Iot am Matterhorn – Drahtlose Sensoren fuer die Naturwissenschaftliche Grundlagenforschung

Presentation

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IoT am Matterhorn

Jan Beutel, ETH Zurich & the PermaSense Team

PermaSense

PermaSense

- Interdisciplinary geo-science and engineering collaboration
- Consortium of several projects, start in 2006
- Fundamental as well as applied research
  - Long-term, high-quality sensing in harsh environments
  - Better quality data, obtained online
  - Measurements that have previously been impossible
  - Enabling new science, answering fundamental questions related to decision making, natural hazard early-warning
- More than 40 people, 30 PhD students – **10+ years continuous experimental data**

FNSNF Fonds national suisse Schweizerischer Nationalfonds Fondo nazionale svizzero Swiss National Science Foundation

nano-tera.ch

NCCR MICS National Competence Center in Research Mobile Information and Communication Systems

Bundesamt für Umwelt BAFU Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra

cces

Investigating Instabilities in Steep Rock Walls

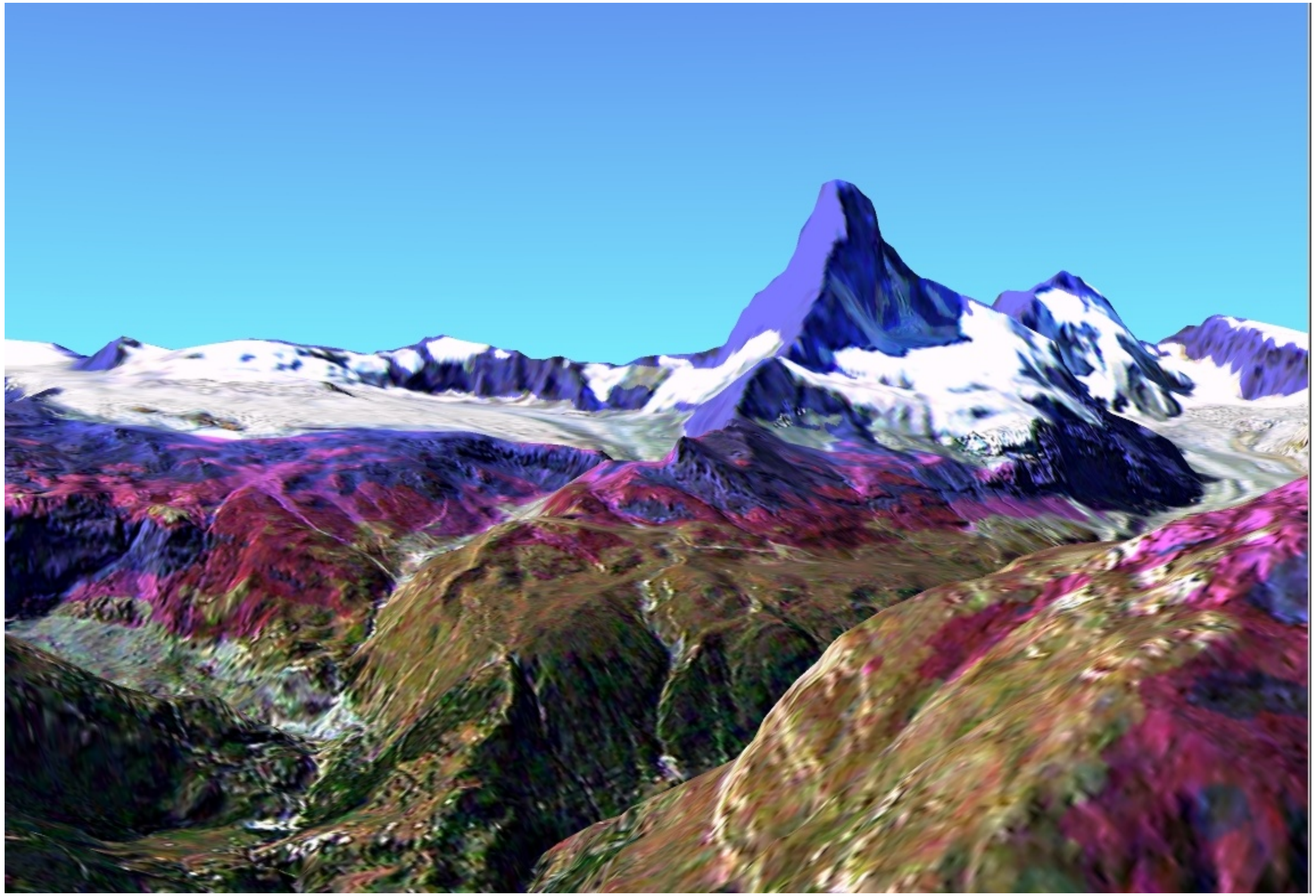
- When are vertical rock walls getting instable?
- When is rockfall happening?
- What are its causes?
- What are the effects of climate change?
- How does this influence our environment and habitat in the Alps?

[Bondo – Piz Cengalo rockfall incident, August 21, 2017, youtube.com]

Goal:
Understanding Root Causes of Catastrophes

What is Permafrost?

- Permafrost is rock, ground and debris frozen throughout the whole year
- Permafrost is not visible
- In summer permafrost thaws at the surface




Our patient does not
fit into a laboratory

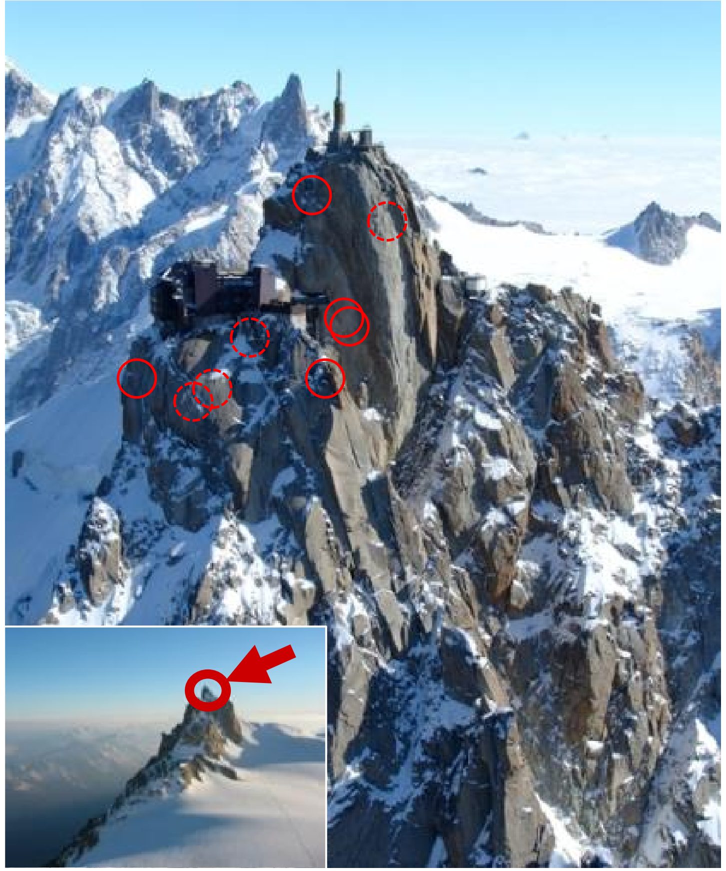

So the laboratory has to go on the mountain

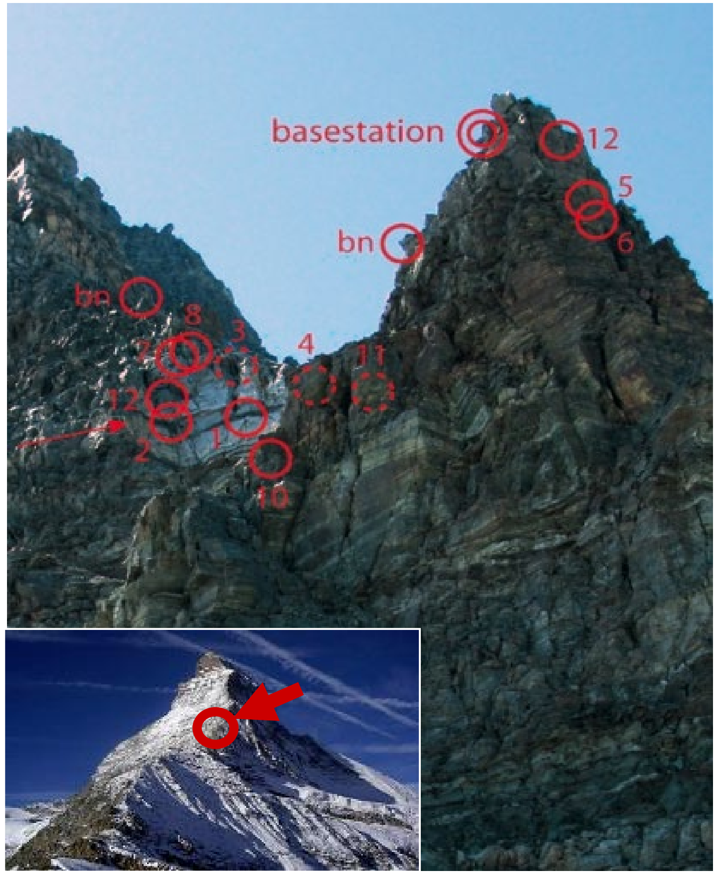
2003 Matterhorn Hörnliridge Rockfall

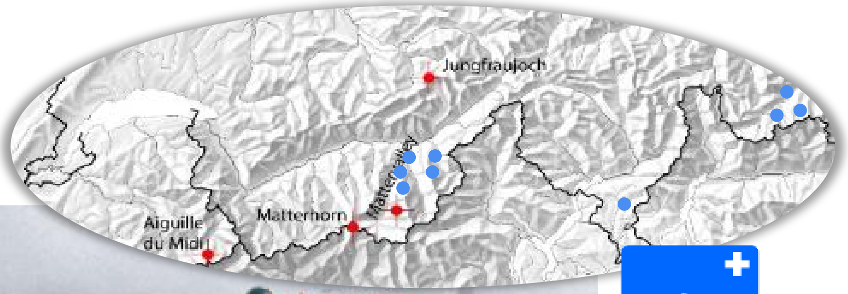
15. July 2003 – 1500-2500 m^3 – 84 alpinists evacuated

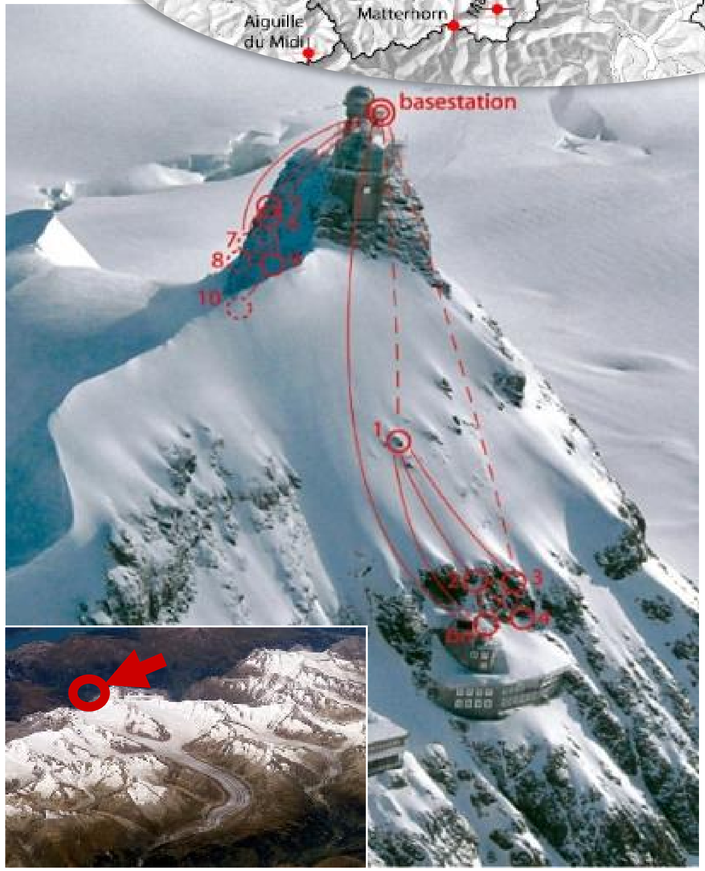
[© Bruno Jelk, Zermatt]

Our Field Sites: Precision Scientific Instruments










The Matterhorn site
at 3500 m in
deep winter snow


Perched high above the
valley on a rocky ridge

Snow and ice cover is missing in summer
[© Noe Flum, Zurich]

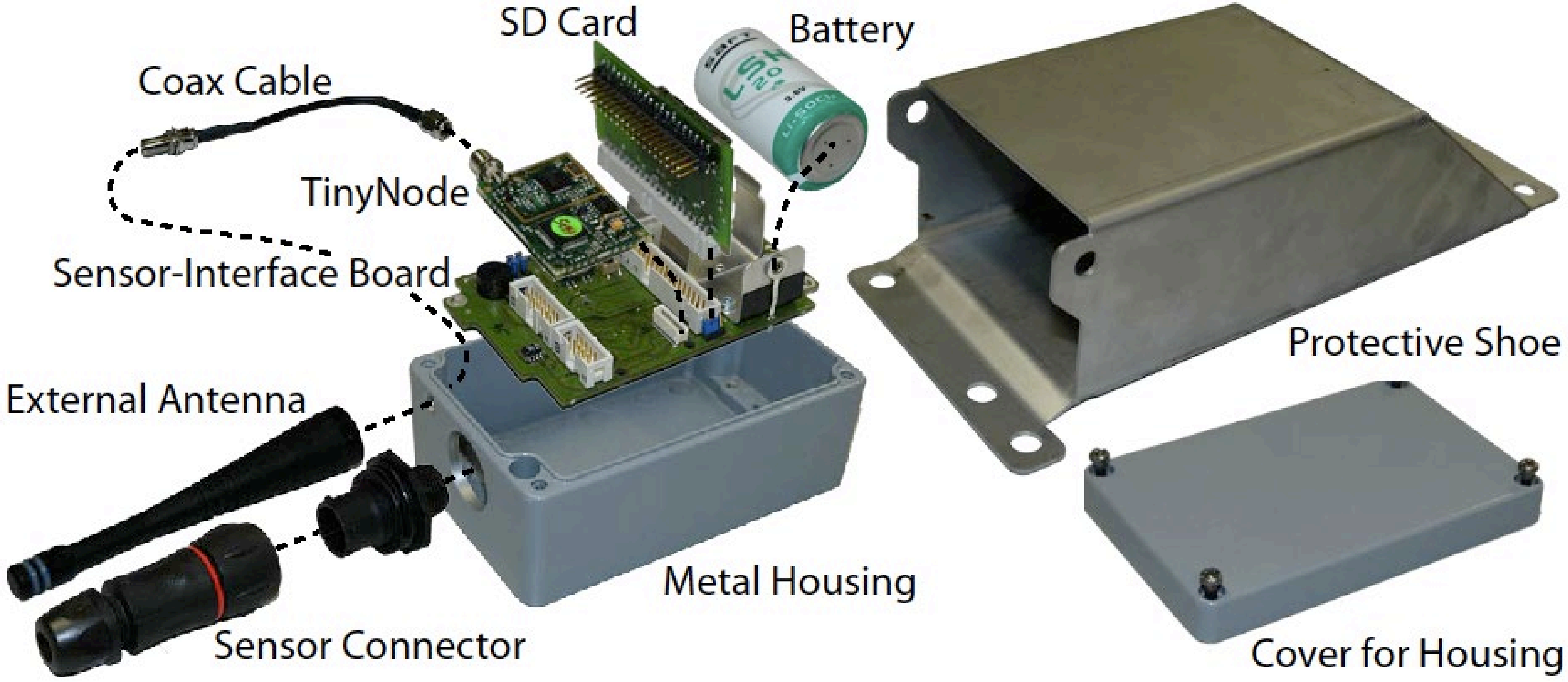
At the core – Wireless sensors tough to withstand the elements

[A. Hasler et al: *Wireless Sensor Networks in Permafrost Research - Concept, Requirements, Implementation and Challenges.* Proc. 9th International Conference on Permafrost (NICOP), 2008.]

Miniature Low-Power Wireless Sensors

- Static, low-rate sensing (120 sec)
- Simple scalar values: voltages, resistivity, digital sensors
- 4-5 years operation (~150 µA avg. power)
- ~0.1 Mbyte/node/day
- 10+ years experience, ~3’764’408’638 data points

Ruggedized for Alpine Extremes



[A. Hasler et al: *Wireless Sensor Networks in Permafrost Research - Concept, Requirements, Implementation and Challenges.* Proc. 9th International Conference on Permafrost (NICOP), 2008.]

A base station collects and relays the data to the valley

[J. Beutel et al: *PermaDAQ: A Scientific Instrument for Precision Sensing and Data Recovery under Extreme Conditions*. Proc. IPSN/SPOTS 09

R. Lim et al: *FlockLab: A Testbed for Distributed, Synchronized Tracing and Profiling of Wireless Embedded Systems.* Proc. IPSN/SPOTS 2013

B. Buchli, F. Sutton, J. Beutel and L. Thiele: *Dynamic Power Management for Long-Term Energy Neutral Operation of Solar Energy Harvesting Systems.* Proc. SenSys 2014.

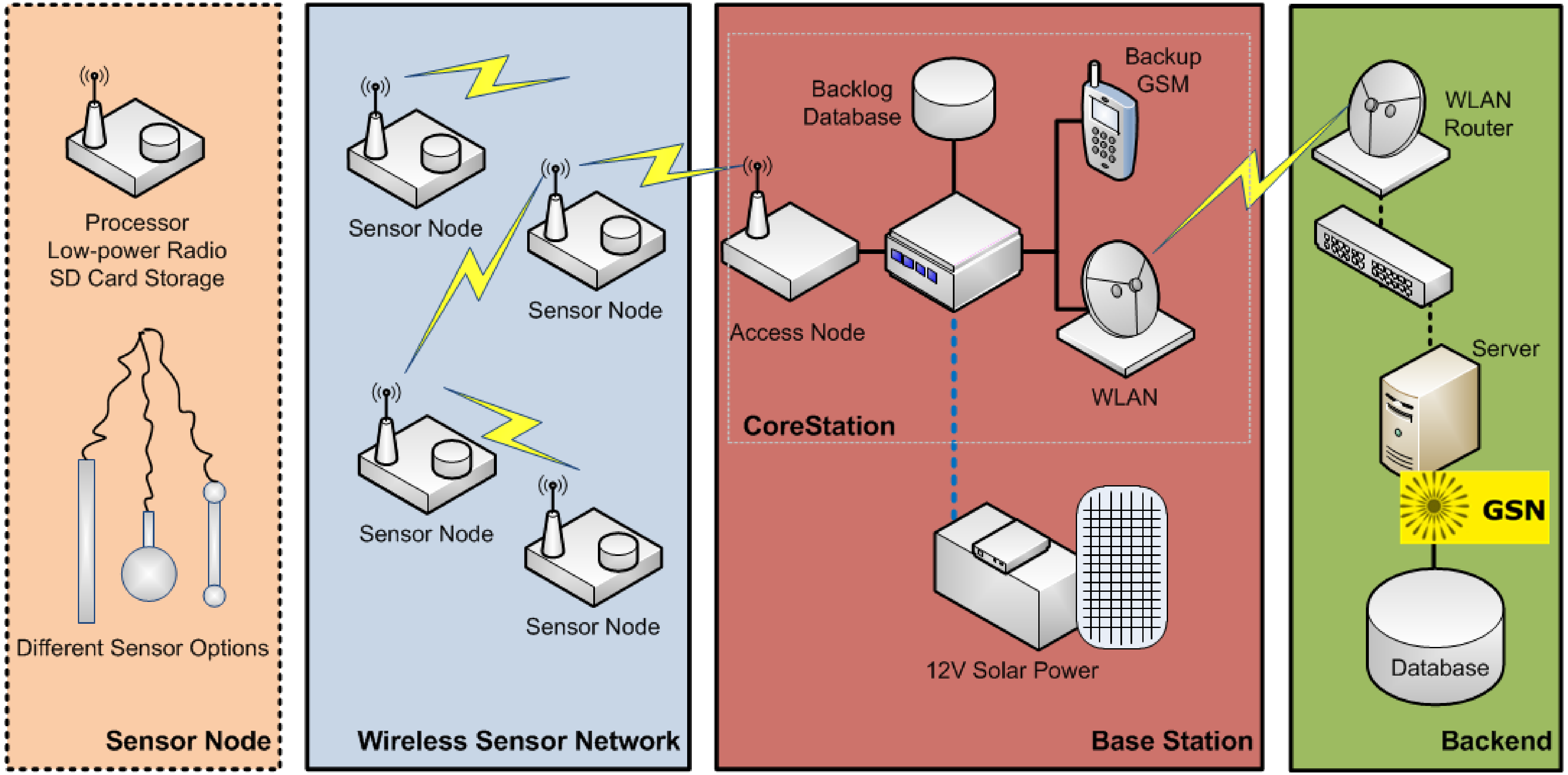
B. Buchli, F. Sutton, J. Beutel and L. Thiele: *Towards Enabling Uninterrupted Long-Term Operation of Solar Energy Harvesting Embedded Systems.* Proc. EWSN 2014

M. Keller, J. Beutel and L. Thiele: *The Problem Bit.* Proc. DCOSS 2013 ★ Best Paper Award ★

B. Buchli, D. Aschwanden and J. Beutel: Battery State-of-Charge Approximation for Energy Harvesting Embedded Systems. Proc. EWSN 2013.

M. Keller, J. Beutel and L. Thiele: *How Was Your Journey? Uncovering Routing Dynamics in Deployed Sensor Networks with Multi-hop Network Tomography.* Proc. SenSys 2012.]

