A Distributed Optical Telescope: Principle and Expected Performance

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Keck Institute for Space Studies Workshop

People Involved during Study Period

Techniques:

- Renaud Binet (stereo imagery),
- Francois Ayoub (COSI-Corr development),
- Lionel Keene (fast computing),
- Remi Michel (optics),
- Neus Sabater (correlation),
- Sergio Pellegrino (micro satellite design).

Applications:

- James Hollingsworth (tectonics),
- Jean-Philippe Avouac (tectonics),
- Bodo Bookhagen (geomorphology/glaciology),
- Mike Lamb and students (geomorphology),
- Pieter Vermeesh (geomorphology),
- Etienne Berthier (glaciology).

Generally Identified Imagery Needs in Earth Sciences from Last Workshop:

- Global coverage,
- High temporal sampling,
- Old archives to create long time series,
- Large, medium , and high spatial resolutions,

To study and monitor: ground deformation and evolution of Earth's topography (relation to earthquakes, landslides, mountainous glaciers, sand dunes), evolution of vegetation, river channels, coastal areas, ice caps, etc...

Coverage of Current Sun-synchronous Optical Satellites

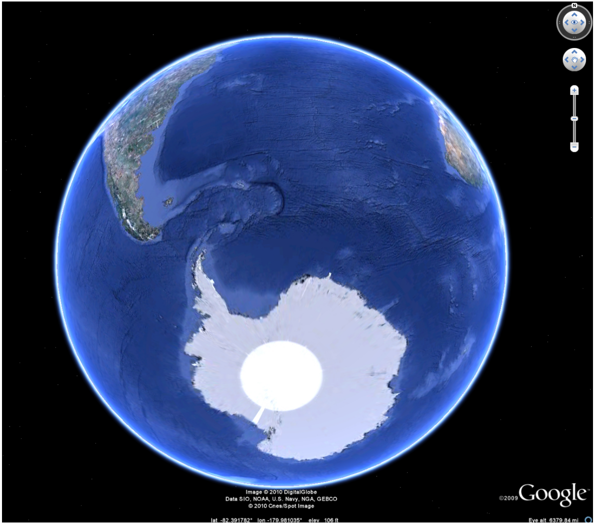
All Sun-synchronous satellites on elliptical orbit with inclination between 96° and 100°, leading to an **Earth coverage between ±81-84° latitude**.

- Landsat: (LS1-3) Inclination of 99.2°, (LS 4-7) Inclination of 98.2°
- SPOT 1-5 satellites: Inclination of 98.7°
- ASTER on-board NASA Terra: Inclination of 98.5°
- IRS: Inclination of 98.7°
- Quickbird, Worldview-1, Worldview-2: Inclinations of 98°, 97.2°, 97.8°
- Formosat 2: Inclination of 99.14°
- Pleiades-HR: Inclination of 98.2°
- ...

Coverage of Current Sun-synchronous Optical Satellites: Landsat example (±82° latitude)

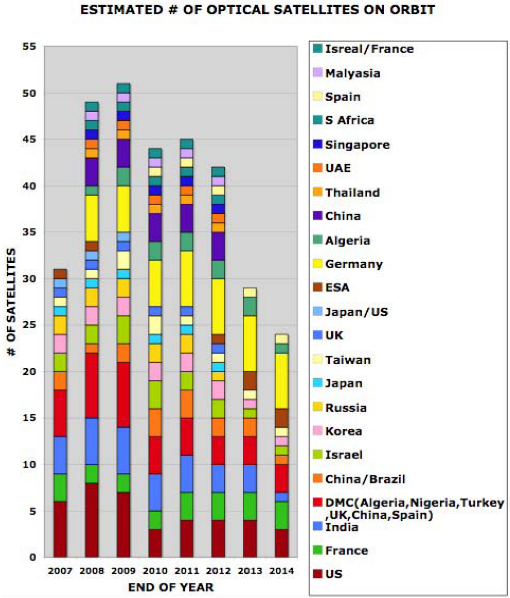
Credit: http://www.planetobserver.com/

Coverage of Current Sun-synchronous Optical Satellites: Landsat example ($\pm 82^\circ$ latitude)



Credit: Google Earth

Temporal Sampling Combining Existing Optical Satellites: How many satellites on orbit?



Number of land observing satellites with ground resolution better than 60 m.

Document current as of the end of 2007. Accurate from 2007-2012.

Consider that there exists, on average, 40 optical land imaging satellites on orbit.

From "ASPRS Guide to Land Imaging Satellites", W.E. Stoney, Feb. 2008

Temporal Sampling Combining Existing Optical Satellites: What is the revisit time?

