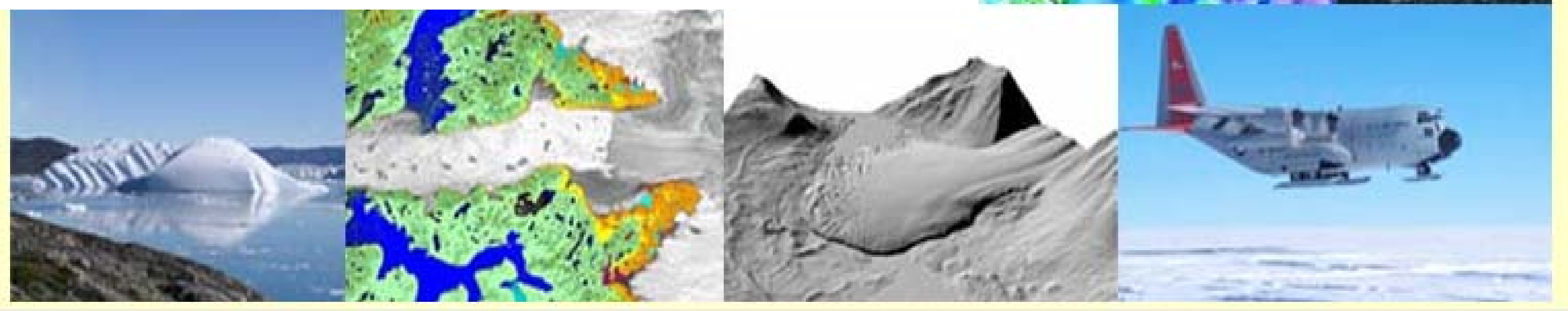
# Registration of and Validation of ICESat Laser Altimetry Products

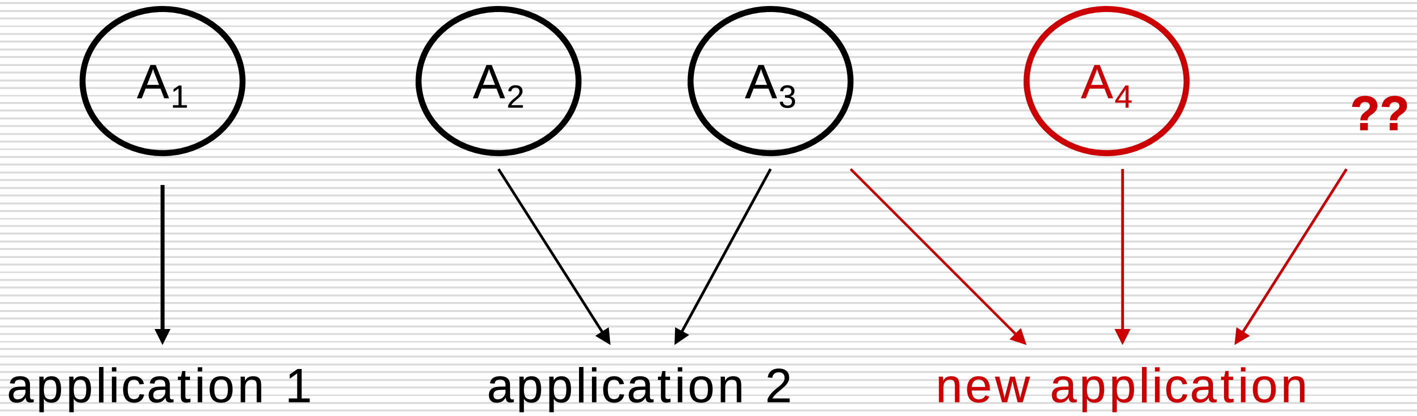
Bea Csatho and Toni Schenk
The Ohio State University
[csatho.1;schenk.2]@osu.edu



# Overview

- Registration
  - Current status
  - General aspects
  - Solutions
  - Problems
  - Examples:
    - Registration of panoramic photographs
    - Registration of imagery to laser points
    - Feature-based registration
- Satellite laser altimetry
  - Waveform simulation
  - Validation of altimetry products

# Current Status



$A_1$ $A_2$ $A_3$ $A_4$ ??

application 1

application 2

new application

# How To Go From Here?

- Current status: seek solution on tool level
  - add/modify algorithms
  - change thresholds and parameters
- Preferred solution: general registration framework
  - what are the relevant processes?
  - what is application independent?

# Marr's Theorem from Computer Vision

1. theoretical level: specifies what the process should do. Purpose of computations and strategy for solution?
2. algorithmic and representational level: investigates representation of input and output and algorithms that transform input to output
3. hardware level: how can representations and algorithms be physically implemented

# Summary

- registration is a difficult but tractable problem
- registration problem cannot be solved on algorithmic and implementation levels
- top down approach: establish first theoretical framework and then choose/develop algorithms

# Registration “Flowchart”

Image to map registration

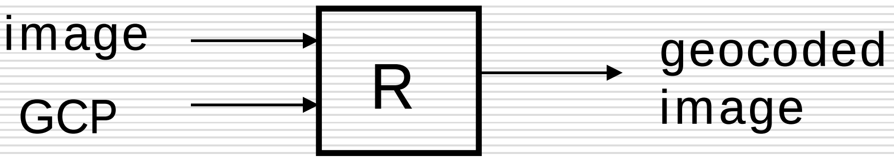
1. identify and measure control points in image
2. run transformation
3. check results
4. edit
5. repeat 1 through 4 until satisfied

# General Aspects

- what (sensors) should be registered?
- what mathematical model?
- how to establish correspondences?
- interpolation, prediction?
- quality control?

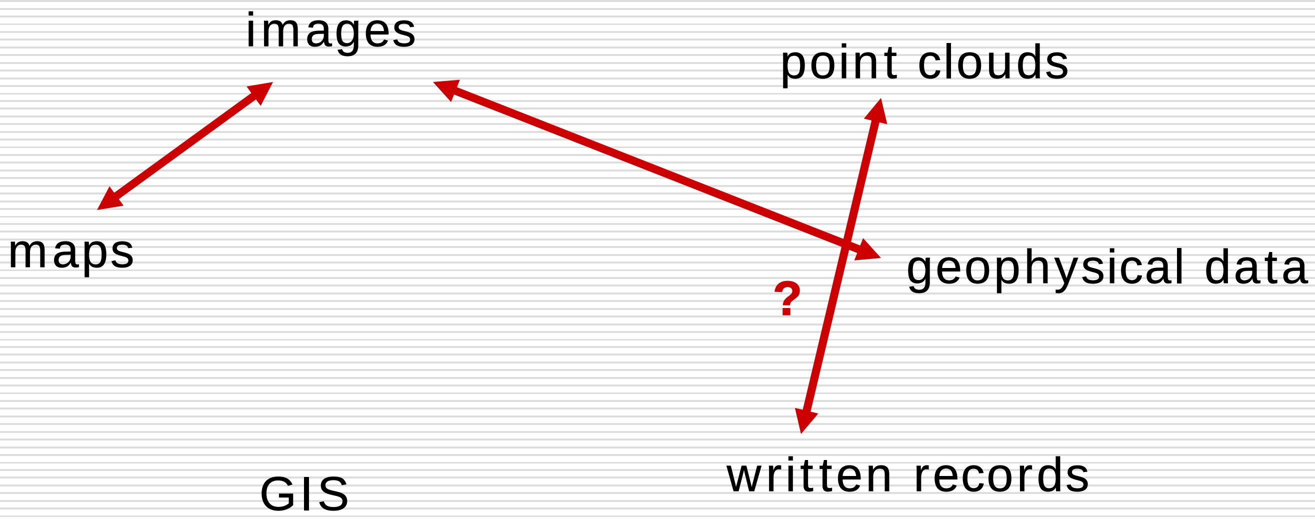
# What should/could be registered?

register A to B



**what 'things' can A and B be?**

# What should/could be registered?



images

point clouds

maps

geophysical data

?

written records

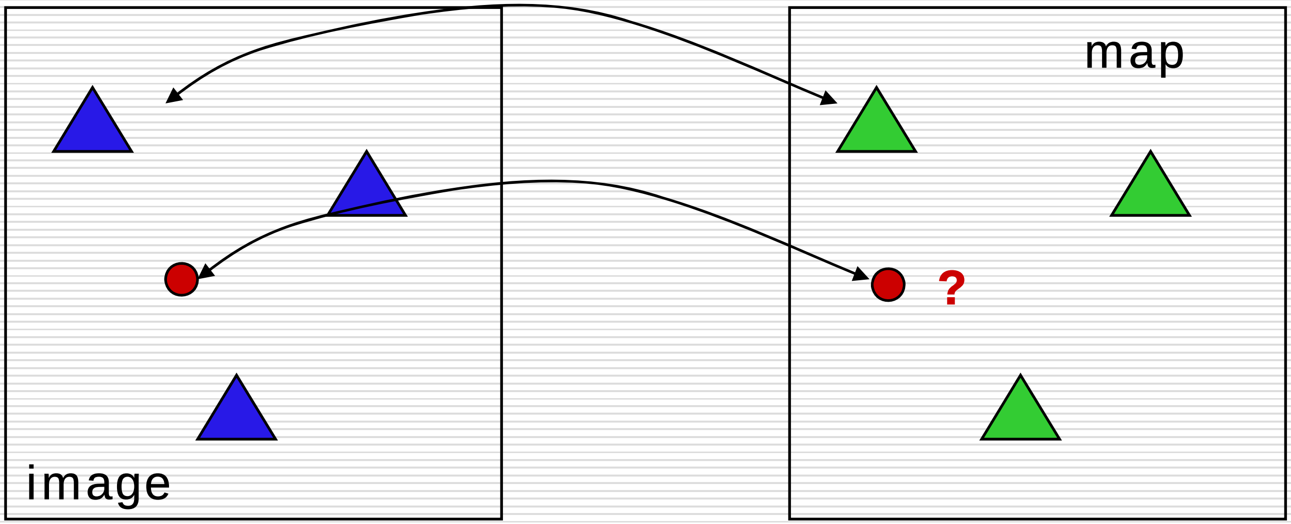
GIS

# Correspondence

- Fundamental problems:
  - what is identical in the sensors to be registered?
  - how are identical 'things' (features?) represented?
  - how are features extracted and organized?
  - how to find correct pairings?

# General Aspects: Interpolation

- general assumption or expectation: after registration every item can be transformed



# Interpolation, Prediction

- Problems:
  - registration established with a few control points➔ how can one generalize
  - there is no one-to-one relationship
    - occlusions
    - space may not be contiguously covered (non-imaging sensors!)

