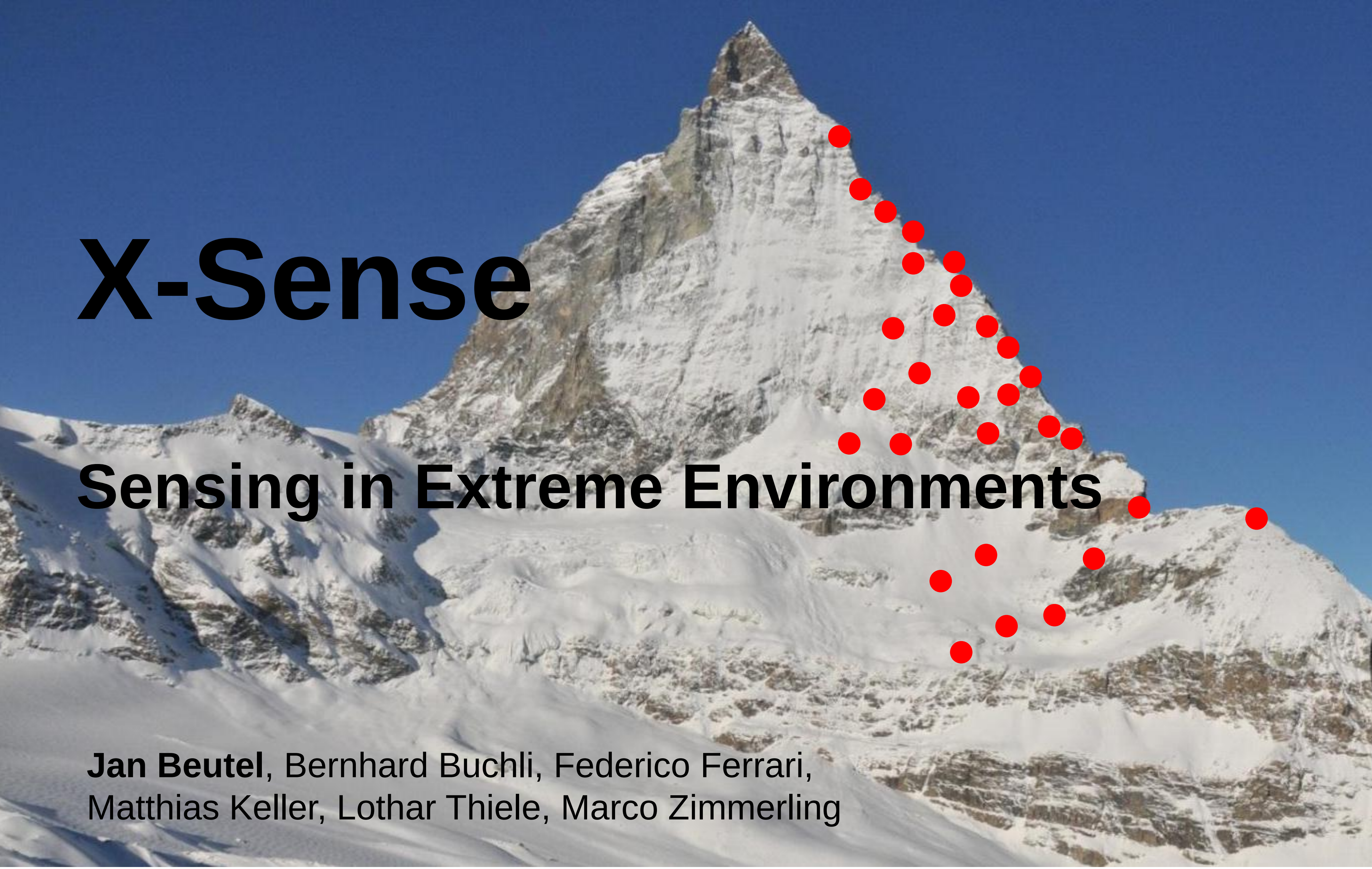

X-Sense

Sensing in Extreme Environments

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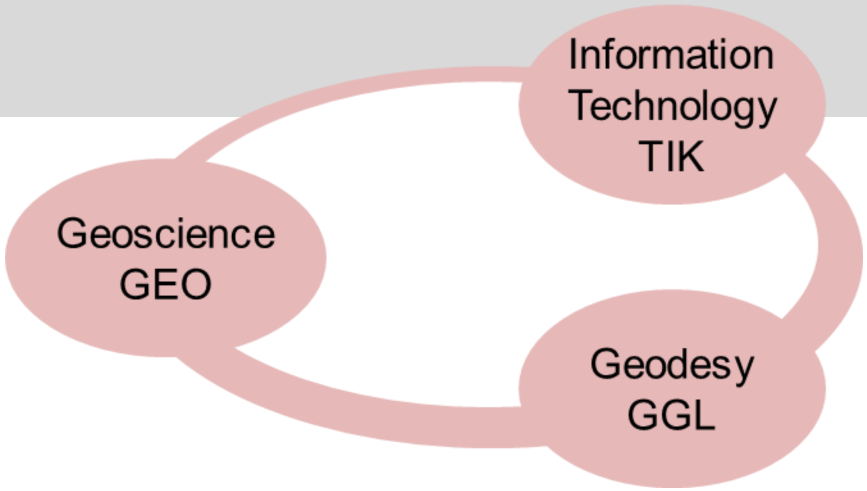
Main Objectives

