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Concurrent Car-Borne Repeat-Pass SAR Interferometry at L-Band and Ku-Band For Mobile Mapping of Ground Motion on Alpine Valley Slopes

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[1] Gamma Remote Sensing, [2] ETH Zurich

Overview

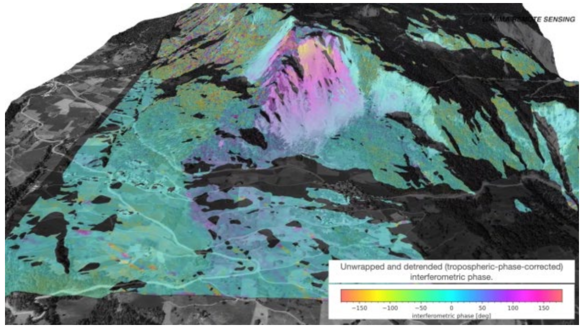
- Quick recap of our recent technology demonstrations on UAV/car-borne DInSAR at L-band to map surface displacements.

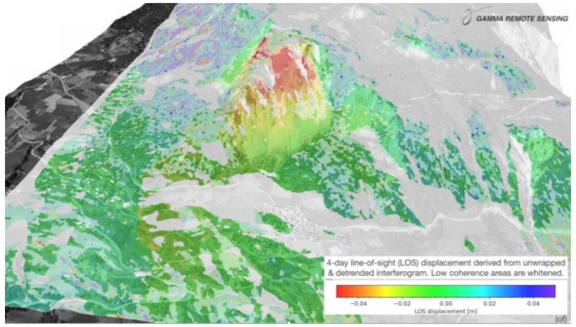
- Motivation for combined L-/Ku-band setup

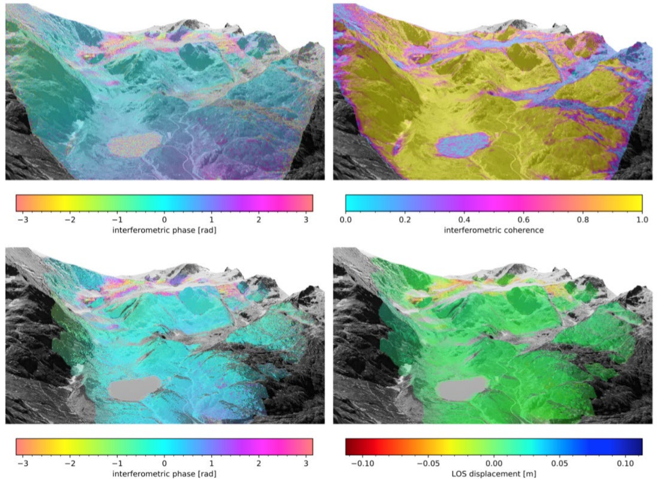
- Analysis of L-/ Ku-band repeat-pass coherence and phase maps from recent measurement campaigns

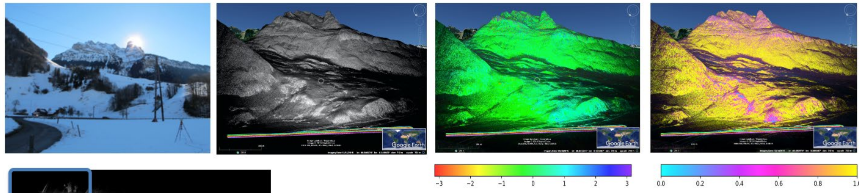
- Summary & Outlook

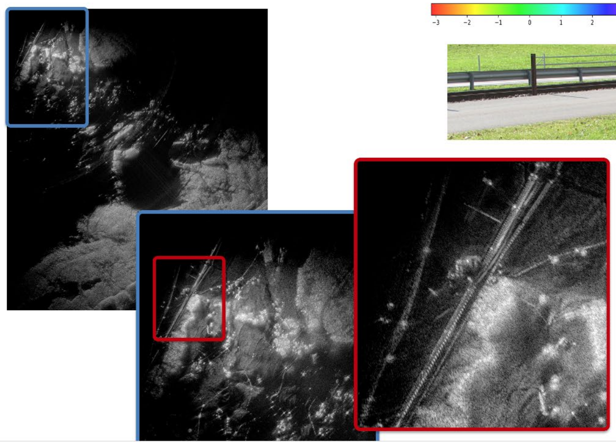
Recap of recent demonstrations **of car-borne** and **UAV-borne** DInSAR at L-band to map surface displacements + **UAV-borne** TomoSAR demo

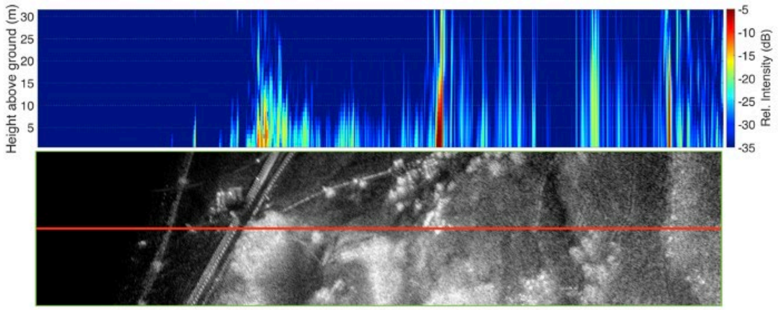


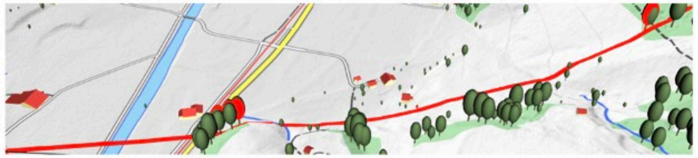




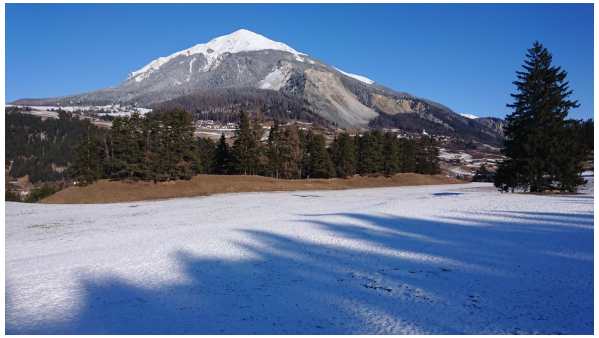






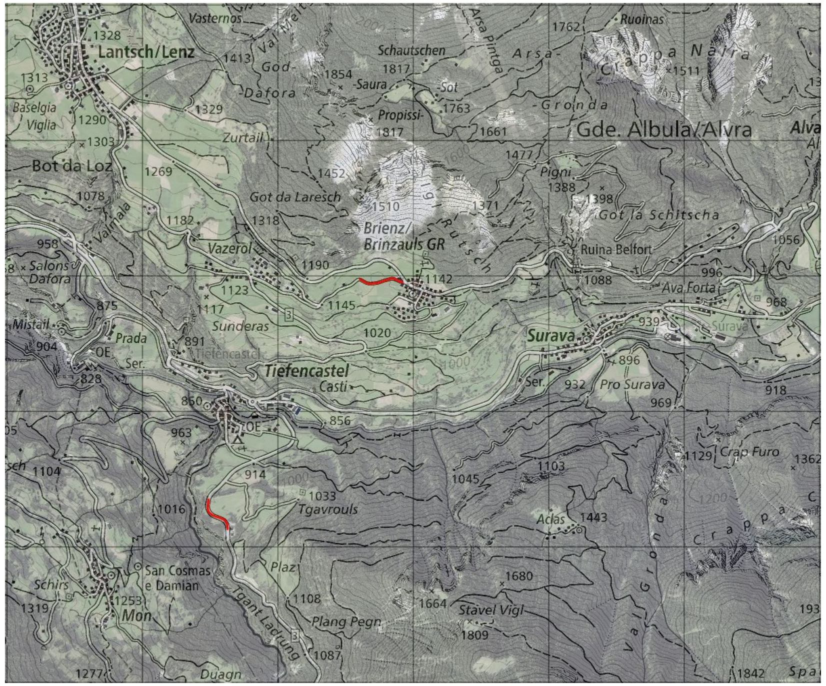


Carborne L-band DInSAR based measurement of surface displacements: demonstration case “Landslide Brinzauls” Jan/Feb 2020



Fast-moving land slide

- lower section, village: up to **~2.5 cm/week**
- upper part: up to ~**2cm/day**



Map/orthophoto: swisstopo

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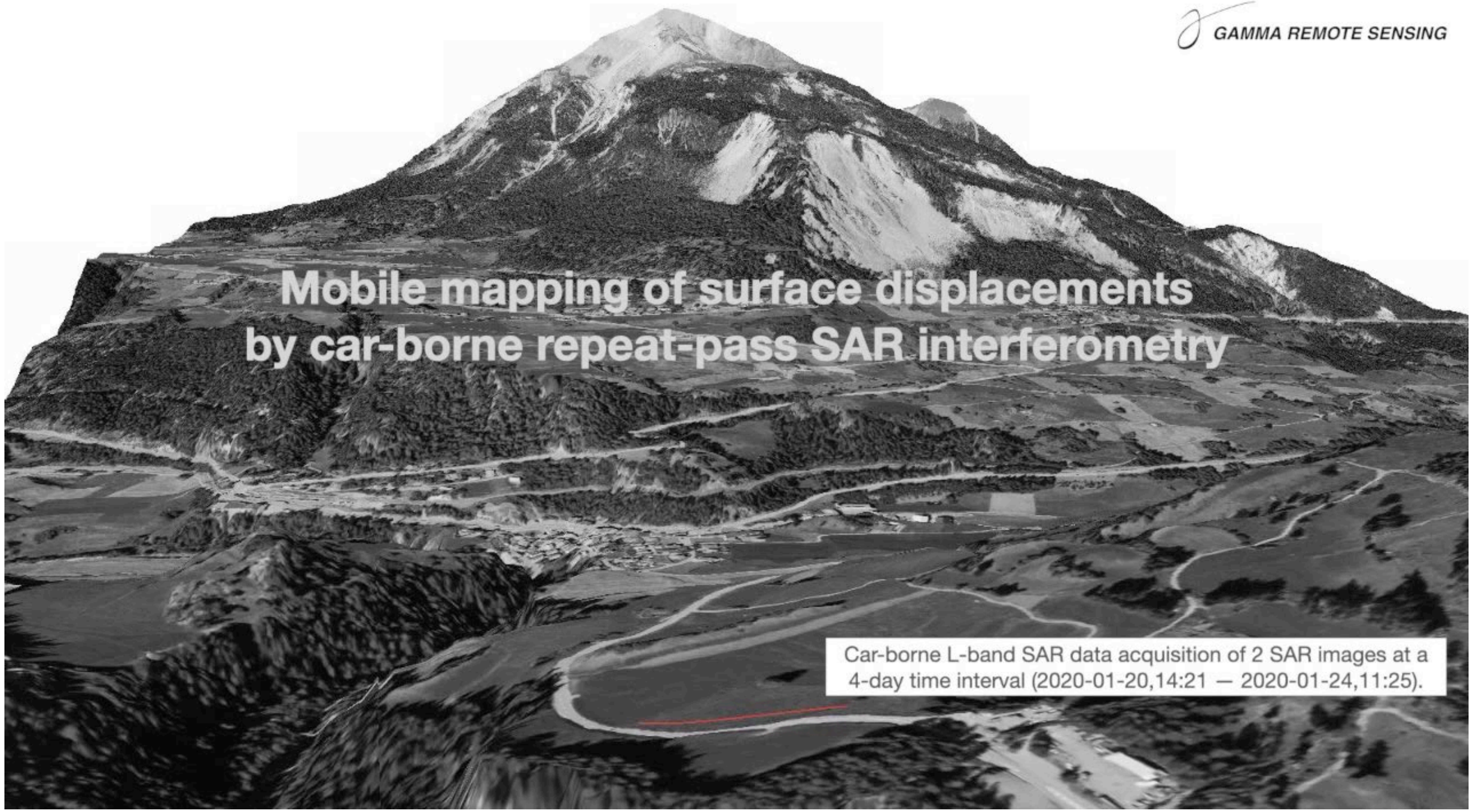
DInSAR processing chain and (intermediate) data products to retrieve surface displacements



14. Juni 16. Juni

Quelle: Gemeinde Albula/Alvra

Meanwhile: major mass movement event

14. Juni 16. Juni

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Motivation for a combined L-band and Ku-band setup

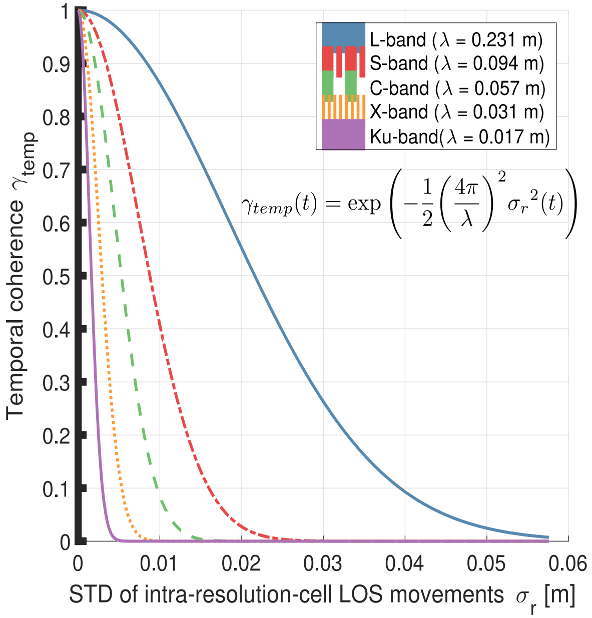
Where are we now?

- **Car-/UAV-borne DInSAR** at **L-band successfully demonstrated** for measuring surface displacements

- **Ku-band** quasi-**stationary systems** provide an established means to measure surface displacements (with zero spatial baseline)

Why a combined L-/Ku-band car-borne DInSAR setup?

- Sensitivity to line-of-sight(LOS) displacement (Ku-band vs. L-band > 10x more sensitive)
- Different areas within the region of interest may have
  - different **temporal decorrelation** and
  - different **displacement velocities**
- "Technical" reasons:
  - Repeat-pass DInSAR at Ku-band from an agile platform is challenging. L-band can help to aid residual motion comp. / unwrapping (also due to atmosphere)
  - Test bed for further DInSAR developments on agile platforms.
- Long-term goal: flexible choice of frequency and (agile) platform



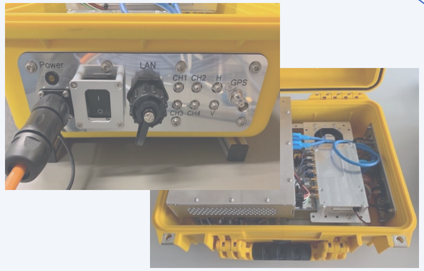
after: Zebker & Villasenor, TGRS 1992

Gamma L-band and Ku-band FMCW SAR instruments

Gamma L-band SAR

Table 1: Gamma L-band SAR specifications

Frequency within	1.2 - 1.4 GHz
used center freq.	1.325 GHz
wavelength at center freq.	22.6 cm
Chirp bandwidth	50 - 200 MHz
used bandwidth	100 MHz
range resolution (@ 100 MHz BW)	1.5 m
Azimuth resolution (@ full SA)	≤ 0.5 m
Azimuth resolution (@ SA = 250m, R=5km)	2.3 m
Type	FMCW
Chirp lengths	250 μs - 8 ms.
Transmit power	max. 10 W (used: 5 W)
Transmit channels	2 (alternating)
Receive channels	4 (simultaneous)
Elev. beamwidth (3dB)	40.0 deg
Azim. beamwidth (3dB)	40.0 deg
Elev. pointing angle	variable (configuration dependent)
Radar hardware assembly	Pelicase 1450
Dimensions	l: 406mm w: 330 mm h: 174 mm
Weight	7.65 kg



Positioning/Navigation INS/GNSS System
Honeywell HGuide n580:
MEMS IMU with dual
GNSS antenna / receiver

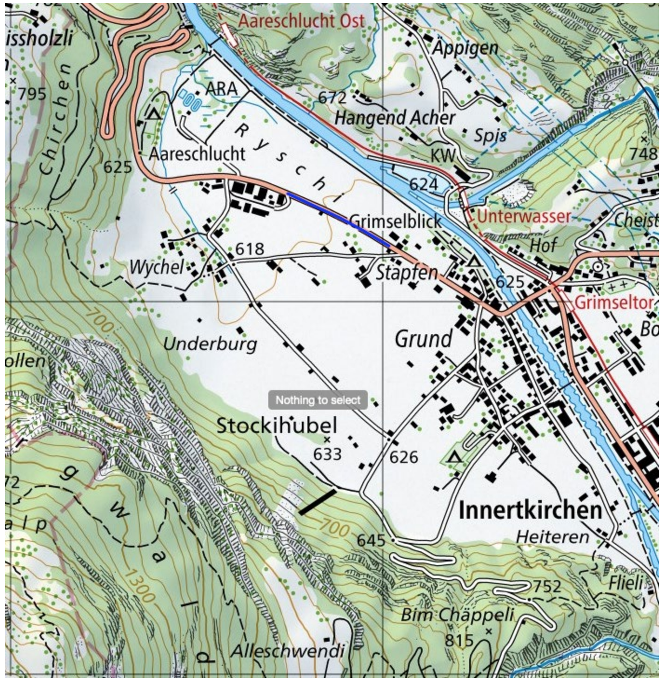
- Combined L-band and Ku-band
- Allows simultaneous data acquisition at both frequencies