# Quality Control

- QC in our example: statistical analysis of registration (transformation), e.g. residuals
  - 3 GCP and affine transformation→ $\sigma = 0$
  - accuracy of interpolated points?
  - the more control points the larger $\sigma$ but the more controlled are the interpolated features

# Rigorous Solution

- exhaustive enumeration of all corresponding features
- example: image to image registration

| i 1 | i 2 |
|---|---|
| r,c | r,c |
| r,c | r,c |
| r,c | r,c |

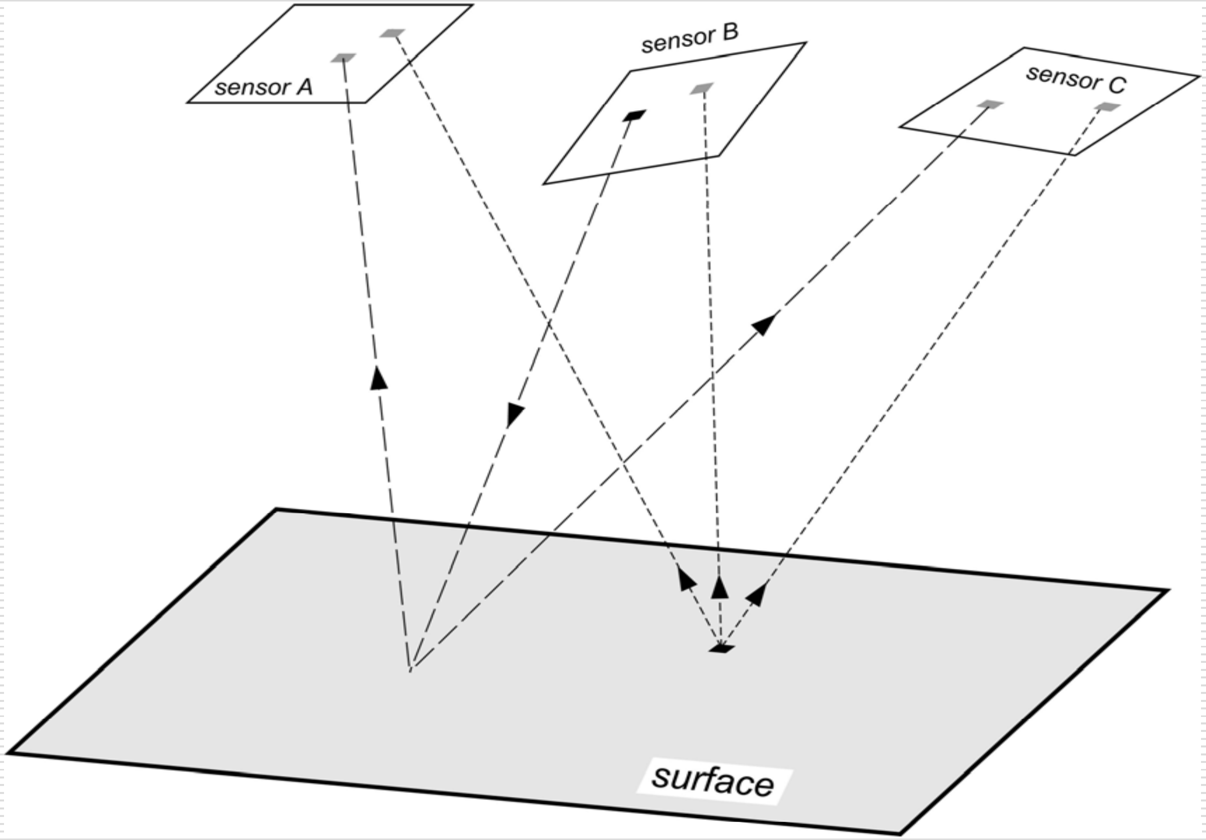
# General Registration Problem

1. Pick entity in one sensor
2. Determine corresponding (conjugate) locations in all other sensors

-or-

1. Pick entity in object space
2. Determine its location in all sensors

# Rigorous Solution



# Rigorous Solution

- registration through contiguous object space
- requires sensor model, sensor orientation and complete surface
- advantage:
  - multisensor scenario
  - quality control, based on error propagation

# Approximate Solutions

- registration function reg(x,y,x′,y′)
- established through corresponding features and mathematical model
- reg combines sensor model, sensor orientation and surface
- any function reg is only an approximation of physical reality

# Approximate Solutions

- affine transformation
  - simple model, can only handle flat surfaces
  - sensor model?
  - sensor orientation?
- RFM
  - more sophisticated but restriction on surface: must be a continuous function
  - RFC absorb not only sensor model but also surface!

# Example 1: Registration of Panoramic Photographs

- CORONA is the 1st satellite imaging system
- specifications compete with modern systems
  - 2 m ground resolution
  - high stability film
  - stereo capabilities
- interesting applications in earth science
  - urban expansion studies
  - ice sheet dynamics
- 1995 Pres. Clinton declassified photographs collected during the cold war, including CORONA photographs → the photographs are known as **D**eclassified **I**ntelligence **S**atellite **P**hotographs (DISP)

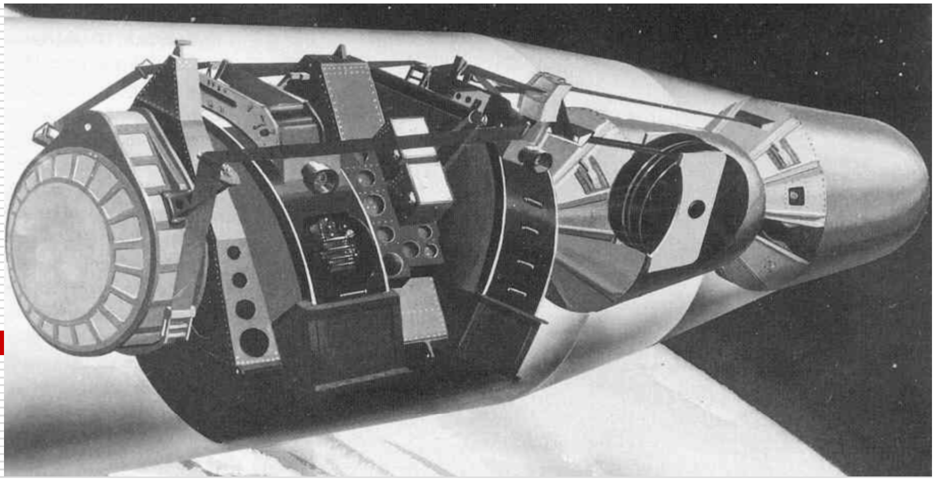
# US Satellite Reconnaisance Systems in the 1960s

| System | Operation | Type of camera | Resolution |
|---|---|---|---|
| Argon | 1962-1964 | Frame | 180 m |
| Corona (KH-1—KH-4B) | 1959-1972 | Panoramic | 2-12 m |
| Lanyard | 1963 | Panoramic | 2 m |

Photographs and design of systems were declassified in 1995

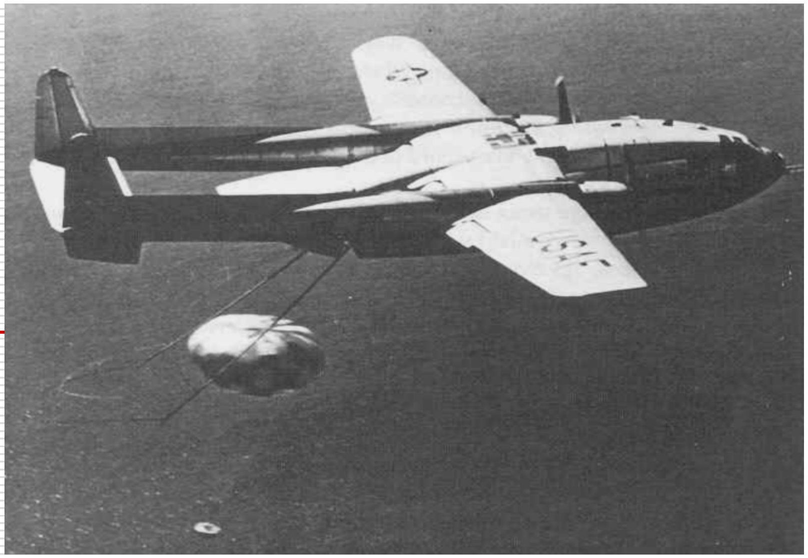
For the history of these early space missions see *Corona, between the Sun and the Earth; The first NRO reconnaissance eye in space*, by R. McDonald, editor, 1997, ASPRS, 440 pages

# Corona KH-4 Missions



- ☐ Mission: 1962-1979
- ☐ Data acquisition: analogue, using special high definition B/W negative film
- ☐ Cameras: two panoramic cameras with 30° separation angle to provide stereoscopic coverage
- ☐ Camera types: KH-4, KH-4A, KH-4B, all manufactured by Itek Corp.
- ☐ Best ground resolution: 3 m
- ☐ Nominal system altitude: 185 km
- ☐ Nominal ground coverage of photographs: 20 by 270 km

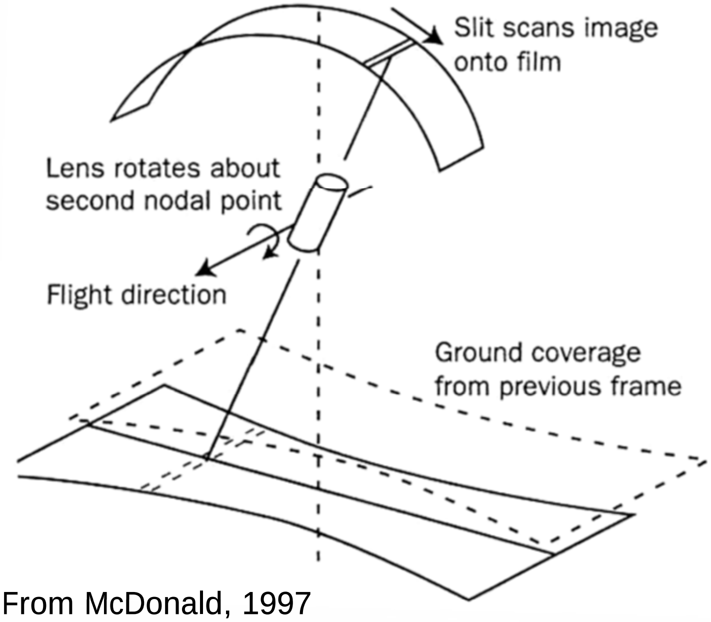
# Corona KH-4 missions (cont)



- Number of satellites: 95
- Orbit: low polar orbit
- Precise attitude control, accuracy of better than 0.2° in pitch, yaw and roll
- Film recovery: reentry capsules descending on parachutes were captured by aircrafts
- Geographic coverage: 95% non-US, 5% US
- Number of images declassified: 800,000 (total from all missions), disseminated by USGS

# Conceptual basis of Corona cameras

- Based on panoramic camera principle
- Slit moves, film is stable during image acquisition
- Image has high resolution over the entire wide-angle format
- Panoramic data acquisition results complicated image distortions
- Image motion compensation was applied to compensate for the motion of the platform with respect to the Earth surface



From McDonald, 1997

# Background

- CORONA: code name for first satellite imaging reconnaissance system
- launched 1958 by President Eisenhower
- last mission 1972
- total of 121 missions
    - 95 successful
    - 69 missions from 1963-1972 of which only 4 failed

# Principles

- photograph targets of interest with high resolution camera
- eject film from satellite
  - reentry vehicle carries film capsule
- recover film mid-air
  - C-130 airplanes catch capsule with line and hook, haul it in open cargo area

# CORONA Panoramic Cameras

- designed + developed by Fairchild and Itek
- camera designators **KH**, systems 1-4
- KH-4 series: twin panoramic cameras
  - convergence angle 30°
  - scan angle 70°
  - film format 2.18" by 29.8"
  - film capacity 32,000' → 19 days missions

