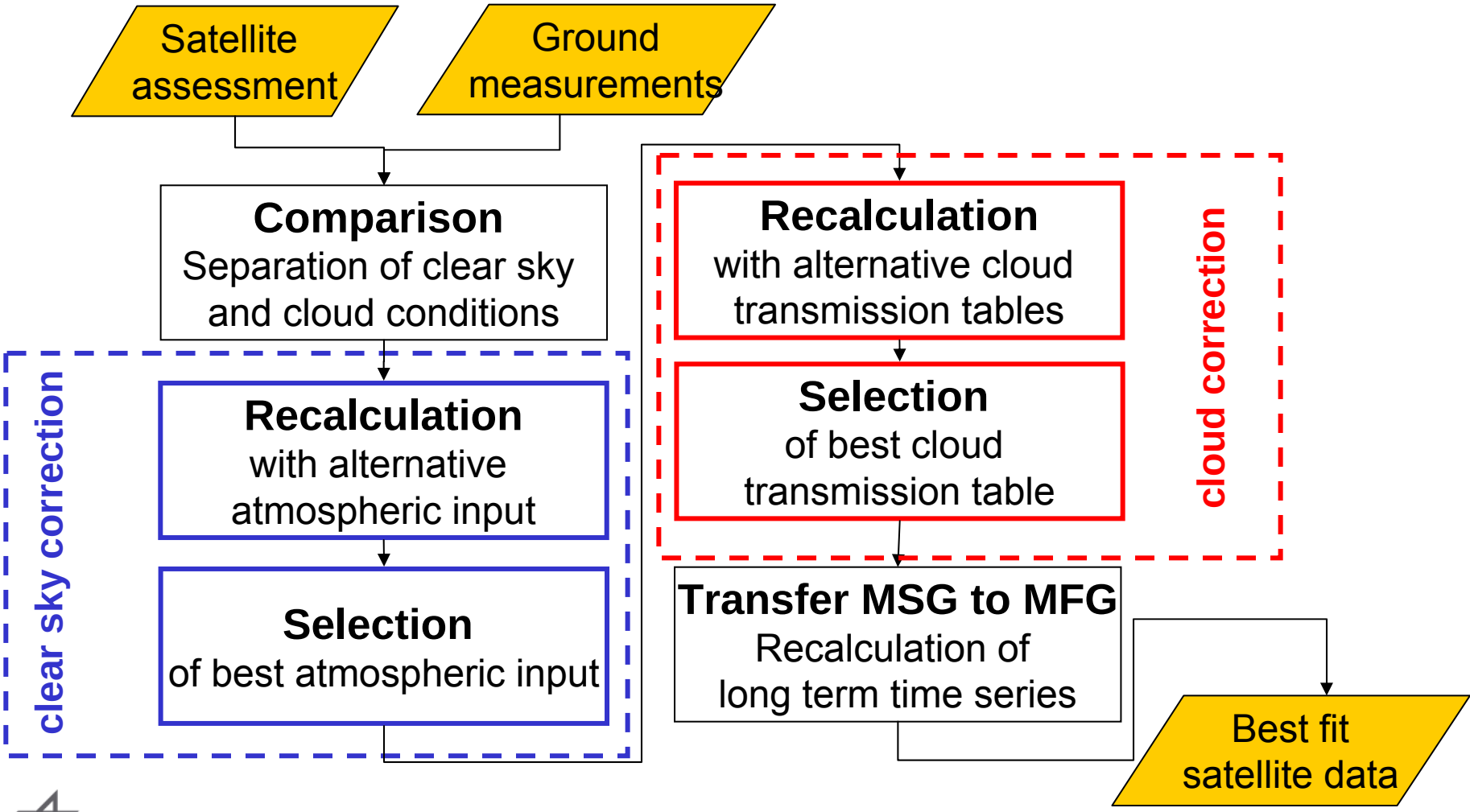
Why do ground and satellite data not match?

Due to uncertainties in:

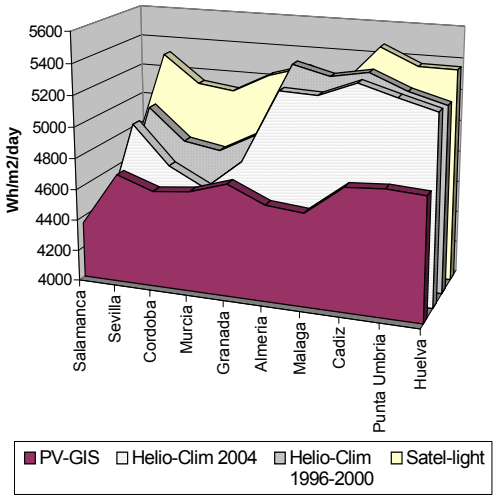
- Atmospheric Parameters, most prominent Aerosols

- Cloud transmission:
  - The cloud index is a combination of cloud fraction and transparency. A semi transparent cloud can be distinguished well from a fractional cloud cover.
  - Parameterization may depend on prevailing cloud types in the region.

Procedure for Matching Ground and Satellite Data



Guidance and Access to Data



- Many sources for solar resource knowledge are available
- Every source has its own access mechanism and data format
- Quality of the sources is often not well known
- Results are difficult to compare

There is quite a number of data sources, but this creates uncertainty of the results, especially if they do not agree

Benchmarking of Time Series Products

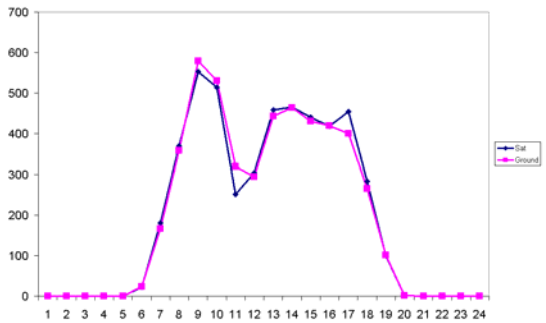
- **First order measures:**
  Bias, root mean square error, standard deviation

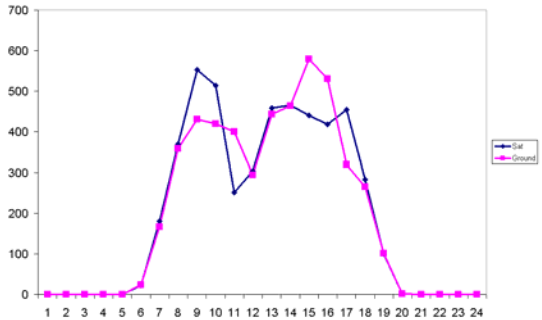
  Exact match of data pairs in time

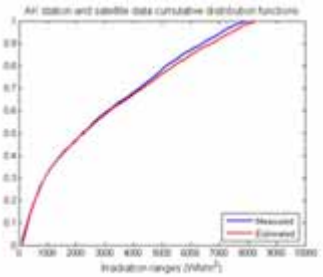
  Sometime this match is not necessary (e.g. system layout with historical data)

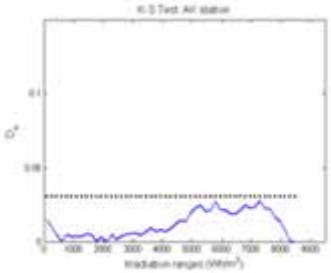
- **Second order measures:**
  Based on Kolmogrov-Smirnov Test

  Match of distribution functions





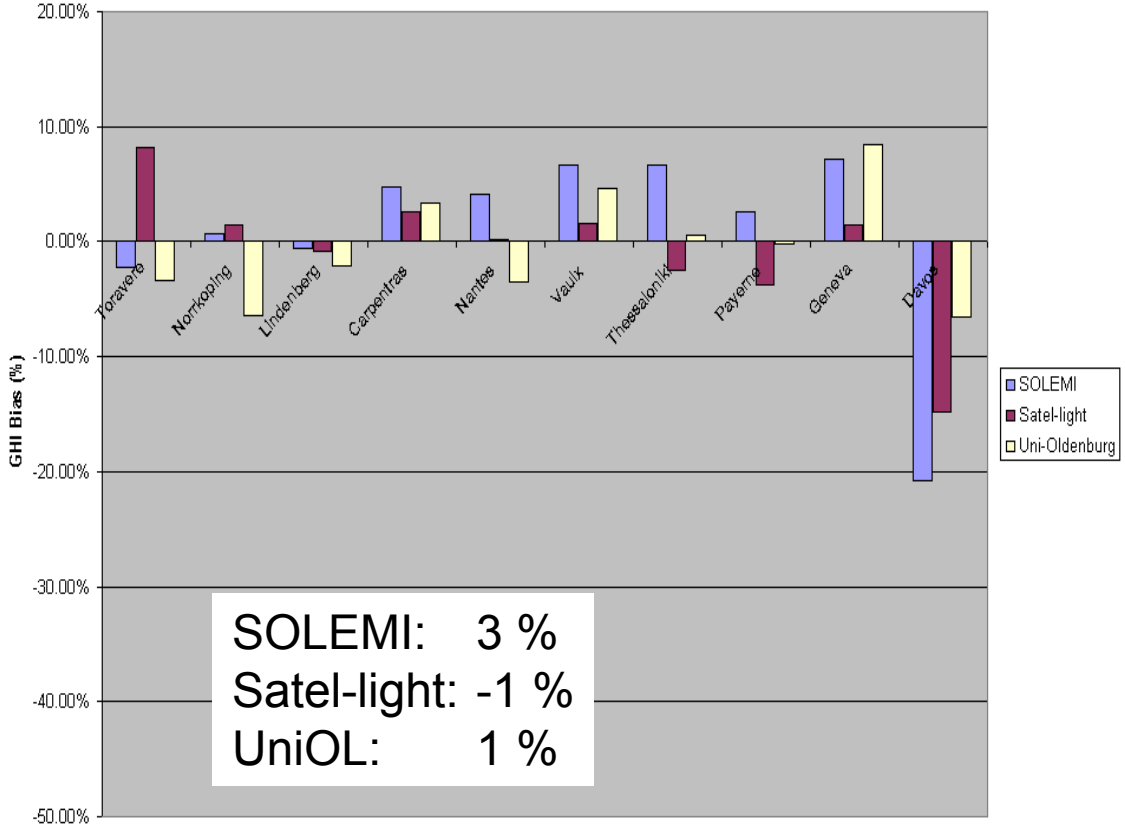




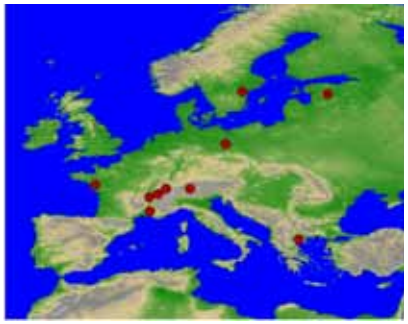
Benchmarking Rules

- The ground data has passed the QC procedure
- Global irradiance/illuminance is greater zero (exclude night values and missing measurements).
- The modelled value is valid.
- Averages are calculated from all valid data pairs.

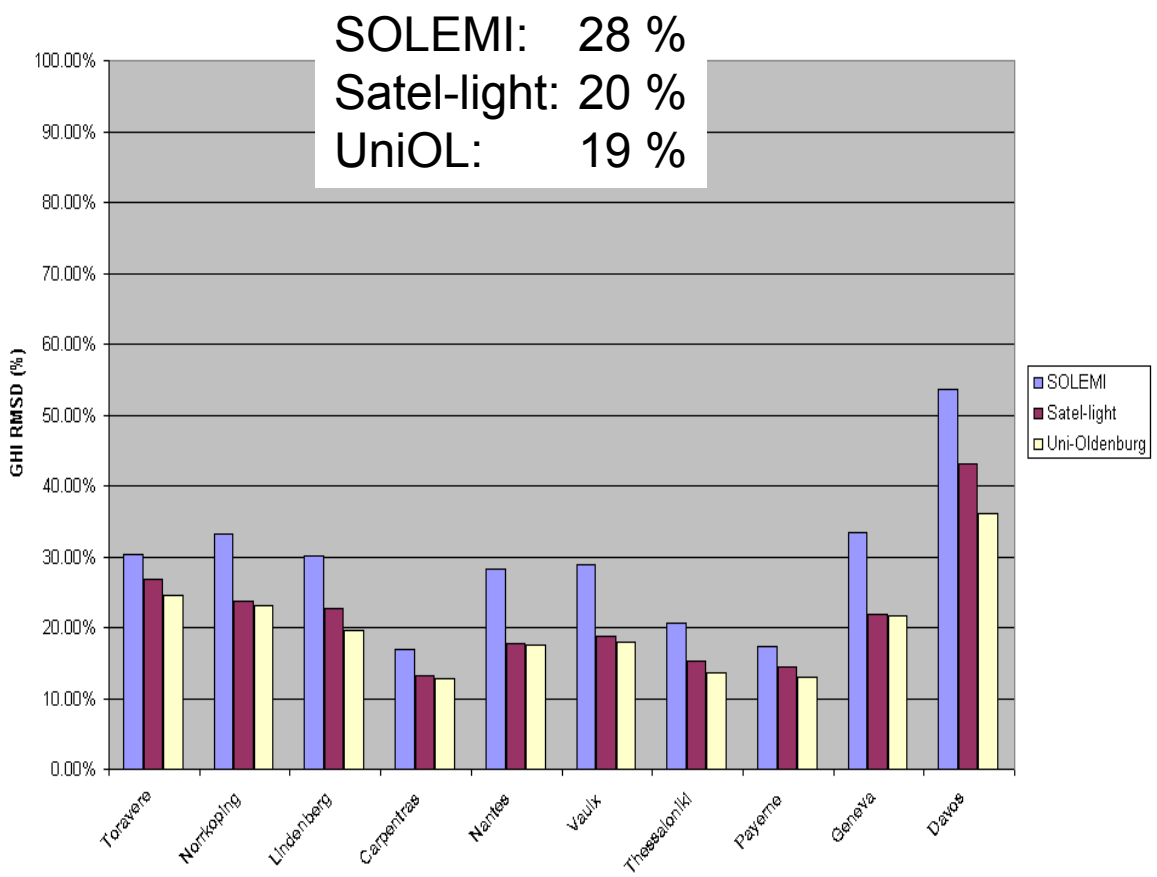
Exercise I – GHI Bias



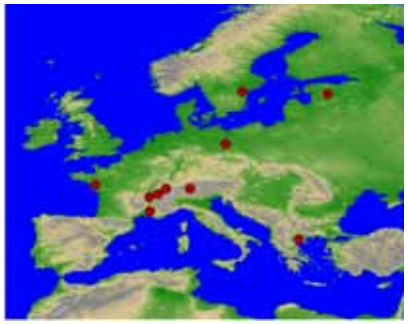
- Large Deviations in Davos
- Overall low bias.



