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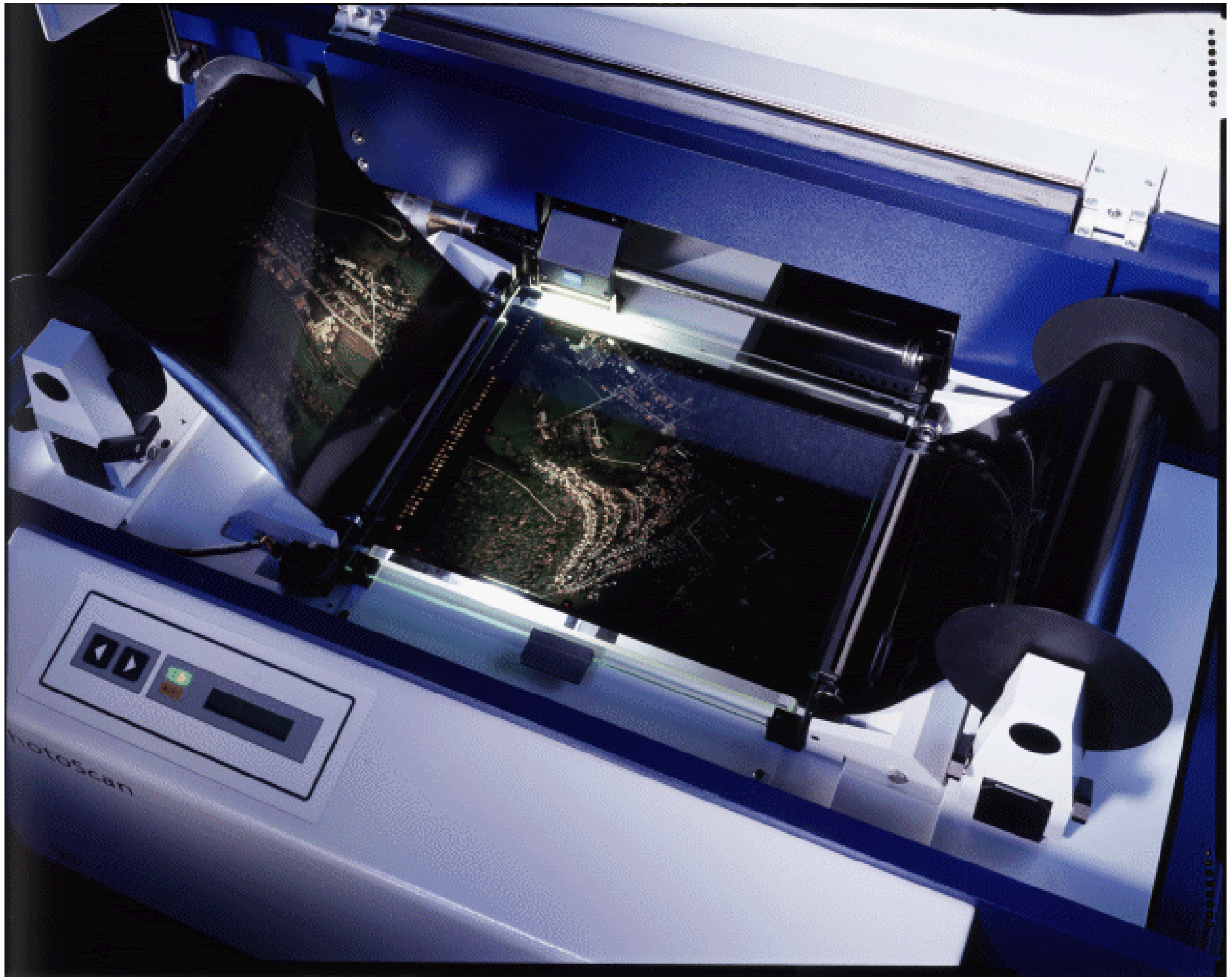


PhotoScan 2000

Technical Specifications of Z/I Imaging PhotoScan 2000

Mechanical movement	flatbed, stationary stage
Sensor type	Kodak KLI trilinear CCD, 10200 pixels (5632 active)
Scanning format x / y (mm)	275 / 250 (mm)
Roll film width / length (mm/m) Motorised transport	241 mm / 150 m manual, automatic
Scan pixel size (µm)	7 - 224, and 21 µm (in multiples of two)
Radiometric resolution (bit) internal / output	10 / 8, 12 bit
Illumination	fan-cooled, tungsten, halogen, 150 W, diffuse, fiber optics
Colour scan passes RGB simultaneously?	1 yes
Density range	0.1 - 2.7D
Geometric accuracy (µm)	2 µm
Radiometric accuracy (DN)	± 1.5 grey values
Scanning throughput and / or speed	0.68 MB/s (14 µm, B/W/ colour) max. 4 MB/s (7 µm, colour) max. 38 mm / s
Host computer / Interface	Pentium III, Windows NT/ UltraSCSI, Unix SGI
Approximate price (US$)	138,000 incl. roll film

Scanner Models

UltraScan 5000

Left: Open cover and illumination arm for films.
Right: roll film option

Technical Specifications of Vexcel Imaging GmBH, UltraScan 5000

Mechanical movement	flatbed, stationary stage
Sensor type	Trilinear CCD, 6000 pixels, Peltier cooling
Scanning format x / y (mm)	280/440 (for 5 μm) 330/440 (for 29 μm) 280/260 roll film
Roll film width / length (mm/m) Motorised transport	Roll film support (option)
Scan pixel size (μm)	5 and 29 μm base resolution and integer multiples(other freely selectable, 2.5 -2,500)
Radiometric resolution (bit) internal / output	12? / 16 or 8
Illumination	controlled, stabilised illumination
Colour scan passes RGB simultaneously?	1 yes
Density range	0D-3.6D, 4D maximum
Geometric accuracy (μm)	2 μm
Radiometric accuracy (DN)	< 1 (for 8 bits)
Scanning throughput and/or speed	0.45/0.37 MB/s (B/W, 10/20 μm) 0.83/0.74 MB/s (color, 10/20 μm)
Host computer / Interface	Windows NT / SCSI-2 UNIX (without GUI)
Approximate price (US$)	39,500

