Photographic Systems

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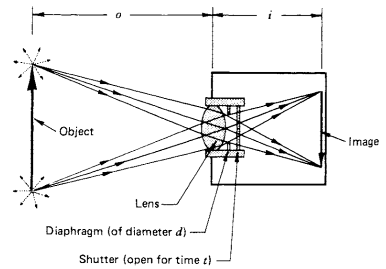
Cameras

- Scheme of acquisition



- Two types of camera
  - Analog (acquisition on film)
  - Digital (acquisition by CCD)
- Analog cameras important and still much used until a few years ago, and still have some advantages
- Most of the applications nowadays use digital cameras.

Analog Cameras

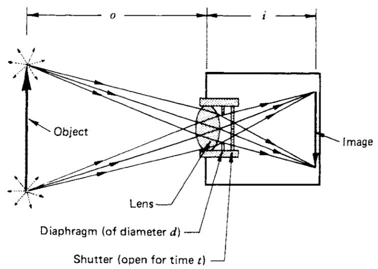
- Pros:
  - Geometric resolution
  - Simple to build
  - Reliable
  - Good for situations where the spatial resolution and geometric precision is more important than radiometric/spectral resolution
- Cons:
  - The film needs to be physically recollected and developed
  - **Data handling** much uncomfortable (needs digitization)
  - They can only be used up to near infrared
  - ... Archiving (this actually has pros and cons)

Digital Cameras

- Pros:
  - They allow the transmission of images (essential for satellite systems)
  - They can be used also in the thermal infrared
  - They give numerical data directly available to be handled on a computer, from which precise information on radiative parameters can be extracted
- Cons
  - Less reliable
  - Need careful calibration of the sensors
  - .... Archiving (in some cases)

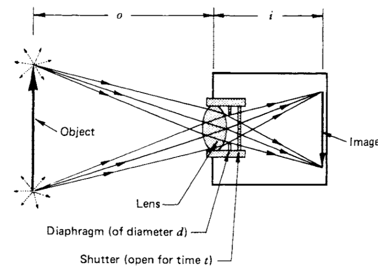
Scheme of acquisition

Main Components



- Lens: it focuses light rays on the image plane
- Diaphragm: it determines the lens opening during the exposure
- Shutter: it controls the duration of the exposure

Focal length



We have three main parameters

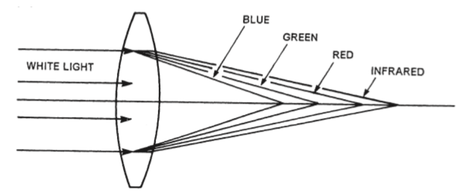
- o: distance from lens to object
- i: distance from lens to image plane
- f: focal length of the lens, which relates i and o according to

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i}$$

Focal length

- Since f is constant, objects at different distances generate images at different distances i
- The camera usually moves the lens in order to keep the image in a fixed position (focused)
- If the object o is very far, however, we see that taking the limit $o \to \infty$, we have
$$\frac{1}{i} + \frac{1}{o} \approx \frac{1}{i}$$
which implies $i \approx f$.
- Hence, the focal length is the distance from the lens of the image generated by an infinitely far object
- In remote sensing applications we can always assume this approximation to be extremely precise.

Chromatic Aberration



- As seen in previous lectures, the refractive index of a material usually depends on the wavelength
- Hence, a single homogeneous lens will act in a different way to different wavelengths of the light
- This results in *chromatic aberration*, that is, different colors are focused on different planes
- To contrast this phenomenon, thin lenses of different refractive properties are combined to get the final one

Photographic Systems

Exposure and f-stop

- Assume we have an object which is seen under a solid angle Ω with radiance L at our lens, so that the total irradiance at the lens is ΩL
- If D is the lens diameter, the total irradiant flux on the lens is

$$\pi \left(\frac{D}{2}\right)^2 \Omega L$$

- It there is no loss in the lens, this flux is distributed on an image portion with surface Ωf^2, with an irradiance on the film (or CCD array) given by the expression

$$\pi \left(\frac{D}{2}\right)^2 \frac{L}{f^2}$$

Photographic Systems

Exposure and f-stop

- The exposure at any point in the film focal plane of a camera is determined by the irradiance at that point multiplied by the exposure time t, that is

$$E = \frac{\pi L}{4} \left(\frac{D}{f}\right)^2 t$$

- Here
  - The lens opening D is regulated by the diaphragm
  - The exposure time is regulated by the shutter
- The f-stop is defined as the ration