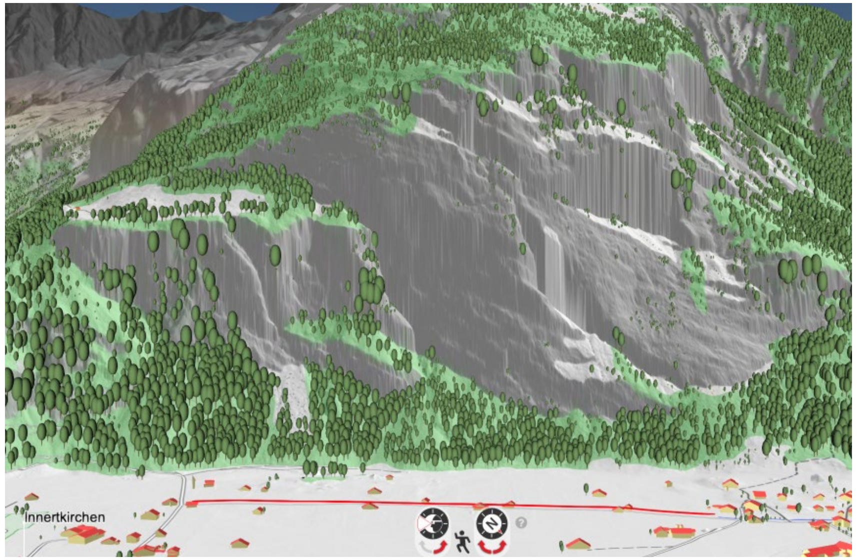
Gamma Portable Radar Interferometer

Table 2: GPRI-based Ku-band SAR specifications

Frequency within	17.1 - 17.3 GHz
used center freq.	17.2 GHz
wavelength at center freq.	1.74 cm
Chirp bandwidth	50 - 200 MHz
range res. (@200 MHz BW)	0.75 m
Type	FMCW
Chirp lengths	250 μs - 8 ms.
ADC sampling rate	6.25 MHz
Elev. beamwidth (3dB)	25.0 deg
Azim. beamwidth (3dB)	12.5 deg

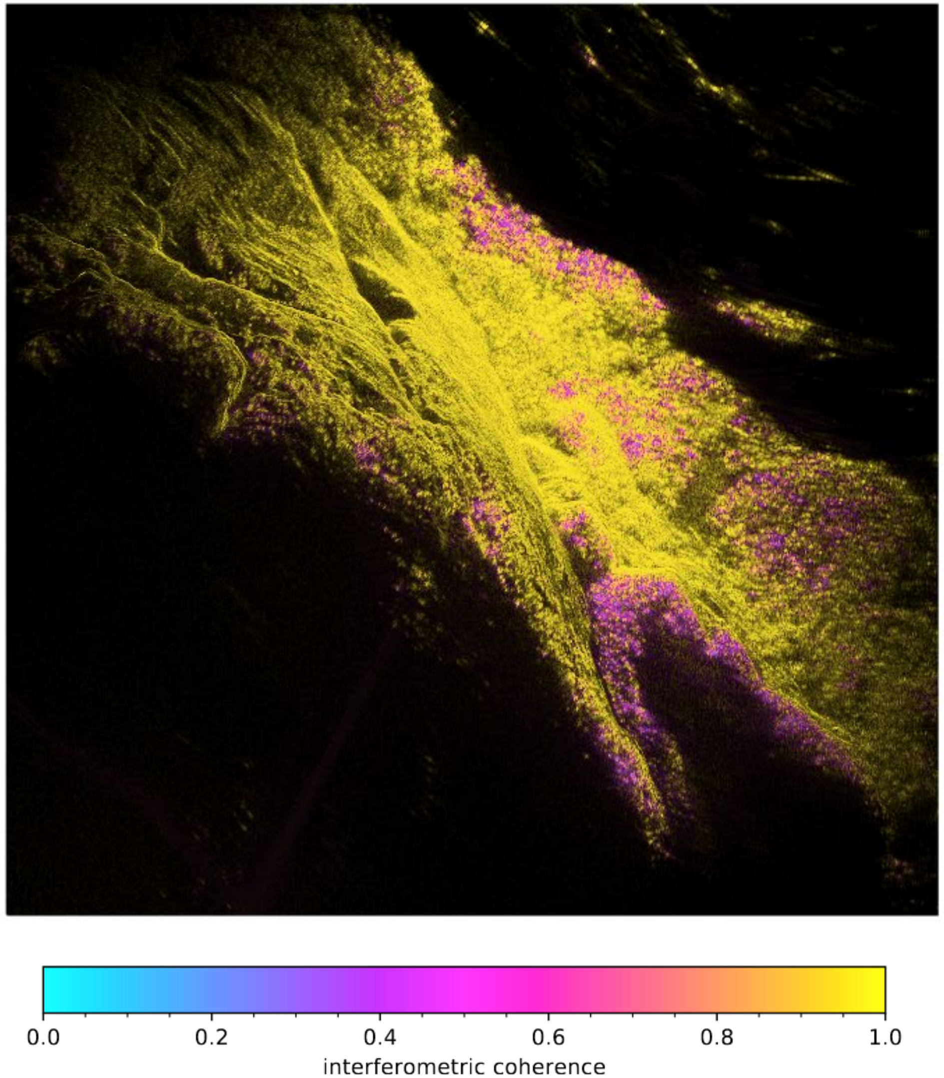
First test site for combined L-/Ku-band campaign

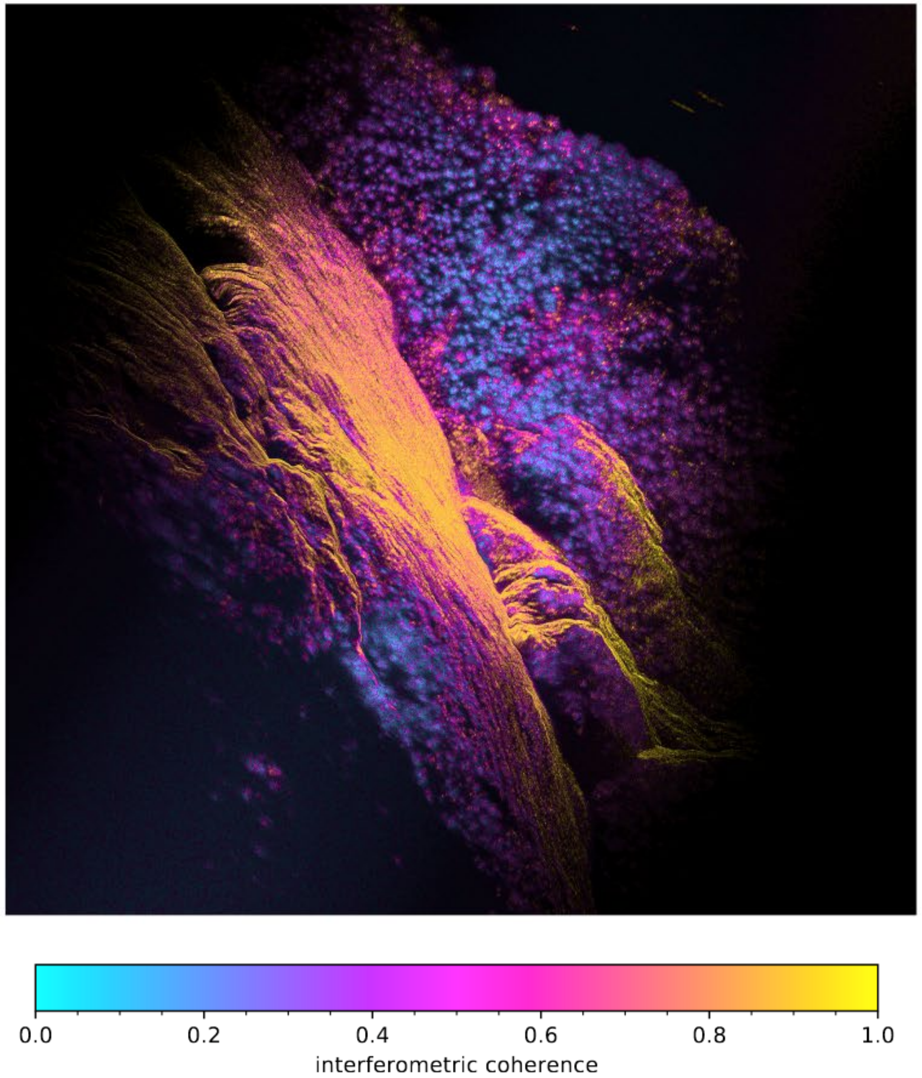




L-band vs. Ku-band repeat-pass DInSAR coherence

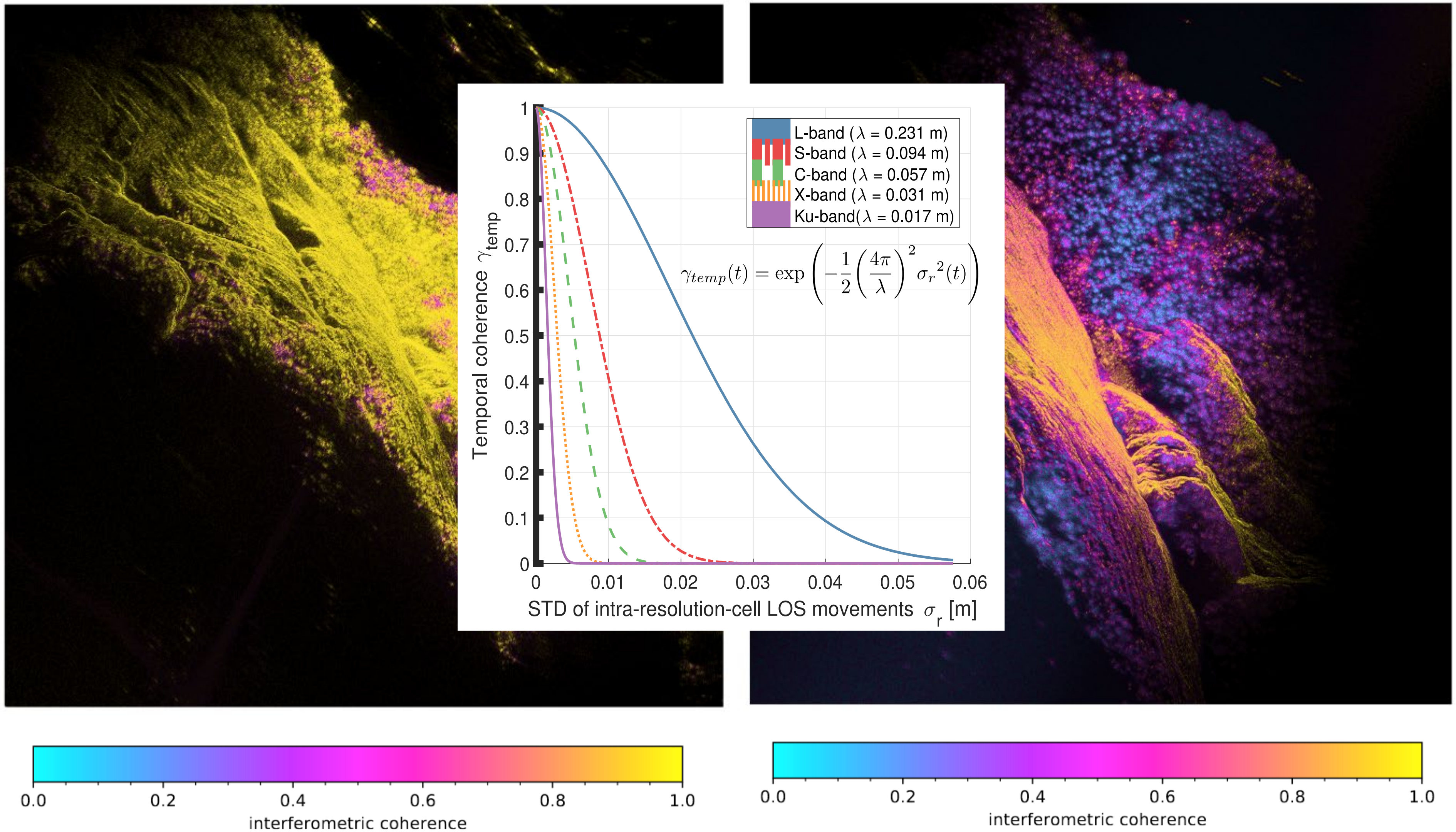
L-band repeat-pass time interval : (approx. 4 min) Ku-band





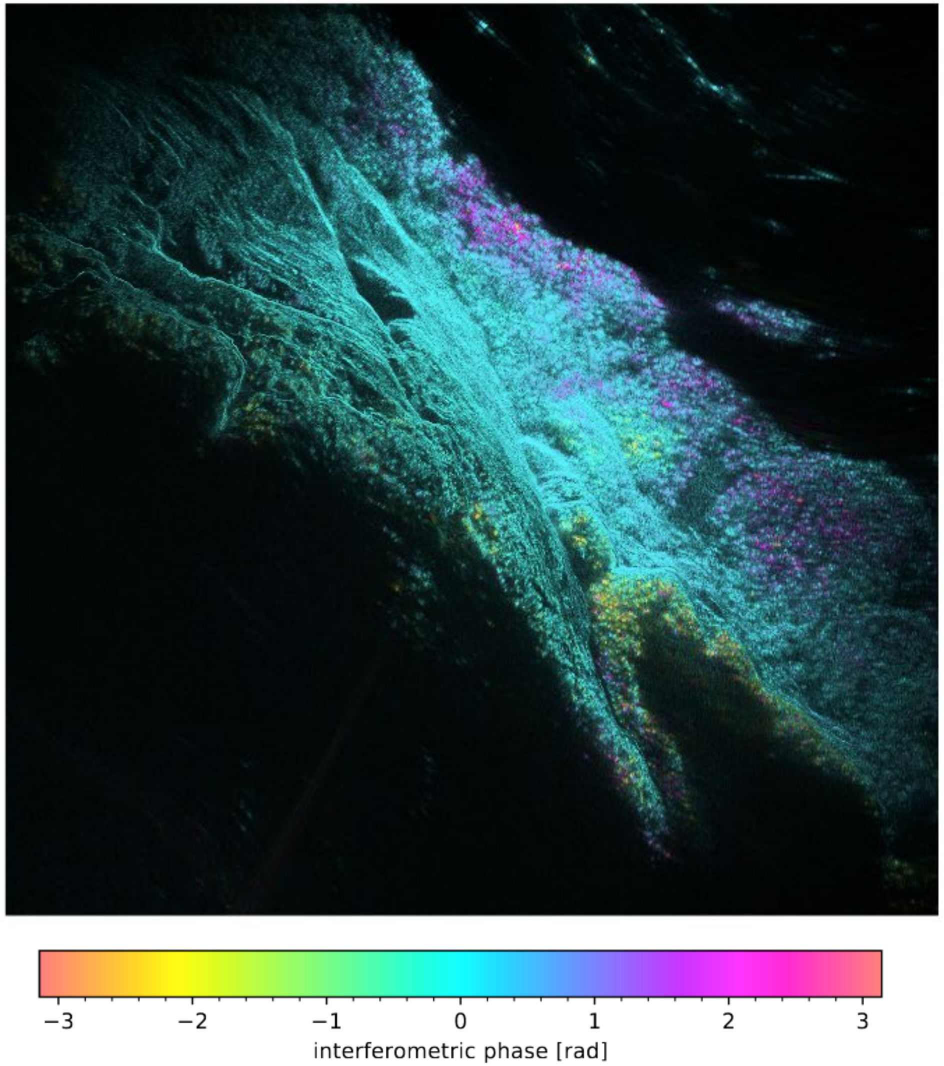
L-band vs. Ku-band repeat-pass DInSAR coherence

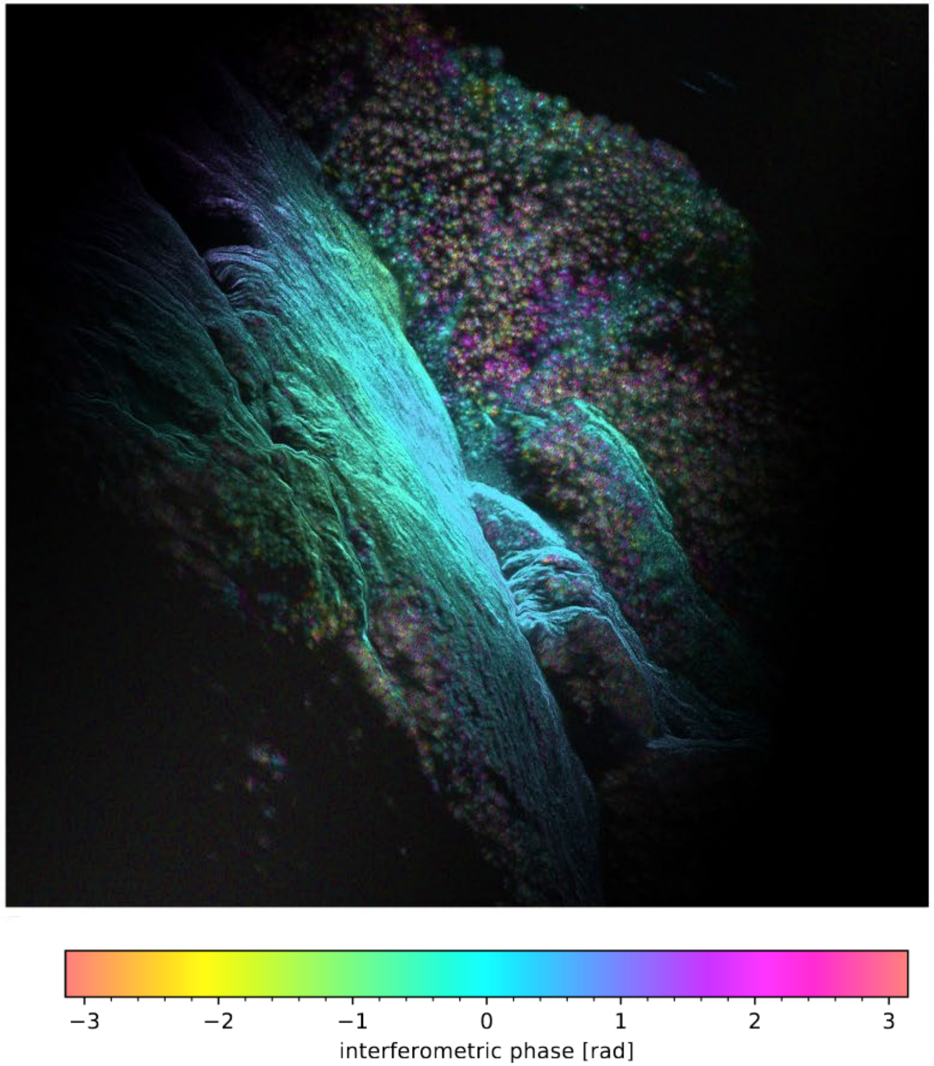
L-band　　repeat-pass time interval : (approx. 4 min)　　Ku-band