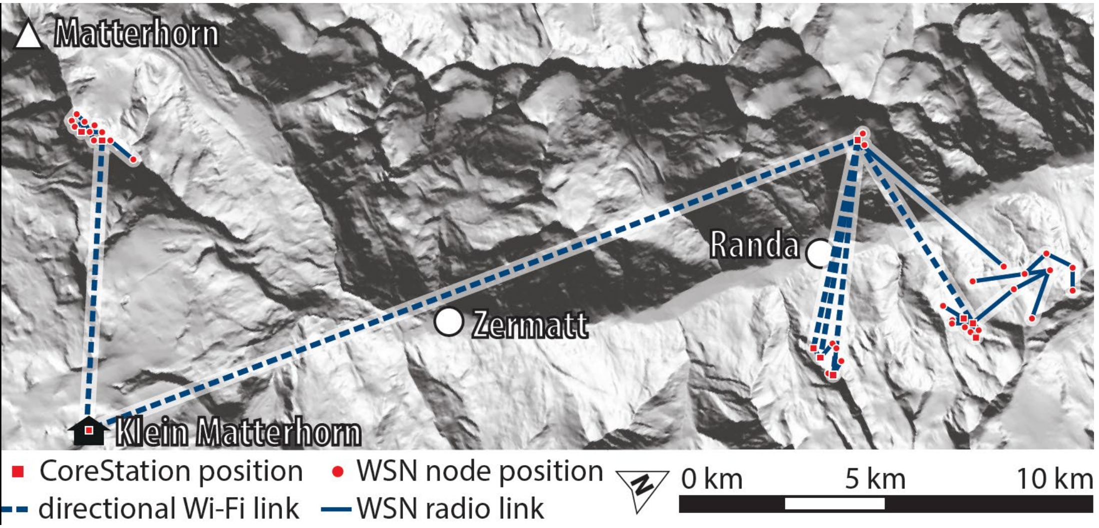
PermaSense Core System Architecture

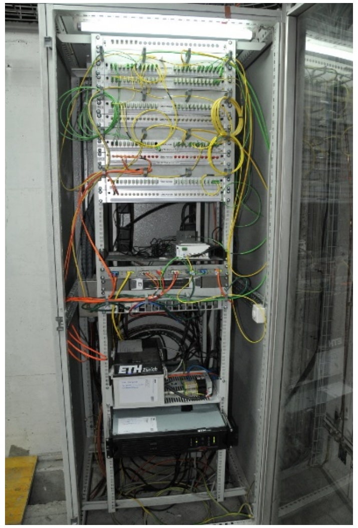


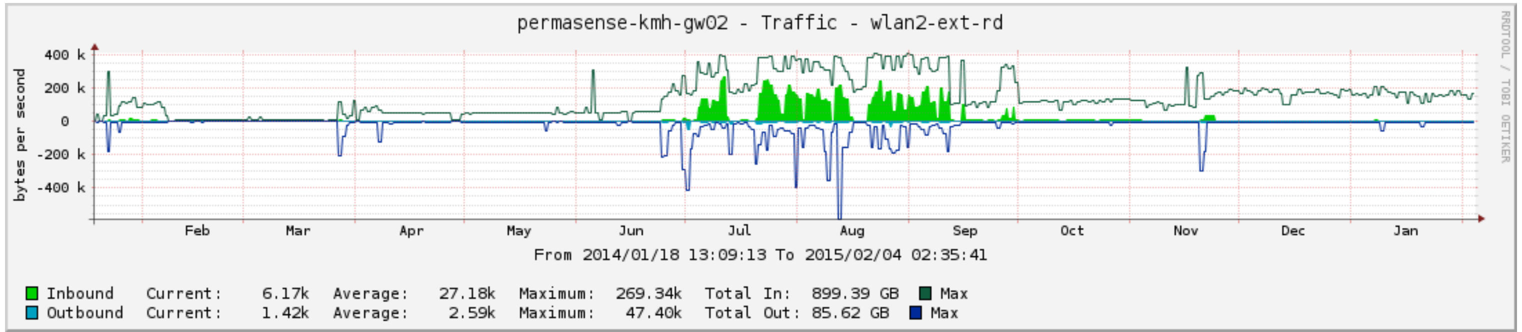
[J. Beutel et al: *PermaDAQ: A Scientific Instrument for Precision Sensing and Data Recovery under Extreme Conditions*. Proc. IPSN/SPOTS 2009.]

WLAN Long-haul Communication

- WLAN (802.11a) backbone using directional links
- Leased fiber/DSL from Zermatt Bergbahnen AG to mountaintop

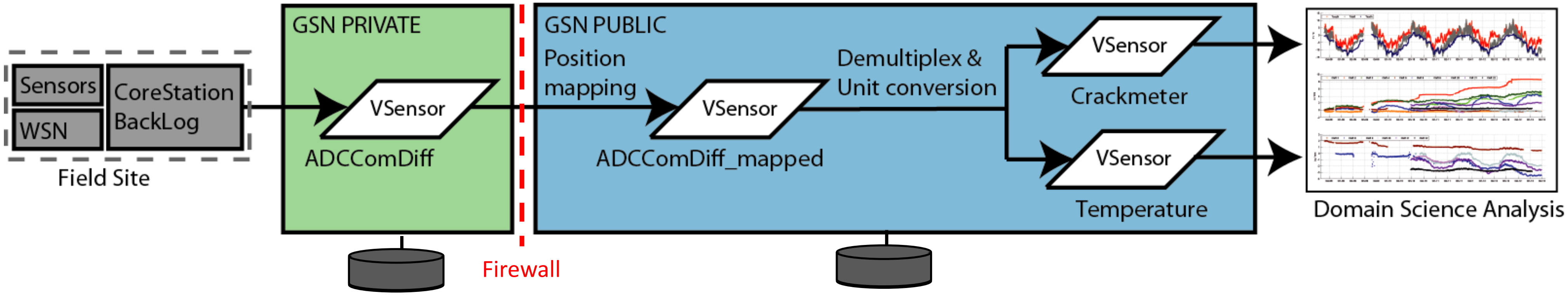






Online Data Management & Access

- Global Sensor Network (GSN)
  - Data streaming framework from EPFL (K. Aberer)
  - Organized in “virtual sensors”, i.e. data types/semantics
  - Hierarchies and concatenation of virtual sensors enable on-line processing
  - Dual architecture translates data from machine representation to SI values, adds metadata



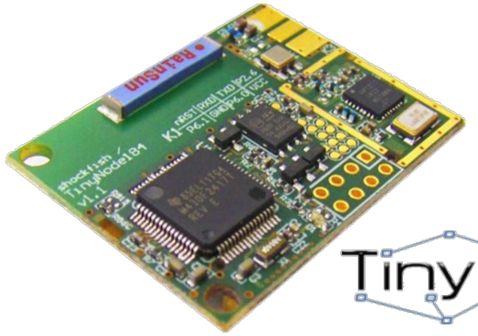
Data from field site is received by the private GSN server “as is” and **stored** in a primary database.

Data is passed on to a public GSN server where it is **mapped** to metadata (positions, sensor types, calibration) and **converted** to convenient data formats.

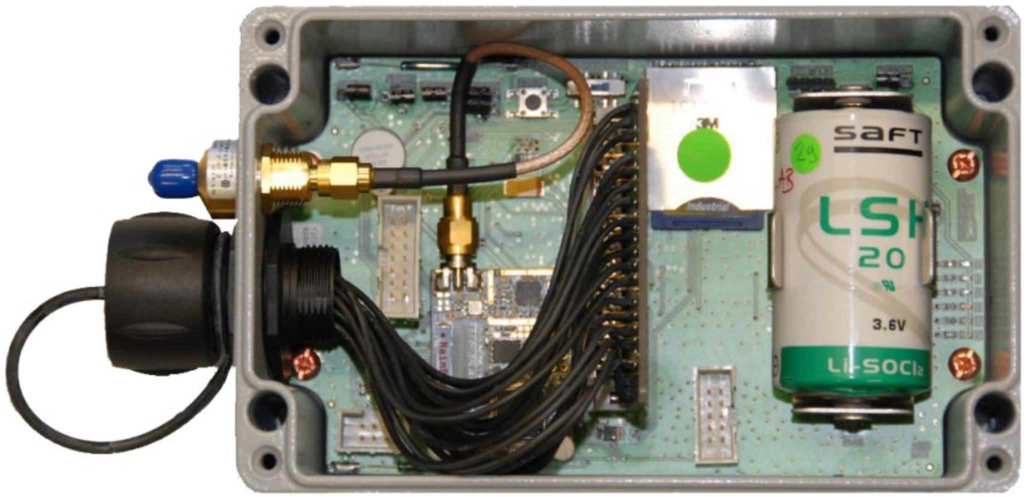
Data is available for download and analysis using **external tools**.

Wireless sensors cover the Hörnligrat from first couloir up to Eisloch

1st Generation Sensor Node Hardware



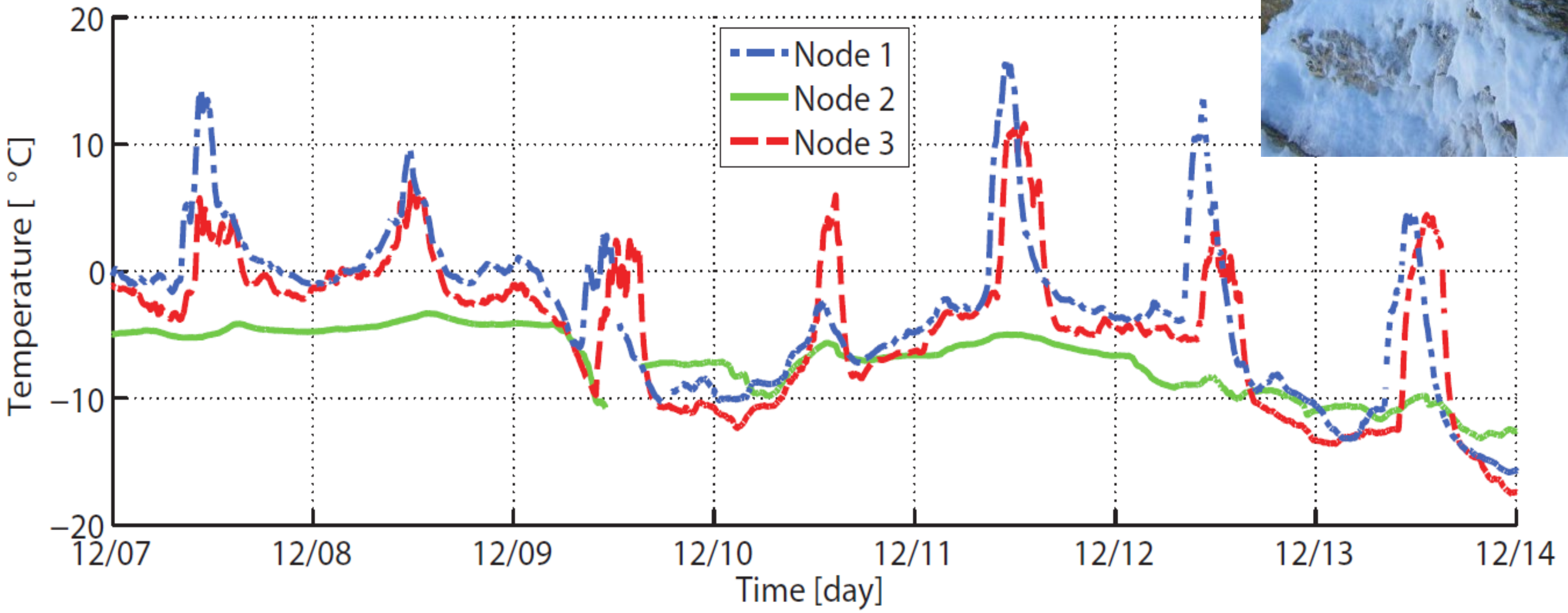
- Shockfish TinyNode184
  - MSP430, 16-bit, 8MHz, 8k SRAM, 92k Flash
  - LP Radio: SX1211 @ 868 MHz, +12.5 dBm
- Waterproof housing and connectors
- Sensor interface board
  - Interfaces, power control
  - Temp/humidity monitor
  - 1 GB Flash memory
- 3-year life-time
  - Single Li-$SOCl_2$ battery, 13 Ah
  - ~300 μA power budget



[J. Beutel et al: *PermaDAQ: A Scientific Instrument for Precision Sensing and Data Recovery under Extreme Conditions*. Proc. IPSN/SPOTS 2009.]

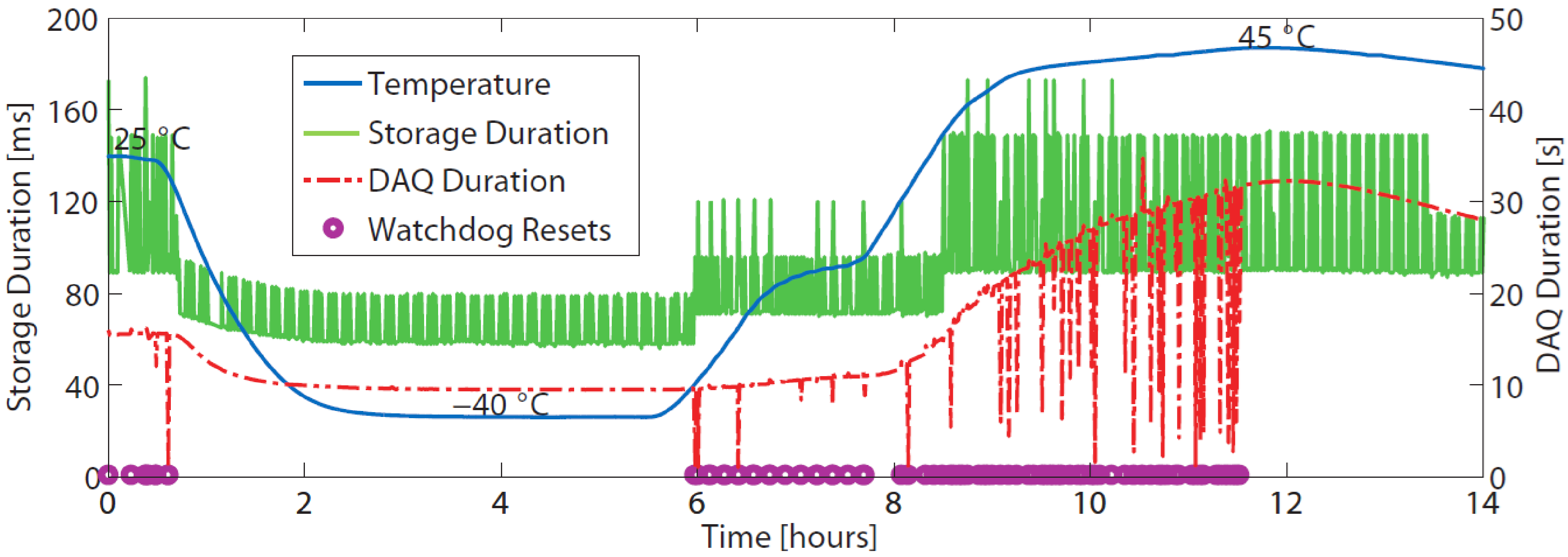
Challenge: The Physical Environment

- Strong daily variation of temperature
  - −30°C to +40°C
  - ΔT ≦ 20°C/hour
- Impact on
  - timing, energy availability, fatigue, **SOFTWARE,** …



Impact of Environmental Extremes

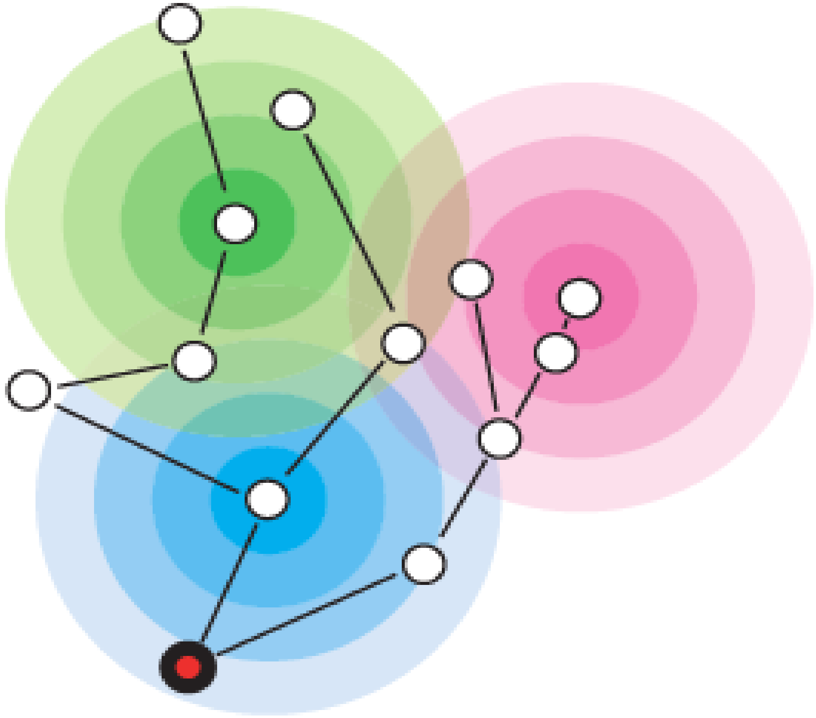
- Tighter guard times increase energy efficiency
- Software testing in a climate chamber
- Validation of correct function, clock drift compensation ± 5ppm

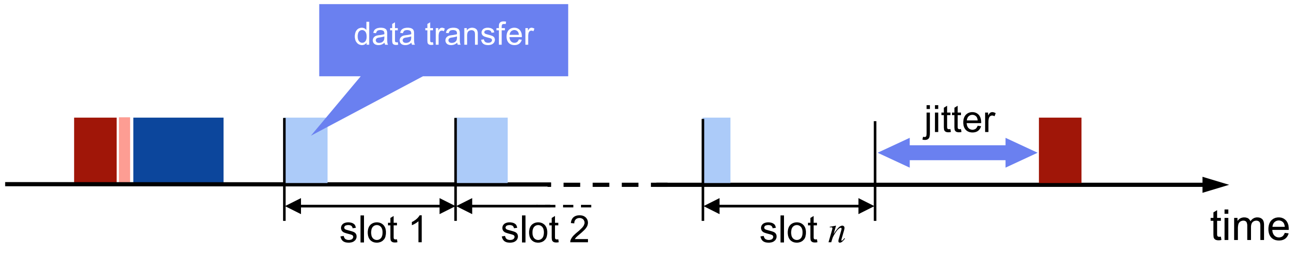


[J. Beutel et al: *X-Sense: Sensing in Extreme Environments*. Proc. Design, Automation and Test in Europe (DATE 2011).]

Ultra Low-Power Data Gathering

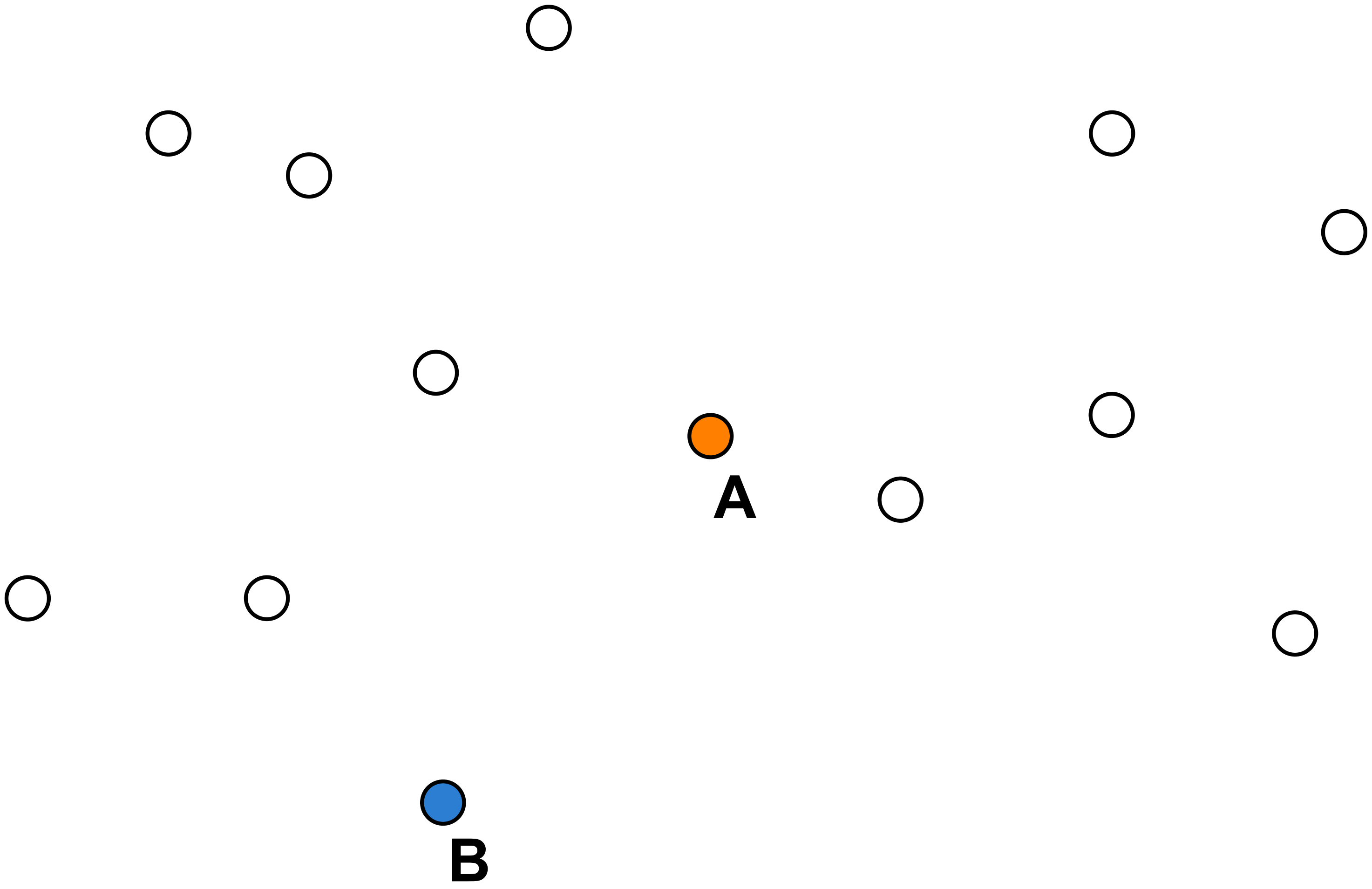
- Dozer – ultra low-power data gathering system
  - Beacon based, 1-hop synchronized TDMA
  - Tree-based routing towards a sink
  - Optimized for ultra-low duty cycles
  - **0.167%** duty-cycle, **0.032mA** (@ 30sec beacons)
- Dynamic adaptation
  - Back-off randomization for diversity
  - Jitter adaptation over multiple hops
  - Adaptive duty-cycle accounts for long-term loss of connectivity





[Burri, N., von Rickenbach, P., & Wattenhofer, R.: *Dozer: Ultra-Low Power Data Gathering in Sensor Networks.* Proc. IPSN 2007.]