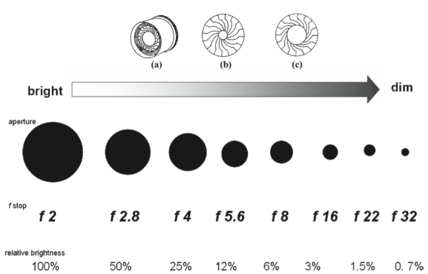
$$F = \text{f-stop} = f/D$$

- The exposure is then usually regulated by specifying the exposure time t and the f-stop

Photographic Systems

Exposure and f-stop

- The f-stop can usually be increased by powers of $\sqrt{2}$

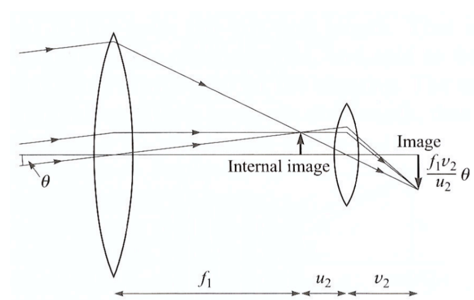


- The exposure time can be changed by powers of 2 ($\frac{1}{125}$ sec, $\frac{1}{250}$ sec, ...)
- This allows to keep a constant exposure with different exposure time

Photographic Systems

Composite lenses

- Real cameras use combination of lenses to obtain different focal lengths



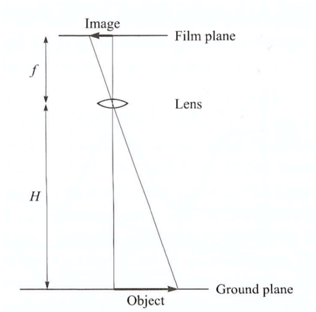
- This combination of lenses behaves like a single lens with focal length

$$f_1 \frac{v_2}{u_2}$$

Photographic Systems

Scale

- The scale is the ratio between the linear extension of an object in the formed image and its real size

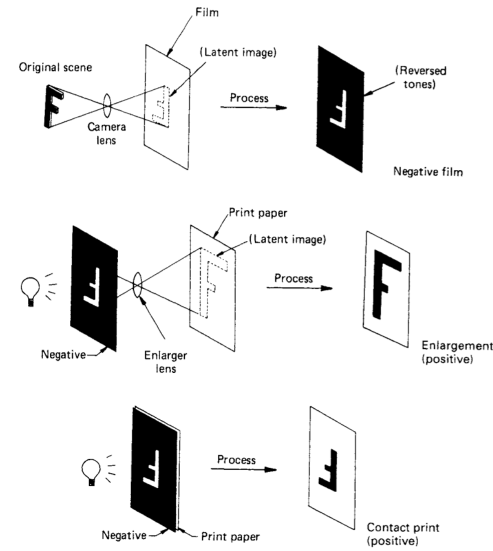


- Simple geometric consideration show that the scale is given by f/H
- Notation: scale 1:(H/f). For example 1:20.000

Analog Cameras

Negative-to-positive

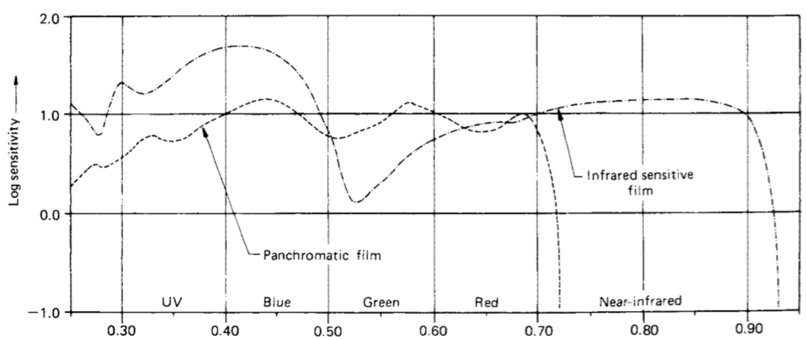
- The film contains different layers of emulsions sensible to different wavelengths
- The film is then developed by mean of chemical processes to generate a negative of the image
- The negative is then used to generate a positive printed image or transparency
- Two main types of film: black and white or color



Analog Cameras

Black and white photographs

- Black and white photographs are usually made with either *panchromatic* or *infrared-sensitive* films.