◆ Scanner Models

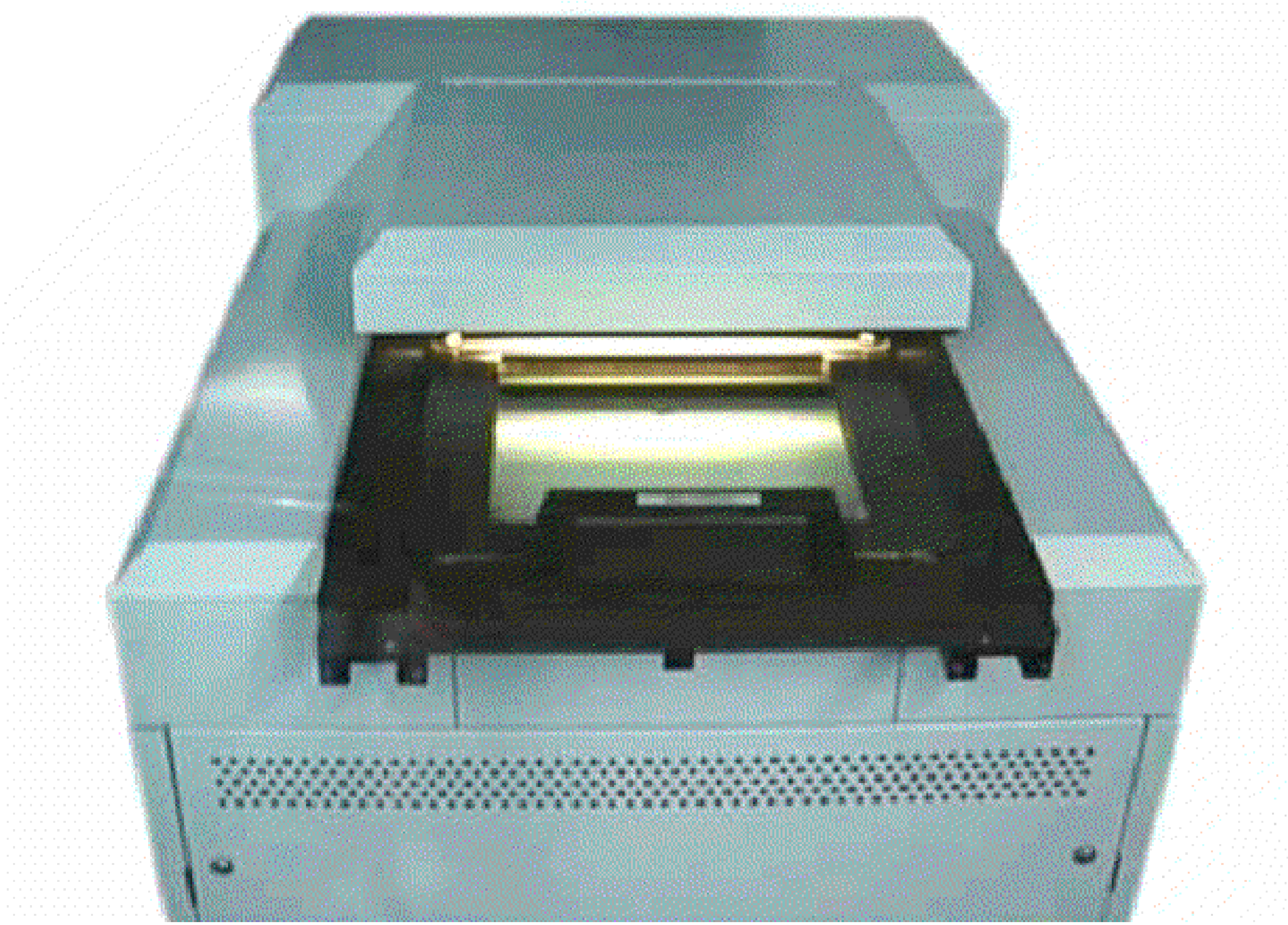
LH Systems DSW 500

Technical Specifications of LH Systems, DSW 500

Mechanical movement	flatbed, moving stage
Sensor type	Kodak Megaplus 2029 x 2044 CCD [a] (960^2 - 1984^2 active)
Scanning format x / y (mm)	265 / 265
Roll film width / length (mm/m) Motorised transport	70 - 240 / 152 manual, automatic
Scan pixel size (µm)	4 - 20 base resolution (any up to 256x base resolution in software)
Radiometric resolution (bit) internal / output	10 / 8 or 10
Illumination	SW controlled, variable intensity, xenon flashlamp, liquid pipe optic, sphere diffusor
Colour scan passes RGB simultaneously?	1 no, filter wheel
Density range	0.1-2.5D
Geometric accuracy (µm)	2
Radiometric accuracy (DN)	1 - 2
Scanning throughput and/or speed	1.4 MB/s (12.5 µm, B/W) 1.8 MB/s (12.5 µm, color) max. 100 mm/s
Host computer / Interface	Sun Ultra 10, 60 / fast 32-bit wide SCSI-2 Windows NT, dual PIII
Approximate price (US$)	145,000 / 125,000 with/without roll film

[a] Other options: 1024x1536, 2056x3072 pixels (price vs. throughput)

Scanner Models

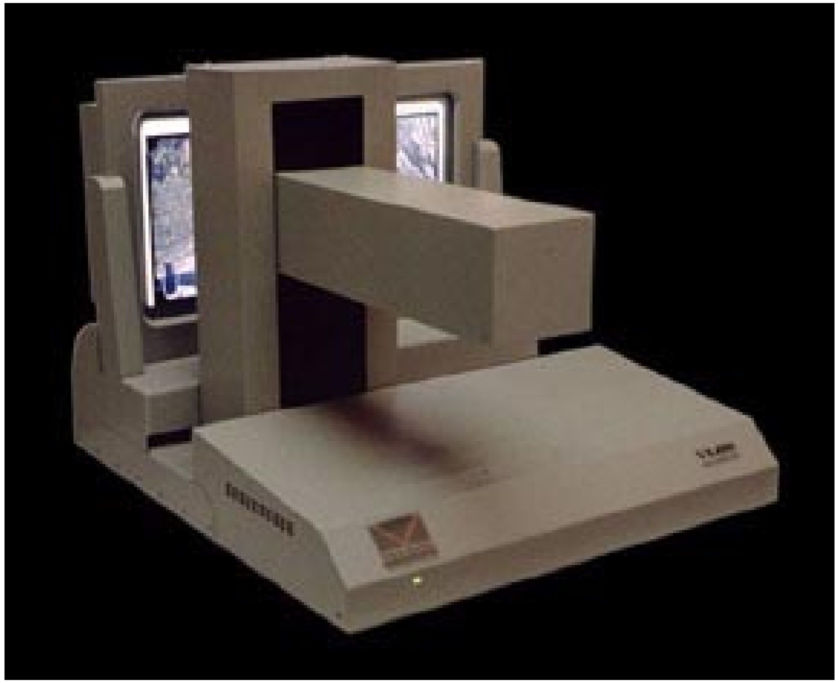


ISM Scan XL-10

Technical Specifications of ISM, Scan XL-10

Mechanical movement	flatbed, 1-D moving stage
Sensor type	Kodak trilinear CCDs, 3 optically butted 3 x 8,000 pixels
Scanning format x / y (mm)	254 / 254
Roll film width / length (mm/m) Motorised transport	241 manual, automatic
Scan pixel size (µm)	10 - 320 (in multiples of two)
Radiometric resolution (bit) internal / output	10 / 8
Illumination	Daylight, fluorescent
Colour scan passes RGB simultaneously?	1 yes
Density range	0.1 - 2.4D
Geometric accuracy (µm)	< 3
Radiometric accuracy (DN)	
Scanning throughput and/or speed	0.73 MB/s (20 µm, color) 0.37 MB/s (20 µm, B/W) 0.59 MB/s (10 µm, B/W) max. 35 mm/s
Host computer / Interface	Dual Pentium, Windows NT
Approximate price (US$)	95,000 incl. roll film

Scanner Models



Vexcel VX 4000. On the right with roll film option.