Glossy – Reliability Through Network Flooding



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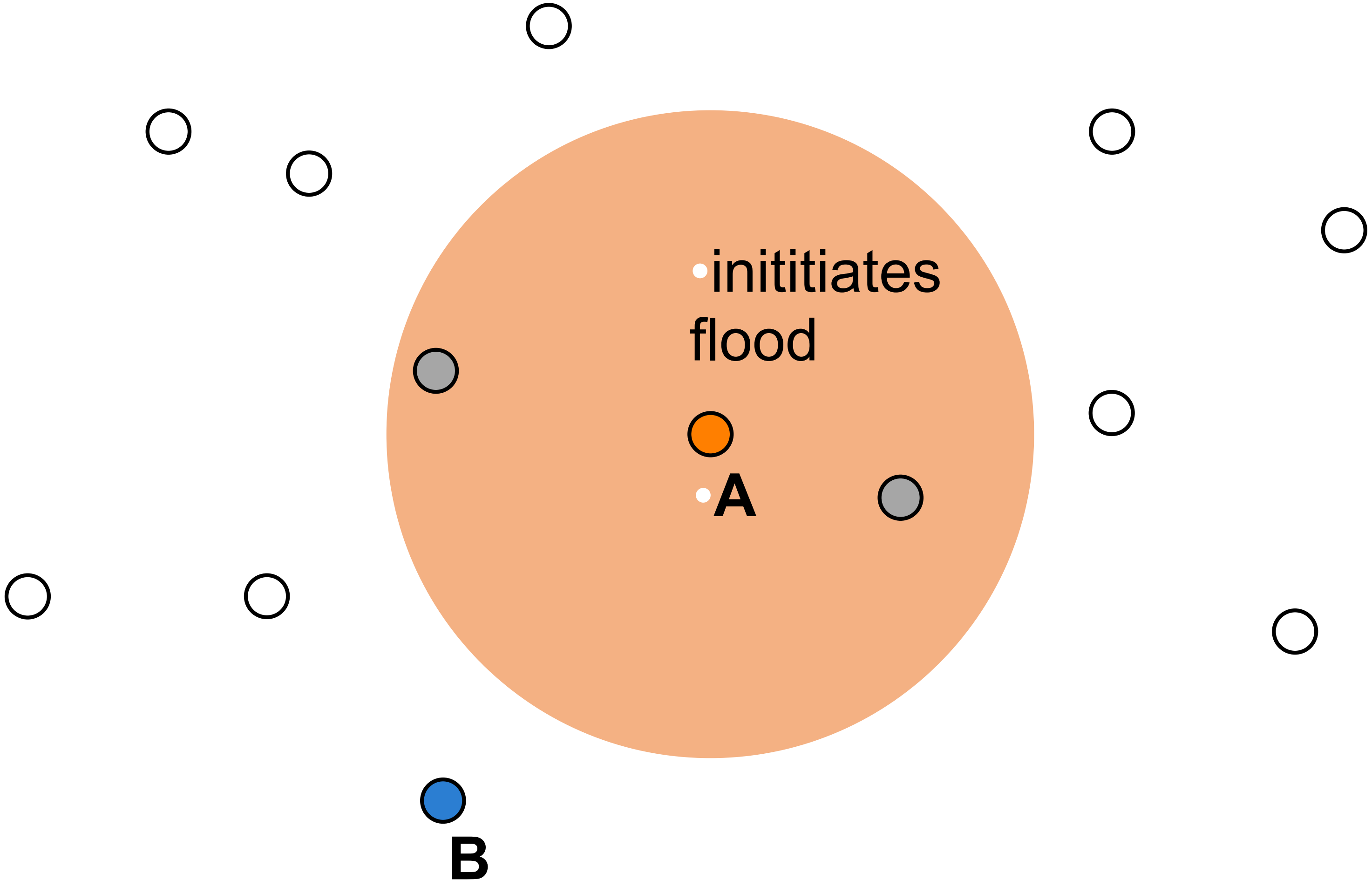

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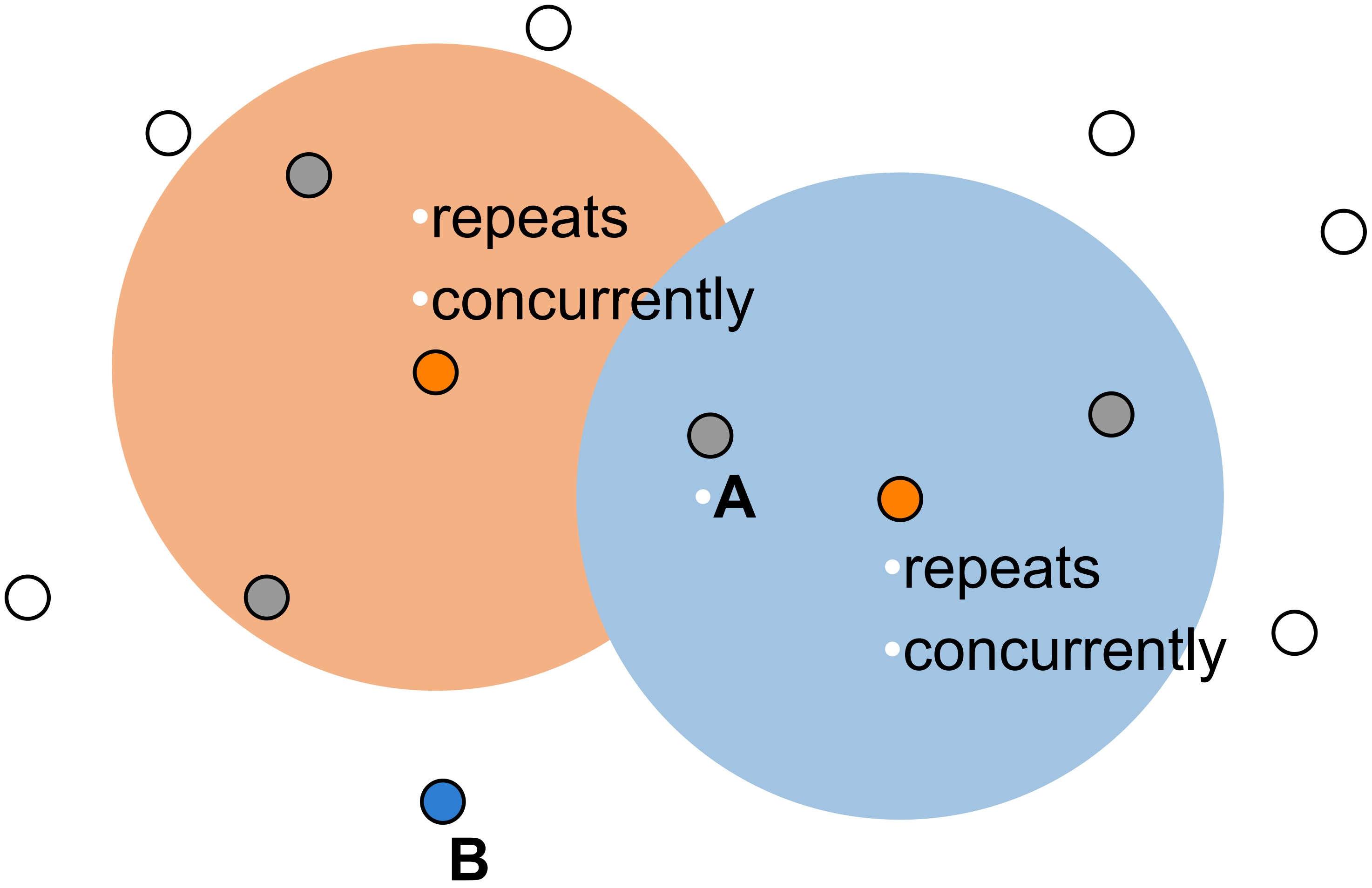

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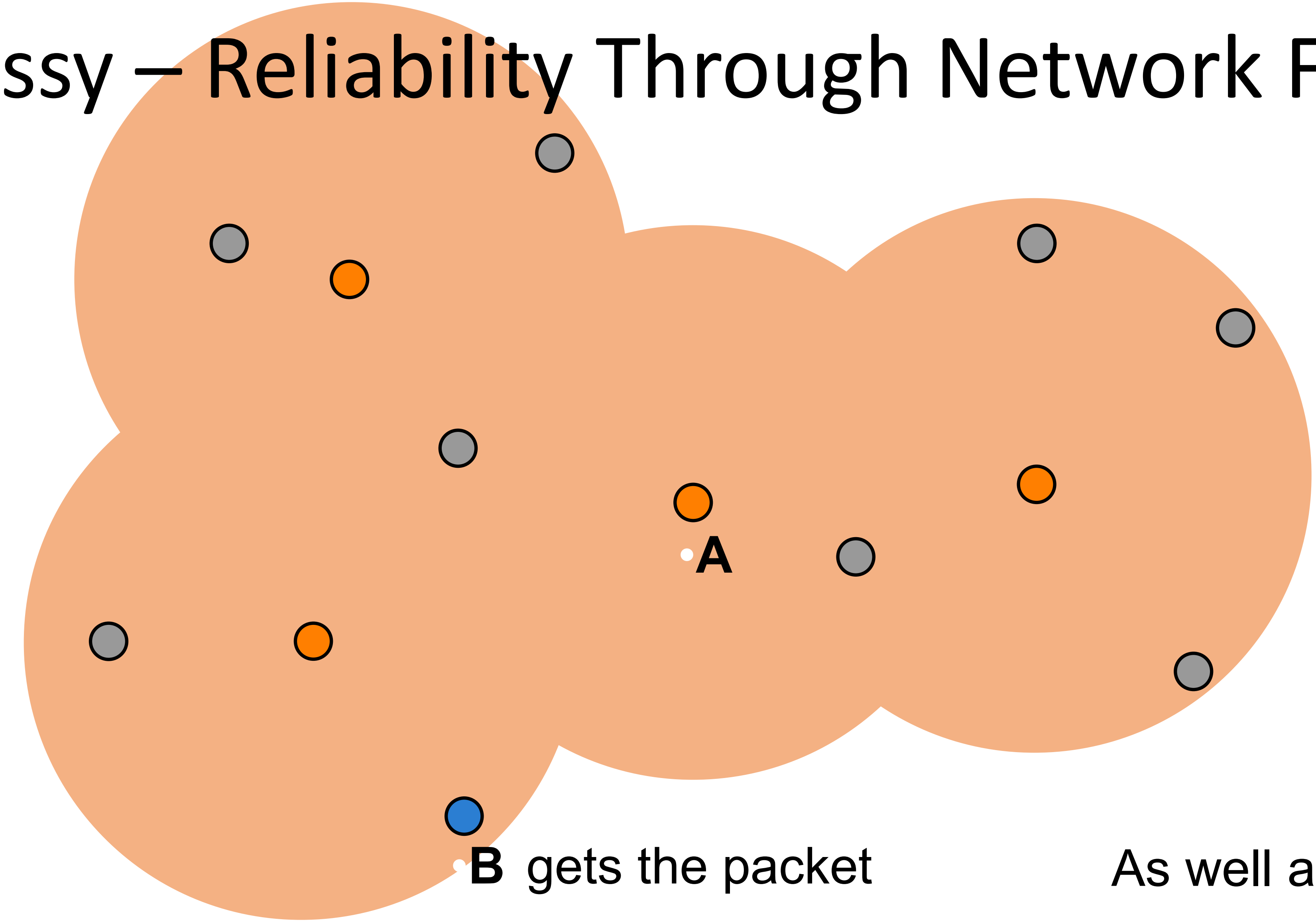
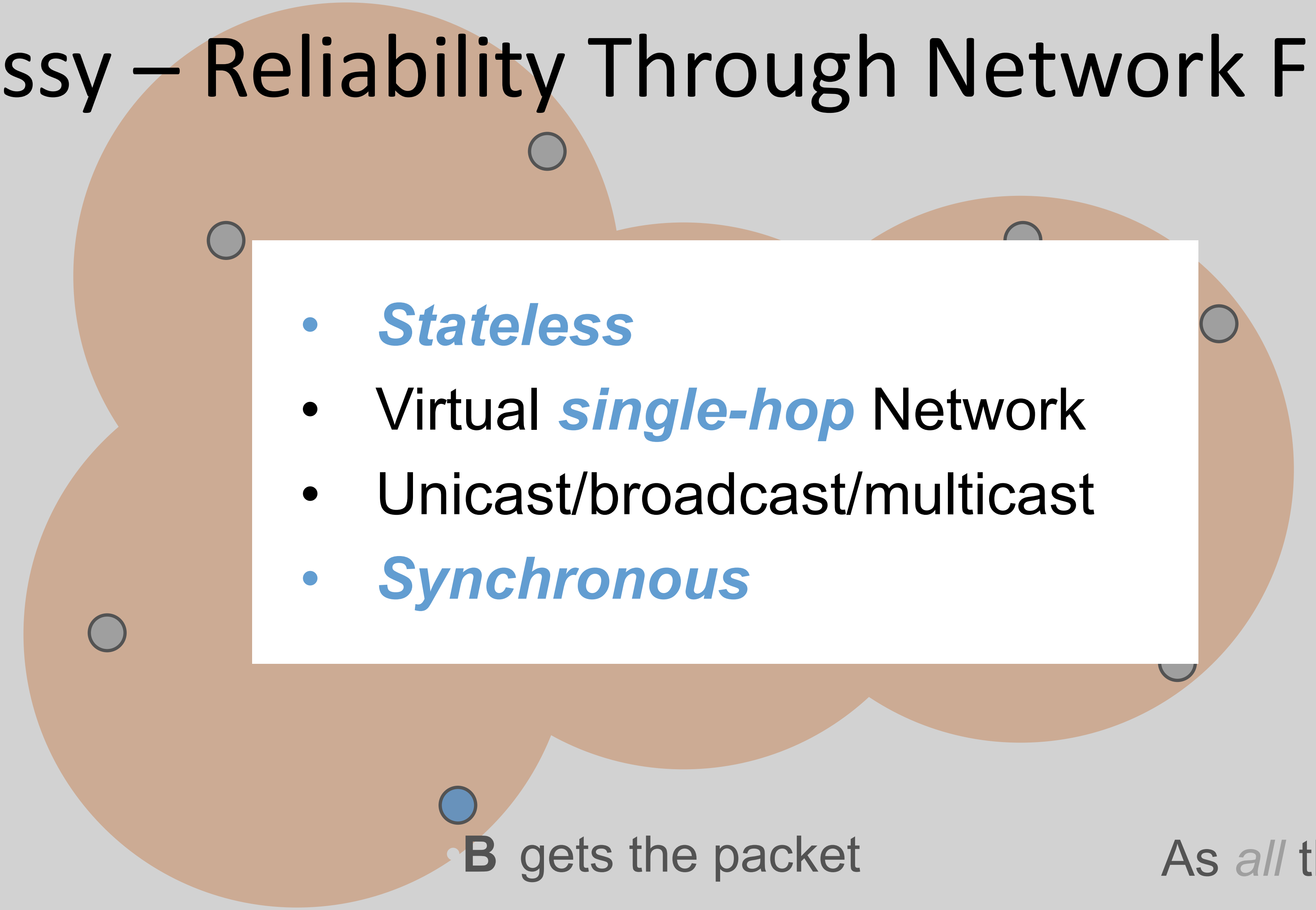


B gets the packet

As well as *all* the others!

Glossy – Reliability Through Network Flooding

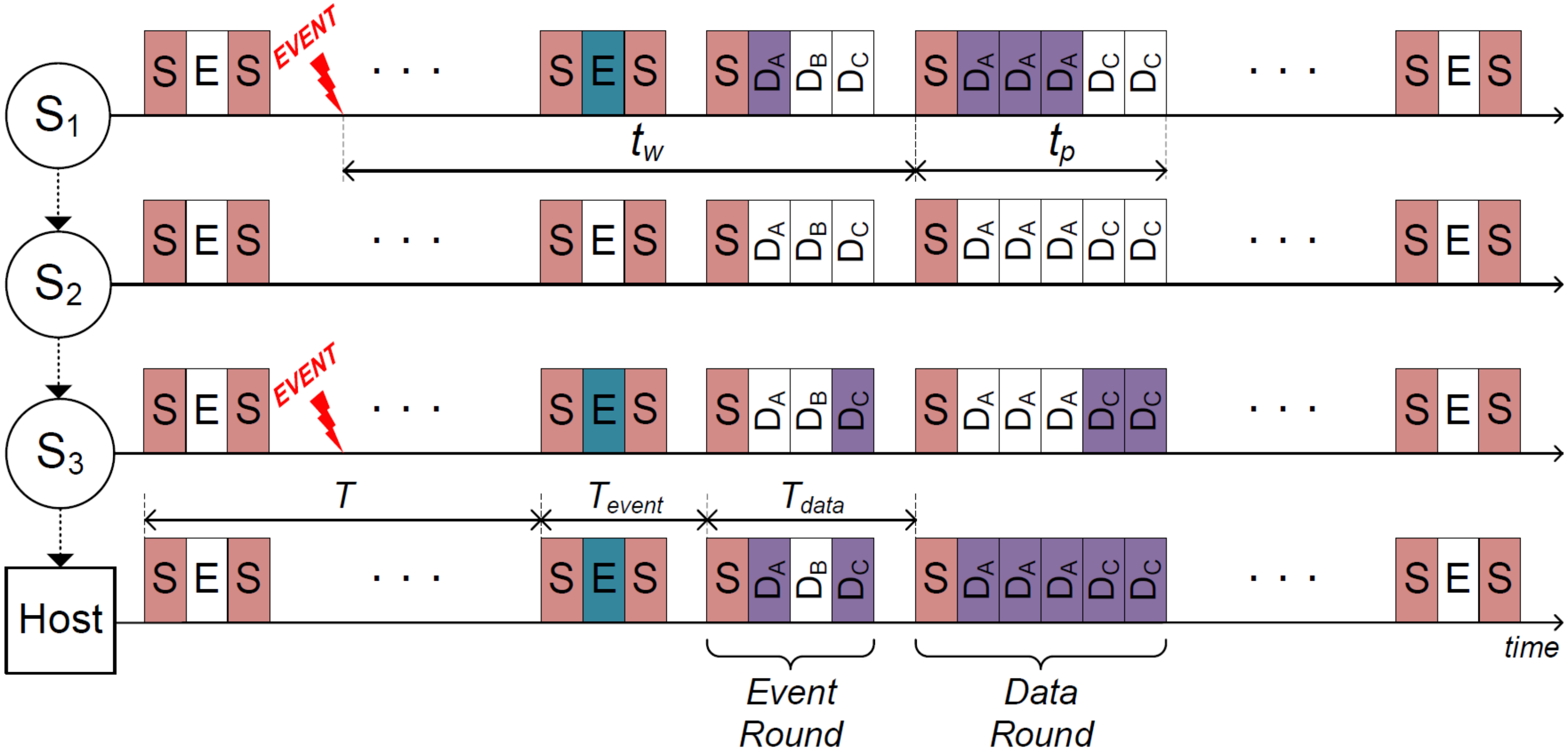


- ***Stateless***
- Virtual ***single-hop*** Network
- Unicast/broadcast/multicast
- ***Synchronous***

B gets the packet

As *all* the others!