- It is very difficult to build films sensitive above 0.9μm and this has been done only for certain scientific experimentation (up to 1.2μm)

Analog Cameras

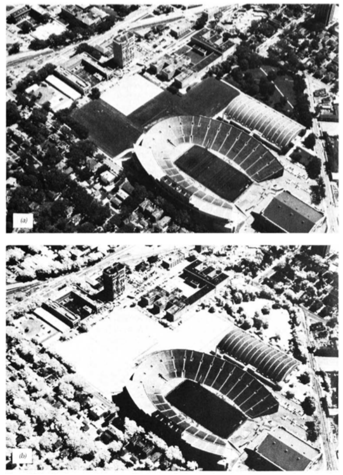
Black and white photographs: example

- IR images can be very useful to distinguish different type of environmental elements which are not easily seen by the human eye
- In the example, we see that the IR image gives very useful information on water and wet soil (which are typically much darker than vegetation in the IR region)

Analog (or digital) Cameras

Filters

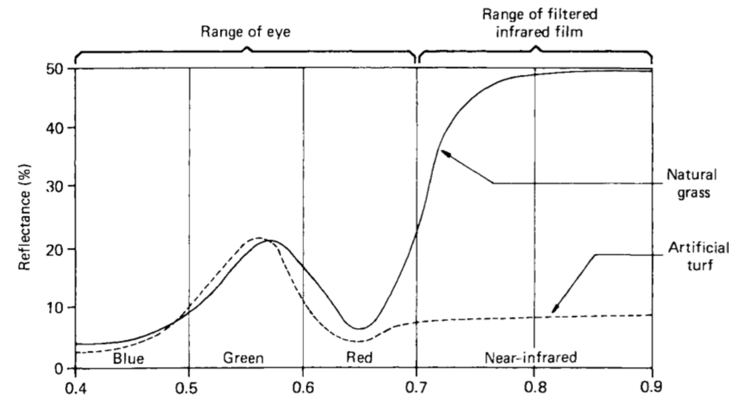
- In addition to the choice of the film, it is possible to apply filters to the camera lens to only acquire in some given region of the spectrum
- In the example, we see an example using a filter that only preserves wavelengths above 0.7μm.
- Artificial turf can be easily distinguished from natural grass



Analog Cameras

Filters

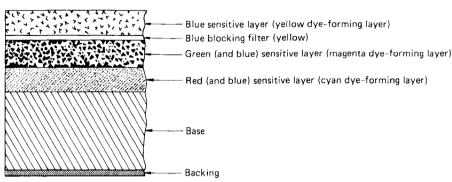
- In fact...



