How to get base geospatial data for SDI from high resolution satellite images

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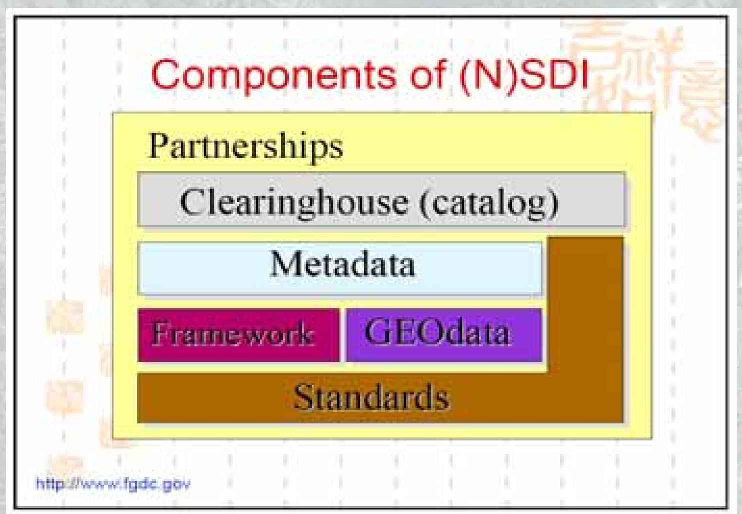
Spatial Data Infrastructure

- Implemented at different levels (global, national, local etc.)
- In an increasing number of countries
- Geodata necessary for development and informed decisions
- Geodata are part of SDI
- Among them base data the most important (framework data)
- Base data: maps, DSMs, DTMs, orthoimages, land cover and land use, roads, buildings, names, boundaries etc.

Spatial Data Infrastructure



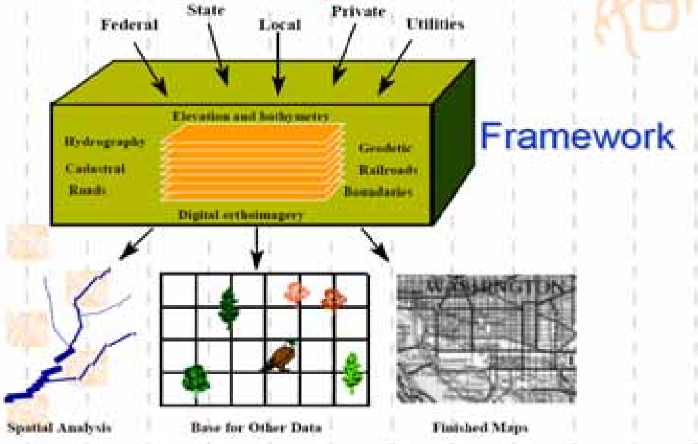
Framework

Framework—provides a core…

- Data sets developed to a common content specification for high re-use potential. These are known as "Framework" data.
  - a foundation to which spatial information and attributes can be added
  - a base on which other themes of data can be compiled
  - context to orient and link the results of analyses to the landscape
- Framework supports…
  - Community development of sets of spatial primitives, feature representation, and attribution to a lowest common denominator
  - Participants collecting or converting information to common Framework specifications
  - Multiple representations of real-world features at different scales and times by feature identifier and generalization
- Framework implementation
  - Performed within thematic communities, composed of federal, local government, academic, and vendor contributions
  - Drafted and tested first on a local scale and propagated upwards to assure compatibility
  - Ownership does not fall to one organization but to a cooperative group

Framework

Framework—provides a core…



Role of satellite imagery

- Imagery an increasingly important source for base data acquisition and update
- Satellite images generally cheaper than aerial images
- Repetitive coverage of large, remote or forbidden areas
- Many satellites, increasing number in future
- Aerial imagery often not readily available in developing countries (also military restrictions)

High spatial resolution (HR) satellites

- Ground Sampling Distance (GSD) down to 0.61 m, 0.4 m in 2007, 0.25 in 2008?
- Almost all are stereo capable
- High geometric accuracy potential
- Increasing support by commercial software packages

But,

- Not high availability. Hopes for improved availability with more such systems planned.
- High costs. Hopes for lower costs with increasing competition and non-commercial systems (like Japanese ALOS-PRISM, 2.5 m PAN GSD, to be launched soon) and small, low-cost HR satellites (like Topsat, UK)

How is a HR sensor defined here?

- **Definition changes with time. 10 years ago, 10 m GSD was considered HR, not now**
- **Here HR, if panchromatic (PAN) GSD max. about 3 m**
- **Multispectral channels (MS) usually employed and have 2-4 times larger GSD**
- **Here only optical sensors, not microwave or laser scanners**
- **Pure military systems not treated here**
- **Most optical HR sensors use linear CCDs**
- **Many have military heritage, and are still used for dual purposes**
- **Some data for HR sensors kept secret. Useful source of info http://directory.eoportal.org/**

Specifications of current HR satellite missions (status July 2005)