Two different scenarios:

- **Tasking:** Observing satellites have either a large swath or depointing capabilities for global coverage. Typically acquire images of a specific area within **less than 1 week of a specific request**. Current average of 5.7 images/day. Since satellites are all Sun-synchronous on descending nodes between 8:30 - 11:30 am, we could achieve temporal sampling of a particular area with opportunistic maximum average of 30 min, during at most a few days. This scenario usually happens after large crises, e.g., Haiti earthquake (Disaster International Charter).

- **Archive mining:** Average long-term revisit time of a particular area is highly variable, between **2 weeks to 1 year**, and depends on swath width, orbital period, downlink capabilities, etc... For instance...

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Temporal Sampling Combining Existing Optical Satellites: What is the revisit time?

- **ASTER, 15 m GSD** on-board Terra: 705 km altitude, 99 min orbital period, 233 orbits and 16-day repeat cycle. For complete coverage the swath should be 172 km wide, but it is only 60 km. Slowly drifting orbit that achieves complete coverage in about three cycles. Every point on Earth is covered at least once every 43 days by the ASTER instrument.

- **Quickbird, 60 cm GSD**: 450 km altitude, 307 orbits and 20-day repeat cycle, 16.5 km swath. Needs eight cycles to achieve global coverage. Every point on Earth is covered every about 160 days by Quickbird.

- **Landsat 7, 15-60 m GSD:** same orbit as Terra, swath of 185 km, Landsat revisit time is 16 days.

- **SPOT 1-5, 10-2.5 m GSD:** 2×60 km swath, 832 km altitude, 363 orbits and 26-day repeat cycle , repeat coverage of 26 days using both instruments, or 52 days with one instrument.

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Temporal Sampling Combining Existing Optical Satellites: What is the revisit time?

Only from the Landsat, ASTER, SPOT, and Quickbird systems, we should expect every point on Earth to be revisited at least once every 6 days.

In practice, satellite availability and cloud cover decrease this estimate. If we consider only 30% probability of clear sky ([Miller et al., 2007] using MODIS), we can expect an average revisit time of about 22 days.

Creating Long Time Series: How far back does the archive goes?

OPTICAL LAND IMAGING SATELLITES WITH 56 METERS OR BETTER RESOLUTION

BY LAUNCH DATE

SATELLITE	COUNTRY	LAUNCH	PAN RES. M	MS RES. M	SWATH KM
Landsat 5	US	03/01/84		30.0	185
SPOT-2	France	01/22/90	10.0	20	120
IRS 1D	India	09/29/97	6.0	23	70, 142
Proba	ESA	10/21/97		18 Hyp	14
SPOT-4	France	03/24/98	10.0	20	120
Landsat 7	US	04/15/99	15.0	30	185
IKONOS-2	*US*	09/24/99	1.0	4	11
TERRA (ASTER)	Japan/US	12/15/99		15, 30, 90	60
KOMPSAT-1	Korea	12/20/99	6.6		17
EO-1	US	11/21/00	10.0	30	37
EROS A1	*Israel*	12/05/00	1.8		14
QuickBird-2	*US*	10/18/01	0.6	2.5	16
SPOT-5	France	05/04/02	2.5	10	120
DMC AlSat-1 (SSTL)	Algeria	11/28/02		32	600
DMC BilSat (SSTL)	Turkey	09/27/03	12.0	26	24, 52
DMC NigeriaSat-1 (SSTL)	Nigeria	09/27/03		32	600
DMC UK (SSTL)	UK	09/27/03		32	600
IRS ResourceSat-1	India	10/17/03	6.0	6, 23, 56	24, 140,740
CBERS-2	China/Brazil	10/21/03	20.0	20	113
FORMOSAT-2	Taiwan	04/20/04	2.0	8	24
IRS Cartosat 1	India	05/04/05	2.5		30
MONITOR-E -1	Russia	08/26/05	8.0	20	94, 160
Beijing-1 (SSTL)	China	10/27/05	4.0	32	600
TopSat (SSTL)	UK	10/27/05	2.5	5	10, 15
ALOS	Japan	01/24/06	2.5	10	35, 70
EROS B1	*Israel*	04/25/06	0.7		7
Resurs DK-1 (01-N5)	Russia	06/15/06	1.0	3	28
KOMPSAT-2	Korea	07/28/06	1.0	4	15
IRS Cartosat 2	India	01/10/07	0.8		10
WorldView -1	*US*	09/18/07	0.5		16
CBERS-2B	China/Brazil	09/19/07	20.0	20	113
THOES	Thailand	02/27/08	2.0	15	22, 90
RazakSat*	Malyasia	03/01/08	2.5	5	?
HJ-1-A	China	04/01/08		30, 100 Hyp	720, 50
HJ-1-B	China	04/01/08		30, 150, 300	720
RapidEye-A	*Germany*	04/01/08		6.5	78
RapidEye-B	*Germany*	04/01/08		6.5	78
RapidEye-C	*Germany*	04/01/08		6.5	78
RapidEye-D	*Germany*	04/01/08		6.5	78
RapidEye-E	*Germany*	04/01/08		6.5	78
SumbandilaSat	South Africa	04/01/08		7.5	?
X-Sat	Singapore	04/16/08		10	50
Hi-res Sterio Imaging	China	07/01/08	2.5, 5	10	?
WorldView -2	*US*	07/01/08	0.5	1.8	16
Venus	Israel/France	08/01/08		10	28
GeoEye-1	*US*	08/23/08	0.4	1.64	15
DMC Deimos-1	Spain	11/15/08		22	660
DubaiSat-1	UAE	11/15/08	?	?	?
DMC UK-2	UK	11/15/08		22	660
Alsat-2A	Algeria	12/01/08	2.5	10	?
IRS ResourceSat-2	India	12/15/08	6.0	6, 23, 56	24, 140, 740
EROS C	*Israel*	04/01/09	0.7	2.8	11
CBERS-3	China/Brazil	05/01/09	5.0	20	60, 120
TWSAT	India	07/01/09		35	140
DMC NigeriaSat	Nigeria	07/01/09	2.5	5, 32	320
ARGO	Taiwan	07/01/09		6.5	78
KOMSAT-3	Korea	11/01/09	0.7	3.2	?
Alsat-2B	Algeria	12/01/09	2.5	10	?
Pleiades-1	France	03/01/10	0.7	2.8	20
CBERS-4	China/Brazil	07/01/10	5.0	20	60, 120
SeoSat	Spain	07/01/10	2.5		?
Pleiades-2	France	03/01/11	0.7	2.8	20
EnMap	*Germany*	07/01/11		30 Hyp	30
LDCM	US	07/01/11	10.0	30	177
SPOT	France	07/01/12	2.0	6	60
Sentinel 2 A	ESA	07/01/12		10, 20, 60	285
Sentinel 2 B	ESA	07/01/13		10, 20, 60	285

