Surface:
- reflection
- scattering
- absorption of electromagnetic radiation

active
artificial radiation

natural radiation

passive
UV, VIS, NIR, IR
MW
FIR

atmosphere

natural radiation

Space Based Remote Sensing
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**Space Based Remote Sensing**

1. Introduction
2. Fundamentals of Remote Sensing
3. Optical Space Sensor Systems
4. Design of a Spaceborne Wide-Angle Optoelectronic Stereo Scanner
5. Systematic Image Processing of the Small Satellite Mission BIRD
1. Introduction

1.1 Active and Passive Remote Sensing Systems

- **active** artificial radiation
  - Lidar
  - Radar

- **passive**
  - natural radiation
    - UV, VIS, NIR, IR
    - MW
    - FIR

- **atmosphere**

- **Surface:**
  - reflection
  - scattering
  - absorption

- **of electromagnetic radiation**
Active and Passive Remote Sensing Systems

Passive Systems
• Can only detect and measure radiation parameters
• Examples: cameras, spectrometer, radiometer, polarimeter, microwave receiver

Aktive Systems
• detect and measure the self generated, radiated and on the target reflected electromagnetic wave
• Example: LIDAR – Light Detection and Ranging, SAR – Synthetic Aperture Radar
1.2 The Remote Sensing Problem

4 Parts of the Remote Sensing Problem:
1. Radiation Source
2. Atmosphere (clouds, aerosols, humidity, temperature)
3. Object of measurement (Transmission, Absorption, Reflection, Emission)
4. Instrument, Sensor

There are two kinds of questions:

- How we can solve the **direct remote sensing problem**?
- How we can solve the **inverse remote sensing problem**?

What are the direct and the inverse remote sensing problem?
Direct Remote Sensing Problem

Computing the sensor signal
\[ U_S = f[L_S(h, \theta)] \]

Calculation of the radiance \( L_S \) of sensor at altitude \( h \)
with visir angle \( \theta \)
\[ L_S(h, \theta) = f[L(0)] \]

Calculation of the radiance \( L \) of the surface at altitude \( h=0 \)
\[ L(0) = f[a_1, a_2] \]
\( a_2 \) – imaging parameter

Determination of the surface parameters \( a_1 \) of the target,
e.g. \( \rho(\lambda) \)

Inverse Remote Sensing Problem

Calibration of the sensor signal
\[ L_S(h, \theta) = g(U_S) \]

Atmospheric correction and calculation of the radiance on ground
\[ L(0) = g[L_S(h, \theta)] \]

Radiometric de-convolution of the radiation source
\[ r = g[L(0)] \]
\( r \) = radiation parameter of the surface

Determination of the characteristic surface parameters of the target,
e.g. \( a_1 = g(r, a_2) \)
1.3 The Electromagnetic Spectrum and the Optical Spectral Range

UV  VIS  NIR

Ultraviolet  Visible  Near Infra-Red
The Electromagnetic Spectrum and Atmospheric Windows

Quelle: http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/
2. Fundamentals of Remote Sensing

2.1 Radiometric Terms

**Radiant Flux \( \Phi \)**

\( \Phi = \text{radiated energy flux through an area per time unit} \)

with \( Q = \text{radiated energy} \)

\[
\Phi = \frac{dQ}{dt} [W] \\
Q = \int_{T_{\text{int}}} \Phi dt [J, Ws]
\]

**Radiant Intensity \( I \)**

Radiant flux emitted per unit solid angle

\[
I = \frac{d\Phi}{d\omega} \left[ \frac{W}{sr} \right]
\]

Area of a sphere = \( 4\pi r^2 \)

Solid angle of a complete sphere = \( 4\pi \)
Radiometric Terms

Radiance $L = \frac{\text{directed radiation flux } \Phi}{\text{unit solid angle } d\omega \times \text{unit of projected radiation area } dA}$

**Radiance $L$:**

$$ L(\Theta, \varphi) = \frac{d\Phi}{d\omega \cdot dA \cdot \cos(\Theta)} \left[ \frac{W}{m^2 \cdot sr} \right] $$

