UAV applications with GNSS for 3D mapping

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about myself

Yuichi S. Hayakawa 早川 裕弌

- Associate Professor at Center for Spatial Information Science (CSIS), The University of Tokyo (co: Dept. Socio-Cultural Environmental Studies, Graduate School of Frontier Sicences)
- lectureships at Keio SFC, Rikkyo U, Kyoritsu WU, Ochanomizu WU, Kawamura WU

about myself

Yuichi S. Hayakawa 早川 裕弌

- field: Geomorphology, Geospatial Information Science, Geoarchaeology
- Topics
  - distribution and processes of WATERFALLS
  - High-Definition Topography & 3D – measurement and analysis of landforms and land surface objects
  - palaeoenvironment around archaeological sites in West/Central Asia

field science & geospatial analysis

Center for Spatial Information Science CSIS

Missions, Aims:
- **Creating**, Developing, and Spreading Spatial Information
- **Developing** Spatial Databases for Research Purposes
- **Promoting** Joint Industry-Government-University Research

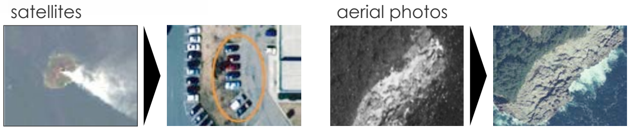
http://www.csis.u-tokyo.ac.jp/

higher-resolution
of land surface information

getting higher resolution

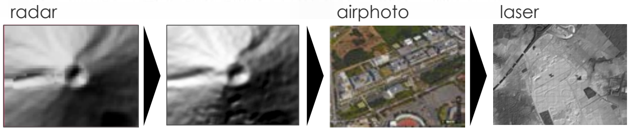
❖2D imagery

satellites / aerial photos



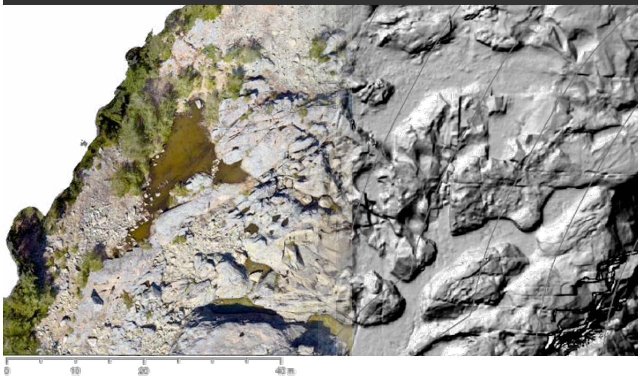
❖3D topography/land-surface items

radar / airphoto / laser



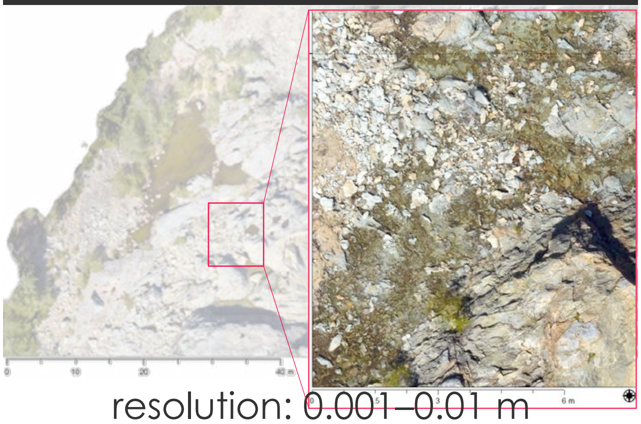
and now…

ultra-high resolution



resolution: 0.001–0.01 m

ultra-high resolution



resolution: 0.001–0.01 m

What is UAS/UAV?

- unmanned aerial vehicle
- various size and types

military
RQ-1 Predator
W 14.8 m

(U.S. Air Force photo)

Agricultural
RMAX
L 3.6 m

(YAMAHA)

hobby
Flying Ball
H 11 cm

(FLYING BALL)

Aerial photo
Phantom 3
W 59 cm

(DJI)

What is UAS/UAV?

Popular UAV

Aerial photo shooting

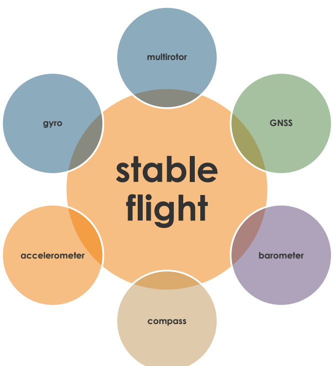
(DJI)

Size: ：ca. 20–100 cm
Weight: ca. 500–2000 g
Price: ca. 500–10,000 USD

Rapid spread for industry, research, and personal hobby

Relatively cheap, light, easy

mechanisms of UAVs



easy operation

▼

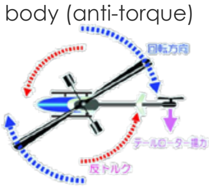
safety

mechanisms of UAV

Reasons for the stability
#1: **multi-rotor**

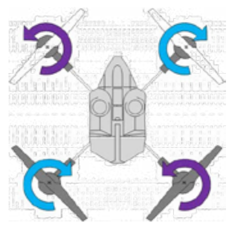
(in case of 4 rotors)

Single rotor
→inverse rotation of body (anti-torque)



(http://plaza.rakuten.co.jp/mmbirdland/)

4 rotors
→paired right and left rotations dismiss the anti-torque

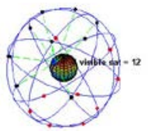


(http://minizbar.blog100.fc2.com/)

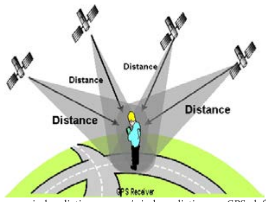
mechanisms of UAV

Reasons for the stability
#2: built-in **GNSS receiver**

Global Navigation Satellite System (GNSS) ▶ Positioning of the UAV body



(https://commons.wikimedia.org/wiki/File:ConstellationGPS.gif)



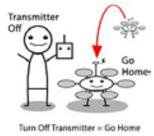
(http://www.wirelessdictionary.com/wireless_dictionary_GPS_definition.htm)

mechanisms of UAV

Reasons for the stability
#2: built-in **GNSS receiver**

Aircraft recognizes its position ▶
- Stay (hover) at the same position if without any operation
- Automatically correct its position even in the wind
- Programmed not to enter the predefined prohibited areas (airport, etc.)

Record the takeoff point ▶
- Automatically come back "home" when any problem occurs (low battery, radio disconnection, etc.)



(http://crazybrain.jp/SHOP/DJI-Drone-F550-NAZA-V2-RTF.html)

mechanisms of UAV

Reasons for the stability
#3: built-in **barometer**

Low pressure in higher altitudes

(http://www.tdk.co.jp/techmag/inductive/200912/)

Air pressures are used to identify the aircraft's relative height

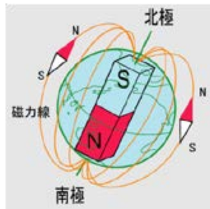
▼

Altitude can be maintained during flight

mechanisms of UAV

Reasons for the stability
#4: built-in **e-compass**

Terrestrial magnetism



(http://www.tokyocompass.co.jp/mame.htm)

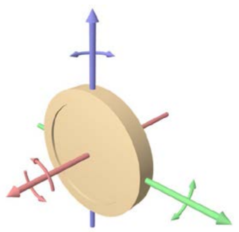
Aircraft identifies its orientation

▼

Keep its right orientation

mechanisms of UAV

Reasons for the stability
#5: built-in **accelerometer and gyro**



(https://commons.wikimedia.org/wiki/File:Gyroscope_wheel-text.png)

Aircraft identifies its inclination and direction of movement

▼

Keep the right course

pros and cons of UAVs

advantages

- unmanned
  remote area can be surveyed without a person
- automatic
  simple, long-term, repeated operations
- high mobility
  freedom of operating location
- size flexibility
  flexible design for various purposes
- high resolution
  close-range sensing
- development
  high potential in industry and market

disadvantages

- limited area
- low altitude
  ~150 m above ground
- slower speed
  10–80 km/h
- too high resolution
  too much data
- difficulty in sharing the space with manned aircrafts
  needs good knowledge and moral of operators
  limited rules after disaster occurrences
  no way to contact to manned aircrafts

for the appropriate use of UAVs

dangerous if wrongly used

governmental activations of various UAV applications

for the appropriate use of UAVs

Alfred Bernhard Nobel

"There is nothing that is not being exploited in the world. Advances in science and technology's back-to-back and always dangerous. It's the first time can contribute to the future of mankind and to overcome it."

Soichiro Honda

"The right thought of human beings is prior to science and technology. The evaluation of humans having science and technology is undertaken by how they use them and how they contribute to the society."

applications of UAVs

Operation of UAS

UAV specifications	
Product name	DJI PHANTOM® 2
Aircraft class	Quadcopter
Dimensions	350 x 350 x 190 mm
Weight	1000 g
Max flight speed	15 m/s
Max ascent/descent speed	6 m/s
Communication distance	1000 m
Max flight time	25 mins.
Payload	400 g (empirical value)

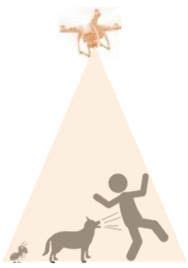
Camera specifications	
Product name	NIKON COOLPIX A®
Pixels	16.2 million
Image sensor	23.6 x 15.6 mm
Dimensions	111.0 x 64.3 x 40.3 mm
Weight	299 g
Interval shooting	More than 1 second
Maximum number of	More than 6,000 photos (SDXC64GB)
Duration of battery	Approx. 70 min.

GNSS unit specification	
Product name	NIKON GP-1A
Tracking channels	18 (SBAS compliant)
Update rate	Once per second
Geodesics	WGS84
Accuracy	Horizontal 10 m RMS
Dimensions	45.5 x 25.5 x 50 mm
Weight	24 g

Flight height, speed, and resolution

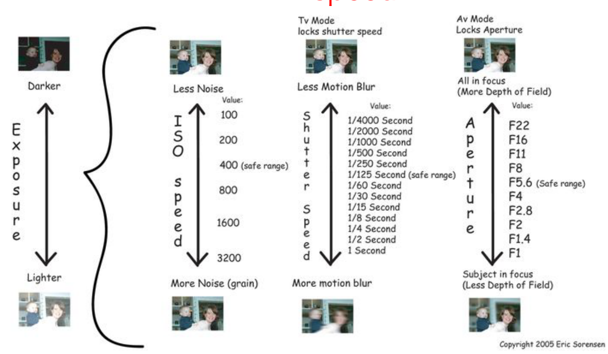
飛行高度・速度と撮影間隔(太字)，焦点距離 28 mm (35 mm フィルム換算)，65 % 重複，短辺方向に飛行を仮定
Shot intervals (bold letters) for various flight heights and flight speeds assuming 28 mm lens (equivalent to 35 mm film size), 65 % overlap, head-forward camera orientation.