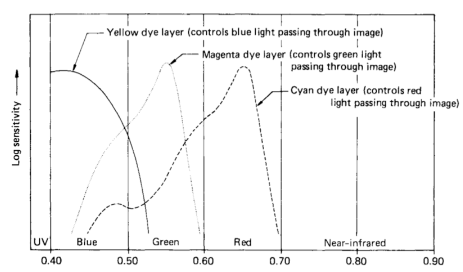
Analog Cameras

Color film

- Color films contain different layers

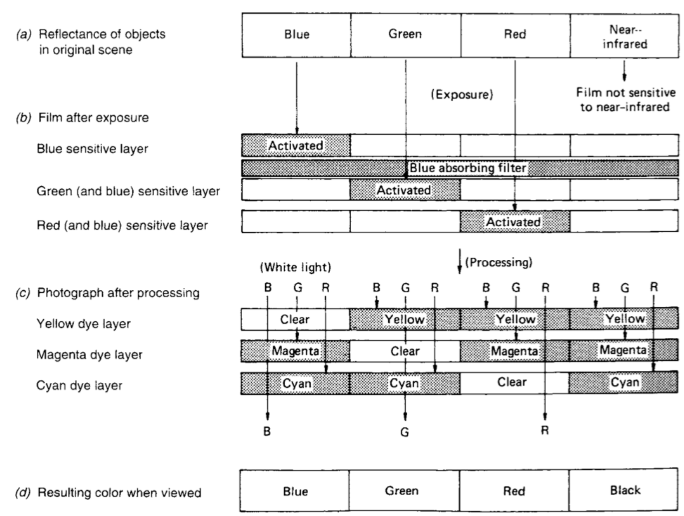


- ... with different sensitivities



Analog Cameras

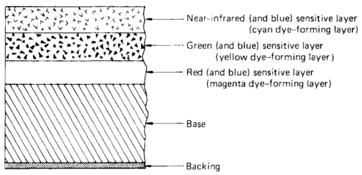
Color photograph formation



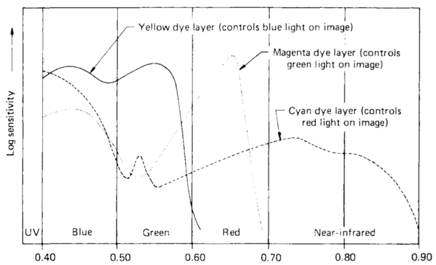
Analog Cameras

Color infrared film

- Again different layers

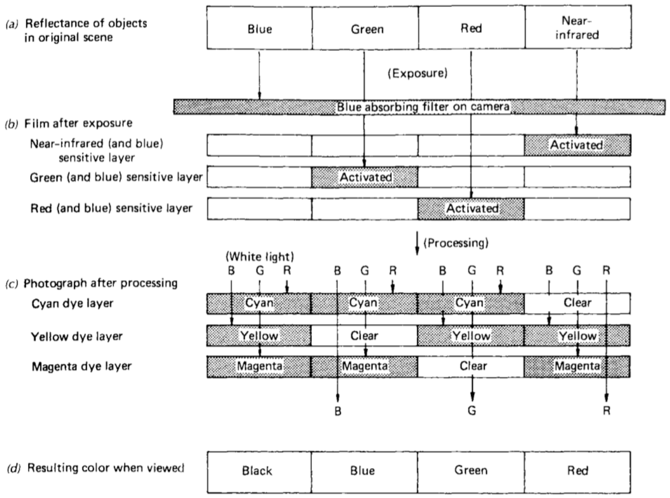


- ... with different sensitivities



Analog Cameras

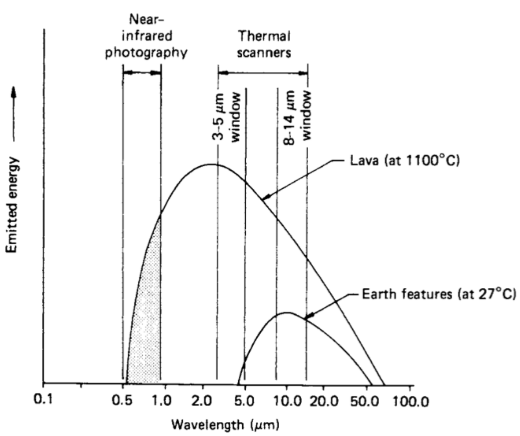
Color infrared photograph formation



Analog Cameras

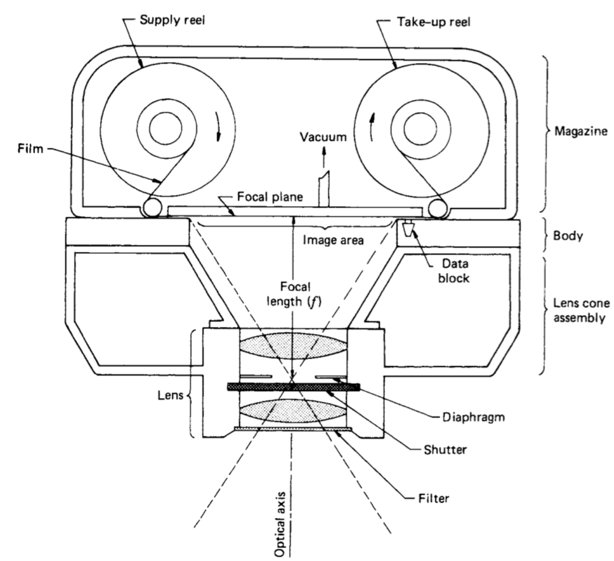
Other applications of infrared sensitive films

- Some natural phenomena at high temperatures can be studied in the near-IR by means of the emitted radiation (not sun-reflected light)



Aerial Photography

Analog mapping cameras



Mapping cameras: some technical characteristics

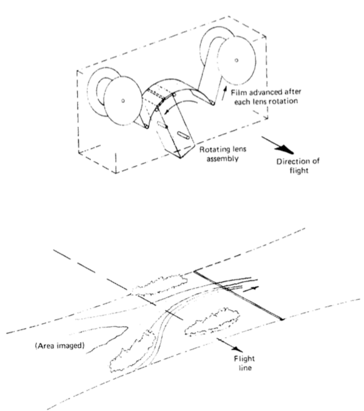
- The film image size is usually 230×230mm. The total film size is usually 240×240mm, additional data are written on the film other than the picture (clock, altimeter, etc..)