**Spectral Radiance $L_\lambda$:**

$$ L_\lambda = \frac{d\Phi}{d\omega \cdot dA \cdot \cos(\Theta) \cdot d\lambda} = \frac{dL(\Theta, \varphi)}{d\lambda} \left[ \frac{W}{m^2 \cdot \mu m \cdot sr} \right] $$
Radiometric Terms

Exitance $M$, radiant emittance $M$

$M = \frac{d\Phi}{dA_1}$

$M = \text{radiant flux pro area unit in the angular unit } 2\pi \text{ (hemisphere) Halbraum}$

Terms at radiation receiver (index 2):

Irradiance $E$

$E = \frac{d\Phi}{dA_2} \left[ \frac{W}{cm^2} \right]$

E = \text{per receiver area intercepted radiant flux}$

Exposure $H$

$H = \frac{Q}{A_2} = \frac{\Phi \cdot T_{\text{int}}}{A_2} = E \cdot T_{\text{int}} \left[ \frac{Ws}{cm^2} \right]$

H = \text{per area incident radiation energy}

= \text{time integral of incident power per area}
2.2 Photometric Terms

- The relationship between radiometric and photometric terms consists in the **spectral sensitivity** $V(\lambda)$ of the human eye.
- The **spectral sensitivity** $V(\lambda)$ is different for day light and in darkness.
Photometric Radiation Equivalent $k(\lambda)$

spectral sensitivity $V(\lambda)$:

$$V(\lambda) = \frac{k(\lambda)}{k_{\text{max}}}$$

$k(\lambda)$ = photometric radiation equivalent
$(k'_{\text{max}} = 1,725 \text{ lm/W @ 510 nm})$

with $k(\lambda) > 0$ für $380 \text{ nm} \leq \lambda \leq 780 \text{ nm}$

$k_{\text{max}} = 673 \text{ lm/W} @ \lambda = 555 \text{ nm}$

[Im = Lumen]
### Radiometric and Photometric Terms

<table>
<thead>
<tr>
<th>Radiometric Terms</th>
<th>Photometric Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant flux $\Phi$ [W]</td>
<td>Luminous flux $\Phi_V$ [lumen]</td>
</tr>
<tr>
<td>Radiant energy $Q$ [Ws]</td>
<td>Luminous energy (light) $Q_V$ [lm·hrs]</td>
</tr>
<tr>
<td>Radiant intensity $I$ [W/sr]</td>
<td>Luminous intensity $I_V$ [cd]</td>
</tr>
<tr>
<td>Radiance $L$ [W/(m²·sr)]</td>
<td>Luminance, brightness $L_V$ [cd/m²]</td>
</tr>
<tr>
<td>Irradiance $E$ [W/m²]</td>
<td>Illumination, illuminance $E_V$ [lux]</td>
</tr>
</tbody>
</table>

- Radiant flux $\Phi$ is given by the integral of the radiant intensity $I$ over the solid angle $d\omega$:
  \[
  \Phi = \int I \cos(\varepsilon) dA
  \]

- Photometric terms:
  - Luminous flux $\Phi_V$ is the integral of the luminous intensity $I_V$ over the solid angle $d\omega$:
    \[
    \Phi_V = \int I_V d\omega
    \]
  - Luminous energy (light) $Q_V$ is the integral of the luminous flux $\Phi_V$ over time $dt$:
    \[
    Q_V = \int \Phi_V dt
    \]
  - Luminous intensity $I_V$ is the radiant flux $\Phi_V$ divided by the solid angle $d\omega$:
    \[
    I_V = \frac{d\Phi_V}{d\omega}
    \]
  - Luminance, brightness $L_V$ is the radiant flux $\Phi_V$ divided by the product of the cosine of the angle of incidence $\cos(\varepsilon)$ and the area $dA$:
    \[
    L_V = \frac{dI_V}{\cos(\varepsilon) dA}
    \]
  - Illumination, illuminance $E_V$ is the radiant flux $\Phi_V$ divided by the area $dA$:
    \[
    E_V = \frac{d\Phi_V}{dA}
    \]
2.3 A Basic Radiometric Law

\[ d\omega_1 = \frac{dA_2 \cos(\varepsilon_2)}{r^2} \]

\[ \Phi = L \frac{dA_1 \cos(\varepsilon_1) \cdot dA_2 \cos(\varepsilon_2)}{r^2} \]
2.4 The Basic Equation of Space Remote Sensing

\[ L_S = L_O + L_A + L_B \]