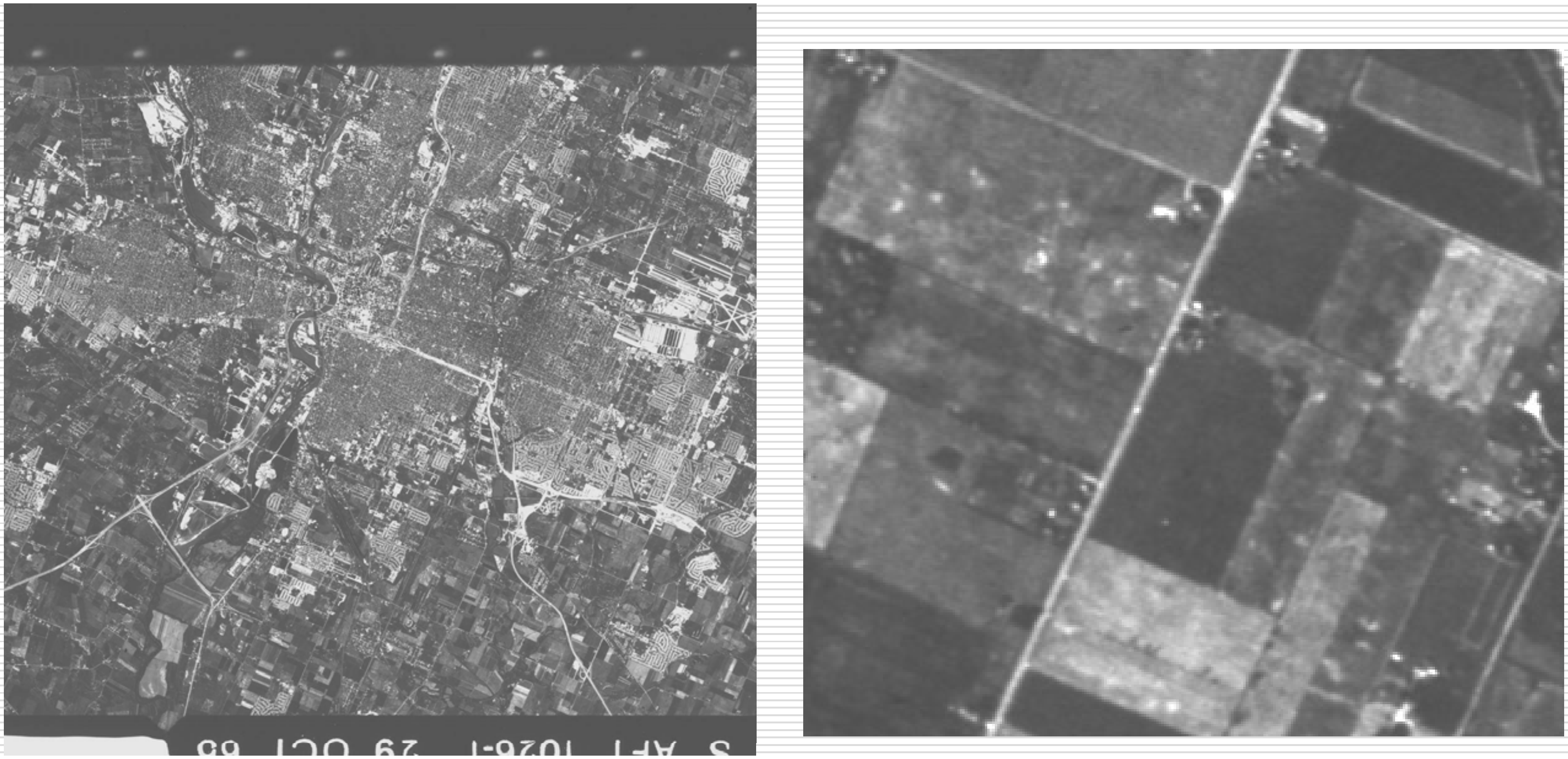
# CORONA Panoramic Cameras (ctd)

- lens system
  - Petzval system, 5 positive lenses
  - focal length 2'
  - lens barrel 3', length 4'
  - f/3.5 aperture ➔ slow film
  - resolution:
    - lab tests: 280 lp/mm
    - operational conditions: 160 lp/mm ➔ ~2 m ground res.

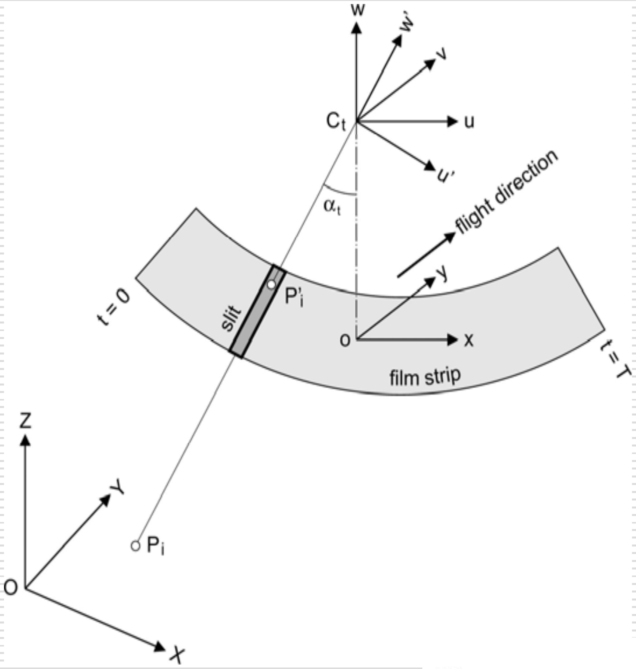
# DISP Imagery

- 1995 Pres. Clinton declassified CORONA, known as **D**eclassified **I**ntelligence **S**atellite **P**hotographs (DISP)
- USGS in charge of archiving and disseminating DISP Imagery
  - 866,000 images
  - browse images on web
  - cost $18 for film, $16 for paper print

# Example DISP Image



# Coordinate Systems



$C_t$-u,v,w: camera system

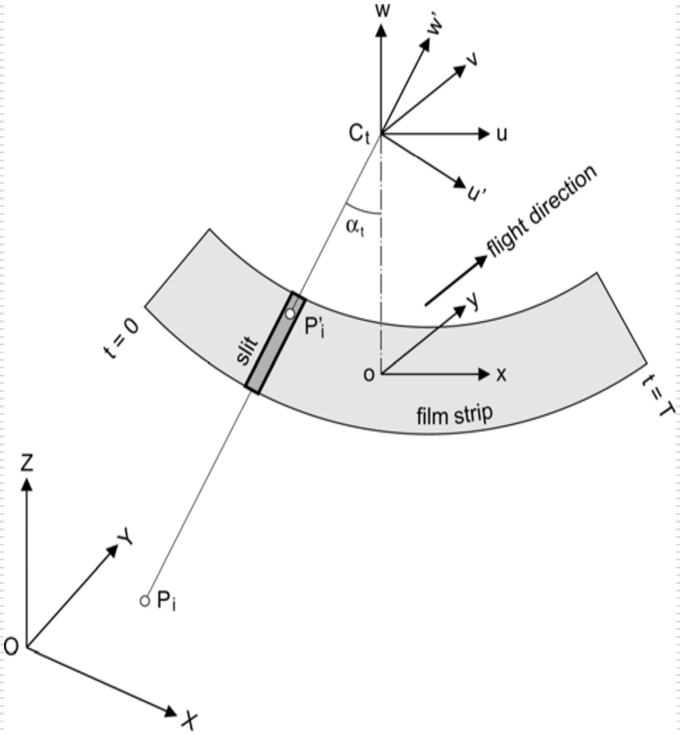
$C_t$-u’,v’,w’: slit system

O-x,y: image system

$$\begin{bmatrix} x_i \\ y_i \\ -f \end{bmatrix} = \lambda_i \begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix}$$

$$\alpha_t = x_i / f$$

# Extended Collinearity Equations



$$\mathbf{m}'_i = \mathbf{R}(t)(\mathbf{p}_i - \mathbf{c}_t)$$

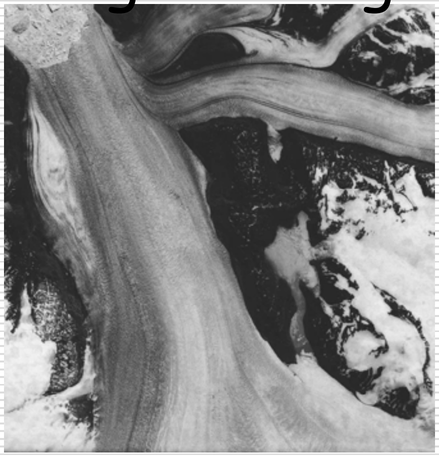
$$\mathbf{m}_i = \mathbf{R}_\alpha \mathbf{m}'_i$$

$$\mathbf{R}_\alpha = \begin{bmatrix} \cos\alpha_t & 0 & \sin\alpha_t \\ 0 & 1 & 0 \\ -\sin\alpha_t & 0 & \cos\alpha_t \end{bmatrix}$$

$$\boxed{\begin{bmatrix} 0 \\ y_i \\ -f \end{bmatrix} = \frac{1}{\lambda_i}\mathbf{R}_\alpha \mathbf{R}(t) \begin{bmatrix} X_i - X(t) \\ Y_i - Y(t) \\ Z_i - Z(t) \end{bmatrix}}$$

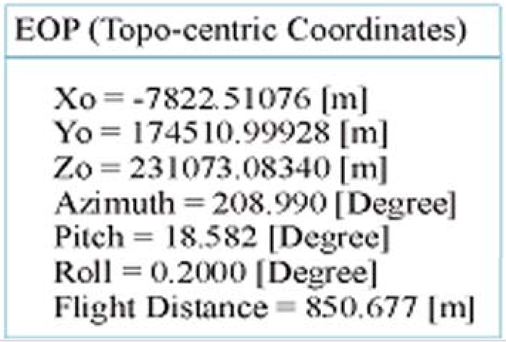
# Rectification of Corona image

Original image



Flight direction

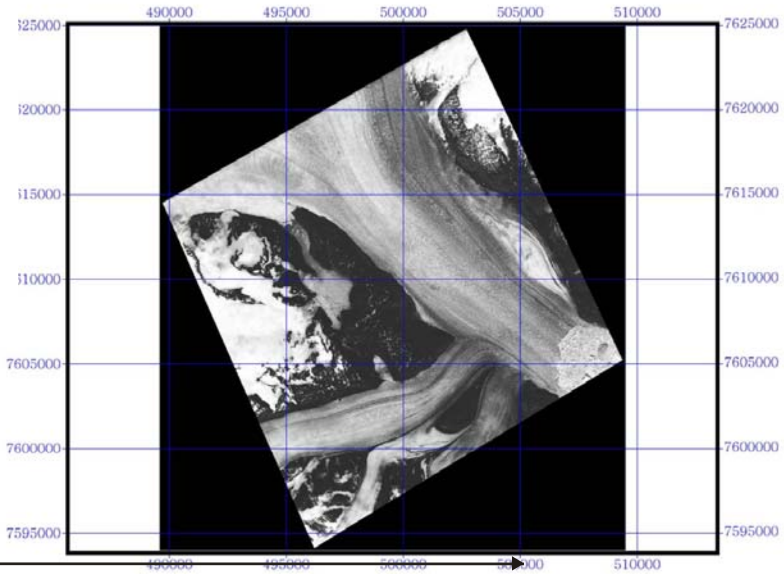
Data acquisition
and camera parameters



EOP (Topo-centric Coordinates)

Xo = -7822.51076 [m]
Yo = 174510.99928 [m]
Zo = 231073.08340 [m]
Azimuth = 208.990 [Degree]
Pitch = 18.582 [Degree]
Roll = 0.2000 [Degree]
Flight Distance = 850.677 [m]