Commercial   * Near Equatorial Orbit   Revised 1/21/08

Note: Read 4/1 = lst quarter, 7/1 = in that year, 11 & 12s = late in that year

Satellites with ground resolution better than 60 m. Document current as of the end of 2007.

What about before 1984?

From "ASPRS Guide to Land Imaging Satellites", W.E. Stoney, Feb. 2008

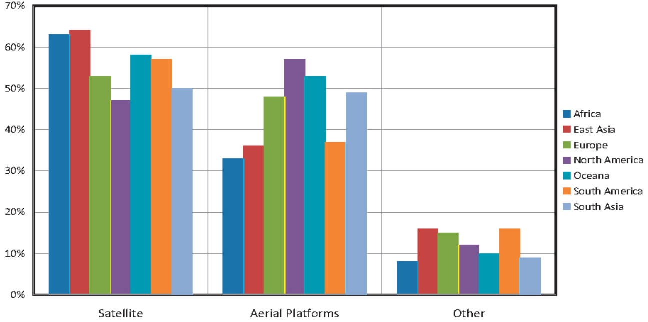
Creating Long Time Series: How far back does the archive goes?

High resolution images acquired before the 1980's:

- **Many spy images are now declassified:** 860,000 photographs from 1960 to 1972 declassified in 1995 (CORONA, ARGON and LANYARD missions). Ground resolution of **9 m (KH 1-4) and 2 m (KH 4b)**. 29,000 images from 1970-1980, from KH-9 HEXAGON missions, **7-9m resolution**, declassified in 2002. Equivalent declassified programs from the Ex-Soviet Union (Zenit, Kosmos).

- **Aerial imagery:** In the United States, the U.S. Geological Survey began using aerial photographs for mapping in the 1930's and archives through today are available at about **1 m ground resolution**. The **NHAP** program was initiated in **1980**, and **NAPP** program in **1987** delivered 1 m resolution imagery of the entire US every five years. Archive exist form other agencies (EPA, NAIP, Caltrans, etc...) and many similar programs in most countries.

Creating Long Time Series: How much aerial data is globably collected?



Average proportion of remote sensing data collected by aerial vs. space-based platforms [ASPRS Ten-year Remote Sensing Industry forecast, Phase V, 2008].

Almost as many aerial data as satellite data collected, potential for a large worldwide archive if imagery can be accessed.

What resolution do we have access to?