(by Inoue et al., 2014)



Flight height (m)		10	20	50	100	150
Left-Right size (m)		12.9	25.9	64.7	129.4	194.1
Front-Back size (m)		8.6	17.1	42.8	85.7	128.5
L-R shot interval (m)		4.5	9.1	22.6	45.3	67.9
F-B shot interval (m)		3	6	15	30	45
Flight Speed (m/s)	2	**1.5**	**3**	**7.5**	**15**	**22.5**
	3	**1.0**	**2**	**5**	**10**	**15.0**
	4	**0.8**	**1.5**	**3.8**	**7.5**	**11.3**
	5	**0.6**	**1.2**	**3.0**	**6.0**	**9.0**
	6	**0.5**	**1.0**	**2.5**	**5.0**	**7.5**
	7	**0.4**	**0.9**	**2.1**	**4.3**	**6.4**
	8	**0.4**	**0.8**	**1.9**	**3.8**	**5.6**
	9	**0.3**	**0.7**	**1.7**	**3.3**	**5.0**
	10	**0.3**	**0.6**	**1.5**	**3.0**	**4.5**
Ground resolution (cm/px)			0.5	1.3	2.6	3.9

exposure ISO shutter speed aperture



Updating UAV survey system

Up to now

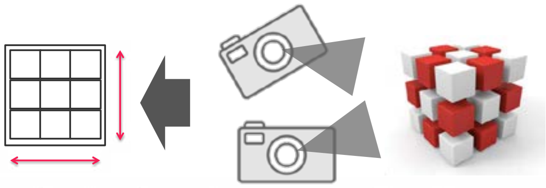
Phantom2
& Coolpix A with GPS unit

Latest

Phantom3

Effective for aerial survey?

	Phantom2 & CoolpixA	Phantom3 (Professional)
Flight time	15 min.	**23 min.**
GPS mode	GPS	GPS/**GLONASS**
Communication distance	1000 m	**2000 m**
FPV	×(additional parts)	○
Auto pilot	×(additional parts)	○
Real time battery monitoring	×(additional parts)	○
Sensor size	**23.6×15.6 mm** (Coolpix A)	6.2×4.7 mm (1/2.3")
Pixel number	**16.2 M** (Coolpix A)	12.4 M
Interval shot	**1s-** (Coolpix A)	5s-
Gimbal	×	**3-axis**
Price	130,000 JPY	175,000 JPY



a technology to measure size, shape and location of objects based on stereo-pair camera images

PHOTOGRAMMETRY

What is photogrammetry?

A technology to measure the size, shape, and location of an object based on photographic images

- Aerial photogrammetry
  - Ground surface images using platforms in the air (or satellites)
- Ground-based photogrammetry
  - 3D objects on ground from handheld or other platforms

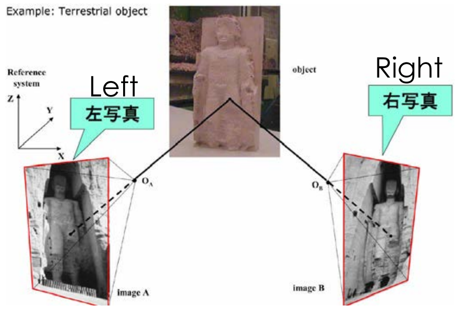
Nature of photographic images

- Large at close range, small at far
- Radial inclination from the central point
- The higher, the more inclinated

(Tsuru and Murai, 2011)

Photo shooting for photogrammetry

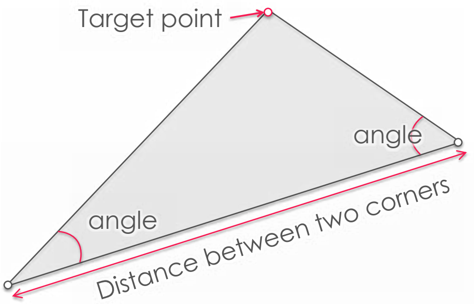
Change camera location → Distortion within a image based on the object shape and location → Reconstruct the surface morphology from the distortion



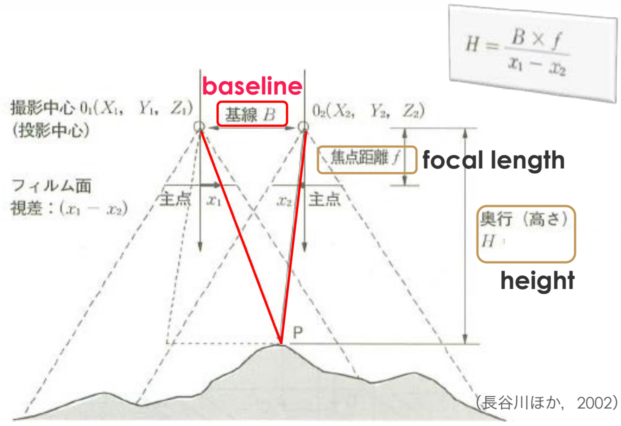
(Tsuru and Murai, 2011)

triangulation

Angle of two corners and distance between them
▶ definition of the triangle

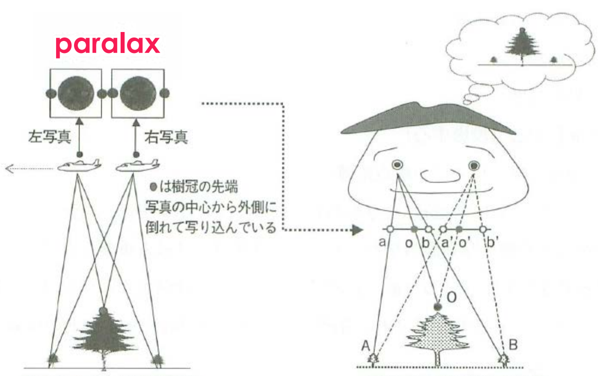


Triangulation for aerial photogrammetry



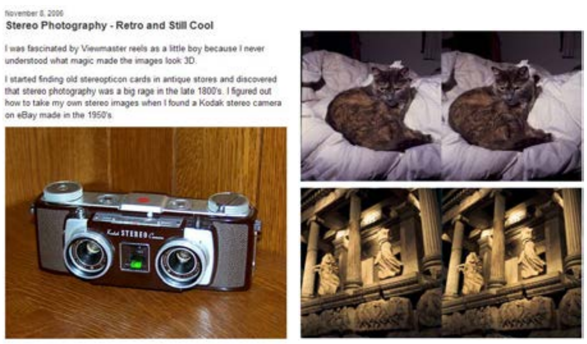
(長谷川ほか，2002)

stereopsis



樹木を上空から写真撮影 （長谷川ほか，2002） 樹木の写真画像を立体視

Stereo photography — 1950s


November 8, 2006
Stereo Photography - Retro and Still Cool
I was fascinated by Viewmaster reels as a little boy because I never understood what magic made the images look 3D.
I started finding old stereopticon cards in antique stores and discovered that stereo photography was a big rage in the late 1800's. I figured out how to take my own stereo images when I found a Kodak stereo camera on eBay made in the 1950's.

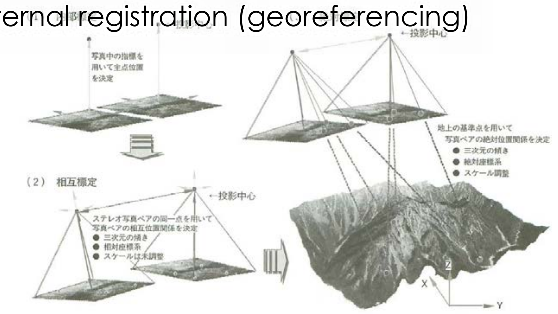
http://artwelner.1000words.kodak.com/default.asp?item=220108

3D digital camera FUJIFILM FinePix REAL 3D

Jul 2009

registrations

- camera calibration
- internal registration
- external registration (georeferencing)



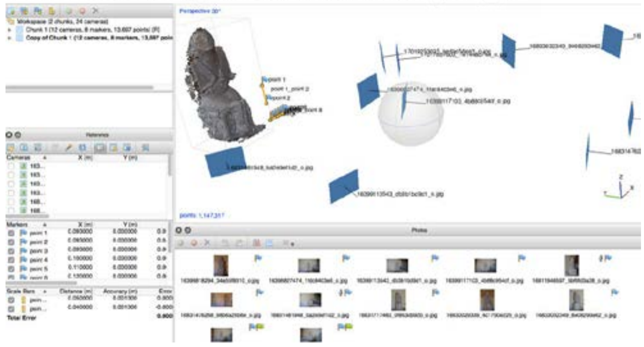
(Hasegawa et al., 2002)

data types by photogrammetry

- 3D point cloud
- Orthorectified image
- DEM (Digital Elevation Model)
- 3D mesh model / bird-eye view (texture mapping)

Structure-from-Motion (SfM) Multi-View Stereo (MVS) photogrammetry

SfM: reconstruction of camera positions by automatic detection of tie-points on a stationary target



SfM-MVS photogrammetry

SfM: structure from motion

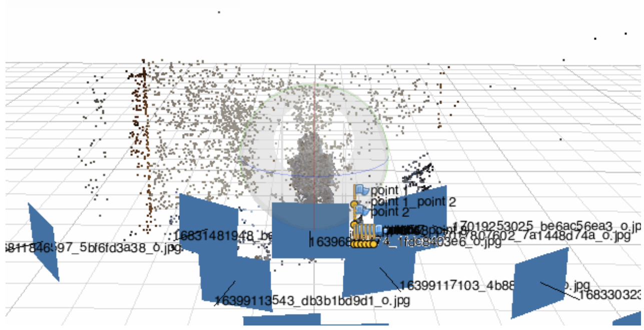
- Developed in computer vision (Ullman, 1979; Szeliski, 2010)
- Reconstruction 3D structure from 2D images
- Sparce point cloud from image matching

MVS: multi-view stereo photogrammetry

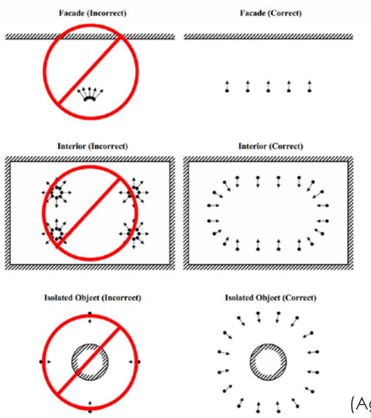
- Photogrammetry from already aligned 2D images
- Dense point cloud (PMVS/CMVS)

Structure-from-Motion (SfM) Multi-View Stereo (MVS) photogrammetry

MVS: further photogrammetric process to generate dense point cloud



Appropriate photo shooting for SfM-MVS



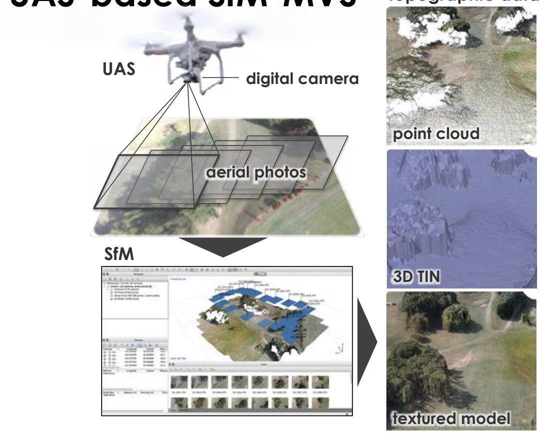
(Agisoft, 2014)

revolution by UAS

小型無人航空機による革命

– much higher, wider & faster –

UAS-based SfM-MVS



Characteristics of SfM-MVS

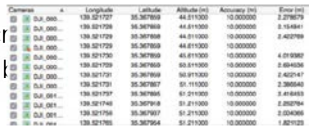
- Various platforms
  - UAV (UAS), balloon, kite
  - pole, handheld
  - undersea etc…
- Low cost: <1,000 USD
- Multiscale: mm – km
- High resolution: >1M points/faces
- Textured images
  - Orthorectified image