Mapping cameras: some technical characteristics

- Usually the focal length is 152mm for mapping purposes, but lenses with 90 and 210 mm focal lengths are also used.
- Longer focal lengths, such as 300 mm, are used for very high altitude applications.
- Frame camera lenses are somewhat loosely termed as being (angles measured along image diagonal)
  - *normal angle*: when the angular field of view of the lens system is up to 75°
  - *wide angle*: when the field of view is 75 to 100
  - *superwide angle*: when the field of view is greater than 100.
- The duration of exposure can vary from 1/1000 sec to 1/100 sec.
- To compensate the image shift during the time the shutter is open, many camera have a built-in image motion compensation apparatus which moves the films to avoid blur.

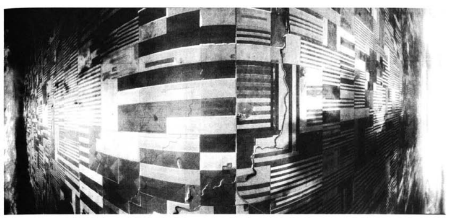
Panoramic Cameras

- A panoramic camera is characterized by having a lens with a small angular view which acquires though a narrow slit
- The lens is however physically made to rotate so as to acquire a very large area in the across-flight direction



Panoramic Cameras

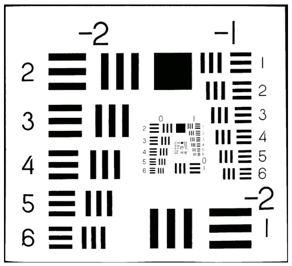
- The main advantage of these cameras is that they provide very detailed images (due to the narrow slit) of very large areas (due to the swinging of the lens)
- Often used at very high altitudes to cover a huge area
- They have been used for example on the Apollo mission to photograph more than half the moon surface
- Disadvantages: lack of geometric fidelity, different illumination and atmospheric distortions in different portions of the image



Aerial Photography

Film Resolution

- The resolution of an acquisition system is affected by different components of the system (lens, motion compensation, aircraft stability, atmospheric conditions etc)
- Some of these elements can be quantified, for example by photographing a test chart like the one below



Aerial Photography

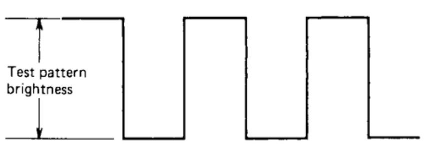
Film Resolution

- Usually the “resolution” of a film is defined as the number of lines (or lines pair, i.e., black-white alternations) per mm that can be “distinguished”
- The resolution of a film depends on the size of the used crystals, usually for aerial photography the resolution is from 20 to 200 lines per mm, i.e., details are “distinguishable” at a distance from 25 down to 2.5μm on the film.
- Larger crystals are more sensitive and thus allow for low exposure time (they are faster) and/or require less illumination, but they also give lower resolution
- The above definition, however, is obviously not too rigorous since ‘distinguishable” is never clearly defined
- Another characterization can be given by using the modulation transfer...

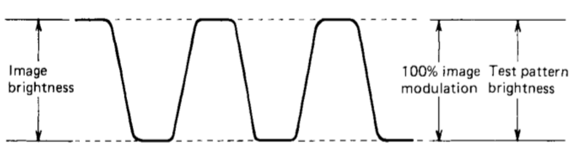
Aerial Photography

Modulation Transfer Function

- Take an input sequence of black and white lines of a given size
- Measure the *modulation*, that is the ration between the contrast obtained on the film and the contrast of the original pattern



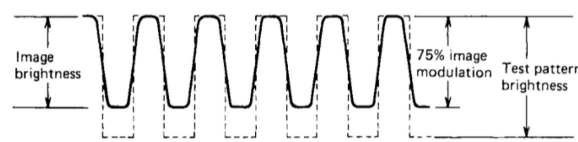
(a)



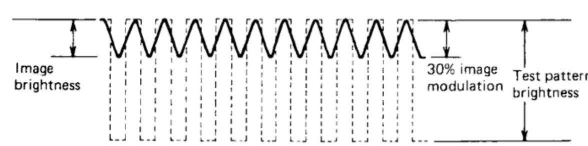
Aerial Photography

Modulation Transfer Function

- Then increase the pattern spatial frequency and see what happens to the modulation