Rectified image



270 km

# Example 2: Registering Images and LIDAR

**image**

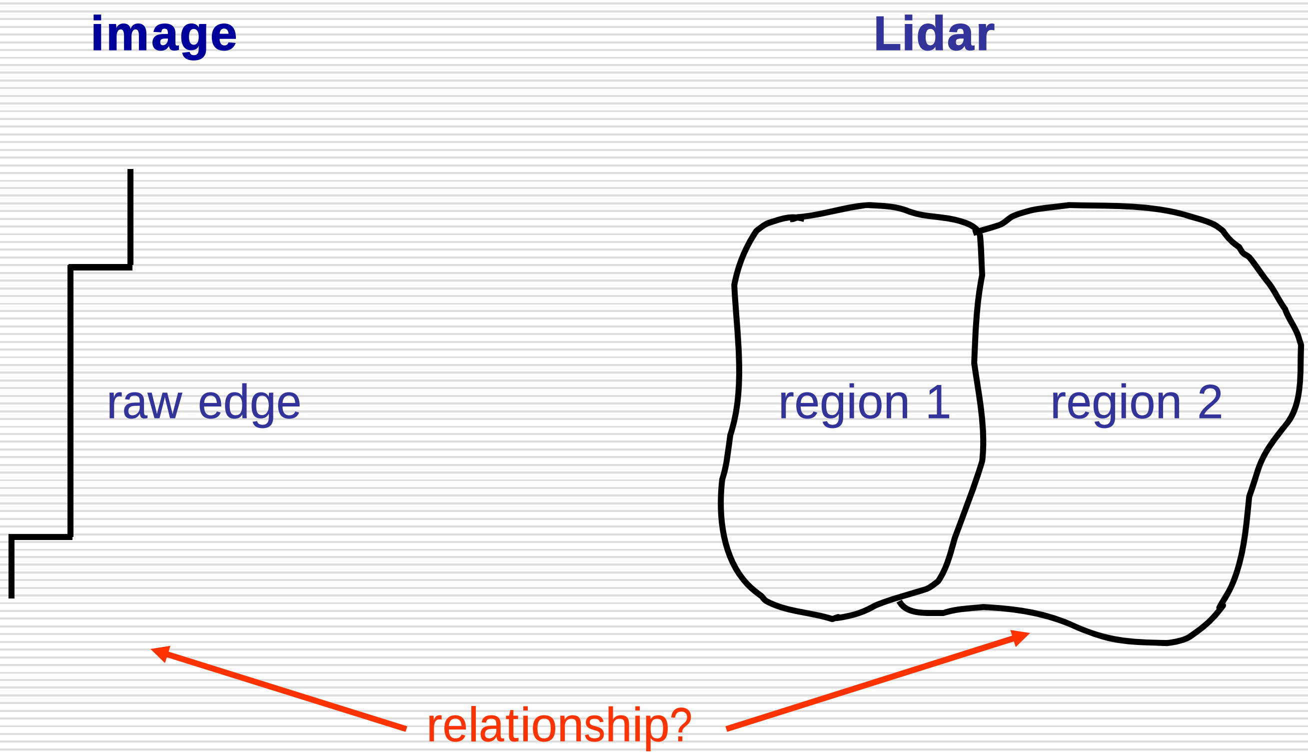
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 11 | 12 | 18 | 15 | 25 | 23 | 26 | 35 | 39 |
| 13 | 14 | 13 | 16 | 27 | 28 | 23 | 29 | 35 |
| 10 | 11 | 14 | 26 | 29 | 24 | 25 | 31 | 33 |
| 8 | 10 | 15 | 27 | 29 | 28 | 24 | 33 | 43 |
| 7 | 11 | 16 | 21 | 31 | 29 | 24 | 38 | 41 |
| 17 | 13 | 15 | 25 | 28 | 31 | 34 | 39 | 37 |
| 12 | 14 | 16 | 22 | 25 | 30 | 35 | 36 | 38 |
| 13 | 15 | 17 | 23 | 27 | 29 | 28 | 29 | 31 |
| 15 | 16 | 12 | 24 | 29 | 22 | 25 | 26 | 36 |
| 12 | 14 | 20 | 19 | 25 | 26 | 28 | 31 | 40 |

**Lidar**

| lat. | long. | elevation |
|---|---|---|
| −77919570 | 160391245 | 2293070 |
| −77919598 | 160391159 | 2292722 |
| −77919627 | 160391070 | 2292269 |
| −77919654 | 160390975 | 2291878 |
| −77919680 | 160390872 | 2291602 |
| −77919705 | 160390762 | 2291472 |
| −77919729 | 160390650 | 2291181 |
| −77919753 | 160390535 | 2290794 |
| −77919774 | 160390407 | 2290911 |

relationship?

# Registering Images and LIDAR



**image**

**Lidar**

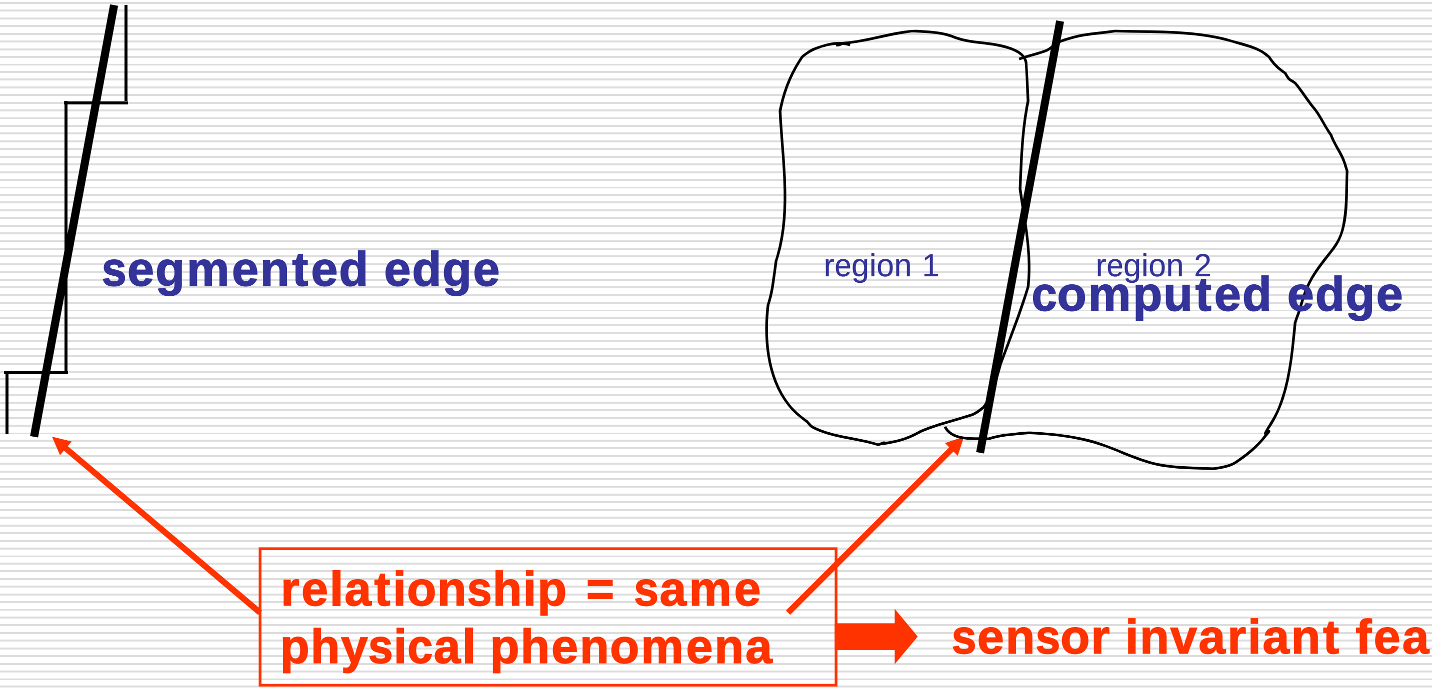
raw edge

region 1

region 2

relationship?

# Registering Images and LIDAR



**image**

**Lidar**

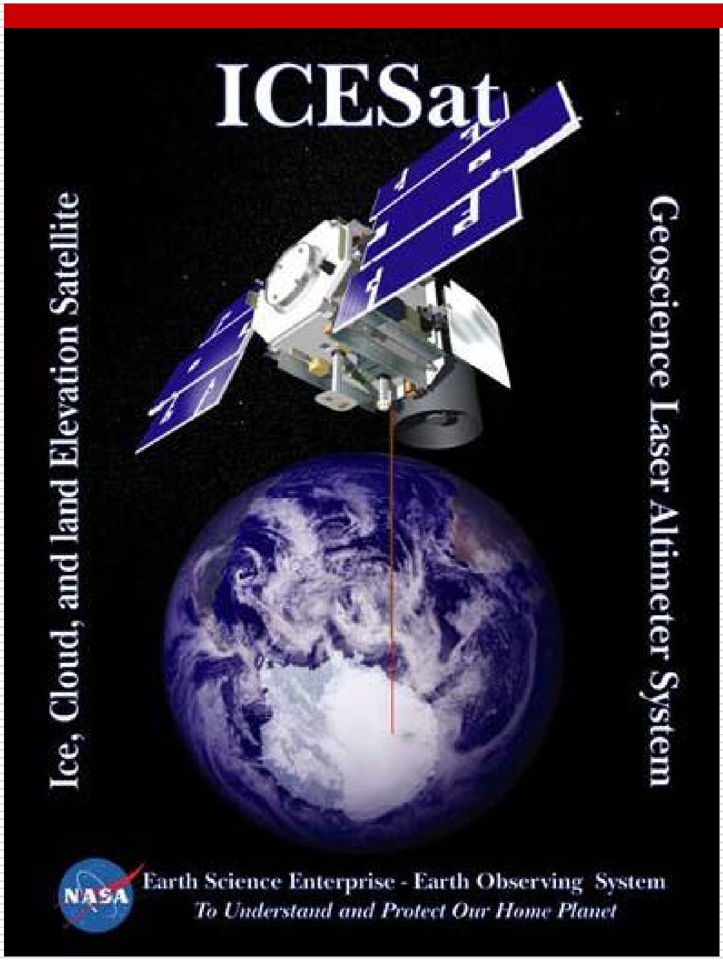
**segmented edge**

**computed edge**

**relationship = same physical phenomena**

→ **sensor invariant feature**

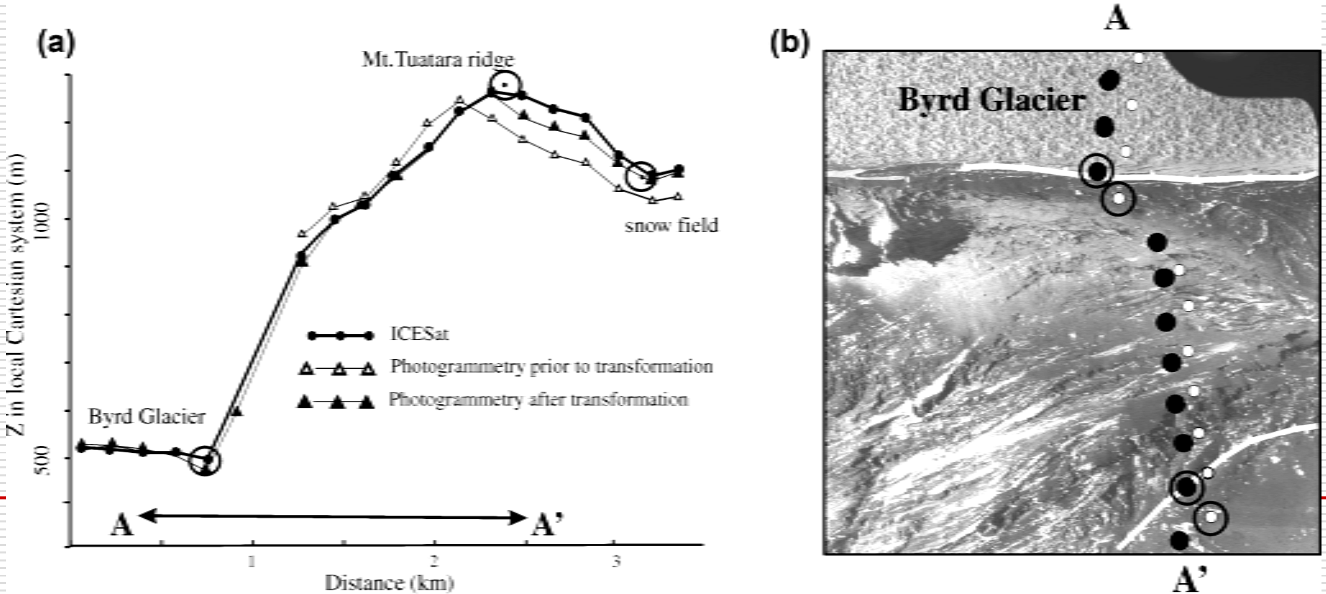
# Satellite Laser Altimatry Data form Ice, Cloud, and land Elevation Satellite (ICESat), 2003-present



- Science Objectives:
  - **Measurement of polar ice sheet mass balance**
  - Mapping and monitoring sea ice distribution and ocean surface
  - Determination of atmosphere-cloud heights and aerosol distribution
  - Mapping land topography
- Main sensor: Geoscience Laser Altimeter System (GLAS)
- ICESat was launched January 2003 from Vandenberg, CA
- 3 year lifetime (5-year design goal)

# Registering Imagery to ICESat Data for Measuring Elevation Changes on Byrd Glacier, Antarctica (Schenk, Csatho et al., 2005, *GRL, ICESat Special Issue*)