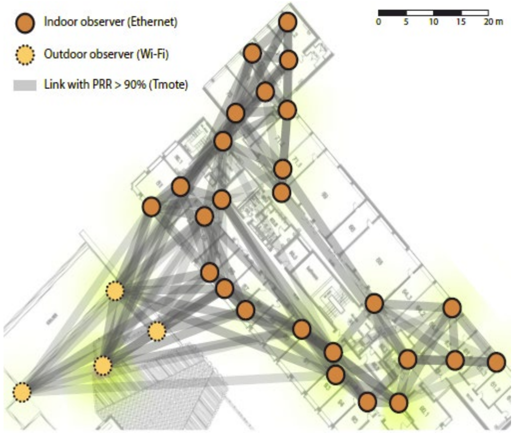
Subsecond Latencies Consuming only µW

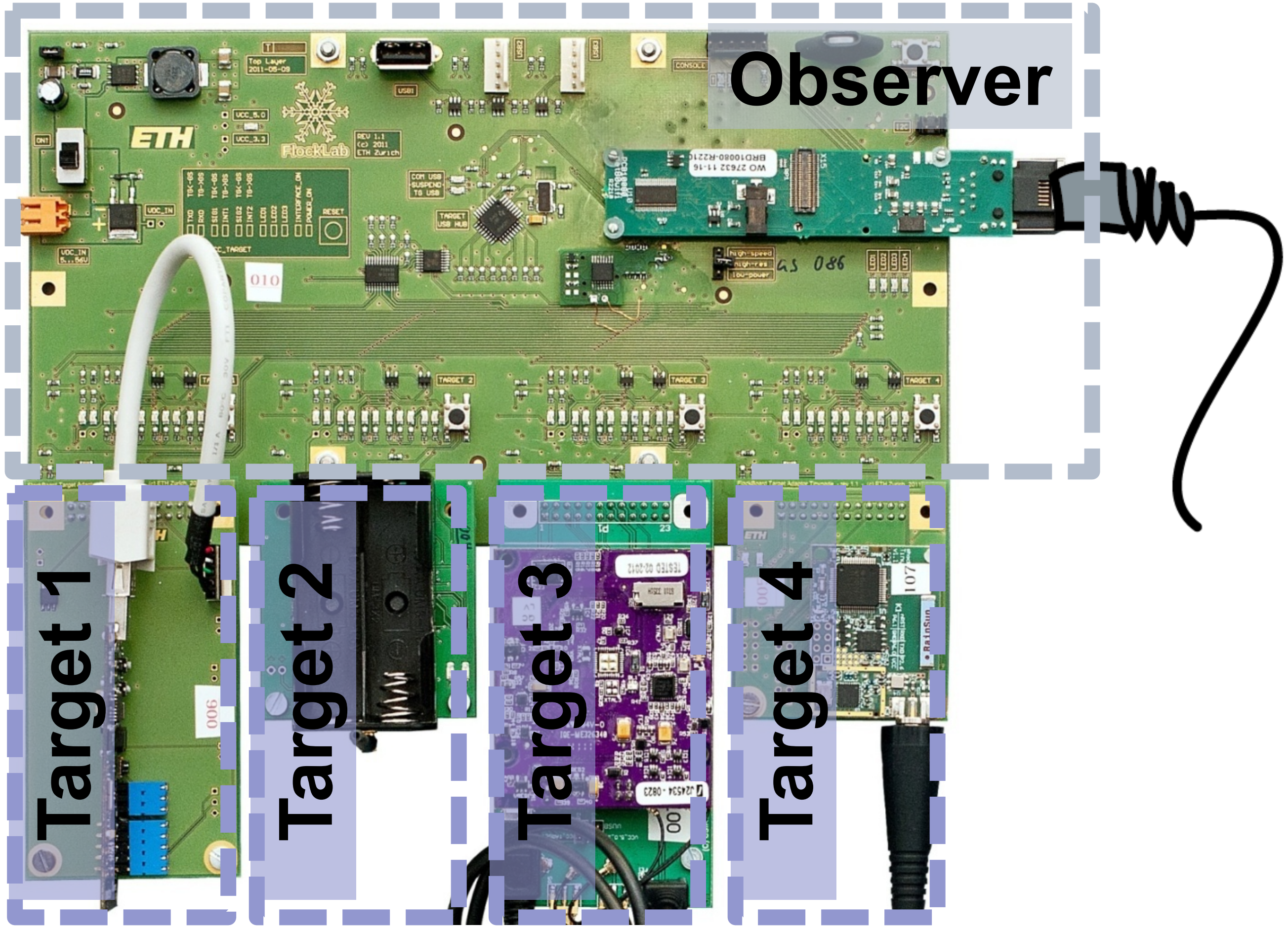


[F. Sutton, R. Da Forno, D. Gschwend, T. Gsell, R. Lim, J. Beutel, and L. Thiele. *The Design of a Responsive and Energy-efficient Event-triggered Wireless Sensing System*. EWSN, 2017.]

Scaling It Up In the Lab – The FlockLab Testbed

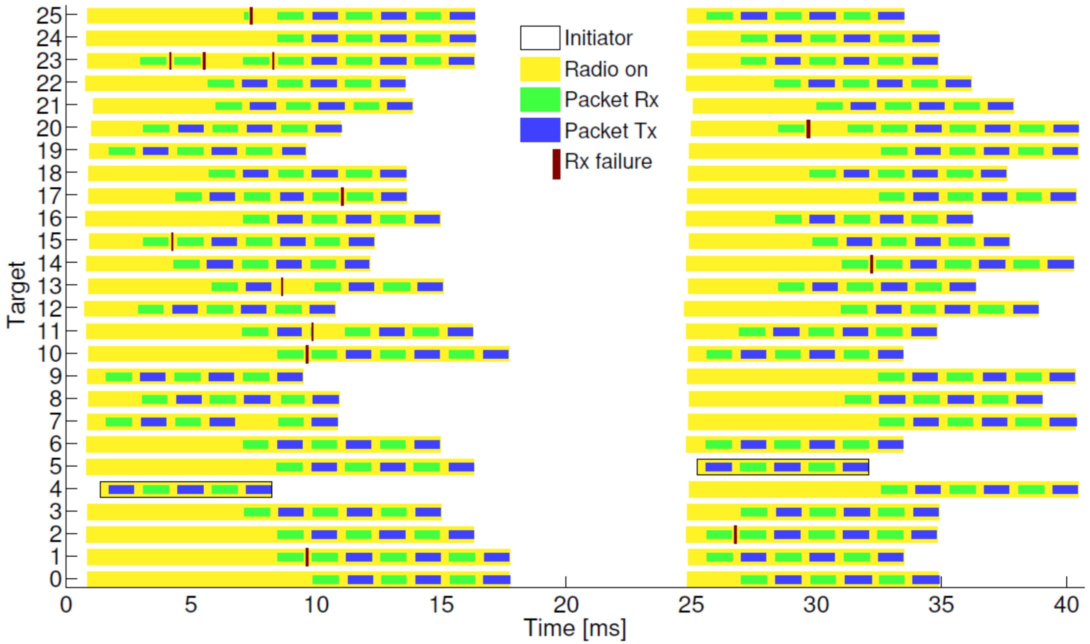
- 31 Node Testbed
  - In- & Outdoor
- Out-of-band backchannel
  - Ethernet/WLAN backbone
- 4 Target HW Architectures
- Logic and power tracing
- Synchronous Actuation



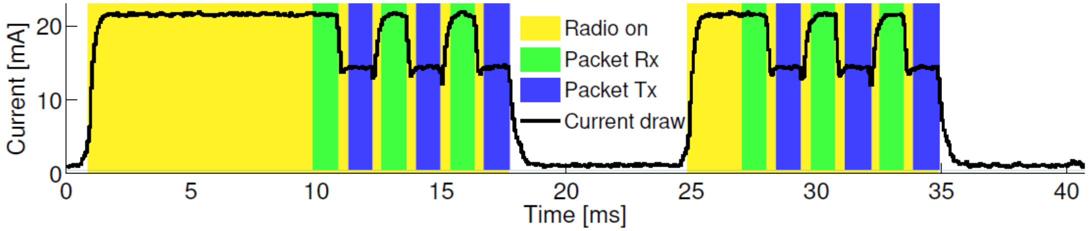


[R. Lim et al: *FlockLab: A Testbed for Distributed, Synchronized Tracing and Profiling of Wireless Embedded Systems.* Proc. IPSN 2013.]

Example Case: Synchronized Glossy Floods



(a) Radio states of 26 Tmote targets obtained from GPIO tracing.

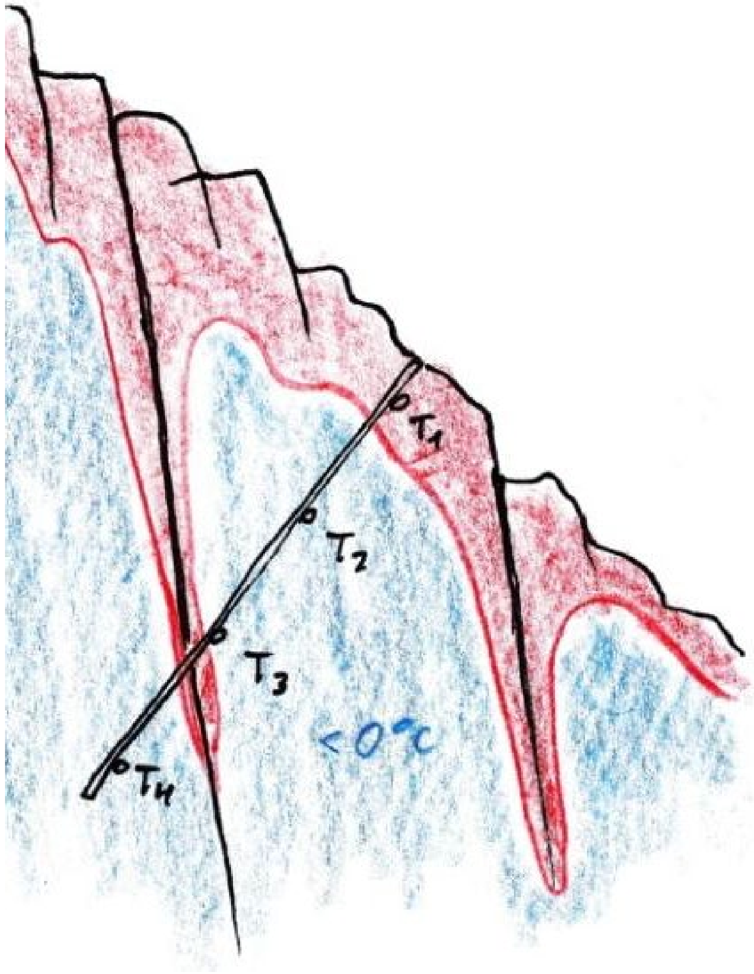


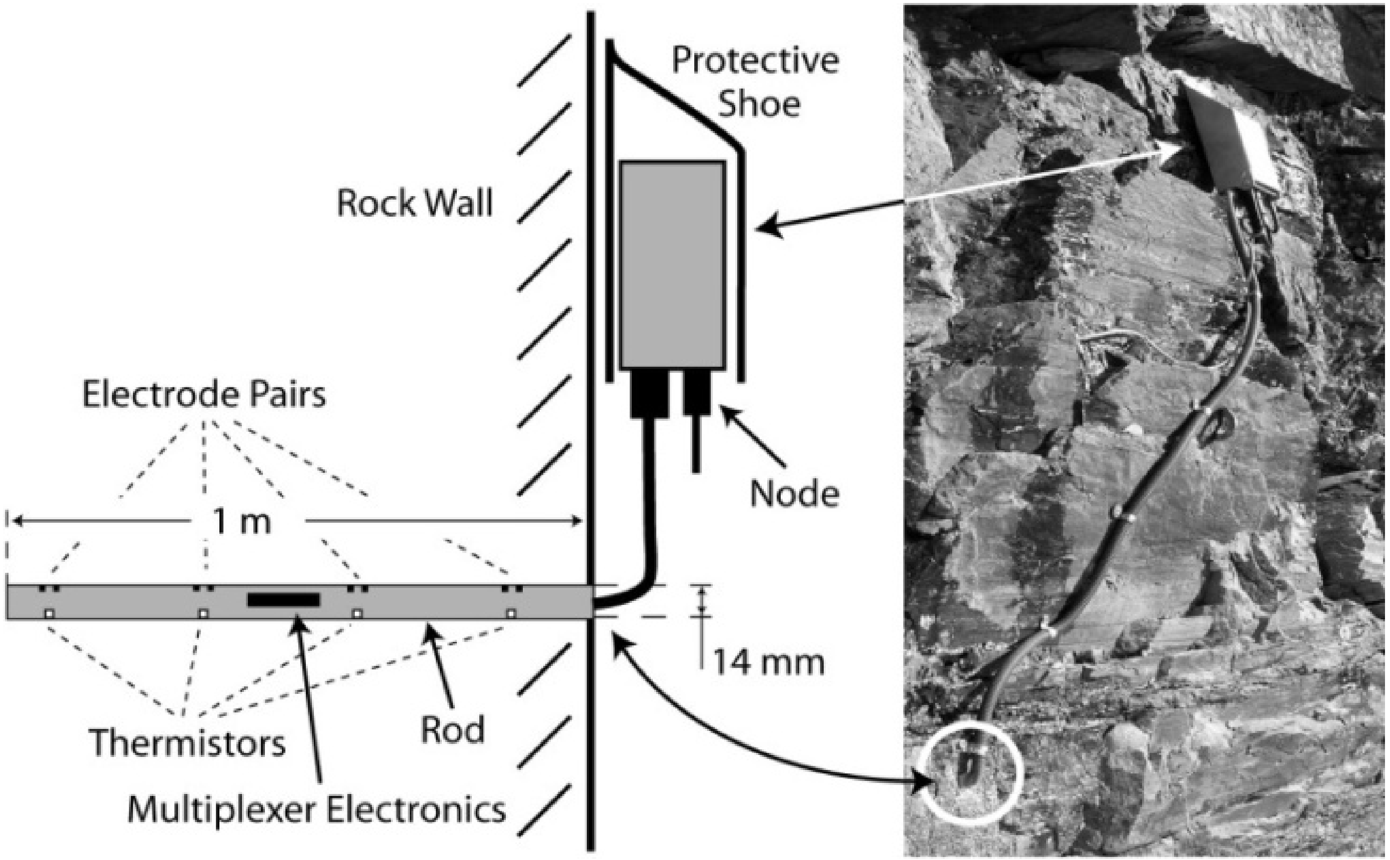
(b) Radio state and current draw of target 0 in (a).

[F. Ferrari et al: *Efficient Network Flooding and Time Synchronization with Glossy.* Proc. IPSN 2011. ★ Best Paper Award ★]

What is being investigated on the Matterhorn?

Understanding How Ice and Water Behaves in Rock Cracks

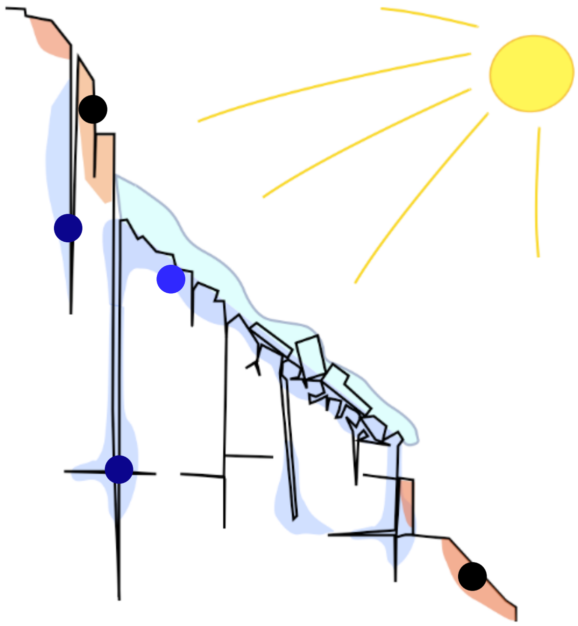




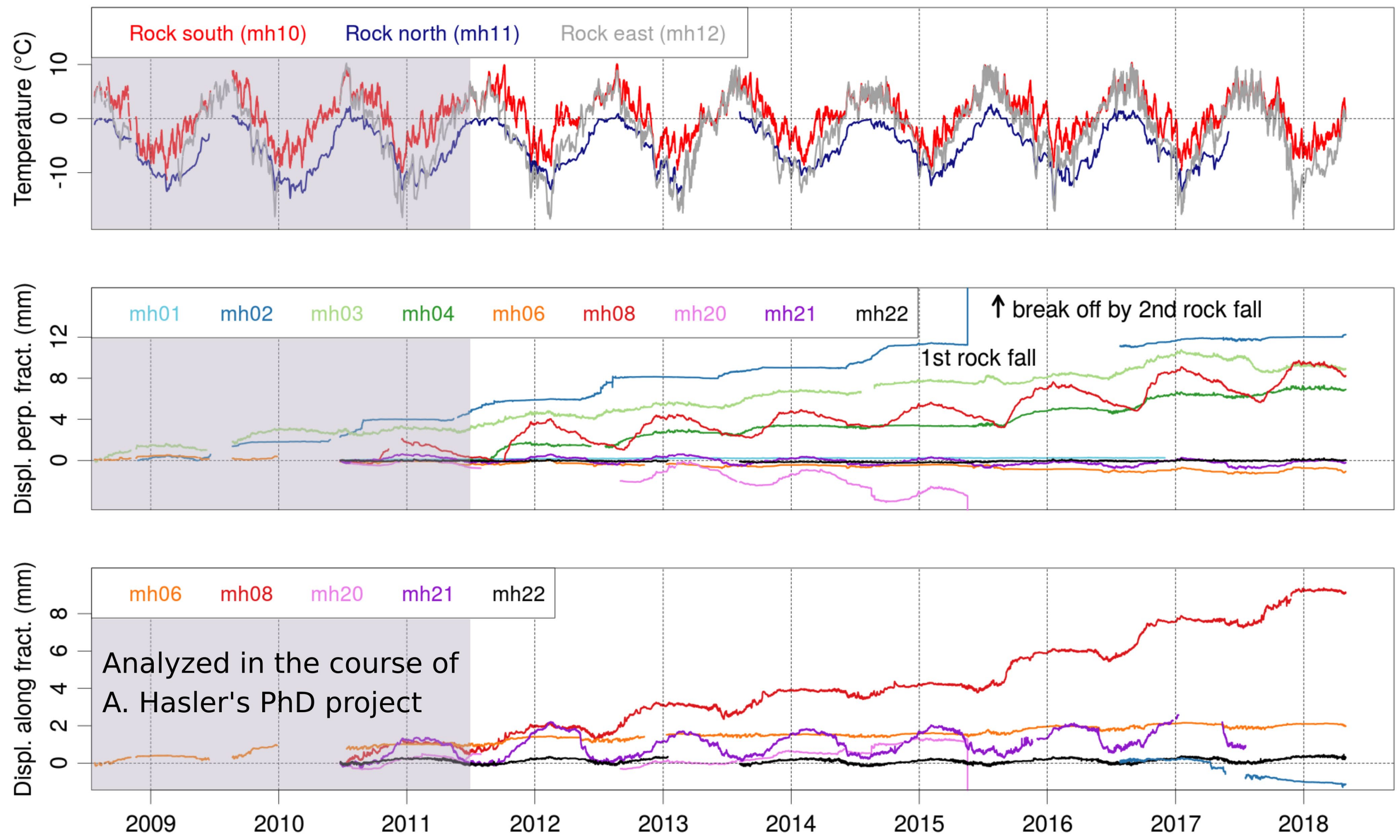
[A. Hasler, S. Gruber & W: Haeberli: *Temperature variability and thermal offset in steep alpine rock and ice faces*. The Cryosphere, 5, 977-988.]

Is Solid Ice in Fissures Acting as Glue or as a Lubricant?

What happens when mountain permafrost is thawing?

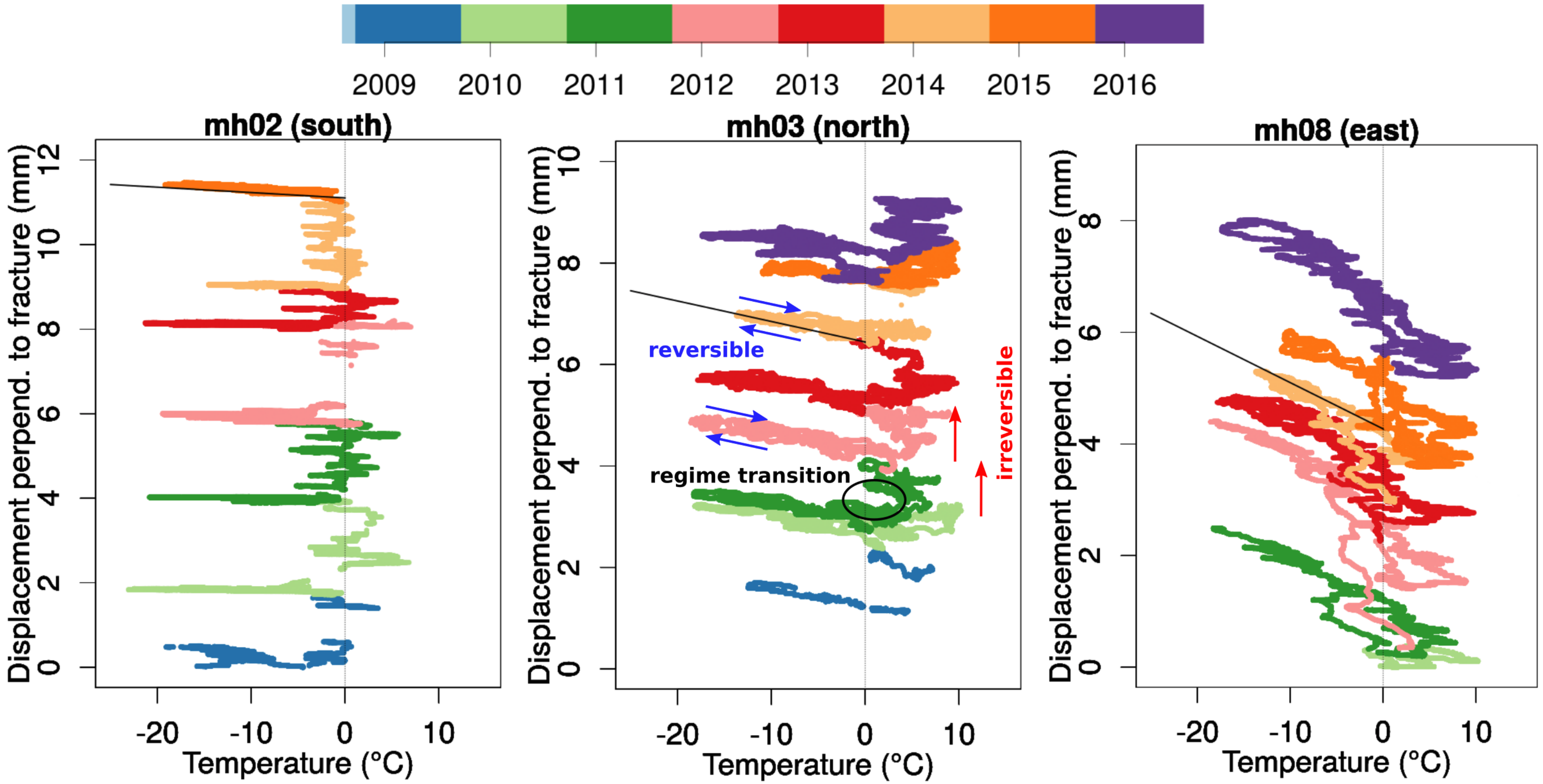


The clefts at Hörnliridge move in distinct patterns



[A. Hasler, S. Gruber and J. Beutel: *Kinematics of steep bedrock permafrost.* J. Geophys. Res., 117, F01016.
Weber, S., Beutel, J., Faillettaz, J., Hasler, A., Krautblatter, M., and Vieli, A.: *Quantifying irreversible movement in steep, fractured bedrock permafrost on Matterhorn (CH)*, The Cryosphere, 11, 567-583.]