Mission or Satellite	**Ikonos-2**	**Quickbird-2**	**Orbview-3**	**SPOT 5**	**IRS-P5 (Cartosat-1)**	**FormoSat-2** (formerly ROCSat-2)	**EROS A1**	**Cosmos [1], many missions**	**Corona (KH-1 to KH-4), many missions**	**KH-7, many missions**
Sensor	OSA	BHRC60	OHRIS	HRG, HRS	2 PAN cameras	RSI	PIC	KVR 1000 panoramic camera (2 working alternatively)	Stereo panoramic cameras	High Resolution Surveillance Camera
Country	USA	USA	USA	France, Belgium, Sweden	India	Taiwan	Israel	Russia	USA	USA
System type	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial	Commercial	Military, declassified	Military, declassified
Launch date or duration	9/1999	10/2001	6/2003	5/2002	5/2005	5/2004	12/2000	1981-2000	1960-1972	1963-1967
Sensor type	digital	digital	digital	digital	digital	digital	digital	film	film	film
PAN GSD (m) (across x along track)	1	0.61	1	5 or 2.5-3 (oversampled) HRG 10 x 5 HRS	2.5	2	1.9 1 or 1.4 (oversampled)	2	2-140	At nadir down to 0.45-0.5
PAN Pixels of line CCD / Pixel spacing (µm)	13,816 / 12	27,568 / 12	8,000 / 6 x 5.4, unknown if numbers here for staggered or not	12,000 (2 lines for HRG) / 6.5	12,288 / 7	12,000 / 6.5	7,043 (2 lines) / ca. 13	NA	NA	NA
Flying height (km), Focal length (m)	681, 10	450, 8.832	470, 2.77	818-833, 1.082 HRG 0.58 HRS	618, 1.98	888, 2.896	ca. 500, 3.4	Variable (190-270), 1	Variable, 0.6069	Variable, 0.96

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Specifications of current HR satellite missions (status July 2005)

Mission or Satellite	Ikonos-2	Quickbird-2	Orbview-3	SPOT 5	IRS-P5 (Cartosat-1)	FormoSat-2	EROS A1	Cosmos, many missions	Corona (KH-1 to KH-4), many missions	KH-7, many missions
No. of MS Channels / GSD (m)	4 / 4	4 / 2.44	4 / 4	(excl. Vegetation instrument) 4 / 10 and 20	0	4 / 8	0	0	0	very few color & CIR images
Stereo [2]	along-track, across-track	along-track, across-track	along-track, across-track	along-track, across-track	along-track	along-track, across-track	along-track, across-track	no stereo	along-track	few images in stereo
Swath width (km) or Image film dimensions (cm)	11	16.5	8	60 HRG, 120 HRS	30	24	14, 10 for oversampled images	18 x 72 (across)	5.54 x 75.69 (across)	22.8 x variable (across)
Field Of Regard [3] (deg)	45, up to 60 deg images shot	45	50	27 (HRG, only across track)	NA	45	45	NA	NA	NA
TDI	Y	Y	N	N	N	N	N	NA	NA	NA
Along track triplette ability	Y	?	?	N	N	?	Y	NA	N	N
Body rotation angular rate [4] (deg/sec)	up to > 1	0.5-1.1	?	NA	NA	0.4-0.75	1.8	NA	NA	NA

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Specifications of current HR satellite missions (status July 2005)

Mission or Satellite	Ikonos-2	Quickbird-2	Orbview-3	SPOT 5	IRS-P5 (Cartosat-1)	FormoSat-2	EROS A1	Cosmos, many missions	Corona (KH-1 to KH-4), many missions	KH-7, many missions
FOV (deg) or film area coverage	0.93	2.12	0.97	4.13 HRG 7.7 HRS	2.49	1.54	1.5	40 x 160 km (typical)	14 x 189 (typical)	
No. of quantization bits	11	11	11	8	10	12	11	NA	NA	NA
Scale factor	68,100	51,100	170,000	762,500 HRG, 1,422,500 HRS	312,000	307,000	145,000	190,000-270,000	Variable, ca. 250,000 typical	Variable
Stereo overlap (%)	up to 100	up to 100	up to 100	up to 100	up to 100	up to 100	up to 100	6-12	up to 100	?
B/H ratio	variable	variable	variable	up to 1.1 HRG, 0.8 (40 deg.) HRS	0.62 (31 deg.)	variable	variable	NA	0.60 (30 deg.)	?

[1] Actual name is Kometa Space Mapping System, on-board of Cosmos satellites, which have been used for other purposes too.

[2] Along-track is often used as synonymous to quasi-simultaneous (QS) stereo image acquisition (time difference in the order of 1 min), while across-track as synonymous to different orbit (DO) stereo image acquisition. Later definition is wrong. Agile satellites can acquire QS stereo images across-track, while with other satellites like SPOT-5 across-track means DO stereo.

[3] The Field Of Regard is given here as +/- the numbers in the table. It is valid for all pointing directions, except for SPOT-5 where it refers only to across-track. Some satellites can acquire images with even smaller sensor elevation than the one mentioned in the table under certain restrictions (e.g. Ikonos images with 30 deg elevation have been acquired).

[4] The angular rate generally increases, the longer the rotation time period is.