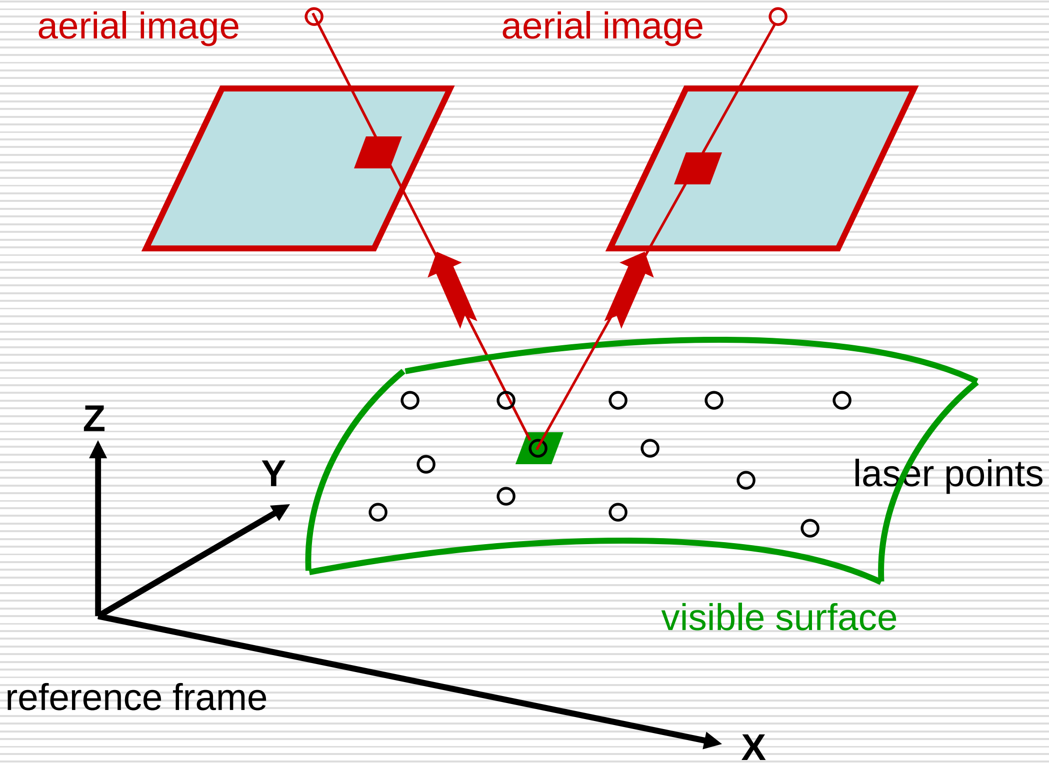
- **Input Data:**
  - Stereo aerial photographs from 1979 and **ICESat** satellite laser altimetry from 2005
- Large error in the registration of the aerial photographs
- Registration is based on correspondence between characteristic landscape points



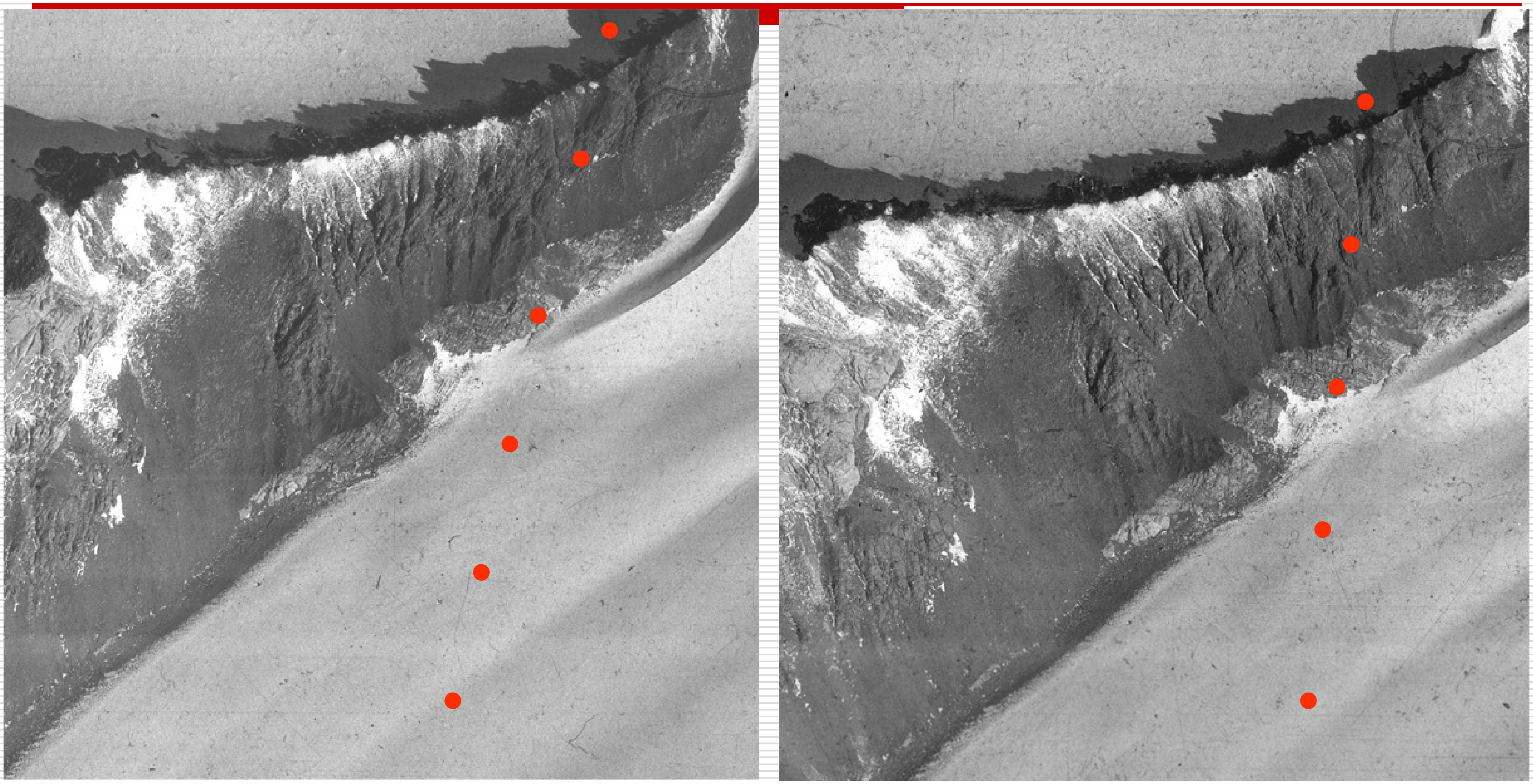
# Change Detection from ICESat Measurements and Aerial Photogrammetric Surveys

- **Processing:**
  - Step1: Orientation of aerial photographs with control information derived from ICESat
  - Step2: Elevation measurements from oriented stereomodels at ICESat points and computation of elevation changes
- **Quality control:**
  - Backproject ICESat points to images using the orientation (registration) of images involved
  - Registration errors or ICESat point errors displace ICESat footprint centers to non-corresponding locations