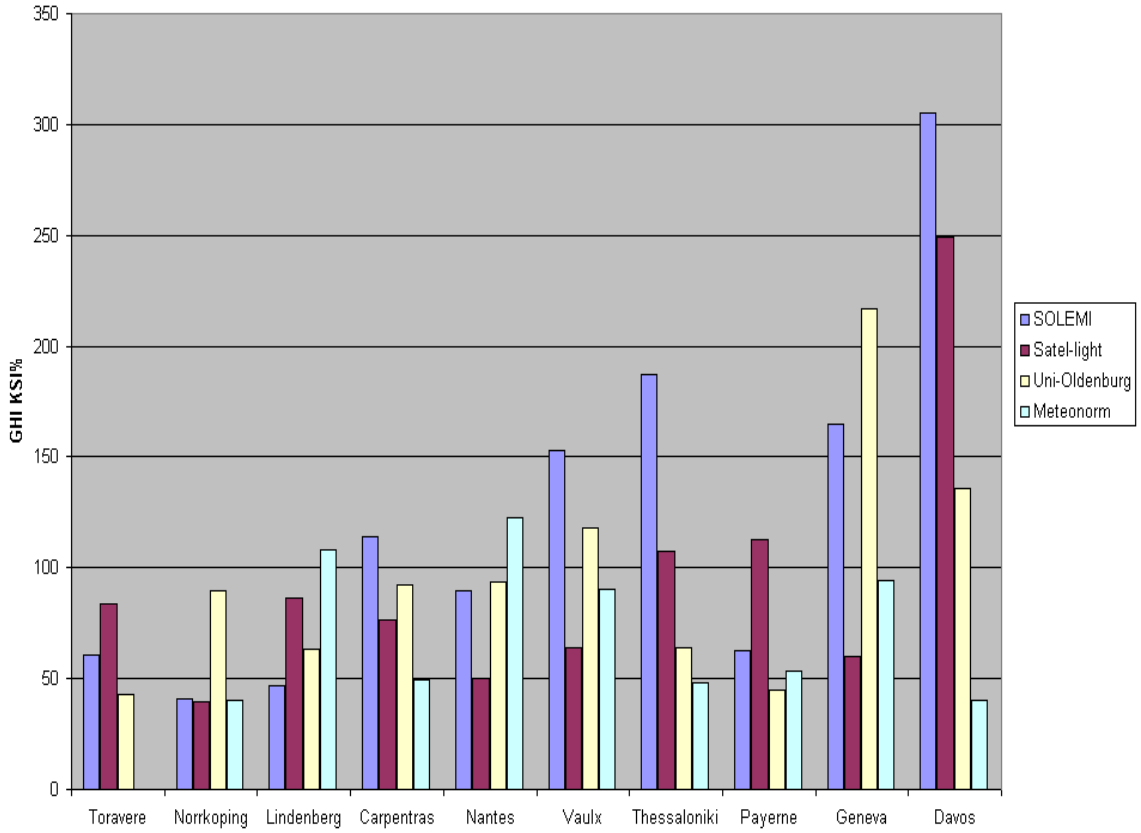
Exercise I – GHI RMSD



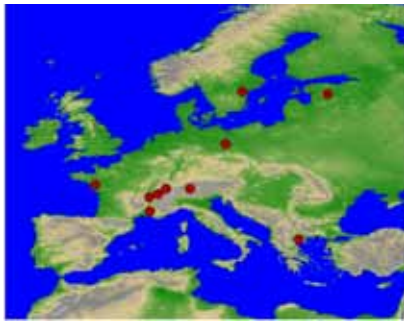
- Large Deviations in Davos



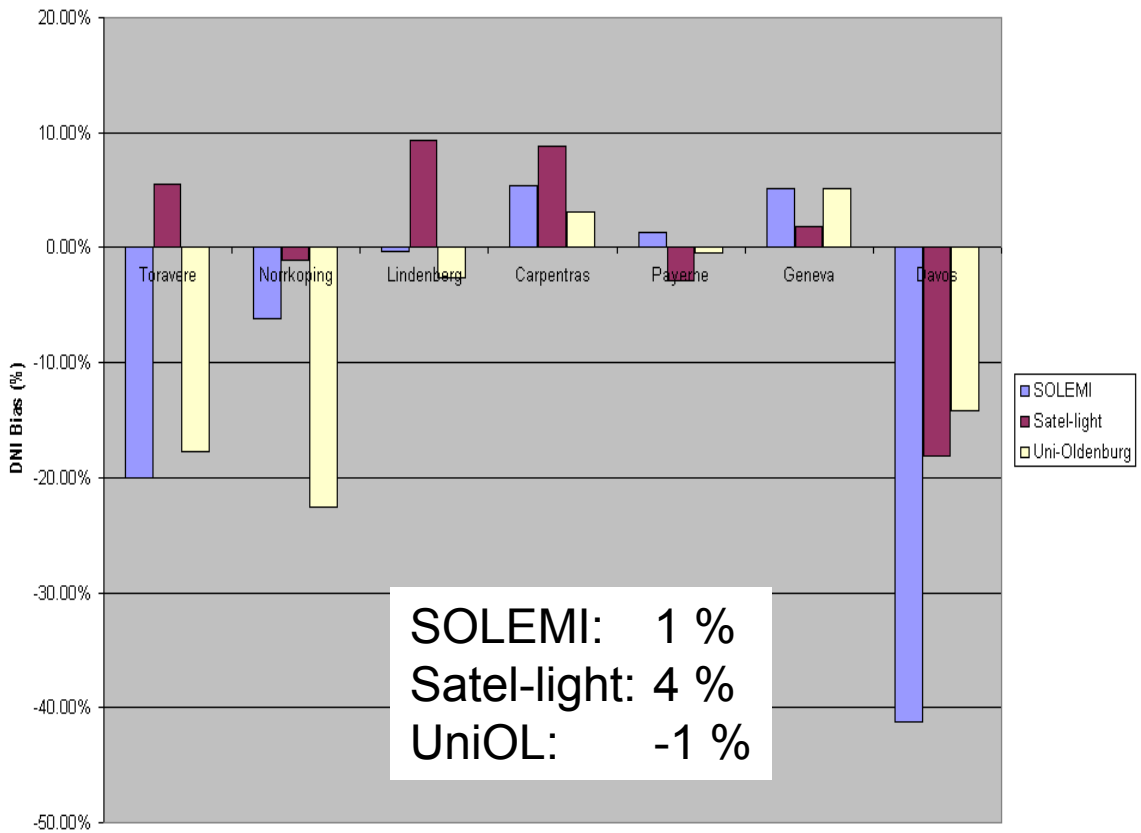
Exercise I – GHI KSI



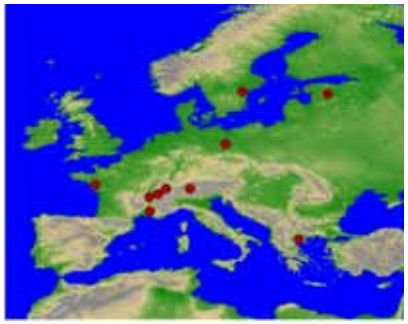
- Large Deviations in Davos



Exercise I – DNI Bias

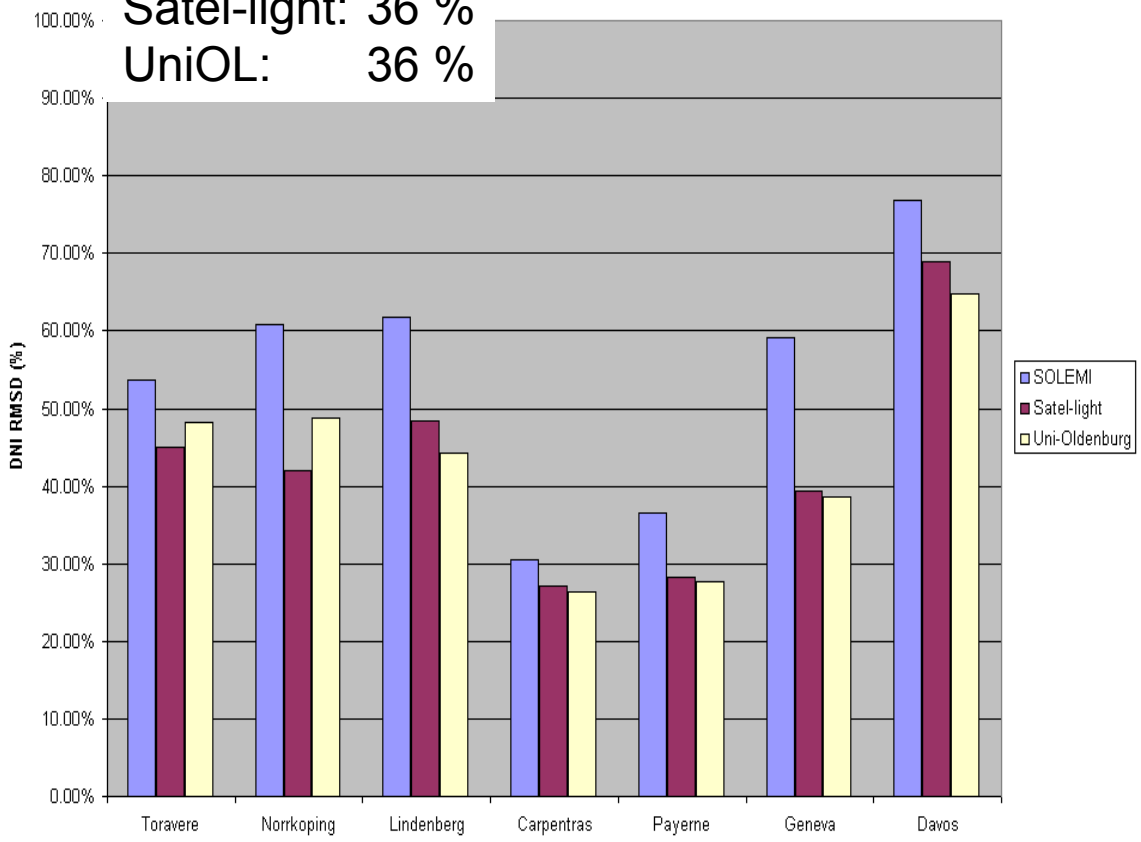


- Large Deviations in Davos, Toravere, Norrkoping, probably Snow
- Overall low bias

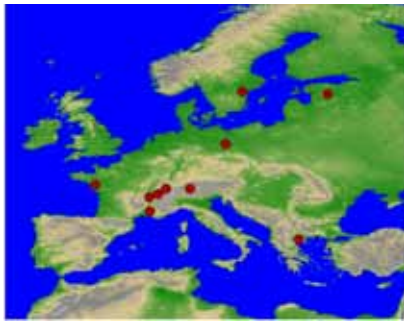


Exercise I – DNI RMSD

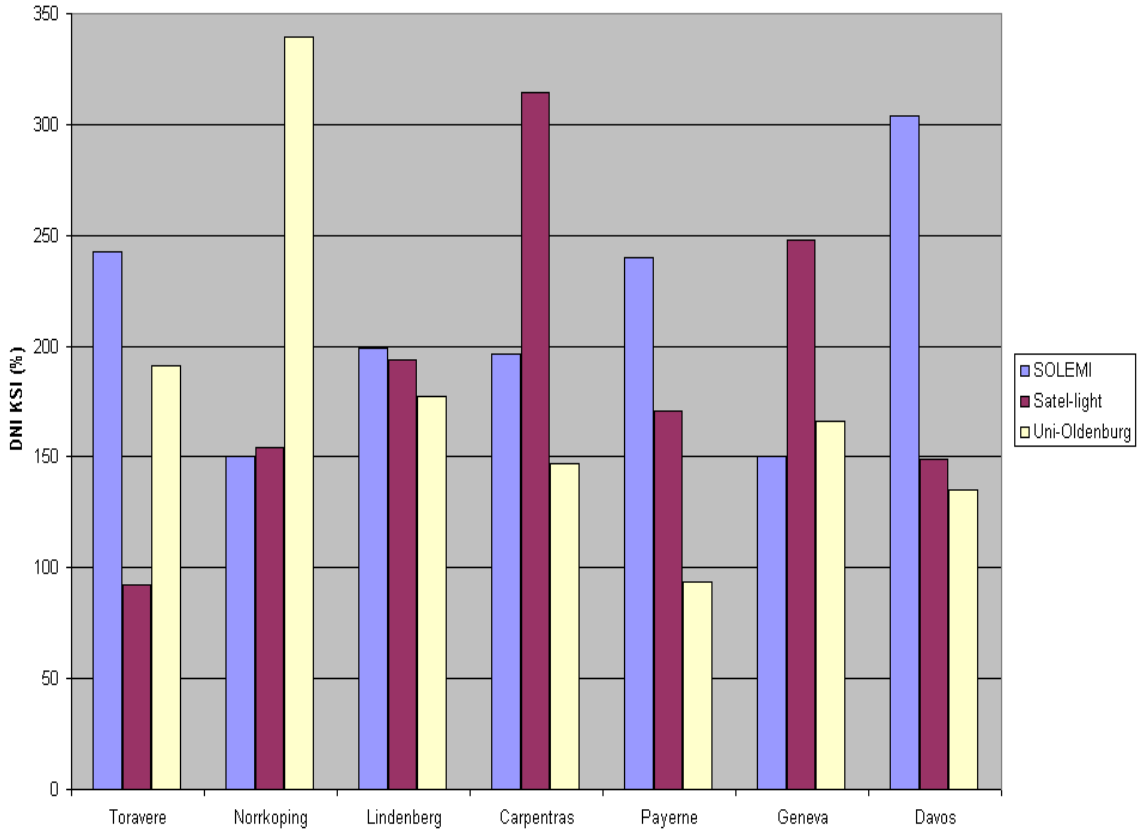
SOLEMI: 48 %
Satel-light: 36 %
UniOL: 36 %



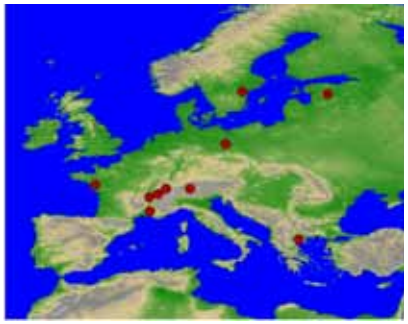
- RMSD is about twice as high as for GHI



Exercise I – DNI KSI

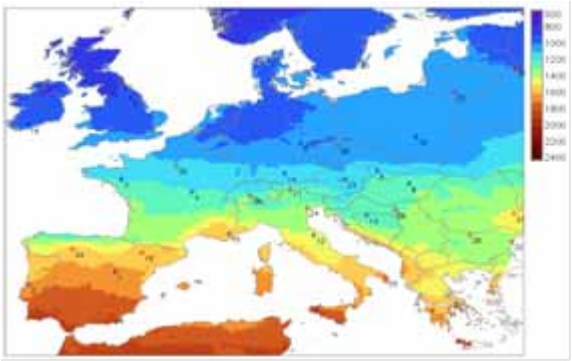


- No clear tendency for specific data set, each one is best and worst in some case.