- \( L_S \): radiance at space sensor
- \( L_O \): radiance of the target object (surface reflection of direct sunlight and diffuse sky radiation)
- \( L_A \): atmospheric scattering
- \( L_B \): background radiance

\[ L_A + L_B = L_{\text{path}} \]

\[ L_A + L_B = \text{path radiance} \]
2.5 Types and Classes of Information and Remote Sensing Sensors

Spatial Information

Imager, Altimeter, Sounder

Imaging Spectrometer

Spectral Information

Imaging Spectroradiometer

Spectrometer

Intensity Information

Imaging Radiometer

Radiometer Scatterometer, Polarimeter

### 3. Optical Space Sensor Systems

#### 3.1 The General Remote Sensor System

<table>
<thead>
<tr>
<th>Wave length</th>
<th>Collector</th>
<th>Detector</th>
<th>Measurement value</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-rays, X-rays</td>
<td>Detector is the collection aperture&lt;br&gt;Particles interchange with the detector material, Ionisation&lt;br&gt;→ light emission or charges are generated, emitted light or generated current is an equivalent for the energy flux</td>
<td>Incident energy flux or photon number</td>
<td></td>
</tr>
<tr>
<td>UV, VIS, IR</td>
<td>Optics, reflecting surfaces (mirrors)</td>
<td>Conversion of EM-Energy in heat, current or state changes</td>
<td>Energy of the field on one point as function of wave length (Spectrometer) or total radiation flux (Radiometer) or Polarisation</td>
</tr>
<tr>
<td>Micro wave</td>
<td>Antenna</td>
<td>EM detector antenna</td>
<td>Amplitude, Polarisation, Frequency, Phase</td>
</tr>
</tbody>
</table>
3.2 System Components of a Passive Optical Sensor System

The scanner unit can be arranged behind the optics, depending on the system design.
3.3 Performance Parameter of an Optical Instrument

- overall sensitivity;
- dynamic range and linearity;
- spectral response and out of band rejection;
- radiometric resolution (expressed through detectivity, NEP);
- spectral resolution (expressed through equivalent bandwidth);
- time resolution (e.g. acquisition time frame);
- polarization measurement accuracy and instrumental polarization;
- straylight rejection;
- preflight and In flight calibration;
- radiation damage and radiation induced transients.
3.4 Passive Sensor System Concepts

~ can be separated by the image sampling principle:

- Film camera
- Whiskbroom
- Pushbroom
- Staring Array
- Time Delay and Integration (TDI)
Film Camera

\[ \tau_{\text{shutter}} = \frac{x}{V_{gt}} \]

image reconstruction:

**Advantages:**
- Large image format
- High information density
- Cartographic precision
- Analogue data

**Drawbacks:**
- Expensive Digitalisation
- Transportation of the film
- Image smearing
**Whiskbroom Scanner**

System concept: opto-mechanical Scanner

Image reconstruction:

\[
\tau_{dwell} = \frac{x}{v_{gt} \cdot n_{pix}} \cdot \eta_{scan}
\]

- \(x\) = ground pixel size
- \(v_{gt}\) = ground track velocity
- \(n_{pix}\) = Pixel number per Swath
- \(\eta_{scan}\) = swath width/x
- \(\eta_{scan}\) = Scan efficiency

\[\text{Dwell-time of the single scanner}\]

Whiskbroom Scanner
Whiskbroom Scanner = Opto-mechanical Scanner

**Advantages:**
- simple detectors
- Optics with small Field of View
- large swath width
- several spectral channels are feasible

**Drawbacks:**
- very short detector dwell time (low signal)
- movable mechanical parts
- expensive geometric image correction
**Pushbroom Scanner**

System concept: Electronic line scanner

- **Flight direction**
- **Swath**
- **Scan direction**
- **Ground pixel**

**image reconstruction:**
detector line across the flight direction

**dwell time:**
\[ \tau_{dwell} = \frac{X}{V_{gt}} \]
Pushbroom Scanner =
Electronic line scanner

Advantages:
• large Swath width and high resolution feasible (depending on pixel number)
• relatively „long“ dwell time for each pixel
• high geometric accuracy across the flight direction
• No movable parts

