
Exam in Remote Sensing (RRY 055)

Place & time:	V-building, 2008-03-13.
Teacher contact:	Johan Mellqvist (7724855) will visit around 9.30 and 11.30.
Language:	Answers can be given in either Swedish or English.
Extent:	Exam has 5 questions and 6 pages.
Points:	The exam carries 50 points, where 20 points are needed to be approved.
Answers:	Begin each question on a new sheet of paper.
Allowed aid:	Calculators, basic math and physics formulae collections (such as Physics Handbook) and enclosed sheet of formulae.

Important: Write short and concise answers. A long answer with a lot of irrelevant information will not help you, rather the opposite as it shows that you are uncertain about the answer. Answers shall be ordered following the question numbering. Begin each question on a new sheet of paper.

1. Satellite considerations (10 p)

Definitions/explanations of terms and principles for satellite systems:

a Describe the most commonly used orbit type for earth observation satellites. Why is this orbit type used? (3 p)

b One of the reasons to why satellites are expensive is that they have to go through a large number of tests before they are launched. Mention at least four dangers that satellites can encounter during launch and in orbit. (2 p)

c Describe how data can be transferred from a satellite sensor to the data user. Your answer should include an explanation to the term station mask. Describe two alternatives when direct downlink is not possible. What are the general limitations in the data transfer? (3 p)

d Data users have different requirements on the satellite data. Mention at least four applications where near real time data delivery is required. (2 p)

2. DOAS (10 p)

A large powerplant releases NO_2 from several chimneys. Measurements were conducted by a zenith viewing DOAS instrument placed in a car that was driven across the gas plume. Figure 1 shows the absorption cross-section for NO_2, and Figure 2 shows a transmission spectrum, in which the zenith sky spectrum measured outside the plume was divided with a spectrum corresponding to light that has passed the gas plume.

a Estimate the column of NO_2 in the spectrum (molecules/cm^2), applying a 2-wavelength DOAS methodology. Describe the methodology clearly. (5 p)

b What are the relevant radiative transfer effects and describe the mechanisms that make the differential methodology essential. (2 p) c Assume that the width of the plume is 40 m, that the concentration is constant across the plume and that the windspeed is 10 m/s. How many kg NO_2 /s is then being releases from the powerplant? (3 p)

3. SAR (10 p)

An airborne SAR operates at C-band (5.3 GHz) and has a broadside looking circular antenna with diameter 1.2 m and efficiency 0.9. The systems bandwidth is 20 MHz and the transmitted power is 10 kW. The aircraft flies at an altitude of 8 km and the radar illuminates a ground range swath 10 - 15 km measured from nadir and out to the side.

a What is the slant range resolution of this SAR? (2 p)

b What is the highest possible pulse repetition frequency (PRF) for avoiding any range ambiguities within the swath? (3 p)

c An echo from a metallic sphere placed on the ground is received 95 μs after pulse transmission. The received power is 8 pW. What is the radar cross section of the sphere? (3 p)

d A second airplane with an identical antenna flies in parallel with the airplane carrying the SAR. This system does not transmit any signal, but passively listens for echoes caused by the signal from the SAR on the other airplane, i.e. a bistatic radar. For simplicity, assume that the signal from the SAR is scattered isotropically from the sphere, i.e. the scattering is the same in all directions. The power received from the sphere by the second system is 6.5 pW. What is the distance between this second airplane and the sphere? (2 p)

4. Temperature sounding (10 p)

A nadir looking satellite IR instrument performs brightness temperature measurements in order to determine vertical temperature profiles. Assume that the only significant absorption in the observed frequency range comes from a single vibrational CO_2 transition. The strength of the transition is such that the transmission at the line centre trough the troposphere is very close to 0.

a Show that the absorption at the line centre is relatively constant with altitude, as long as the impact of Doppler broadening can be neglected. (3 p)

b Show that the absorption in the far wing region is proportional to P^2, where P is the pressure. (2 p)

c Make a sketch of a typical measurement spectrum. Treat the surface to be a blackbody. Include an approximation of minimum and maximum observed brightness temperature. (2 p)

d Make a sketch of the weighting functions for some frequencies at different distances from the line centre. (3 p)

5. The human vision (10 p)

The human vision can be seen as a remote sensing system:

- a Give two reasons to why it is most favourable for the human eye to observe the world at wavelengths around 550 nm. (1 p)
- b Estimate the wavelength resolution of the human vision. (1 p)
- c How does the color of the light and the intensity of the scene affect the spatial resolution of the human eye? (1 p)
- d Estimate at what distance the human vision can resolve objects of the size of a golf ball (45 mm). (1 p)
- e Discuss, how atmospheric propagation and other conditions for the scene observed, affect the ability to perceive the golf ball. (2 p)
- f Given that the size of the fovea centralis (gula fläcken) is 1.5 mm and contains around 5 million detectors (cones), determine if the eye is over- or under-sampled. (2 p)
- g Discuss the performance of the human vision from an image processing / retrieval perspective. (2 p)

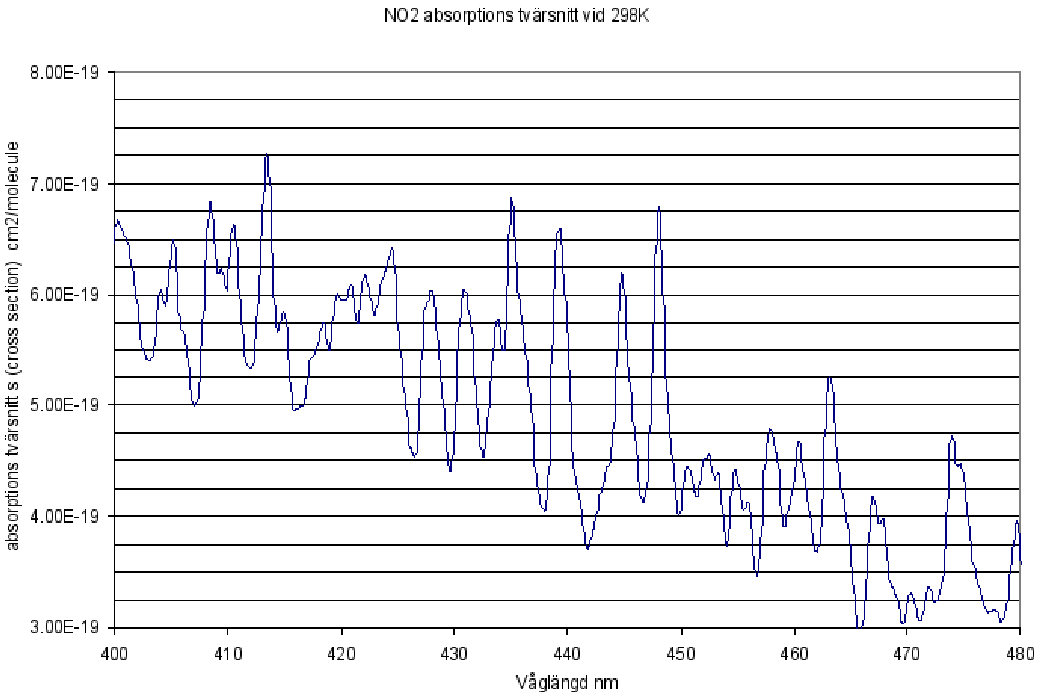


Figure 1: Full absorbtion cross section (cm^2/molecule) for NO_2 at 298 K.