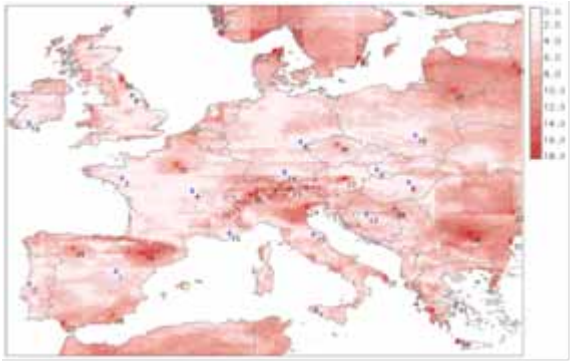


Benchmarking of Maps

- Assessment of the uncertainty of map based products by comparing a number of maps



Average solar radiation from different maps



Uncertainty at 95% confidence interval

Data Sources

Resource products: input and extension

product	input	area	period	provider
NASA SSE	ISCCP	World	1983-2005	NASA
Meteonorm		World	1981-2000	Meteotest
Solemi			1991->	DLR
Helioclim			1985->	Ecole de Mines
EnMetSol			1995->	Univ. of Oldenburg
Satel-light		Europe	1996-2001	ENTPE
PVGIS Europe		Europe	1981-1990	JRC
ESRA		Europe	1981-1990	Ecole de Mines

<10 years 10-20years >20 years

Resource products: Resolution

product	input	temp resolution	spatial resolution
NASA SSE	ISCCP	averag. daily profile	100 km
Meteonorm		synthetic hourly/min	1 km (+SRTM)
Solemi		1h	1 km
Helioclim		15min/30min	30 km // 3-7 km
EnMetSol		15min/1h	3-7 km // 1-3 km
Satel-light		30min	5-7 km
PVGIS Europe		averag. daily profile	1 km (+ SRTM)
ESRA		averag. daily profile	10 km

synthetic high resolution values measured high resolution values

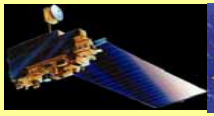
Resource products: parameters

product	parameters
NASA SSE	GHI, DNI, DHI, clouds
Meteonorm	GHI,DNI,DHI, shadowing, illuminace
Solemi	GHI, DNI
Helioclim	GHI, DNI
EnMetSol	GHI, DNI,DHI, spectra
Satel-light	GHI,DNI, DHI, illuminance
PVGIS Europe	GHI,DHI, shadowing
ESRA	GHI, DNI, DHI

NASA-SSE

Earth System Science → **Applied Science Outcome**

NASA Satellite Measurements, Analysis and



Terra

Aqua

ISCCP

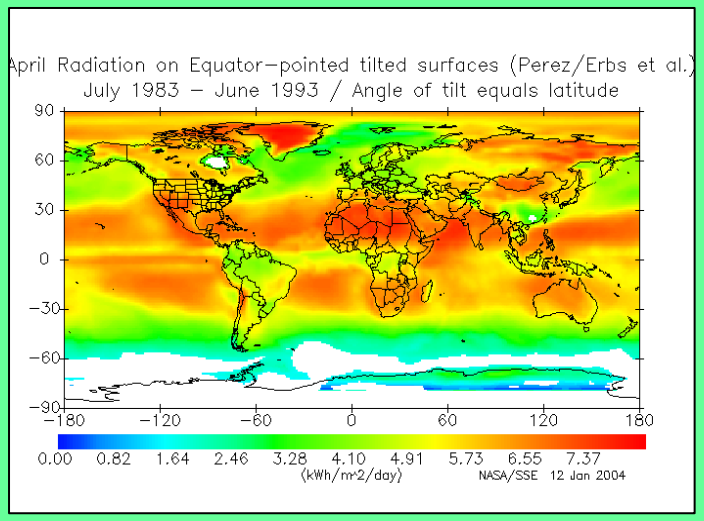
SRB

GMAO

CERES

Surface Meteorology and Solar Energy (SSE) Datasets And Web interface

SSE



Growing over the last 7 years to nearly 14,000 users, nearly 6.4 million hits and 1.25 million data downloads

SSE Web Site

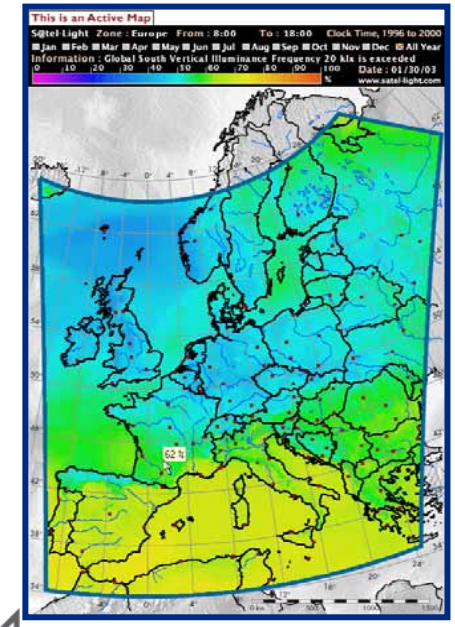
http://eosweb.larc.nasa.gov/sse/

Over 200 solar energy and meteorology parameters averaged from 10 years of data

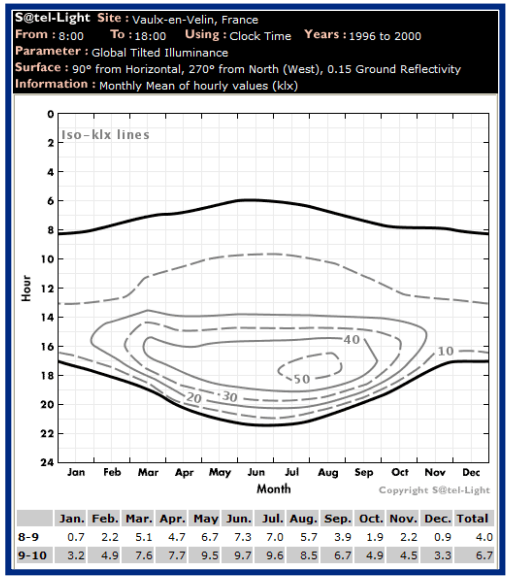
Satel-light – www.satel-light.com

- 5 years of half hour data from 1996 to 2000
- Coverage: Europe

Maps

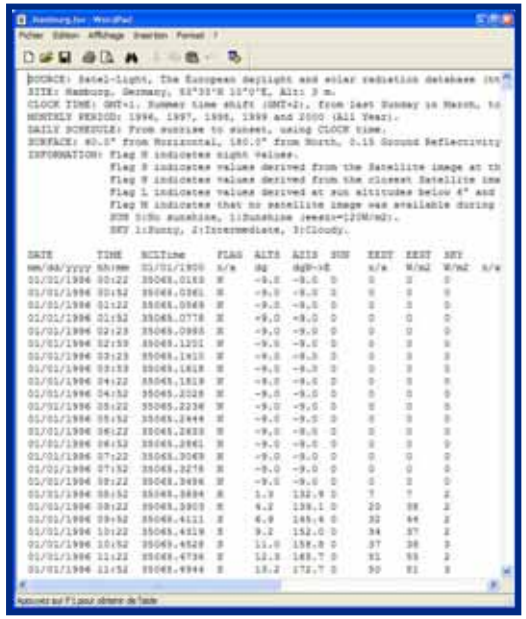


Diagrams



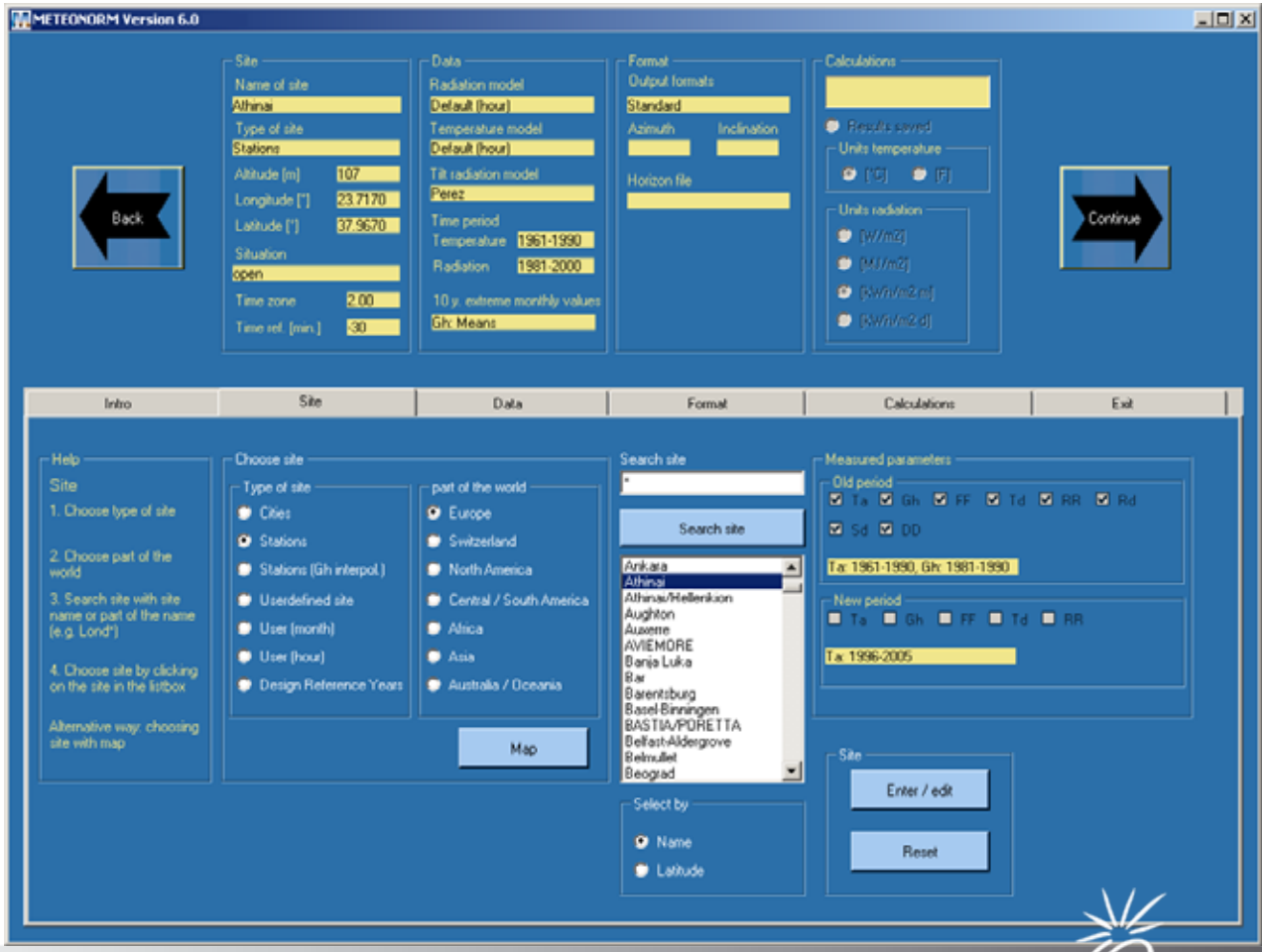
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
8-9	0.7	2.2	5.1	4.7	6.7	7.3	7.0	5.7	3.9	1.9	2.2	0.9	4.0
9-10	3.2	4.9	7.6	7.7	9.5	9.7	9.6	8.5	6.7	4.9	4.5	3.3	6.7

Data files



Meteonorm

- Based on ground data
- Satellite assisted interpolation between stations
- stoacstic models to derive higher resolution data
- global to tilted models

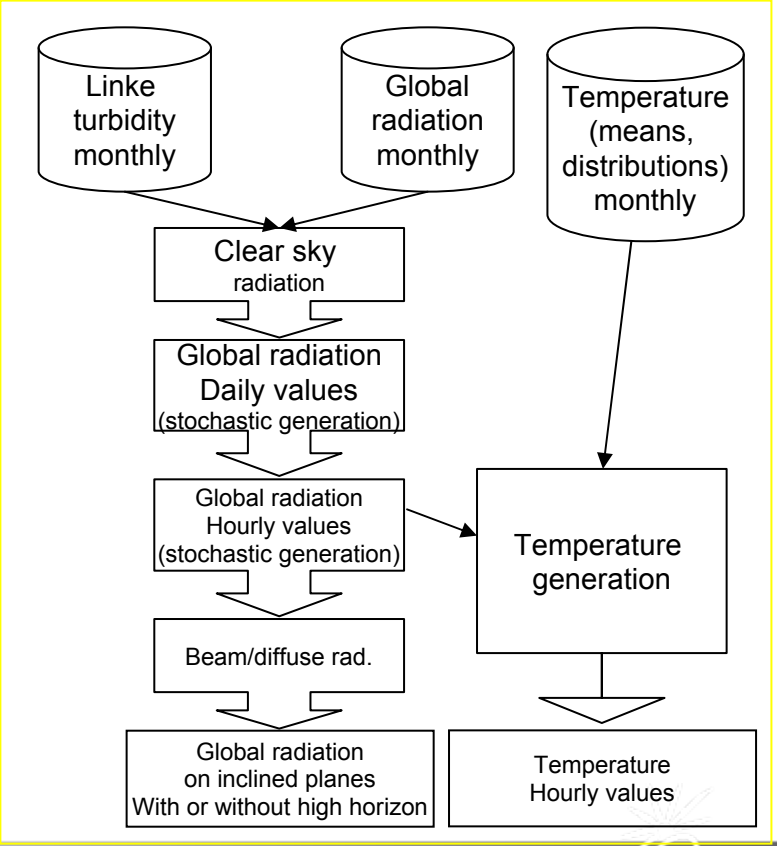


Meteonorm

Climate data

- 8050 stations
- 8 parameters:
  - Global radiation (horizontal, inclined)
  - Air temperature
  - Dewpoint temperature
  - Wind speed and direction
  - Sunshine duration
  - Precipitation
  - Days with precipitation