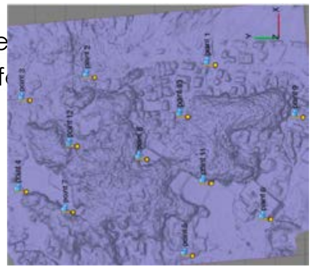
Software

- SfM and MVS (free)
  - **Bundler**
    - basic SfM reconstruction
  - **PMVS2** and **CMVS**
    - Patch-based Multi-view Stereo
    - Clustering Views for Multi-view Stereo
    - dense point cloud reconstruction
  - other derivatives (Bundler + PMVS/CMVS)
    - VisualSFM
    - Bundler Photogrammetry Package
    - Python Photogrammetry Toolbox
- commercial
  - Agisoft **PhotoScan**
  - PIX4D
- web-based services
  - Microsoft Photosynth
  - Autodesk 123D Catch

GNSS for SfM-MVS photogrammetry

- Aircraft positions
  - Built-in receiver on aircr
  - Camera positions can l AND GNSS positions
- GCP positions
  - Optional points can be
  - Distribution of GCPs aff accuracy



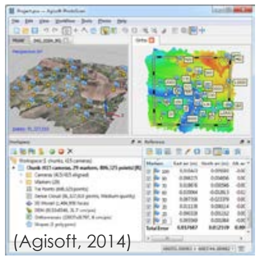


GNSS for SfM-MVS photogrammetry

- Aircraft positions
  - Built-in receiver for many aircrafts
    - low in accuracy (1–10 m)
    - ready to use
  - Optional antenna
    - potentially high in accuracy (~10 cm)
    - either realtime or post-processed

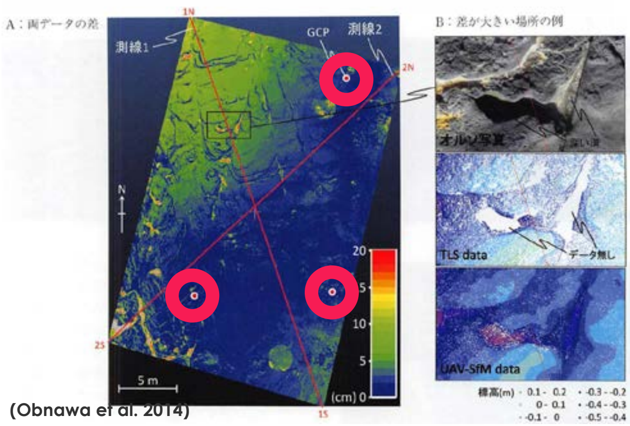
GNSS for SfM-MVS photogrammetry

- GCP positions
  - separately measured
  - Wide (unbiased) distribution for the appropriate model calibration



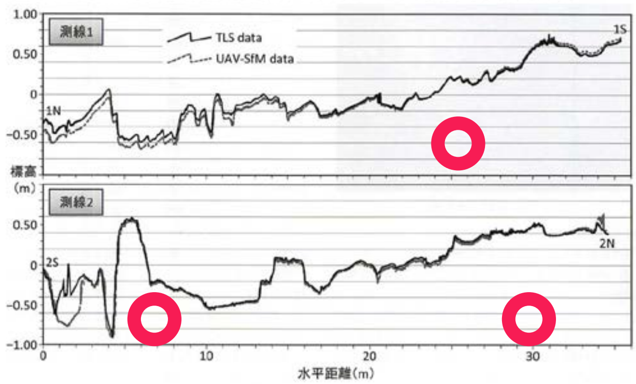
(Agisoft, 2014)

GCP distribution and model accuracy



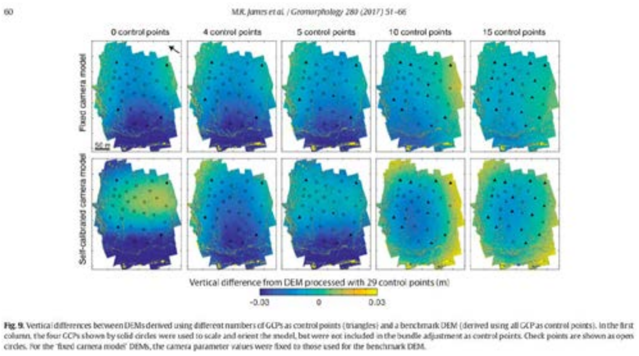
(Obnawa et al. 2014)

Lower accuracy apart from GCPs



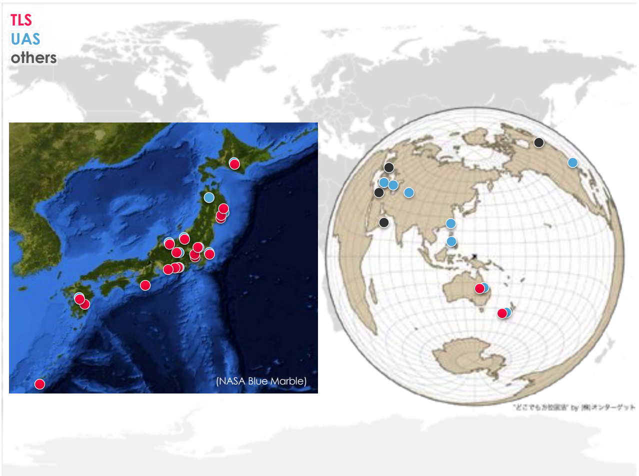
(Obnawa et al. 2014)

GCP and data quality

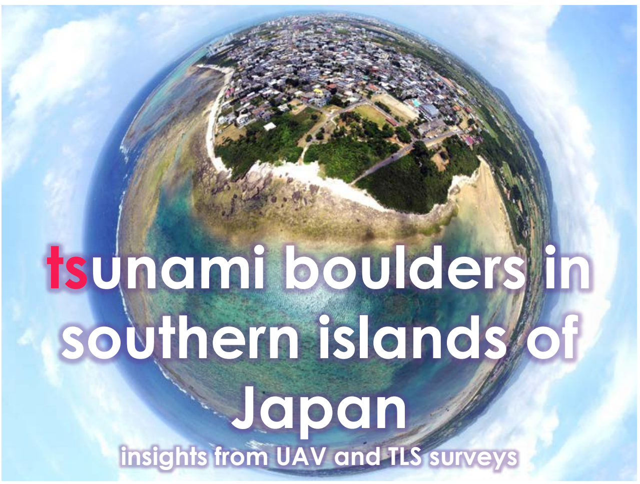


(James et al. 2017)

case studies



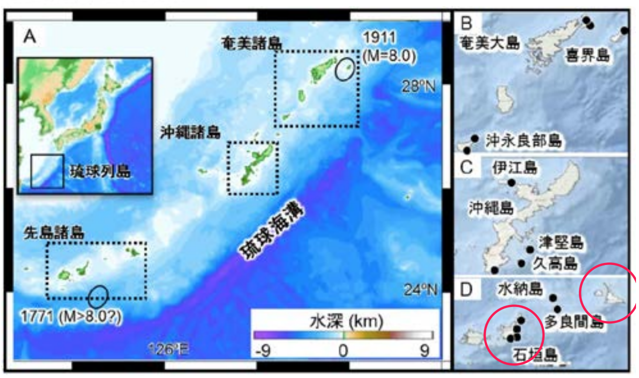
tsunami boulders



introduction

- tsunami boulders – key features to reconstruct past tsunamis (e.g., Imamura et al., 2008, JGR; Goto, 2012, JSSJ)
- accurate volume measurements in the field have been a challenging issue (e.g., Spiske et al., 2008, EPSL; Watt et al., 2010, USGS-OFR, Gienko and Terry, 2014, ESPL)
- high-definition topographic measurements are applied to obtain the volume of tsunami boulders in southwestern Japan

study sites



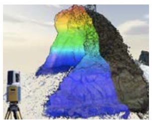
(Goto et al. 2013 *Geology*)

How to measure the shape of boulders?

(Goto et al. 2013 *Geology*)

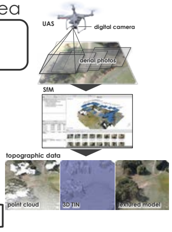
methods

individual rock — wide area



terrestrial laser scanning (TLS)

TLS → SfM → point clouds → cleaning / extraction → poisson surface reconstruction → 3D mesh → volume measurement

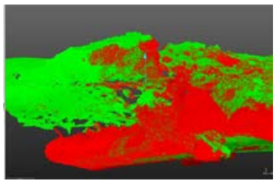


methods: TLS – terrestrial laser scanning [66]

Trimble TX5

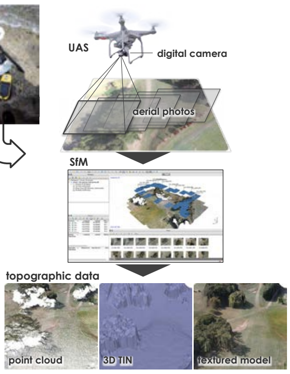
a short-range scanner
– max. distance: 120 m
– max. frequency: 900,000 pts/s
– range accuracy: 2 mm @25 m
– weight: 5 kg

Post processing by RealWorks & CloudCompare
– cloud-based ICP registration



methods: UAS – unmanned aerial system [67]

DJI hantom 3 Professional/Advanced



post processing
- SfM-MVS photogrammetry by PhotoScan
- positioning accuracy: GCP by PPK-GNSS (Trimble GeoXH), fix solution

case studies in southwestern Japan [68]

- Miyakojima Island (Cape Higashi-Henna)
- Shimoji Island
- Ishigaki Island
- Kuroshima Island

tidal waves vs tsunami waves

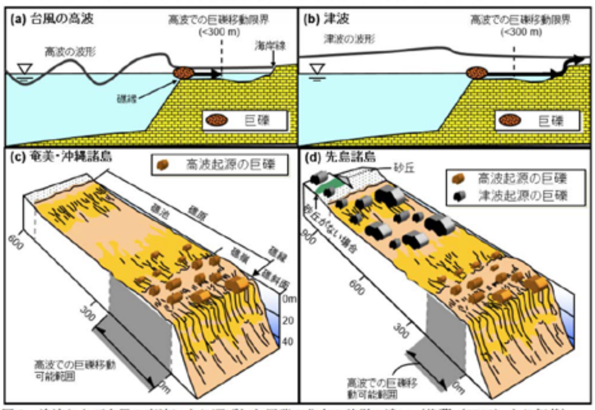
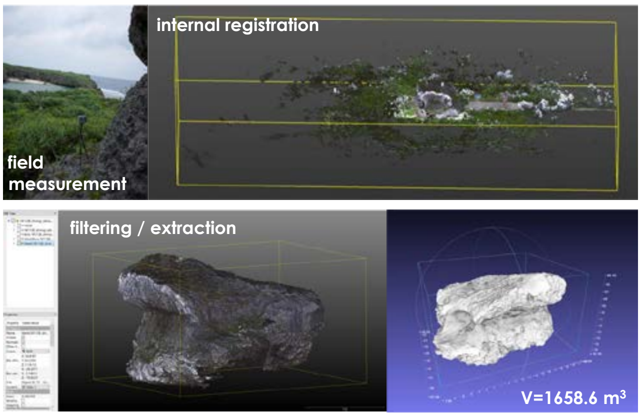