Technical Specifications of Vexcel Imaging Corp., VX 4000HT/DT (VX 5000 in Amsterdam)

Mechanical movement	vertical back-lit stage, moving sensor/optics invisible réseau
Sensor type	area CCD 1024 x 1024 / 768 x 494
Scanning format x / y (mm)	508 / 254
Roll film width / length (mm/m) Motorised transport	70 - 241 / 305 manual, automatic
Scan pixel size (µm)	7.5 - 210 / 8.5 - 120, continuously variable
Radiometric resolution (bit) internal / output	8 / 8
Illumination	cold cathode, variable intensity
Colour scan passes RGB simultaneously?	1 no
Density range	0.2 - 2D
Geometric accuracy (µm)	4 - 5 or 1/3 of scan pixel size
Radiometric accuracy (DN)	± 2
Scanning throughput	0.35 MB/s
Host computer / Interface	Windows NT and X-Windows PCs required / RS 232 and 422
Approximate price (US$)	60,000 (for VX4000DT) excl. roll film

◆ Scanner Models

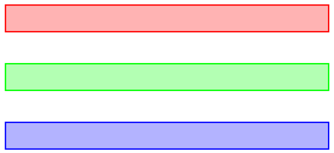
Wehrli RM Rastermaster

Technical Specifications of Wehrli and Assoc. Inc., RM-2 Rastermaster

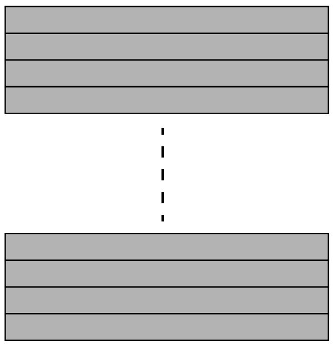
Mechanical movement	flatbed, moving stage
Sensor type	Dalsa TDI linear CCD, 96 x 2048 pixels (1024 active) (option, Peltier cooling)
Scanning format x / y (mm)	250 / 250
Roll film width / length (mm/m) Motorised transport	No support
Scan pixel size (µm)	10 - 80 or 12 - 96 (in multiples of two, other in software)
Radiometric resolution (bit) internal / output	12 or 8 / 8
Illumination	stabilised, high frequency, fluorescent, variable intensity
Colour scan passes RGB simultaneously?	3 no
Density range	0.2D - 2D
Geometric accuracy (µm)	< 4
Radiometric accuracy (DN)	
Scanning throughput	1.2 MB/s (12µm, B/W) 0.9 MB/s (12µm, colour)
Host computer / Interface	Pentium PC, Windows NT/ DOS PCI bus / SCSI
Approximate price (US$)	55,000

Sensor Types

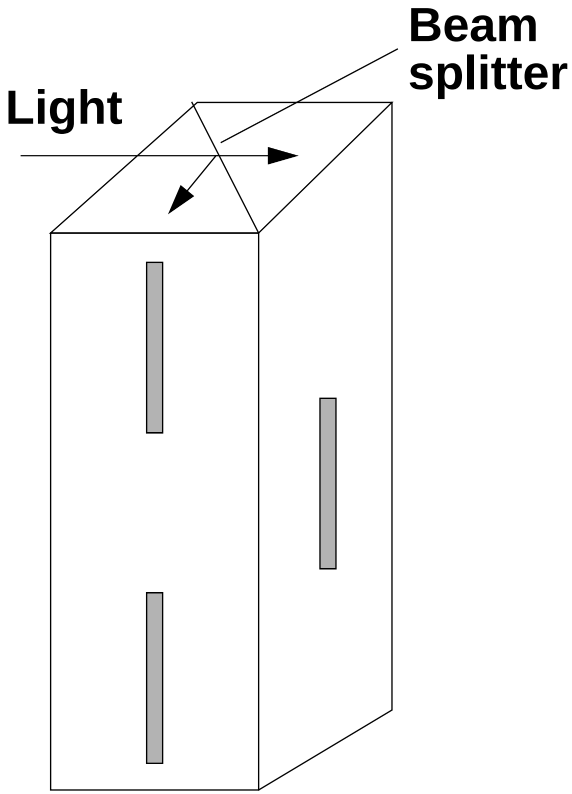
linear CCD



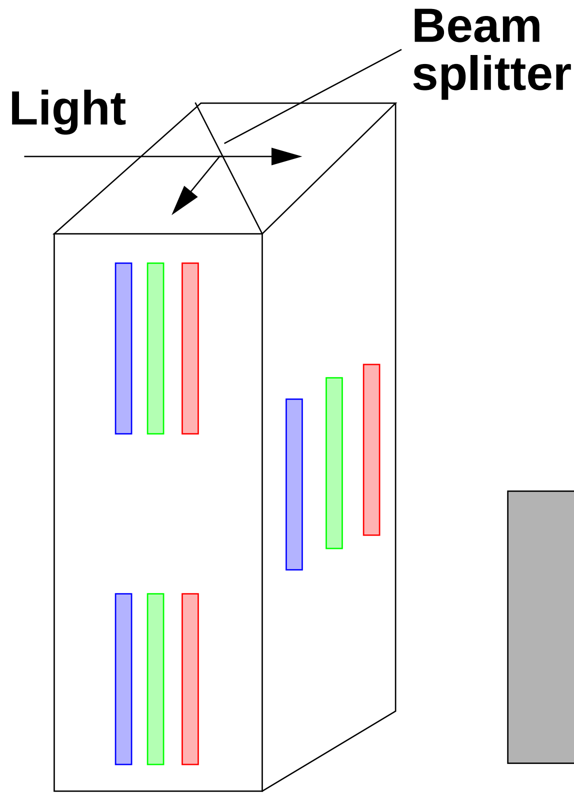
trilinear CCD
(SCAI, UltraScan 5000)



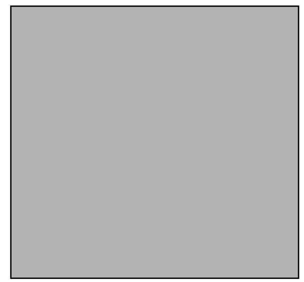
Time Delay and Integration (TDI) CCD (RM-2)



Optically butted CCDs

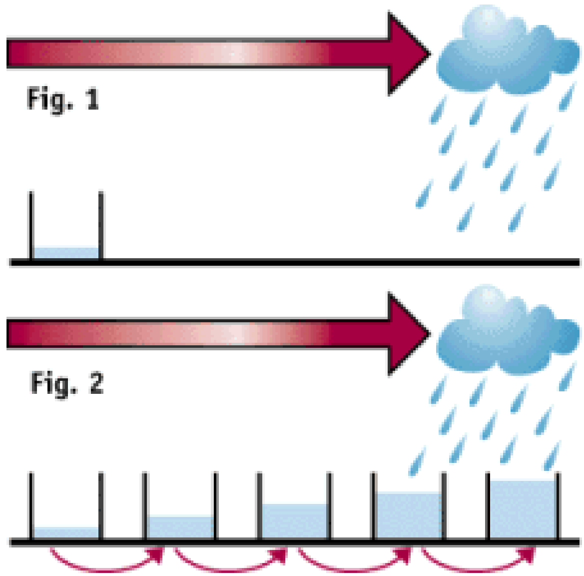


Trilinear optically butted CCDs (XL-10)



area CCDs (DSW500, VX 4000)