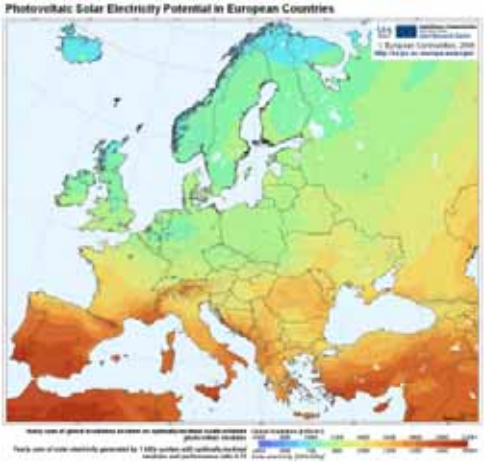
Chain of Algorithms



PVGIS - http://re.jrc.ec.europa.eu/pvgis/

- **DATA**
  - *solar radiation (Europe, Africa & SW Asia)*
  - *ambient temperature (Europe)*
  - *+ terrain, land cover…*

- **ASSESSMENT TOOLS**
  - *solar radiation for fixed and sun-tracking surfaces*
  - *output from grid-connected PV*
  - *performance of standalone PV (only Africa)*



- **MAPS**
  - *interactive*
  - *static*

PVGIS

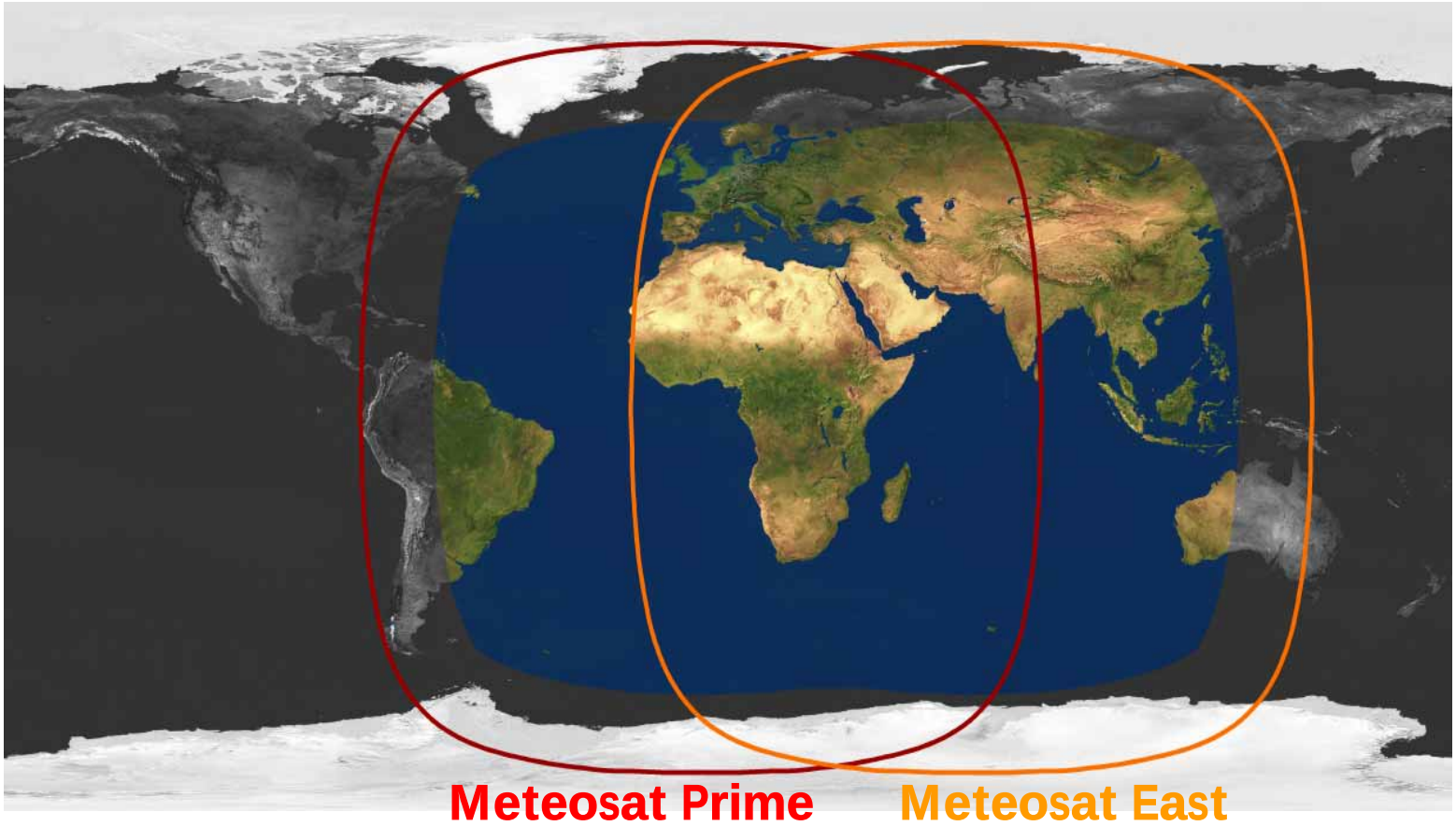
Calculation of grid-connected PV performance

- Calculation takes into account angle-of-incidence effects
- For crystalline silicon and CIS/CIGS, the effects of temperature and irradiance on the conversion efficiency are modelled.
- Generic (user-selected) value for BOS losses.
- Calculates output for:
  - Specified inclination and orientation
  - Optimum inclination for given orientation
  - Optimum inclination and orientation
  - 1- and 2-axis flat-plate tracking

Helioclim

- same area for H1, H2, H3
- uncertainties of irradiance values assessed and provided
- dissemination through the SoDa Service
  - *www.soda-is.com*
- access to data in one click
- access on-pay, except 1985-1989 (daily) and 2005
- coupled to other services, e.g. irradiance on inclined surface

Satellite data: SOLEMI – Solar Energy Mining

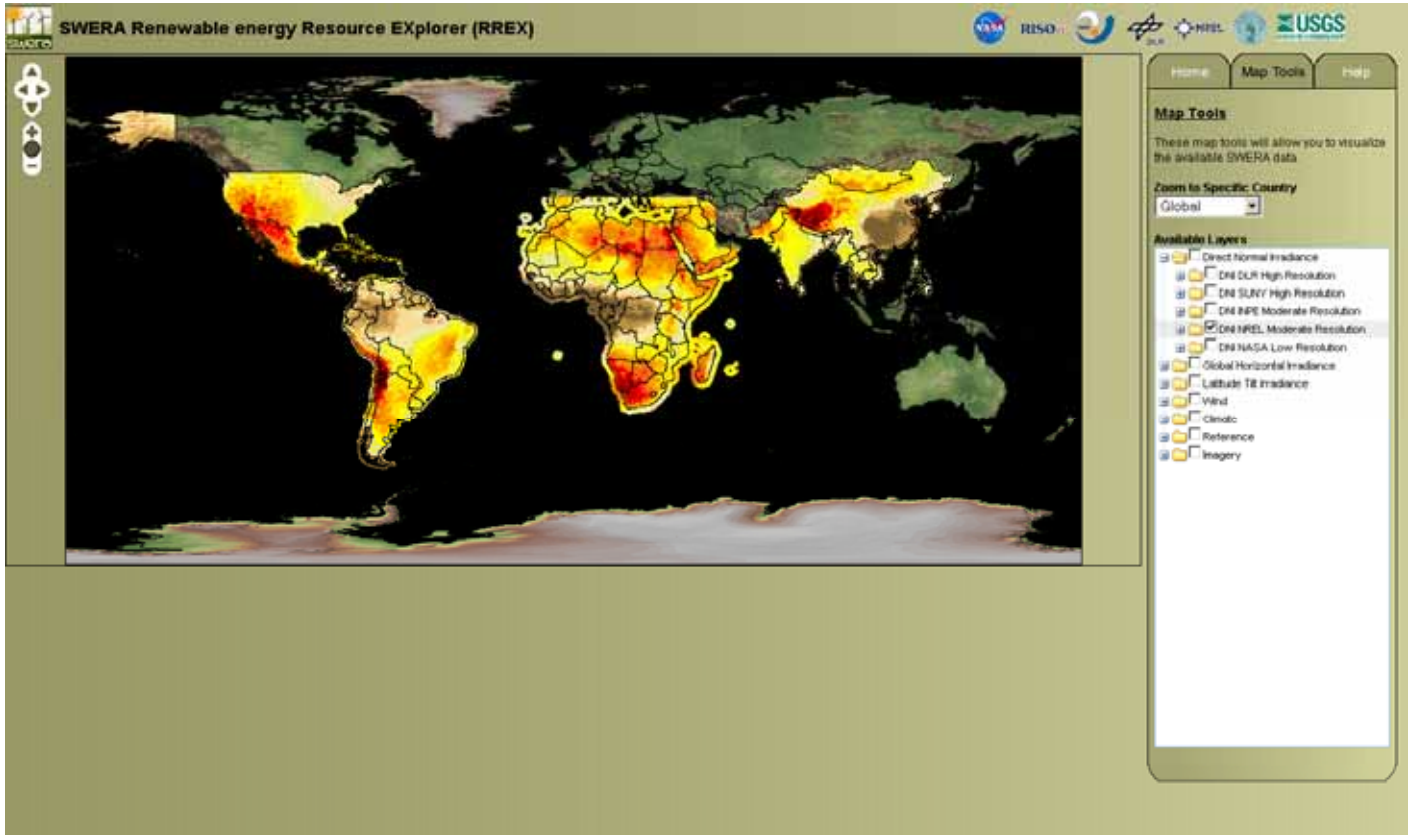


- SOLEMI is a service for high resolution and high quality data
- Coverage: Meteosat Prime up to 22 years, Meteosat East 10 years (in 2008)

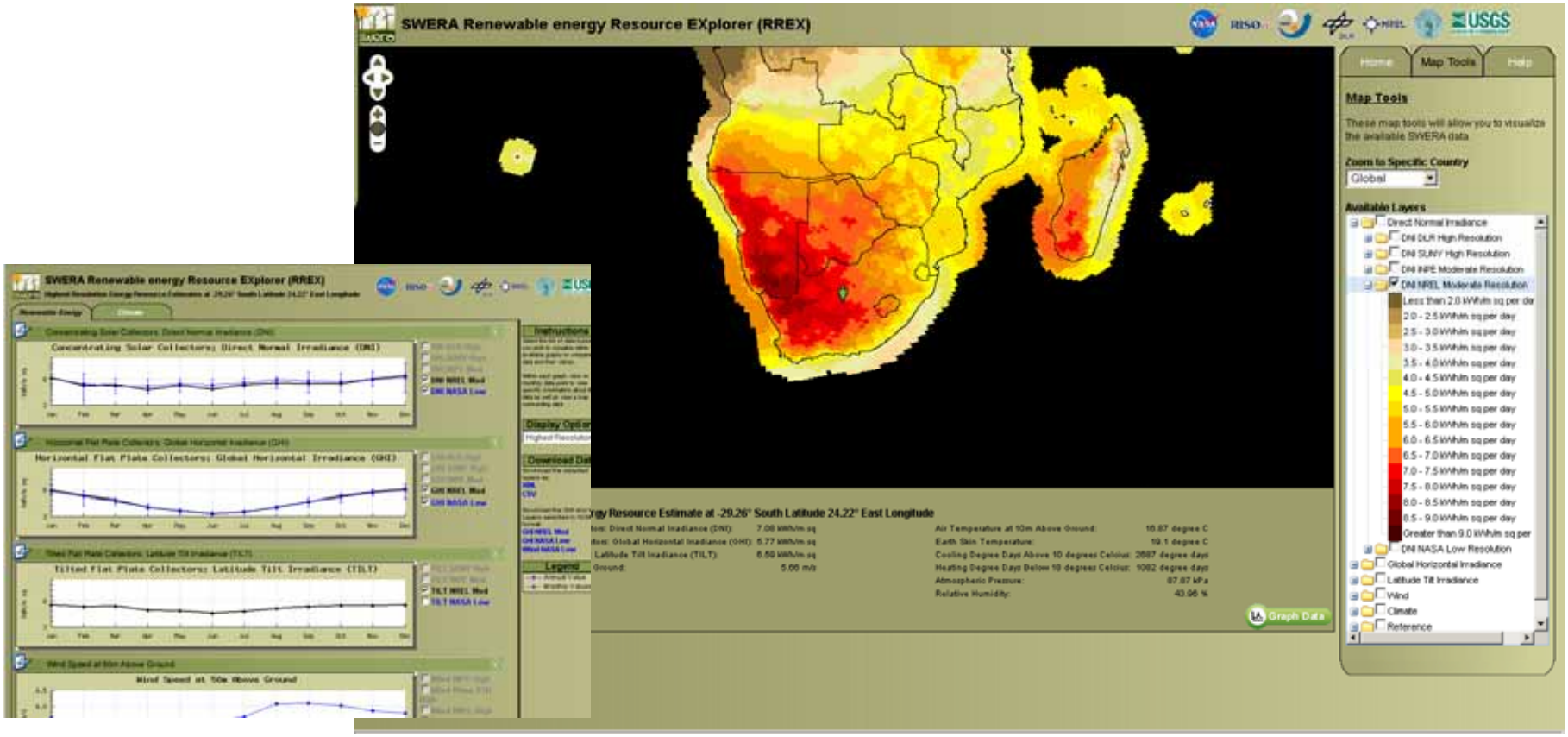
SWERA – Solar and Wind Energy Resource Assessment

- Initial GEF funded project to asses solar and wind resources in 13 developing countries
- Now turned into a programme of UNEP, most recent assessment in the United Arab Emirates
- Archive consists a number of different country specific and regional data sets
- Access at: http://swera.unep.net