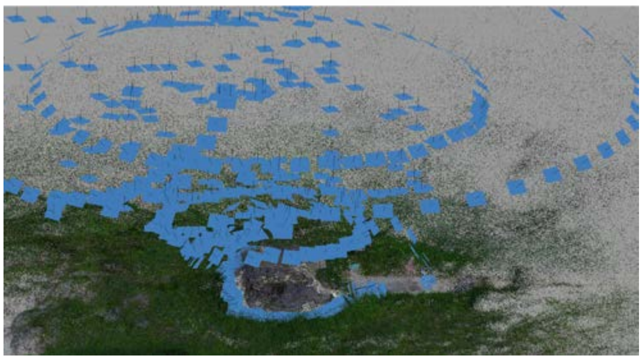
図 3 津波および台風の高波により運ばれた巨礫の分布の特徴の違い（後藤（2012）より転載）

one of the largest tsunami boulders in the world: "Obi-iwa" in Shiomji Is. [70]

TLS and volume [71]

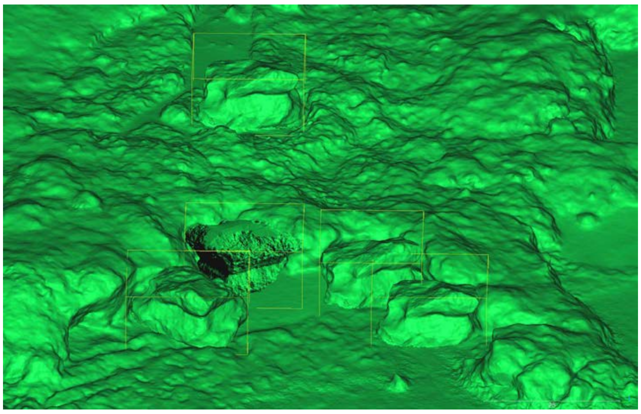


SfM by UAS and ground-based camera [72]

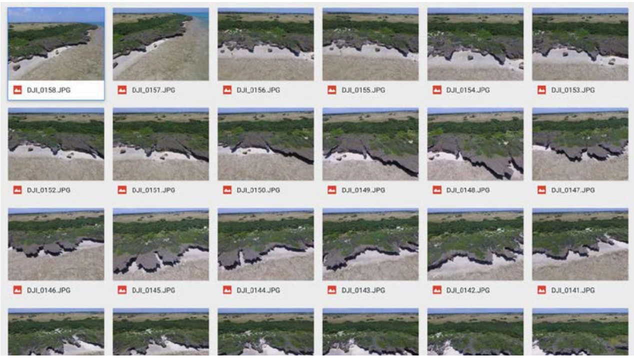


UAS: DJI Phantom 3; ground-based camera: RICOH GR II
→ entire 3D model generated

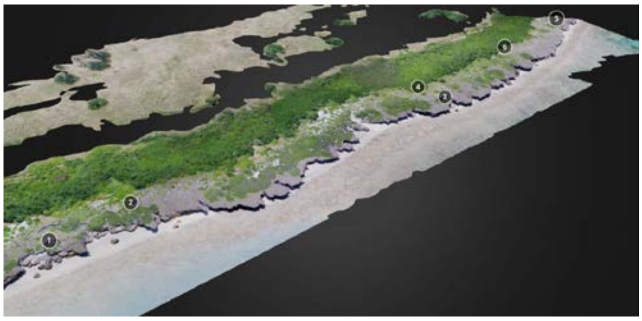
3D puzzle



photographs taken

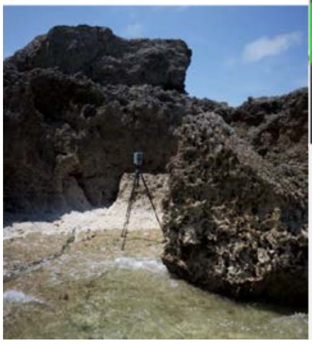


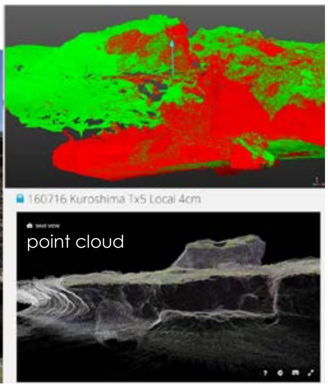
tsunami boulders targeted



TLS measurement of the boulder #03

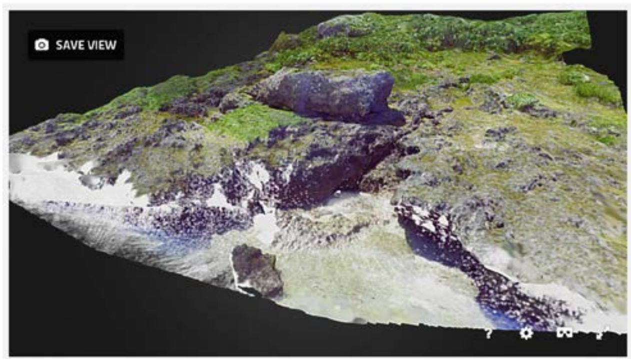
- registration error: **6.66 mm**
- 3D point cloud https://skfb.ly/QJC9



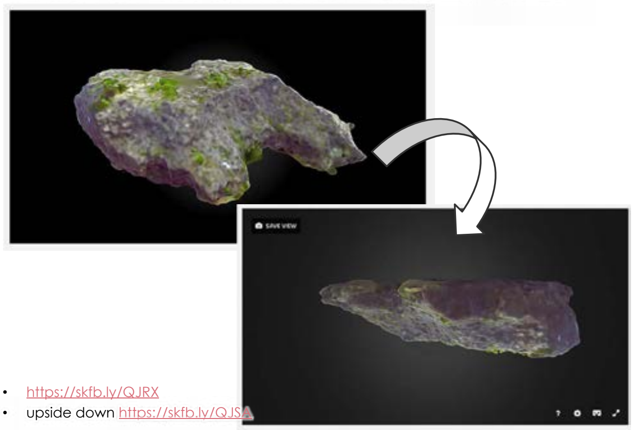


3D mesh model around boulder #03 (TLS)

- https://skfb.ly/QMKC



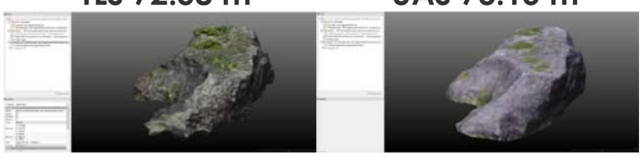
mesh of the boulder #03: flip-side



- https://skfb.ly/QJRX
- upside down https://skfb.ly/QJSA

comparison: TLS and UAS

TLS 72.58 m³ UAS 73.15 m³

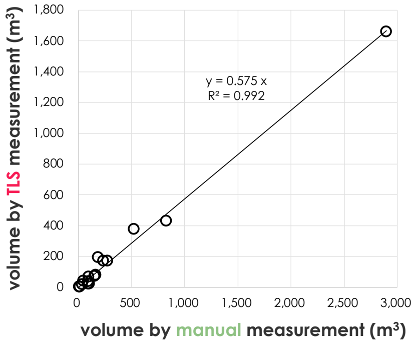


<1% of difference!

volumes for the other boulders

- #01: 24.78 m^3
- #02: 5.60 m^3
- #03: 73.15 m^3
- #04: >15.33 m^3
- #05: 40.44 m^3
- #06 (possible): >44.45 m^3

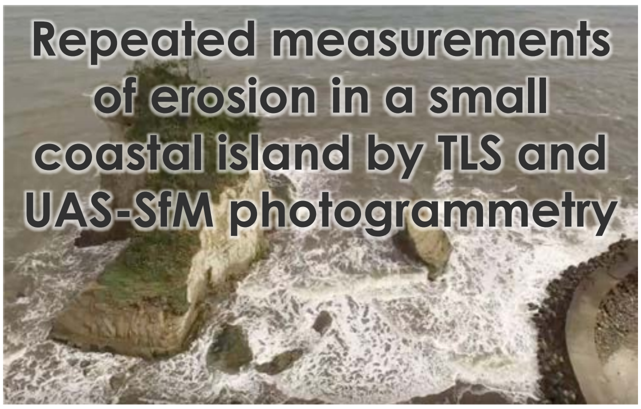
manual (bounding box) vs TLS volumes



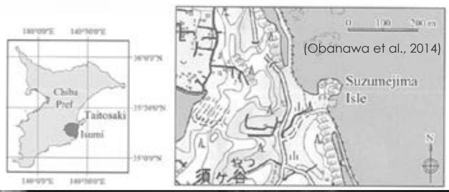
concluding remarks

- successful volume measurements using 3D point clouds derived from either TLS or UAS-SfM
  - ca. x0.6 of manual measurements
  - TLS is good for accessible individual boulder, while UAS is also good enough for inaccessible remote boulders
- time consuming: manual filtering
- possibility: shape analysis
  - identification of source location

volume of rocky coast erosion

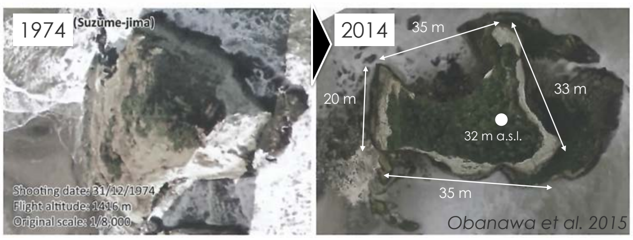


study site: Suzumejima Island

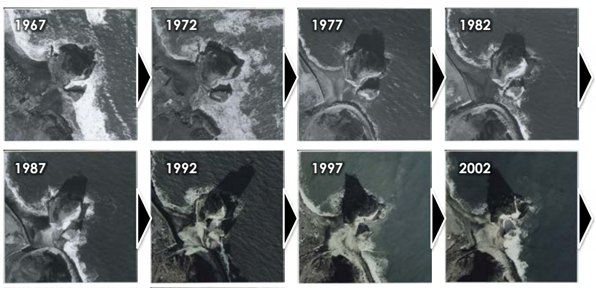


natural processes of rocky coast erosion at Suzumejima Island

- a rare place: natural processes of coastal erosion
  - out of the coastal protection
  - oceanic waves directly attacks the bedrock cliff
- rapidly shrinking for decades



changes of the island for 50 years



- constant erosion
- shore platform formation
- reported erosion rates around this site: 1 m/y
  - (1960–1966 by 1:1,000 topo maps; Horikawa and Sunamura 1967)

methods: TLS – terrestrial laser scanners

TLS #1: TOPCON GLS-1500

a medium-range scanner
– max. distance: 500 m
– max. frequency: 30,000 pts/s
– range accuracy: 4 mm @150 m
– weight: 16 kg (body) + batteries

TLS #2: Trimble TX5

a short-range scanner
– max. distance: 120 m
– max. frequency: 900,000 pts/s
– range accuracy: 2 mm @25 m– weight: 5 kg

methods: UAS – unmanned aerial system

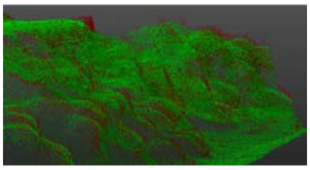
DJI Phantom 2 + NIKON COOLPIX A / Phantom 3 Professional/Advanced