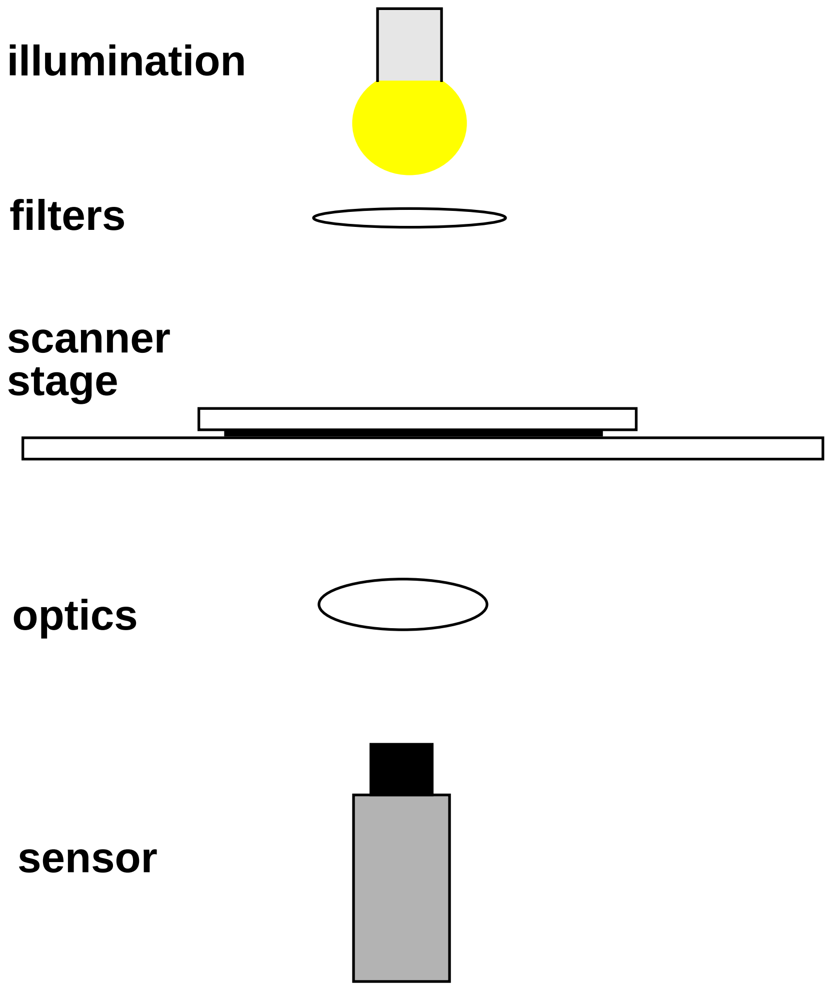
TDI CCDs



Principle of Time Delay and Integration

Collection of same signal by multiple parallel CCD lines (stages).
Suitable for low-illumination and moving object applications.

Major Scanner Components

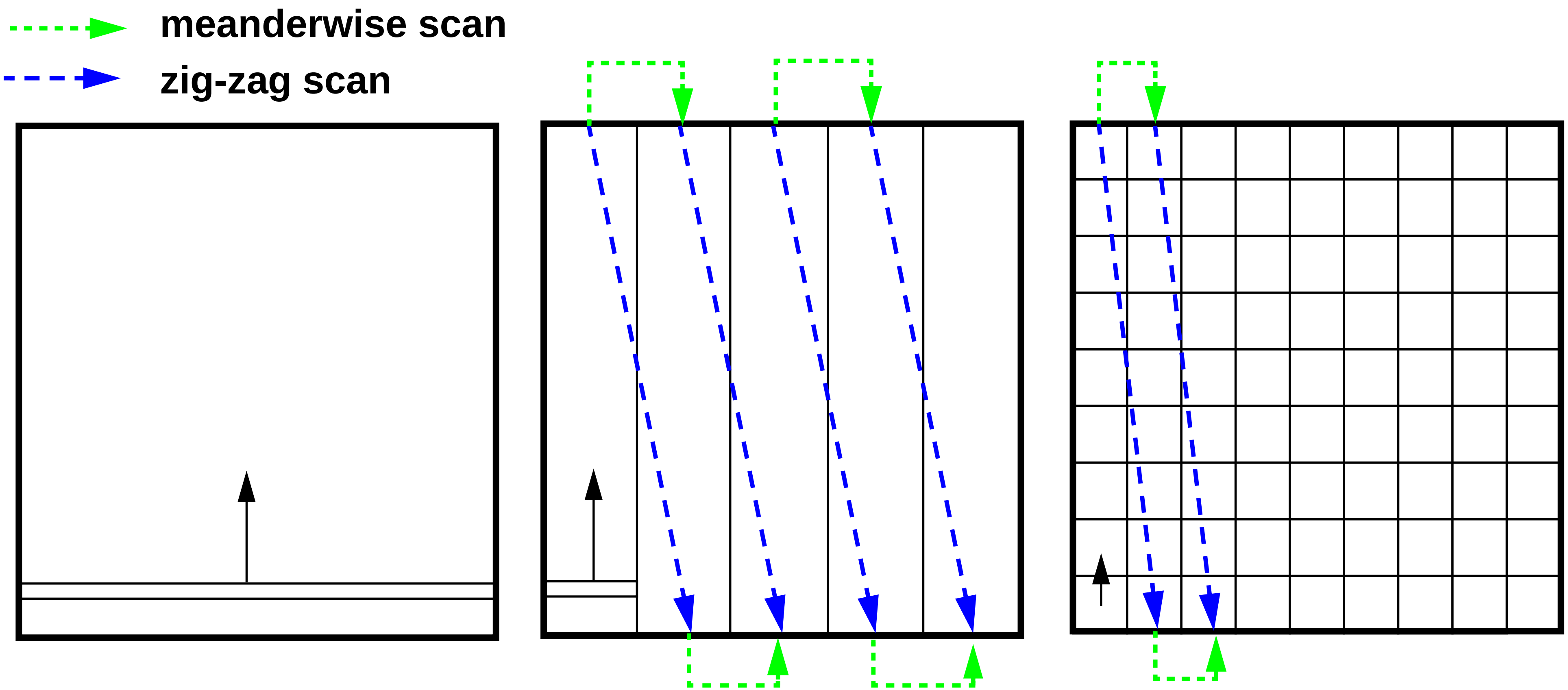


Scanning options

1. Scanner stage moves, rest fixed (DSW500, XL-10, RM-2)
2. Scanner stage fixed, rest moves (SCAI, VX 4000, UltraScan 5000)

- Illumination covers only IFOV of sensor (except VX 4000 -> whole scan area illuminated)
- Filters can also be between optics and sensor or on the sensor elements
- Vertical distance of optics and sensor to scanner stage fixed or variable (optical zoom)

Mechanical Scanning Options



One swath
Optically butted (tri)linear CCDs (XL-10)

Multiple swaths
(tri)linear CCDs (SCAI, RM-2, UltraScan 5000)

Multiple image tiles
area CCDs (DSW500, VX 4000)

Overview of photogrammetric scanners

- **Coupling to photogrammetric systems**
- **3 price groups**
- **Sensors: USED linear (1000 - 8000 pixels), area (770 x 500 - 2000 x 3000 pixels)**

  POSSIBLE Kodak KLI 14400 (14,400 pixels), Lockheed Martin F-979F $9{,}216^2$ pixels

  Linear sensors: trilinear, optically butted, TDI & cooled

- **Mechanical scanning**

  - moving sensor (SCAI, VX) vs. moving stage (all others)