SWERA – Renewable Energy Explorer



SWERA Renewable Energy Explorer



Typical Meteorological years

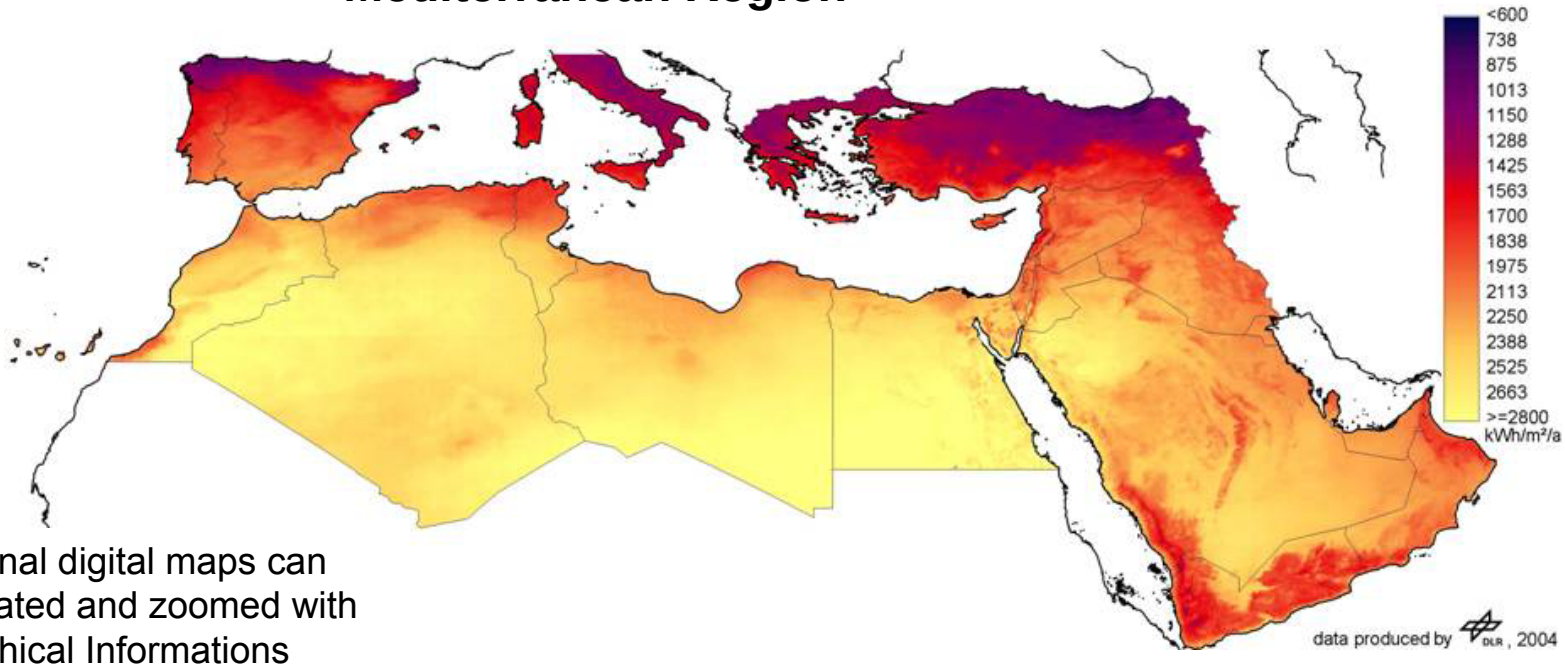
- A typical meteorological year (TMY) data set provides designers and other users with a reasonably sized annual data set that holds hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years.
- The TMY data set is composed of 12 typical meteorological months (January through December) that are concatenated essentially without modification to form a single year with a serially complete data record for primary measurements. These monthly data sets contain actual time-series meteorological measurements and modeled solar values, although some hourly records may contain filled or interpolated data for periods when original observations are missing from the data archive.

Typcial Meteorological Years II

- The Sandia method is an empirical approach that selects individual months from different years of the period of record. For example, in the case of the NSRDB that contains 30 years of data, all 30 Januarys are examined, and the one judged most typical is selected to be included in the TMY.
- The Sandia method selects a typical month based on nine daily indices consisting of the maximum, minimum, and mean dry bulb and dew point temperatures; the maximum and mean wind velocity; and the total global horizontal solar radiation. Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns. The process may be considered a series of steps.

Results of the satellite-based solar assessment

Digital maps: e.g. annual sum of direct normal irradiation in 2002 in the Mediterranean Region



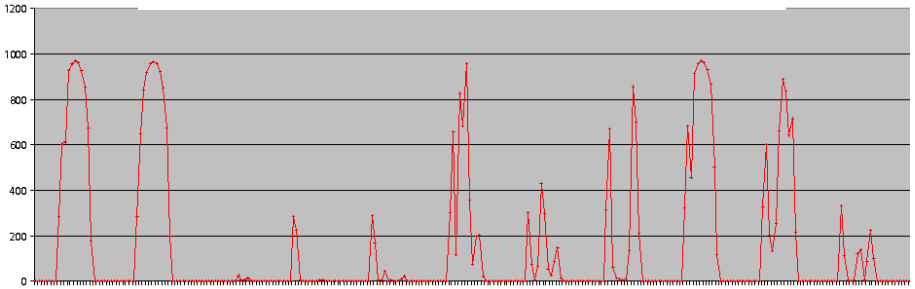
The original digital maps can be navigated and zoomed with Geographical Informations Systems like ArcView or Idrisi.

Temporal resolution of input data: 1 hour
Spatial resolution of digital map: 1 km x 1 km per Pixel
Long term analysis: up to 20 years of data

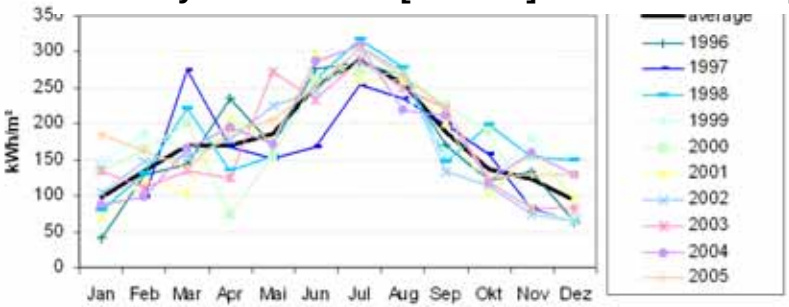
Results of the satellite-based solar assessment

Time series: for single sites, e.g. hourly, monthly or annual

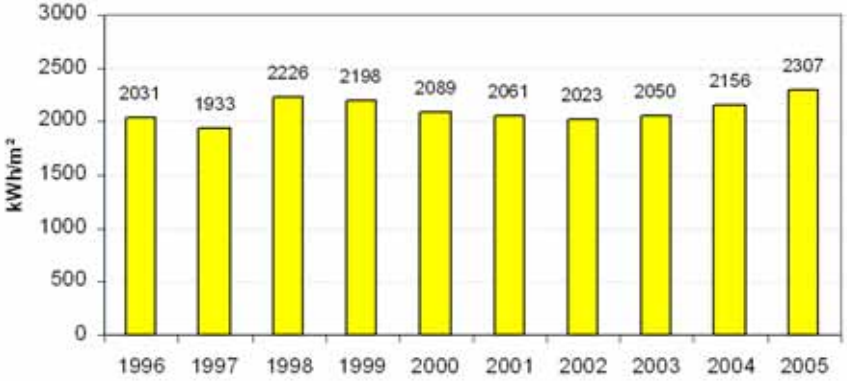
Hourly DNI [Wh/m²] for one site in Spain



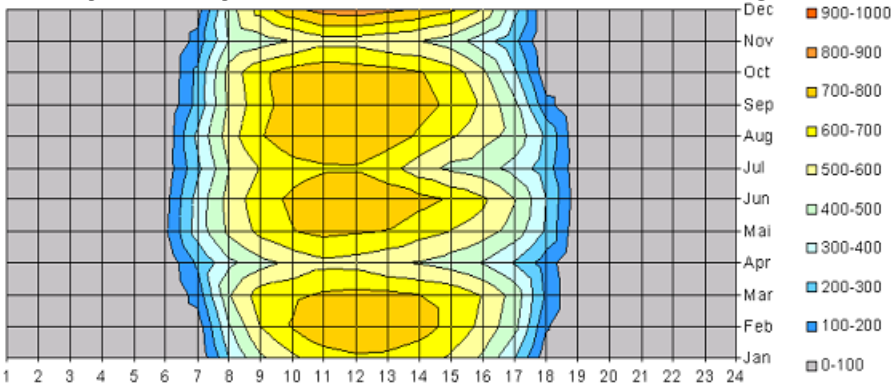
Monthly sums of DNI [kWh/m²] for one site in Spain



Annual sums of DNI [kWh/m²] for one site in Spain

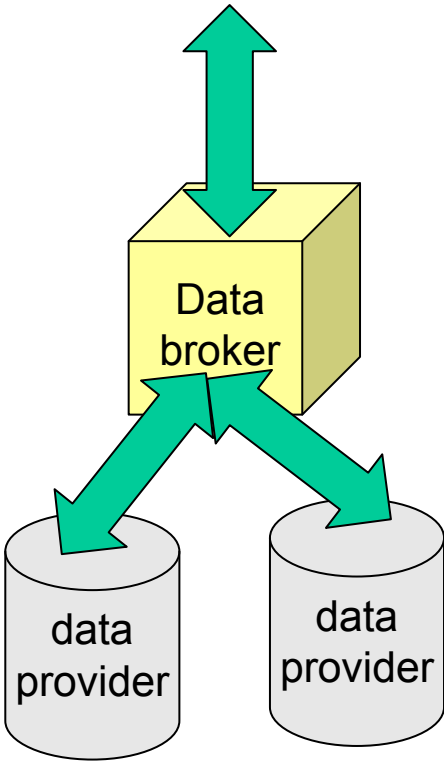


Hourly monthly mean of DNI in Wh/m², Solar Village 2000

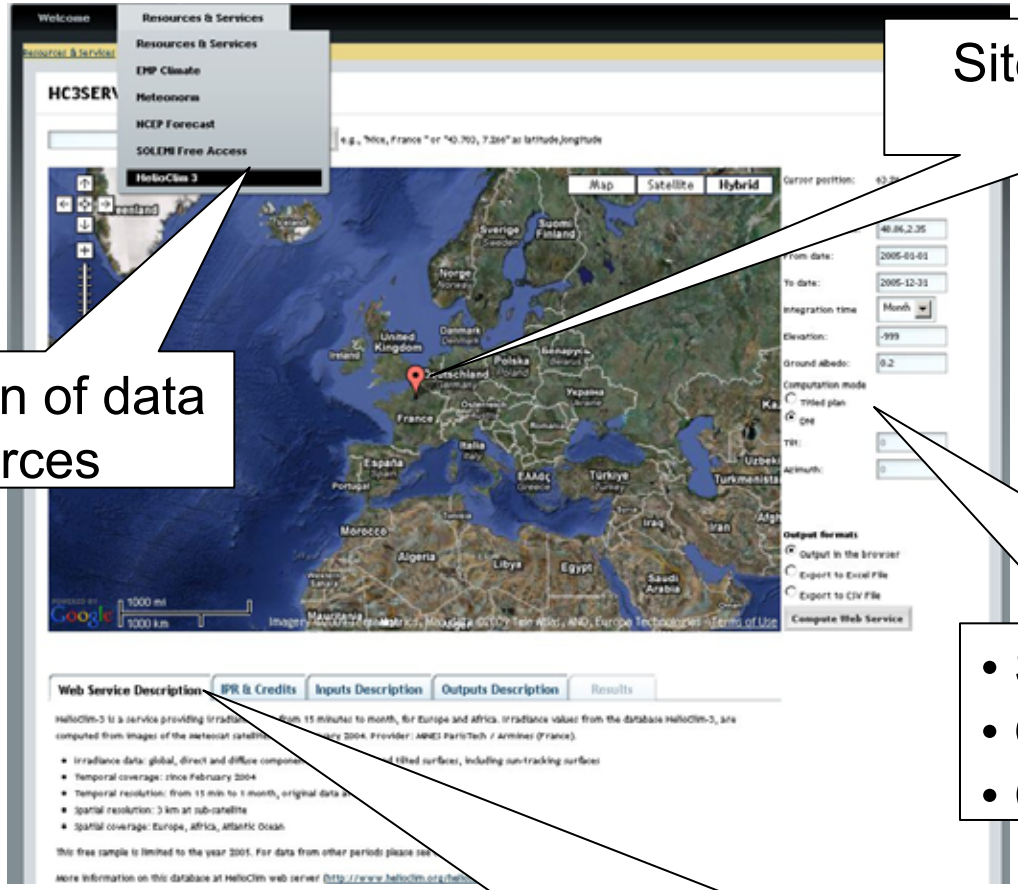


Unifying Access

- Lessons learned from SoDa:
  - General portal is beneficial for solar energy users
  - SoDa used proprietary software and communication standards
  - High maintenance efforts in operating the portal
- New approach in MESoR:
  - Open source software portal with large development community Internet standard communication protocols
  - Google Maps API for ease of use
  - The portal is a broker for data bases located elsewhere, it does not store and offer data itself
  - Connexion with larger intiative (GEO/GEOSS - IEA-Task36 SHC)