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SATELLITE	PAN RES. M	MS RES. M	SWATH KM
GeoEye-1	0.4	1.64	15
WorldView -1	0.5		16
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EROS B1	0.7		7
EROS C	0.7	2.8	11
KOMSAT-3	0.7	3.2	?
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FORMOSAT-2	2.0	8	24
THOES	2.0	15	22, 90
SPOT-6	2.0	6	60
SPOT-5	2.5	10	120
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ALOS	2.5	10	35, 70
RazakSat*	2.5	5	?
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Geomorphology applications stated a need for 10 cm topography accuracy. Could we do it from space?

From "ASPRS Guide to Land Imaging Satellites", W.E. Stoney, Feb. 2008

What Limits the Resolution of Space Acquisitions?

National Defense Authorization Act for Fiscal Year 1997 (S. Rep No.104-278, 104th Cong 2nd Sess., s.1745 (1996):

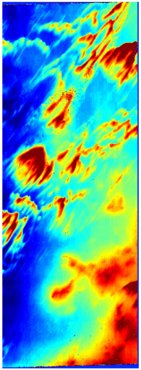
(Sec. 1044) Prohibits any Federal department or agency from licensing the collection or dissemination by any non-Federal entity of, or from declassifying or otherwise releasing, satellite imagery with respect to Israel and other countries or areas designated by the President, unless such imagery is no more detailed or precise than the imagery of the country or area concerned that is routinely available from public sources.

"Currently, none of our customers outside of the U.S. government can receive imagery better than 0.5 m resolution. Its a limit specified by the government. For the foreseeable future, it doesnt look like 0.5 m resolution will be broken for commercial satellites." Chuck Herring, DigitalGlobe's corporate communications director interview from 01/2008.

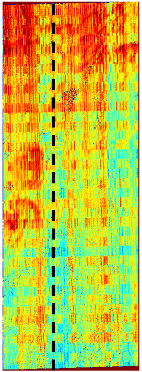
This defense limitation explains the large success of aerial imagery for very high resolution applications! Wait, how about 40 cm GeoEye images?

Ground Resolution Limitation for Commercial Satellites: Slide from Renaud Binet, CEA, last KISS Workshop

Geoeye stereo sub-pixel correlation artifacts

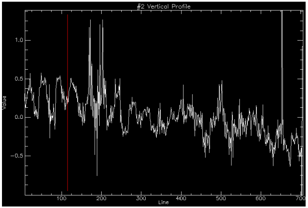


Epipolar direction



Perp.Epi. direction

GEOEYE stereoscopic pair, 50cm resolution



0.5 pixel high frequency pattern
No subpixel measurement allowed with Geoeye !

Subpixel artifacts are introduced when the original 40 cm GeoEye images are degraded to 50 cm resolution for commercial customers!

Very High Resolution Requires using Aerial Photography

- Because of space policy limitations, applications requiring very high resolution have to rely on aerial surveys. Aerial photographs commonly acquire images with resolution **up to 1-5 cm**.

- Unmanned Aerial Vehicles (UAVs) are appearing as a new source of cheap high resolution aerial data.

A Distributed Optical Telescope

We propose a **computational framework for subpixel registration** of optical images, **regardless of their acquisition method** and **regardless of their resolution**. In particular, the system could assimilate optical data acquired:

- At **any altitude**: drones, uav, aircraft, low-orbiting satellites, geostationary satellites (processing methods developed here can be used for the optical Geo-seismometer project),
- From **any frame or pushbroom** sensors (typical for medium and high resolution imaging).