- Investigation of fundamentals of the mountain cryosphere
  - provide **long-term high-quality** sensing in **harsh environments**
  - near-complete **data recovery** and near **real-time delivery**
  - obtain **better quality** data, more effectively
  - obtain measurements that have **previously been impossible**
  - provide relevant information for research or decision making, **natural hazard early-warning systems**



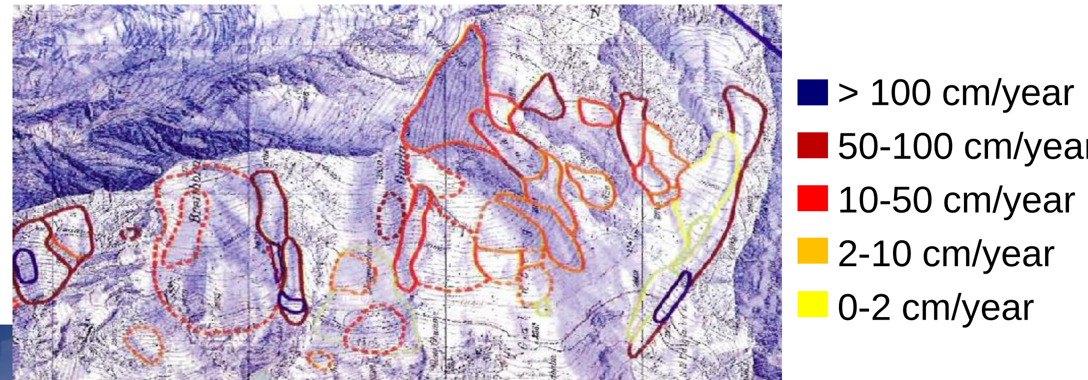
[Eiger east-face rockfall, July 2006, images courtesy of Arte Television]

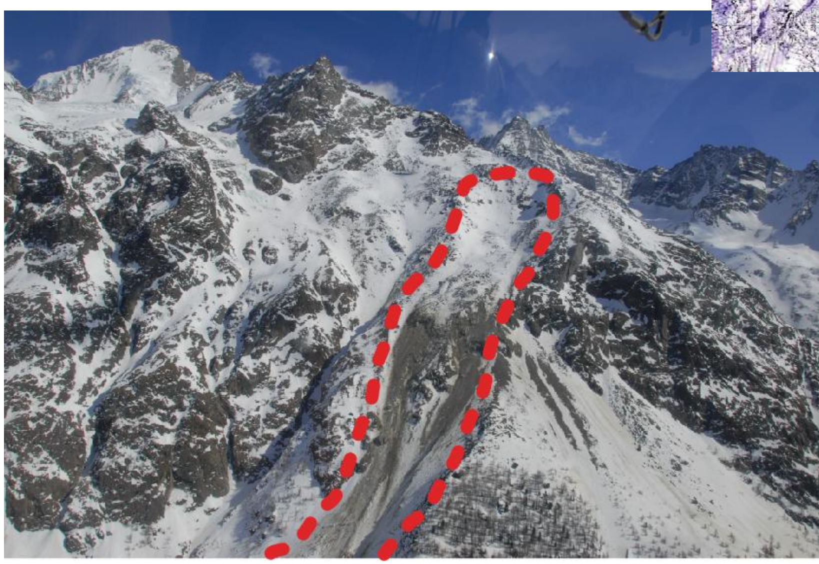

Our patient does not fit into a laboratory


So the laboratory has to
go on the mountain

New Avenues for X-Sense

- Application: Large-scale terrain movement detection
  - Understanding rock-glacier creep
- Current methods:
  - InSAR measurements
  - Manual D-GPS





- Sensor challenges
  - Complex sensors (combinations of sensors, different scales)
  - Variable data rates
  - User interaction (feedback)
  - In-network processing