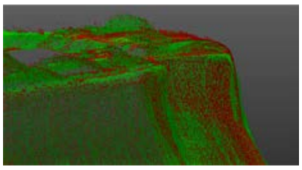
post processing

- SfM-MVS photogrammetry by PhotoScan
- 500-1,000 photos for each time
- positioning accuracy 1: camera-mounted GNSS, >1 m
- positioning accuracy 2: GCP by PPK-GNSS (fix solution) (Trimble GeoXH), 13.4–14.9 mm (14.4 mm RMS)

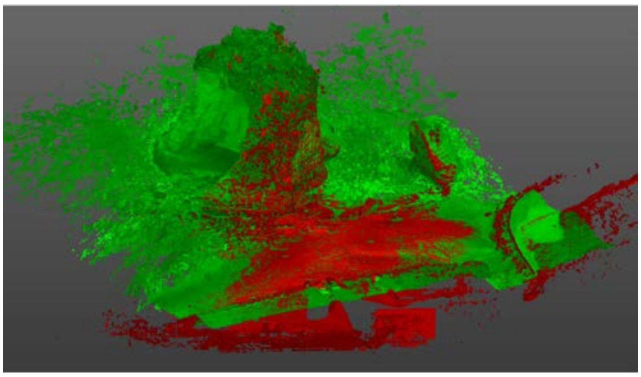
fusion of UAS & TLS

- further aligned by ICP
  - UAS dense cloud → TLS cloud
  - CloudCompare / Trimble RealWorks
  - cloud-based registration (ICP), errors: 25.1–39.7 mm



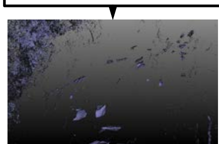


fusion of UAS & TLS



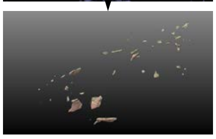
an example of data processing

C2C distance
(detectable distance: 3~10 cm or more)

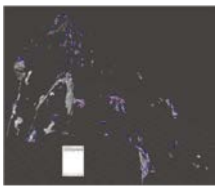


invert normals for the "after" dataset

3D mesh polygons
poisson surface reconstruction

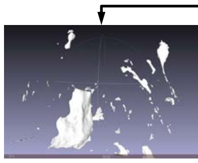


an example of data processing



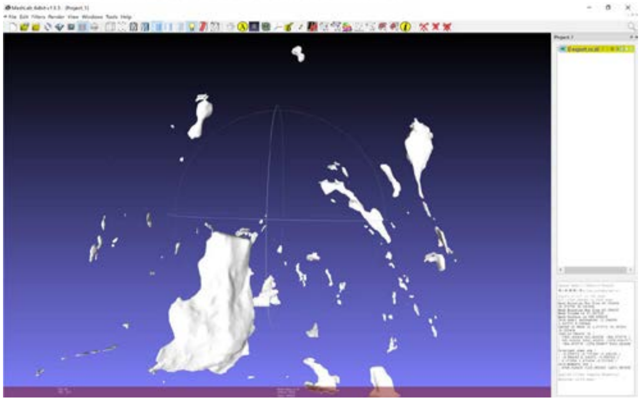
mesh with holes

solid mesh (w/o holes)

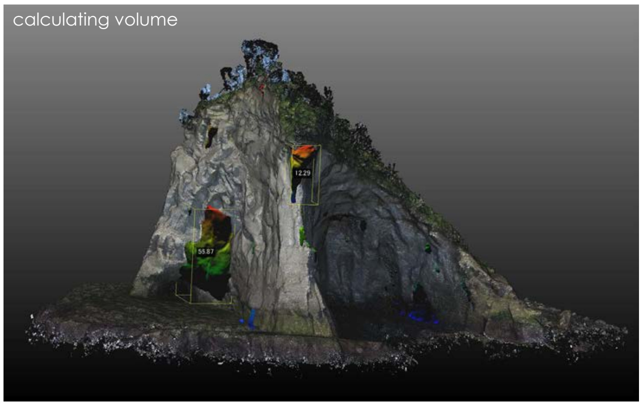


remove noise mesh

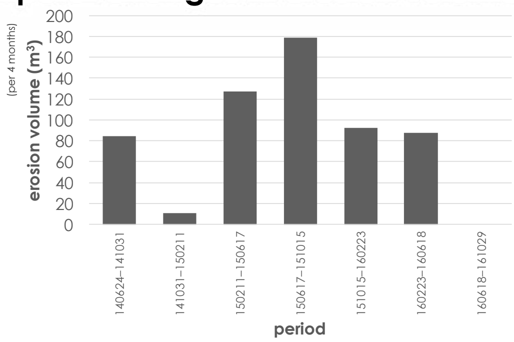
3D volume calculation



an example of data processing

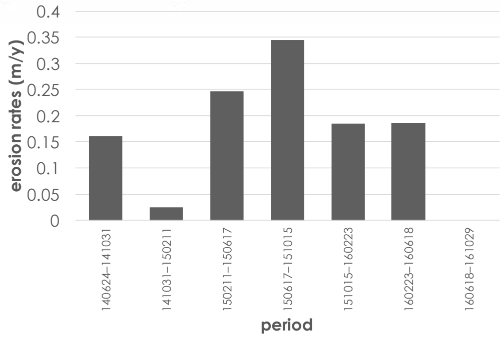


temporal changes in erosion volume



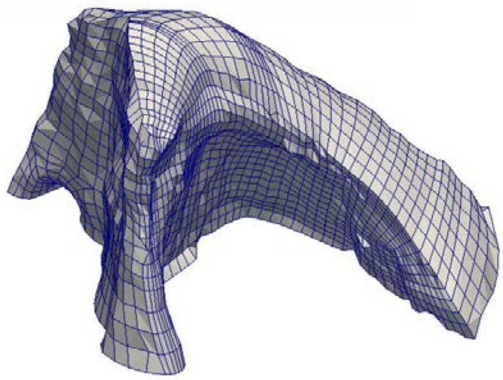
volume and rates of erosional changes
- by UAS data only
- the volume varies, **10.6 – 178.5 m³** per 4 months

temporal changes in erosion volume

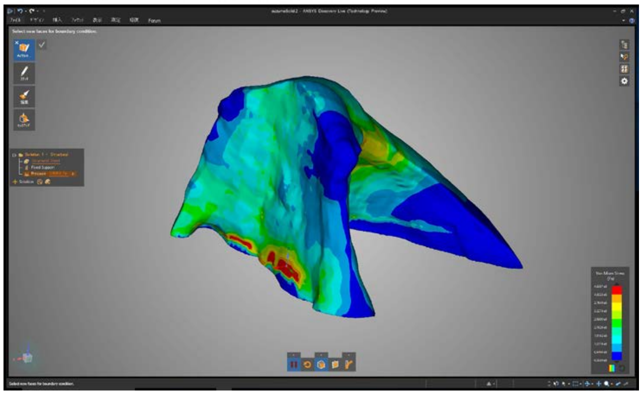


volume and rates of erosional changes
- approx. area of bedrock planes: 1,436 m²
- equivalent annual erosion rates: **0.03 – 0.35 m/y**

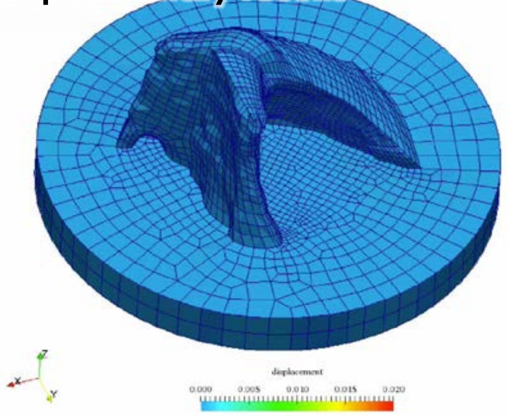
remeshing for FEM analysis



FEM preliminary results



FEM preliminary results

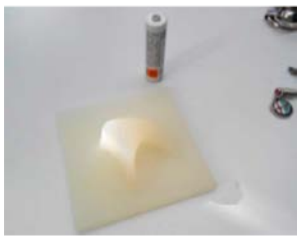


educational/outreach applications

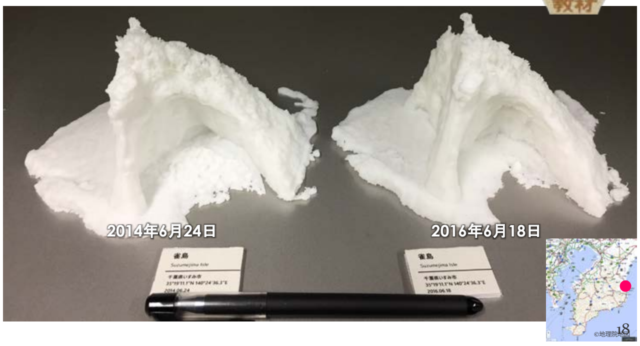
online 3D viewer

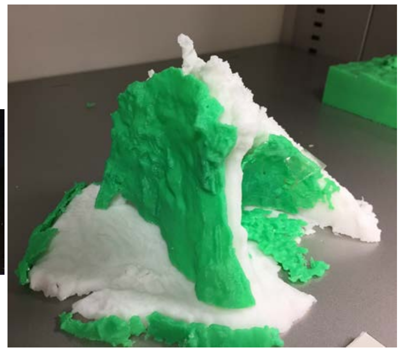
https://skfb.ly/QUwS

3D print



3D print examples





educational/outreach applications[107]

cardboard 3D builder

mini workshop at Kashiwa Open Campus 2017

archaeological applications

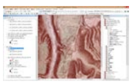
UAS-based SfM-MVS photogrammetry

- acquisition of aerial photos by UAS
  - 100–300 photos per each flight (typically 15–20 min)
  - coverage area can be adjusted by the flight height and distance

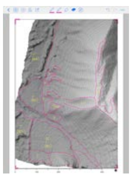
- SfM-MVS processing
  - software: PhotoScan by Agisoft
  - tie point (sparse cloud)
  - dense cloud
  - triangular mesh
  - image texture
  - export orthophoto and DEM

spatial data management

- GIS data processing
  - import as spatial data layers
  - orthorectified images
  - DEM (digital elevation model) to hillshade, slope, etc.
  - extraction of topographic profiles
  - export as TIFF or PDF images

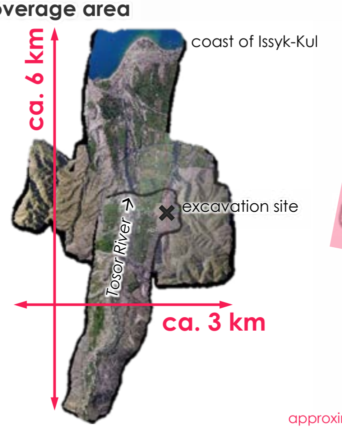


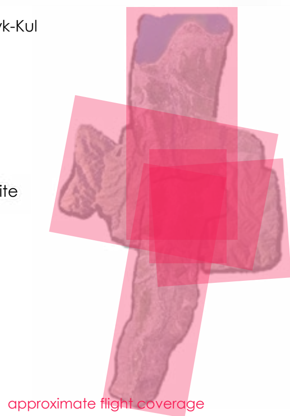
- On-site geomorphological mapping
  - import data
  - tracing topographic features using iPad (GoodNotes app)
  - realtime matching of the map-derived features with field observation



Uchu-Kurbu and surroundings (Issyk-Kul)