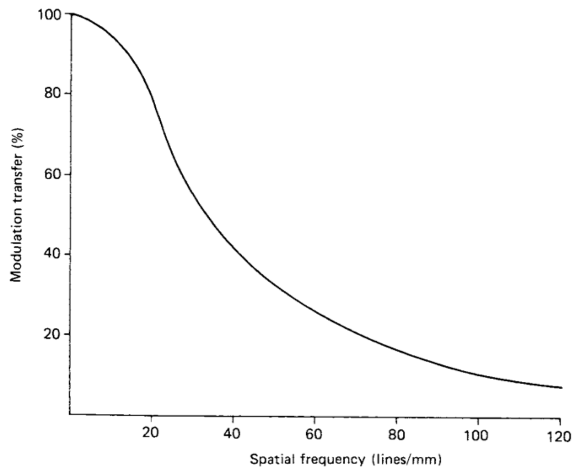


(c)



Modulation Transfer Function

- We get a modulation as a function of the pattern spatial frequency



Ground Resolution

- From the film resolution we can deduce the *Ground Resolution Distance* (GRD), that is the minimal distance on the ground between two "distinguishable" objects
- We need to consider the scale, and we obtain

$$\text{GRD [mm]} = \frac{\text{scale}^{-1}}{\text{film resolution [mm}^{-1}]}$$

- Example:
  - Altitude $H = 1000$ m
  - Focal length 152 mm
  - Film resolution 100 lines/mm

$$GRD = \frac{1000}{0.152 \cdot 100} = 65\text{mm}$$

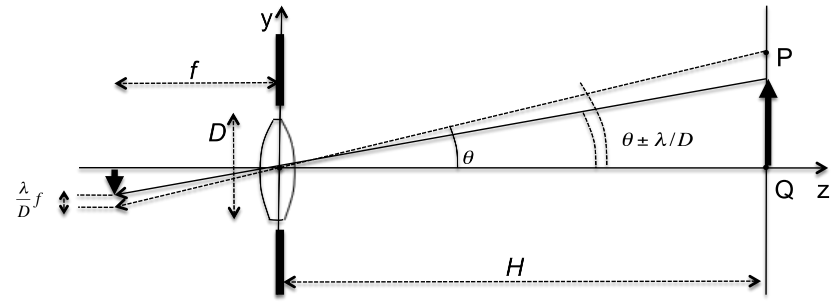
  - But... diffraction! See later

Resolution

- Note that a 23×23cm film with resolution of 100 lines (pairs) per mm contains something like $(200 \cdot 230)^2 \approx 2.1$ Gigapixels.
- An analog film can be as long as 120m, that means around 500 photographs. This means something like at least 1 Terabyte of data.
- Consider the problem of archiving Terabytes of data for tens of years... magnetic tapes are preferred in this case.
- This makes clear that analog aerial photograph may still have something to say.

Resolution: Diffraction

- The resolution of a system is not always determined by the resolution of the film; diffraction plays an important role.
- We have seen that with an aperture of diameter D the angular resolution of any acquisition system is limited by λ/D due to the Fraunhofer diffracion, where λ is the wavelength



Aerial Photography

Resolution: Diffraction

- This leads to a resolution of about

$$\frac{\lambda}{D} f$$

  on the film plane.
- Hence, if $\frac{f\lambda}{D}$ is larger than the spacing between distinguishable lines on the film, then the resolution of the systems is not determined by the film but by the diffraction phenomenon
- Example
  - A lens of diameter $D = 1$cm, focal length 15cm, wavelength $\lambda \approx 0.5\mu$m.
  - We get $\frac{f\lambda}{D} \approx 7.5\mu$m
  - Hence, more than 70 lines/mm are useless on the film, the resolution is determined by diffraction

Aerial Photography

Digital Cameras

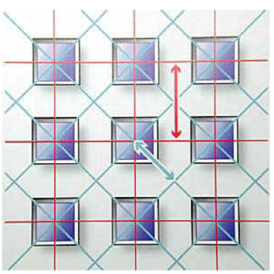
- The use of a digital camera is the same as for an analog one, but the image is acquired by a CCD array rather than by a film
- In general, for a color “photograph” different colors are sampled in different positions on a regular grid

G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G

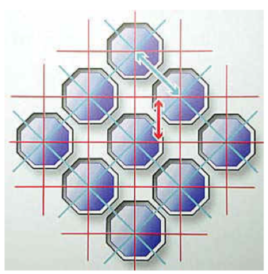
Aerial Photography

Digital Cameras

- There are different possible solutions for the grid
- And different possible solutions for the color patterns