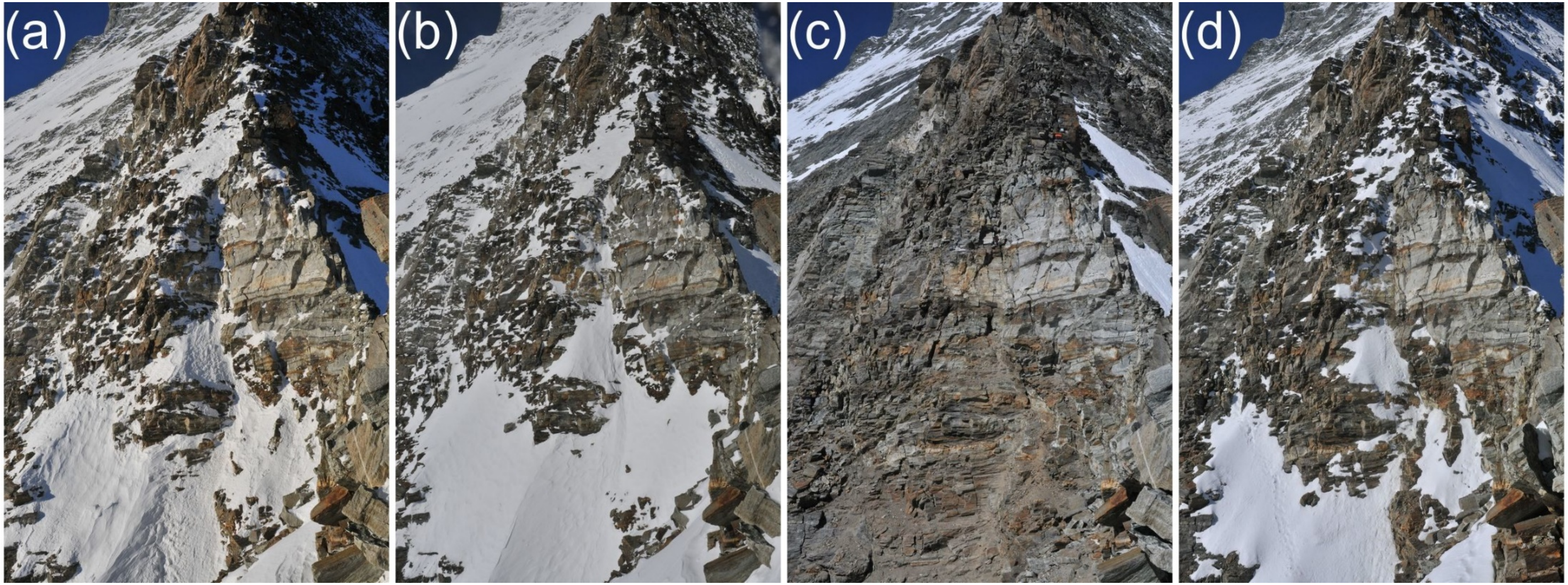
Learning from Freezing and Thawing



[Weber, S., Beutel, J., Faillettaz, J., Hasler, A., Krautblatter, M., and Vieli, A.: *Quantifying irreversible movement in steep, fractured bedrock permafrost on Matterhorn (CH)*, The Cryosphere, 11, 567-583.]

High-resolution Time Lapse Photography

- Stationary D-SLR camera with Wireless LAN data link since 2010




2009
C2


2014
C2

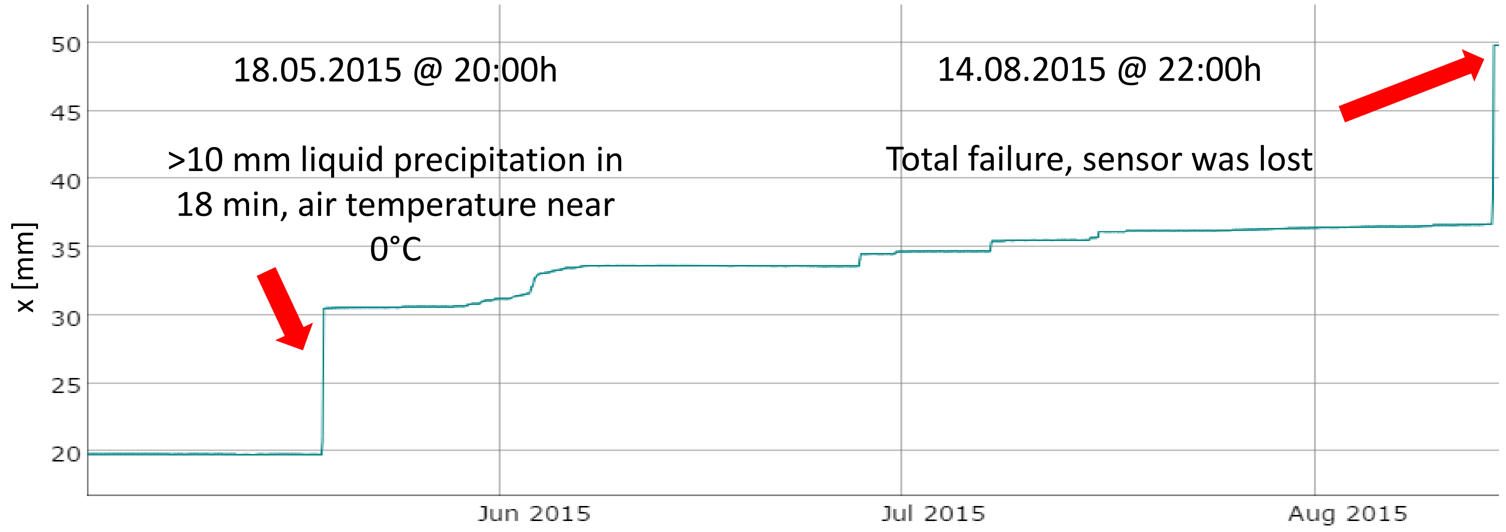
18.05.2015
C2


19.05.2015
C2

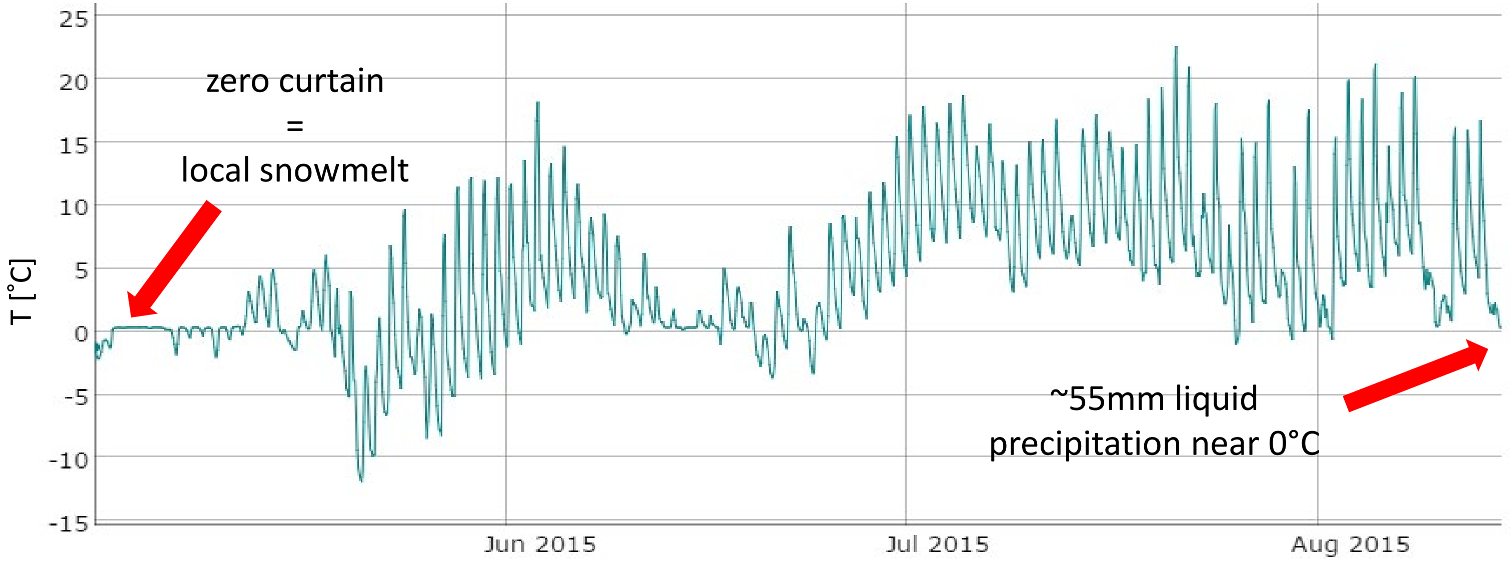

29.05.2015
C2

C2 Detachment Event Summer 2015

Cleft opening

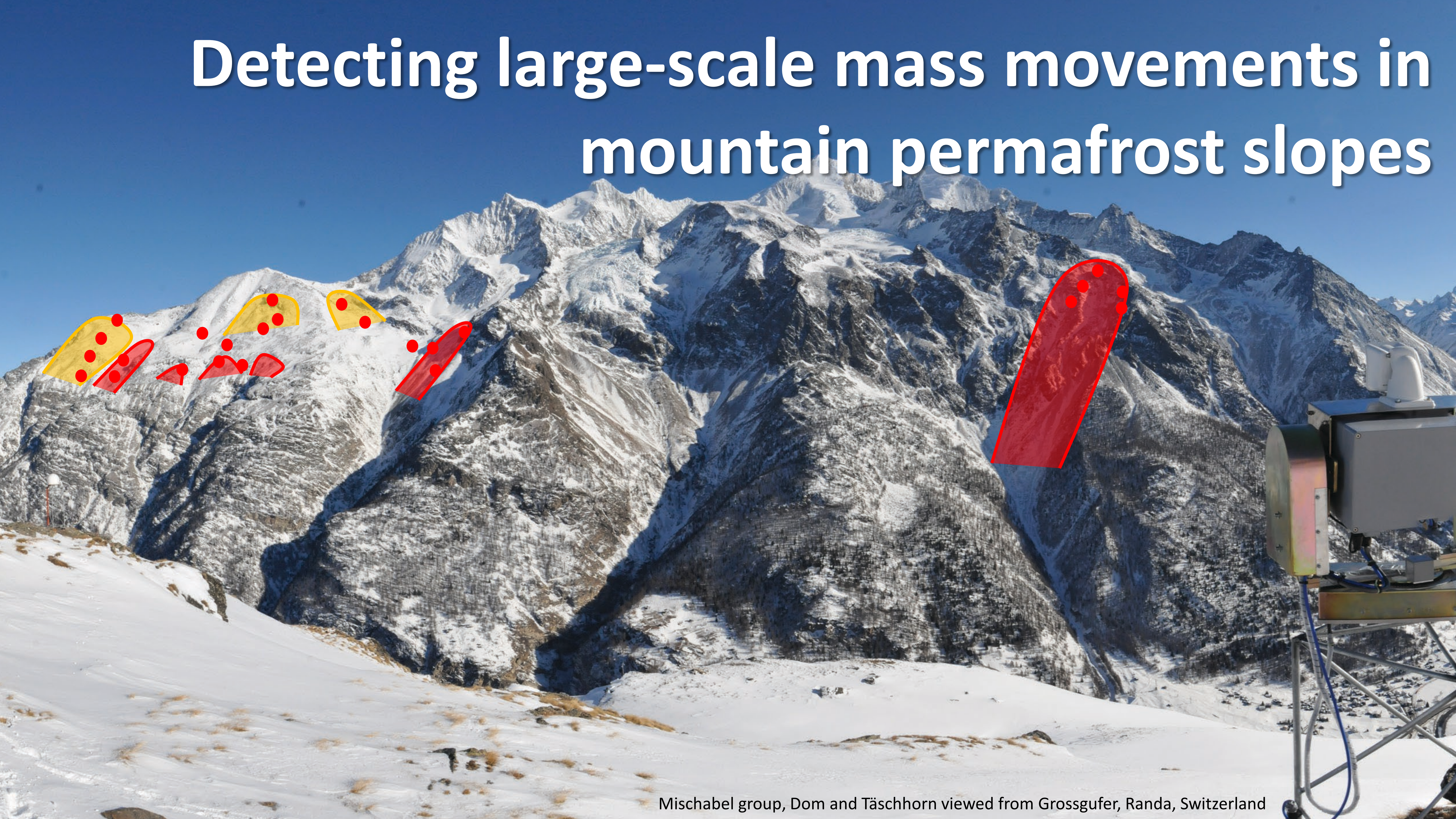


Rock temperature



Complex Sensing: Continuous L1-DGPS

Detecting large-scale mass movements in mountain permafrost slopes

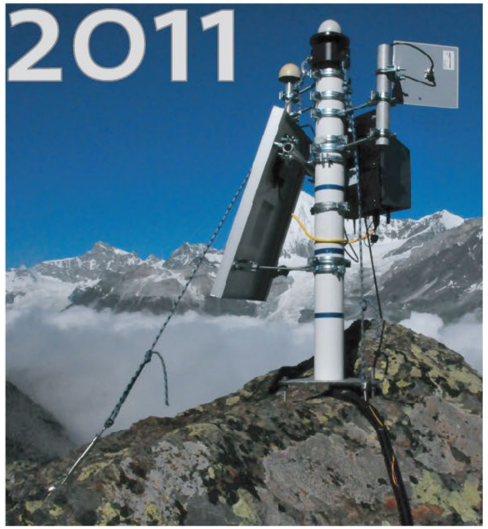


Mischabel group, Dom and Täschhorn viewed from Grossgufer, Randa, Switzerland

Wireless L1-GPS Sensors

GPS Logger

Large-scale,
early access data



GPS CoreStation

Experimentation, variable use

Wireless GPS Sensor

Fully integrated, low-power

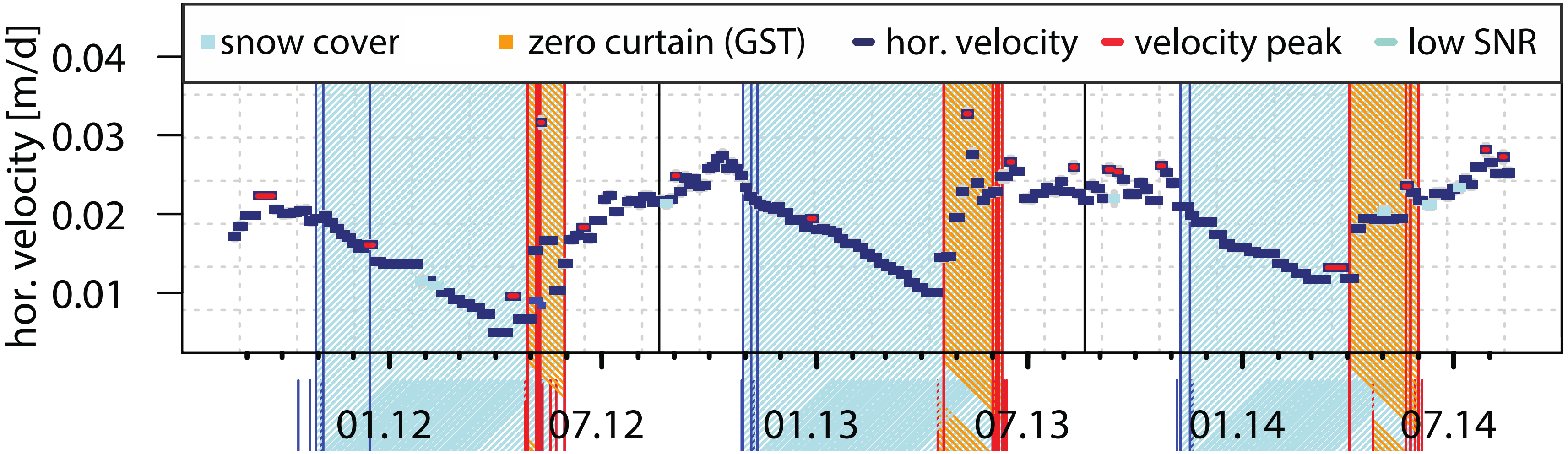
- Wireless communication
  - Wireless sensor network cluster
  - 868 MHz ultra low-power radios
  - Up to ~7km range
- Sensors
  - ublox LEA-6T L1-GPS
  - Trimble Bullet III active antenna
  - 2-axis SCA830 inclinometer
  - Ambient temp/hum/battery
- Standalone data logger functionality
  - Local 2GB data buffer
- Remote configurable
  - Duty-cycle (1-24h)
  - Sampling rate (30 sec)
- Data transfer in near real-time

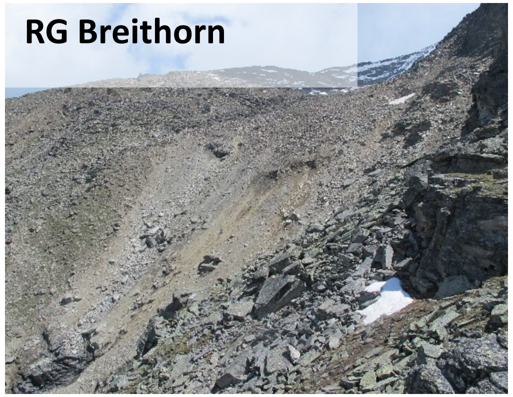
[J. Beutel et al: *X-Sense: Sensing in Extreme Environments*. Proc. Design, Automation and Test in Europe (DATE 2011)

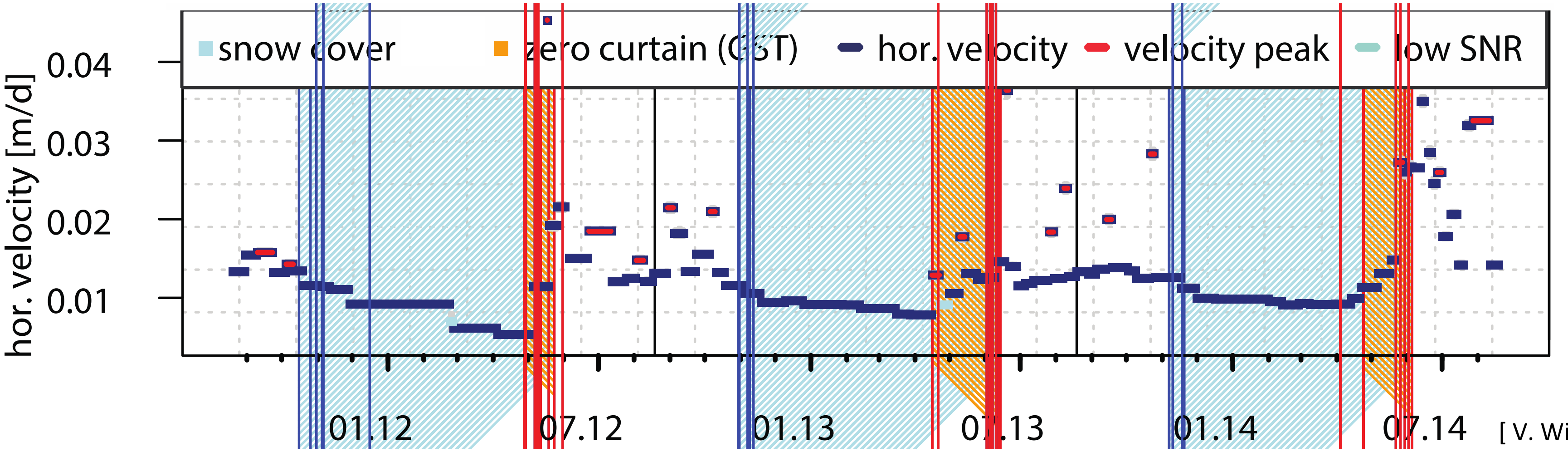
V. Wirz et al: *Temporal characteristics of different cryosphere-related slope movements in high mountains*. Proc. Second World Landslide Forum, 2011.

B. Buchli, F. Sutton and J. Beutel: *GPS-equipped Wireless Sensor Network Node for High-accuracy Positioning Applications*. Proc. EWSN 2012.]