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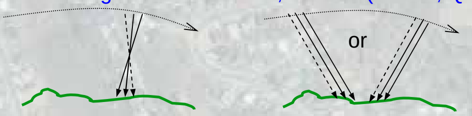
Important characteristics of HRS

- Very narrow across-track Field of View
  - down to 0.9 deg for Ikonos
  - small influence of height errors, accurate orthoimages when high sensor elevation, even with poor quality DTM/DSM
- Variable scanning modes – reverse, forward (Ikonos, Quickbird)



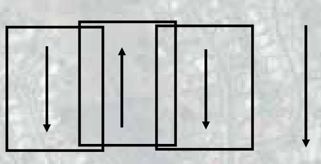
Flight direction from N to S

First line scanned is dotted

Usual and preferred mode is reverse

Forward (scan from S to N)   Reverse (scan from N to S)

Forward used to scan more images within a given time, by reducing time needed to rotate the satellite body, e.g. when acquiring multiple neighbouring strips, or triplettes within a strip. The satellite body rotates continuously with an almost constant angular velocity

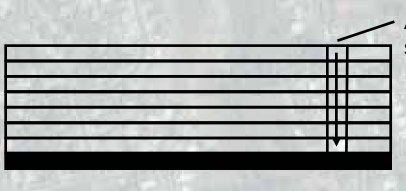


Flight direction from N to S

Middle strip scanned in forward mode

Important characteristics of HRS

- Often use of TDI (Time Delay and Integration) technology (Ikonos, Quickbird)
  - Aim: to increase pixel integration time in scanning direction for better image quality and signal to noise ratio, by summing up the signal of multiple lines
  - Used especially for fast moving objects (or platforms) and low light level conditions
  - Necessary, especially when the GSD is small (thus, used mainly for PAN only)
  - TDI is rectangular CCD chip with many lines (called also stages). Ikonos and Quickbird use max. 32 stages. How many are actually used is programmable from the ground station. Usually 13 with Ikonos. Use of more can lead to saturation. They can have 1 or 2 readout registers. The readout register must be at the TDI end in the scanning direction. Ikonos and Quickbird use older technology with 1 register. Thus, need 2 TDI to scan in both forward and reverse mode.



A ground sample is imaged by multiple TDI lines, the signal is summed up and shifted to the readout register

Readout register needed to scan from N to S

N

S

Important characteristics of HRS

- Rotation of satellite from S to N done also for other reasons

  a) to achieve a smaller GSD (the nominal one) in flight direction

  With Quickbird, GSD in flight direction would be larger than 0.61 m in PAN, for the given satellite speed and pixel integration time. Thus, the satellite rotates from S to N a bit to achieve 0.621 m GSD. This happens in both Reverse and Forward mode !

  Satellite body rotation can introduce nonlinearities in the imaging geometry.

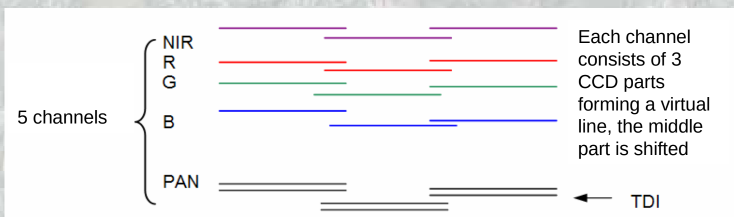
  b) to increase pixel integration time and achieve better image quality, when the sensor does not use TDI, e.g. EROS A1

  This feature is inferior to TDI, can introduce nonlinearities in the imaging geometry and may cause pixel and edge smearing (unsharpness)

  In both cases, the imaged earth part (given often as line scan frequency for line CCDs), is shorter than the ground track of the satellite. A linescan frequency of e.g. 1500 lines/s, means 1/1500 s (0.67 ms) integration time (IT). Note: linear CCDs can have an exposure time (effective IT) smaller than the nominal IT. We assume that satellite firms use the term IT in the sense of exposure time.

Important characteristics of HRS

- Use of multiple CCDs
  - butted (Ikonos, Quickbird) to increase the across track FOV (swath width)
  - staggered (SPOT-5 HRG, Orbview-3) to decrease, usually by about the half, the GSD
- Multiple butted CCDs (example below Ikonos)



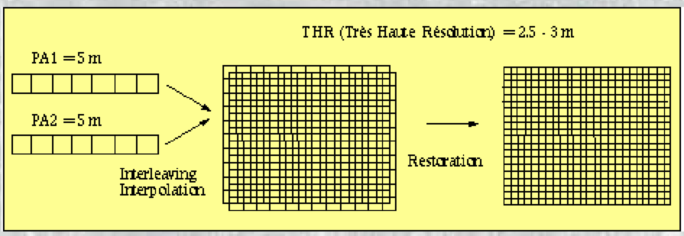
From top to bottom:

- MS linear CCD (4 channels/lines)
- Reverse TDI PAN (32 lines/stages)
- Forward TDI PAN (32 lines/stages)

Quickbird has similar focal plane but double width and 6 CCD parts per virtual line, with a total of 18 linear CCD chips and 408 partial CCD lines!