L-band vs. Ku-band repeat-pass DInSAR phase

L-band repeat-pass time interval : (approx. 4 min) Ku-band



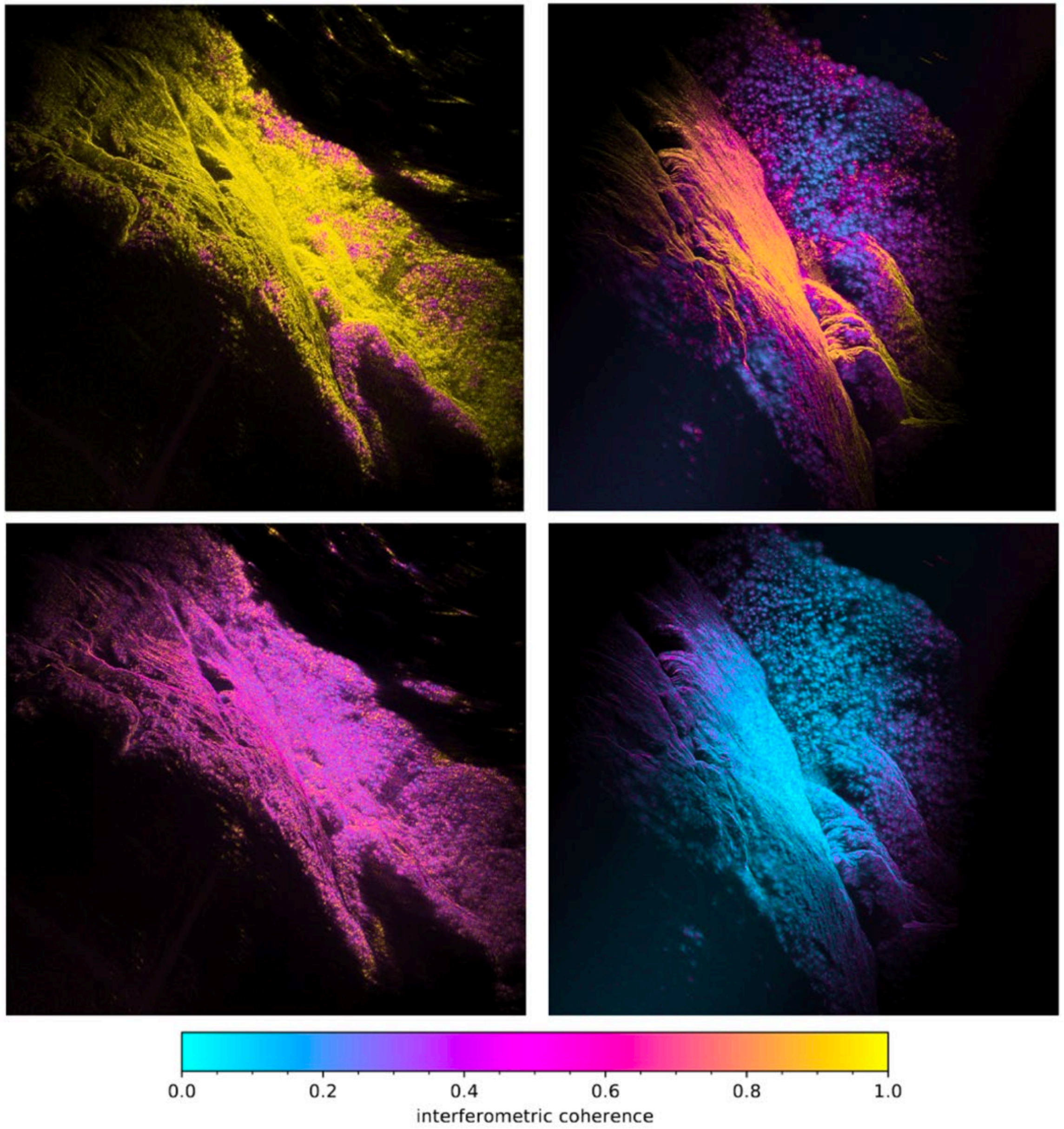


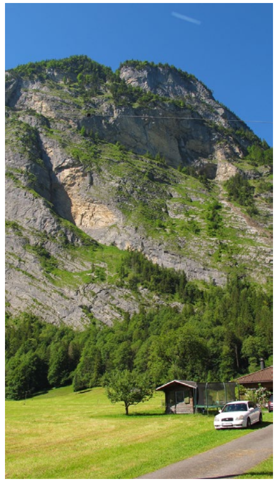
- Short term (4min) versus more challenging “extreme” case:
- 4 months temporal baseline winter /summer w/ varying surface properties

L-band | Ku-band

4 min

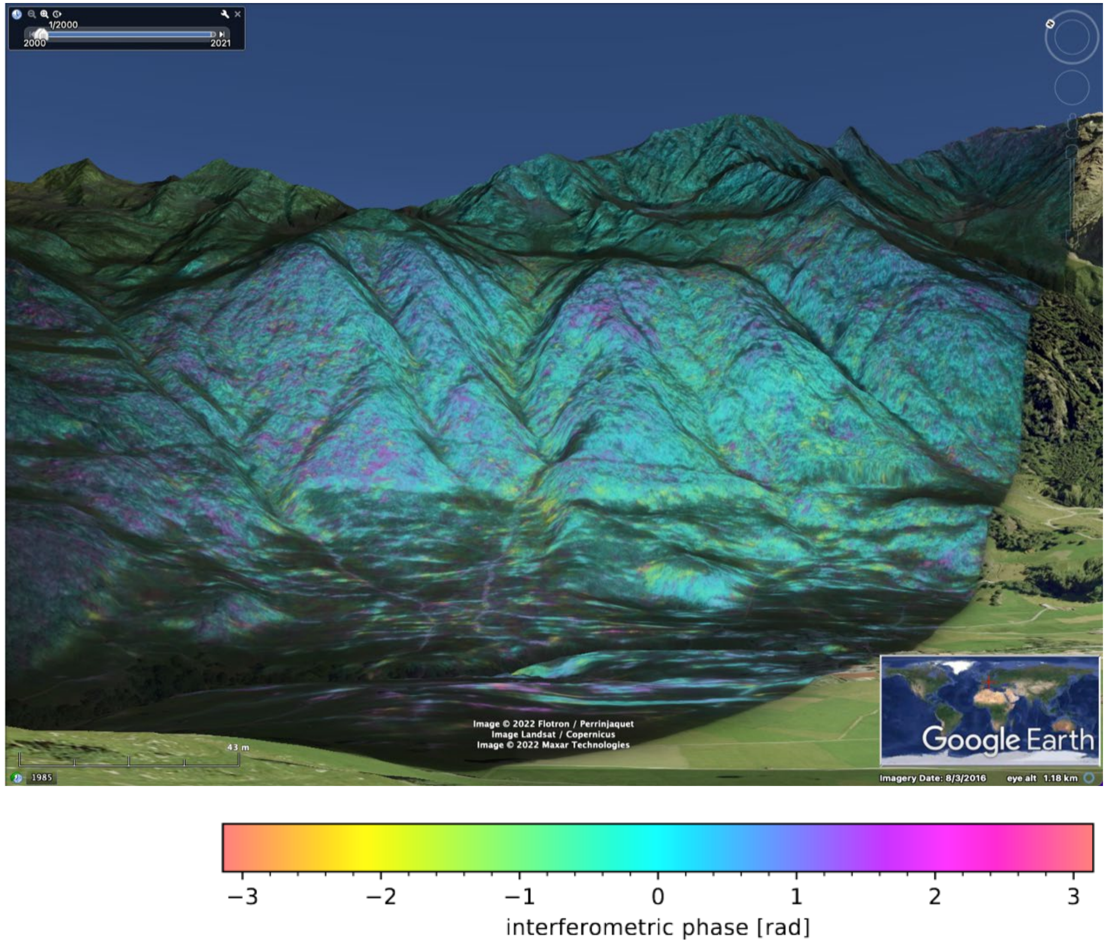
4 months

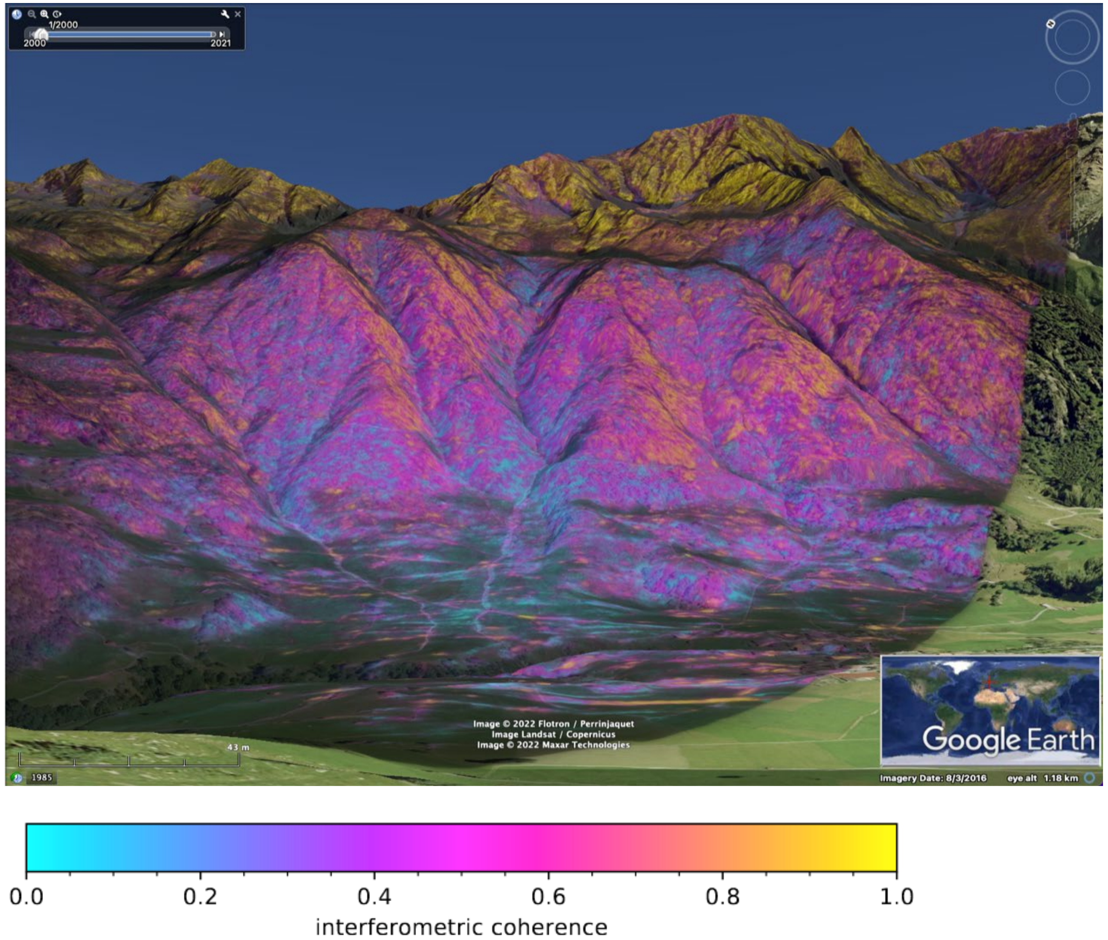




....ongoing campaigns:
building up L-band / Ku-band interferometric time series
at Guttannen and other locations in CH.

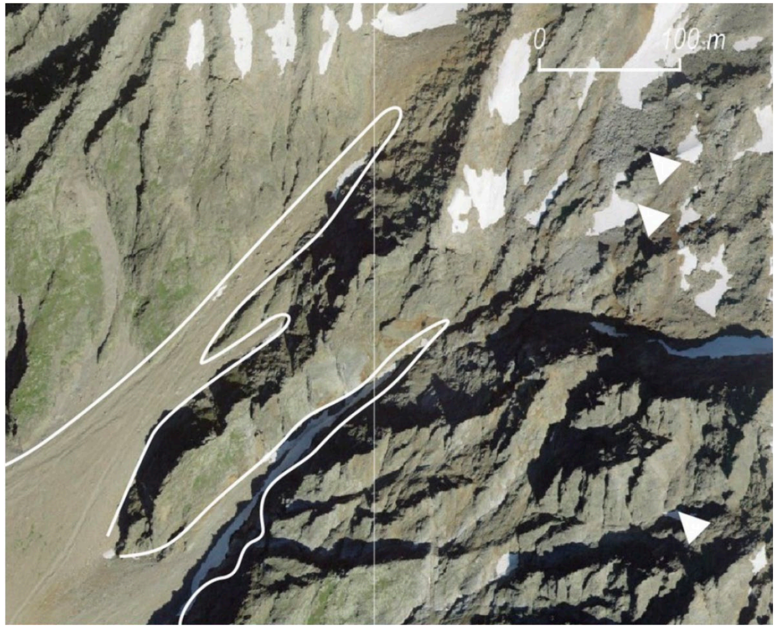
20211011_141613_20220614_112638
L-band interferogram

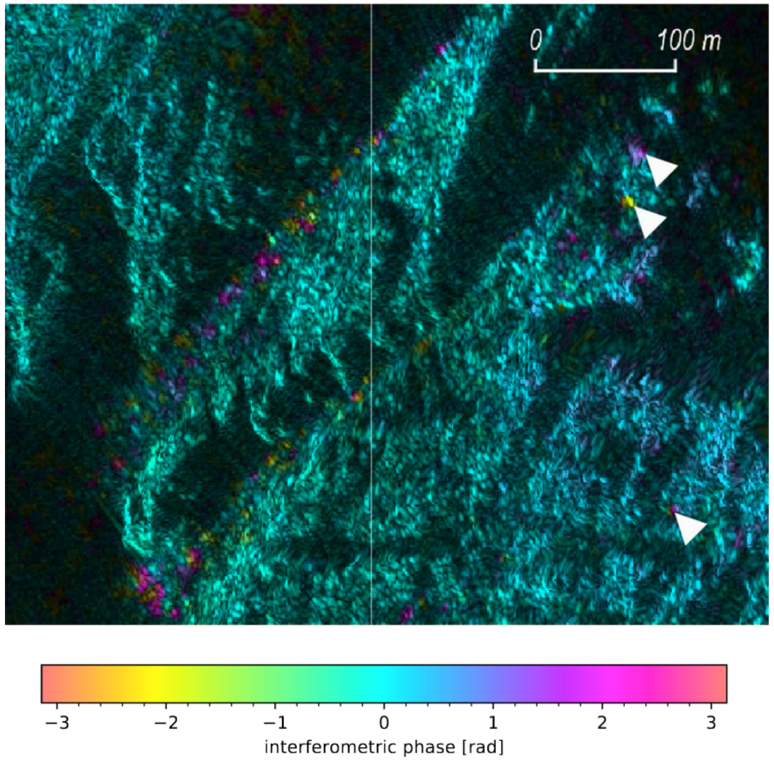


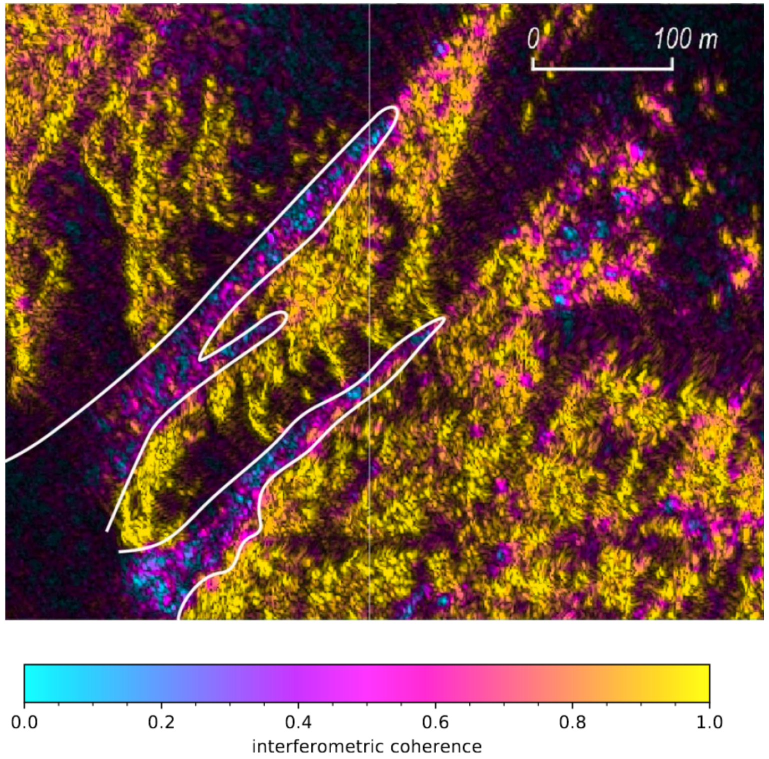


Close-up view at a range distance of ca. 4 km:

- car-borne L-band SAR 246-day coherence and interferogram
- at a high spatial resolution showing
  - decorrelation along the scree channels (white lines).
- White arrows indicate distinct spots with non-zero phase that could either be caused by remnant snow patches or local motion of the rocks.