X-Sense Hypothesis

Anticipation of future environmental states and risk

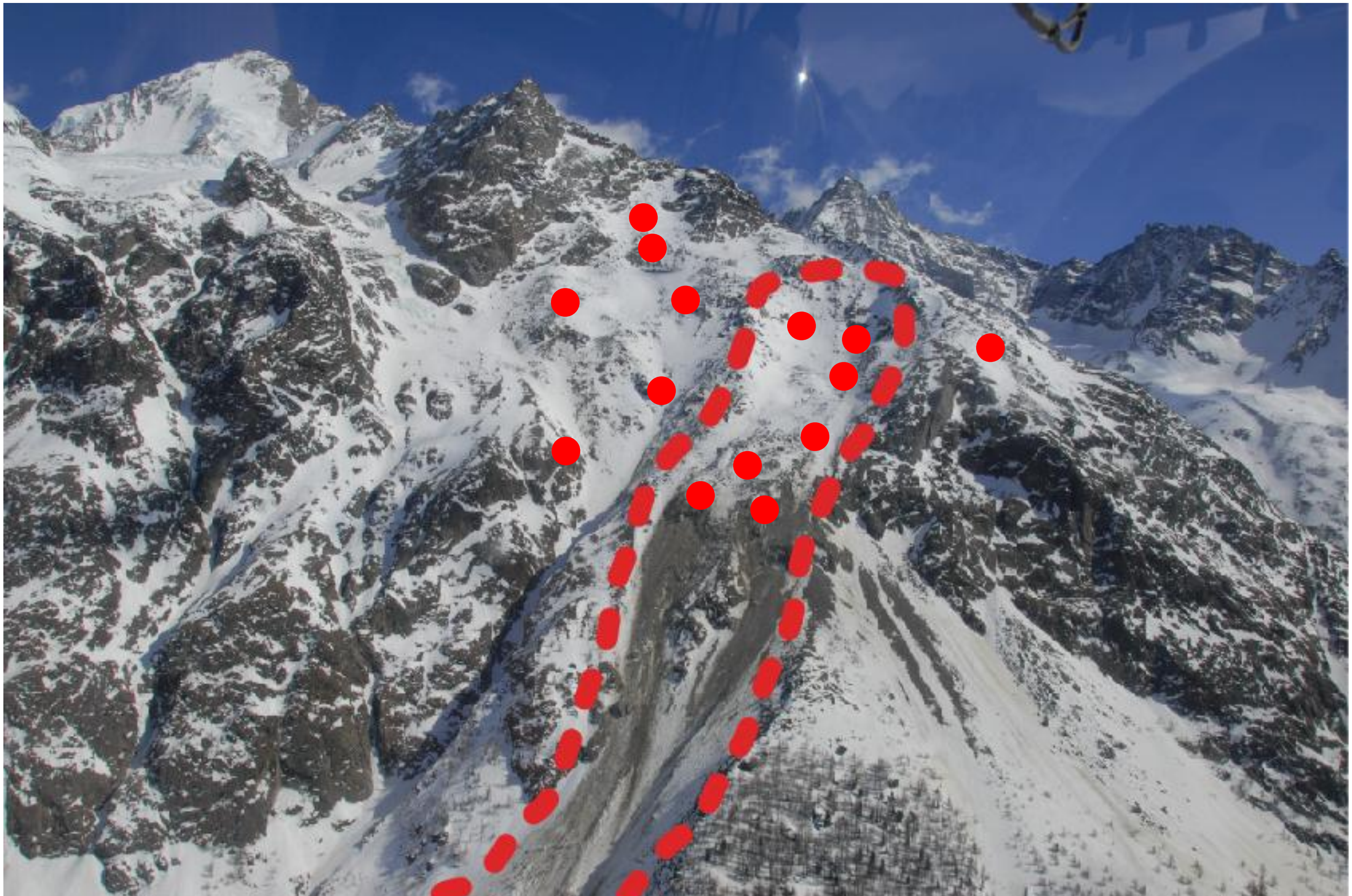
is improved by

- a systematic combination of environmental *sensing* at diverse temporal and spatial scales and
- process *modeling*