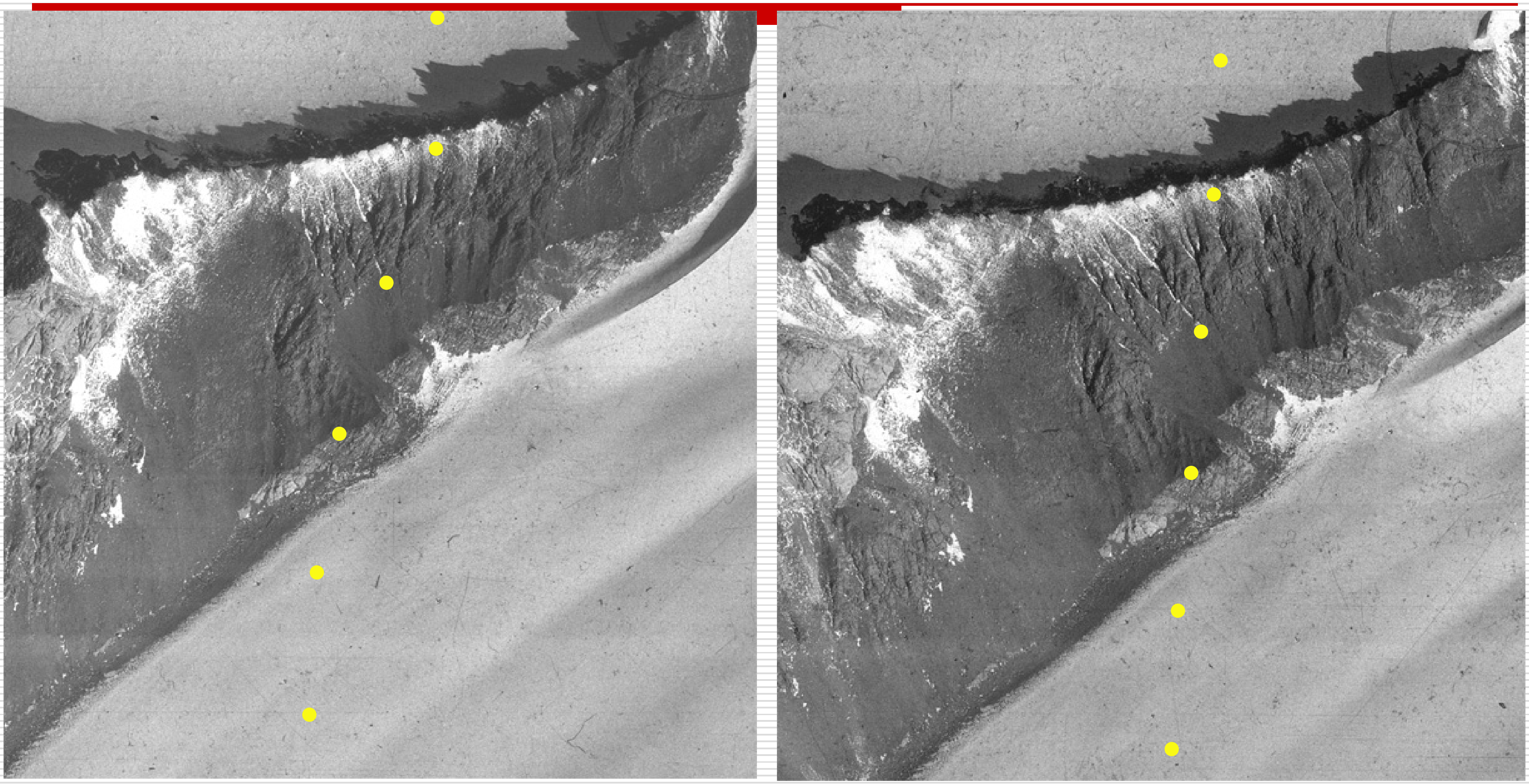
# Principle of Image Registration



# ICESat Laser Points Back-Projected To Stereo Images: Before Registration

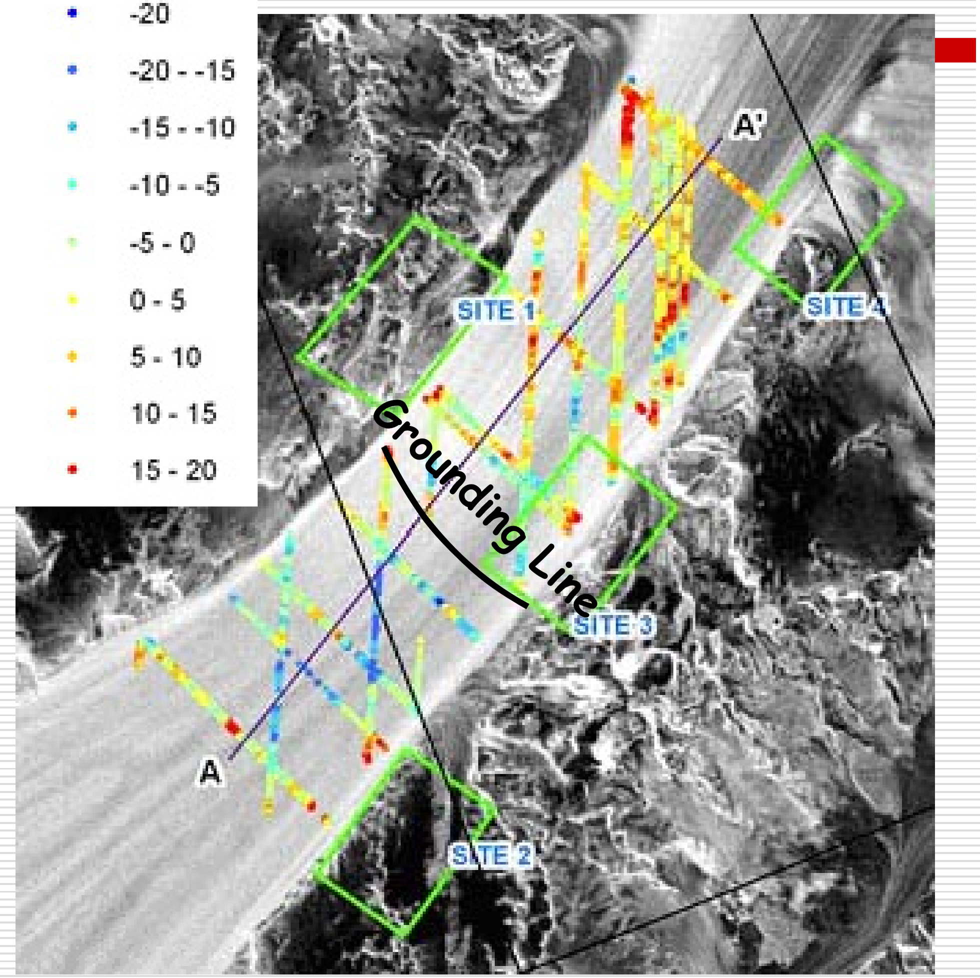


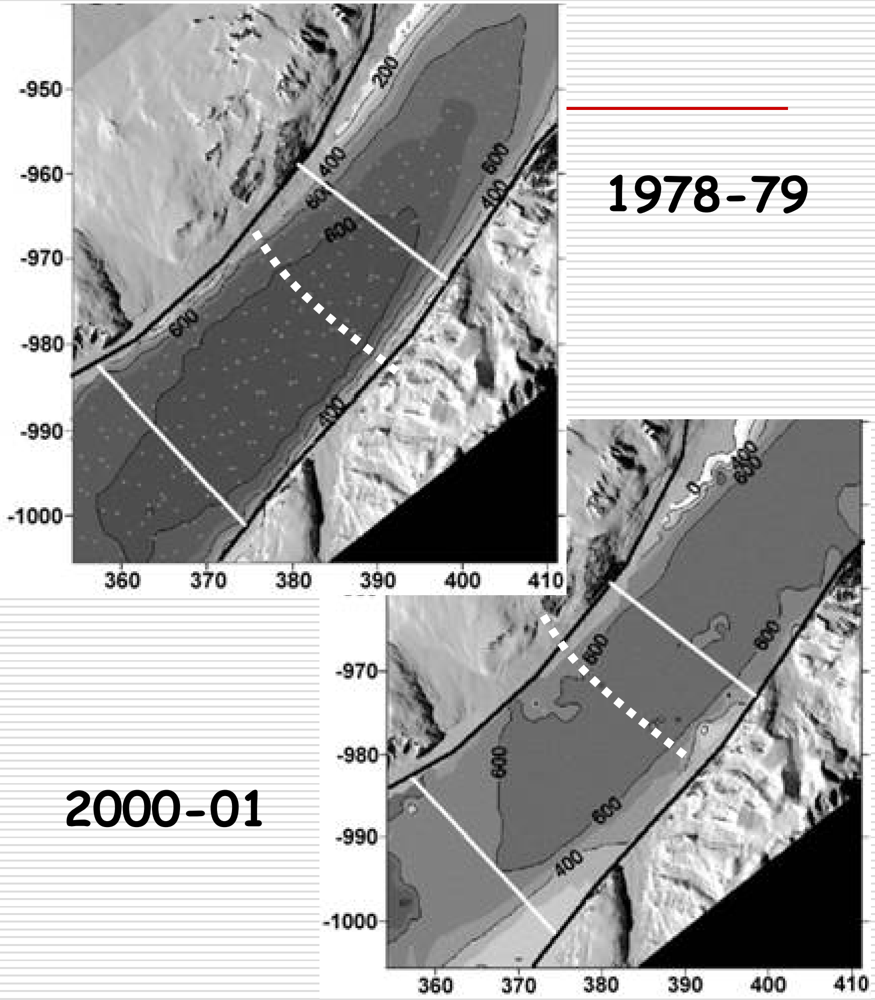
# ICESat Laser Points Back-Projected To Stereo Images: After Registration



# Byrd Glacier: Elevation Changes from 1978-79 to 2003-2005 (left) and Ice Velocity in 1978-79 and in 2000-01 (right)

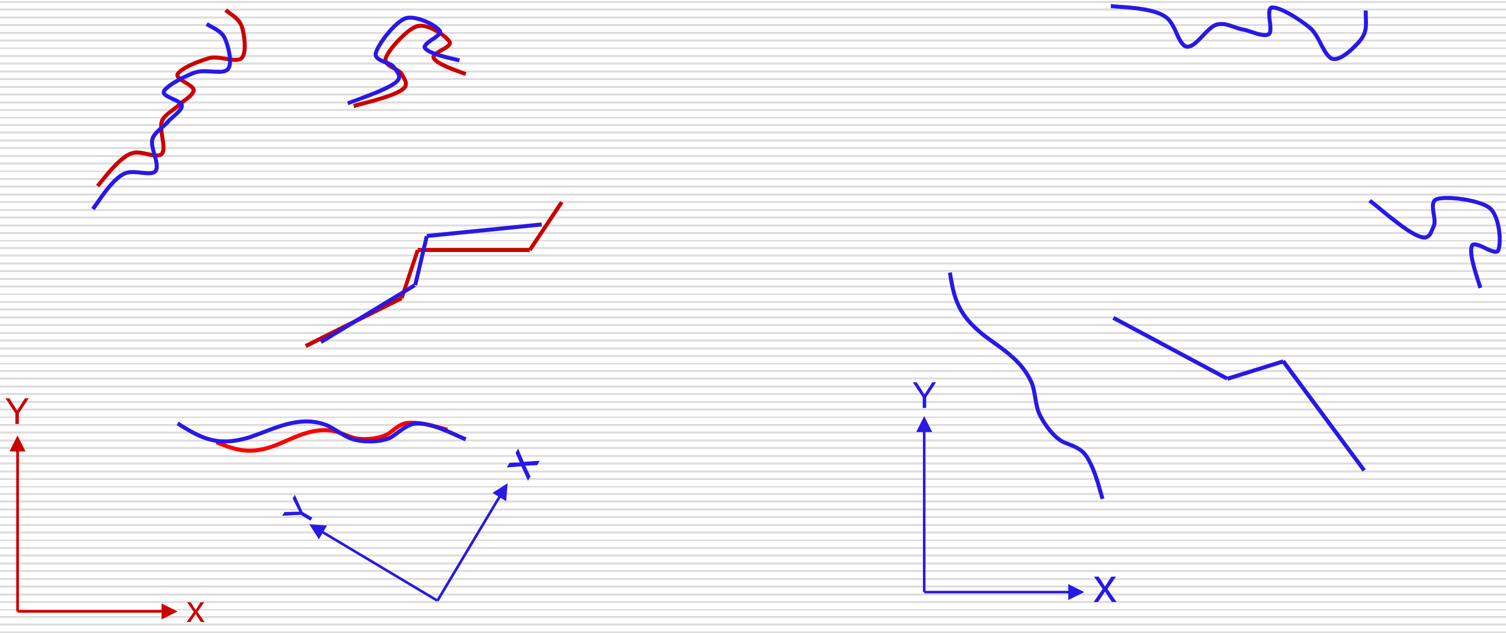
Elevation differences (m)





(Stearns and Hamilton, submitted)

# Example 3: Feature-based Registration



registration = ‘best’ fit of features

# Motivation for Using Features

- points carry nearly no semantic information
- main task of photogrammetry is to reconstruct the object space
- object space consists of features
- ➔ establish relationship between extracted features and objects

# Motivation for Using Features

- human operators select high-quality pts
- as few as possible points are measured
- computer operators are far inferior
- selection of high-quality pts requires IU
- matching features is more robust but more complex to implement
- use same features as other processes

# What are Control Features?

- ☐ linear features
  - straight lines
  - analytical curves
  - free-form curves
- ☐ areal features
  - planar surfaces
  - higher order analytical surfaces
  - free-form surfaces (DEM, DTM)

For details on feature-based approach refer to Schenk, 2004. From point-based to feature-based aerial triangulation. ISPRS Journal of Photogrammetry and Remote Sensing, 58, 315-329.

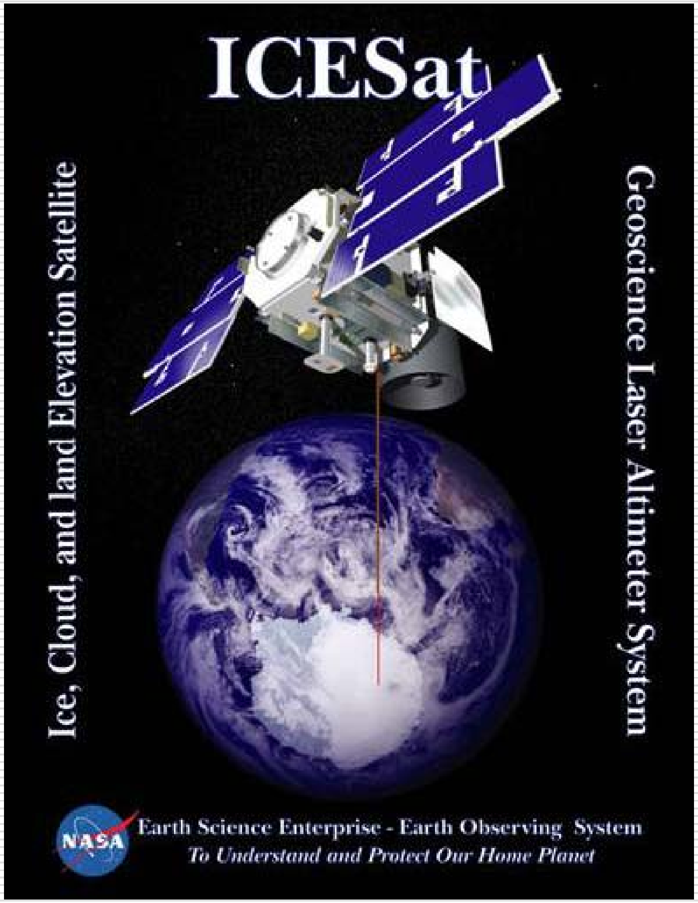
# Registration: Summary and Issues

- scope of registration
  - ➔ define input and output
  - input: what sensors, what combinations
  - additional input: surface
  - output: registration is not end result, it is a prerequisite for many applications
  - registration = sensor alignment in fusion?