Important characteristics of HRS

- Staggered CCDs (example here SPOT-5 HRG)
  - Used to decrease the GSD by avoiding too long focal length, small pixel spacing or low flying height
  - Used primarily only for PAN
  - Use of 2 identical CCD lines, shifted in line CCD direction, by 0.5 pixel
  - Distance of 2 lines in scanning direction, as small as possible, for SPOT 3.45 pixels
  - The data from 2 CCDs are interleaved and interpolated with various algorithms
  - Then, often a restoration (denoising) is performed
  - Thus, for SPOT-5 HRG the original GSD of 5 m, can be improved to 2.5 – 3.5 m



Important characteristics of HRS

- Multispectral CCDs
  - Often the pixel size given by the firms, e.g. 48 microns for Ikonos and Quickbird, is not correct.
  - Linear CCDs with so large pixel size not available in standard products
  - Usually the MS CCDs are identical to the PAN CCDs with very thin filters covering the pixels, thus for Ikonos and Quickbird they have 12 microns pixel size.
  - The larger effective pixel size (e.g. 48 microns) is achieved in scanning direction by increasing the integration time (e.g. for Ikonos by 4) and in the CCD line direction by averaging (binning) of pixels (e.g. 4 pixels)
  - This mode of generation leads to better image quality than producing images with real 48 microns pixel size. This may explain why geometric accuracy with MS images is only about 2 times worse than that of PAN, and not 4 times as might have been expected.

Image quality analysis - Ikonos

PAN with DRA (Luzern)

Radiometric Quality

Preprocessing by Space Imaging (similar by other firms too):

- **Modulation Transfer Function Correction (MTFC)**

Sharpen image especially in scan direction due to TDI imaging (typically 13 lines), which causes blurring

- **Dynamic Range Adjustment (DRA)**

Stretch grey values to better occupy grey value range

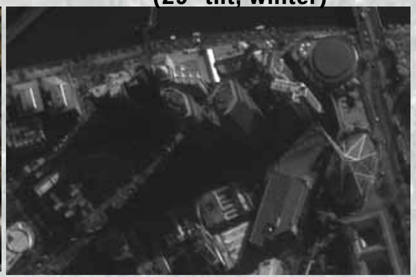
Additional artifacts are due to compression from 11 to 2.6 bit (esp. in homogeneous areas)

Radiometric Quality

Important aspects for Feature Extraction and Interpretation

Pan-Sharpened 1m *Ikonos*
(7^0 tilt, summer end)

Stereo 1m *Ikonos*
(29^0 tilt, winter)



- ♣ View angle
- ♣ Sun angle & Shadowing
- ♣ Season
- ♣ Atmospheric conditions
- • Stereo or mono
- • Colour or B&W
- ♣ Image preprocessing
- • Building characteristics & size

♣ *factors over which there is no or limited user control*

Radiometric Quality

- Image quality / interpretability can vary dramatically
- Images taken the same day of April from the same orbit

Luzern (CH)

Greek village (Nisyros)

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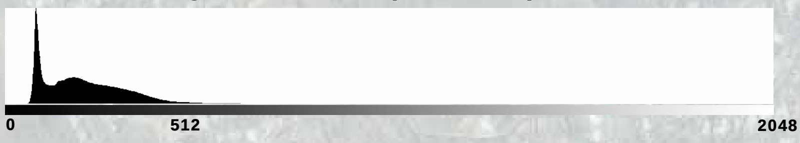
Radiometric Quality

11bit histogram Nadir PAN (Melbourne) - without DRA



11bit histogram Nadir PAN (Luzern) - with DRA

D R A stretches the grey values (GVs) to cover more uniformly the 11 bit range .

Result : Absolute radiometric accuracy is destroyed + leads to combination of GVs that are not frequently occupied. Better methods of contrast stretch exist.

Radiometric Quality

Noise characteristics analyzed in areas:

- **homogeneous (lake and sea surfaces)**

Image type	Mean std. dev.
PAN-MSI	5.2
MSI	2.0
PAN	4.6
PAN-DRA	5.0

Noise generally high since 11bit data represent 8-9 effective bits

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Radiometric Quality

Noise characteristics analyzed in areas (PAN images):

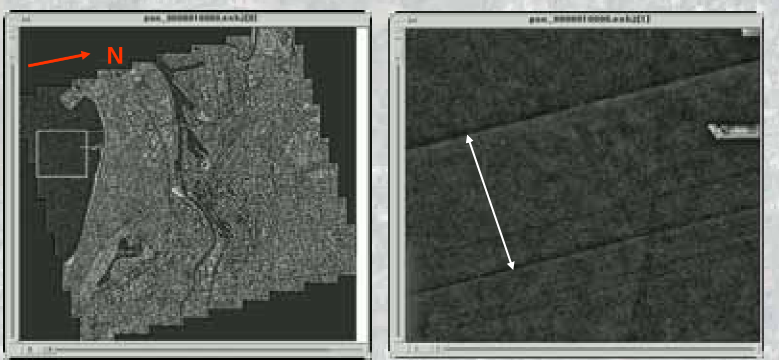
• non-homogeneous (whole image excluding large homog. areas)

GV range	0-127	128-255	256-383	384-511	512-639	640-767
Raw Image	2.6	3.1	4.1	4.7	5.6	6.6
with Noise Reduction	0.8	1	1.3	1.5	1.8	2.5

- **Noise generally increases with intensity**
- **Adaptive filtering reduces noise by ca. factor 3**