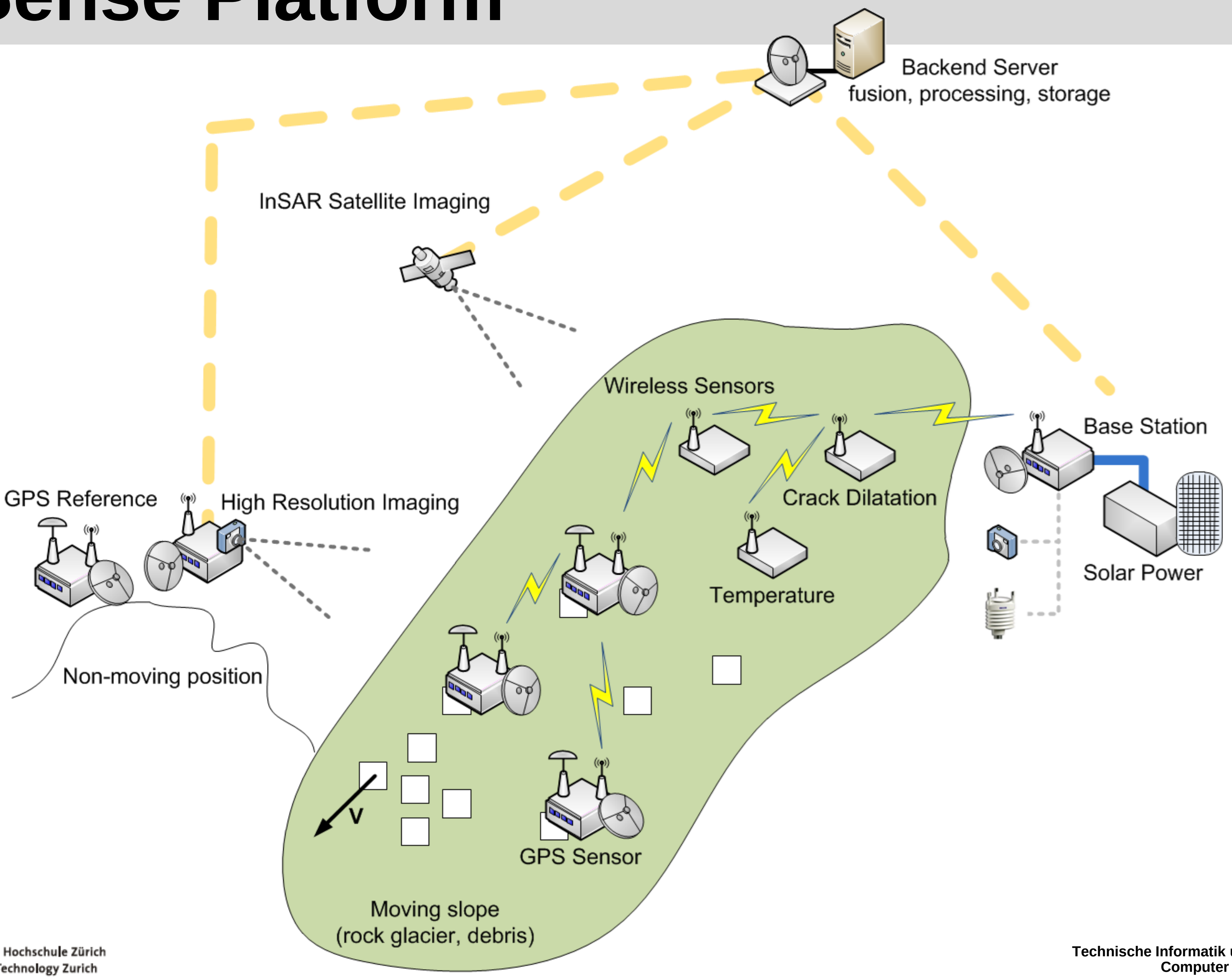
Wireless Sensor Network Technology

- allows to *quantify mountain cryosphere phenomena* and their transient response to climate change
- can be used for *safety critical applications* in an hostile environment