Drawbacks:
• Optics with a large Field of View necessary
• Expensive geometrical image correction due to flight attitude necessary (line by line)
Staring Array ("digital camera")

System concept: electronic matrix imager

image reconstruction:
2D-image within the dwell time

\[ \tau_{\text{dwell}} = \frac{X}{V_{gt}} \]

Flight direction

Satellite

Staring imaging principle
Staring Array („digital camera“)

Advantages:
• fix geometry of the complete 2D-image
• high geometric accuracy
• Large spectral range feasible

Drawbacks:
• Pixel number across the flight direction less then pixel number of a line sensor (lower swath width)
• High read-out velocity necessary
• Additional smearing effects during read-out possible
3.5 Optics
Basic Parameters of an Optical System

Focal Length \( f \)

= distance of the focal point to the main plane

\[
\frac{1}{f} = \frac{1}{g} + \frac{1}{b}
\]

imaging scale:

\[
m' = \frac{b}{g} = \frac{b}{f} - 1
\]

\( f \) = focal length
\( g \) = object distance
\( b \) = image distance
\( y \) = object size
\( y' \) = image size
\( m' \) = imaging scale
\( F' \) = focal point
Basic Parameters of an Optical System

Back Focal Length (BFL)

\[ \text{Back Focal Length (BFL)} = \text{distance of the last lens to the image plane} \]

- Can be measured directly (in contrast to the focal length)
- Important parameter for the opto-mechanical system design

![Diagram showing the relationship between back focal length, focal length, and main planes](image)
Basic Parameters of an Optical System

Field of View (FOV)
- Maximum view angle of an optical system
- Maximum image field angle
- Can be rotational symmetric (Total Field of View) or be different in 2 directions (FOV1, FOV2)

\[
\phi = \frac{1}{2} \text{FOV}
\]

\[
\text{FOV} = \pm \arctan\left(\frac{\text{image field}}{2 \cdot f}\right)
\]
Basic Parameters of an Optical System

Aperture D

- Maximum entrance aperture limits the rays on the border
- Determines the light quantum on the focal plane

F/number, F/# or k

- Reciprocity of the entrance aperture
- F/number sequence: factor $\sqrt{2}$

$$k = 0,7; 1; 1,4; 2,8; 4; 5,6; 8; 11; 16; 22; \ldots$$
Limits of Spatial Resolution

Effect:

An ideal point light source is depicted in the image plane as an blurring or smearing circle. The energy is distributed over an area.

2 reasons:

- Diffraction (of the light ray at the entrance pupil) and
- Aberrations, i.e. imaging failures of the optics

Point Spread Function PSF

- The spatial distribution of an ideal point light source in the image plane is called Point Spread Function. It represents the performance of sharpness of the image.
Diffraction Limit

The diffraction limit of the resolution of an optical system can be determined by:

\[ D_{\text{Airy}} = 2.44 \cdot \lambda \cdot \frac{f}{D} \]

\[ D_{\text{Airy}} = 2.44 \cdot \lambda \cdot k \]

mit \( D = \) diameter of the free aperture (Airy circle)
\( f = \) focal length
\( k = \) aperture number
Aberrations

- Aberrations are imaging failures in the image plane if the diffraction is ignored
- Aberrations lead to an additional smearing effect (additional to the diffraction)

It can be differentiated in
5 monochromatic aberrations:
  1. aperture failure
  2. Coma
  3. Astigmatism
  4. Image plane curvature
  5. Image distortion

and 2 chromatic aberrations.
The Point Spread Function PSF

Ideal spot (point) light in object plane is changed by the transfer function of optics to a spread point image:

The function is called **Point Spread Function**.
The Modulation Transfer Function MTF

- The Fourier Transformed Function of the Point Spread Function is the **Optical Transfer Function OTF**.
- The OTF consists of an absolute value and a phase function in dependence from the spatial frequencies in x and y direction.