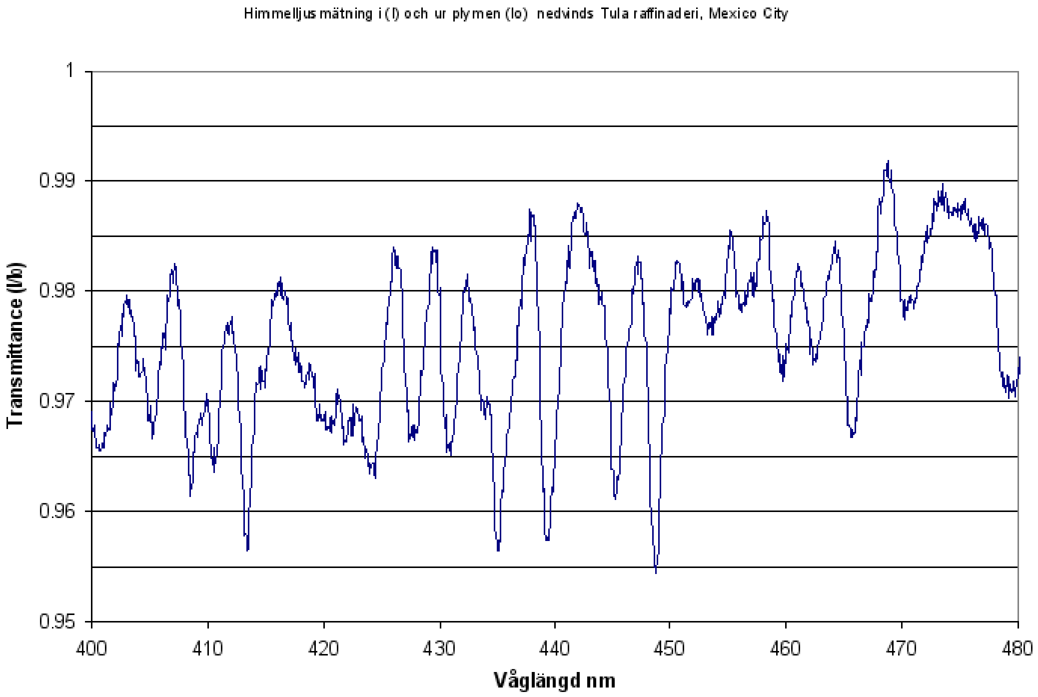


Figure 2: A transmission spectrum of NO_2 measured in the gasplume, downwind a powerplant. The spectrum corresponds to a zenith sky spectrum in the gasplume divided to one measured outside the plume.

Formulae

Solid angle of an unit sphere

$$\int \mathrm{d}\Omega = 2\int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi}\sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi = 4\pi$$

Ideal gas law

$$N = \frac{PV}{k_B T}, \qquad \frac{\rho T}{P} = \frac{M}{R}$$

Energy of a photon

$$E = hf$$

Wavenumber as spectroscopic unit

$$\tilde{\nu} = 1/\lambda$$

Stokes Vector

$$\begin{aligned} \mathbf{s} &= [S_0\ S_1\ S_2\ S_3]^T \\ S_0 &= \langle E_{0x}^2\rangle + \langle E_{0y}^2\rangle \\ S_1 &= \langle E_{0x}^2\rangle - \langle E_{0y}^2\rangle \\ S_2 &= \langle 2E_{0x}^2 E_{0y}^2 \cos(\phi_y - \phi_x)\rangle \\ S_3 &= \langle 2E_{0x}^2 E_{0y}^2 \sin(\phi_y - \phi_x))\rangle \end{aligned}$$

Degree of polarisation

$$\frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

Refractive index

$$n = n' - in'' = \sqrt{\epsilon_r}$$

Angular frequency

$$\omega = 2\pi f$$

Complex (angular) wavenumber

$$k = \frac{\omega n}{c}$$

Absorption length

$$l_a = \frac{c}{2\omega n''} = \frac{1}{\gamma_a}$$

Snells law

$$n_1' \sin(\theta_1) = n_2' \sin(\theta_2)$$

Fresnel coefficients ($\varepsilon_1 = 1$)

$$\begin{aligned} \Gamma_\perp &= \frac{\cos(\theta_1) - \sqrt{\epsilon_{r2} - \sin^2(\theta_1)}}{\cos(\theta_1) + \sqrt{\epsilon_{r2} - \sin^2(\theta_1)}} \\ \Gamma_\parallel &= \frac{\sqrt{\epsilon_{r2} - \sin^2(\theta_1)} - \epsilon_{r2}\cos(\theta_1)}{\sqrt{\epsilon_{r2} - \sin^2(\theta_1)} + \epsilon_{r2}\cos(\theta_1)} \\ r &= |\Gamma|^2 \end{aligned}$$

Irradiance / Exitance

$$E \,\mathrm{or}\, M = \int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi} L\cos(\theta)\sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi$$

BRDF / surface reflectivity

$$\begin{aligned} L(\theta_1, \phi_1) &= R(\theta, \phi, \theta_1, \phi_1) F(\theta, \phi)\cos(\theta) \\ M &= r(\theta, \phi) F(\theta, \phi)\cos(\theta) \\ r(\theta, \phi) &= \int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi} R\cos(\theta)\sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi \end{aligned}$$

Blackbody radiation

$$B(f, T) = \frac{2hf^3}{c^2}\frac{1}{e^{hf/k_B T} - 1}$$

Rayleigh-Jeans approximation

$$(hf/k_B T \ll 1) \Rightarrow$$
$$B(f, T) \approx 2k_B T f^2/c^2$$

Absorption coefficient

$$\gamma_a = N\sigma_a = N\left\{\sum [sF] + \sigma_{\mathrm{cont}}\right\}$$

Doppler broadening

$$\begin{aligned} F_d &= \frac{1}{\sqrt{\pi} w_d}\exp(-((f - f_0)/w_d)^2) \\ w_d &= \frac{f_0}{c}\sqrt{\frac{2RT}{M}} \end{aligned}$$