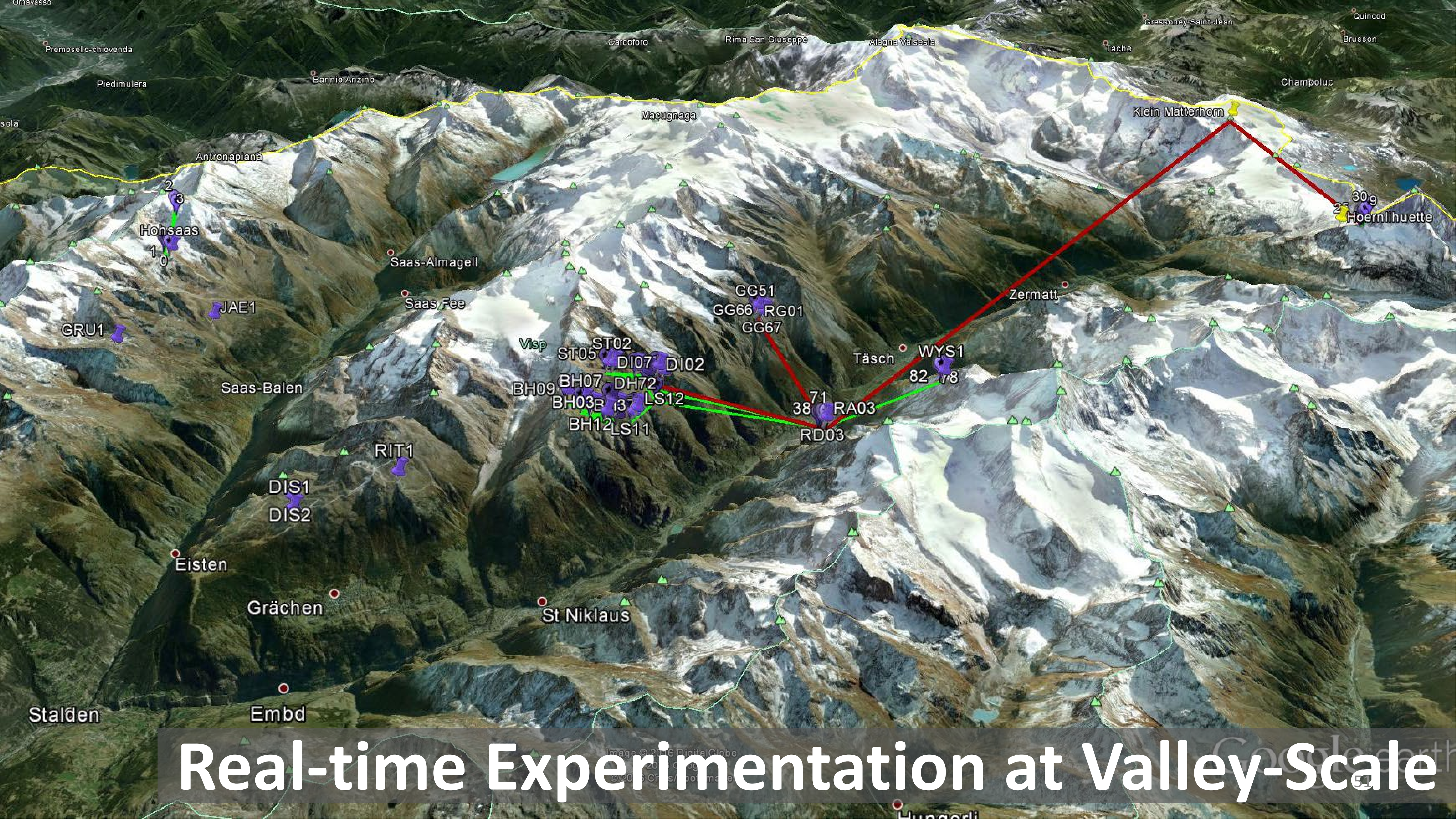
Movements In the Context of Meteorological Factors







[V. Wirz et.al.: *Short-term velocity variations at three rock glaciers and their relationship with meteorological conditions.* Earth Surface Dynamics, Vol 4, p. 103-123, January 2016]

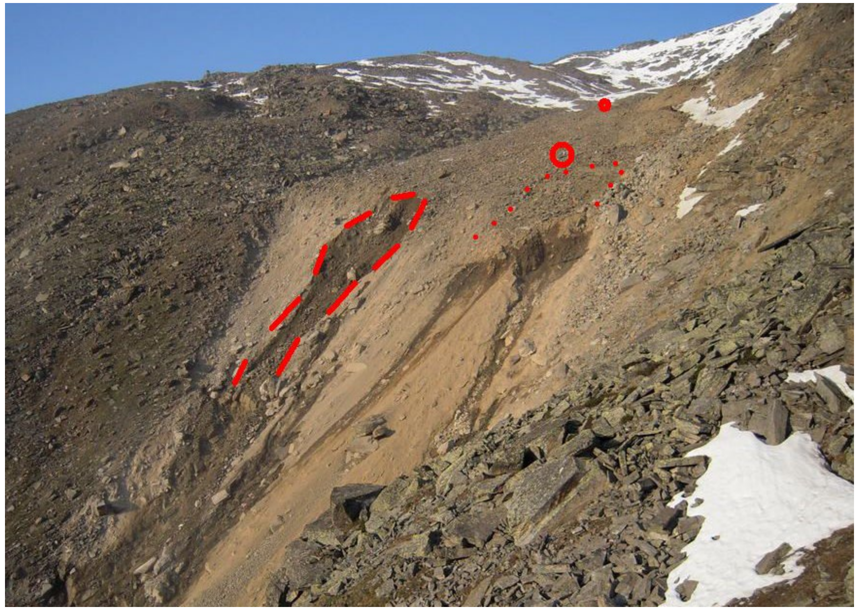


Real-time Experimentation at Valley-Scale

Access to Real-time Data for Early Warning Decision-making

Bielzug Debris Flow, June 2013

- Critical natural hazard event
- Herbriggen partial village evacuation
- Closure of road and railway to Zermatt



[Bielzug/Breithorn rock glacier, C. Graf, WSL, Switzerland]

Längschnee, Fall 2014

- Constructive measures securing rock boulders above Herbriggen
- Extension of sensor coverage in collaboration with authorities

[Willi Gitz, GFS, Stalden, Switzerland]

Technology Transfer
PERMOS Continuous GPS Pilot

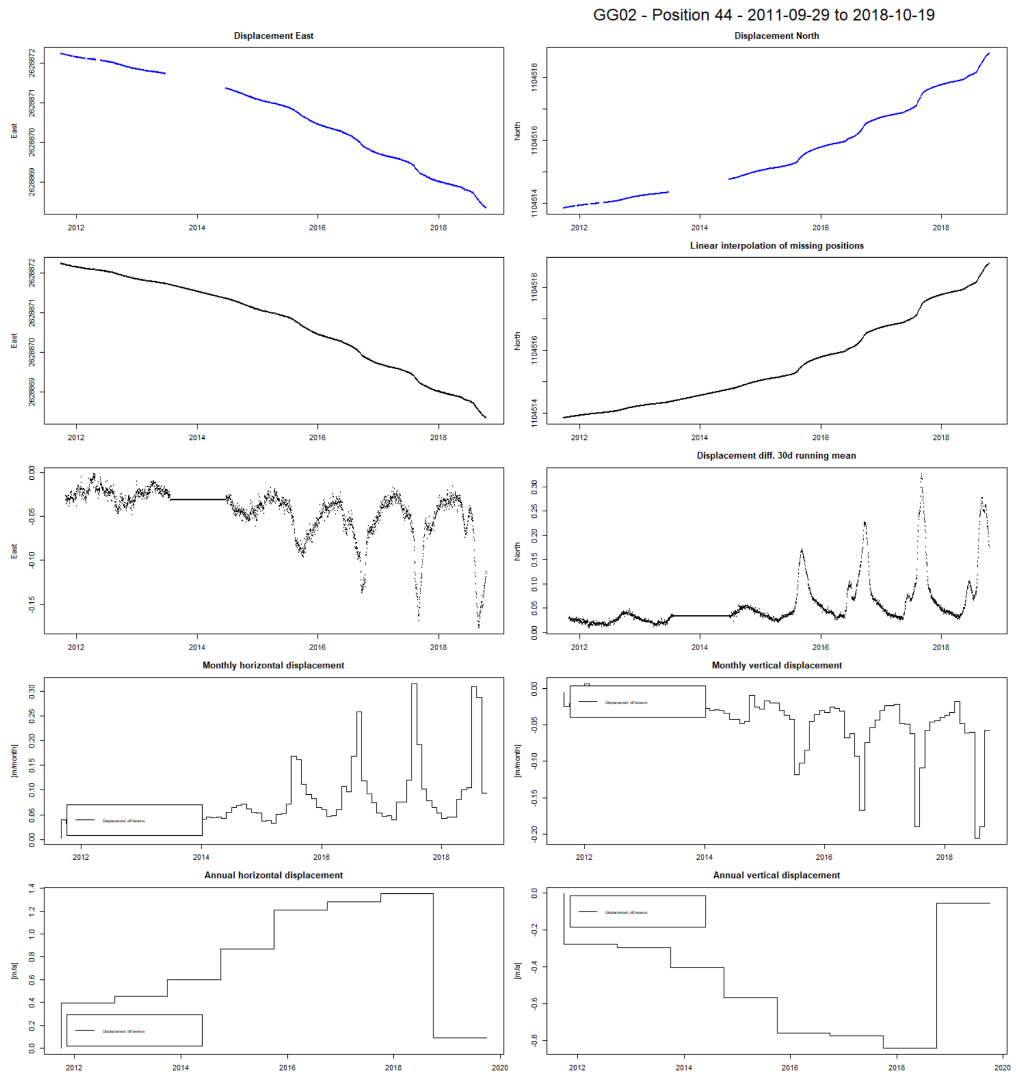
PERMOS Swiss Permafrost Monitoring Network

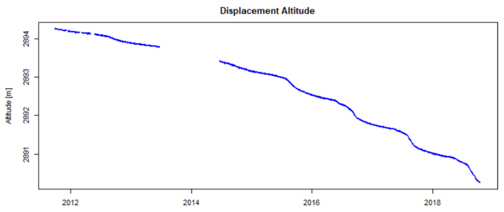
- Pilot program to make L1-DGPS sensors developed in a research project available to PERMOS partner on their field sites
- First sensor installation in summer 2012, extensions in 2014, 2015, 2016
  (Valais: Herbriggen Bielzug, Breithorn + Längschnee, Grächen Distelhorn + Ritigraben, Saas-Balen Gruben + Jäggihorn, Wysse Schije, Randa Grossgufer)

PERMOS site Largario rock glacier, Sept. 2014

Wysse Schije avalanche protection galleries, Randa, Switzerland

Active Measures: Randa, VS, June 2018





WALLIS | Walliser Bote | Samstag, 30. Juni 2018 | 3

Gefahr. Der ausserordentliche Grossblock befand sich an der Front des Blockgletschers Grabengufer und drohte in Richtung Randa abzustürzen. FOTOS WB/ANDREA SOLTERMANN

Naturgefahren | Instabile Gesteinsmassen auf dem Blockgletscher Grabengufer drohten in Richtung Randa abzugehen

Tauender Permafrost lockert Fels

RANDA | Oberhalb von Randa ist am Freitagabend ein Gesteinsblock in der Grösse zweier Chalets vorsorglich gesprengt worden. Aus Sicherheitsgründen mussten 211 Personen aus 76 Häusern in Randa diese während der Sprengung verlassen.

NORBERT ZENGAFFINEN

Der Blockgletscher Grabengufer oberhalb von Randa, der sich auf einer Höhe von circa 2850 Meter über Meer an der Nordwestflanke des Grabenhorns befindet, ist ein steter Unruheherd. «Am Fuss dieses kleinen Gletschers liegen sehr viele Felsblöcke in steilem Gebiet. Wegen der steten Talwärtsbewegung des Gletschers werden auch die Felsblöcke instabil. Gehen sie ab, können sie bis in den Talgrund rollen», erklärt Kantonsgeologe Raphaël Mayoraz gegenüber dem «Walliser Boten».

Computersimulationen zeigten Restrisiko

Zu solchen kleineren Abgängen sei es in den zurückliegenden Jahren aufgrund von tauendem Permafrost schon mehrere Male gekommen. «Nach der Versetzung der neuen Europabrücke im Grabengufer stellen solche kleineren Ereignisse keine Gefahr für die Passanten der Hängebrücke dar. Bei dem grossen Block von rund 2000 Kubikmeter Grösse, der am Freitag gesprengt wurde, bestand aber die Gefahr, dass er beim absehbaren spontanen Abgang in Richtung Randa gerollt wäre. Dieses Restrisiko, das Computersimulationen aufzeigten, machte eine Sprengung nötig», so der Kantonsgeologe.

Schwierige Vorbereitungsarbeiten

Die Vorbereitungen zur Sprengung dauerten rund drei Wochen. Diese wurden von der Sprengtechnik GFS aus St. Niklaus ausgeführt. Eine spezielle Herausforderung für die Felssicherungsspezialisten. «Der Grossblock befand sich auf einer Rutschmasse von einigen Zehntausend Kubikmetern. Die Arbeiter, welche in den letzten Wochen rund 20 Böhrlocher bis zu einer Tiefe von 20 Meter in den Block trieben, waren der ständigen Gefahr ausgesetzt, dass der Block spontan abgeht», erklärt Geschäftsführer und Sprengmeister Willy Gitz.

Wegen dieser latenten Gefahr sei ein Überwachungssystem eingerichtet worden, das die Arbeiter übers Handy gewarnt hätte, wenn sich der Block innerhalb einer Stunde mehr als einen Zentimeter talwärts bewegt hätte. «Allerdings ist der Handy-Empfang auf dieser Höhe nicht immer gewährleistet, was die Aufgabe nicht einfacher machte.» Am Freitag schliesslich konnten die Bohrlöcher von drei Zentimeter Durchmesser mit insgesamt 1000 Kilogramm Sprengstoff befüllt werden. Dieser wurde um 19.00 Uhr abends gezündet und der Fels erfolgreich gesprengt. Der anschliessende Rekognoszierungsflug über das Gebiet zeigte auf, dass die Sprengung den Verlauf nahm, den man sich erhoffte.

Häuser evakuiert

Durch die Sprengung des 5000 Tonnen schweren Felsblocks entstand Steinschlaggefahr oberhalb von Randa. «Deshalb musste vorgängig eine Sperrzone definiert werden, welche neben den Wanderwegen auch einen Teil des Dorfes betraf. Am Freitag mussten deswegen in Randa 217 Personen aus insgesamt 79 Häusern evakuiert werden. Ab 17.00 Uhr mussten die betroffenen Personen ihre Häuser verlassen und sich bis um 20.00 Uhr in einem sicheren Gebiet oder in der Mehrzweckhalle aufhalten», erklärt Daniel Roten, Gemeindepräsident von Randa. Dabei standen 36 Feuerwehrleute, 27 Zivilschützer, drei Bergführer und Polizisten unter der Leitung von Krisenstab-Chef Andreas Brantschen.

Gefährlich. Die Vorbereitungsarbeiten zur Sprengung des Grossblocks waren für die Spezialisten nicht ungefährlich.

Informierten. Leo Jörger, Kantonsgeologe Raphaël Mayoraz, Gemeindepräsident Daniel Roten und Krisenstab-Chef Andreas Brantschen (von links).

Evakuation. Feuerwehrmann Sebastian Brantschen schaut auf dem Aushang nach, ob die angeordnete Evakuation befolgt wurde.

Complex Sensing: Acoustic Emissions and Micro-Seismics

Frequency Profiling Experiment at Matterhorn

AS = acoustic sensor

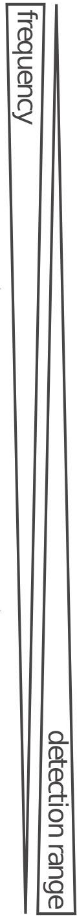
- low: 5 – 30 Hz
- high: 35 – 100 kHz
- triggered sampling

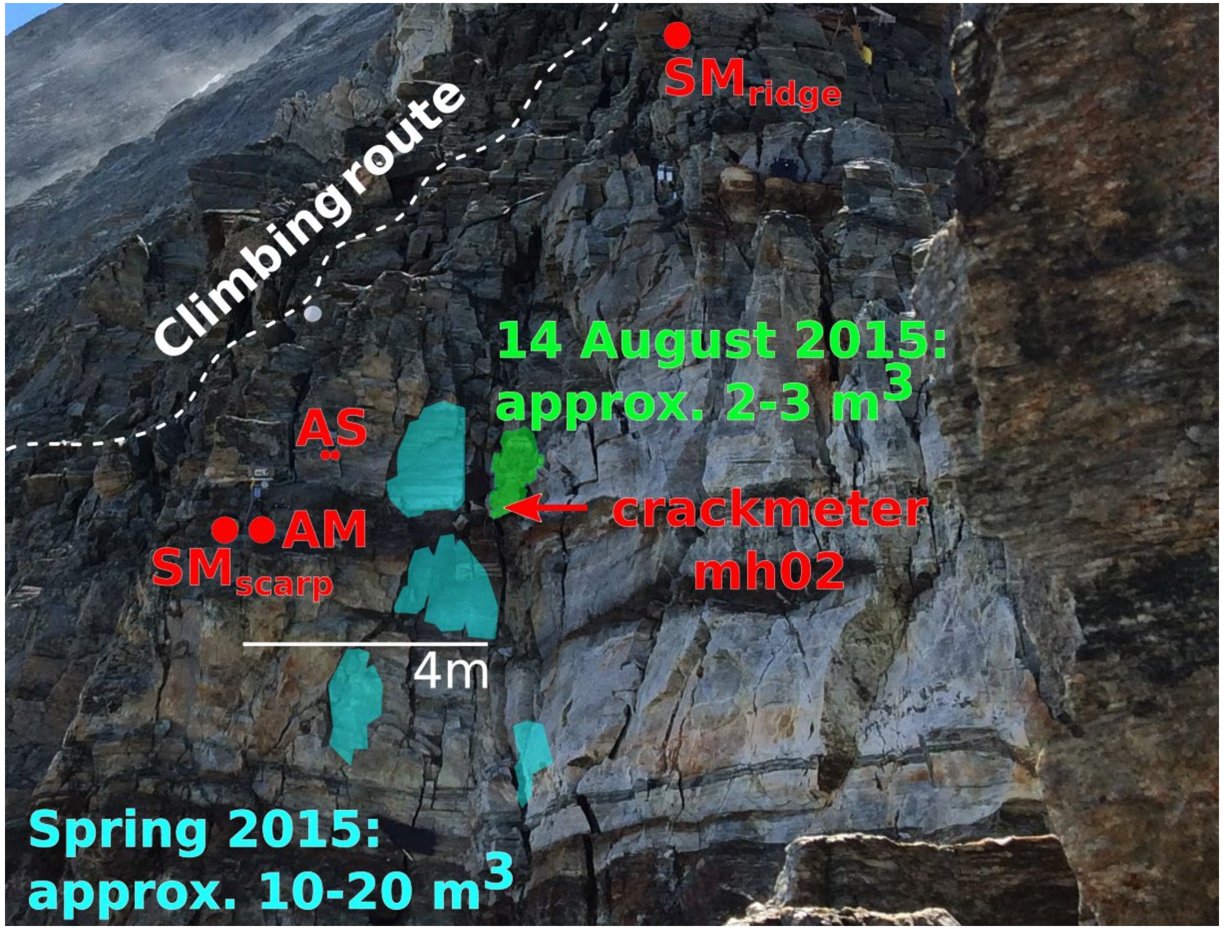
AM = accelerometer

- 10 – 6000 Hz
- continuous sampling

SM = seismometer

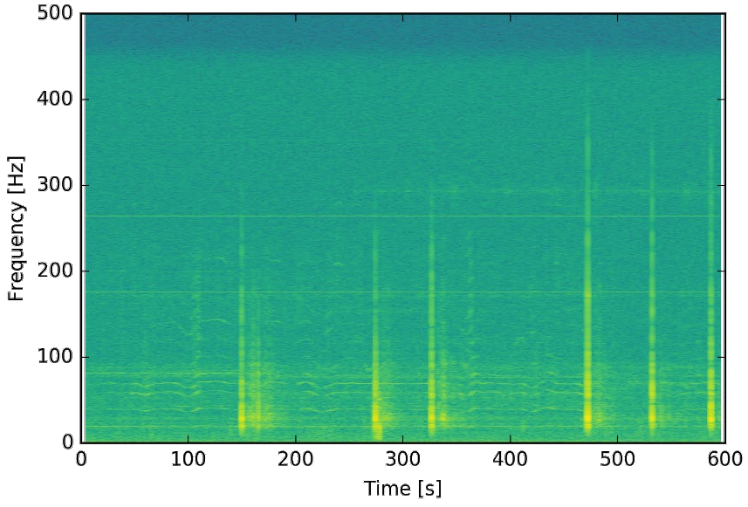
- 1 – 100 Hz
- continuous sampling



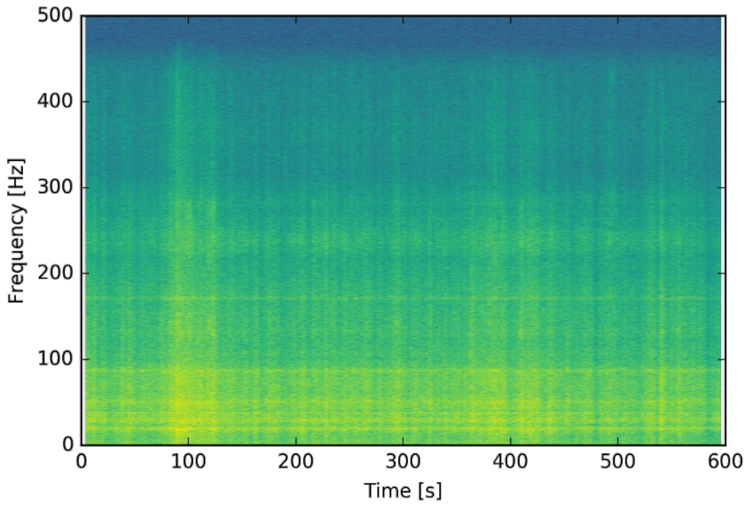


Acoustic and Seismic Event Characterization

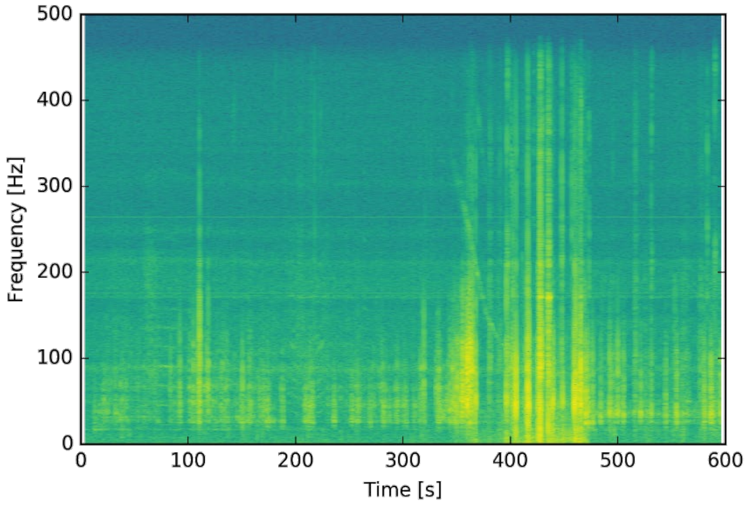
- Temporal and spectral patterns define acoustic and seismic events
- Example: Geophone waveforms