X-Sense – Natural Hazard Scenario

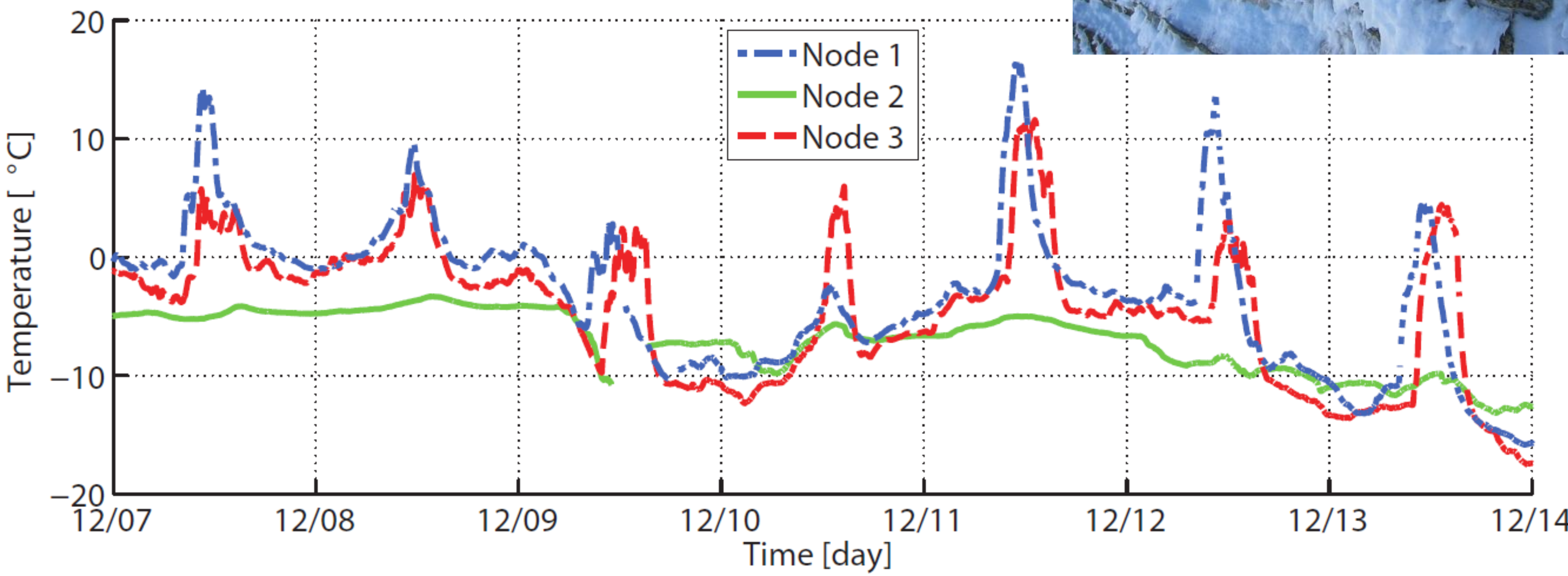


X-Sense Platform



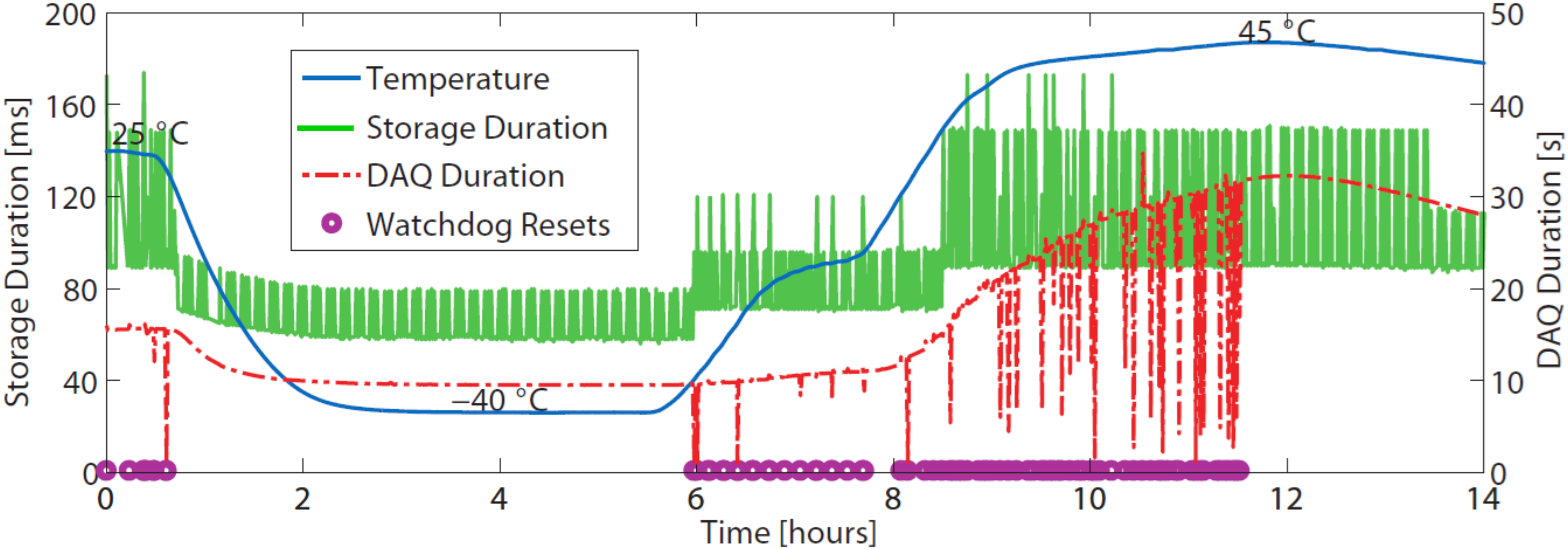
Challenge: The Physical Environment

- Lightning, avalanches, rime, prolonged snow/ice cover, rockfall
- Strong daily variation of temperature
  - −30 to +40°C
  - ΔT ≦ 20°C/hour

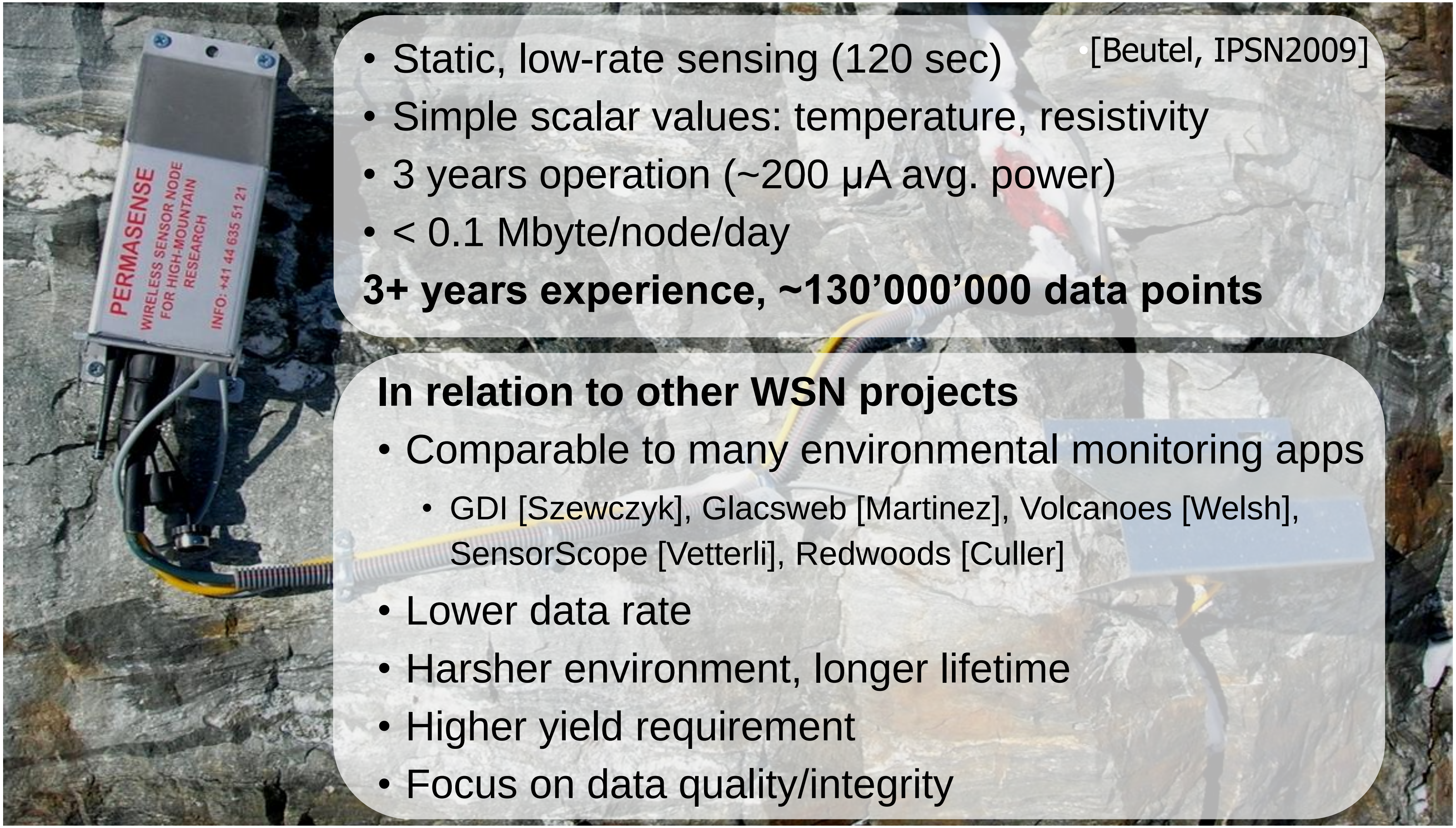


Impact of Environmental Extremes

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



Simple Low-Power Wireless Sensors



- Static, low-rate sensing (120 sec)
- Simple scalar values: temperature, resistivity
- 3 years operation (~200 µA avg. power)
- < 0.1 Mbyte/node/day