Radiometric Quality

Image Artifacts



Visible bands in epipolar images

Radiometric Quality

Image Artifacts

Left Stereo

Right Stereo

•Staircase effect in left image

•Nonexisting white dotted lines

Radiometric Quality

Image Artifacts

- Strong reflection/saturation
- Spilling (blooming)
- Edge sharpening artifacts

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Radiometric Quality

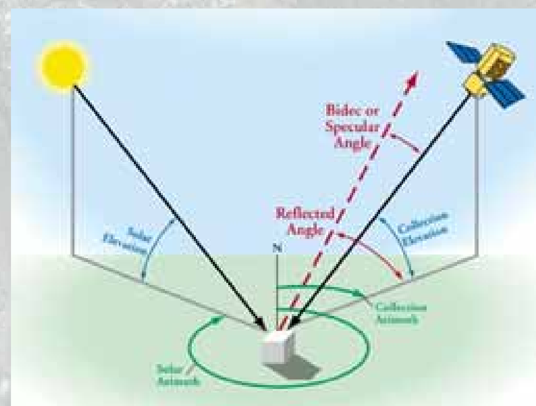
Spilling

Spilling in images over Geneva. Left and middle Ikonos, right Quickbird. The smaller the GSD, the larger the problems. The spill is always in the scan direction (forward in left image, reverse for the other two images).

ETH

Radiometric Quality

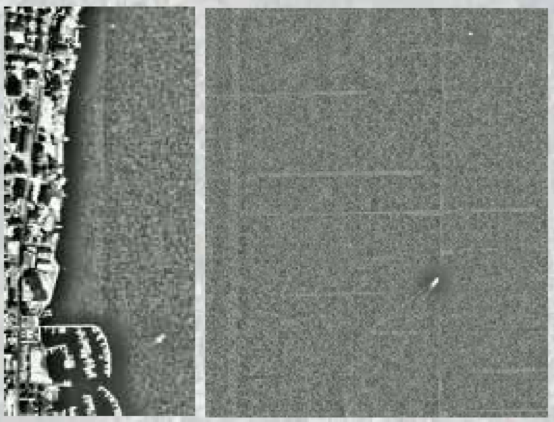
Cause of Spilling



Bidec angle (Space Imaging, Eye on Quality, How collection geometry affects specular reflections, 2002)

Radiometric Quality

Image Artifacts



Left: grey level jumps ; Right: bright horizontal and vertical stripes

Radiometric Quality

Image Artifacts
Pan-Sharpened Ikonos

Ghosting of moving object due to the 0.5 s time difference between acquisition of PAN and MSI

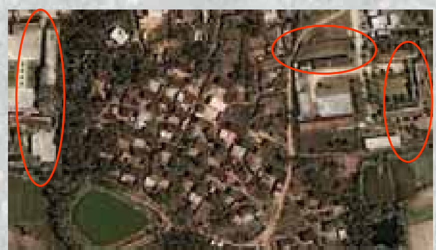
Radiometric Quality

• **Role of shadows and saturation (bright walls)**

Image feature variation - *Ikonos* GEO 1m pan sharpened (RGB), Chinese military base in Hainan
Similar sun elevation / azimuth, quite similar sensor elevation

4 / 4 / 2001

9 / 4 / 2001



10 / 4 / 2001

30 / 4 / 2001

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Preprocessing

Aim: Noise reduction, contrast & edge enhancement

Methods:

1. - linear reduction from 11 to 8-bit
   - Gaussian filtering
   - Wallis filter
2. Like 1 but after Gaussian filtering
   - unbiased anisotropic diffusion
3. - adaptive noise reduction (2 methods)
   - Wallis filtering
   - reduction to 8-bit (histogram equalisation or normalisation)

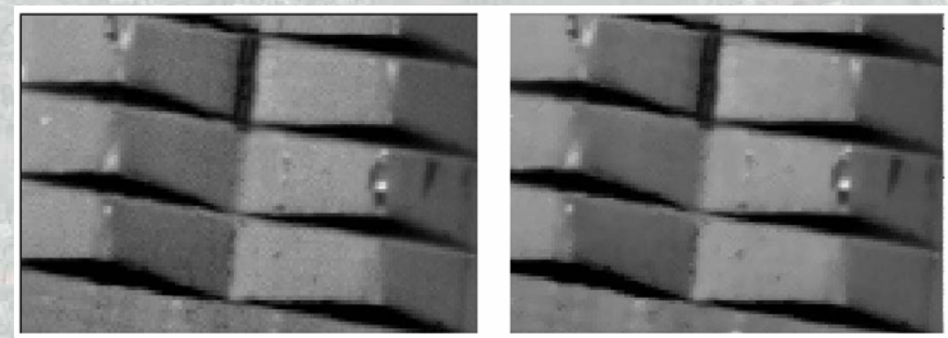
Preprocessing - Noise reduction , contrast & edge enhancement