  - 2-D or 1-D mechanical movement (only OrthoVision)

- **Illumination: only IFOV or whole film (VX)**

Overview of photogrammetric scanners

- Geometric accuracy: 2 - 5 μm (worse results have been achieved in some tests)
- Minimum pixel size (4 - 12.5 μm)
- Photogrammetric software (interior orientation, image pyramid)
- UNIX and Windows NT, standard interfaces (SCSI-II)
- One colour scan pass (except RM)
- Diffuse illumination, often with fiber optics
- Typical scan throughput 1MB/s
- Tendency, ADC with 10-12 bit

Overview of photogrammetric scanners

- Maximum density 1.5 - 2.3D (often less than declared)
- Radiometric accuracy 1 - 2 grey levels (often more, local noise, log LUT, dust)
- Still problems with negatives, esp. colour ones
- Colour balance no major issue, yet!
- Calibration problems may occur -> poor algorithms, software errors

  Potential for improvement (normalisation, local systematic errors)
- Improved software, hardware real-time LUTs, on-line effect of changes
- Automatic density control does not exist -> roll film scanning
- Increased output image formats
- Important new feature: roll film scanning (all except RM)

Roll film scanning (important parameters)

- Good radiometric performance -> negatives
- Automatic density control
- Automatic coarse and fine film detection (also with gaps), free scan area definition
- Image re-orientation
- User selection of scanned images, e.g. every second
- Automatic detection of beginning/end of the film
- No film damage
- Film width and length, reel diameter, rewinding speed
- High contrast of fiducials causes problems (saturation)

Illumination

- Relation to speed, heat
- Spectral properties (fit to filters, sensor)
- Temporal stability
- Uniformity
- Diffuse
- Variable intensity (or ET) -> balanced colours
- Halogen, xenon, fluorescent

Scanner Aspects

Quantisations bits

- **Often 10 - 12 bit -> reduction to 8-bit (linear, log LUT), user influence?**
- **Wrong statements (relation) of bits to dynamic range, e.g.**

  if 10-bit ADC -> DR = log (1023) = 3 D
- **Sometimes selling argument, not necessarily better than 8-bit**
- **Number of required bits depends on noise and input signal range**
- **Meaningful grey level discrimination, if e.g. noise < 0.5 grey levels**

  -> for lowest noise among all densities 0.5 grey values, 8-bit suffice

Quantisation Bits

- **Advantages of more bits**

  - less quantisation error

  - effective # of bits less with high speed ADC -> buy two bits more

  - finer radiometric corrections possible

  - possibly better image with appropriate reduction to 8-bit (research needed)

- **If noise same, increase bits, only if input signal range also increases**

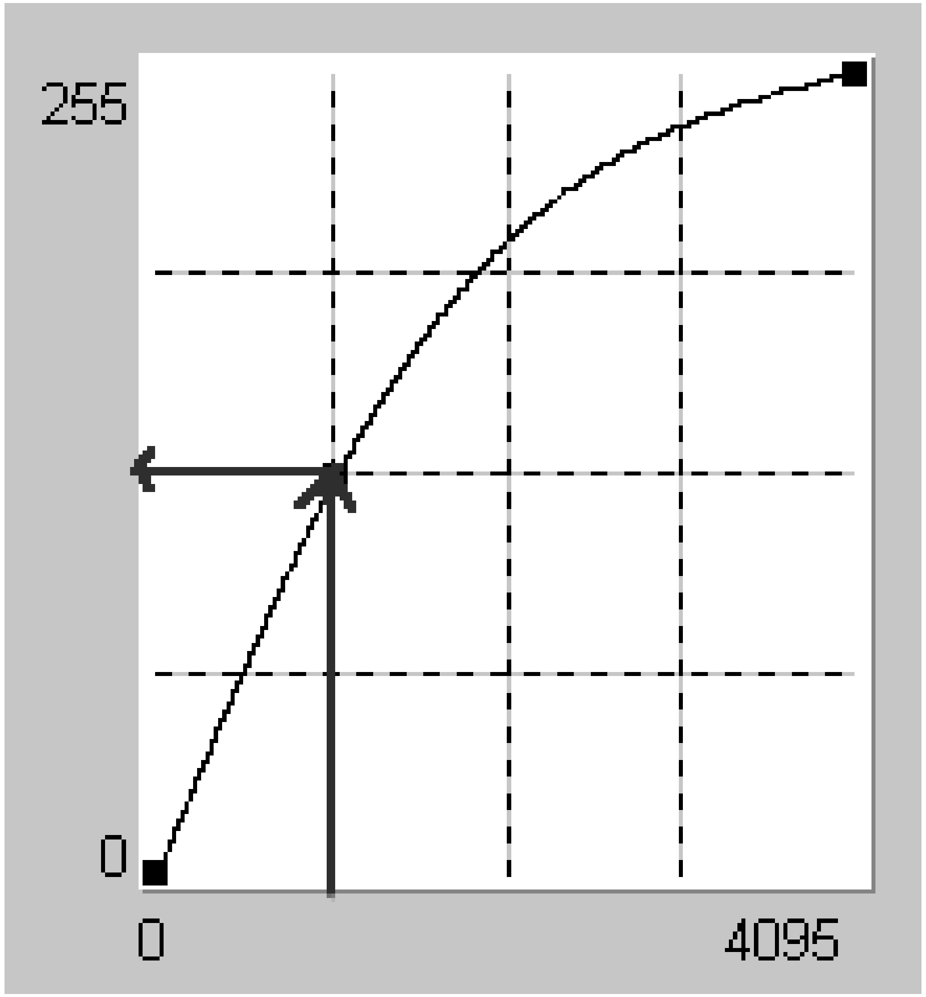
  (example)

24 bit Uncorrected Input			24 bit Scanner Output	
Photo Density	CCD Response		Mapped Response	
0.1	255			255
0.4	128			227
0.7	64			198
1.0	32			170
1.3	16			142
1.6	8			113
1.9	4			85
2.2	2			57
2.5	1			28
2.8	0			0

Mapping by a LUT (logarithmic) to achieve equal grey values steps for equal density steps. In the uncorrected input, it is assumed that for each higher density, the corresponding grey value is halved.

30 bit Uncorrected Input		24 bit Scanner Output	
Photo Density	CCD Response	Mapped Response	
0.1	1023		255
0.4	512		233
0.7	256		209
1.0	128		186
1.3	64		163
1.6	32		140
1.9	16		116
2.2	8		93
2.5	4		70
2.8	2		46
3.1	1		23
3.4	0		0

Same as above but for 10-bit input and 8-bit output.



Mapping via a LUT of 12-bit input data to 8-bit output. What is the optimal mapping?