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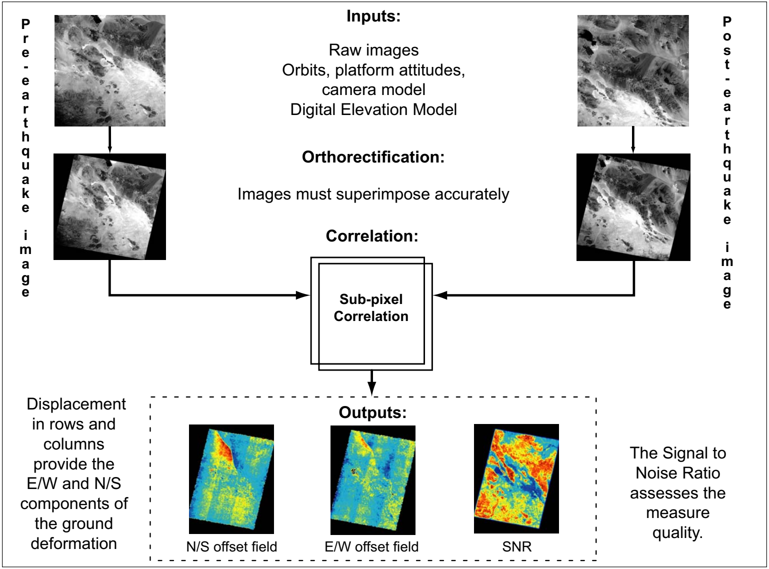
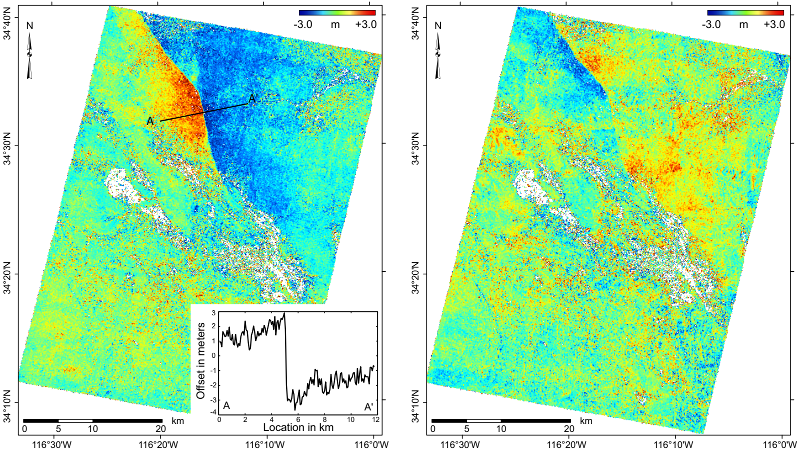
Brief Overview of COSI-Corr: Co-registration of Optically

Sensed Images and Correlation

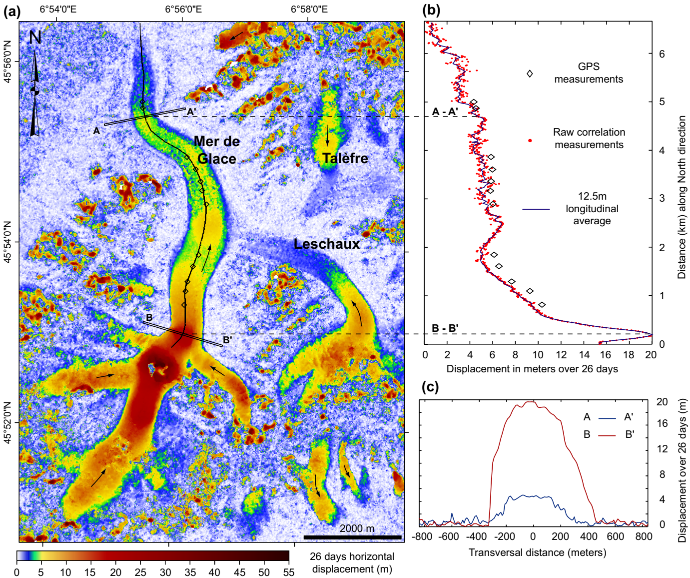


The 1999 Mw 7.1 Hector Mine Earthquake



The Hector Mine horizontal coseismic field (NS and EW) once CCD distortions from SPOT4 and SPOT2 have been modeled during orthorectification. Accuracy better than 1/10 pixel.