Pressure broadening

$$\begin{aligned} F_p &= \frac{1}{\pi}\frac{w_p}{(f - f_0)^2 + w_p^2} \\ w_p &= w_0 P\left(\frac{T}{T_0}\right)^{-n} \end{aligned}$$

Scattering coefficient

$$\gamma_s = N\sigma_s$$

Rayleigh scattering

$$\sigma_s = \frac{128\pi^5 d^6}{3\lambda^4}$$

Optical thickness

$$\tau(l_1, l_2) = \int_{l_1}^{l_2}\gamma(l)\mathrm{d}l$$

Beer-Lambert's law

$$I = I_0 \exp(-\tau)$$

DOAS

$$N = \frac{ln(I_1/I_2)}{h[\sigma(\lambda_2) - \sigma(\lambda_1)]}$$

Radiative transfer without scattering

$$\begin{aligned} I(h) &= I_0 e^{-\tau(0,h)} + \int_0^h \gamma_a B e^{-\tau(l,h)} \mathrm{d}l \\ T_b &= T_b^0 e^{-\tau(0,h)} + \int_0^h \gamma_a T e^{-\tau(l,h)} \mathrm{d}l \\ I^{out} &= I^{in} e^{-\tau} + B(1 - e^{-\tau}) \end{aligned}$$

Photographic scaling factor

$$s = \frac{f}{h}$$

f/number

$$f/number = \frac{f}{D}$$

Photogrammetry

$$x' = -\frac{fx}{h-z}, \qquad y' = -\frac{fy}{h-z}$$

Michelson interferometry

$$\begin{aligned} I &= \frac{I_0}{2}\left[1 + \cos(2kl)\right] \\ V &= \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \\ I(l) &= \int_0^\infty I(f)\cos(2\pi l f/c)\mathrm{d}f \end{aligned}$$

Diffraction limited angular resolution

$$\sin(\theta) \geq \frac{\lambda}{D}$$

Antenna relationships

$$\begin{aligned} G &= \eta D_0 = \eta \frac{4\pi}{\Omega_A} \\ \Omega_A &= \frac{\lambda^2}{A_e} \end{aligned}$$

Radiometer sensitivity

$$\Delta T_b = C \frac{T_{sys}}{\sqrt{\Delta f \Delta t}}$$

Noise power

$$P_N = k_B B T_a$$

Footprint of radar altimeter

$$r = \sqrt{ch\Delta t}$$

Radar equation

$$\frac{P_r}{P_t} = \frac{\lambda^2 G^2}{(4\pi)^3 \eta h^4} \sigma^o A$$

Radar Doppler shift

$$f_D = -2v_r/\lambda$$

Weighting functions

$$\begin{aligned} y &= \int_0^h K(z)x(z)\mathrm{d}z + \varepsilon \\ \mathbf{y} &= \mathbf{Kx} + \varepsilon \end{aligned}$$

Optimal weighting

$$\begin{aligned} \hat{x} &= \frac{\sigma_2^2 x_1 + \sigma_1^2 x_2}{\sigma_1^2 + \sigma_2^2} \\ \hat{\sigma} &= \frac{\sigma_1 \sigma_2}{\sqrt{\sigma_1^2 + \sigma_2^2}} \end{aligned}$$

Answers to exam in Remote Sensing 2008-03-13

Question 1:

a The sun-synchronous orbit is a low earth orbit (LEO), usually with an altitude between 500 and 1000 km and with an inclination close to 90 degrees (= polar orbiting). The orbit precesses ("rotates") about the Earth axis at the same rate that the Earth orbit the Sun. This has the advantage that the orbit will cross the same latitude at the same local solar time, regardless of the longitude or the date. Solar panels do not have to be rotated to give the optimal angle towards the sun. The polar orbit can give (nearly) global coverage (depending on orbit inclination and sensor swath width). For earth observation, the relatively low altitude give better spatial resolution than orbits at higher altitudes.

b
- Vibrations and acceleration during launch
- Failure of launcher (loss of satellite or wrong orbit insertion)
- Large temperature differences
- Radiation
- Cosmic particles and the Van Allen belts
- Electrostatic discharge
- Micro meteorites and space debris
- Malfunction of satellite systems or sensors (repair not possible, redundant systems used when possible)

c Direct downlink = data is transmitted from the satellite to a ground station directly after it has been acquired by a sensor. This is only possible when the line of sight between the satellite and the ground station is not obscured. The elevation angle between the line of sight and the horizon should also be large enough that atmospheric degradation of the signal is not significant. These requirements define the size and shape of the station mask for each ground station.