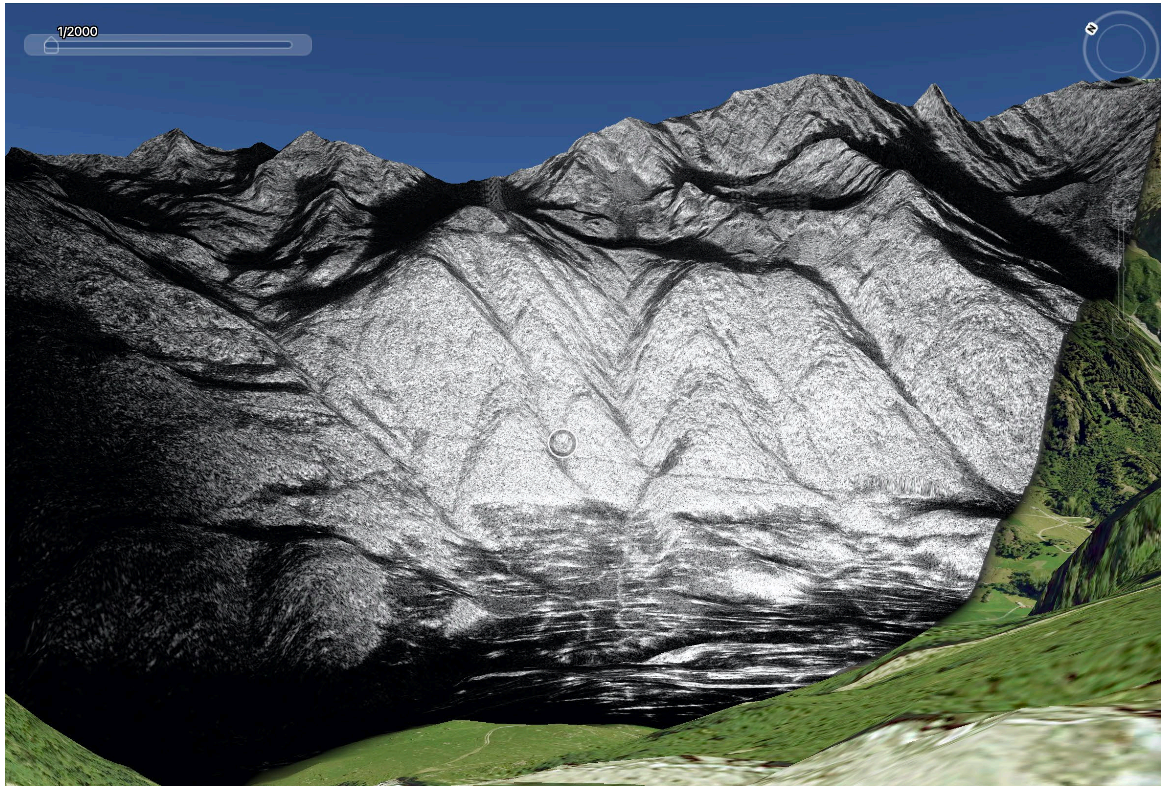




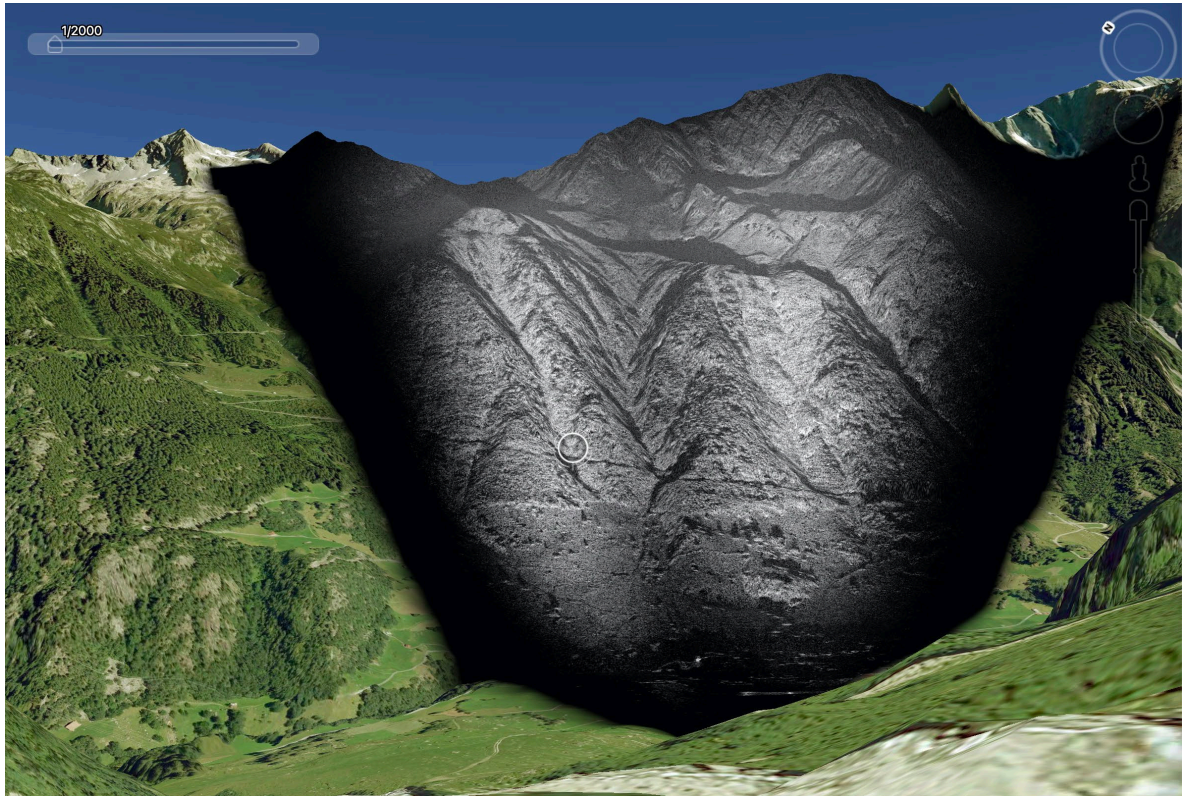


....ongoing campaigns:
building up L-band / Ku-band interferometric time series
at Guttannen.

L-band SAR image

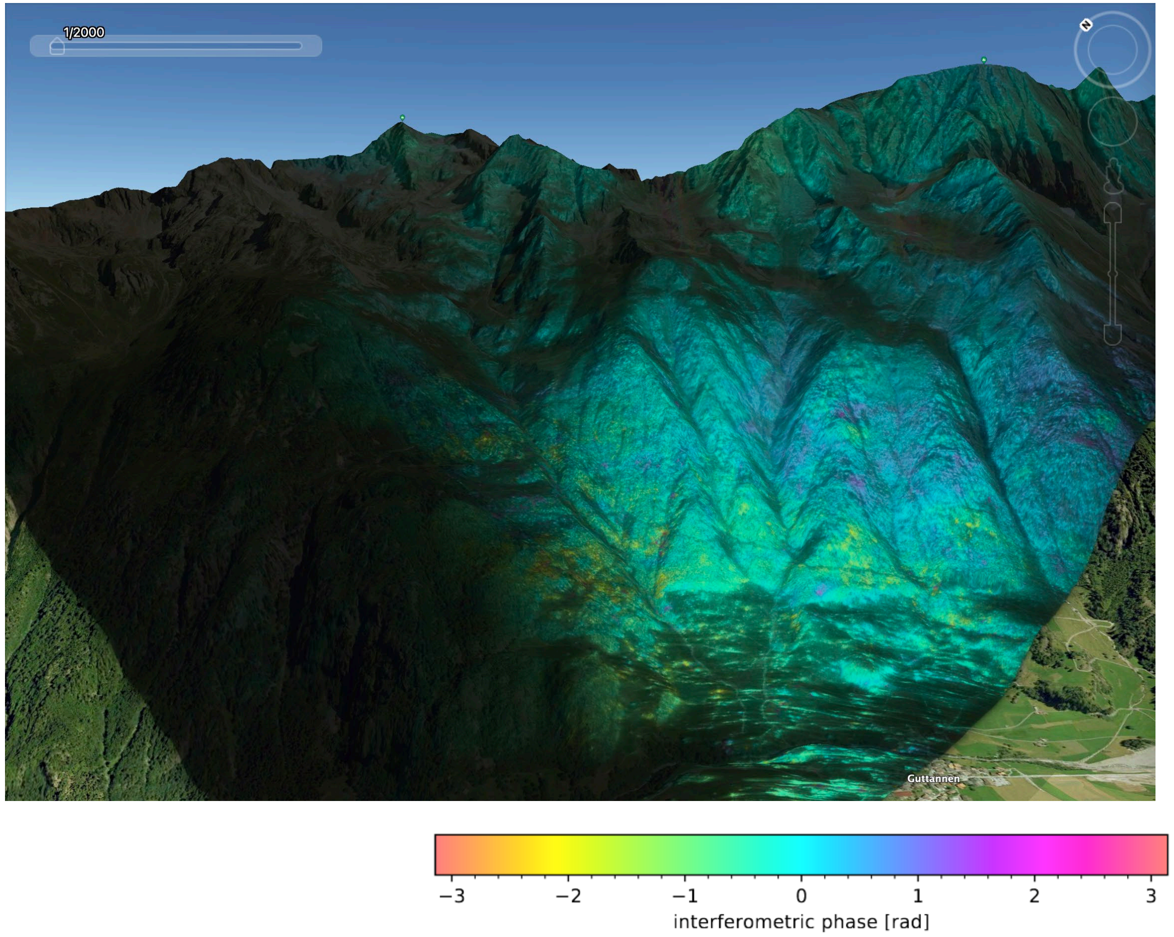


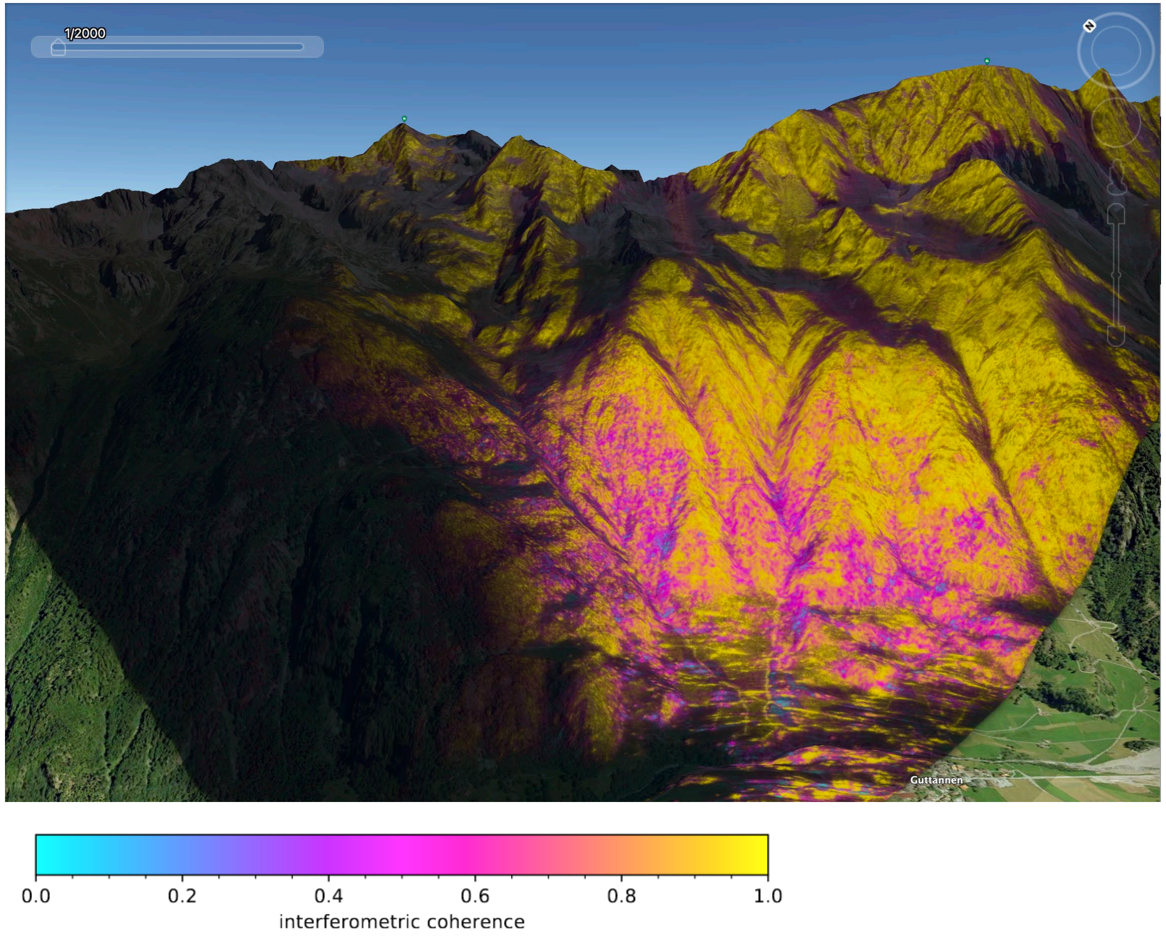
Ku-band SAR image



....ongoing campaigns:
building up L-band / Ku-band interferometric time series
at Guttannen.