Quantisation Bits

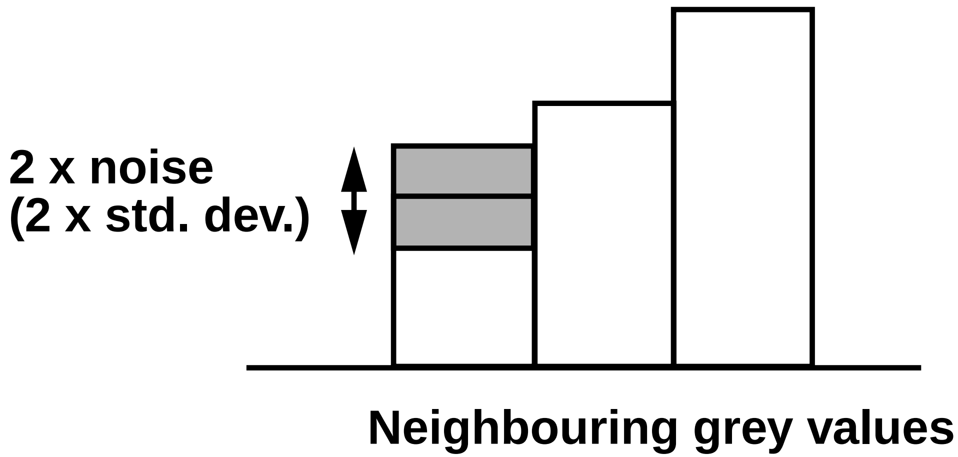
Number of bits in A/D conversion	Max. possible grey values	Log of largest grey value
4	$2^4 = 16$	Log (15) = 1.2
5	32	1.5
8	256	2.4
10	1024	3.0
12	4096	3.6
14	16384	4.2

Log (largest GV) IS NOT the max detectable density

Quantisation Bits

Number of bits required

- **Assumption: maximum storage capacity of each sensor element = 50,000 electrons**
- **Proposition: noise < 0.5 grey value. But note: noise varies with density (higher for lower densities), so proposition should be valid for all densities**



- **Example: noise = 100 electrons -> min quantisation step (1 grey value) = 200 electrons**

  -> 50,000 / 200 = 250 grey values needed -> 8-bit suffice (buy 1-2 bits more).

Scanner Aspects

Dynamic range

- Definition of min. and max. detectable density. From min to max density:

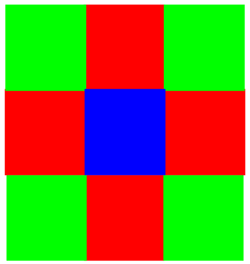
  No saturation, linear response, separable neighbouring densities
- To increase max D -> increase signal, decrease noise
- Increase signal by: light focussing, increase of illumination, ET, CCD quantum efficiency, max charge storage capacity
- Reduce noise by: multiple scans, slow scan, cooling, appropriate CCD and electronics
- Limiting factor -> film granularity

  - 0.008 - 0.033D for 1D and 38 μm pixel size

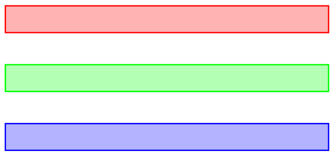
  - 0.039-0.161D for 2.5D and 12.5 μm pixel size

  -> argument in favour of digital cameras

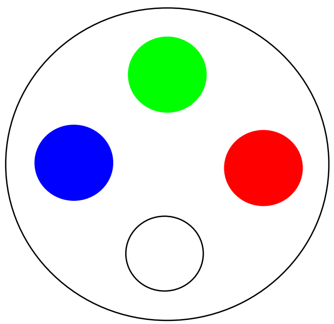
Colour Scanning



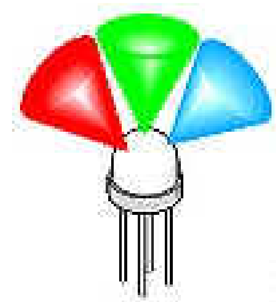
Color filters on sensor: not used in scanners.



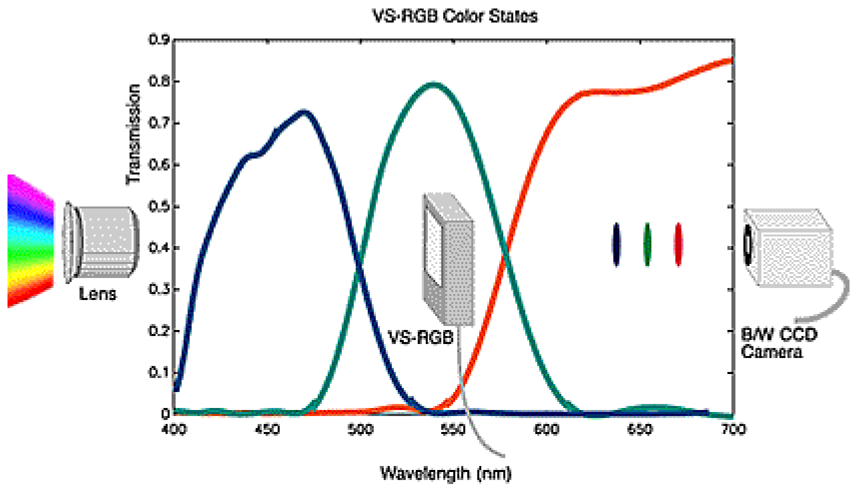
3-chip CCDs:
SCAI, UltraScan 5000, XL-10



RGB and neutral filters, sequentially:
a) for each IFOV (DSW500, VX 4000)
b) for whole scan area (RM-2)



strobing RGB LED arrays for sequential line scan with monochrome CCDs: used in slide scanners.



electronically tunable, < 1 ms speed, LC filter (for area CCDs) for sequential scan with monochrome CCDs

Linear CCDs (vs. area CCDs)

- Spatial multiplexing (colour filters on sensor, 1-chip, not used in scanners)
- 3-chip CCDs (SCAI, OrthoVision)
- Temporal multiplexing (sequential for each IFOV, only area CCDs, DSW300, VX)
- Temporal multiplexing (sequential for whole film, linear CCDs, RM)
- Disadvantages of 3-linear CCDs
  - change of ET impossible or creates artifacts
  - no change of illumination intensity possible
  - multiplexing -> crosstalk or 3 ADC/electronics
  - geometric errors more possible (mounting etc.)
- Colour misregistration due to: mechanical positioning, optics, electronics

Linear CCDs (vs. area CCDs)

- Danger of geometric errors in optically butted or trilinear CCDs

  -> better colour registration under conditions

- More correlated noise -> vertical stripes
- Sensor normalisation easier, but errors have larger spatial influence
- Unequal treatment of x/y directions -> smear, possibly smaller y-pixel size
- Changes of scan speed -> oscillations of grey values, e.g. ± 2 grey values
- Usually smaller pixel size -> smaller max charge storage capacity
- Longer -> higher demands upon optics

Linear CCDs (vs. area CCDs)

- Cannot work in stop-and-go mode
- Less electronic noise
- Adjustable integration time
- Higher speed

- TDI in RM no better performance:

  - 1.5D dynamic range
  - systematic radiometric deviations along CCD

Area CCDs

- **Resolution > 4K x 4K pixels impractical**
- **Only advantages of higher resolution**