Typical CCD array

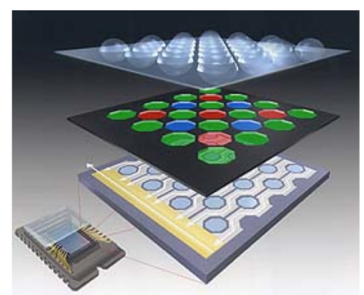


Fuji Super CCD

Aerial Photography

Digital Cameras

- Each light-sensitive pixel is identical, image sensors record only the gray scale. Basically, they only capture brightness.
- In order to get colour, coloured filters are added in front of the sensors.



Digital Cameras: resolution

- For a digital camera, the resolution can be defined in a very simple way by specifying the distance between two sensors (well... not really for color photographs)
- Moderns digital aerial photography cameras can incorporate more than one sub-cameras shooting pictures with tens of Megapixels each, that can then be recombined to generate a larger image
- Usually, for digital aerial photography camera it is useful to specify the *ground pixel* size, that is the side of a square of land surface which is mapped to one single pixel in the digital image
- This is the same as the linear *Istantaneous Field Of View* IFOV. If the sensors are spaced by d mm, the IFOV is

$$IFOV_{linear}[mm] = \frac{d}{\text{scale}}$$

Examples of cameras

- Typical analog camera for airborne photography
  - Film 23×23cm
  - focal length $f = 15.2$cm
  - Resolution 50 lines/mm
  - Reel of 500-1000 images
  - At an altitude of 3000 meters, the FOV is 4.6Km and the IFOV is 0.2m
  - These images can be used to creat maps with scales up to 1:500
  - The height resolution can be computed as $\approx H/1000$ as 3m

Examples... from space

- Metric Camera (Spacelab-1, 1983)
  - Spacecraft at an altitude of 250Km
  - Film 23×23cm (different with respect to airborn missions)
  - focal length $f = 30.5$cm
  - Resolution 35 lines/mm
  - FOV is 190Km and the IFOV is 12m
  - These images can be used to creat maps with scales up to 1:50000
- KFA-1000 (Russian space station Mir)
  - Altitude 350Km
  - Film 30×30cm
  - focal length $f = 1$m
  - Resolution 35 lines/mm
  - FOV is 100Km and the IFOV is 20m

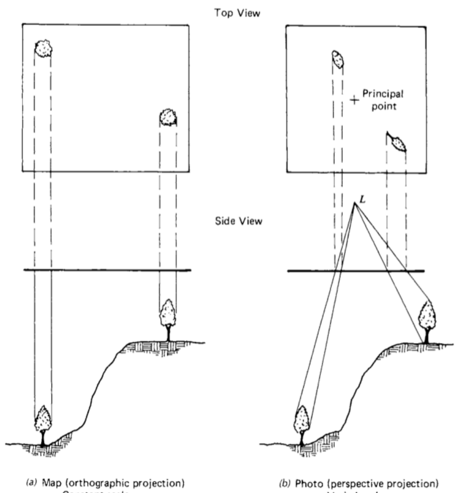
Examples... from satellite

- Corona, Argon e Lanyard (American satellites,1960-70)
  - Very low orbits, $\approx$ 150Km
  - Film 55×76cm
  - focal length $f = 61$cm
  - Resolution 160 lines/mm
  - FOV is 14×19Km and the IFOV is 1m
  - Capsules with the images were ejected and picked by airplanes at high altitudes (?!?)

Aerial Photography

Relief Displacement

- An important phenomenon in aerial photography is the so called *relief displacement*



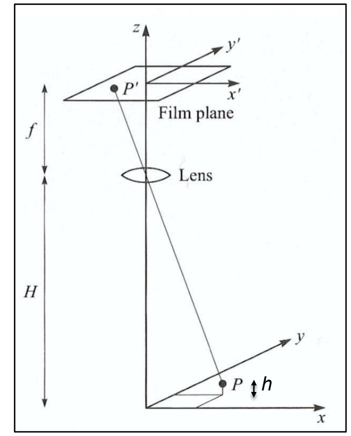
Aerial Photography

Relief Displacement

- A point $P = (x, y, z)$, with $z = h$, is mapped by the photograph to a point $P' = (x', y', z')$ with