L-band : 20220614_112638_20220614_124409 **~ 1h 17 min**





....ongoing campaigns:
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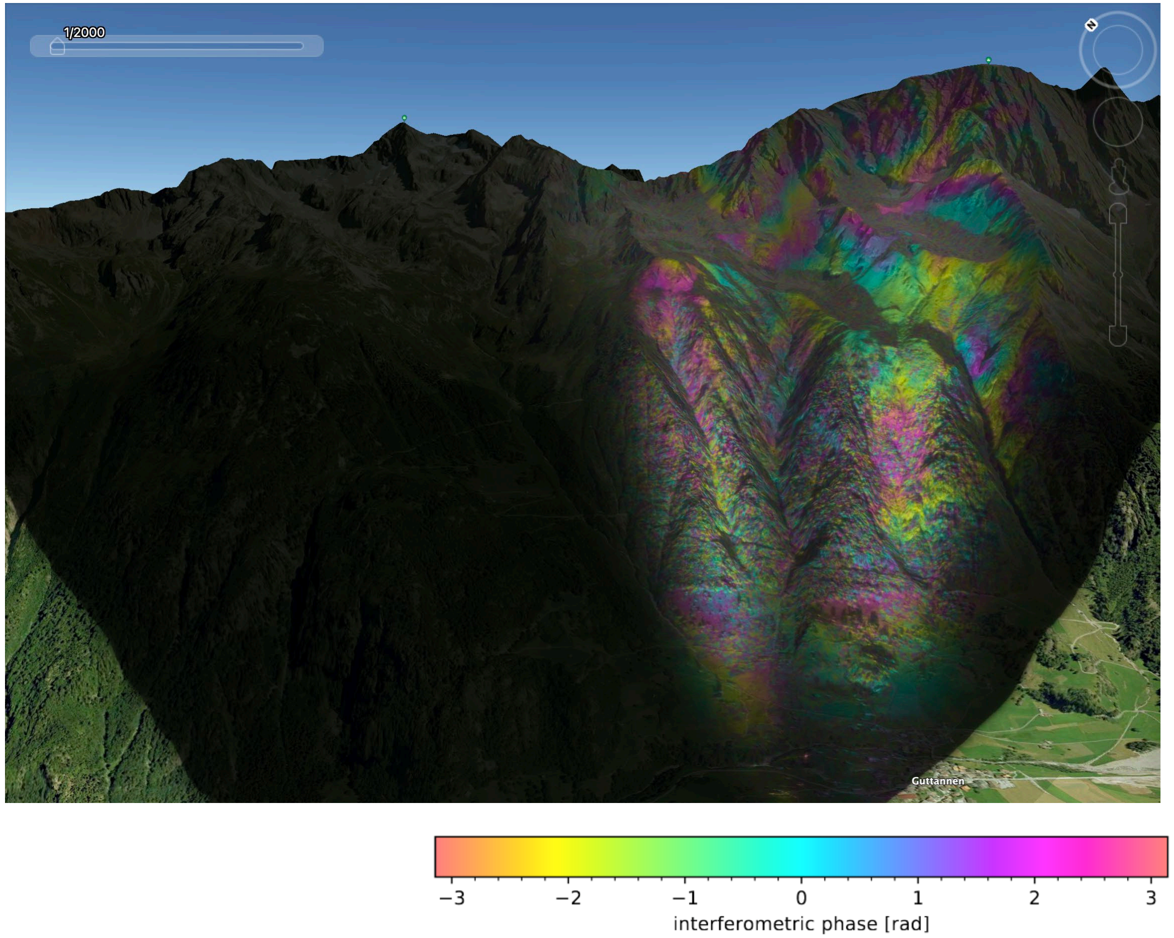
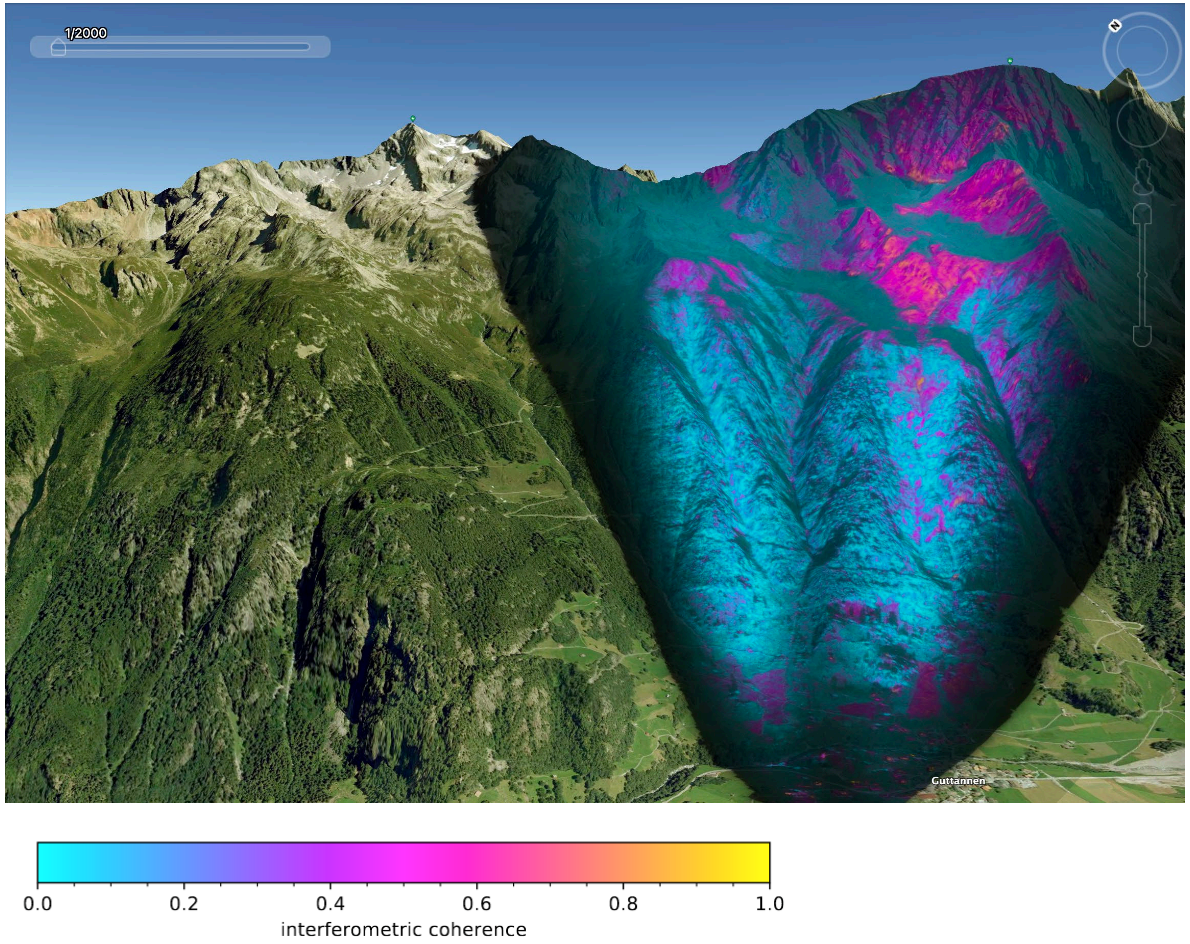
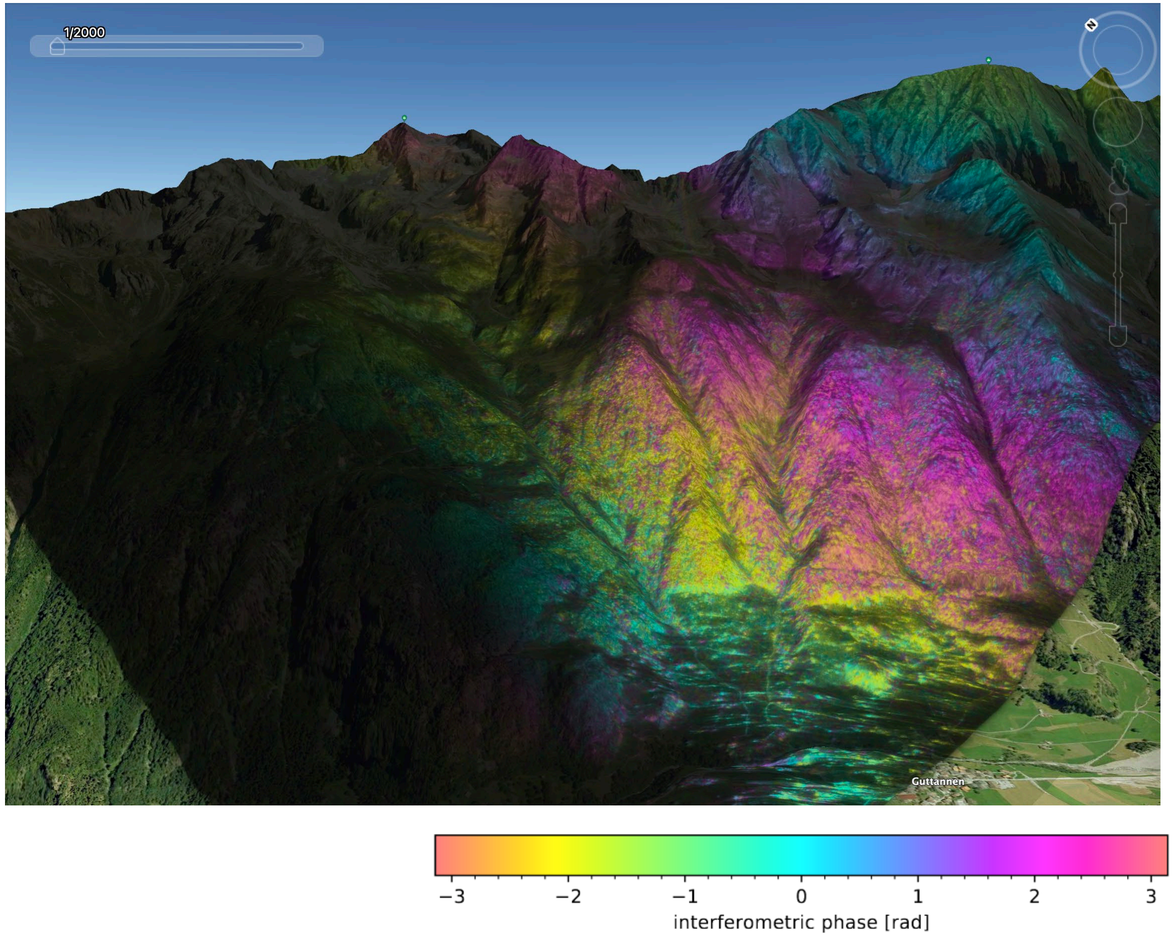
Ku-band : 20220614_112638_20220614_124409 **~ 1h 17 min**

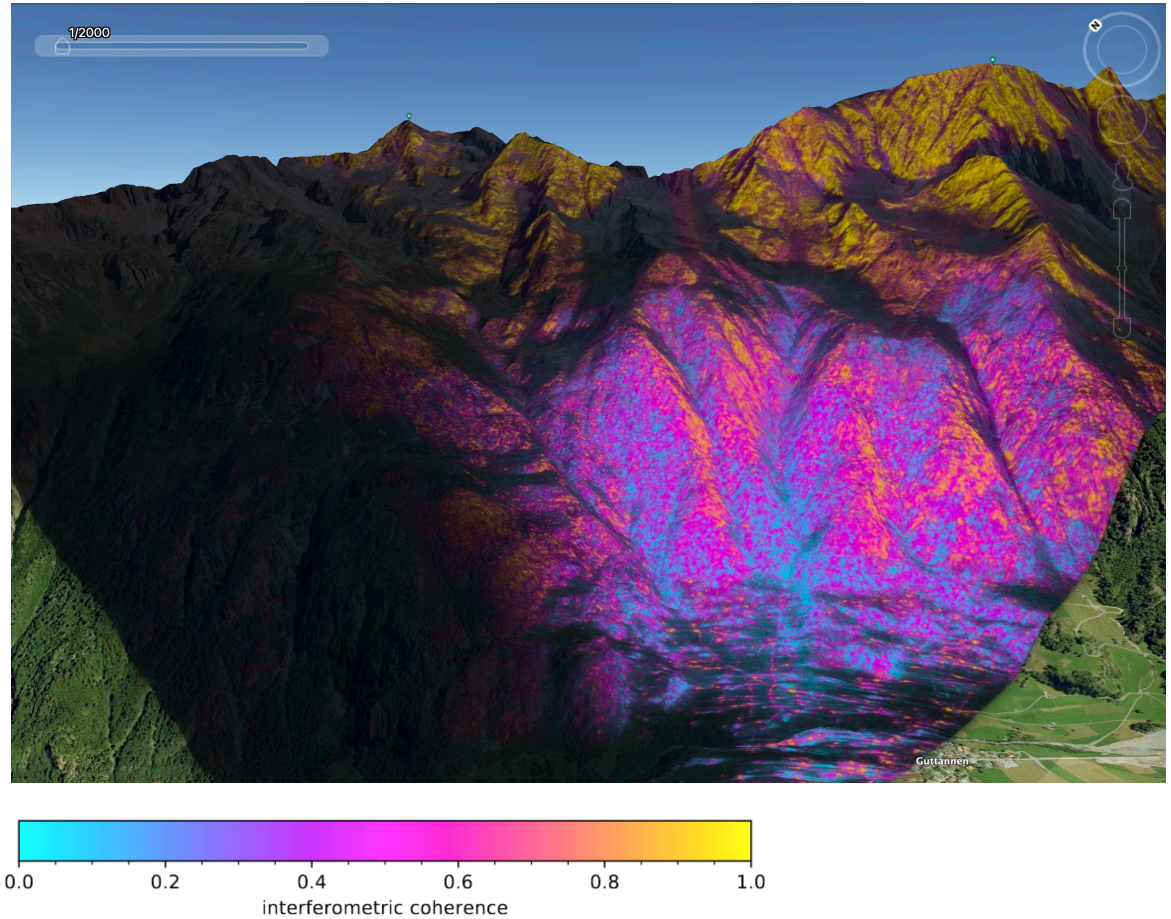




....ongoing campaigns:
building up L-band / Ku-band interferometric time series
at Guttannen.

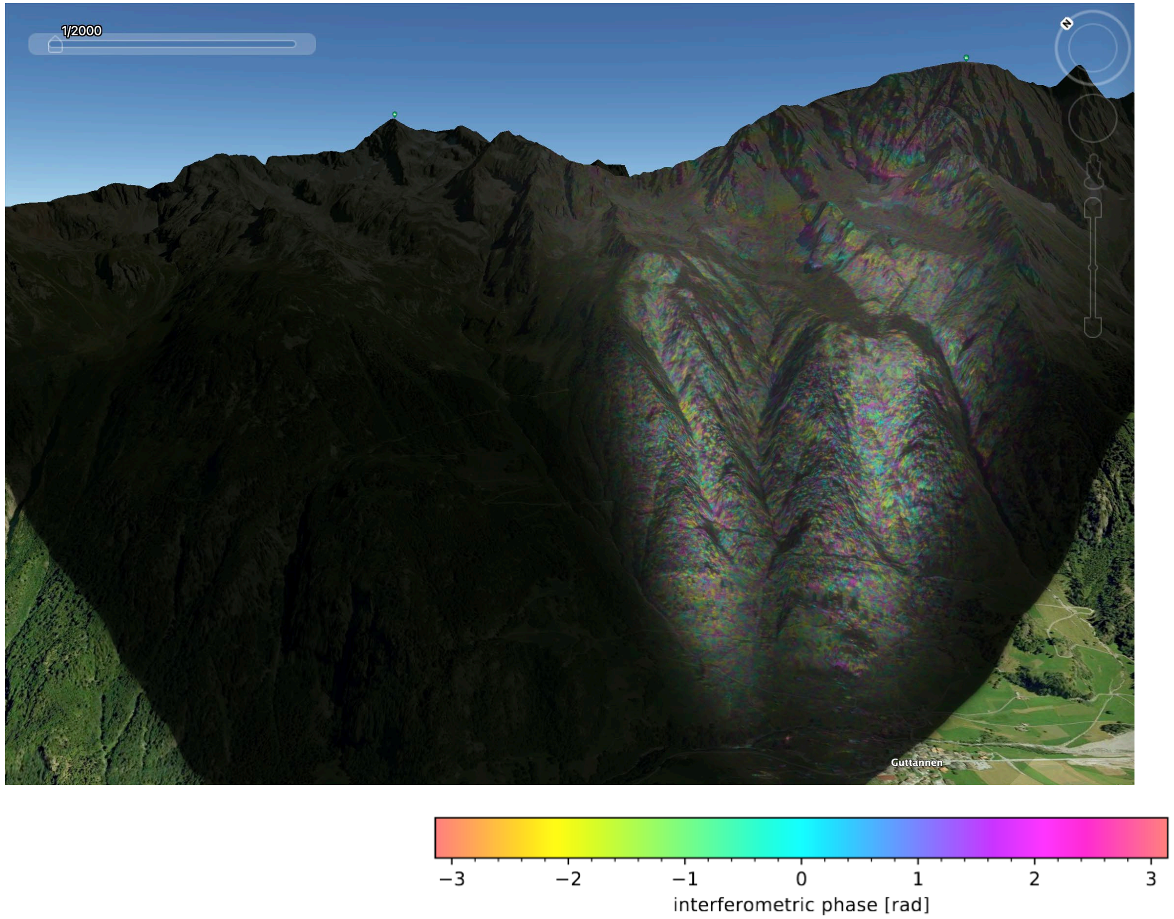
L-band : 20220614_112638_20221018_113024 **~ 4 months**

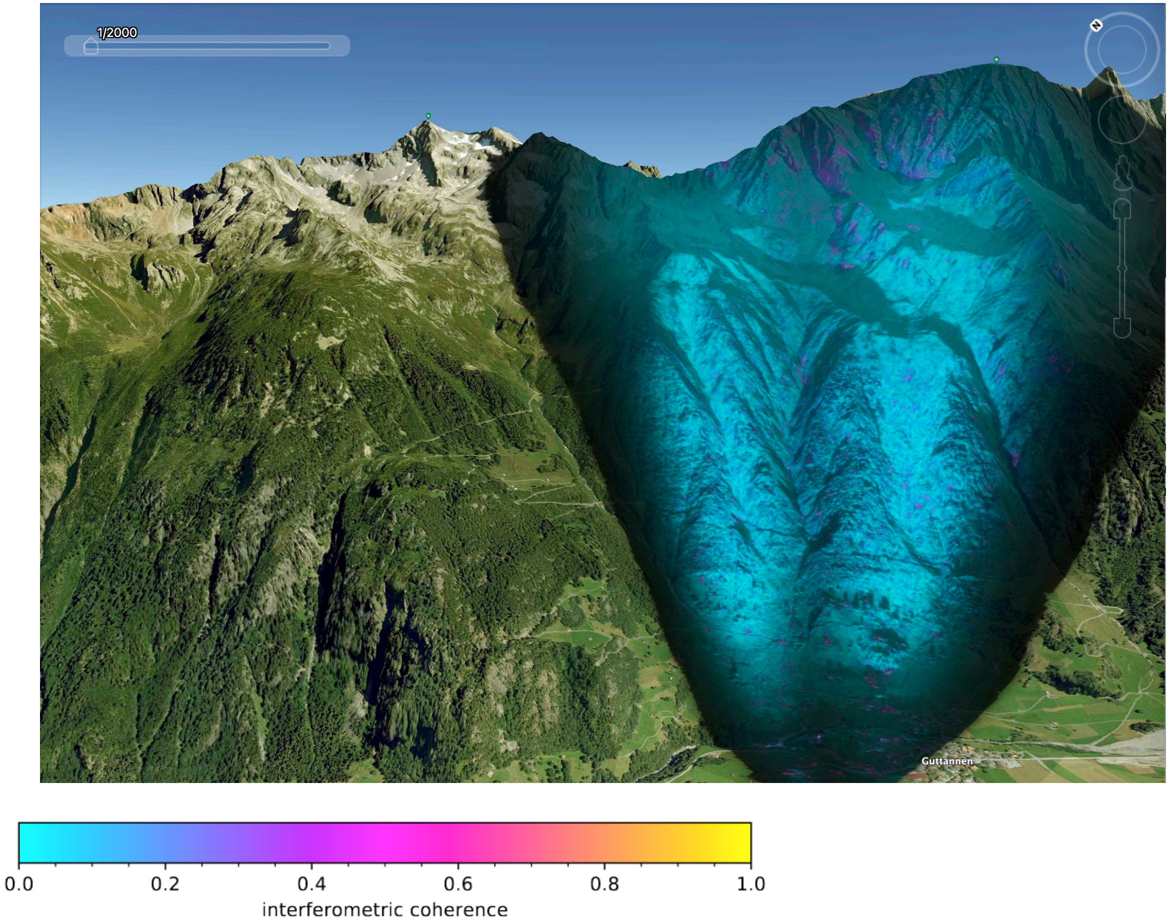




....ongoing campaigns:
building up L-band / Ku-band interferometric time series
at Guttannen.