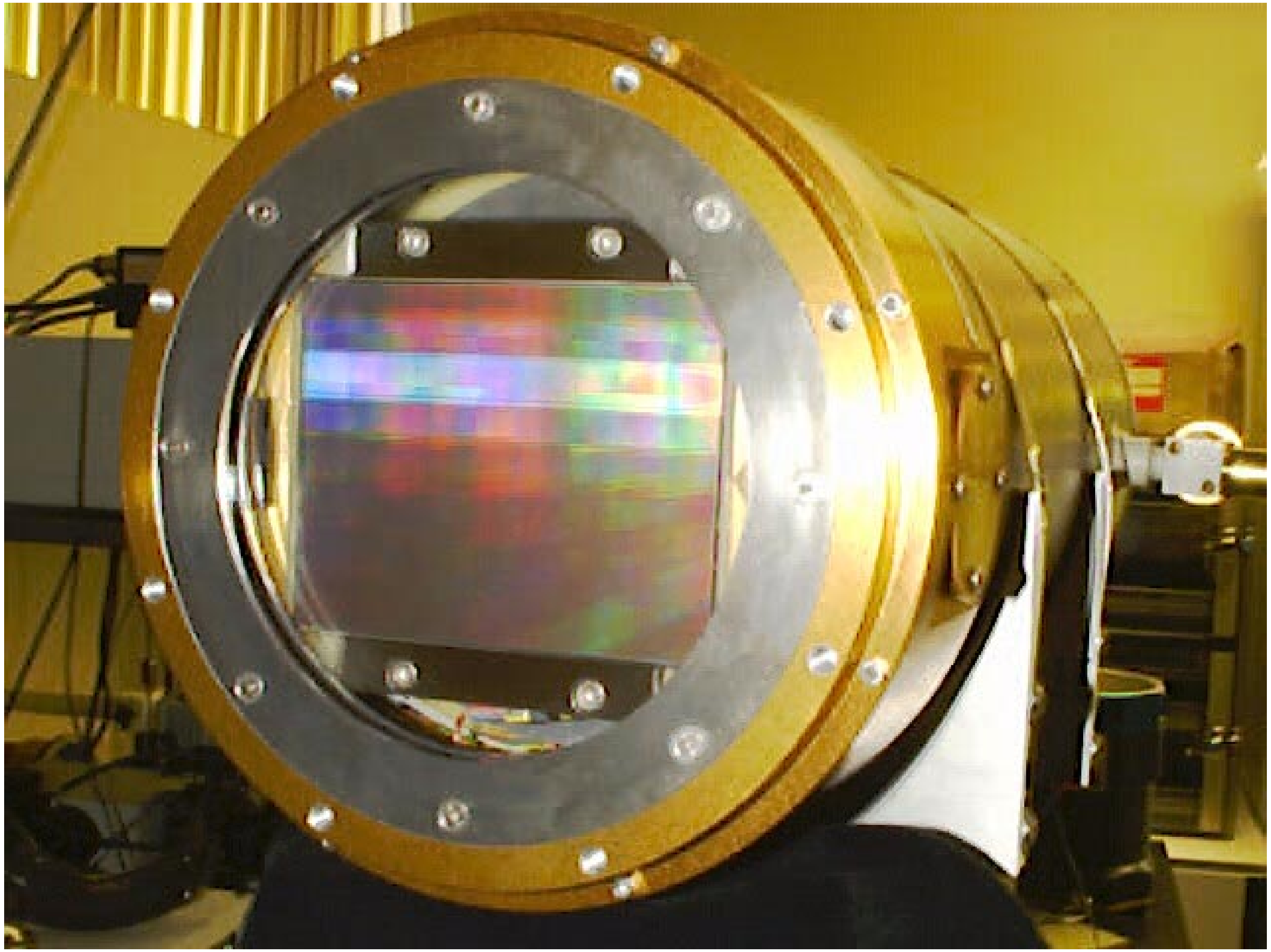
  - slightly faster scan

  - radiometric differences between tiles spatially less

Alternative technologies

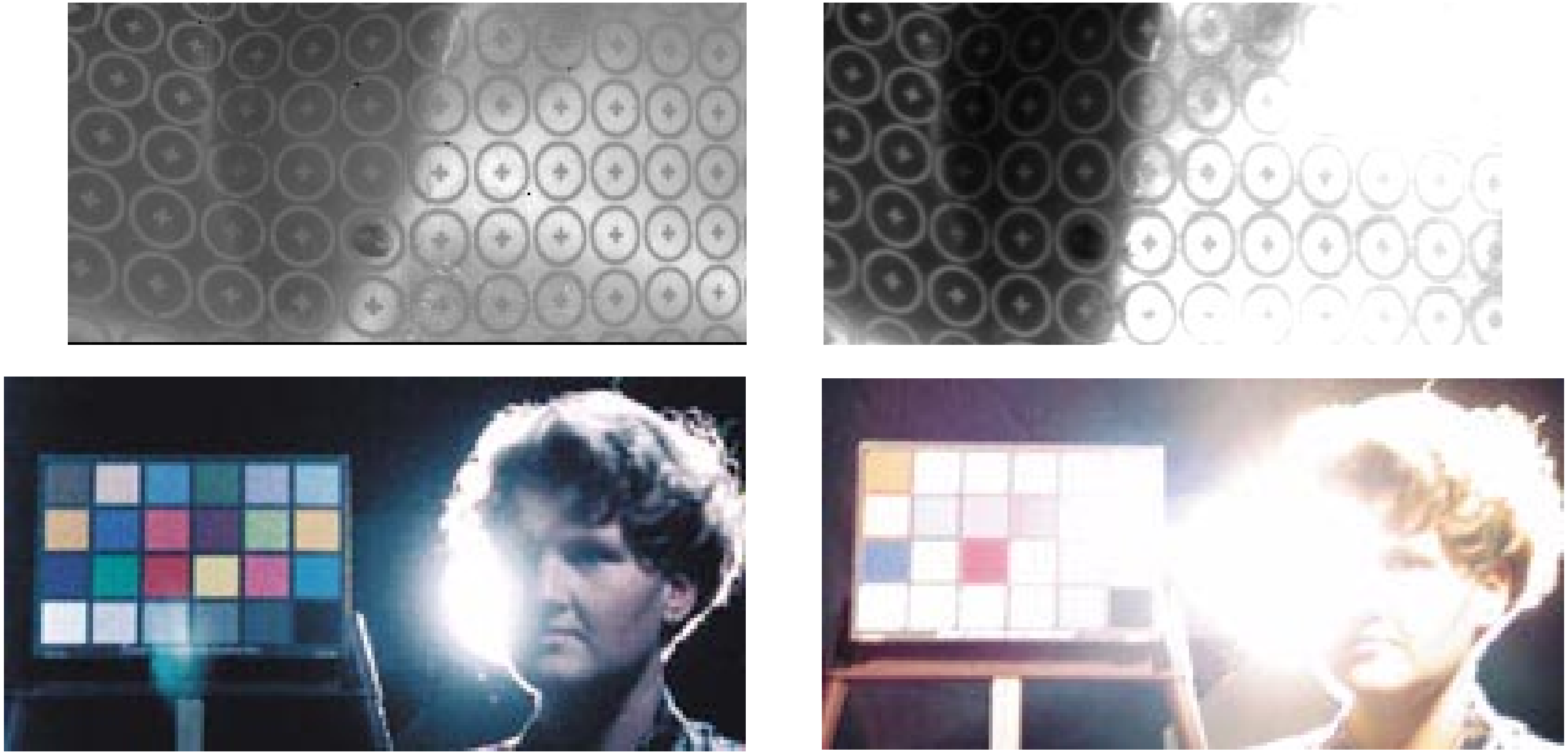
- **CMOS sensors**
- **CID sensors**
- **IEEE-1394 standard: no framegrabber, computer controlled, fast transfer rates**

Area CCDs: Large Chip



A very large CCD (7000 x 9000 pixels, 84 x 108 mm) at Steward Observatory, Univ. of Arizona. Developed by Philips for American Digital Imaging. Such chips are very expensive, usually have defect pixels, and may exhibit deviations from planarity.