The Mer de Glace Glacier, France

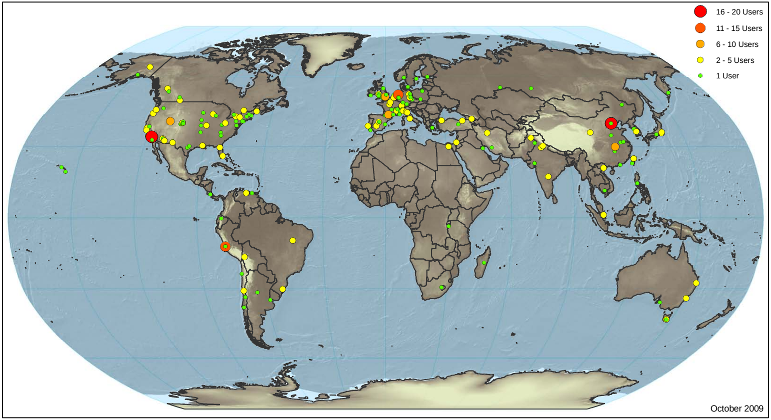


S. Leprince, et al., EOS, 2008

COSI-Corr Basics

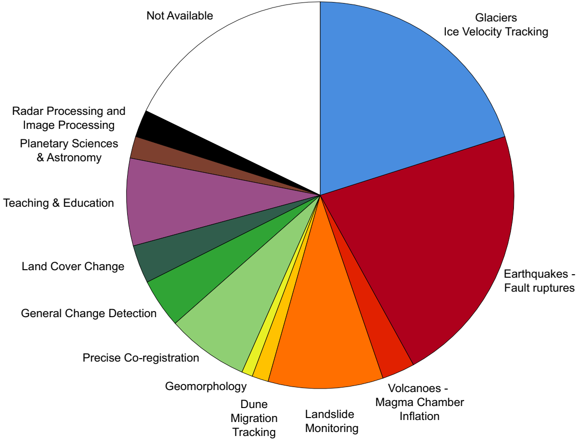
- Accurate geometrical modeling of pushbroom and frame camera sensors (SPOT 1-5, ASTER, Quickbird, Formosat, Worldview 1-2, aerial sensors),
- In-flight calibration of pushbroom CCD misalignment,
- Subpixel optimization of tie points and ground control points,
- Measurement of ground displacement via multi-scale phase correlation method with accuracy better than 1/10 of the image pixel size,
- Distributed freely since 2007 via Caltech Tectonics Observatory.

Distribution of COSI-Corr Users



Distribution of registered users. 529 users and 660 downloads as of March 25, 2010

Main COSI-Corr Uses



As reported by users during registration

Identified Improvement for Distributed Telescope

- Currently semi-automatic process. Need complete automatic generation of tie points between heterogeneous data,
- Bias and sensitivity to topography errors when measuring ground displacements,
- Loss of resolution when resampling high resolution and high incidence images,
- Need correlation with small window sizes to allow for high resolution topography retrieval,
- Need Accurate estimates of correlation uncertainty to allow assimilation of many correlation results (including topography),
- Need faster processing time,
- Need Bundle block adjustment with aerial photographs,
- Need to better understand and possibly compensate aliasing biases in correlation.

Investigated Techniques during Study Period

- Determination of disparities in direction perpendicular epipolar direction to avoid topography sensitivity,
- Rigorous adaptive resampling of high resolution images on very irregular terrain,
- Reproducing aliasing biases via simulation,
- Assimilation of data from different sensors and at different resolution, example on Krafla, Iceland, see next talk by James Hollingsworth,
- Precise determination of uncertainty in correlation estimation to allow for precise assimilation of data, see next Neus Sabater talk,
- Fast multi-processor computing (for large volume and fast response to large disasters - was a limiting factor for Haiti). First proof of concept by Lionel Keene, up to 40 times faster on some processes.

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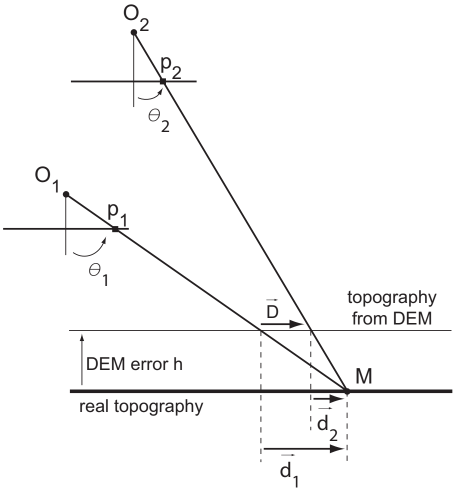
Disparities in Perpendicular Epipolar Direction and 3D Deformation, Initiated by R. Binet during first workshop

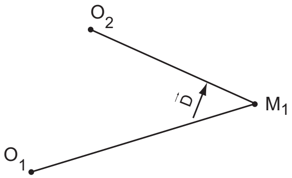


$$D = h(\tan(\theta_1) - \tan(\theta_2))$$

- Measurement error $\vec{D}$ bias ground deformation measurement if the DEM is not accurate. This is often a limiting factor.
- **$\vec{D}$ lives in the plane $(O_1 M O_2)$, called the epipolar plane.**

Study will be presented at IEEE IGARSS in July 2010.

Disparities in Perpendicular Epipolar Direction and 3D Deformation, Initiated by R. Binet during first workshop



- Ground deformation measurements will be biased by DEM errors along the epipolar direction.
- No DEM bias in the epipolar perpendicular direction
- Full 2D deformation field can be recovered from three images even if DEM unknown. 3D field with four images.