Rockfall



Strong Wind

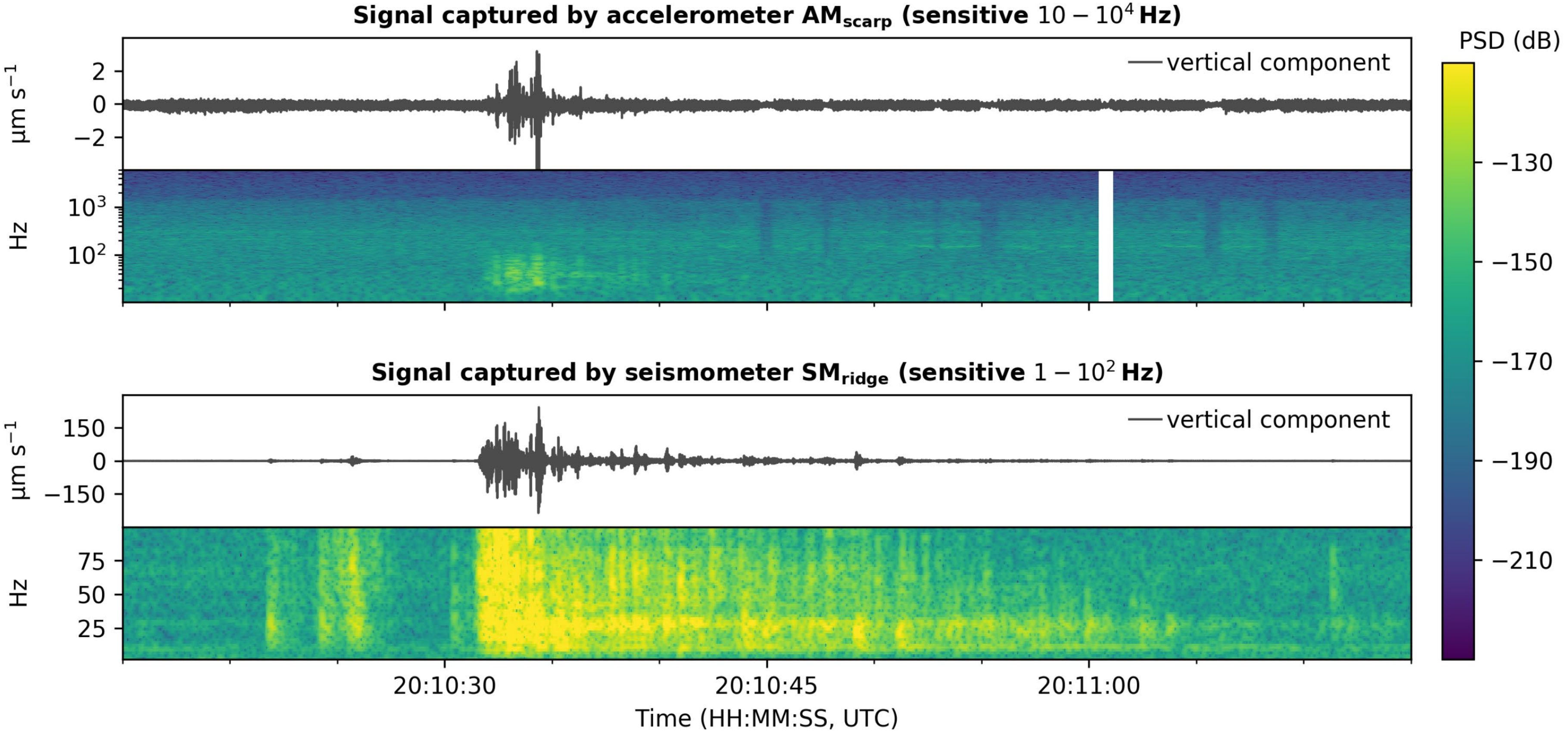


Mountaineers

[M. Meyer, J. Beutel and L. Thiele: *Unsupervised Feature Learning for Audio Analysis.* Proc. Conf. Learning Representations, April 2017.

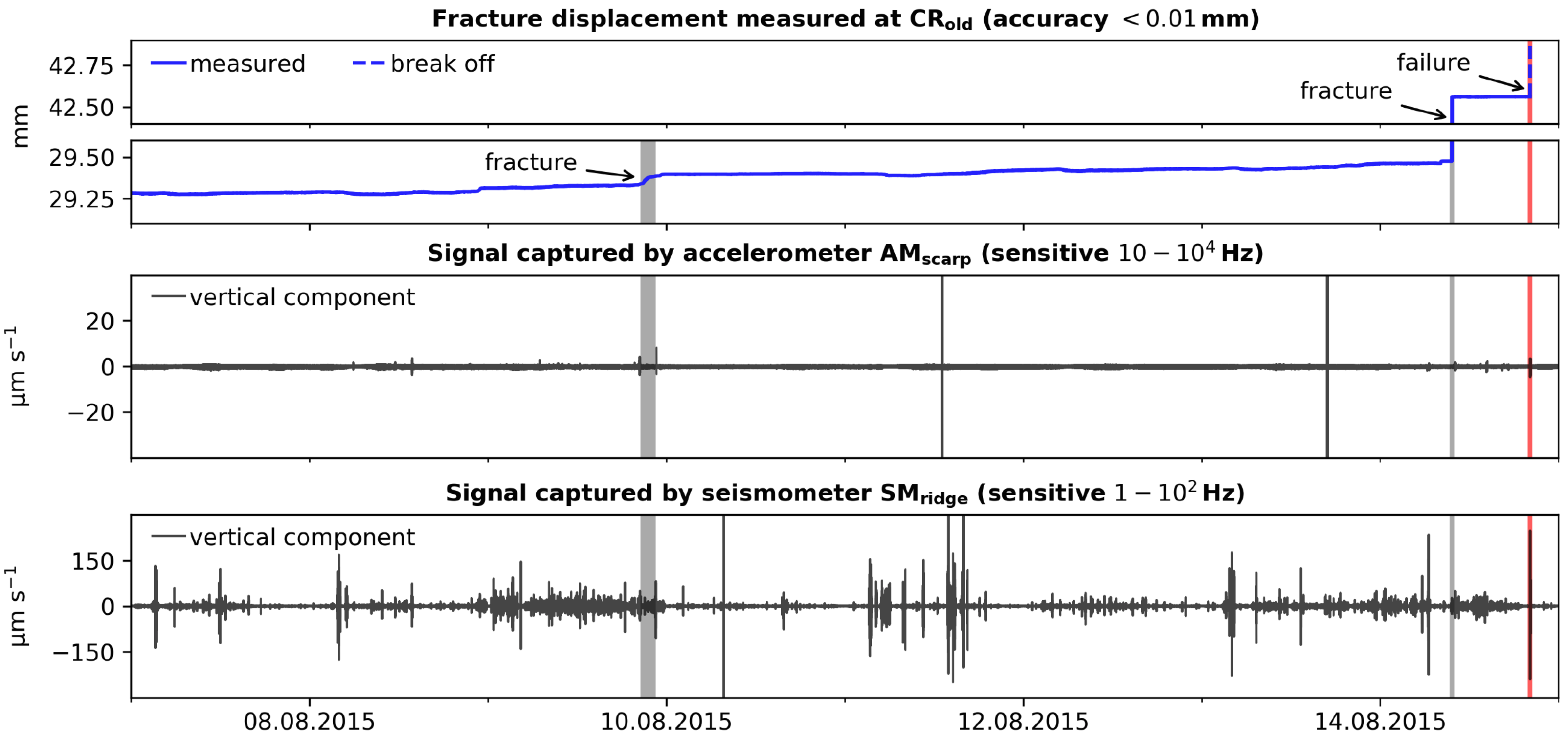
Meyer, M., Weber, S., Beutel, J., and Thiele, L.: *Systematic Identification of External Influences in Multi-Year Micro-Seismic Recordings Using Convolutional Neural Networks*, Earth Surf. Dynam. Discuss., in review, 2018.]

Detecting Fracture Events in Seismic Signals



[S. Weber, J. Faillettaz, M. Meyer, J. Beutel, A. Vieli: *Acoustic and micro-seismic characterization in steep bedrock permafrost on Matterhorn (CH)*. Journal of Geophysical Research: Earth Surface, 2018.]

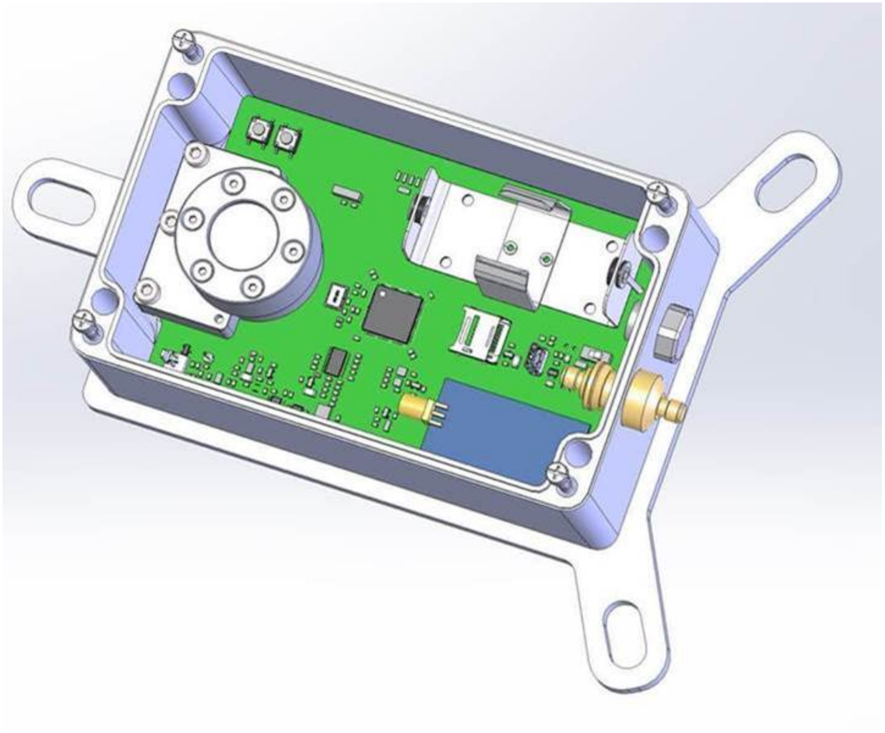
Combining Different Signals in the Analysis

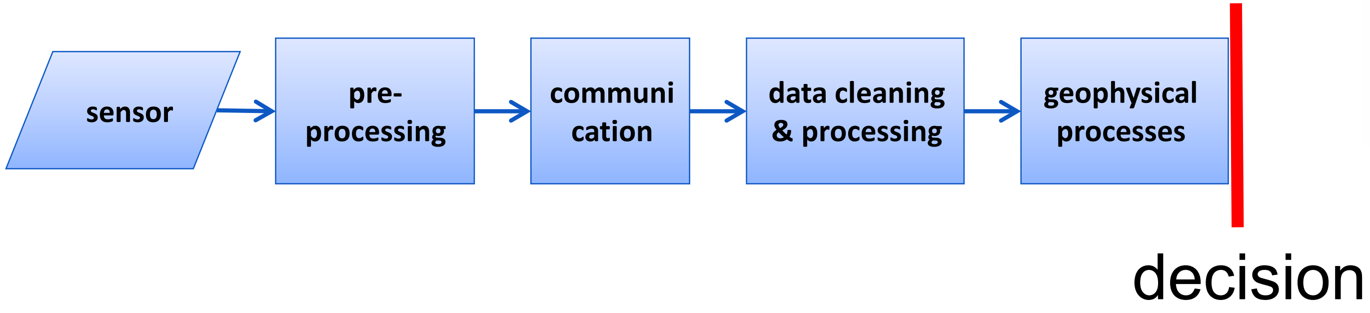


Complex Sensing: Reducing the Data Deluge

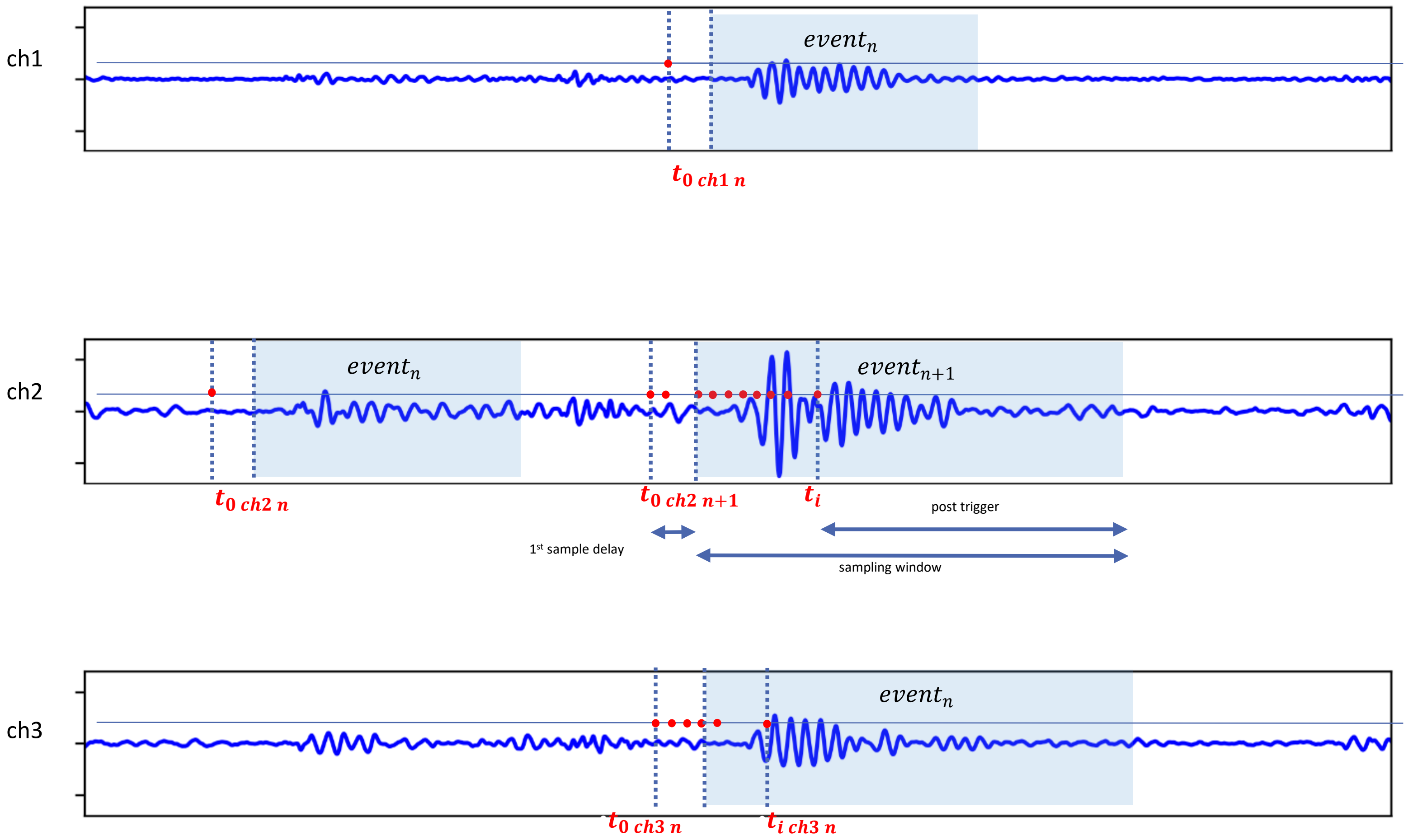
“Intelligent” Triggered Sensors

- Moving the decision into the sensor
- Asynchronous operation, jitter
- Data: Timing and event characteristics
- Co-detection over many sensors
- Less data, less power



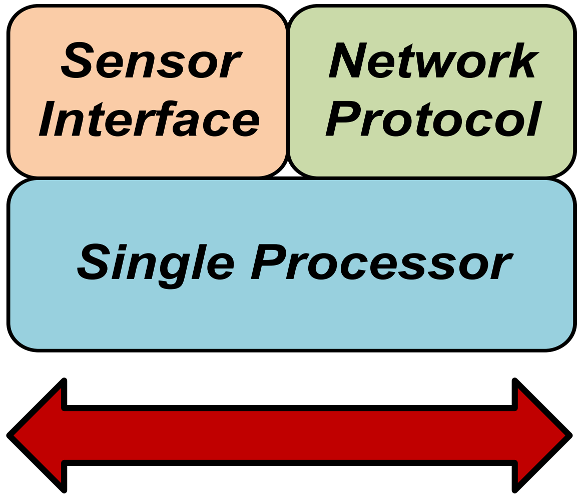


From Spectral Analysis to Event-based Statistics



Wireless Sensing Platform 2.0

Classic Architecture



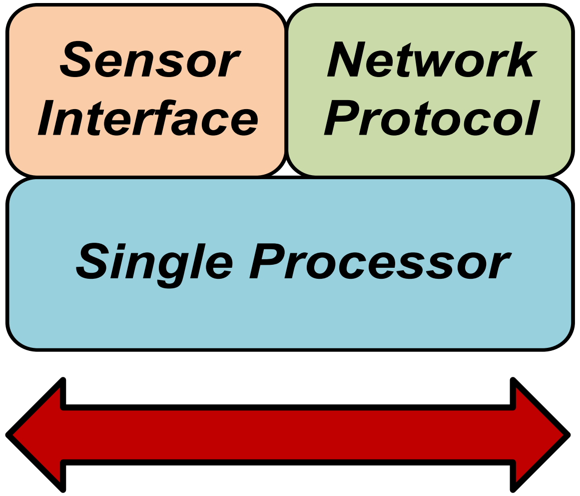
memory interference

time-interference

no fine-grained power control

Wireless Sensing Platform 2.0

Classic Architecture

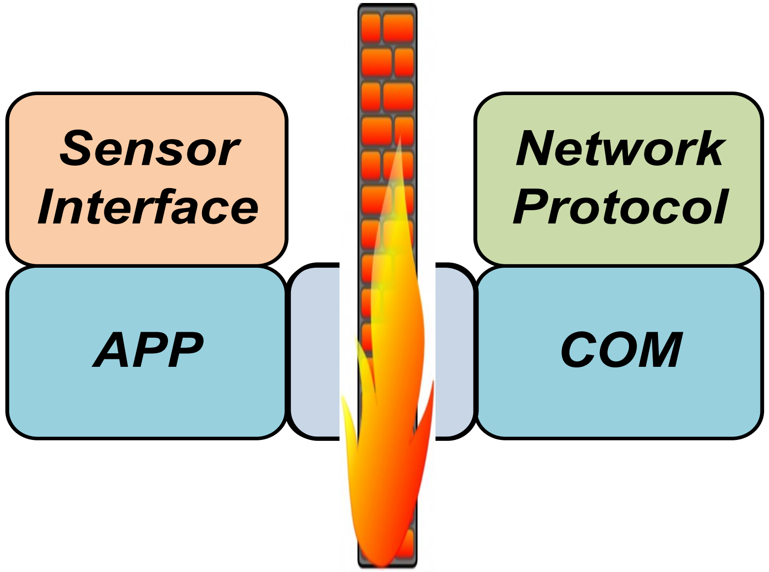


memory interference

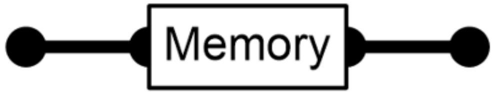
time-interference

no fine-grained power control

Dual Processor Platform Architecture



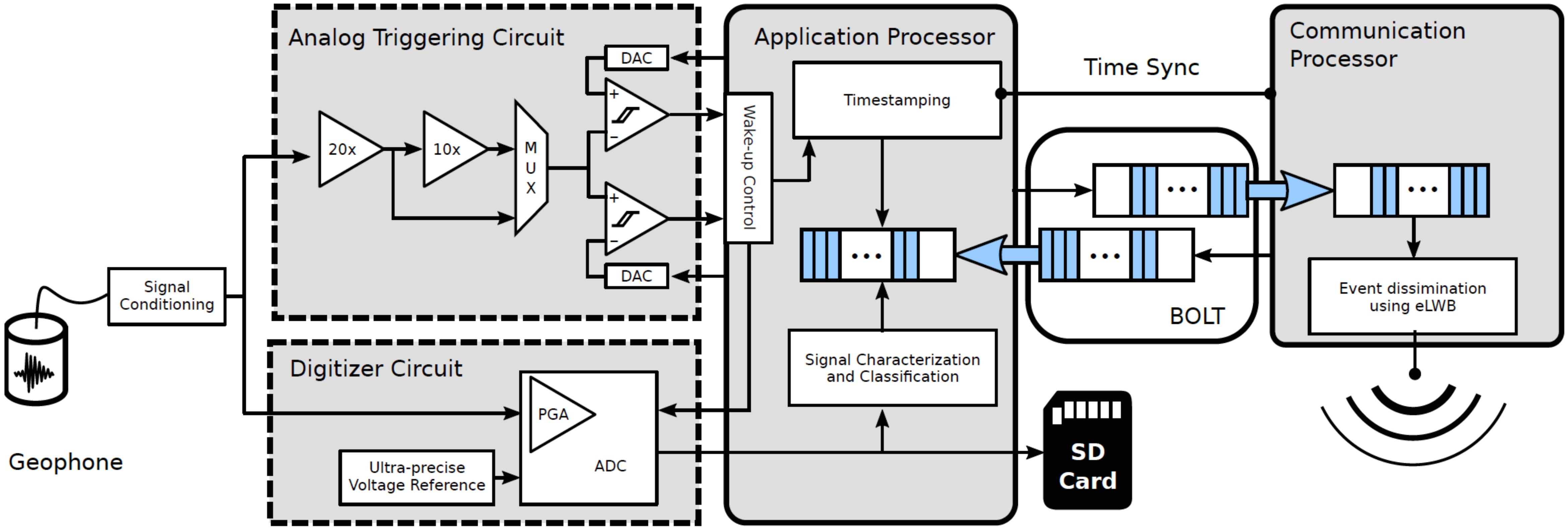
BOLT – A firewall for memory, clock and power