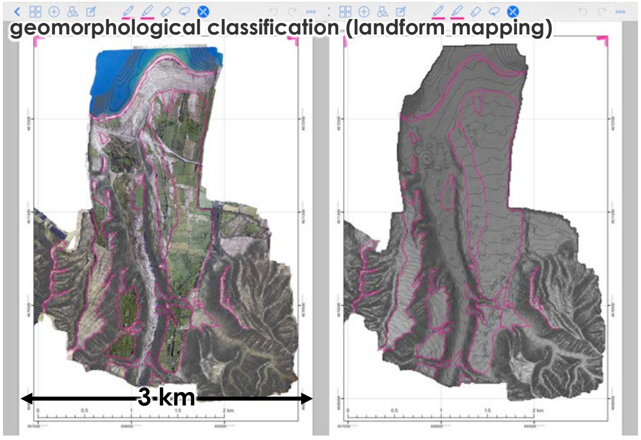
coverage area





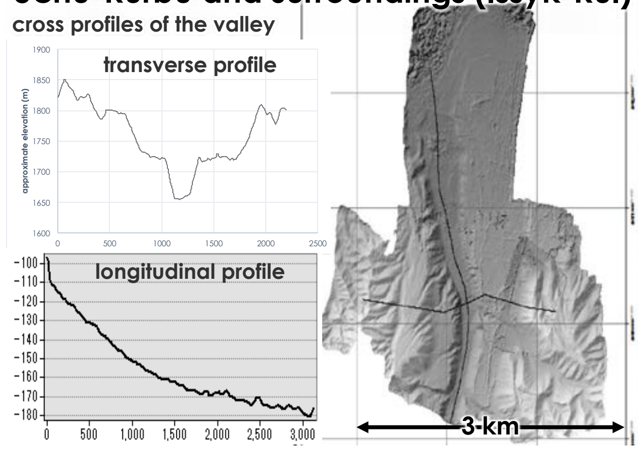
Uchu-Kurbu and surroundings (Issyk-Kul)

geomorphological classification (landform mapping)



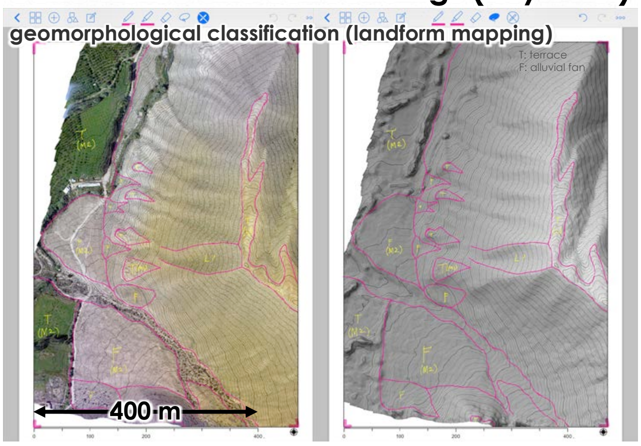
Uchu-Kurbu and surroundings (Issyk-Kul)

cross profiles of the valley



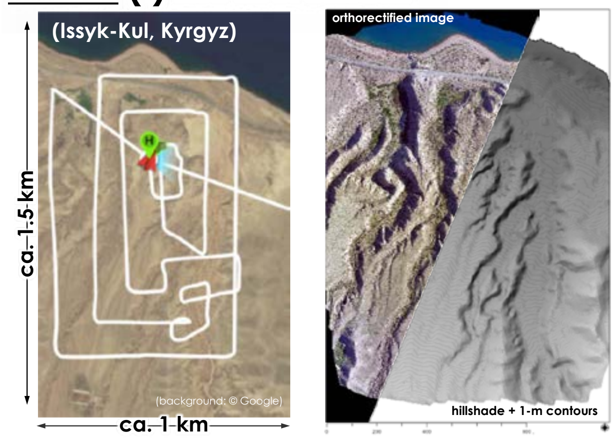
Uchu-Kurbu and surroundings (Issyk-Kul)

geomorphological classification (landform mapping)

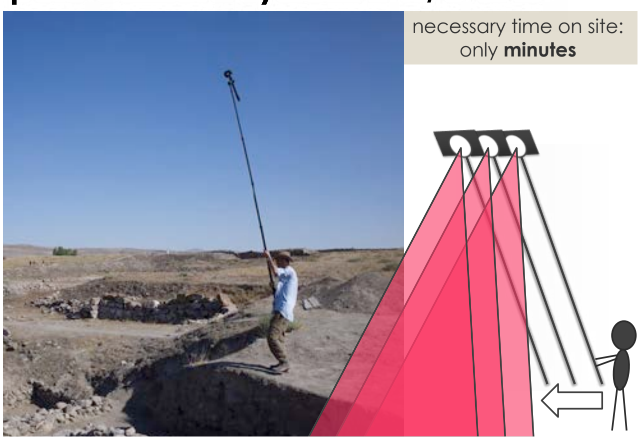


ultra-rapid measurement for archaeology

1-hour (!) measurement



pole camera system if w/o UAS

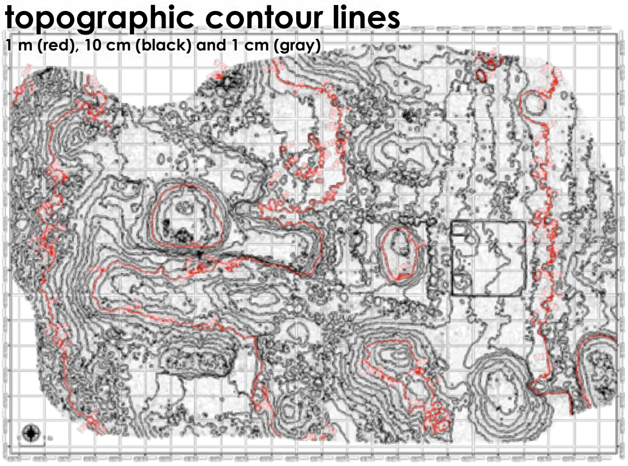


orthorectified image

resolution = 1 mm, grid interval = 1 m

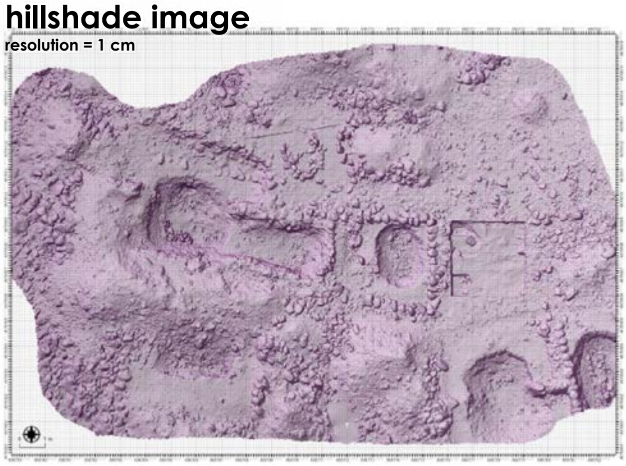
topographic contour lines

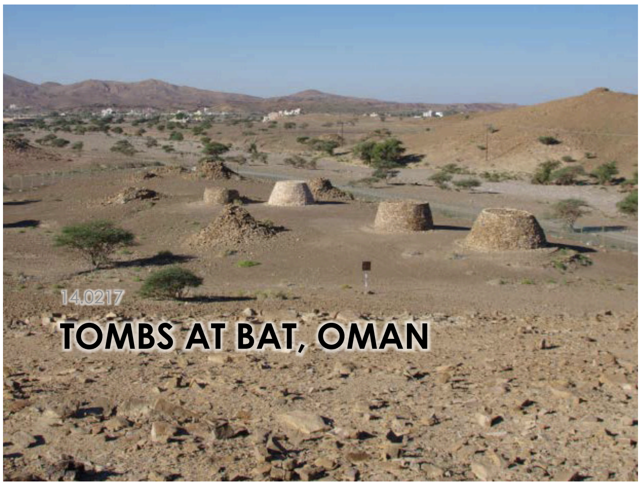
1 m (red), 10 cm (black) and 1 cm (gray)



hillshade image

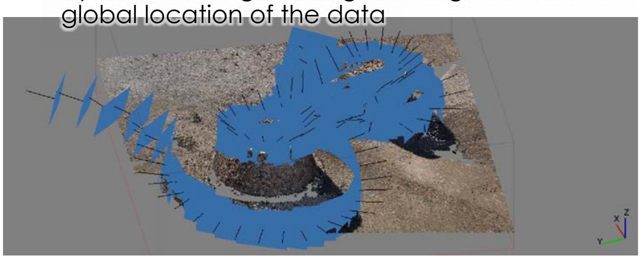
resolution = 1 cm

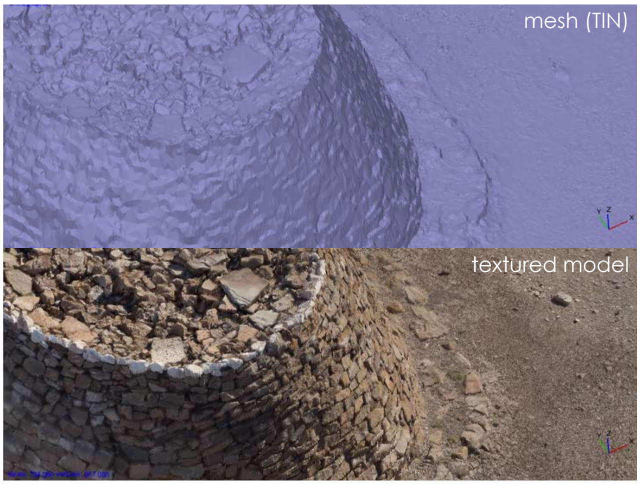




test for two tombs

- 102 photos
- processing time: ca. 45 min
- w/o GCPs
  - but the coordinates of camera positions taken by Garmin Oregon 300 gives rough estimate of global location of the data



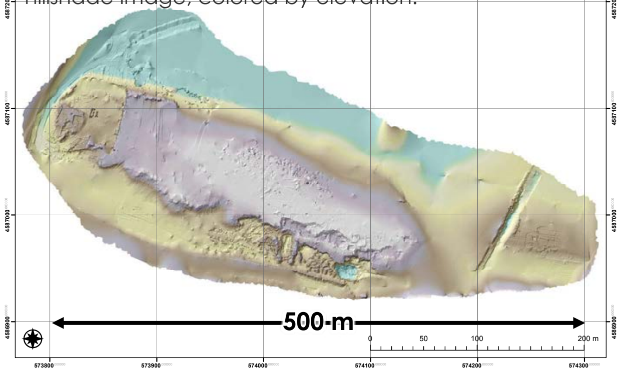


pole-camera for a wider area:
Aigurzhal II/III sites (Naryn)

Sparse point cloud generated by SfM from the photographs taken in and around the site. Camera positions of the photographs are shown as blue rectangles.

pole-camera for a wider area:
Aigurzhal II/III sites

hillshade image, colored by elevation.



pole-camera for a wider area:
Aigyrzhal II/III sites

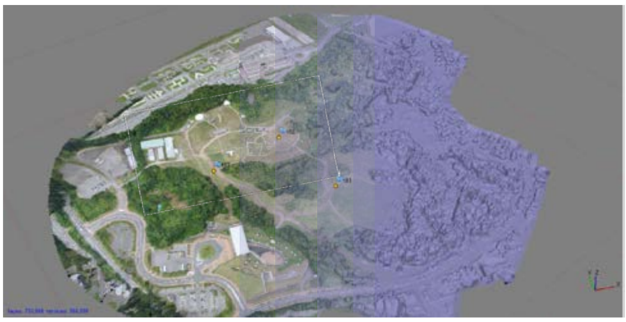
Orthorectified image shown in Google Earth.