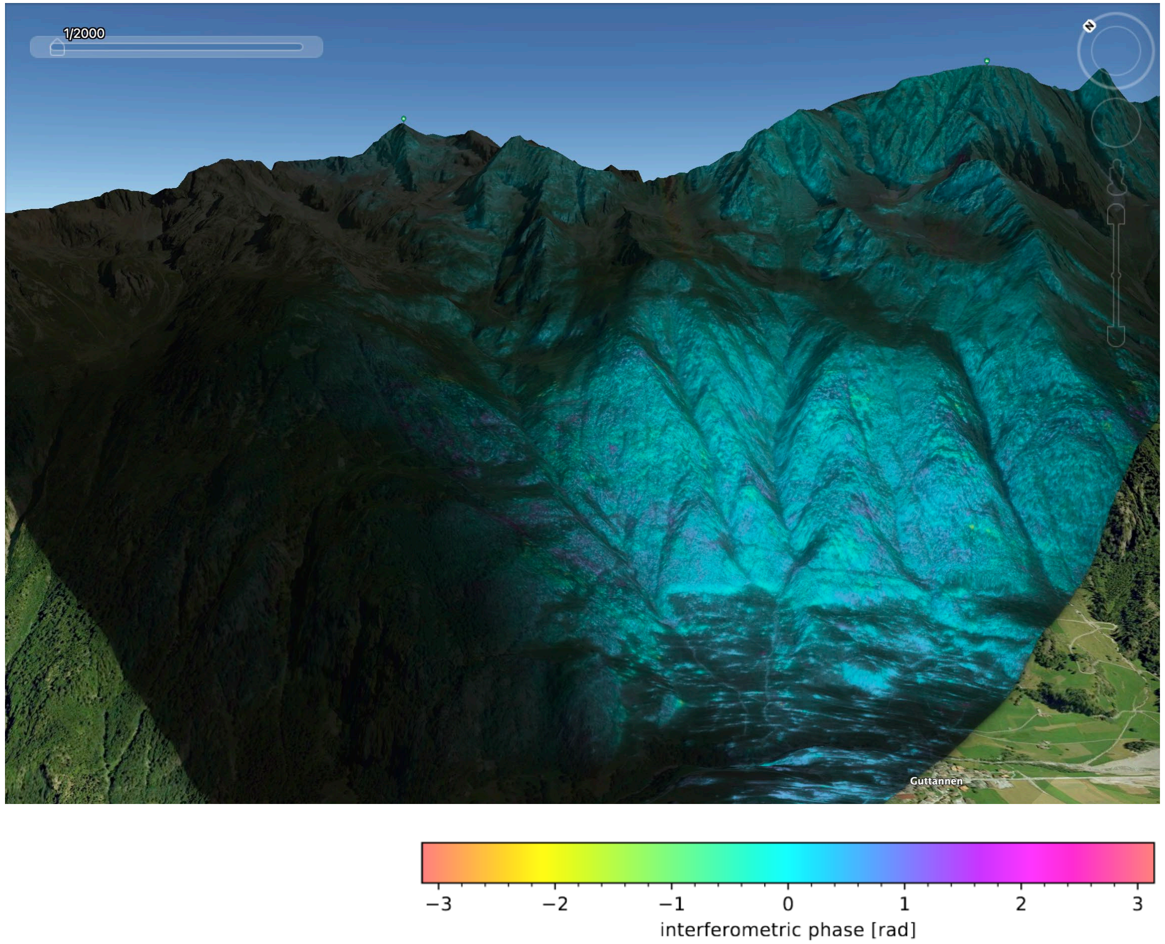
Ku-band : 20220614_112638_20221018_113024 **~ 4 months**

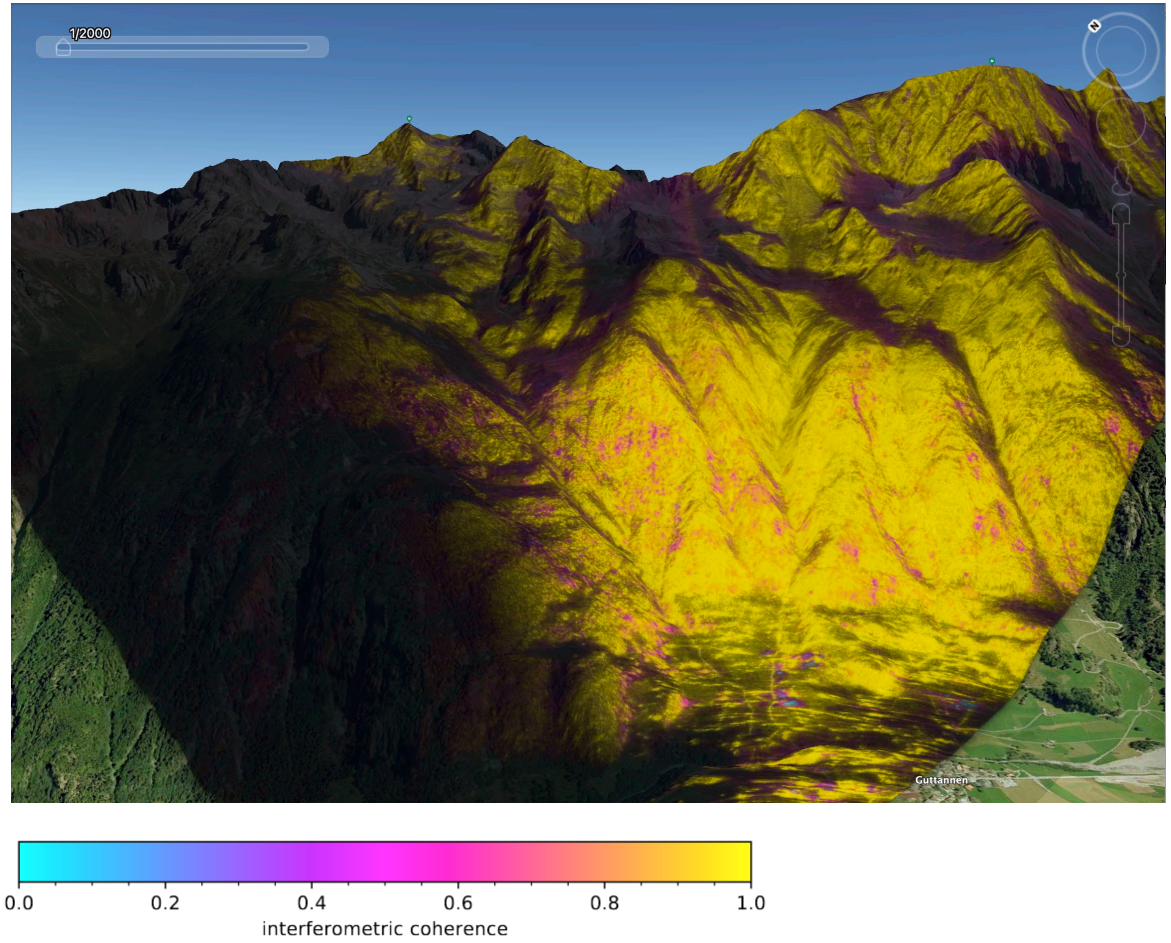




....ongoing campaigns:
building up L-band / Ku-band interferometric time series at Guttannen.

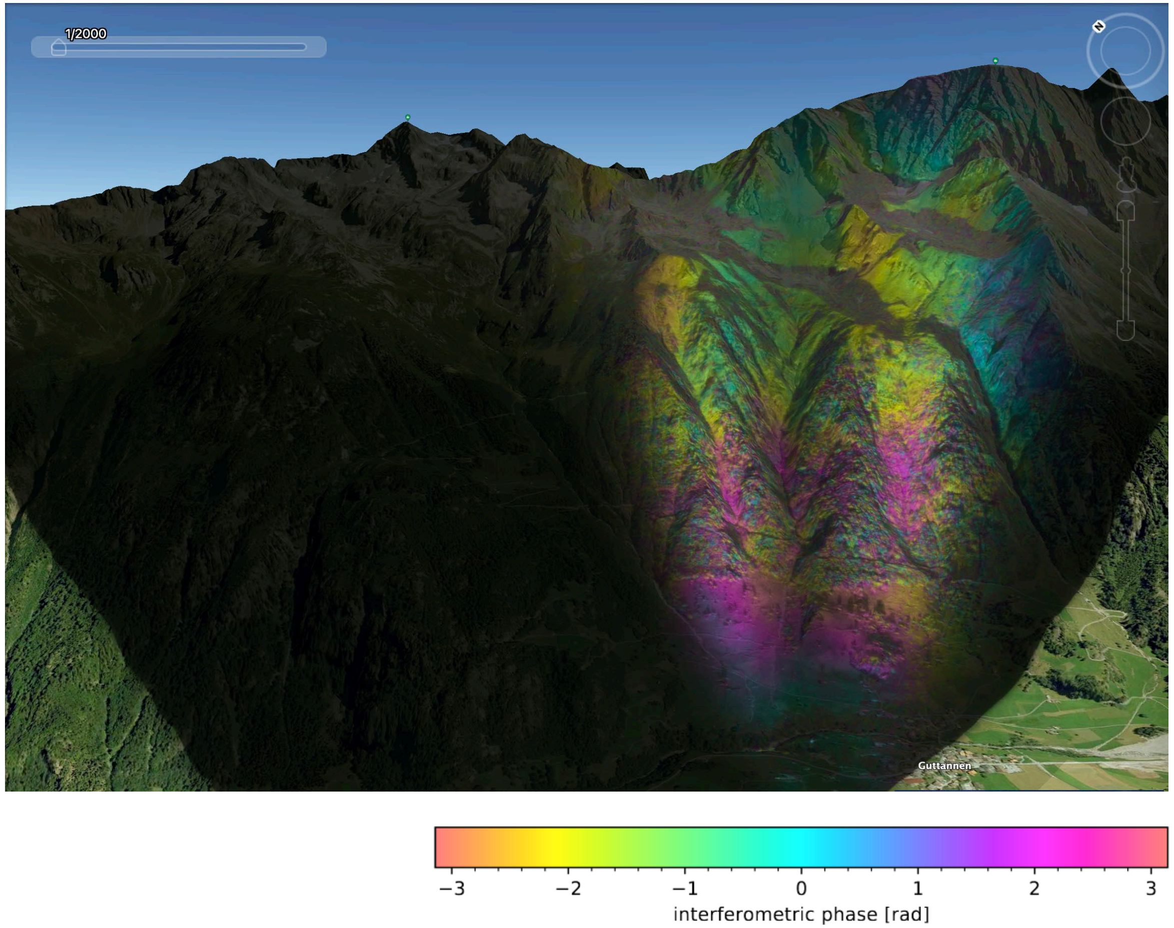
L-band : 20221018_113024_20221018_114751 **~ 17 min**

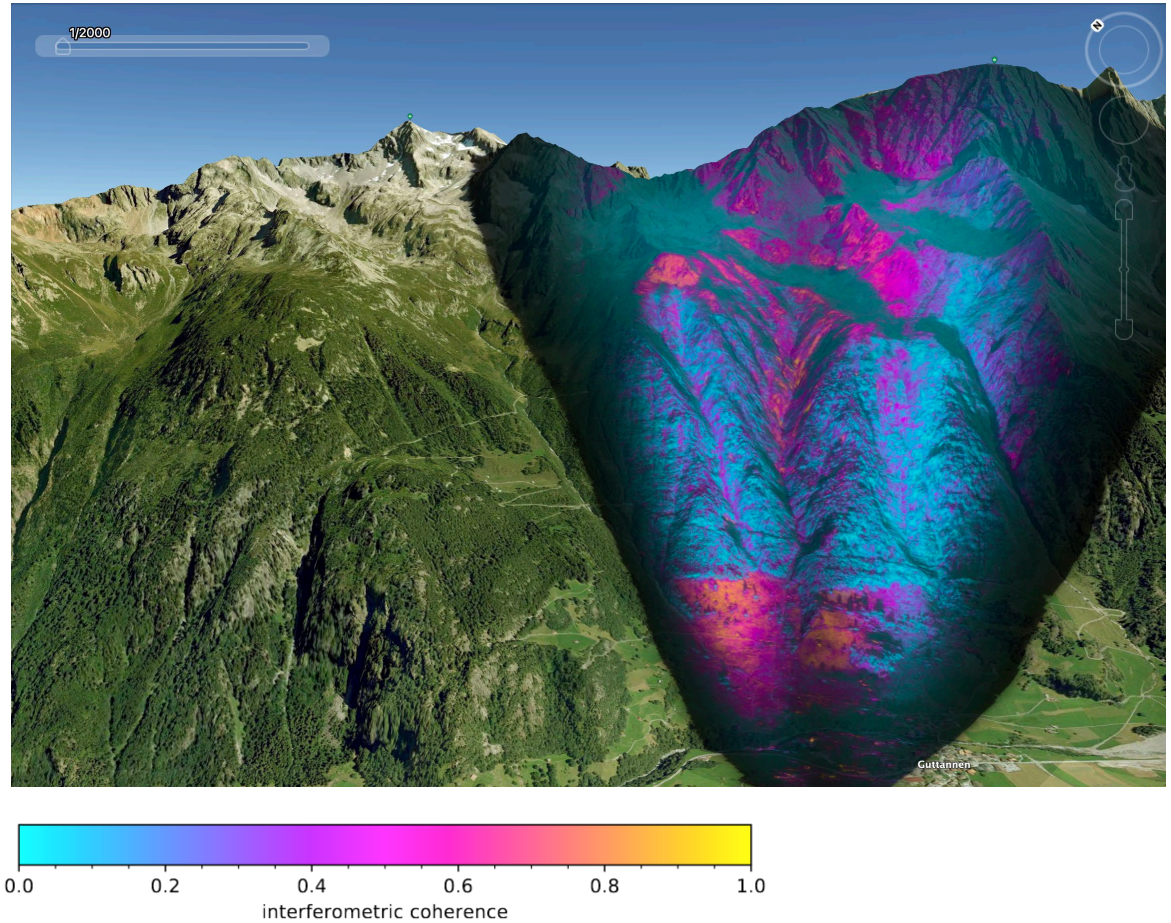




....ongoing campaigns:
building up L-band / Ku-band interferometric time series at Guttannen.

Ku-band : 20221018_113024_20221018_114751 **~ 17 min**





Summary

High-resolution repeat-pass **DInSAR** from **agile platforms**

- **works at L-band. Operational!** → Decent INS/GNSS required.
- at Ku-band: we are on a good track, but not entirely there, yet:
  - First car-borne **simultaneous L-/Ku-band repeat-pass DInSAR** measurements are promising:
    - **Good SAR image focusing quality** also at Ku-band, in general.
    - **High-resolution** SAR imagery/phase/coherence maps were obtained at both **L-band and Ku-band.**
    - As expected, the coherence is lower at Ku-band for natural terrain but **good coherence and phase quality** were obtained for **short-term intervals in similar conditions at Ku-band**.
      ➔ Ku-band DInSAR is promising to measure subtle displacement at rock surfaces with **high-spatial resolution**.
- Car-based **Ku-band** repeat-pass DInSAR is still **work in progress...** with on-going campaigns at different sites**.**
- First results with the **dual-frequency setup** confirm the potential and **complementarity of L-band and Ku-band measurements** for different ground motion processes and varying conditions.

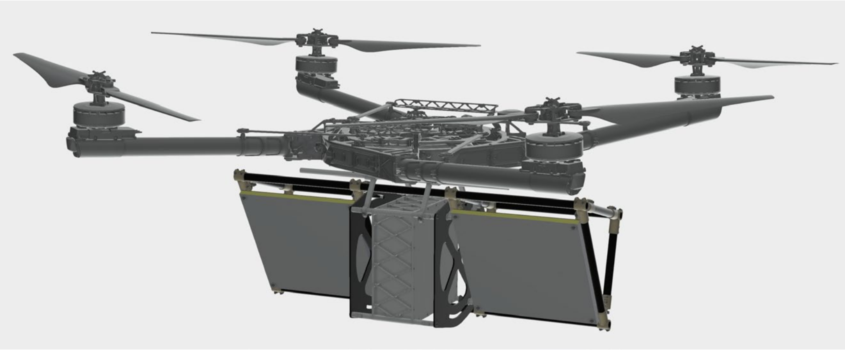
Outlook

Car-borne DInSAR campaigns:

- Building up carborne DInSAR time series at L-band and some Ku-band at several locations to develop and support ground motion applications/services.

UAV-borne DInSAR:

- Down-sized L-band SAR being developed
  - total payload : < 8 kg
  - for quadcopter drones
  - and other platforms …



Acknowledgements

- The SAR imagery is processed onto the high-resolution digital elevation model swissALTI3D copyright: swisstopo.
- 3D visualizations in Google Earth with respective copyrights of the data provider.

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Additional slides

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Good repeat-pass performance for short-term and zero-baselines & InSAR volume decorrelation for increasing spatial baselines

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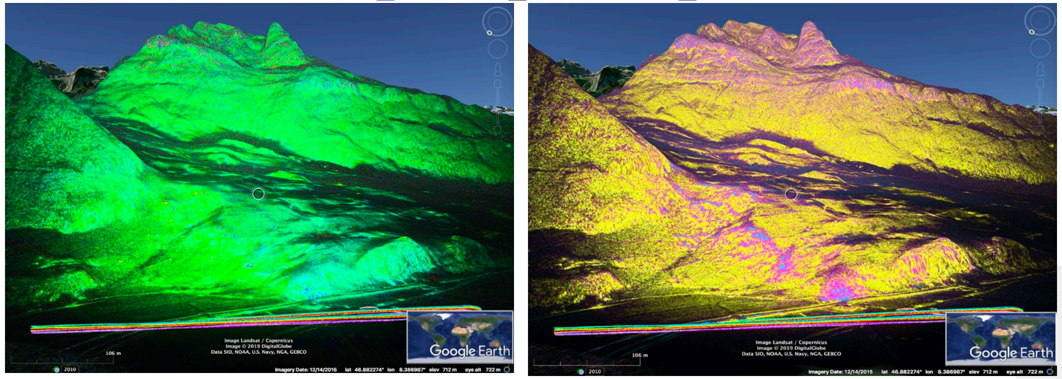

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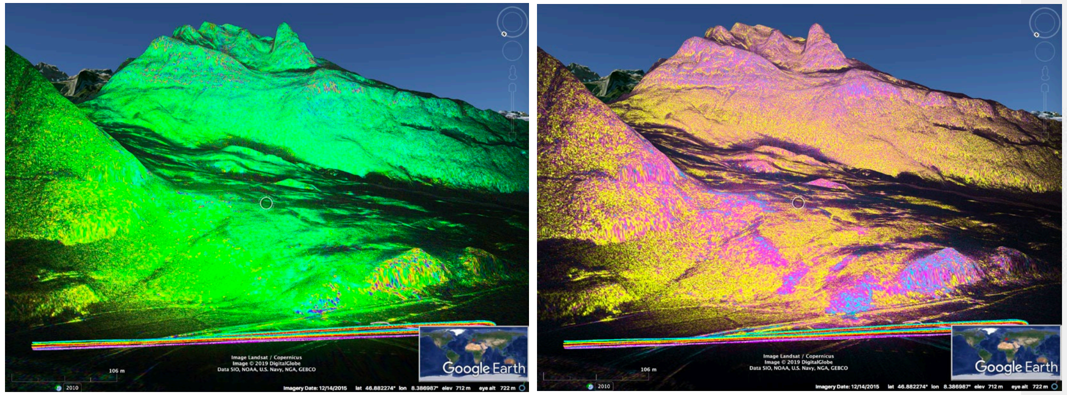