# Issues (cont)

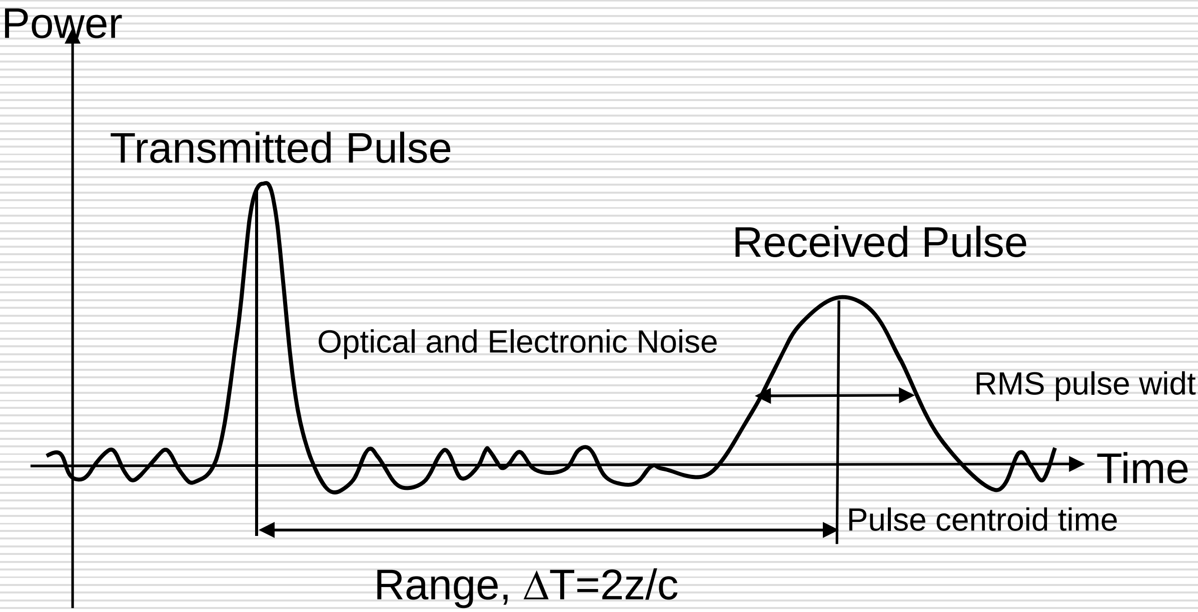
- realization:
  - interactive or autonomous?
  - a priori or on demand?
- does registration only deal with geometry?
  - symbolic registration, e.g. topological relationships?
- features: extraction, segmentation, grouping
- correspondence of features extracted in different sensors
- quality assessment
- 'hidden' assumptions

# Laser Altimetry Waveform Simulation and Validation of Derived Products



- ☐ ICESat laser altimetry products include within footprint slope, roughness and intensity derived from closed form for simple geometric models
- ☐ Precisely mapped terrain is used to validate these products

# Derivation of Received Waveform



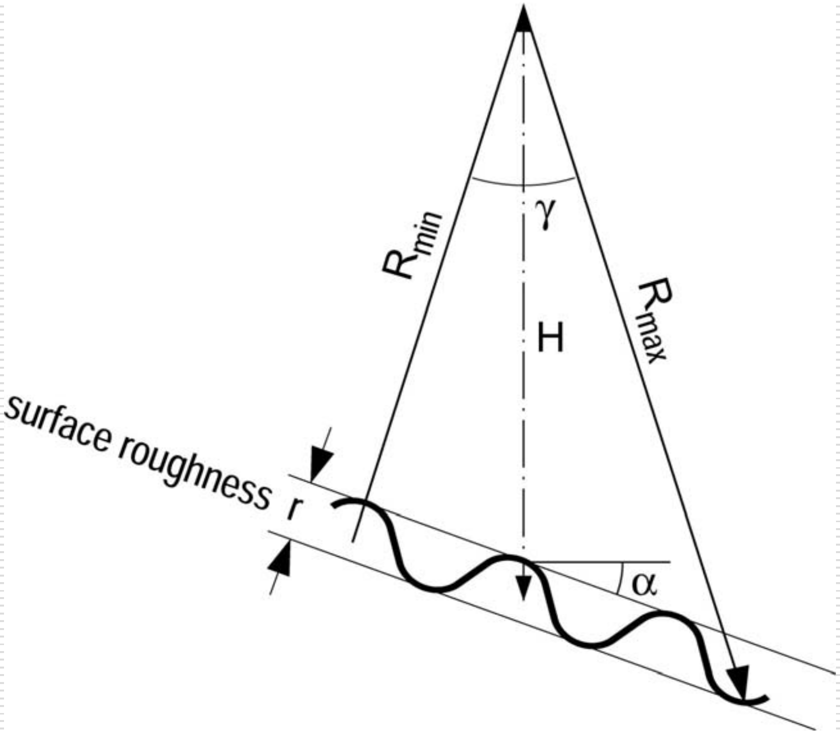
Received waveform = Transmitted pulse shape * Atmospheric transmission * Function defined by elevation distribution of reflectors within the footprint * Atmospheric transmission * Receiver impulse response

# Computation of Received Waveform

- Planar surface with random surface roughness: closed-form equation
- Arbitrary, single layered 3D surface: numerical simulation
- Multi-layered objects, such as trees over bare earth: multiple reflection should be considered, for example geometric optical and radiative transfer model

# Estimation of Range and Pulse Width for Sloping Terrain

- Closed-form expression are given for range, pulse width, range error and pulse width error in Gardner, 1992
- Pulse broadening and range errors are increasing with increasing surface roughness, beam curvature, off-nadir angle, and surface slope



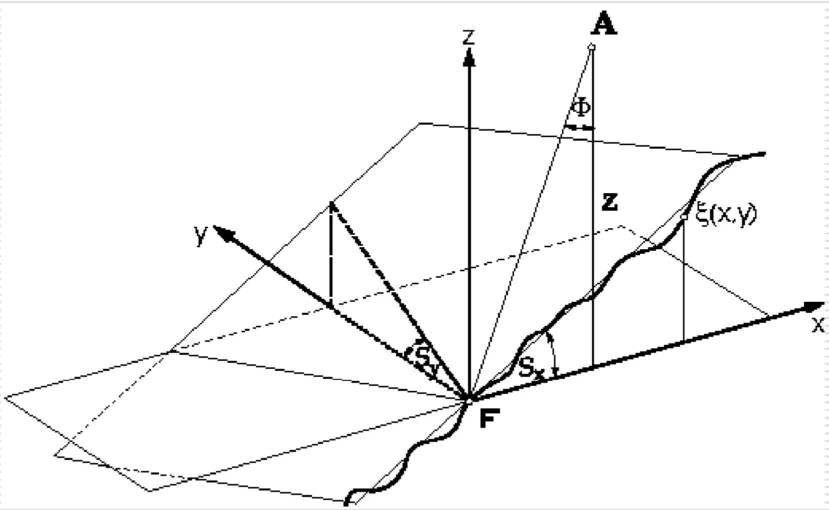
Gardner (1992), *IEEE Trans. on Rem. Sens. 30*(5), 1061-1072

# Computation of Slope and Roughness

$$E(\sigma_P^2) = (\sigma_l^2 + \sigma_h^2) + \frac{4Var(\Delta\xi)\cos^2 S_x}{c^2\cos^2(\phi + S_x)} + \frac{4z^2\tan^2\theta_T}{c^2\cos^2\phi}\left[\tan^2\theta_T + \tan^2(\phi + S_x) + \frac{\tan^2 S_y \cos^2 S_x}{\cos^2(\phi + S_x)}\right]$$

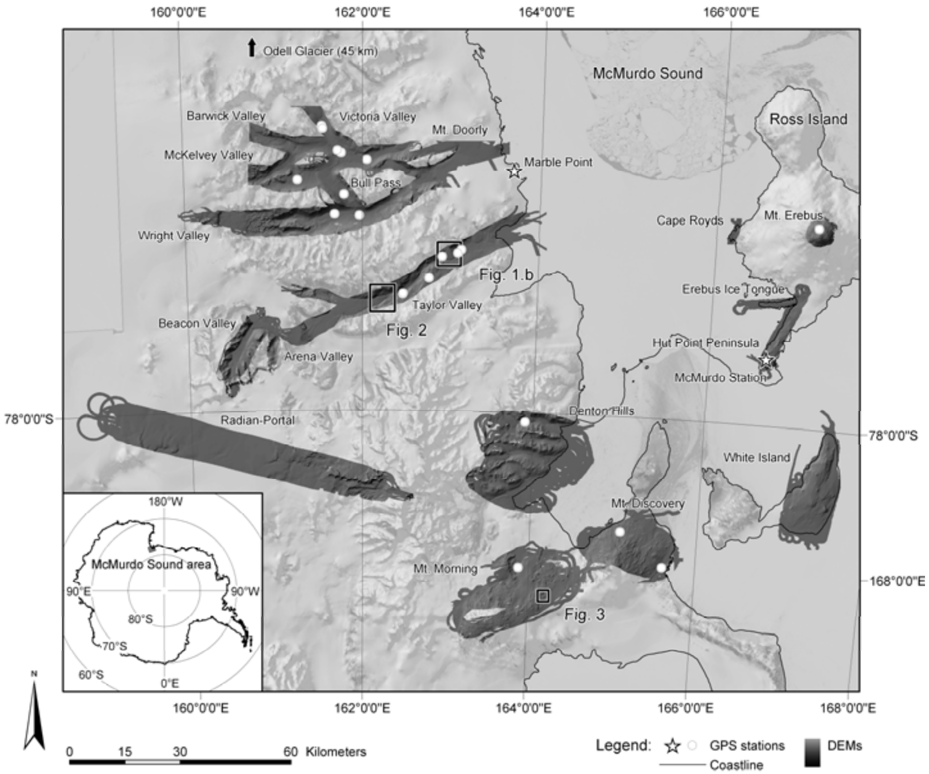
Slope and roughness is computed from the closed form expression above by using simple assumptions:

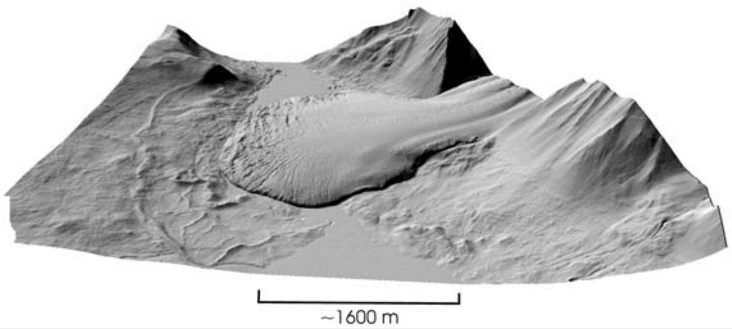
1. For slope computation roughness is assumed to be equal to 0
2. For roughness computation slope is assumed to be equal to 0