Area CCDs: CMOS vs. CCD



Left: High Dynamic Range CMOS camera
(logarithmic response, dynamic range beyond 140 dB)
Right: standard CCD

Scan throughput and speed

- Overestimated by manufacturers and users
- Scan time includes: prescan, parameter setting, scan, integration, ADC and H/W processing, transfer, save on disk, S/W processing (subsampling, mosaicking, re-orientation, formatting, compression, display and control), possible rescan
- Depends on pixel size, film (B/W, colour), image format, film orientation
- Firm specs exclude interactive operations, for native image format, no rescan
- Bottlenecks: transfer and save, electronic bandwidth, scan speed, integration time

Scan throughput and speed

- **Not sacrifice quality for speed:**

  - high dynamic range and SNR

  - colour balance -> for blue longer ET or lower scan speed

  - less effective bits for fast ADC

  - vibrations

  - stage settling (area CCDs)

- **Example for an aerial image:**

  linear CCD, 10,000 pixels, 14 μm pixel size, 2.5 MHz scanning rate, 4 ms ET -> 1.8 min

  10 times faster -> 11 s ; gain = ?

- **Slow scan also leads to advantages regarding: scan mechanism, illumination and heating, smear, lag noise, electronic bandwidth, internal image buffer / transfer rate**

Optimal scan pixel size

- No agreement among users, scientists, manufacturers
- Depends on application, data amount able to be handled
- Today, limit for practical handling -> 10 - 15 μm
- DTM, AT, often ortho-image generation -> sufficient results with 25 - 30 μm
- Interpretation, mapping, fine details -> 10 - 15 μm
- Preserve original aerial film resolution -> 6 - 12 μm, for reconnaissance down to 4 μm

◆ Subsampling

- **Optical zoom**: optomechanically (UltraScan, DSW 500 planned?) or self-calibration (réseau, VX 4000)
- **Electronic zoom** with low-pass filtering and resampling in hardware (RM-2, SCAI, XL-10)
  - linear CCDs: only in CCD direction, in scan direction increase of scan speed
  - area CCDs: in both direction
  - problems with linear CCDs (smear in scan direction, different pixel size and resolution in 2 directions may occur)
- **On-chip electronic binning**
  - with area CCDs possible, (usually by factor 2) but not used
  - with linear CCDs in line direction or both (used in UltraScan)
- **Software zoom** (multiples of 2, any integer multiples, any output pixel size) (DSW500)
- **Multiple lenses** (in DTP scanners)
- **Hybrid** methods: e.g. UltraScan, 2 optical settings, electronic binning (integer multiples) -> many “native” resolutions, software interpolation -> any pixel size

Geometric / radiometric calibrations

- Sometimes: incomplete, slow, not often / accurate enough, not whole scan format, robust against dust?, manual measurements required / allowed
- Radiometric problems: stripes, electronic noise, sensor normalisation (electronic dust)
- Geometry could/should improved, even with best scanners

  -> local systematic errors 6 - 8 mm: should not be ignored, correction possible

- Calibration by user: patterns, software, how often?
- Stress proper environmental and maintenance conditions
- Manufacturers -> provide technical specifications, tolerances, quality certificate

Radiometric problems - Improvement

- Careful choice and co-ordination of illumination, optical components, colour filters, sensor, mechanical scanning, camera electronics
- Possible additional measures (avoiding changes of current hardware):
  - averaging (not possible with line-CCDs)
  - cooling
  - longer exposure time/higher illumination
  - slower scan and read-out
- Software/calibration methods, adapt scan parameters for film type, density range
- Aims:
  - reduce the noise to minimum and cover for each image whole dynamic range, with proper color balance BEFORE ADC
  - after ADC, improve using software. All preprocessing possibly in 16-bit
  - intelligent reduction to 8-bit

Radiometry and Colour

- Understimated but increasingly important:

  - automated image analysis (DTM, AT, feature extraction) heavily depends on image quality

  - demands on image quality increase (digital orthoimages, visualisation)

  - geometry and radiometry are siamese sisters

- Colour is getting cheaper and is increasingly used
- Colour is essential in orthoimages, visualisation and automated feature extraction

Competition from:

- High-res satellite imagery
- Airborne digital sensors, esp. planned digital photogrammetric cameras

Perspectives - Are scanners needed in the future?

Current photogrammetric market situation

	Amount sold	Still in use	Equivalent to digital systems	Time span	Annual selling rate
Film cameras	3,500	50%		Last 60 years	20-25, stable
Film scanners	600	90%		Since 1990	
Analogue plotters	10,000	60% (6000)	3000 (36%)	Last 70 years	
Analytical plotters	3,700	80% (3000)	2300 (28%)	Since 1980	35-40, - 5% - 10% / year
Digital systems	3,000	98% (3,000)	3000 (36%)	Since 1990	

Scanners needed by digital systems and hybrid production modes (digital and analogue/ analytical)

Arguments for Scanners

- Highres spaceborne images can not replace in most cases film cameras
- In the next future digital photogrammetric cameras can not replace film cameras

  - can not reach film camera performance in most aspects
  - digital and film cameras produced by same firms
  - technology not mature enough or in development
  - software development for digital cameras needed -> 4-6 years transition to maturity

    most critical factor for success or not of digital cameras
  - production chains, hardware, software geared towards23 cm x 23 cm film
- Costs: digital cameras more expensive, nobody will just throw away existing film cameras, scanners and analytical/analogue plotters

CONCLUSION

- Long co-existence of film and digital cameras (10-20 years)
- Scanners will still be required, with improved performance, for at least a decade, albeit with a decreasing demand

Conclusions

- **Number of scanners since 1996 fairly stable (6 main products)**
- **Changes with DSW, SCAI, RM-2 and introduction of UltraScan**
- **Improvement of performance, functionality, costs (2nd generation scanners)**

  - roll film, software, faster, slightly better geometry and radiometry
- **Significant differences between scanners wrt geometry, radiometry, software**
- **Geometric accuracy of 2 μm RMS feasible and sufficient (< 0.25 pixel)**

  Larger local errors of 6-8 μm need to be better modelled
- **Radiometric accuracy of 1-2 grey values in best case. Artifacts create larger systematic errors -> need of improvement (stripes, electronic noise)**

Conclusions

- **Dynamic range still low (1.5 - 2.2D)**
- **Good geometric and radiometric balance between color channels possible**

  - improved performance in blue in comparison to old CCD technology possible
- **Need for tests, and frequent, accurate, automated calibrations (manufacturers, users)**
- **Importance of environmental and maintenance conditions**
- **Need of tests for color reproduction (esp. relative accuracy)**
- **Is quality control and scanner homogeneity sufficient ??**

  -> Quality assurance certificate, error tolerances

Conclusions

- **Software**

  - Automatic density control (esp. for roll films)

  - Adaptivity to film at hand

  - On-line visualisation or better automation of scan parameter settings

  - New functionality needed

  On-the-fly image processing, dodging, correction of light fall-off, hots spots -> negative roll film scanning

- **Future developments**

  - sensors: more pixels, better radiometry

  - more quantisation bits -> intelligent reduction to 8-bits?

  - faster scans

  - extended software functionality, better calibration