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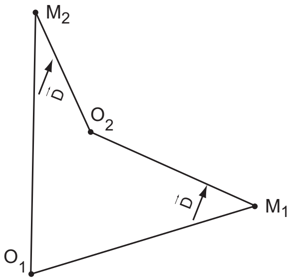

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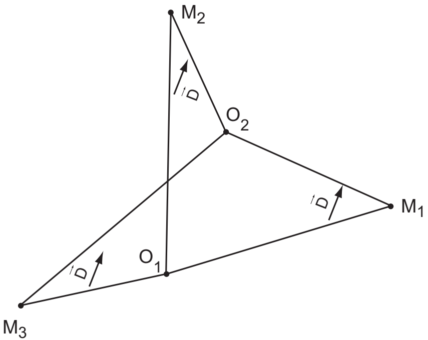

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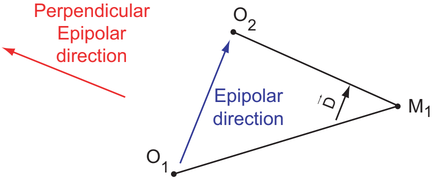

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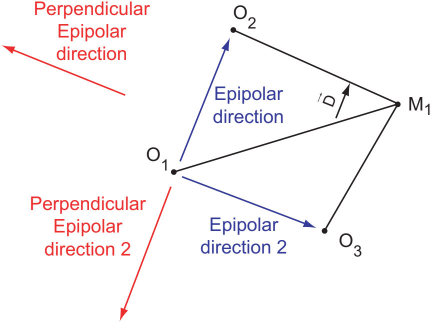

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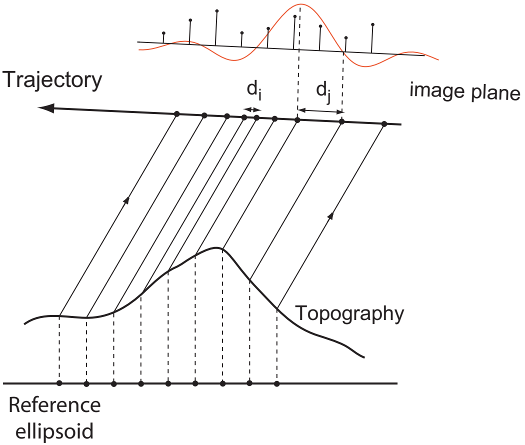
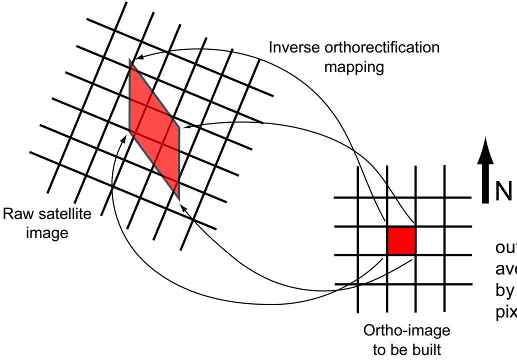
Orthorectification: An Irregular Mapping



Resampling irregularities depend on the local viewing angle and topography gradient. They increase with image resolution and can vary by up to a factor of 10 in high resolution images over steep topography.

Rigorous Adaptive Resampling: principle



output pixel = area weigthed average of input pixels covered by inverse mapping of output pixel

- Kernel locally warped according to local mapping warp (linearized locally = Jacobian of projection mapping)
- Use approximated sinc kernels-like kernels to preserve subpixel information and limit aliasing.

Rigorous Adaptive Resampling: equivalent kernel

General resampling kernel in sensor geometry:

$$\rho_s(\mathbf{x}) = r_s(\mathbf{x}) \circledast h_g(\mathbf{J}\mathbf{x})|\mathbf{J}|,$$

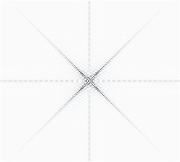
- r_s reconstruction kernel defined in sensor geometry,
- h_g anti-aliasing filter defined in the mapped geometry (on the ground),
- $\mathbf{J}$ Jacobian of the warping function.

A new kernel is computed at each resampling point

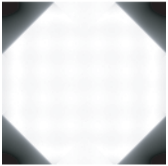
Study will be presented at IEEE IGARSS in July 2010.

Rigorous Adaptive Resampling: demonstration for simple cases

45 degrees rotation



Impulse response



Kernel Spectrum

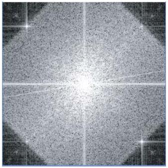


Image Spectrum

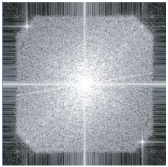
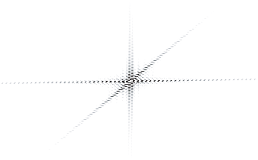
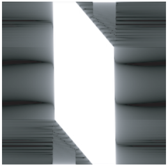