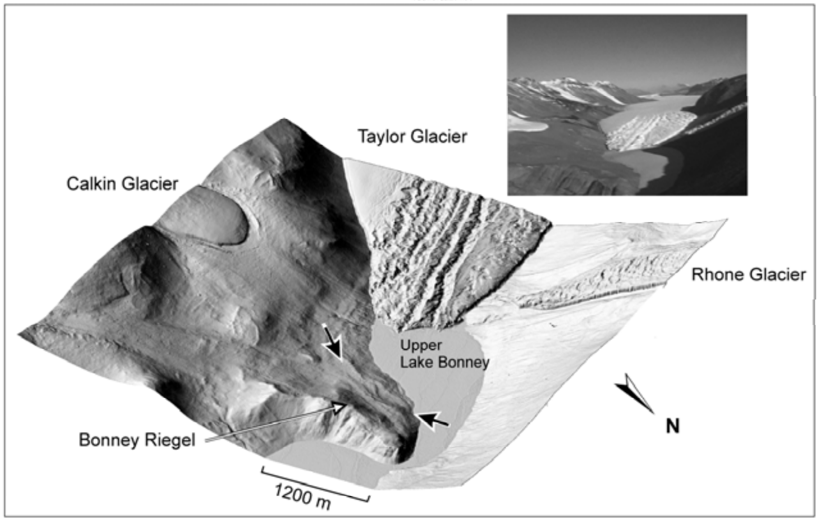


# Validation of ICESat Products by NASA's Airborne Topographic Mapper (2001/2002-present)

Resolution: 1-4 point/m$^2$; accuracy is better than 0.1 meter

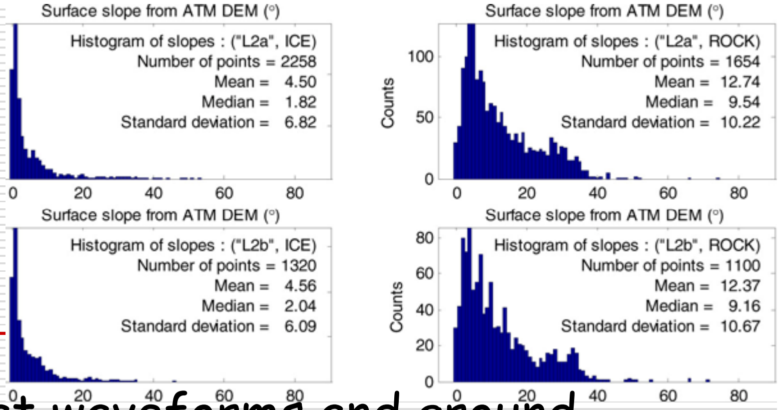




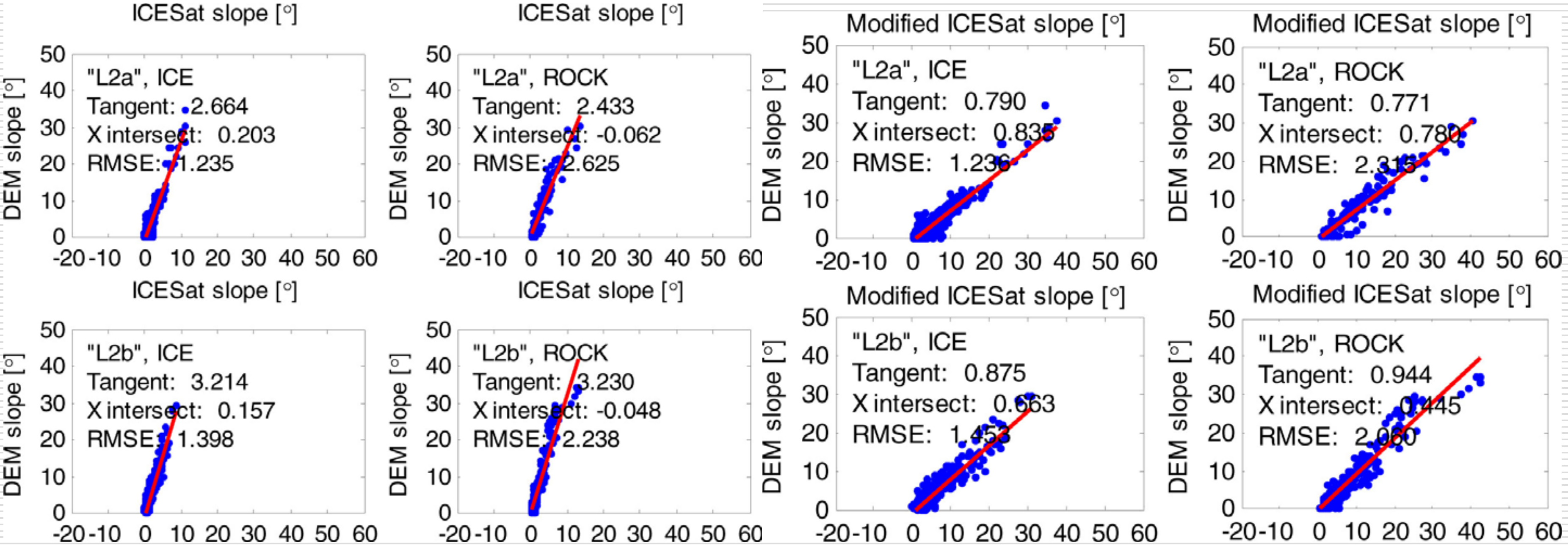


(Csatho, Schenk et al., EOS, 2005)

# Validation of Slopes



- ☐ Comparison of slopes derived from ICESat waveforms and ground-truth DEM indicated a scaling factor of ~3 (left). Correction of input parameters of slope computation by NASA has resulted a much better agreement.



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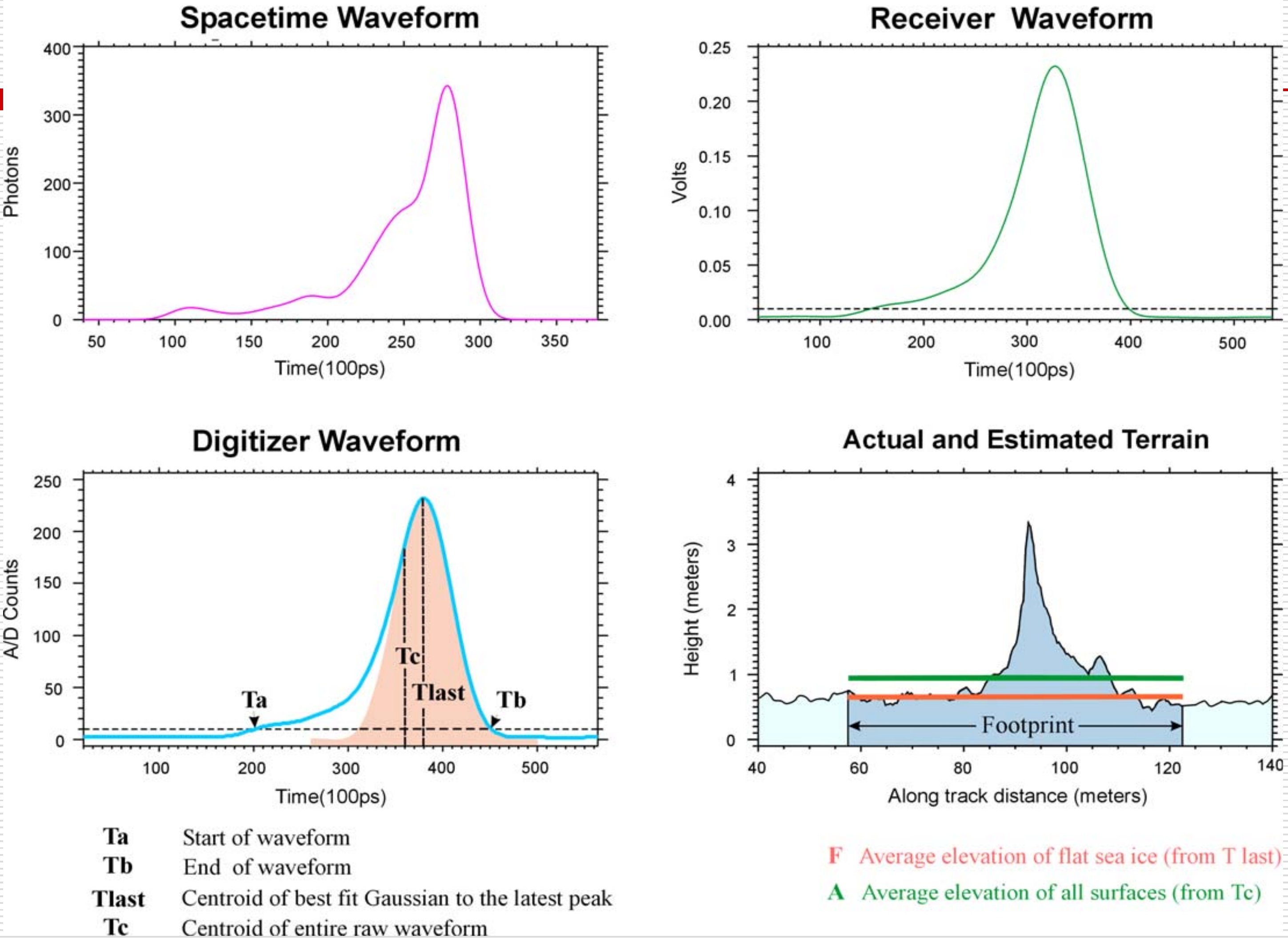
# Simulation of Laser Waveforms

- Simple: geometric simulation, using ray-tracing to compute the interaction of the laser beam with the surface
  Filin, Sagi, 2002, An efficient algorithm for the synthesis of laser altimetry waveforms, BPRC Technical Report 2000-02. Report and software: http://www-bprc.mps.ohio-state.edu/ohglas/Waveform_simulator.htm

- More realistic: simulation includes the effect of transmitter and receiver electronics and background solar radiation, for example NASA GSFC's simulator
  Abshire, J.B., J.F. McGarry, L.K. Pacini, J.C. Blair and G.C. Elman (1994) Laser Altimetry Simulator, Version 3.0 User's GuideNASA/GSFC Laser Altimetry Simulator, NASA Technical Memorandum 104588

# Laser Altimetry Waveform Simulated by NASA/GSFC Software

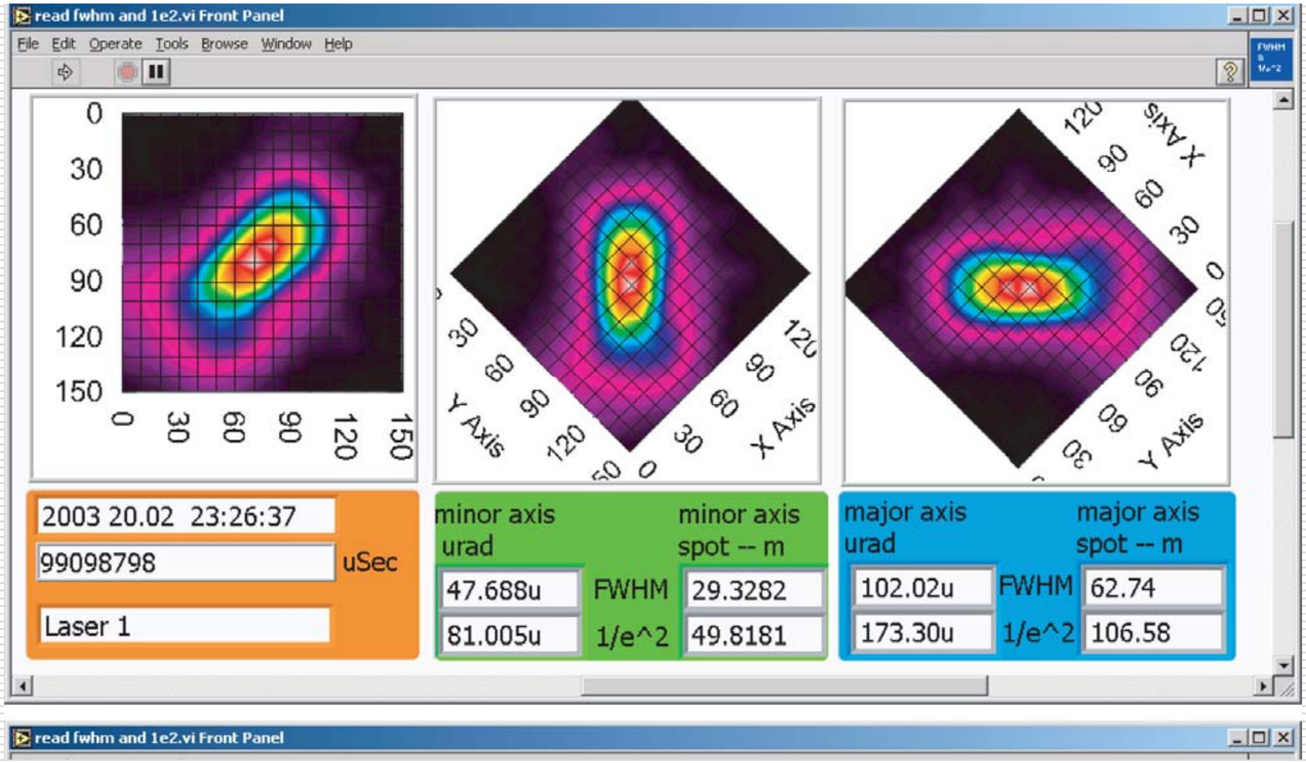


| | |
|---|---|
| **Ta** | Start of waveform |
| **Tb** | End of waveform |
| **Tlast** | Centroid of best fit Gaussian to the latest peak |
| **Tc** | Centroid of entire raw waveform |

**F** Average elevation of flat sea ice (from T last)

**A** Average elevation of all surfaces (from Tc)

# Ongoing Work: Develop Approaches to use Near-Field Laser Energy Distribution



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99098798 uSec

Laser 1

| minor axis urad | | minor axis spot -- m |
|---|---|---|
| 47.688u | FWHM | 29.3282 |
| 81.005u | 1/e^2 | 49.8181 |

| major axis urad | | major axis spot -- m |
|---|---|---|
| 102.02u | FWHM | 62.74 |
| 173.30u | 1/e^2 | 106.58 |

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