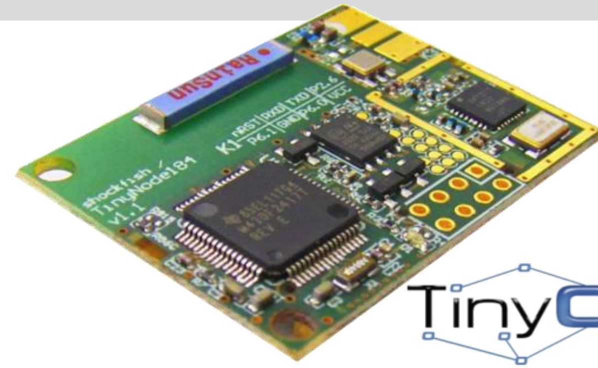
[Beutel, IPSN2009]

3+ years experience, ~130’000’000 data points

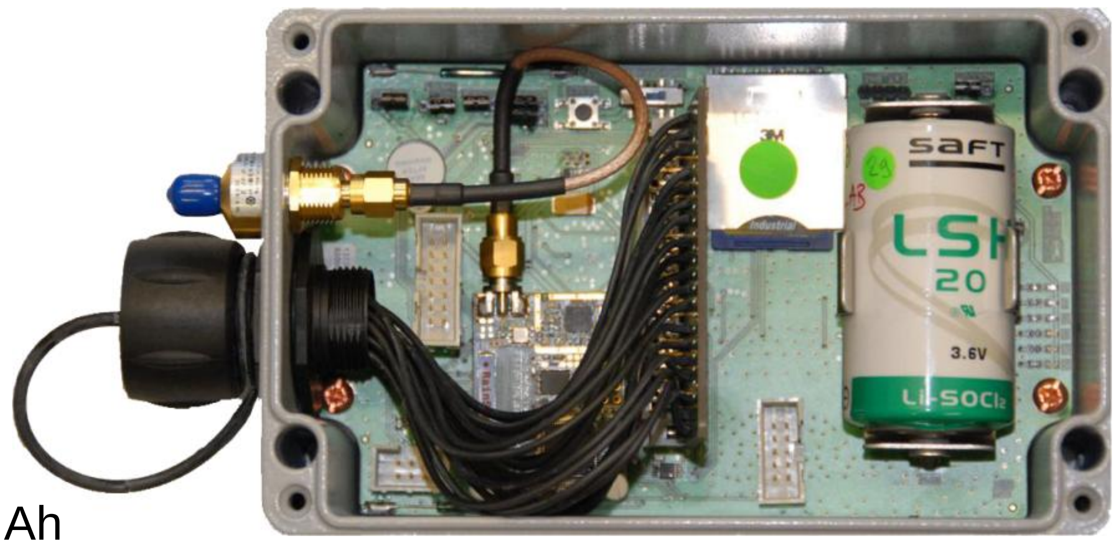
In relation to other WSN projects

- Comparable to many environmental monitoring apps
  - GDI [Szewczyk], Glacsweb [Martinez], Volcanoes [Welsh], SensorScope [Vetterli], Redwoods [Culler]
- Lower data rate
- Harsher environment, longer lifetime
- Higher yield requirement
- Focus on data quality/integrity

Sensor Node Hardware

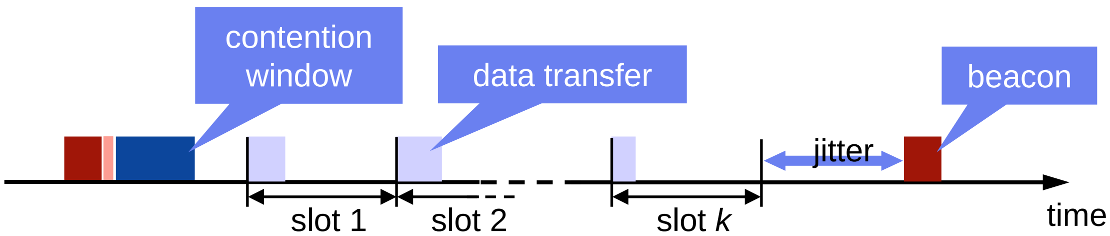


- Shockfish TinyNode584
  - MSP430, 16-bit, 8MHz, 10k SRAM, 48k Flash
  - LP Radio: XE1205 @ 868 MHz
- Waterproof housing and connectors
- Sensor interface board
  - Interfaces, power control
  - Temp/humidity monitor
  - 1 GB Flash memory
- 3-year life-time
  - Single Li-$SOCl_2$ battery, 13 Ah
  - ~300 μA power budget