\[
\text{F(PSF)} = \text{OTF} \\
\text{OTF}(k_x, k_y) = |\text{OTF}|e^{j2\pi\varphi(k_x, k_y)}
\]

with \((k_x, k_y) = \text{spatial frequency in the x- and y-plane, respectively}
[k_x, k_y] = \text{lp/mm or 1/mm}

- The Modulation Transfer Function is the absolute value of the Optical Transfer function and a measure for the sharpness of the image.

\[
\text{MTF} = |\text{OTF}|
\]
Optical Concepts

3 Optical concepts for optical space sensor systems:

- **Refractive Optics**
  - optical system consists of lenses only

- **Katadioptical System**
  - optical system consists of lenses and mirrors

- **Reflective Optics**
  - optical system consists of mirrors only
Refractive Optics

When

- the focal length less than 500 mm
- the Field of View is large (90° or more)
- the spectral bands are wide (200 nm or more)

Examples:

- Symmetric lenses for different applications
- Wide angle lens systems
- Telescopes and Zoom lenses
Refractive Optics

Advantages:

- Low costs because of spherical lens surfaces
- High image quality and strong light signal possible, because of no obscuration by mechanical elements
- Inexpensive optic adjustment by circular lenses and axial locations
- Diversity of optical lens materials allows spectral corrections in a wide range of applications
- Stray light suppression by simple baffle arrangements possible

Drawbacks:

- No long focal length with high aperture numbers possible
- Chromatic aberrations at high spectral band with (> 200nm) have to be corrected
Katadioptical System

When

- The focal length is larger than 500mm
- The Field of View is large

Examples:
Schmidt-Camera, Schmidt-Cassegrain-Telescope, Maksutov-Telescope
Katadioptical System Example: Maksutov-Telescope at the German Mars Camera

- The Super Resolution Channel is a separate 1024 x 1024 framing camera with a Maksutov-Cassegrain telescope (f= 974.5mm)
- Ground pixel size: 2.3 m/pix at pericenter of Mars Orbit
- Pericenter altitude = 250 km

High Resolution Stereo Camera of DLR for the Mars Express Mission. The lower optical system is the Maksutov-Cassegrain telescope of Super Resolution Channel (Photo: DLR)
Reflective Optics

- Consists of 2 or 3 mirrors (primary mirror, secondary mirror(s) and supporting elements
- No lenses
- All telescopes with an diameter > 1m are reflective telescopes

Examples: Newton-telescope, Cassegrain-telescope, Richey-Chrétien-telescope, Three Mirror Anastigmat)
Reflective Optics

Advantages:
- Only one surface of an optical element has to be manufactured with high precision (the mirror)
- The backside can be lightweight
- High numerical aperture feasible
- Distortions and optical performance are not dependent from the wavelength
- Many different materials are suitable for a mirror (optical glasses, metals, Zerodur, SiC, etc.)

Drawbacks (in comparison to refractive systems):
- For small Field of Views only
- More expensive in manufacturing, assembly and integration (higher precision)
- Obscuration due to supporting elements for secondary mirror
- Higher mass and volume
- More stray light
Reflective Optics Example: Richey-Chrétien-Cassegrain-Telescope of HST

- main telescope of the Hubble-Space-Telescope HST
- Diameter of the primary mirror = 2.4 m
- Diameter of the secondary mirror = 0.30 m
- Baffle for stray light suppression at secondary mirror and at centre hole of primary mirror
Reflective Optics Example:
3 Mirror Anastigmat (TMA) on British TOPSAT-Mission

- Optics: 3 mirror off axis system (TMA)
- Focal length = 1.68 m
- FOV = 1,4° across track
- Aperture = 20 cm
- Volume = 75x52x35 cm
- Hyperbolic primary mirror
- Ground resolution = 2,5m
- SNR-improvement by TDI
Reflective Optics Example: TMA-Implementation on TOPSAT