Original

Original, contrast enhanced

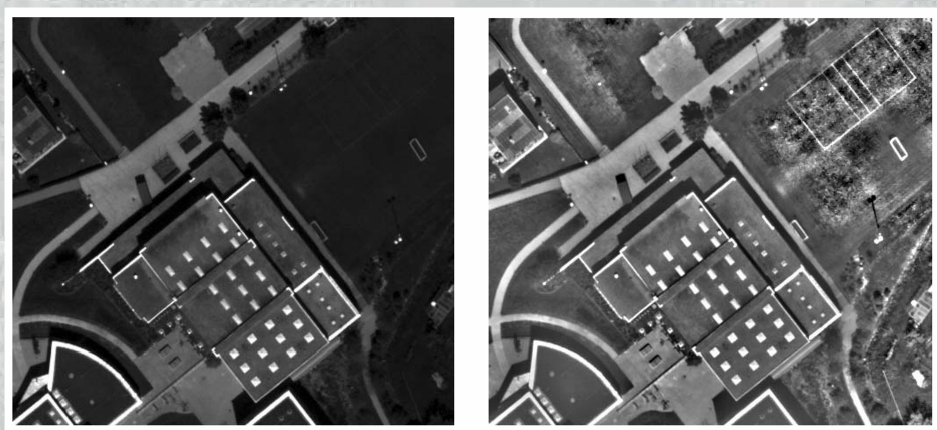
Preprocessed 2

Preprocessed 3

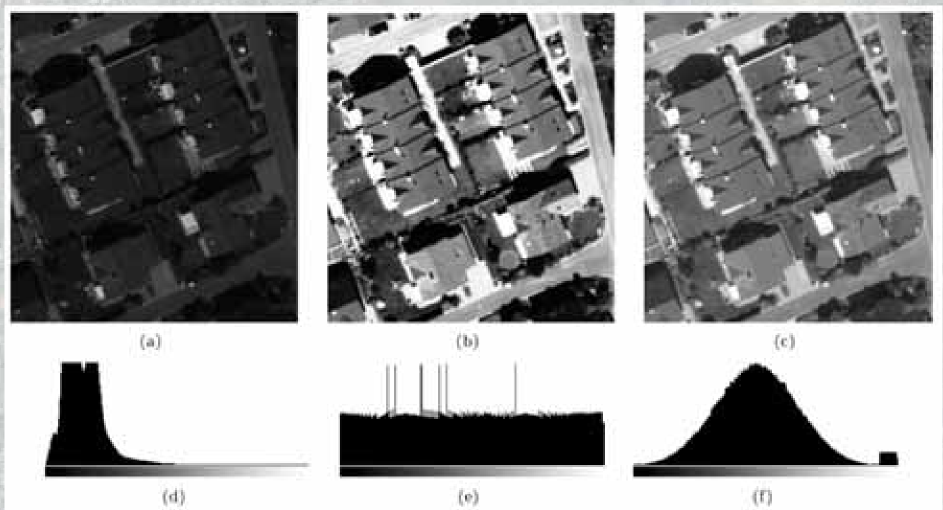


Edge preserving noise reduction (right) with adaptive fuzzy filtering.

Small details are kept and edges are in addition sharpened.



Contrast enhancement with Wallis filter. Left before, right after filtering.



Reduction to 8-bit. Left with linear transform, middle histogram equalization, right histogram normalization.

Sensor Modeling and Block Adjustment (for linear CCDs)

- Rigorous sensor model

  + Physical imaging geometry (nearly parallel projection in along-track and perspective projection across-track); high accuracy; easier for statistical analysis

  - Mathematically more complicated; depends on sensor type; often many parameters involved, especially in the interior orientation; many parameters are highly correlated.

- Sensor model based on RPCs

  + RPCs (e.g. for IKONOS, Quickbird) provided by firms computed from rigorous model, not using simply GCPs !

  + Need of corrections, else errors can be 10-20m to several hundred m

  + At ETHZ, RPCs and then

    - 2 shifts (RPC1)

    - affine transformation (RPC2)

  + Ikonos: 2 shifts suffice, scale in strip direction needed, if strip long, e.g. > 50 km (Grodecki & Dial, 2003)

  + Quickbird: affine transformation needed, due to nonlinearities

  + Min. 1-3 ground control points (GCPs) needed

- Simple sensor models (terrain corrected 2D affine, 3D affine, DLT) (Fraser et al., 2002)

  + For Ikonos similar or slightly worse accuracy, except forward scan (where accuracy decreases due to body rotation)

  + With Quickbird much worse accuracy than with RPCs (due to nonlinearities)

  + Min. 3-4 GCPs needed

Rational Functions (RFCs or RPCs)

A polynomial based restitution approach which will enable 2D & 3D exploitation of satellite imagery, to a given degree of accuracy, without knowledge of the camera model.

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ + a_7XYZ + a_8X^2 + \ldots + a_{19}Z^3}{1 + b_1X + b_2Y + b_3Z + b_4XY + b_5XZ + b_6YZ + b_7XYZ + b_8X^2 + \ldots + b_{19}Z^3}$$

$$y = \frac{c_0 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ + c_6YZ + c_7XYZ + c_8X^2 + \ldots + c_{19}Z^3}{1 + d_1X + d_2Y + d_3Z + d_4XY + d_5XZ + d_6YZ + d_7XYZ + d_8X^2 + \ldots + d_{19}Z^3}$$

x,y = image coordinates; X,Y,Z = object coordinates (coordinates typically offset & scaled)

- **RPCs derived by the image provider via a rigorous model.**
- **For the Ikonos *Geo* product, RPCs are derived using only IO & EO data from the satellite ephemeris & star trackers - no GCP data is employed.**
- **RPCs can be expected to yield higher relative than absolute 3D point precision due to EO biases (specs. not available on relative accuracy)**
- **RPCs are sensor independent & support non-iterative solution for the real-time restitution loop in a range of object space coordinate systems.**

Sensor models

- GCPs

- important their quality, not their number
- try to use well defined points (centers of circular objects), straight lines with large intersection angle. Measure them semi-automatically (ca. 0.1 pixel accuracy).
- distribution of GCPs can be suboptimal (e.g. 1/3 of image dimensions covered), but safer to have a good planimetric and height distribution.