visualization

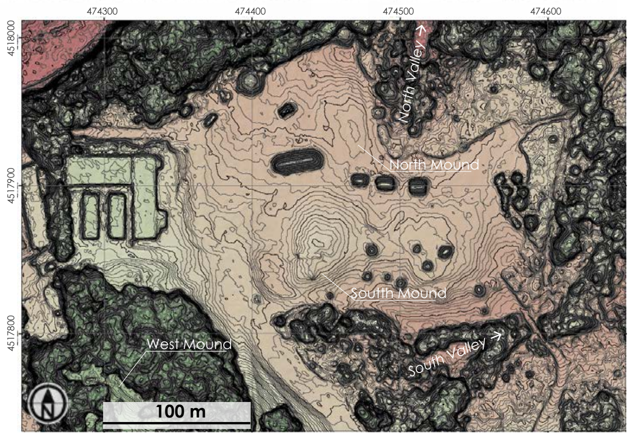
supports for archaeological landscape reconstruction

aerial panorama of Sannai Maruyama Site, Aomori, northern Japan

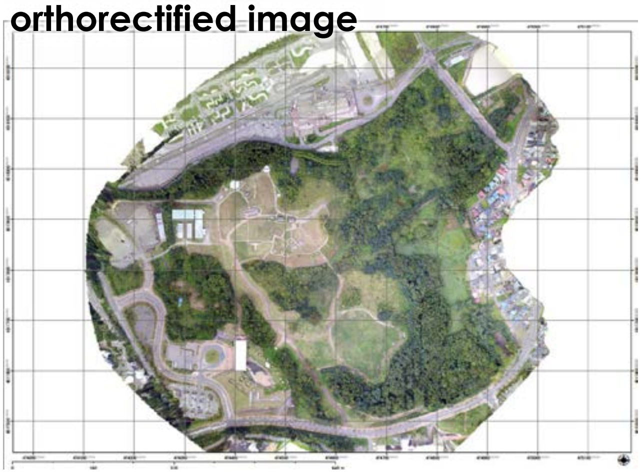
3D model construction by UAS-SfM



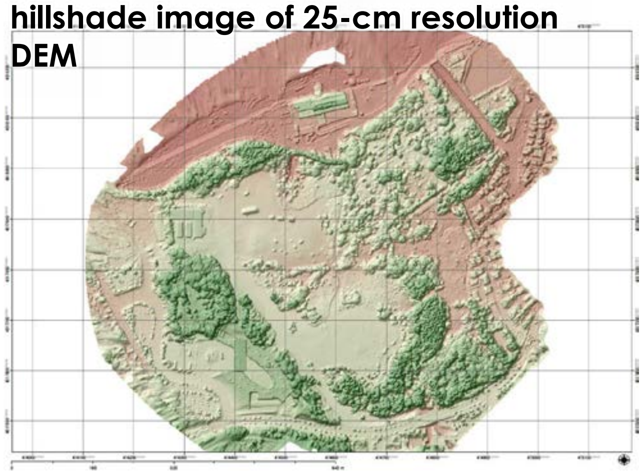
topographic map of Sannai Maruyama Site



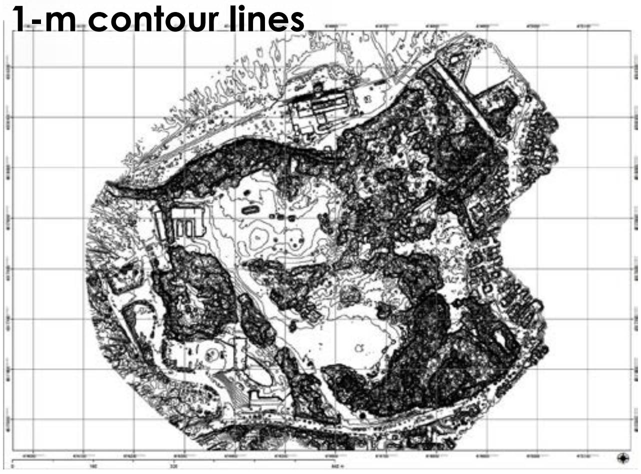
orthorectified image



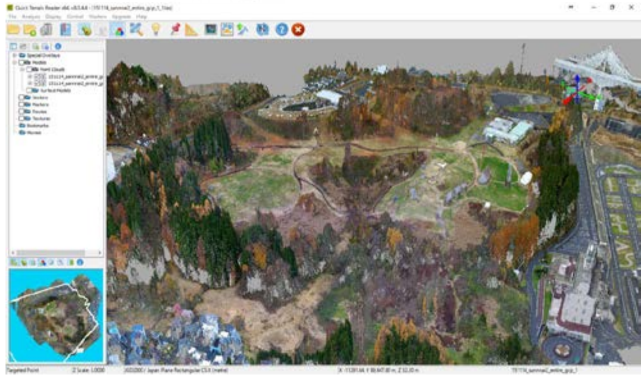
hillshade image of 25-cm resolution DEM



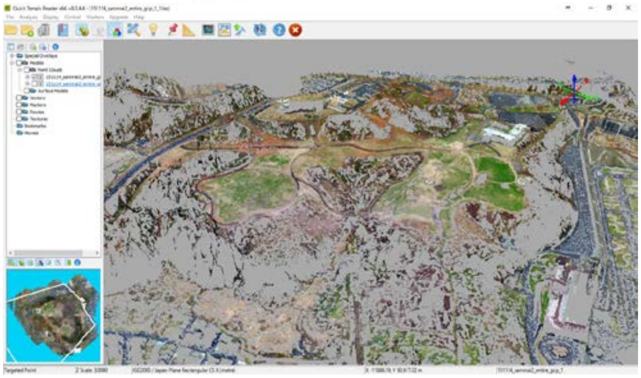
1-m contour lines



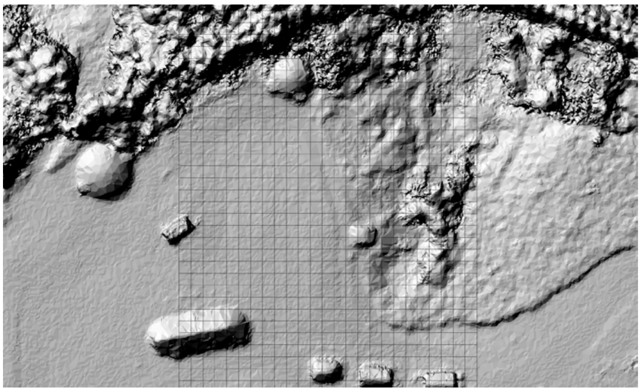
before filtering



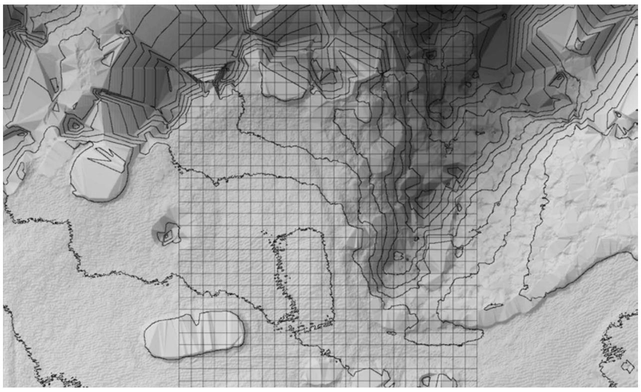
after filtering



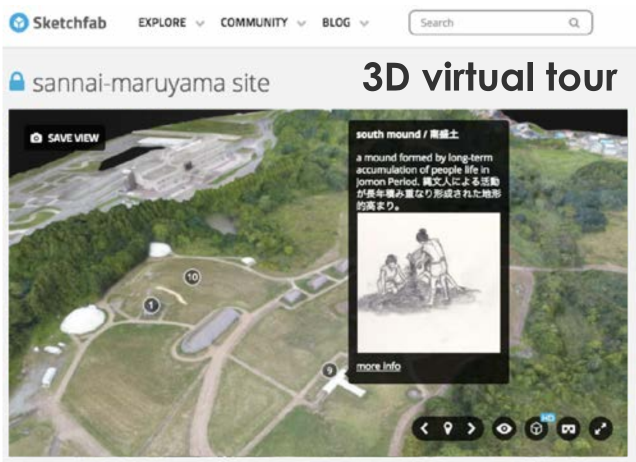
hillshade before filtering



hillshade after filtering



3D virtual tour



https://sketchfab.com/models/85f309f1204e4115ae4a3d4dbe885069

exhibition at The Museum of Kyoto

high-precision GNSS for UAS

Tateyama volcano

Reach RTK on Phantom 3

Shutter sync via hot-shoe

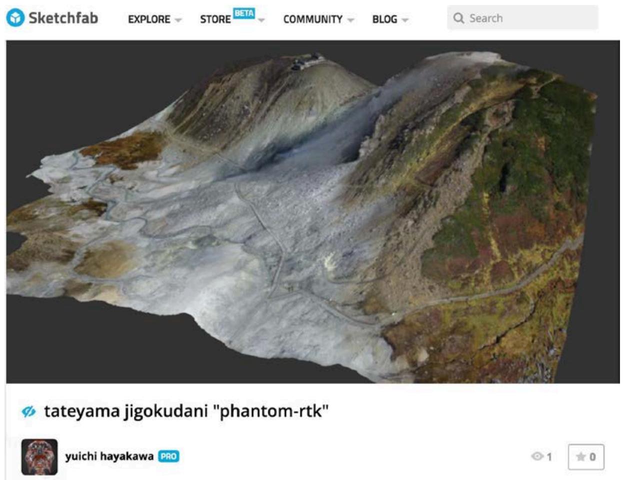
(not for this case, though)