TMA-Telescope on a micro-satellite platform of SSTL
## Filters

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GLASS FILTERS</strong></td>
<td></td>
</tr>
<tr>
<td>low impact of inclined entrance ray</td>
<td>limited filter assortments</td>
</tr>
<tr>
<td>robustness and long-term stability</td>
<td>very limited band-pass characteristics feasible</td>
</tr>
<tr>
<td>high transmission within a large bandwidth</td>
<td>fine tuning not possible</td>
</tr>
<tr>
<td><strong>INTERFERENCE FILTERS</strong></td>
<td></td>
</tr>
<tr>
<td>any narrow bandwidth feasible</td>
<td>near parallel incidence of light required</td>
</tr>
<tr>
<td>spectral fine tuning feasible</td>
<td>sensitive against environmental impacts</td>
</tr>
<tr>
<td>steep edges in the spectral characteristics</td>
<td>additional glass blocking filters necessary</td>
</tr>
<tr>
<td>feasible</td>
<td></td>
</tr>
</tbody>
</table>
# 3.5 Detectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensitivity (QE)</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Film               | ~0.01            | Non-linear  
• Dyn. Range: 1/100  
• Detector is memory  
• High capacity |
| Photo Multiplier Tube | 0.1 ... 0.3     |  
• Photocathode, SE - Multiplier  
(10^6 ... 10^7)  
• distortions |
| Micro Channel Plate    | 0.1 ... 0.2     |  
• Photocathode, SE - Multiplier  
(10^6 ... 10^7)  
• no distortions |
| CCD                | 0.3 ... 0.9      |  
• Dyn. Range to 1/1000,  
Limited by photon noise  
• Very sensitive  
• Linear system (200000 e-/ pixel)  
• High capacity |
3.6 Charge Coupled Devices

- CCD = Charge Coupled Device
- CCD sensors consist of a one or two dimensional array of light sensitive and storage elements
- It can be differentiated:
  - CCD-lines
  - CCD-Matrices
CCD-Matrix: Interline transfer
**Interline transfer**

1. Integration phase
   photons generate charges (green dots) in the pixels

2. Parallel transfer of the charges in light protected shift registers
Interline transfer

3. Vertical shifting into the read-out register

4. The read-out process is an serial process.
Frame Transfer Matrix

- The complete image (frame) is transferred into a light-protected frame area.
- The light sensitive area is also the transfer register field.
- Actually there are two CCD matrices, one is sensitive and the other in a shadow area.
- They have a higher pixel density but they are more expensive (2 matrices).
- Smearing is an important impact.
Frame Transfer Matrix

1. Integration phase

2. Transfer phase into the temporal memory
Frame Transfer Matrix

• 3. read-out of the temporal memory.
Full Frame CCD

- No light-protected memory area.
- Integration time can not be controlled electronically.
- Mechanical shutter necessary.
- Maximum use of the light sensitive area.
- Application for high sensitivities and long integration times.
1-chip-Colour-CCD

• Color filter mosaic in front of the light sensitive sensor area

• Each pixel records only one colour, the object colour has to be interpolated from the surrounding pixels

• Interpolation algorithms are different from supplier to supplier

50% green
25% blue
25% red

give an interpolated colour image
Dark Current of CCD

- In the semiconductor material charge carrier are generated in dependence from the temperature.

- The effect of generation and recombination of the carriers and electrons is called thermal noise or dark signal or dark current.

- For applications with a long integration time or high sensitivity the sensor has to be cooled or and the dark signal has to be corrected.
Blooming Effect of a CCD

- Blooming is the loss of contrast in high illuminated image regions.
- If the CCD pixel is saturated then the new generated electrons overflow to the neighbour pixels.
- The CCD manufacturer can build in a special potential wall to prevent the overflow effects. In this case the CCD is called “with anti-blooming”.
Smear effect of a CCD

- The Smear effect is a light vertical stripe in a CCD image across a very bright image region.
- The reasons are different but they are connected with light impact during transport mechanisms.
- **Interline Transfer CCD**: the smear effect is generated by photons, penetrating the darkening stripes on the vertical shift register (light transmission up to 0.1%).
- **Frame Transfer CCD**: the smear effect is generated by very bright light points during the fast transport of the image into the darkening region of the CCD.
- The instrument designer has to take into account the possibility of this effect and can build in a mechanical shutter as a countermeasure.
References and Literature

1. Basics

2. Signal and System Theory

3. Optical Sensor Systems

5. Infrared Sensors

6. Sensor Technology for the Far Infrared

7. Micro-wave Sensors