[F. Sutton et.al.: *Bolt: A Stateful Processor Interconnect*. Proc. SenSys 2015

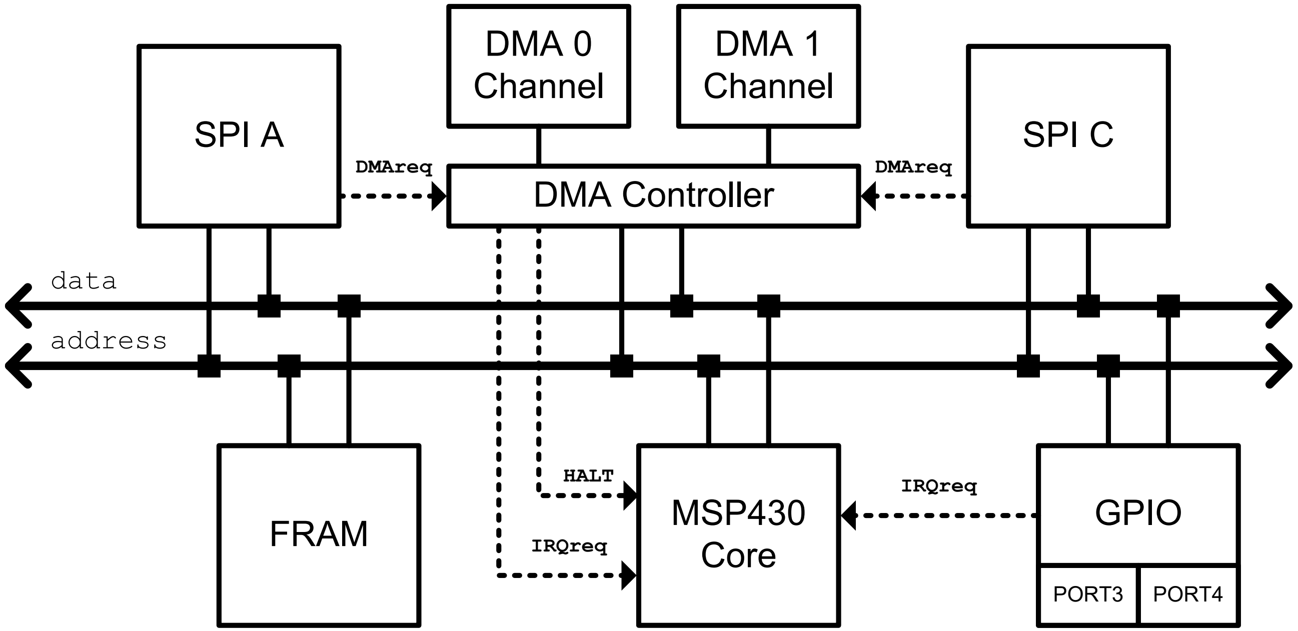
F. Suttonet.al.: *The Design of a Responsive and Energy-efficient Event-triggered Wireless Sensing System.* Proc. EWSN 2017]

BOLT Interface – Architecture Example

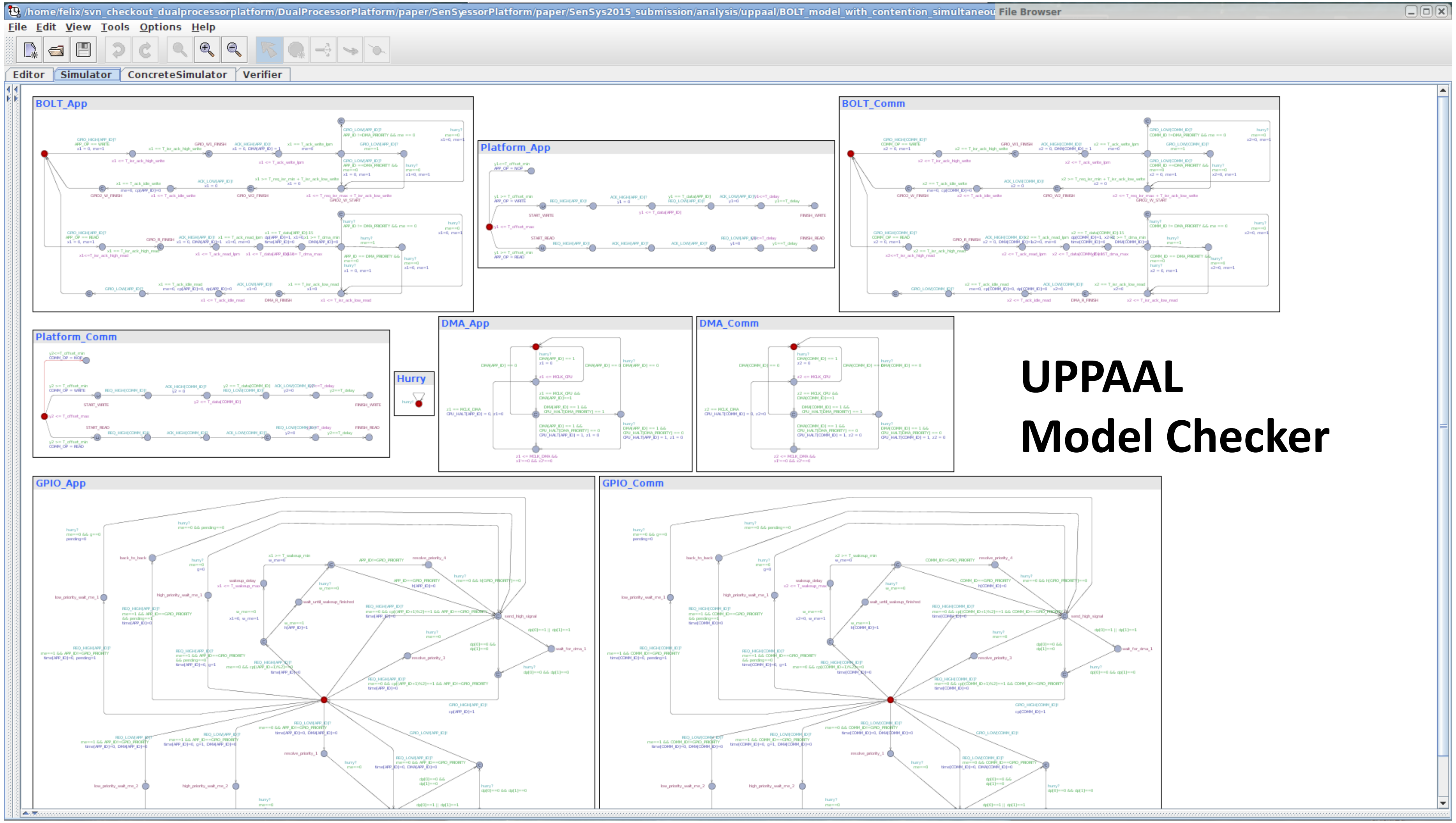


[M. Meyer et.al.: *Event-triggered Natural Hazard Monitoring with Convolutional Neural Networks on the Edge. Submitted, 2018]*

Bolt Interface – Implementation Using a Dedicated Microcontroller

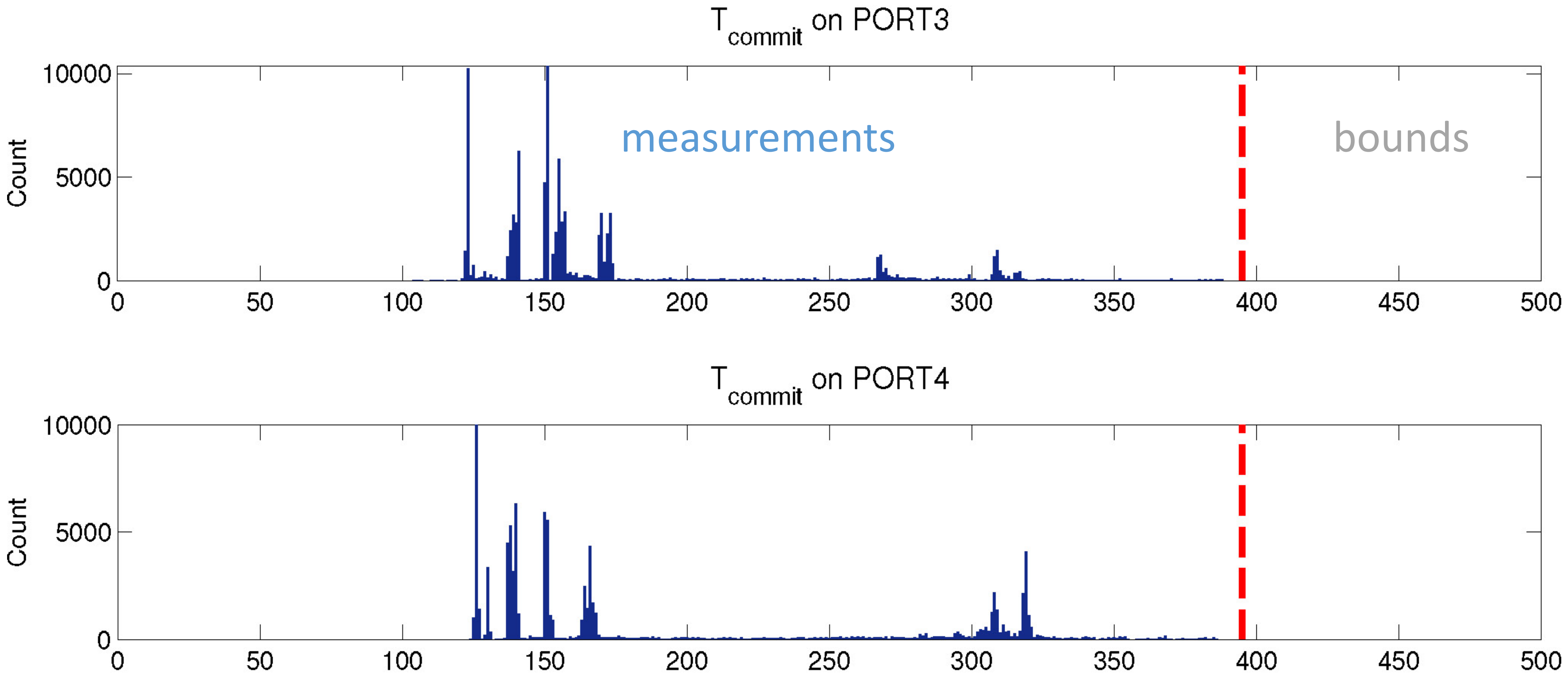


BOLT Interface – Formal Analysis



UPPAAL Model Checker

BOLT Interface – Experimental Analysis



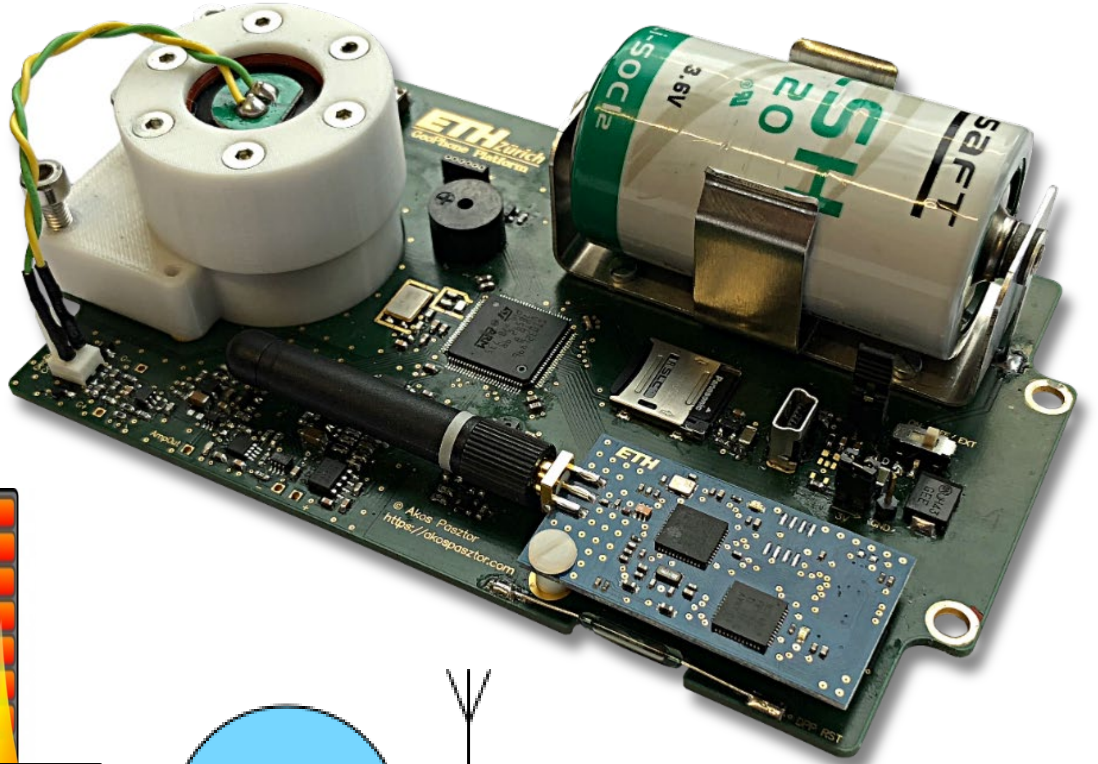
Application: Triggered Micro-Seismic Monitoring

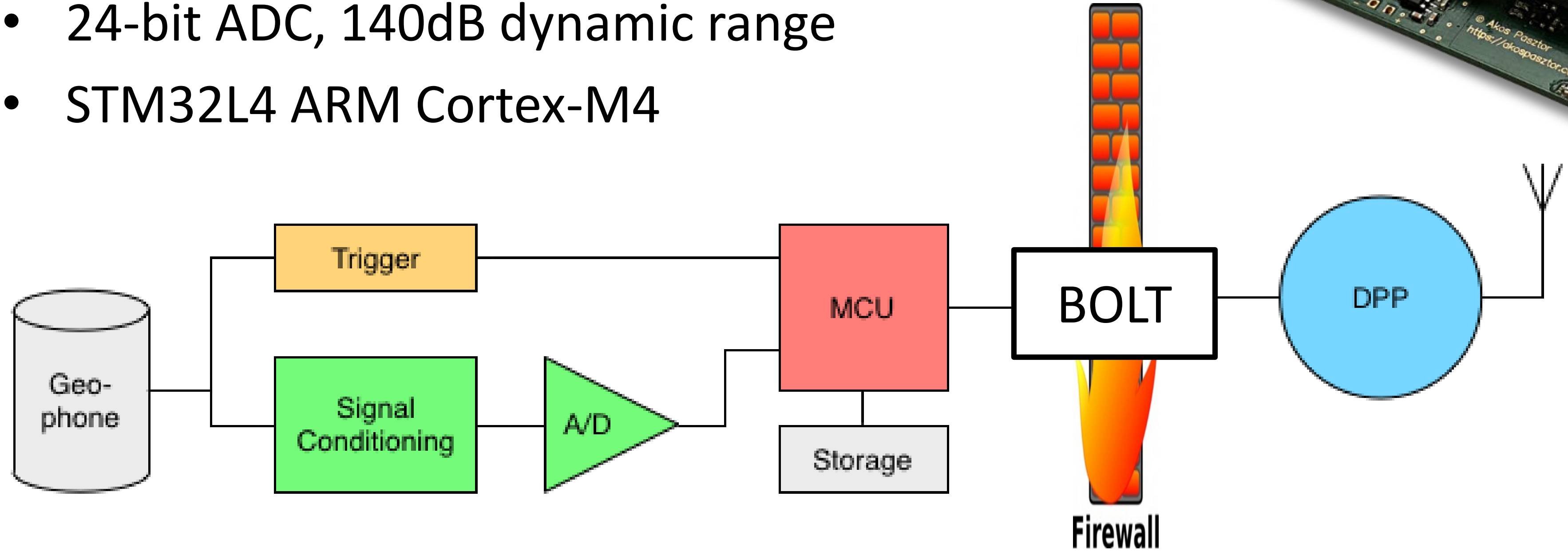
Continuously active seismic trigger:

- 25 µA @ 3.0V
- 50 µV sensitivity

Wake-up latency <2.7 msec

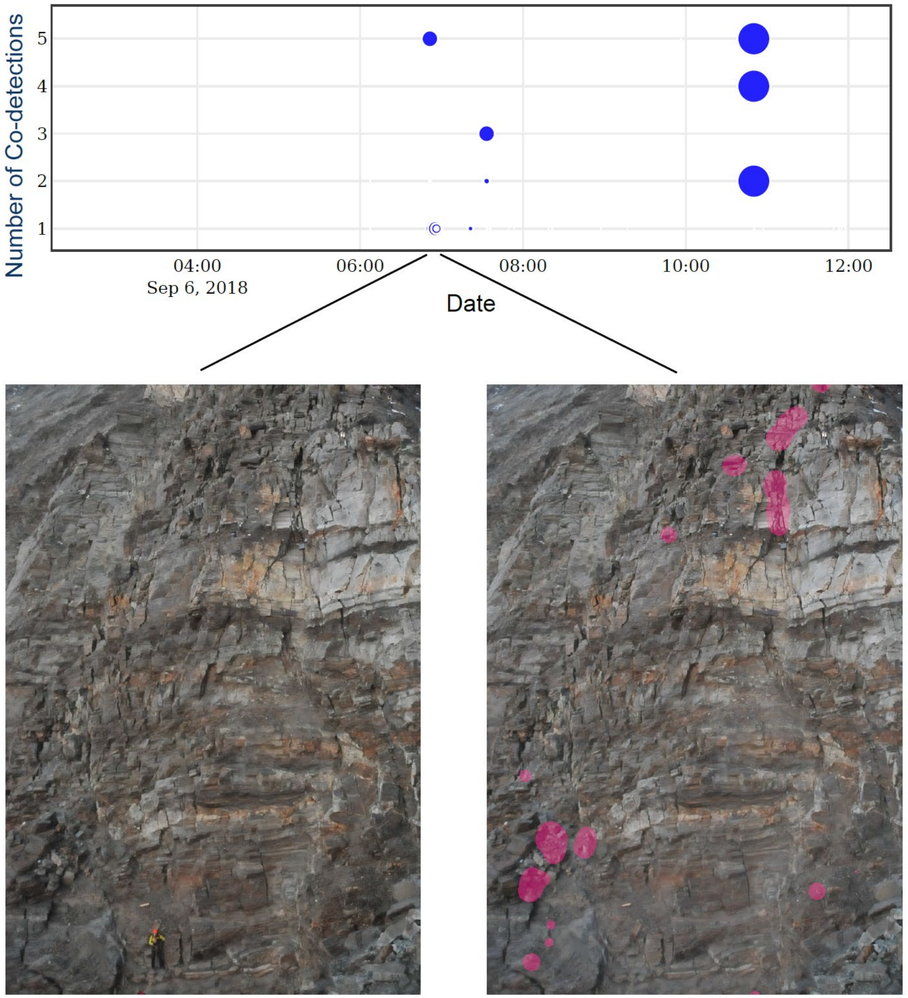
- 24-bit ADC, 140dB dynamic range
- STM32L4 ARM Cortex-M4





[A. Pasztor: *Event-based Geophone Platform with Co-detection*. MA Thesis, ETH Zurich, 2018.]

It Works - !?



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[M. Meyer et.al.: *Event-triggered Natural Hazard Monitoring with Convolutional Neural Networks on the Edge*. Submitted, 2018.]

ETH Zurich

Computer Engineering and Networks Lab

Geodesy and Geodynamics Lab

Micro and Nanosystems

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http://data.permasense.ch

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NCCR MICS
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cces

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

Bundesamt für Umwelt BAFU
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Alpine Rescue Center by Air Zermatt

PERMOS Swiss Permafrost Monitoring Network

ARC'TERYX

Art of Technology

evoNET INTERNET & COMPUTER SOLUTIONS

Blétry AG

HILTI

MATTERHORN ZERMATT BERGBAHNEN

AIR ZERMATT

HFSJG High Altitude Research Stations Jungfraujoch & Gornergrat