Reach RTK DF13 connector

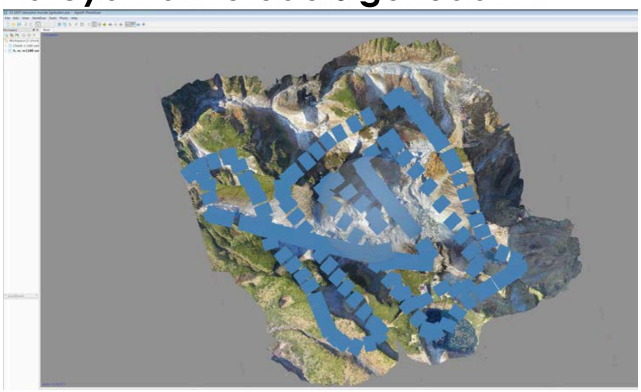
Ricoh GR + adapter AS-15 + sync code SC-11 & DF-13 connector

by Shoichiro Uchiyama

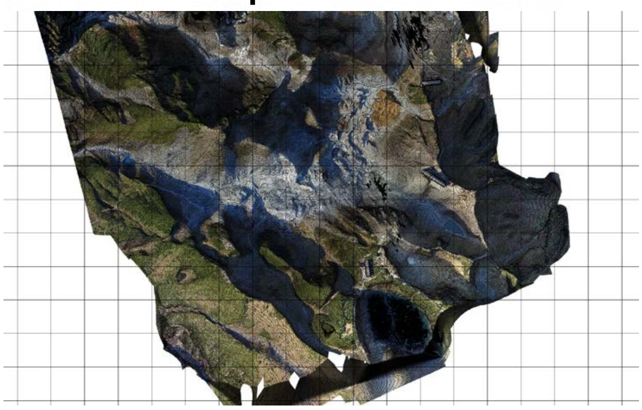
UAV flight over volcanic crater



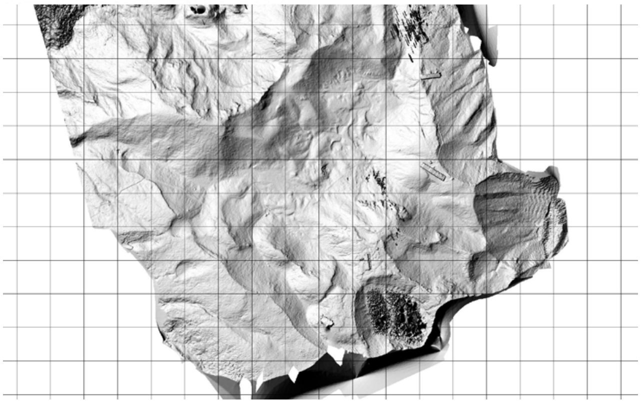
Tateyama Murodo Jigokudani



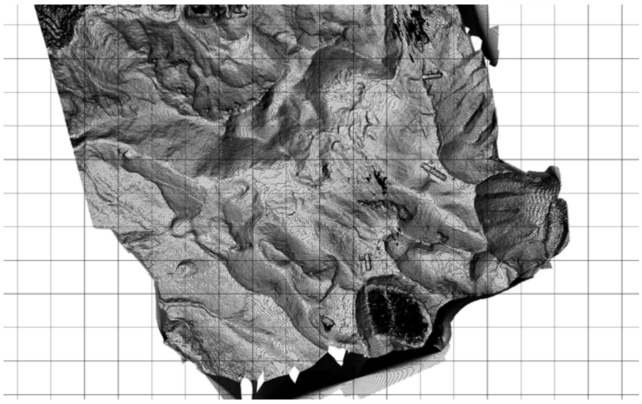
orthorectified photo + contours



hillshade (4 cm)

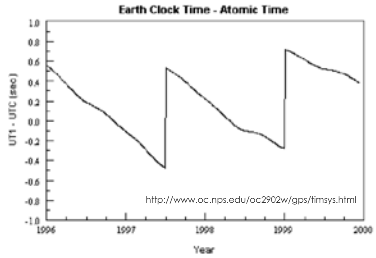


hillshade (4 cm) + contour 1 m



Leap second

- **GPS Time**: unchanged since Jan 6, 1980
- **UT1**: the principal form of Universal Time
- **UTC**: Universal Time Coordinated; slow, inconstant drift over decades
- occasional intercalary of **leap seconds**



Screenshot of the UTC clock from www.time.gov during the leap second on December 31, 2016.

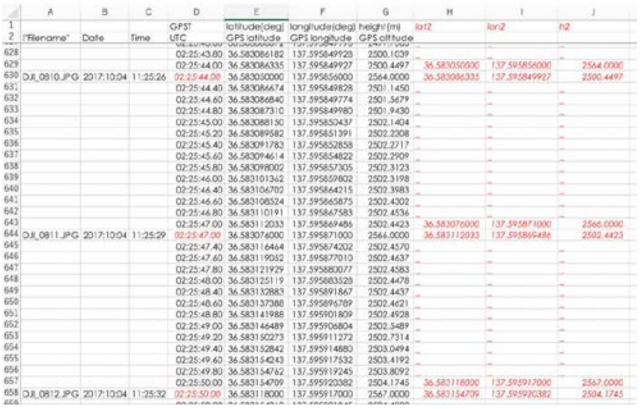
Accumulation of leap seconds

GPS Time – UTC =

18 seconds

as of late 2017

assignment of camera positions (1 Hz)



	A	B	C	D	E	F	G	H	I	J
1				GPST	latitude(deg)	longitude(deg)	height(m)	lat2	lon2	h2
2	"Filename"	Date	Time	UTC	GPS latitude	GPS longitude	GPS altitude			
628				02:25:43.80	36.583086182	137.595849928	2500.1039			
629				02:25:44.00	36.583086335	137.595849927	2500.4497	36.583050000	137.595856000	2564.0000
630	DJI_0810.JPG	2017:10:04	11:25:26	02:25:44.00	36.583050000	137.595856000	2564.0000	36.583086335	137.595849927	2500.4497
631				02:25:44.40	36.583086674	137.595849828	2501.1450			
632				02:25:44.60	36.583086840	137.595849774	2501.5679			
633				02:25:44.80	36.583087310	137.595849980	2501.9430			
634				02:25:45.00	36.583088150	137.595850437	2502.1404			
635				02:25:45.20	36.583089582	137.595851391	2502.2308			
636				02:25:45.40	36.583091783	137.595852858	2502.2717			
637				02:25:45.60	36.583094614	137.595854822	2502.2909			
638				02:25:45.80	36.583098002	137.595857305	2502.3123			
639				02:25:46.00	36.583101362	137.595859802	2502.3198			
640				02:25:46.40	36.583106702	137.595864215	2502.3983			
641				02:25:46.60	36.583108524	137.595865875	2502.4302			
642				02:25:46.80	36.583110191	137.595867583	2502.4536			
643				02:25:47.00	36.583112033	137.595869486	2502.4423	36.583076000	137.595871000	2566.0000
644	DJI_0811.JPG	2017:10:04	11:25:29	02:25:47.00	36.583076000	137.595871000	2566.0000	36.583112033	137.595869486	2502.4423
645				02:25:47.40	36.583116464	137.595874202	2502.4570			
646				02:25:47.60	36.583119052	137.595877010	2502.4637			
647				02:25:47.80	36.583121929	137.595880077	2502.4583			
648				02:25:48.00	36.583125119	137.595883528	2502.4478			
649				02:25:48.40	36.583132883	137.595891867	2502.4437			
650				02:25:48.60	36.583137388	137.595896789	2502.4621			
651				02:25:48.80	36.583141988	137.595901809	2502.4928			
652				02:25:49.00	36.583146489	137.595906804	2502.5489			
653				02:25:49.20	36.583150273	137.595911272	2502.7314			
654				02:25:49.40	36.583152842	137.595914880	2503.0494			
655				02:25:49.60	36.583154243	137.595917532	2503.4192			
656				02:25:49.80	36.583154762	137.595919245	2503.8092			
657				02:25:50.00	36.583154709	137.595920382	2504.1745	36.583118000	137.595917000	2567.0000
658	DJI_0812.JPG	2017:10:04	11:25:32	02:25:50.00	36.583118000	137.595917000	2567.0000	36.583154709	137.595920382	2504.1745

Test case: SfM – GCP RMS <1 cm

t00	0.0103965	-0.04772625	-0.583418
t01	0.1138475	0.13749075	0.0476117
t02	-0.0466595	-0.03062325	-0.042255
t03	-0.0775845	-0.05914125	-0.005356
averag	*1.81899E-12*	*-1.81899E-12*	*0*
RMS	*0.00532*	*0.00640*	*0.00136*

by the way,

higher-resolution

is **higher-resolution**

is **higher-resolution** **always good?**

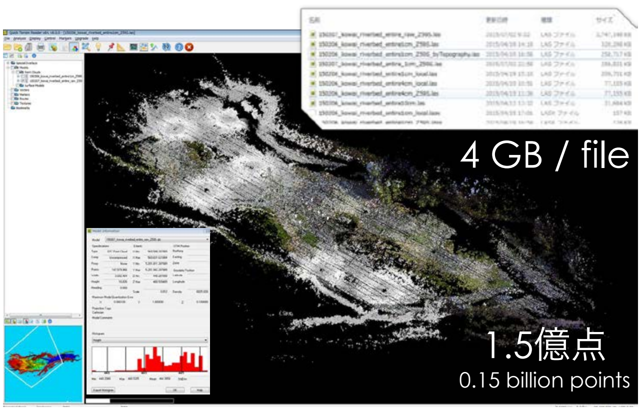
example of Google Earth

privacy

unexpected points over moving items

noise

large datasets → time cost for analysis



data size

high resolution, but...

one step back, then you will see it.

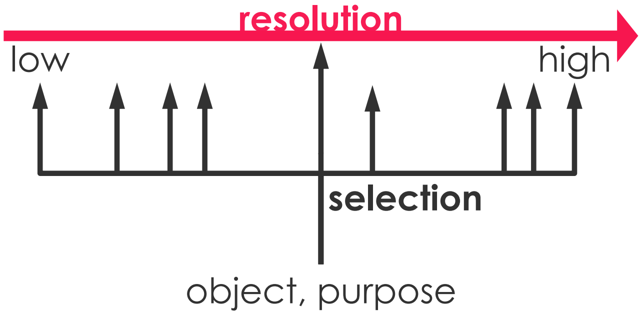
higher-resolution

≠

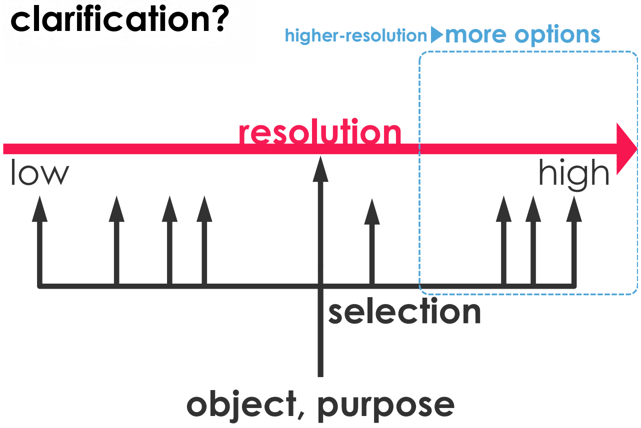
higher-definition

or **clarification**

clarification?



clarification?



high resolution

optimum resolution

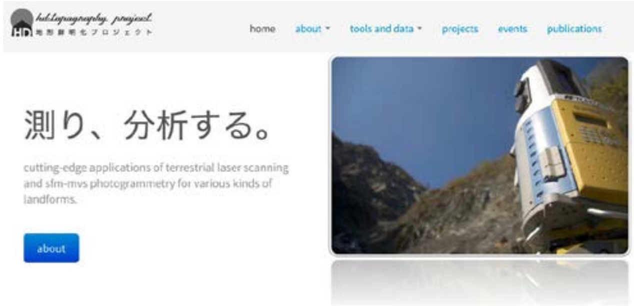
remarks

what comes after having these data?

- technological development enabled rapid, accurate acquisition of high-definition topographic data on site
- now we have (hopefully) more time for:
  - geomorphological mapping and surveys
  - archaeological surveys
    - # with support of detailed maps
  - visualization and sharing ideas of palaeo-landscapes
    - # 3D viewpoints with realistic feelings

other issues

- selection of appropriate **resolution/scale** of data, as well as appropriate **methods**, depending on
  - purposes (area of interest)
  - restrictions (legal)
- more efficiently, more easily…
  - for further applications in many field sites
  - establishment of "protocols"
    - including manual distribution and hosting seminars…



http://topography.csis.u-tokyo.ac.jp/

ODSM open drone safety manuals project

Joint Research Assist System

JoRAS

OPEN DATA for researchers!

Jan 26 – Abstract – Feb 19