The new MESoR Portal



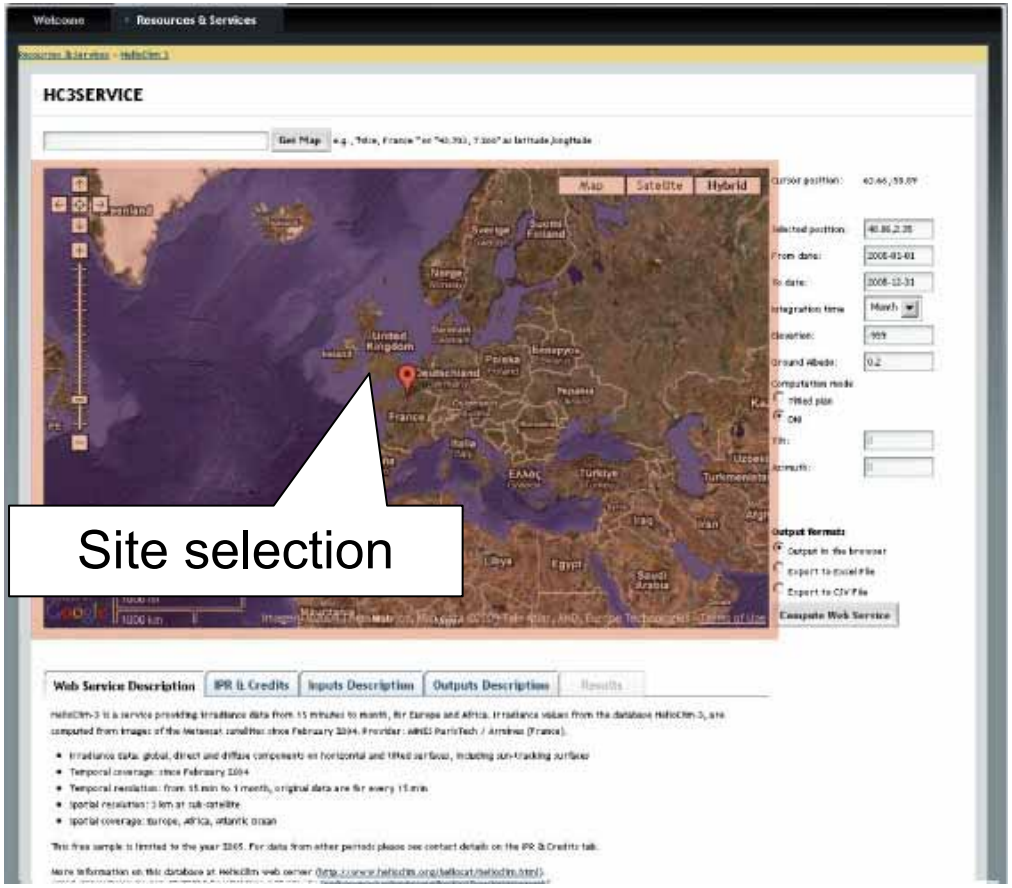
Site selection

Selection of data sources

- Service dedicated forms
- Output to various formats
- Computation launch

- Information about the data source
- Results display

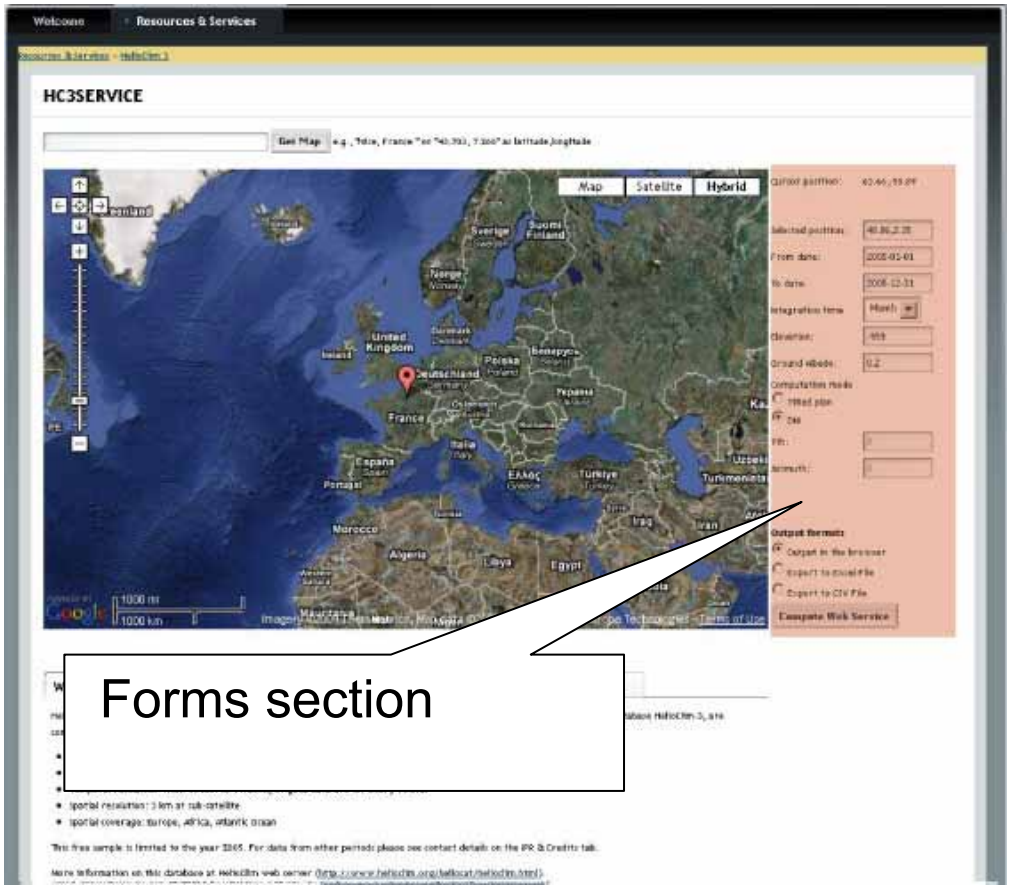
The new MESoR Portal



Google Map API

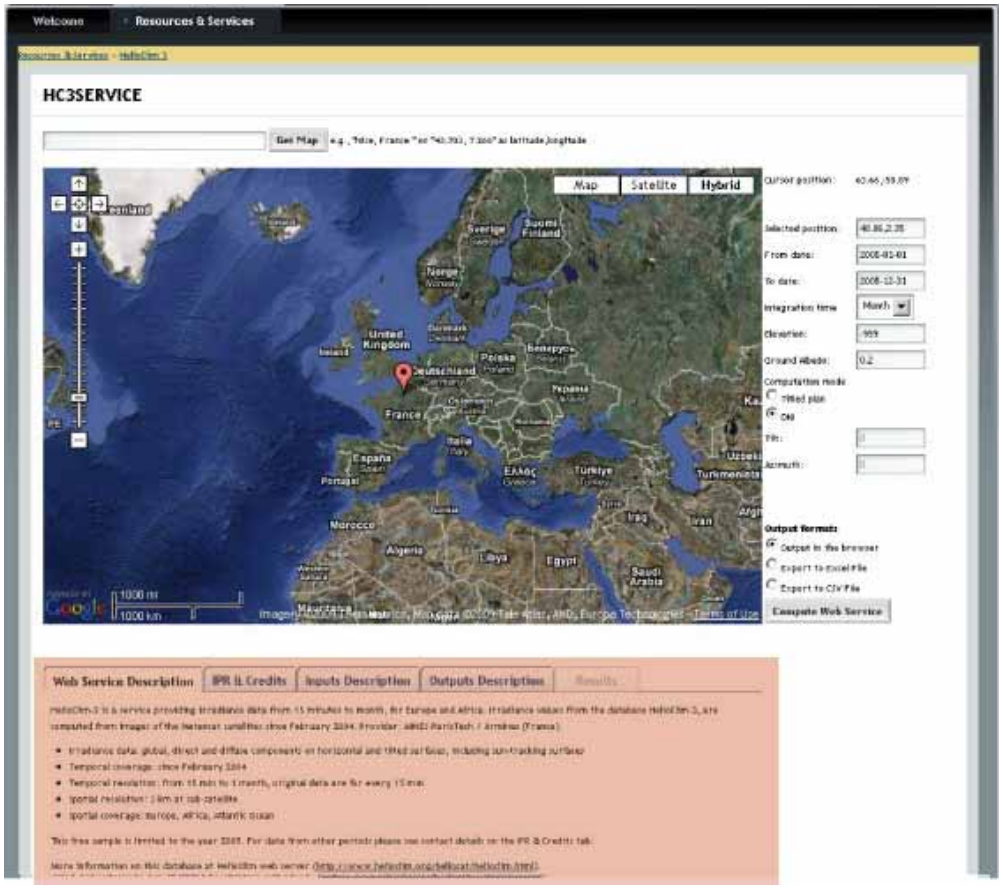
- Ease of use
- No learning curve
- De facto Standard

The new MESoR Portal



- Forms tailored for each applications
- Handle various output formats
  - Tabular in browsers
  - Excel Spreadsheet
  - PDF
  - CSV

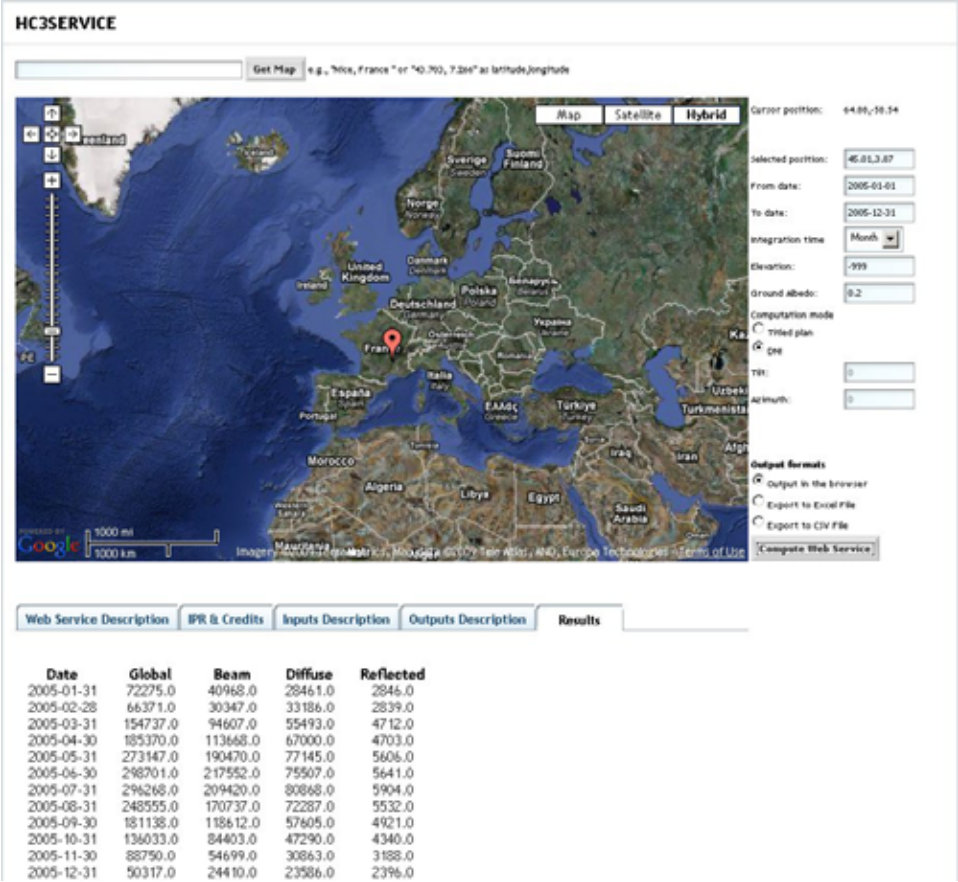
The new MESoR Portal



- Tabs handle Service's information
- Build with AJAX (Asynchronous)

- Result tab handle the selected output formats
  - Tabular in browsers
  - Excel Spreadsheet
  - PDF
  - CSV

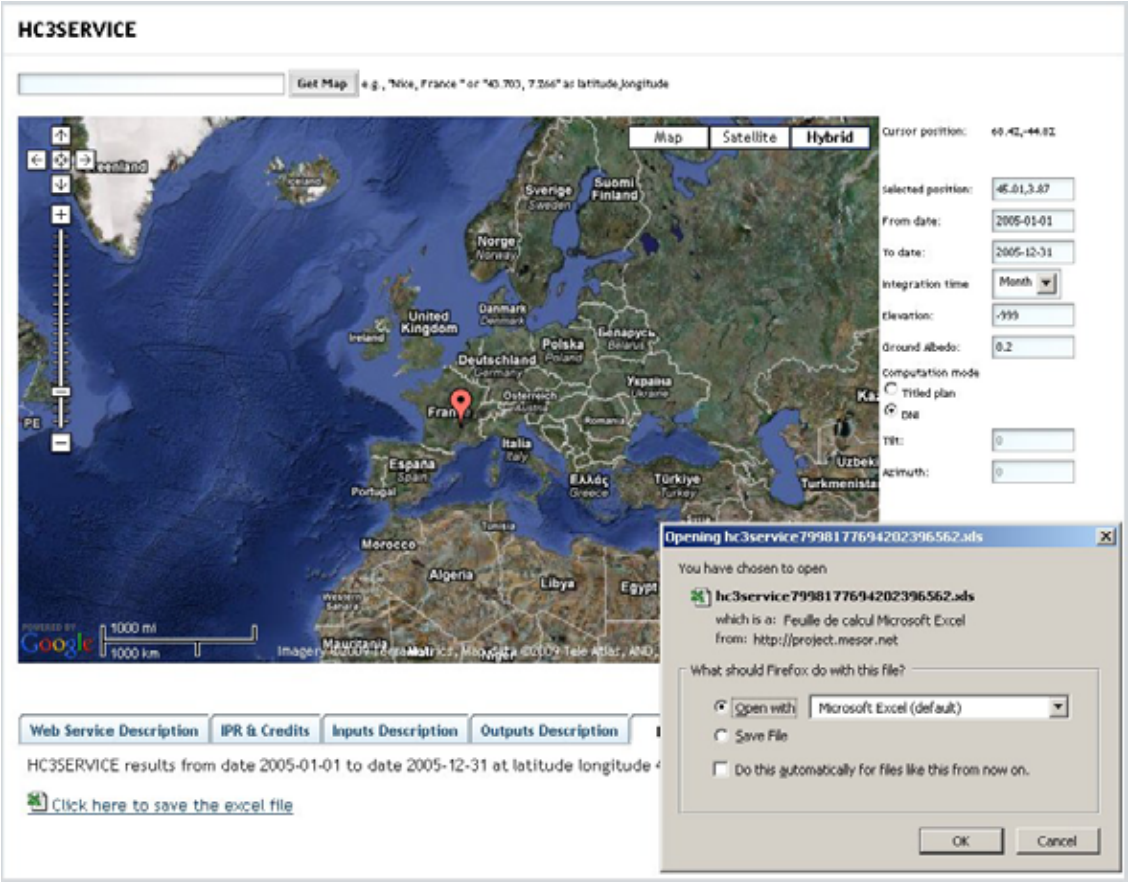
The new MESoR Portal



Date	Global	Beam	Diffuse	Reflected
2005-01-31	72275.0	40968.0	28461.0	2846.0
2005-02-28	66371.0	30347.0	33186.0	2839.0
2005-03-31	154737.0	94607.0	55493.0	4712.0
2005-04-30	185370.0	113668.0	67000.0	4703.0
2005-05-31	273147.0	190470.0	77145.0	5606.0
2005-06-30	298701.0	217552.0	75507.0	5641.0
2005-07-31	296268.0	209420.0	80868.0	5904.0
2005-08-31	248555.0	170737.0	72287.0	5532.0
2005-09-30	181138.0	118612.0	57605.0	4921.0
2005-10-31	136033.0	84403.0	47290.0	4340.0
2005-11-30	88750.0	54699.0	30863.0	3188.0
2005-12-31	50317.0	24410.0	23586.0	2396.0