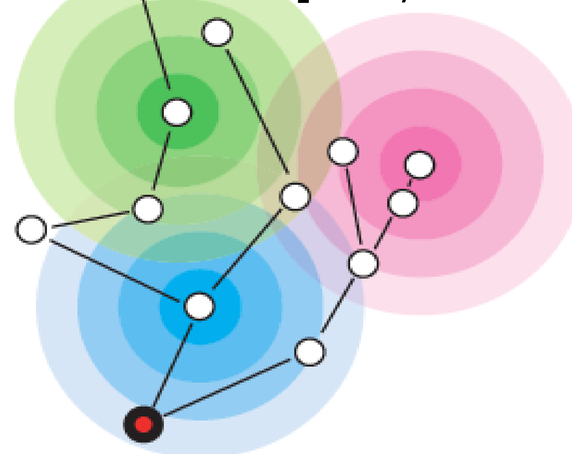


Ultra Low-Power Multi-hop Networking

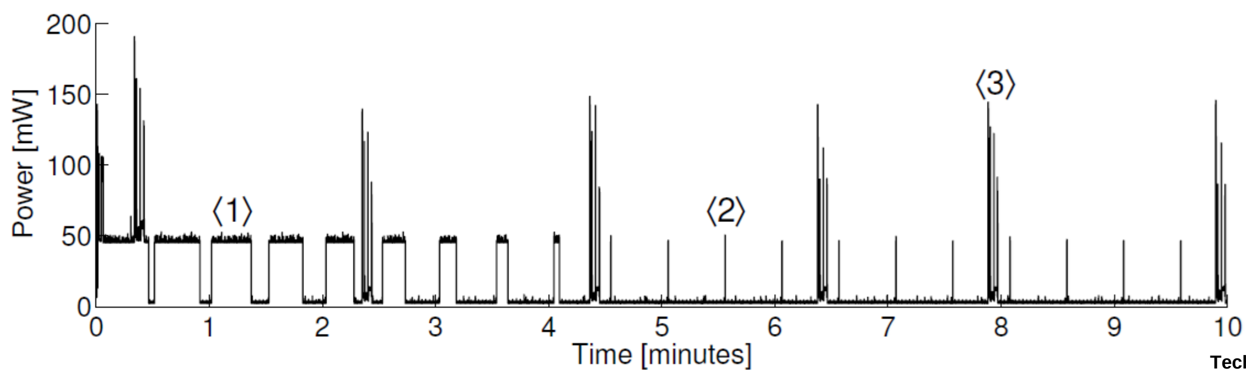
- Dozer ultra low-power data gathering system
  - Beacon based, 1-hop synchronized TDMA
  - Optimized for ultra-low duty cycles
  - **0.167%** duty-cycle, **0.032mA** (@ 30sec beacons)



[Burri, IPSN2007]

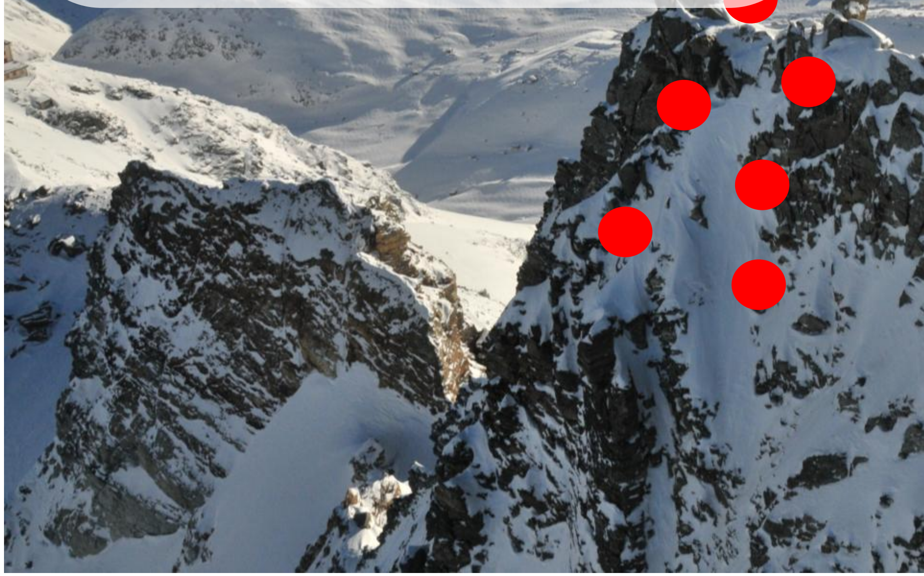


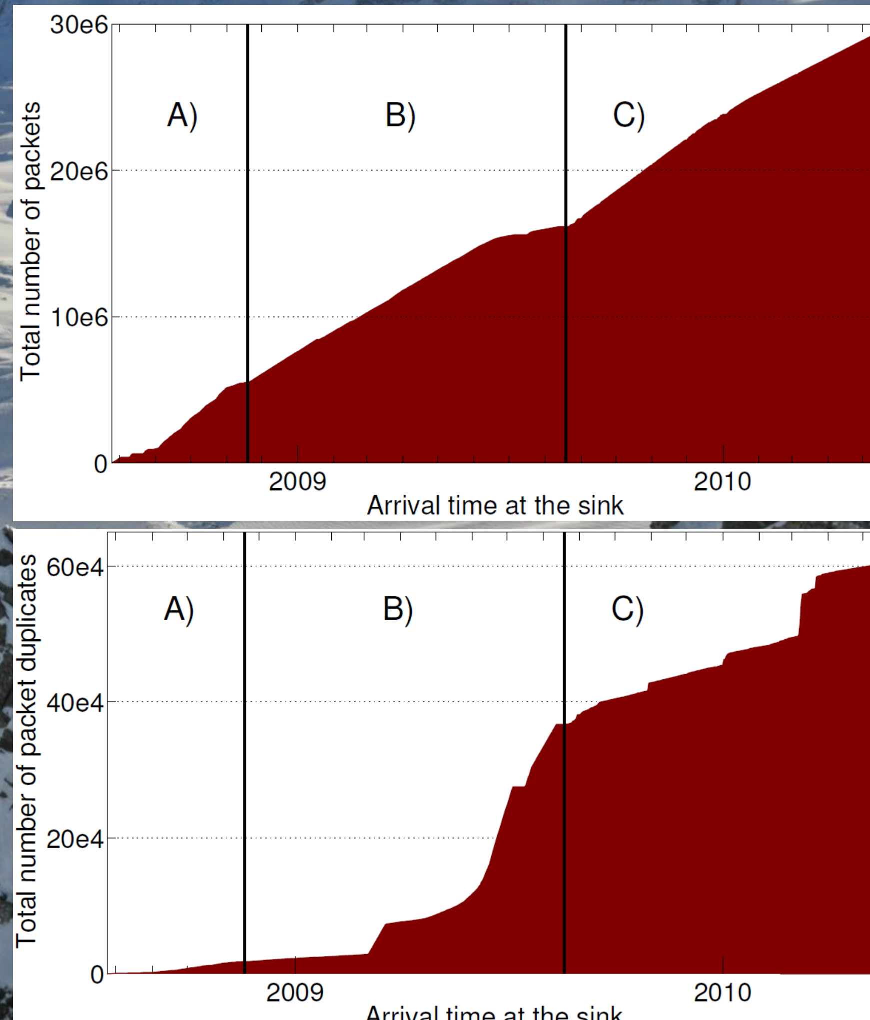
- But in reality: Connectivity can not be guaranteed…
  - Situation dependent transient links (scans/re-connects use energy)
  - Account for long-term loss of connectivity (snow!)