- Ikonos vs. Quickbird

- Similar accuracy although Quickbird smaller GSD
- Quickbird has many non-linearities -> higher order terms needed in sensor model
- Quickbird: due to higher satellite speed and lower flying height, less frequent stereo images than Ikonos, no triplette possible?

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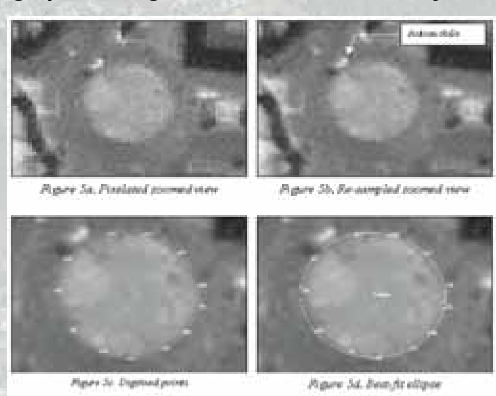
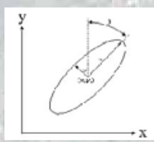
GCP example: roundabout (Melbourne testfield)

Roundabout measurement via ellipse fit

Edge points digitized semi-automatically, followed by ellipse fit

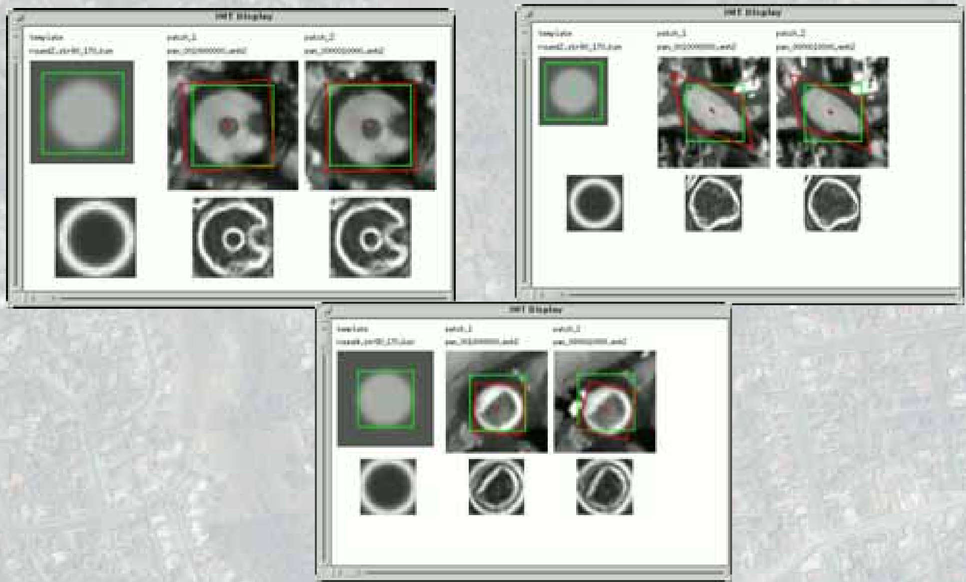




$$\left(\frac{\cos^2\theta}{a^2}+\frac{\sin^2\theta}{b^2}\right)(x-x_D)^2+\sin 2\theta\left(\frac{1}{a^2}-\frac{1}{b^2}\right)(x-x_D)(y-y_D)+\left(\frac{\sin^2\theta}{a^2}+\frac{\cos^2\theta}{b^2}\right)(y-y_D)^2=0$$

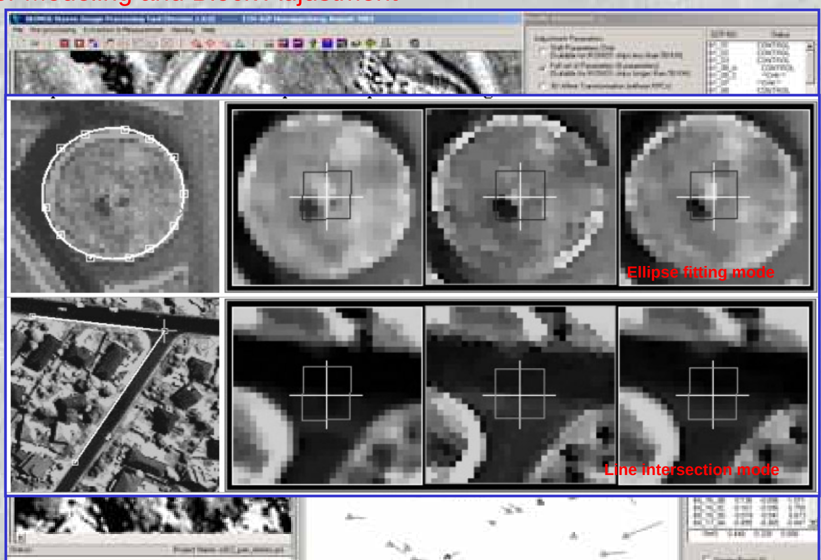
E. Baltsavias – ISPRS Tutorial, AfricaGIS 2005, Tshwane (Pretoria)