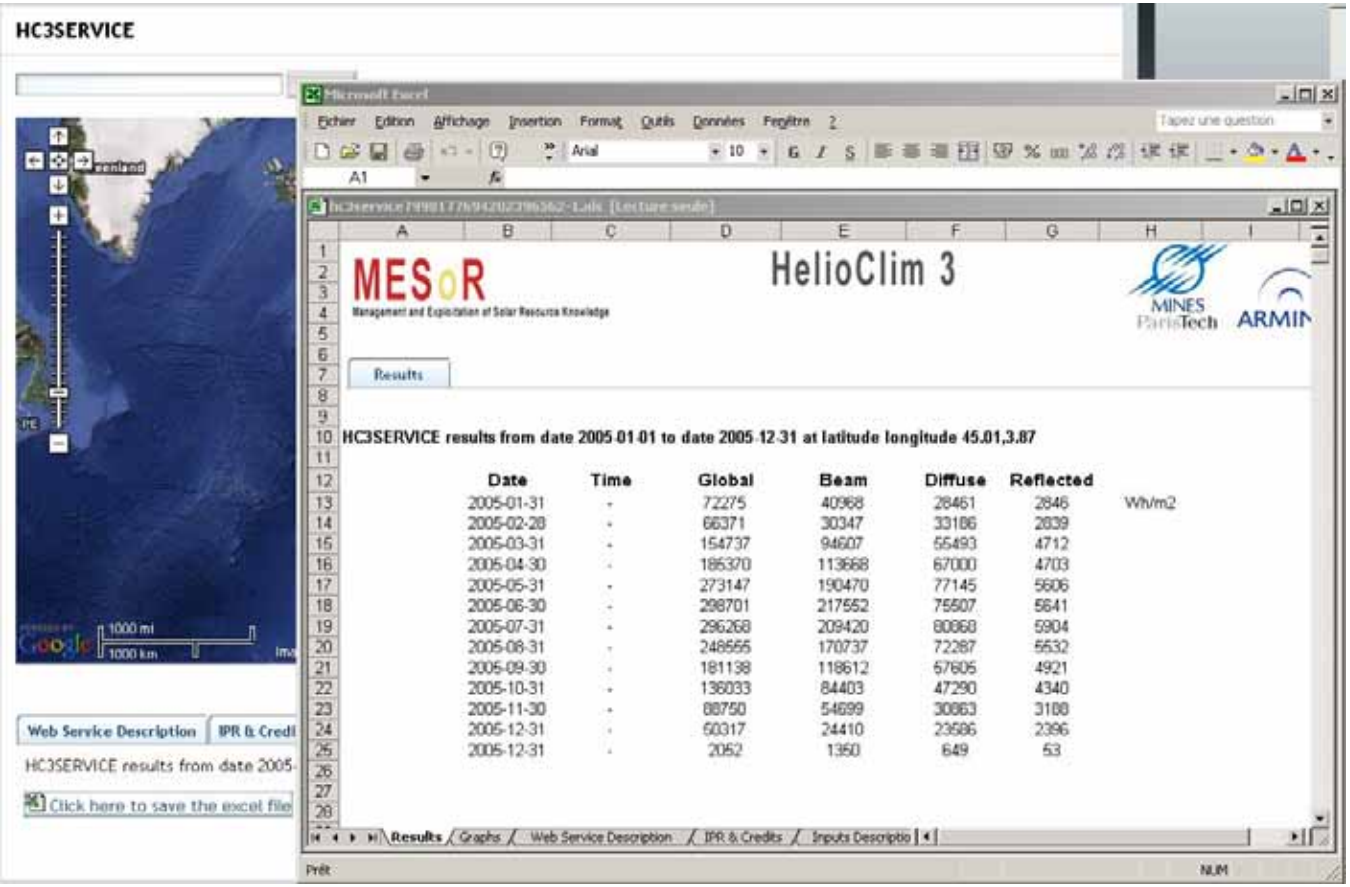
Tabular results output in browser

The new MESoR Portal



Excel file output sample

The new MESoR Portal

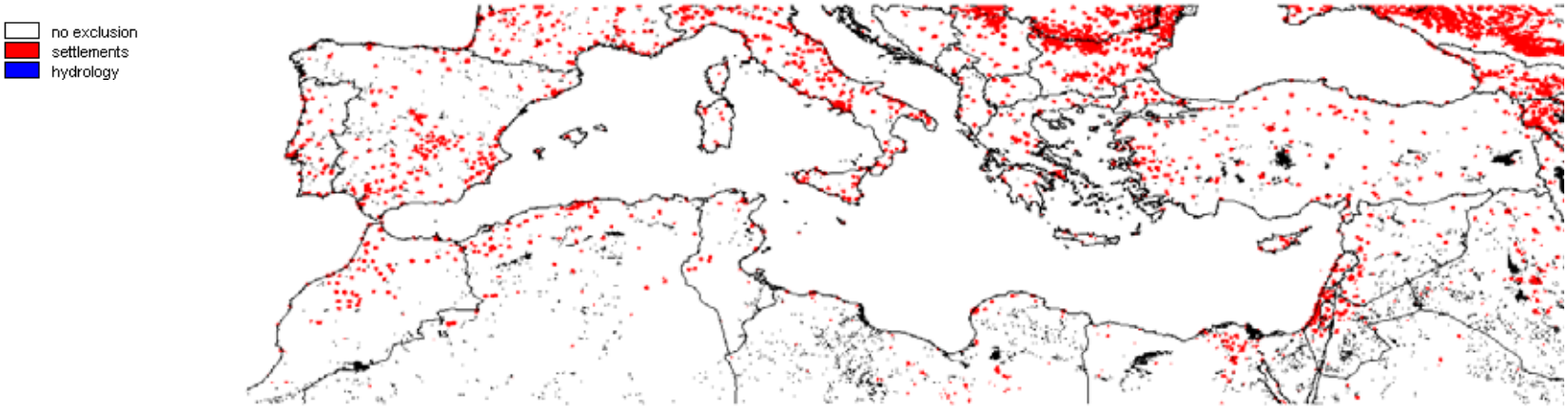


Excel file output result

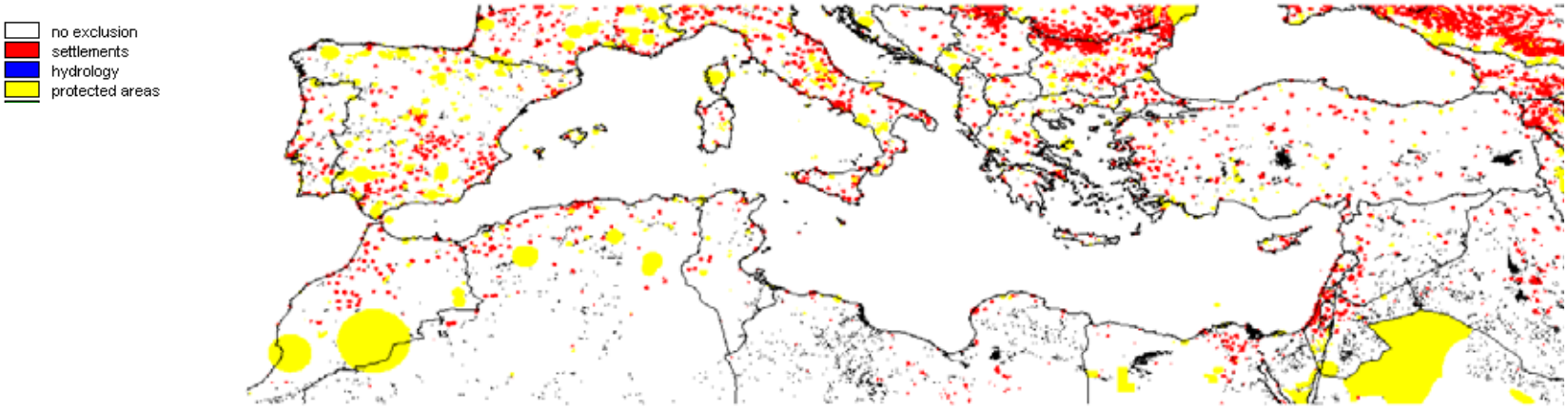
GIS Analysis

Generation of an Exclusion Map

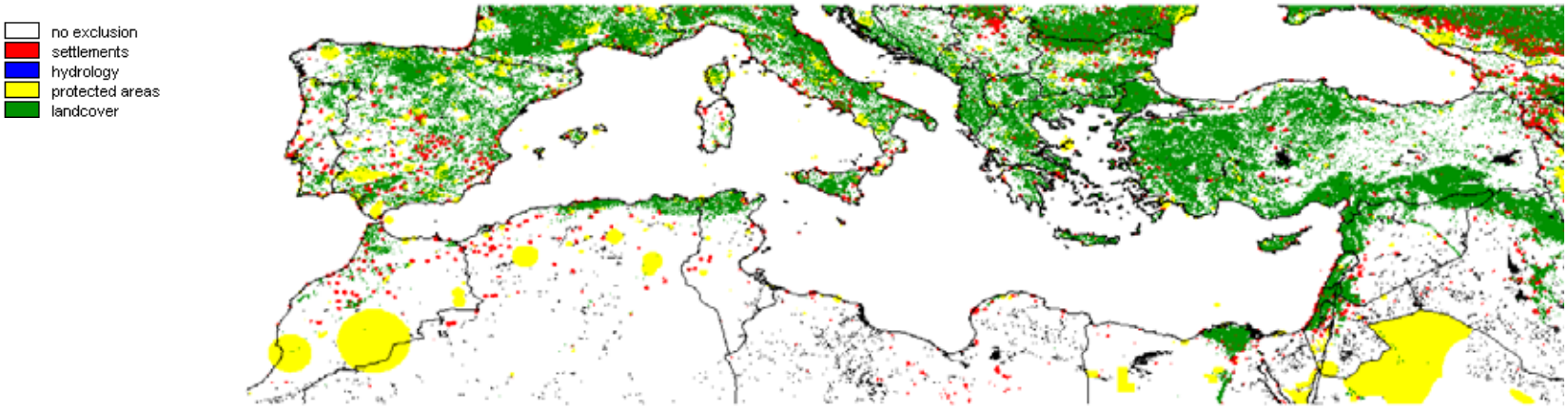
Generation of an Exclusion Map



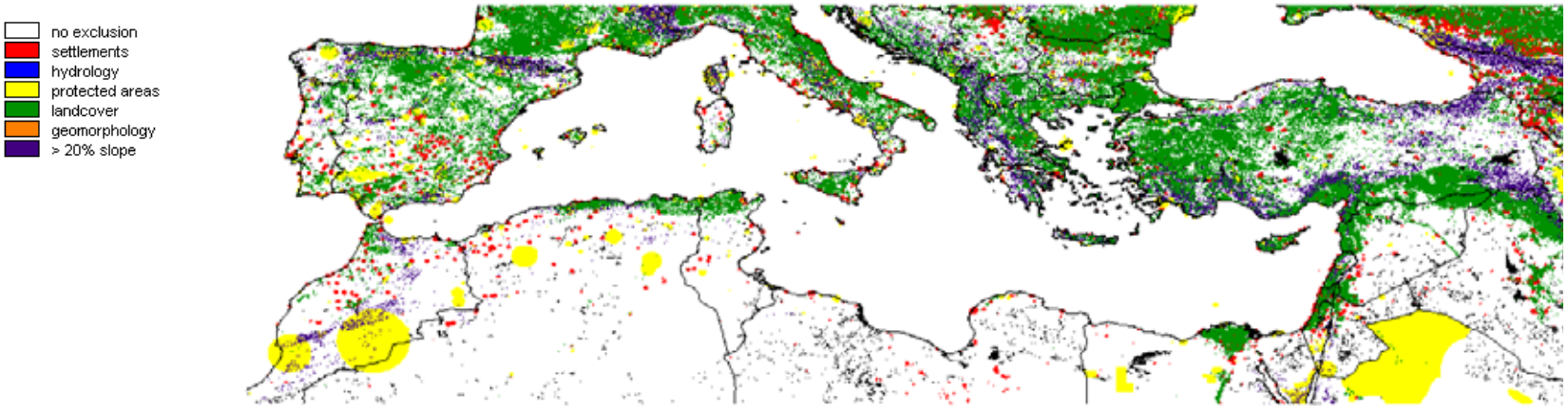
Generation of an Exclusion Map



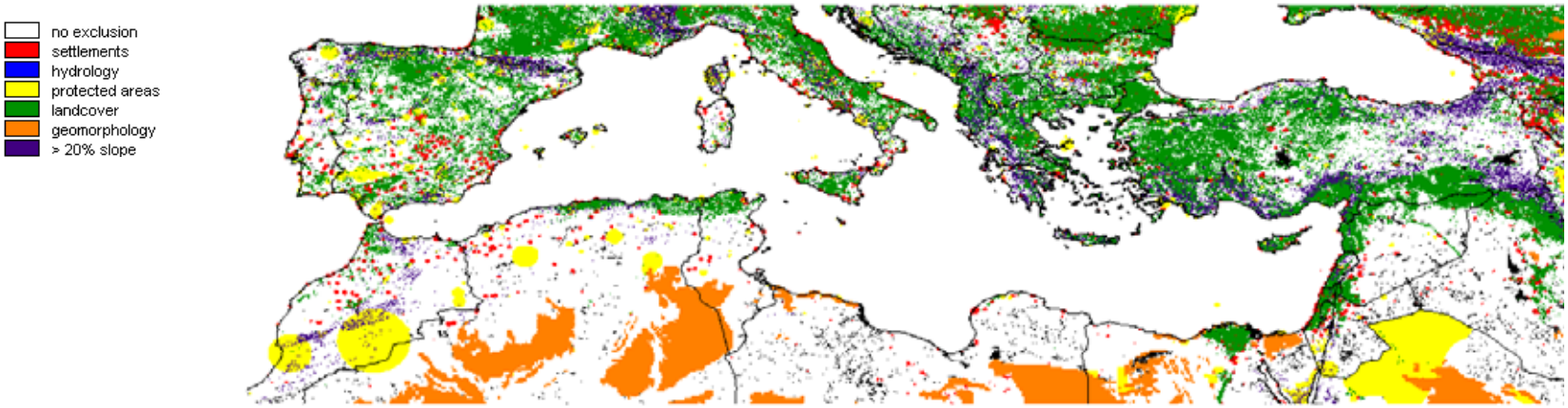
Generation of an Exclusion Map



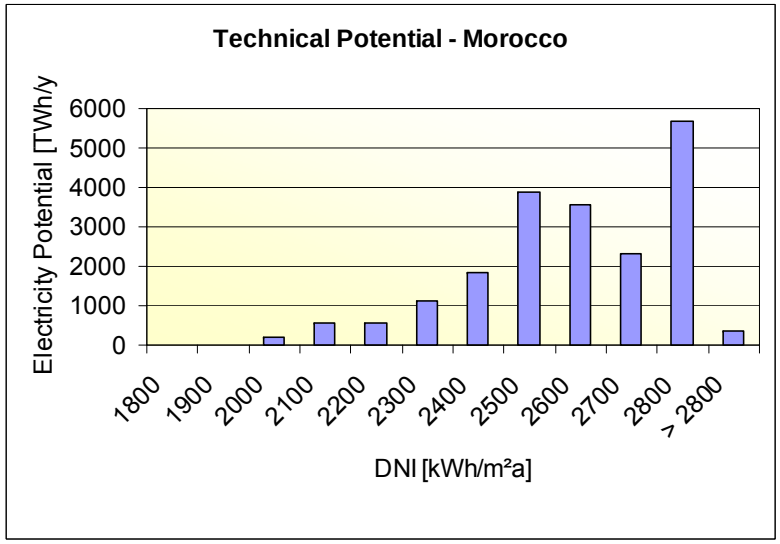
Generation of an Exclusion Map

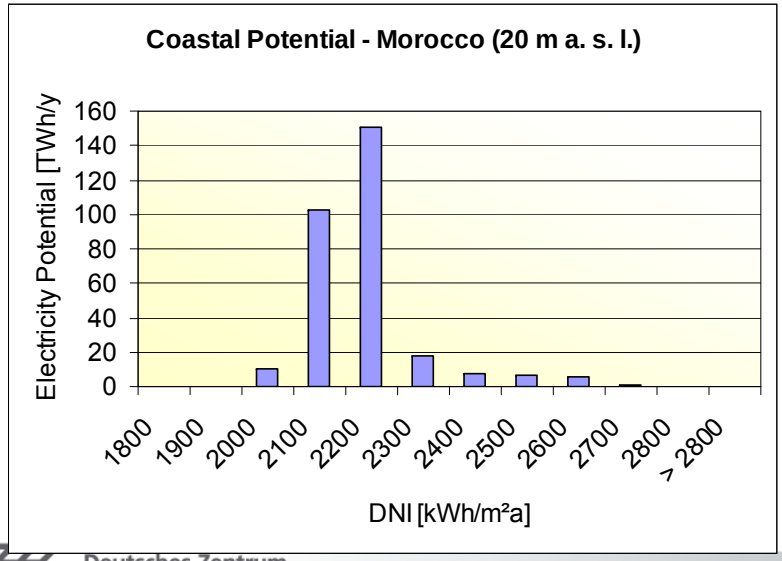


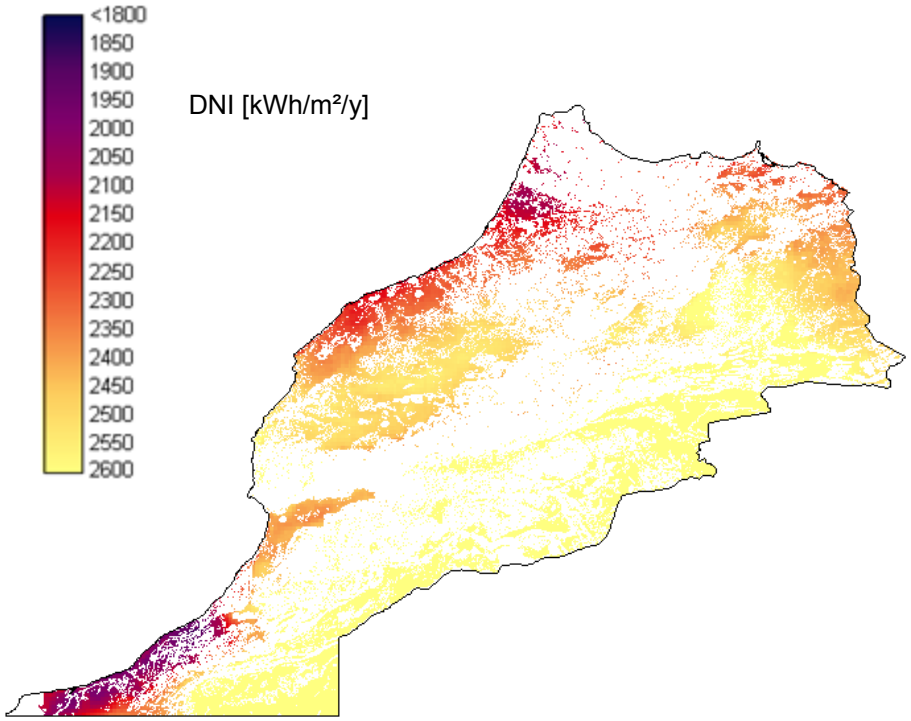
Generation of an Exclusion Map



Solar Thermal Electricity Generating Potentials in Morocco





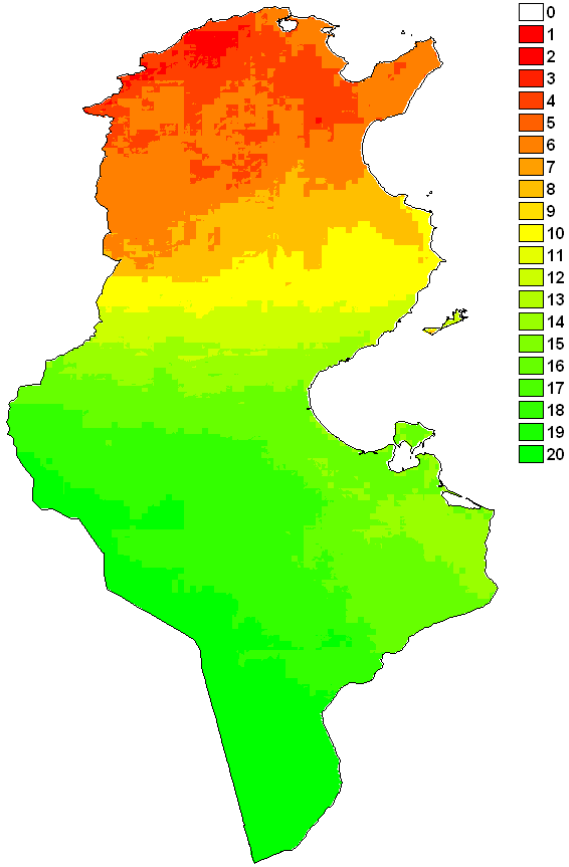


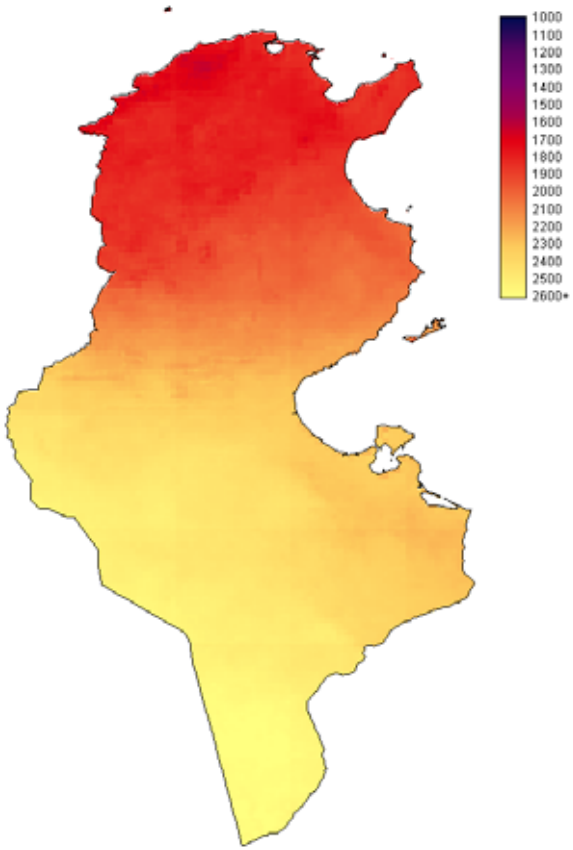
Technical Potential:	**20151 TWh/y (DNI > 1800 kWh/m²/y)**
Economic Potential:	**20146 TWh/y (DNI > 2000 kWh/m²/y)**
Power Demand 2000:	**15 TWh/y**
Power Demand 2050:	**235 TWh/y (Scenario CG/HE)**
Tentative CSP 2050:	**150 TWh/y (Scenario CG/HE)**
Coastal Potential:	**300 TWh/y (< 20 m a. s. l.)**
Water Demand 2050:	**1.2 TWh/y (Power for Desalination)**

New Approach for Site Ranking

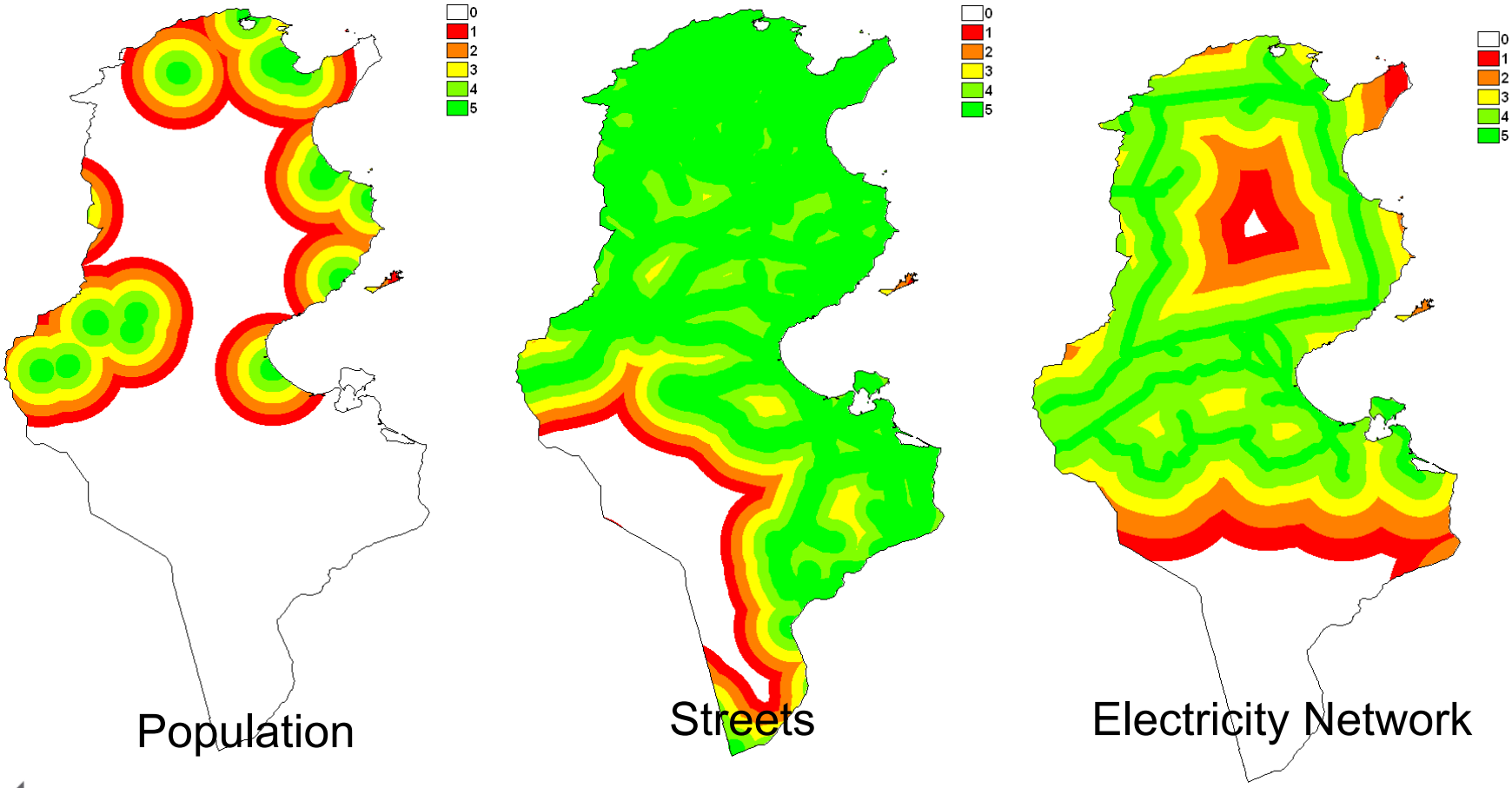
- Prerequisite: GIS data for resources and infrastructue
- Idea, giving Points to:
  - Level of available resource
  - Distance to the electricity grid
  - Distance to settlements
  - Distance to infrastructure