When the satellite is not within the station mask of any ground station there are two alternatives:

- the data can be stored onboard and be transmitted later
- the data can be transmitted via a relay satellite to a ground station

From the ground station the data is transferred either directly to the user (near real time delivery) or to an archive from which users can order data later.

The amount of data that can be transferred from the satellite is limited by:

- availability of suitable ground stations
- availability and size of onboard data storage
- availability of suitable relay satellites
- bandwidth for data transmission

d
- weather forecasting
- sea-ice monitoring for ship routing
- oil spill detection
- ship detection and surveillance
- assessment of danger and disaster (earth quake, volcano eruption, tsunami, flooding, land slide, forest fire, storm damage

Question 2:

a The methodology is as follows. We are hence using the ratio between two nearby absorption lines to derive the amount of NO_2 in the measured spectrum. Here we use the absorption structures around 430 nm with an absorption cross section that varies between $6 \cdot 10^{-19}$ and $4.5 \cdot 10^{-19}$ cm^2/moleules as can be seen in the figure provided. The differential absorption cross section is here $\Delta\sigma = 1.5 \cdot 10^{-19}$ cm^2/molecule. In the measured intensity/transmittance spectrum it can be seen that the intensity is 0.9675 and 0.984 for the corresponding intensities (note that they are reversed). The Beer-Lambert law hence yields:

$$\ln(0.9675/0.984) = -0.017 = -\Delta\sigma cx = 1.5 \cdot 10^{-19} cx$$

that gives

$$cx = 0.017/1.5 \cdot 10^{-19} = 1.21 \cdot 10^{17}$$

The answer is thus $1.21 \cdot 10^{17}$ moleules/cm^2.

b In the UV visible region there is conserable light extinction due to light scattering on molecules (Rayleigh scattering) and particles (Mie scattering). The light scattering varies fairly slowly with wavelength. There is also spectral interferences between different absorbing gas species. To overcome this problem, differential methodology is applied in which spectra are high pass filtered and only the part of the spectrum that varies rapidly with wavelength is used. Usually the filtering is conducted by fitting a low order polynomial to the spectrum. Instead of highpass filtering it is possible to use the ratio between two nearby absorption lines to estimate the number of molecules in a spectrum. It is then assumed that the wavelengths are so close so that the scattering is similar for both wavelengths

c The flux of gas corresponds to the column*plumewidth*windspeed. Hence the flux is $1.1 \cdot 10^{17}$ [mol/cm2] * ($40*1 \cdot 10^2$) [cm] * ($10*1 \cdot 10^2$) [cm/s] = $4.4 \cdot 10^{23}$ molecules/s. The weight of NO_2 is (14+2*16)u = 46u = $7.6 \cdot 10^{-26}$ kg. Hence the massflux is $4.4 \cdot 10^{23}$ * $7.6 \cdot 10^{-26}$= 0.033 kg/s.

Question 3:

a $\rho = \frac{c}{2B} = 7.5$ m

b Distance in slant range to the nearest point in the swath:

$$R_{near} = \sqrt{8^2 + 10^2} = 12.8 \text{ km}$$

And to the furthest point:

$$R_{far} = \sqrt{8^2 + 15^2} = 17 \text{ km}$$

The condition on the PRF is that echoes from consecutive pulses should not overlap, i.e. longer time between pulses than between possible echoes from one pulse.

$$\frac{1}{PRF} > \frac{2R_{far}}{c} - \frac{2R_{near}}{c} \Rightarrow PRF < \frac{c}{2(R_{far} - R_{near})} = 35.7 \text{ kHz}$$

c Distance from antenna to the sphere is $h = ct/2 = 14.2$ km. Use the radar equation to calculate the radar cross section of the sphere.

$$\frac{P_r}{P_t} = \frac{\lambda^2 G^2 \sigma}{(4\pi)^3 \eta h^4} = \frac{\lambda^2 \sigma}{(4\pi)^3 \eta h^4} \left(\eta \frac{4\pi A_e^2}{\lambda^2} \right)^2 = \frac{\sigma \eta A_e^2}{4\pi h^4 \lambda^2} \Rightarrow \sigma = 1.15 \text{ m}^2$$

d In the bistatic radar equation, the factor h^4 is replaced with $h_1^2 h_2^2$ representing the two distances from the antennas to the target.