Roundabout measurements via least-squares template matching



E. Baltsavias – ISPRS Tutorial, AfricaGIS 2005, Tshwane (Pretoria)

Sensor Modeling and Block Adjustment



User-interface for GCP measurement & block adjustment (Sat-PP ETHZ)

E. Baltsavias – ISPRS Tutorial, AfricaGIS 2005, Tshwane (Pretoria)

Sensor Modeling and Block Adjustment (results from Thun, CH)

Comparison of sensor models and number of GCPs for the IKONOS triplet (T_DEC_O). CPs are check points.

Sensor Model	GCPs (CPs)	X-RMSE (max. error) [m]	Y-RMSE (max. error) [m]	Z-RMSE (max. error) [m]
M_RPC2	22 (0)	**0.32** (0.70)	**0.78** (1.53)	**0.55** (0.78)
M_RPC2	18 (4)	**0.33** (0.80)	**0.79** (1.48)	**0.56** (1.41)
M_RPC2	12 (10)	**0.32** (0.73)	**0.82** (1.64)	**0.60** (1.04)
M_RPC2	5 (17)	**0.44** (1.04)	**0.92** (1.83)	**0.65** (1.15)
M_RPC1	22 (0)	**0.35** (0.82)	**0.41** (0.91)	**0.67** (0.80)
M_3DAFF	22 (0)	**0.32** (0.73)	**0.78** (1.50)	**0.55** (0.78)

Comparison of sensor models and number of GCPs for the IKONOS triplet (T_DEC_N). CPs are check points.

Sensor Model	GCPs (CPs)	X-RMSE (max. error) [m]	Y-RMSE (max. error) [m]	Z-RMSE (max. error) [m]
M_RPC2	22 (0)	**0.37** (0.70)	**0.32** (0.79)	**0.48** (1.07)
M_RPC2	18 (4)	**0.38** (0.79)	**0.33** (0.75)	**0.50** (0.98)
M_RPC2	12 (10)	**0.40** (0.92)	**0.35** (0.85)	**0.69** (1.66)
M_RPC2	5 (17)	**0.45** (1.08)	**0.43** (0.96)	**0.76** (1.86)
M_RPC1	22 (0)	**0.37** (0.76)	**0.34** (0.66)	**0.64** (1.26)
M_3DAFF	22 (0)	**0.43** (0.89)	**0.53** (0.90)	**0.76** (1.83)

Sensor Modeling – 2D Positioning (Ikonos results from Melbourne, Fraser (2001))

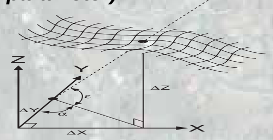
Object point XYZ coordinates 'rectified' to a 'projection plane' based on satellite position to remove height effects

Three 2D transformations carried out:

1) Similarity (rigid body, 4 parameter)

2) Affine (6 parameter)

3) Projective (8 parameter)



Accuracies of XY determination to better than 0.5m - shows good 'linearity' of the *Ikonos* sensor system

RMS XY Coordinate Discrepancies in Pixels (& Metres)

Image; num of points	Similarity X	Similarity Y	Similarity XY	Affine X	Affine Y	Affine XY	Projective X	Projective Y	Projective XY
1. Near Nadir; 31	0.27	0.33	0.30	0.26	0.32	0.29	0.23	0.30	0.27
2. 'Left' Stereo; 26	0.35	0.39	0.37	0.33	0.37	0.35	0.33	0.36	0.35
3. 'Right' Stereo; 28	0.39	0.37	0.38	0.38	0.36	0.37	0.39	0.35	0.37

Sensor Modeling – 2D Positioning (Ikonos results from Melbourne, Fraser (2001))

Object point XYZ coordinates transformed to pixel coordinates via RPCs

Pixel coordinate differences

	Ellipse fitting			
	Left Image		Right Image	
	x	y	x	y
Mean	28.94	-16.07	28.00	-16.52
Stand. Dev.	0.40	0.35	0.56	0.46

Sensor Modeling – 3D Positioning (Ikonos results from Melbourne, Fraser (2001))

- **Stereo-image triangulation performed (standard least-squares model)**
- **Mean biases in absolute positioning:**
  - **Easting: 8.2m**
  - **Northing: 31.5m**
  - **Height: 1.7m**
- **Provision of 3 GCPS & 3D similarity transformation yielded accuracies of**
  - **Planimetry: 0.5m**
  - **Height: 0.8m**
- **Use of translation in pixel space enough to correct the biases**
- **Even 1 GCP & translation reduces biases to 1- 2 m in the worst case**

For different 6-GCP sets & 20 checkpoints:

- RMS XY = 0.4- 0.6m
- RMS Z = 0.6 - 0.8m