- Ranking based on the sum of points.

Determination of weights - DNI

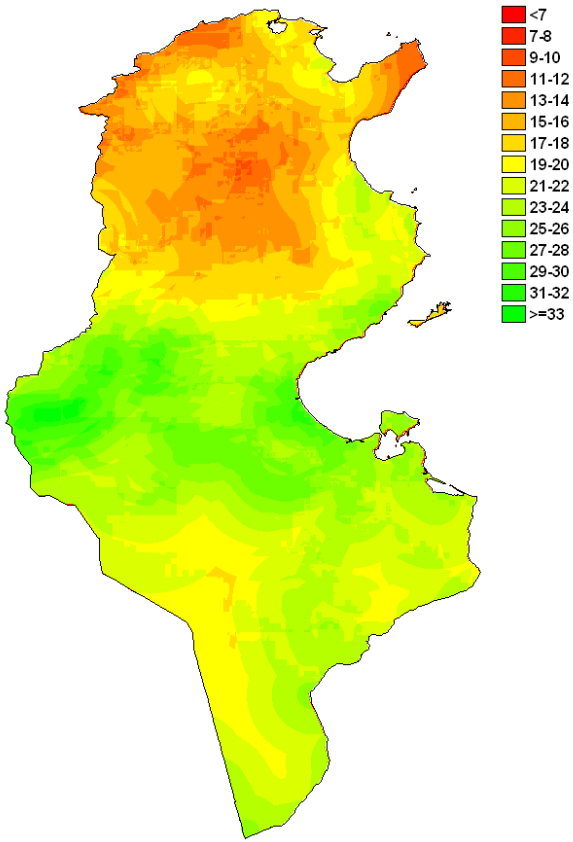




Determination of weights – Population and Infrastructure



Site Ranking for CSP Tunisia



Site Ranking based on:

	Value		Points	
	Min	Max	min	max
Resource DNI	1900	2300	2	20
Transmission	0	75	5	0
Substations	0	75	10	0
Settlements	0	50	5	0
Roads	0	50	5	0

Good Solar Resource Assessments

- Based on long term data
- Site specific, high spatial resolution
- Sufficient temporal resolution for the application
- Modeled data set has been benchmarked, information on quality is available
- For large projects: Based on different sources (e.g. Satellite and ground data).

Conclusions

- **High quality resource assessments are part of the basic infrastructure for market development and investments into an energy technology**
- **Nobody would invest in an oil field if he would not have a pretty good idea on what he expects from it.**
- **Renewable Energy Sources are highly variable in time and space: Their assessment needs a detailed investigation of high quality long term measurements from ground and space which requires a lot of effort.**
- **Planning infrastructures (as good maps) may be a public good. Everybody profits of it, but no single one will be willing to pay for it alone.**

Acknowledgements

- Many thanks for a large number of slides by Detlev Heinemann, University of Oldenburg, Energymeteorology group
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