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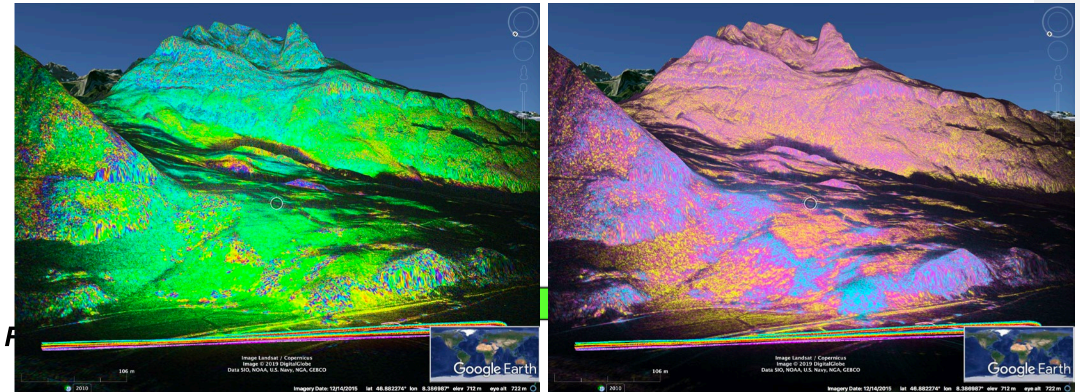
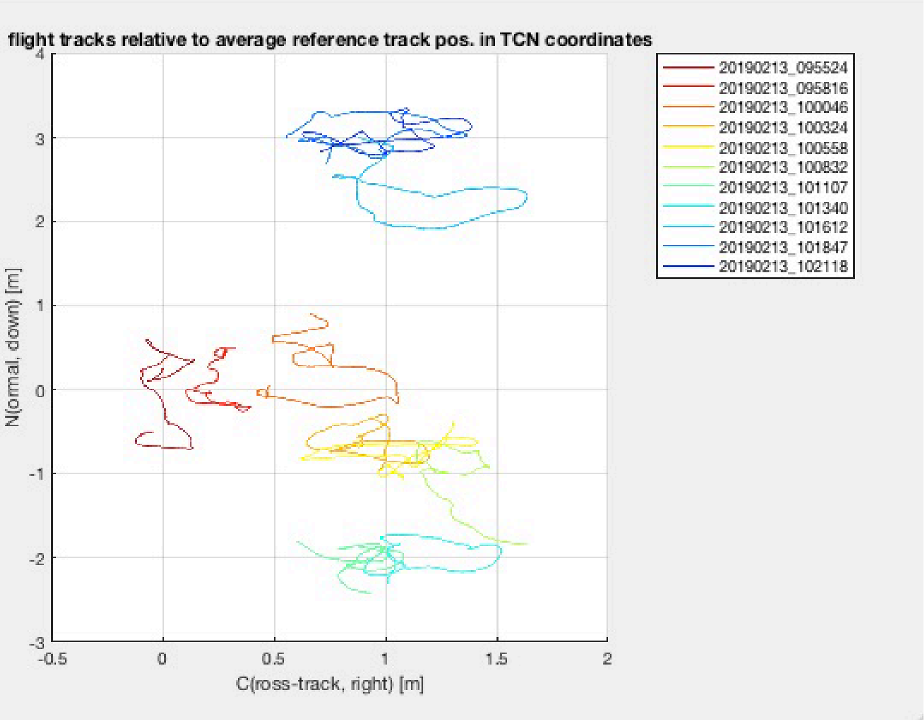
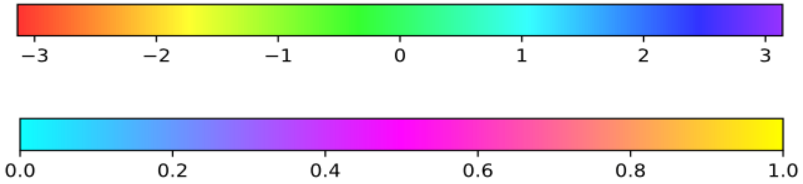


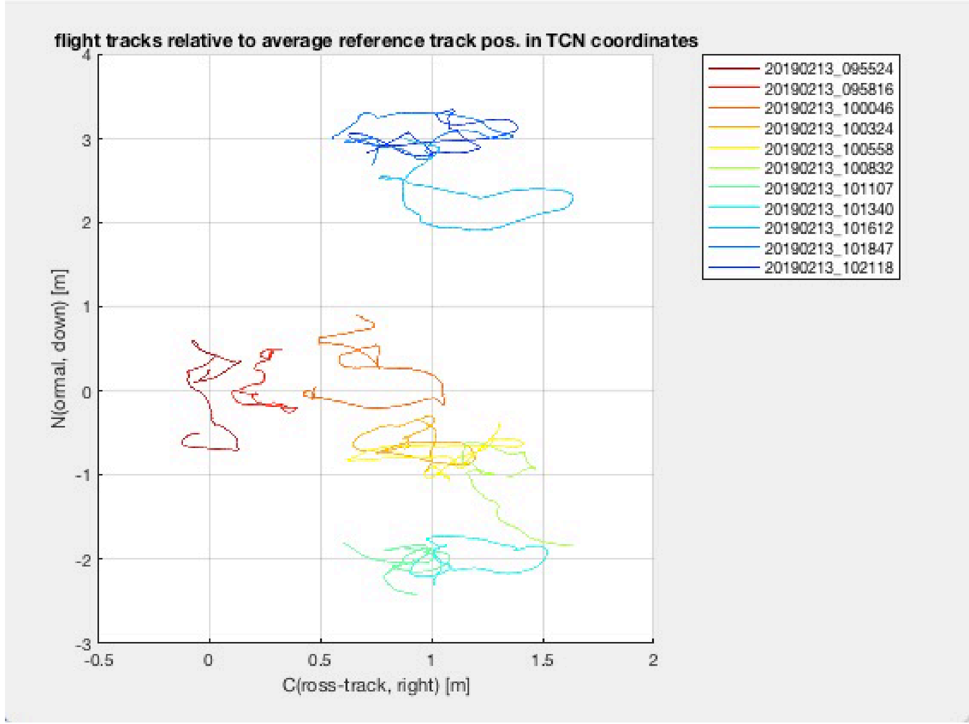
- Per track, the flight trajectory tube is within < 1m diameter.
- over time the positioning/altitude drifts (GNSS code solution / barometric height).
- With the Scout B-100 UAV it is difficult to fly exactly on the a priori-defined tracks.

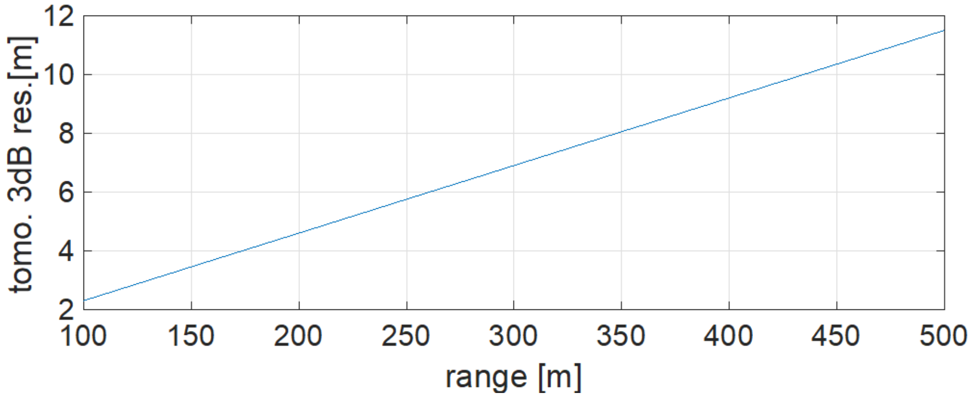


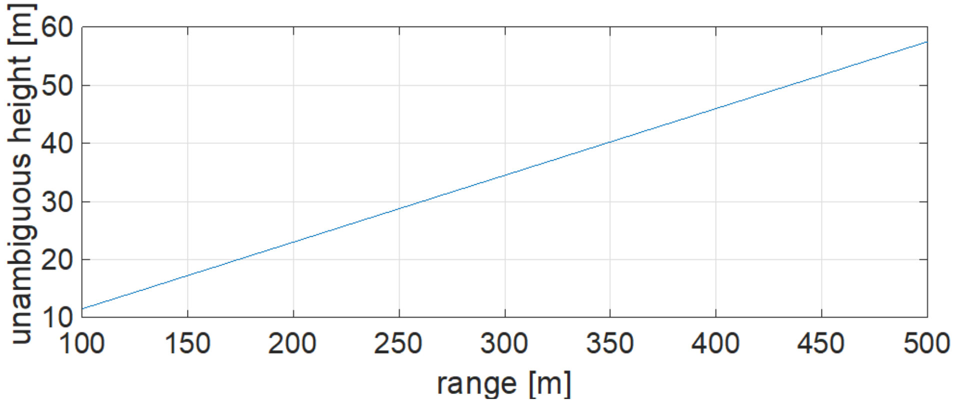


SAR Tomography processing of repeat-pass multi-baseline data

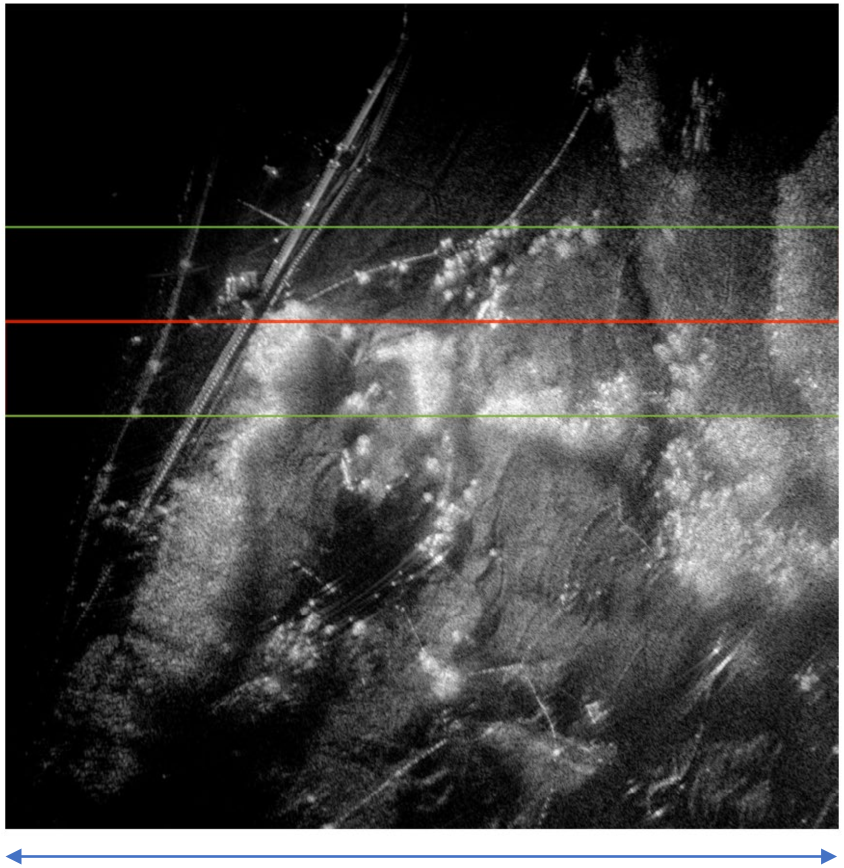
- Scout B-100 UAV : difficult to fly "exactly" on a-priori-defined tracks.
  → Non-ideal sampling (common problem):
  - Per track, the flight trajectory tube is within < 1m diameter.
  - Non-uniform baseline distribution
- We picked **6 tracks** that
  - cover a **total** vertical **baseline span** of approx. 5 m
  - have an **average** vertical **track spacing** of 1m with reasonable distribution.
  - Nominal resolution: $\delta_n = \frac{\lambda r}{2L}$
  - Unambiguous height: $H_{unamb} = \frac{\lambda r}{2d_n}$



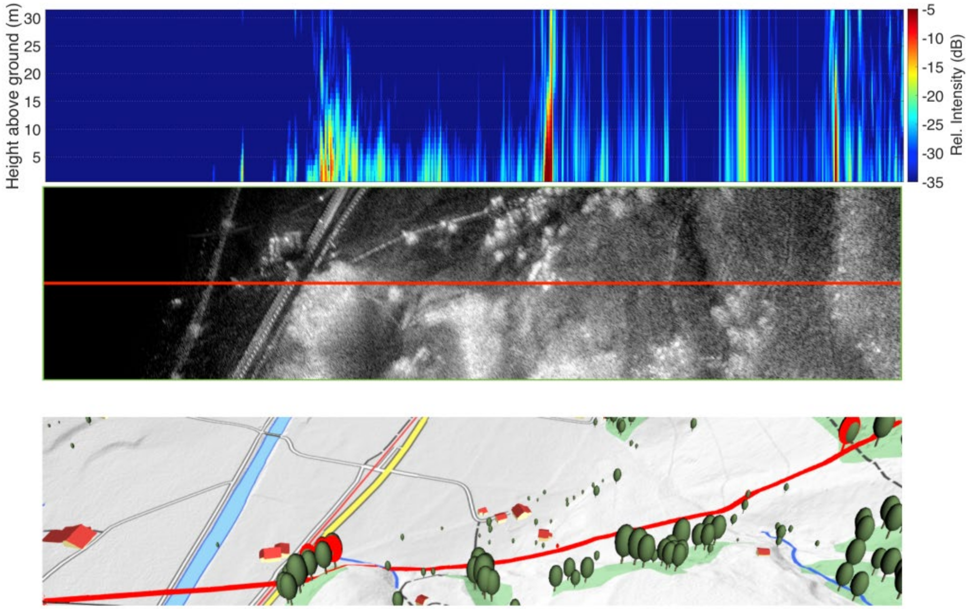




SAR tomography (multi-look beamforming): vertical transect



750 m



$$\hat{P}_B(z) = \mathbf{a}^H(z)\hat{\mathbf{R}}_y(z)\mathbf{a}(z)$$

$$\mathbf{a}(z) = [1 \; e^{i\varphi_2(z)} \; \ldots \; e^{i\varphi_K(z)}]^T$$

$$\varphi_m(z) = -2k_c(r_m(z) - r_1(z)),\; m = 1,..,K$$

$$\hat{\mathbf{R}}_y(z) = \frac{1}{N}\sum_{n=1}^{N}\mathbf{y}(n,z)\mathbf{y}^H(n,z)$$

Frey, O., Meier, E.:
"3-D Time-Domain SAR Imaging of a Forest Using Airborne Multibaseline Data at L- and P-Bands".
IEEE Trans. Geosci. Remote Sens., 49(10):3660-3664, 2011.

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Solution for SAR imaging

➔ GPU-Based Parallelized Time-Domain Back-Projection

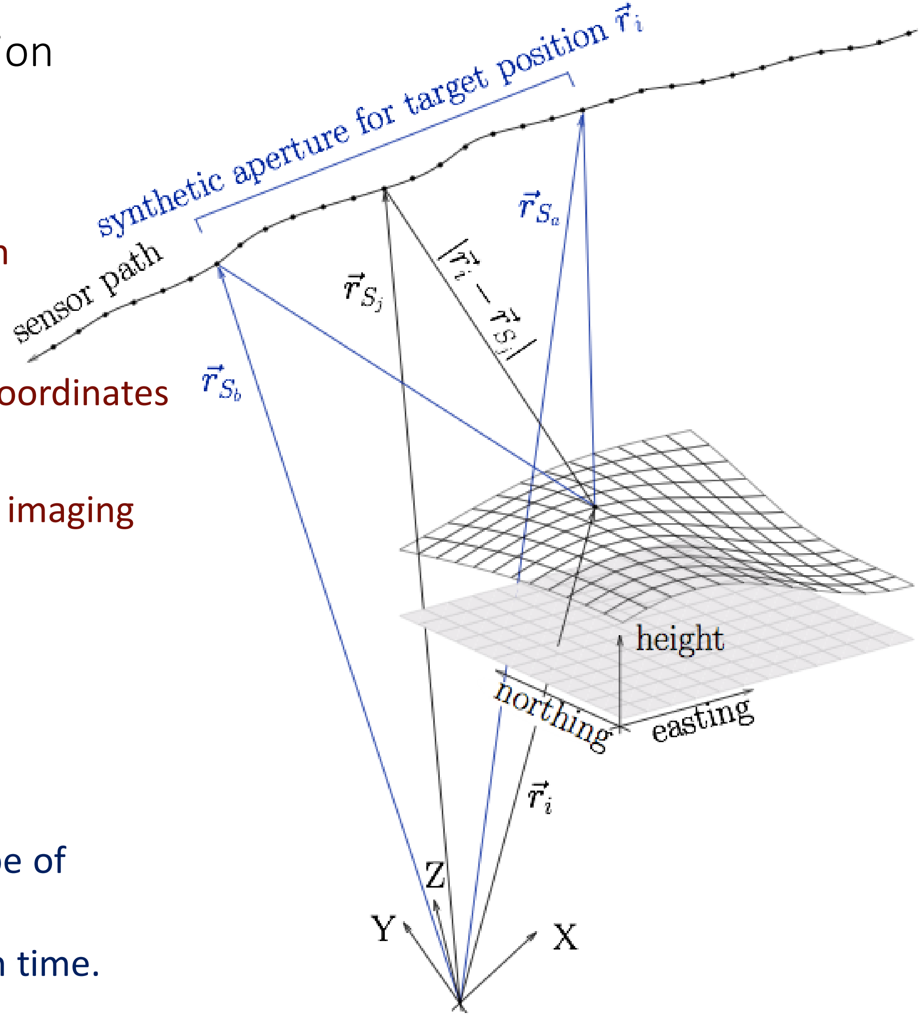
Why time-domain back-projection (TDBP) focusing?