$$x' = -\frac{fx}{H-h}$$
$$y' = -\frac{fy}{H-h}$$
$$z' = H + f$$

- Let's now study what happens when we consider P moving vertically

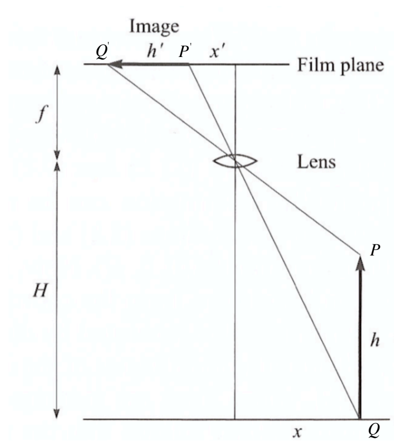


Aerial Photography

Relief Displacement

- Forget about the y component, and consider the situation in figure
- By applying the previous computations both for P and Q we get

$$\begin{aligned} h' &= -\frac{fx}{H-h} - \frac{fx}{H} \\ &= -\frac{hfx}{H(H-h)} \\ &= \frac{hx'}{H-h} \\ &\approx h\frac{x'}{H} \end{aligned}$$



Aerial Photography

Relief Displacement: Photogrammetry

- We thus observe a proportional factor x'/H between h and h'
- This clearly holds also on differences, that is, $\Delta h' \approx \Delta h \frac{x'}{H}$.
- We can use this phenomenon to study the height of targets
- As intuition suggests, the displacement is larger for points far from the focal axis
- We can determine the resolution in the detectable heights we can make x' to its largest value, say $w/2$ for a $w \times w$ image, to get

$$\Delta h \approx \frac{2H\Delta h'}{w}$$

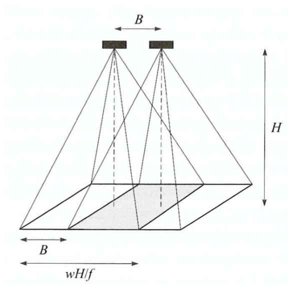
- In a typical system with $w = 23\text{cm}$ and $\Delta h' \approx 0.1\text{mm}$, from which

$$\Delta h \approx H/1000$$

Aerial Photography

Stereogrammetry

- The displacement phenomenon can be used efficiently by combining two different photographs
- Assume we take two pictures, one from position $(0, 0, H)$ and another from position $(B, 0, H)$



- Let's see how the point position changes in the two pictures according to its altitude

Aerial Photography

Stereogrammetry

- The same point P as before will appear in the second picture with $y'_2 - y'_1$ but x'_2 given by

$$x'_2 = -\frac{f(x - B)}{H - h}$$

- So, using two pictures, we have three numerical known values x'_1, y'_1, x'_2 for three unknowns x, y, h, and we can solve to obtain

$$x = -\frac{x'B}{x' - x'_2}$$
$$y = \frac{y'B}{x' - x'_2}$$
$$h = H + \frac{fB}{x' - x'_2}$$

Aerial Photography

Stereogrammetry

- In order to improve the resolution in height we should thus increase B as intuition suggests
- This however reduces the overlap region to a length

$$\frac{wH}{f} - B$$

- Typically, a value of $B \approx 0.4\frac{wH}{f}$ is chosen
- This means a 60% overlap and a resolution in height of about

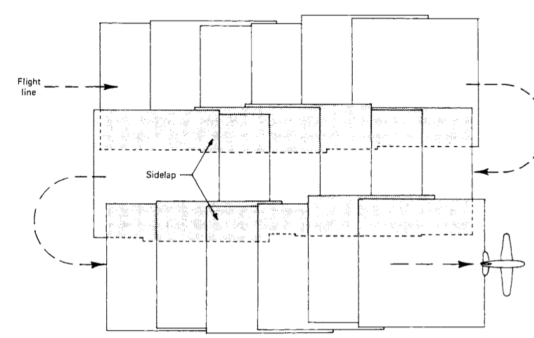
$$\Delta h \approx \frac{H \Delta h'}{0.4w}$$

- Taking again typical values $w = 23\text{cm}$, $f = 15\text{cm}$, $\Delta h' \approx 0.1\text{mm}$, we obtain $\Delta h \approx H/900$ (but on the whole overlap region!)

Aerial Photography

Overlap

- During a flight, however, there is always overlap between images for a robust acquisition
- Usually there is about 60% overlap along track and 20% overlap across-track



Overlap... complications

- Things are not so simple however...