$$\frac{P_r}{P_t} = \frac{\sigma \eta A_e^2}{4\pi h_1^2 h_2^2 \lambda^2} \Rightarrow h_2 = 15.8 \text{ km}$$

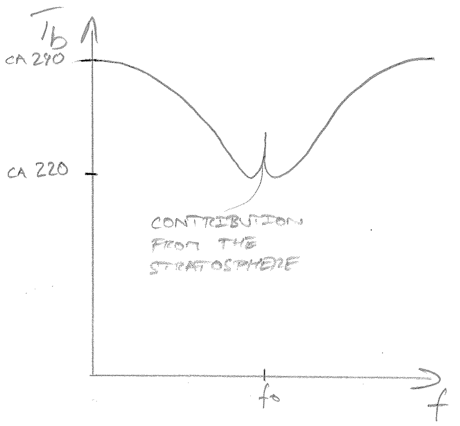
Question 4:

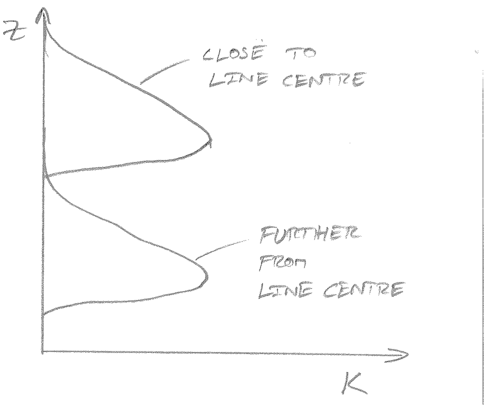
a The absorption can be written as $\gamma_a = NsF$. All temperature variations are here neglected. The line instensity, s, is then constant, and the number of molecules, N, is proportional to P. The line shape is at the line centre $1/(\pi w)$, that is proportional to P^{-1} as the line width, w, is proportional to P. This gives that $\gamma_a$has no pressure dependency.

b As above, but now $F \sim w$. Both N and F are then proportional to P. This gives that $\gamma_a \sim P^2$.

c See sketch below. The temperature far from the line centre approaches the surface temperature. That is ~ 290 K. The minimum temperature is somewhat above the tropopause temperature.

d See sketch below.





Question 5:

a The intensity of solar radiation is here highest. This is also the atmospheric window of shortest wavelength, and thus provides the best reolution for a fixed size of the eyes.

b There is no general definition of resolution. Two alternatives:

- The visible range is about 300 nm wide and the eyes have three types of "cones". The wavelength resolution can thus be said to be 100 nm.

  - We can distinguish not more than 20 colors in the rainbow. The wavelength resolution can thus be said to be about 20 nm.

  In any case, the wavelength resolution shall not be confused with the capacity to distinghuish the intensity of the light. That is, that can seperate between about 200 intensity levels (for each “color channel”).

c The resoluton is best for blue wavelengths (shortest). The pupil size decreases with increasing light intensity, and the resolution is then deteriorated.

d Some reasonable assumptions could be a pupul size of 4 mm and a pre-factor of 1.22 for the λ/D relationship. This gives $45 \cdot 10^{-3} \cdot 4 \cdot 10^{-3}/(1.22\lambda) \approx 250\,\mathrm{m}$ for 600 nm.

e A first condition is that the sun is above the horizon. Both the solar zenith and azimuth angles are important. Thick clouds decreases the light intensity to be reflected. Haze and fog decrease the radiation reflected by the golf ball. The properties of the material surrounding the golf ball is important. A highly reflective or white material will make it much harder to distinguish the golf ball. For example, compare the cases if the golf ball lies on top of snow or (short) grass.

f If 5 million detectors are evenly distributed (not entirely true) in the fovea centralis, which could be approximated by a 1.5×1.5 mm square, this gives a distance between two detectors of around $1.5 \cdot 10^{-3}/\sqrt{5 \cdot 10^{6}} \approx 0.7\mu$m. The resolution from diffraction (on the retina), if assumed a small viewing angle (distant object), is given by $1.22\lambda f/D$, where f is the focal length of the eye (≈4 cm). This gives around 7μm at wavelength 600 nm. Hence the human eye is over-sampled by approximately a factor of 10.

g Many things can be discussed here such as:

  1. The image is formed in the brain
  2. Parallell processing unit regarding speed, color, shape, direction...
  3. A priori information is added
  4. Automatic edge-enhancement filter (lateral inhibition)
  5. Night vision (especially the rods)
  6. Stereography gives better distance perception

  The student should mention nr 1 and 3 together with at least one more