- Assets of TDBP focusing:
  - Full 3-D motion compensation including terrain information
  - Arbitrary sensor trajectory!
  - Focused complex SAR images directly in map coordinates
- Our current focus:
  - Agile platforms: UAV-borne and car-borne SAR imaging along (curvilinear) roads:
  - Envisaged application:

Goal: → Displacement/geohazard monitoring

Why GPU-based TDBP processing?

- TDBP is a single instruction multiple data (SIMD)- type of algorithm
- Ideal for implementation on GPU → Faster execution time.



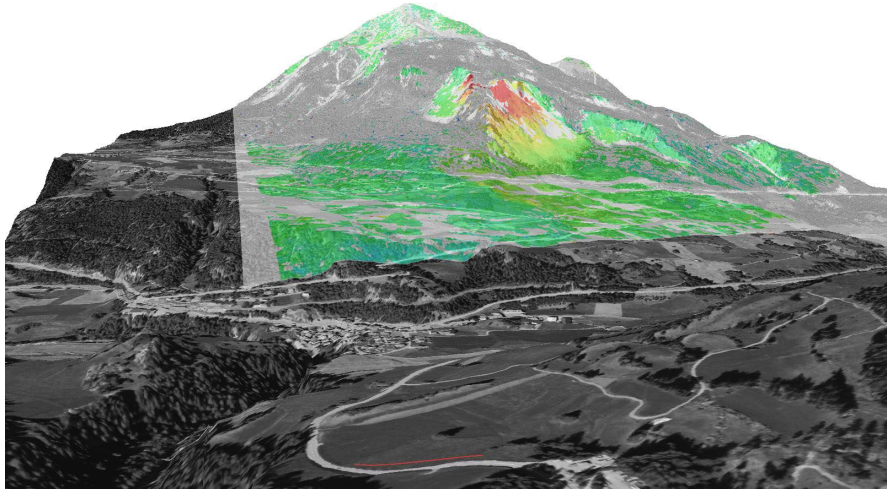
Frey, O., Magnard, C., Rüegg, M., Meier, E.:
"Focusing of Airborne Synthetic Aperture Radar Data from Highly Nonlinear Flight Tracks".
IEEE Trans. Geosci. Remote Sens., 47(6):1844-1858, June 2009.

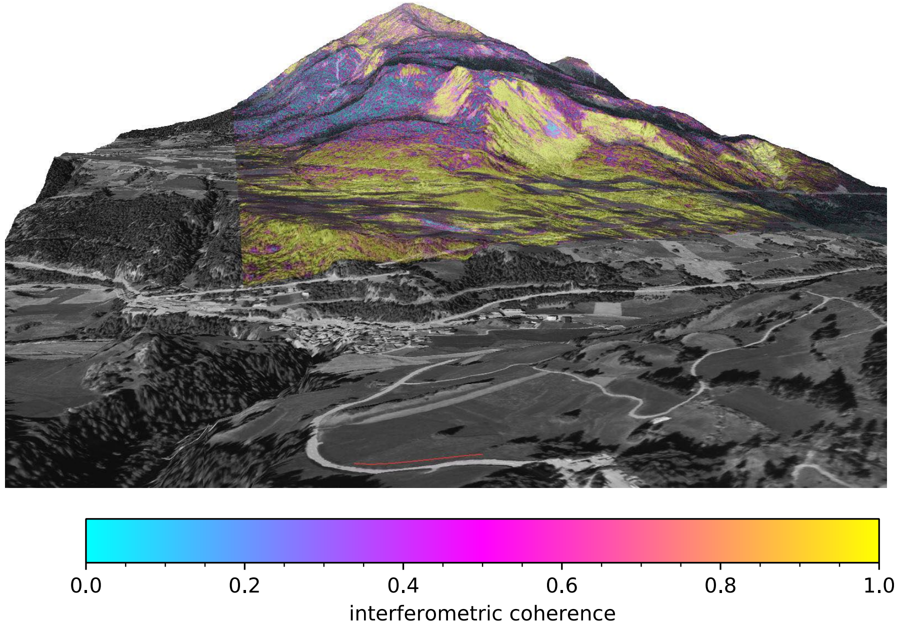
Interferometric-coherence-based estimate of the quality of the interferometric phase/displacement measurement

To assess the precision of the interferometric phase measurement the formula by Rodriguez & Martin 1992 can be used:

$$\sigma_\phi = \sqrt{\frac{1}{2 \cdot N_L} \frac{1 - |\gamma|^2)}{|\gamma|^2}}$$

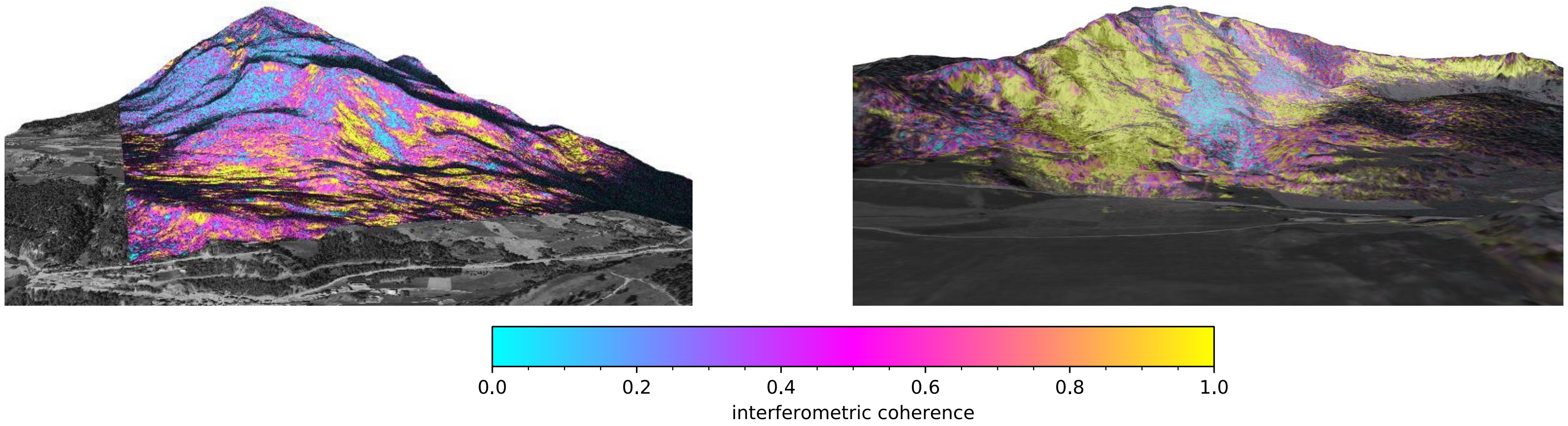
e.g.:
with a number of looks N_L=50
a coherence = 0.7 corresponds to a **phase standard deviation of 5.8 deg**
or:
a **standard deviation of the LOS displacement of 1.8 mm** for our L-band system.

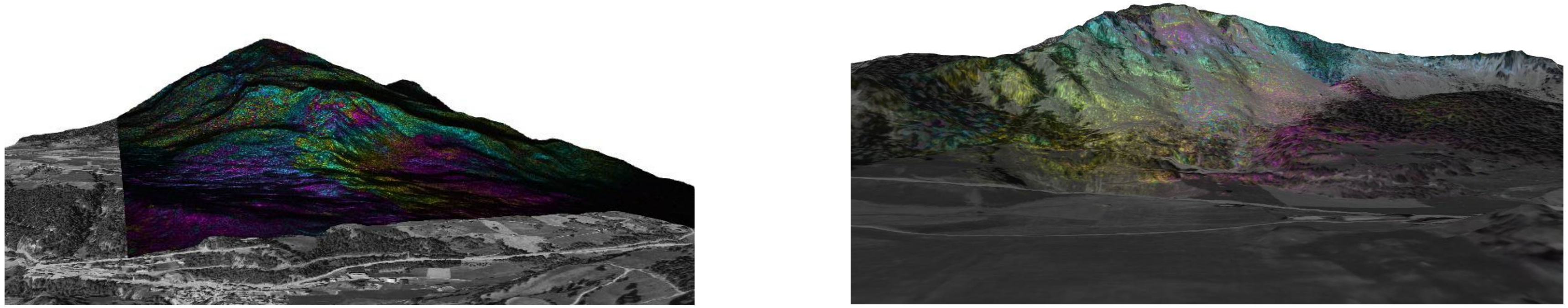


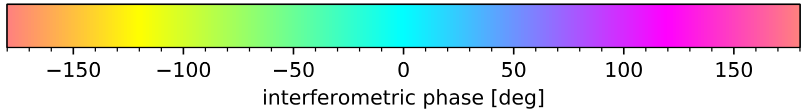


14-day coherence and phase
2020-01-20 to 2020-02-03

2020-01-20: dry
2020-02-03: partially light rain, tot. 5.9 mm (Thusis, MeteoSchweiz: THS)







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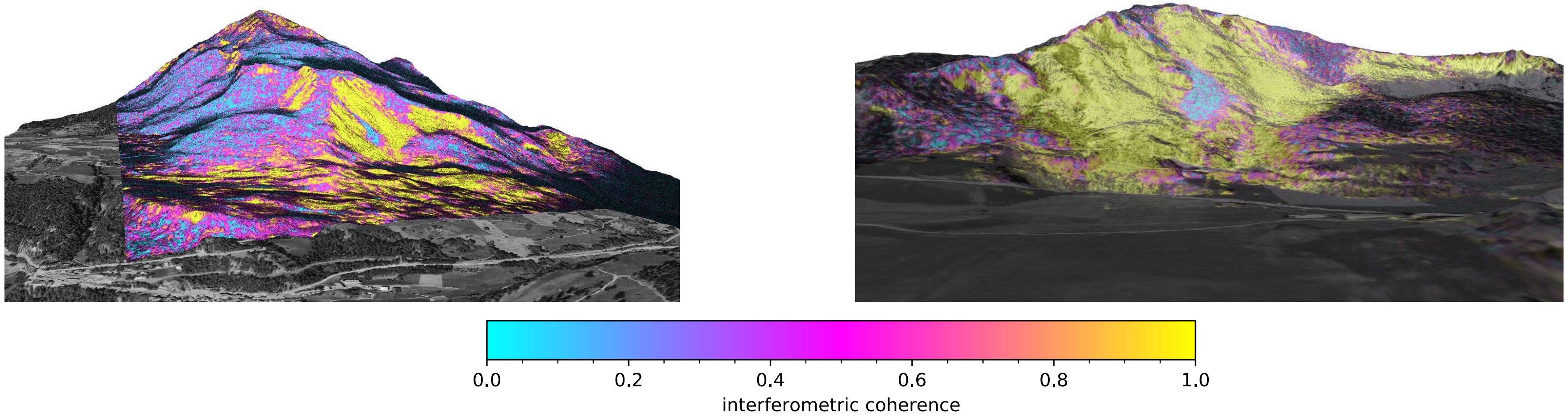
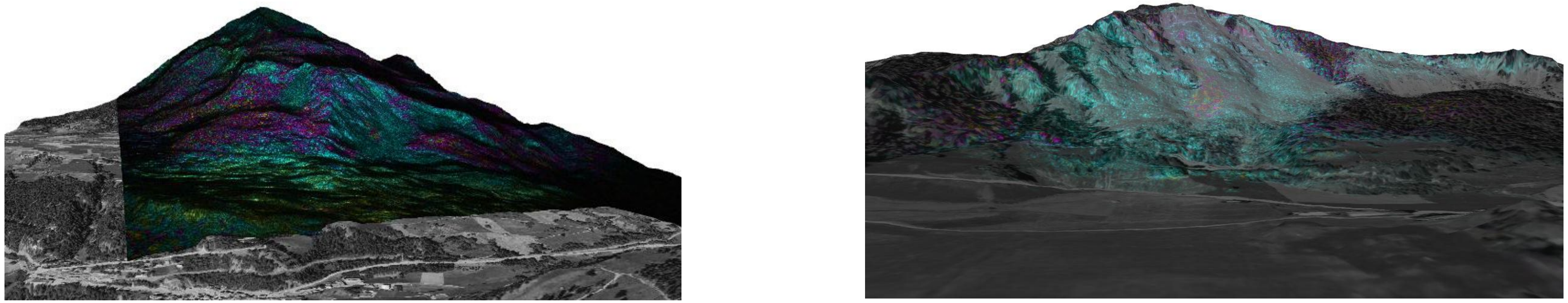
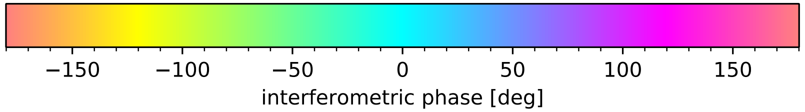
Impact of changing weather conditions/precipitation
1-day coherence and phase
2020-02-03 (rainy) to 2020-02-04 (snow)

- 2020-02-03: partially light rain, tot. 5.9 mm (Thusis, MeteoSchweiz: THS)
- 2020-02-04: snow fall, tot. 5 cm (Thusis, MeteoSchweiz: THS)







Solution for highly-precise navigation

HGUIDE n580 TYPICAL KEY CHARACTERISTICS	
GNSS Capability (Varies by Configuration)	SBAS, Post-Processed Kinematic (PPK), and RTK mode options Single or Dual Antenna capable
GNSS Signals (Varies by Configuration)	GPS L1 C/A, L1C, L2C, L2P, L5; GLONASS L1 C/A, L2 C/A, L2P, L3, L5; BeiDou B1, B2; Galileo E1, E5 AltBOC, E5a, E5b; NavIC (IRNSS) L5; SBAS L1, L5 QZSS L1 C/A, L1C, L2C, L5; L-Band up to 5 channels
Supply Voltage	+9VDC to +36VDC
Power Consumption	7 Watts (Varies by Configuration)
Weight	495g (1.1 lbs)
Volume / Size	324 cm^3 (19.8 in^3), 9cm x 6cm x 6cm (Not Including Mounting Feet)
Operating Temperature Range	-40°C to +71°C
Packaging Rating	IP68
Communication Ports	Primary Navigation Interface, 1MBit, RS-422 Secondary Navigation Interface, 1MBit, 5V CMOS RTCM3 Corrections Interface, 115.2KBit, RS-422
Discrete Signals	PPS 5V CMOS Output

HGUIDE n580 NAVIGATION PERFORMANCE			
POSITION ACCURACY		HEADING ACCURACY[1]	PITCH/ROLL ACCURACY
Horizontal (m, 1σ)	Vertical (m, 1σ)	(°, 1σ)	(°, 1σ)
0.01 RTK 0.6 SBAS	0.025 RTK 0.6 SBAS	0.05	0.015

HGUIDE n580 RTK DUAL ANTENNA PERFORMANCE - GNSS OUTAGES WITH NO AIDING			
RMS Error	3 Second	10 Second	30 Second
Horizontal (meter)	0.09	0.2	1
Vertical (meter)	0.045	0.1	0.5
Heading (degree)	0.06	0.07	0.08

Solution for highly-precise navigation

iMAR
GESELLSCHAFT FUER INERTIALE MESS-, AUTOMATISIERUNGS- UND REGELSYSTEME MBH
WWW.IMAR-NAVIGATION.DE

Technical Data of iNAV-RQH-10018

Data Output:	Heading, Roll, Pitch, Angular Velocity, Velocity (body and world), Position, Raw data, internal statuis information, odo and GPS inf.	
True Heading:	< 0.025° sec(lat) free inertial; 0.01° with DGPS, 0.005 ° postproc RTK	
Attitude Accuracy:	< 0.01° free inertial (< 0.005° with DGPS, 0.002° postproc with RTK aiding)	
Position Accuracy:	0.6 nm/hr free inertial; < 1 m GPS (S/A off) and < 10 cm RTK online, < 30 cm DGPS and 2 cm RTK/INS postproc, < 0.1 % distance travelled (with odometer and GPS, applic. depend.) < 0.2 % dist.trav. on underwater vehicles (incl. RDI DVL interface)	
Velocity Accuracy:	5 mm/s (aided with L1/L2 RTK GPS receiver, < 2 mm/s postproc RTK)	
Alignment Time:	< 10 minutes on-shore, < 25 minutes off-shore	
Range:	± 400 °/s (no angle limitation)	±20 g
Drift (unaided) / Offset:	< 0.002 °/hr	< 25 µg
Bias Stability:	< 0.002 °/hr (const. temp.)	< 10 µg
Random Walk / Q:	< 0.0015 $°/\sqrt{h}$	< 8 µg/sqrt(Hz)
Resolution:	0.0003 ° (1,13"), < 0.001 °/s	< 5 µg (depends on data rate)
Scale/Linearity Error:	< 5 ppm / < 5 ppm	< 100 ppm / < 20 µg/g²
Axis Misalignment:	< 25 µrad	
Data Output Rate:	1...300 Hz, internal bandwidth 300 Hz	
Data Latency:	< 3 ms	
Data storage:	up to 16 GByte on internal flash drive (option)	
Output (options):	RS232/422 UART, Ethernet TCP/IP / UDP, PPT (Pulse Per Time), PPS, CAN, MIL-STD1553B	
Inputs (options):	internal/external (RTK)GNSS (standard: GPS/GLONASS/GALILEO integrated), marker event trigger, 3 x odometer (RS422 level), [PPS / SYNC]	
Connectors:	MIL-C-38999 III	
Temperature (case):	-40...+65°C operating, (+71°C opt.), -46...+85°C not operating	
Rel. Humidity:	8...100%, IP67	
Magnetic. insensitivity:	< 500 µTesla (5 Gauss)	
MTBF / MTTR:	> 25,000 hrs (estimated for surveying applications) / < 30 minutes	
Shock, Vibration:	25 g, 11 ms ;60 g, 5 ms (operating); 20…2000 Hz, 3 g rms	
Qualification:	MIL-STD-810F, MIL-STD-461E, MIL-STD-704D, DO160E	
Power:	11...34 V DC, < 45 W; 50 ms hold up time according to DO160E	
Weight / Size:	9.0 kg / approx. 299 x 213 x 179 mm (without connectors)	
Software:	internal online Kalman filter, NavCommand, INS/RTK-GPS postproc. (option)