Image Spectrum
with oversampling

Shear transformation



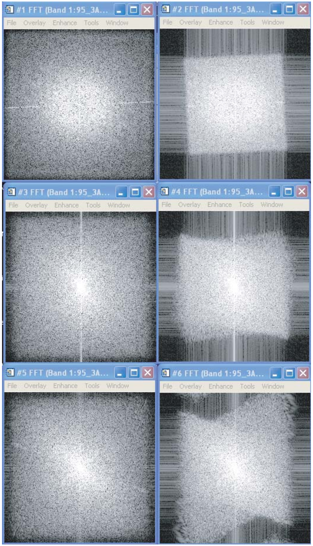
Impulse response



Kernel Spectrum

Rigorous Adaptive Resampling: test case in glaciology

Adaptive resampling | Non-adaptive resampling



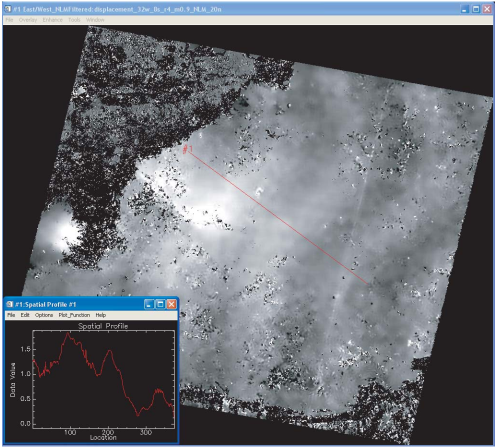
Adaptive resampling

Non-adaptive resampling

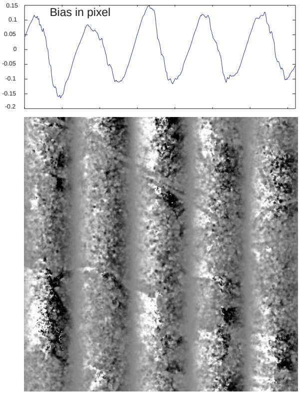
Images courtesy of D. Quincey

Aliasing Biases in Correlation

Aliasing generated artifacts in EW correlation results



Aliasing artifacts can be reproduced in simulation



Scheduled Studies and Collaborations

- **Technical:**
  - Multiprocessor programming and fast algorithms implementation (Lionel Keene),
  - Characterization of aliasing bias in correlation measurements (3 months summer internship),
  - Automatic robust tie point selection and subpixel bundle block adjustment (6 months internship),
  - High resolution disparity determination (Neus Sabater).
- **Thematic:**
  - Changes in the hydrologic and glacial regime in High Asia (Bodo Bookhagen),
  - River hydrology and geomorphology, and landslides evolution in California Mike Lamb and students

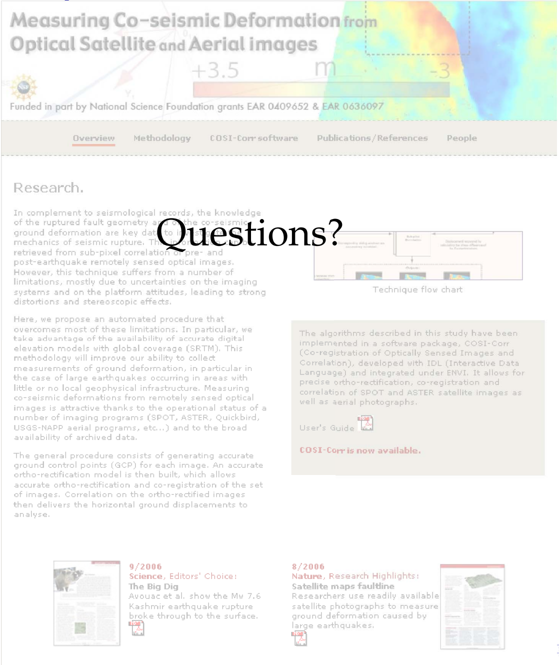
Long Term Questions to be Investigated

- Effects and compensation of shadowing changes,
- Integration with SAR data,
- Effects of change of incidence angle on reflectivity to produce radiometrically correct ortho-images,
- Integration with Lidar and retrieval of 3D deformation from Lidar.

Conclusion:

- We propose a computational framework to enable global monitoring of Earth surface changes using past, current and future imaging systems.
- Techniques developed would also work for the geostationary project to be presented by Remi Michel,
- Large implication for Earth Sciences, e.g., global monitoring of mountainous glaciers, landslides, sand dunes migration, desertification, earthquakes, volcanoes, land monitoring, agriculture, deforestation, etc...
- Optical imaging satellites have not yet been designed for measuring ground deformation. Earth Sciences applications put new constraints on the design of future missions, and we started to investigate the design of a small satellite that would monitor the evolution of topography. Collaboration with Sergio Pellegrino's KISS study on large space structures, discussion on Wednesday morning March 31st.

The End: Thank you!



Questions?