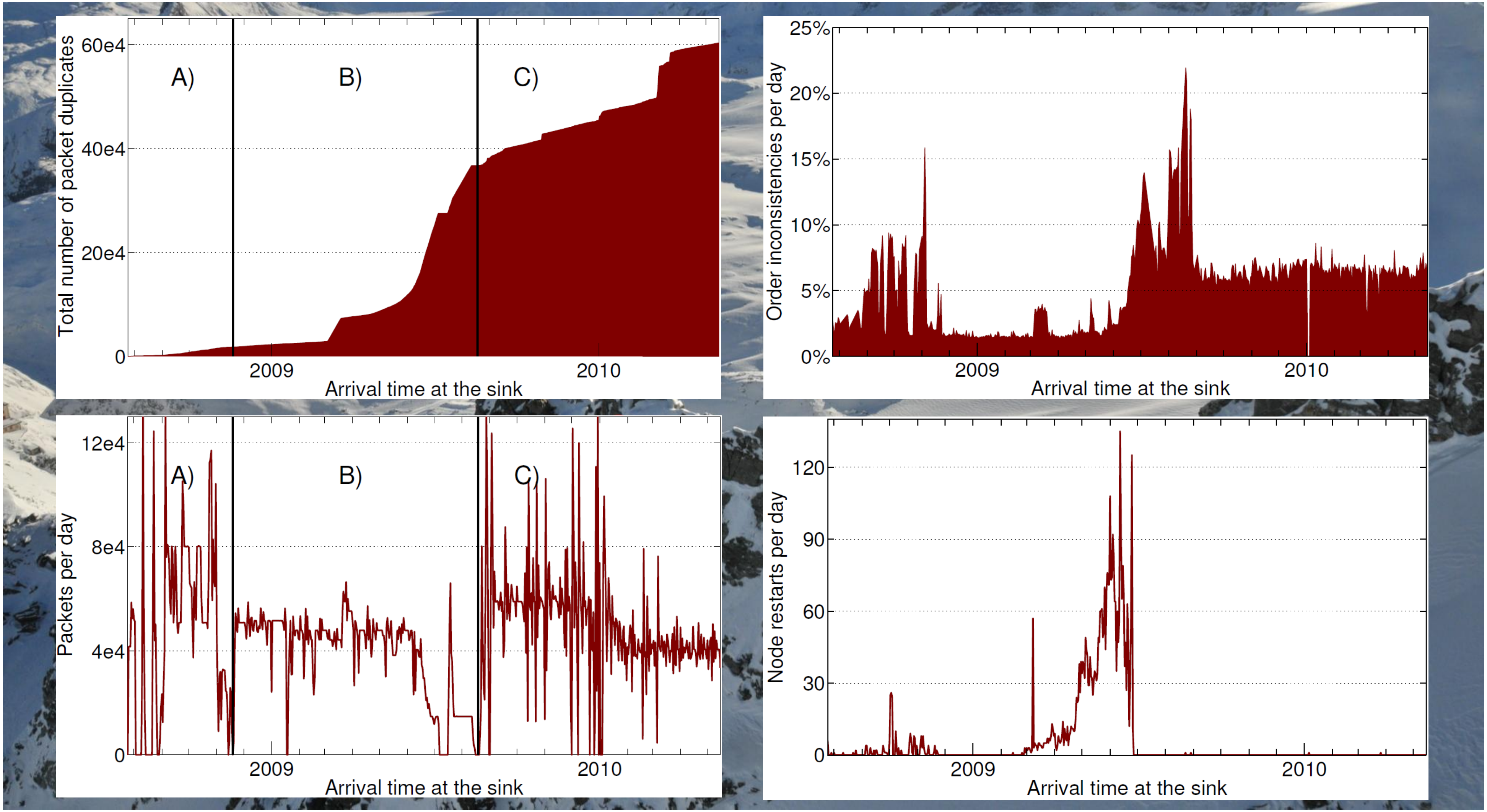
Challenge: Data Integrity/Validation

- August 2008 – June 2010
- Single sink
- Up to 19 sensor nodes
- TinyOS/Dozer [Burri, IPSN2007]
- Constant rate sampling
- < 0.1 MByte/node/day



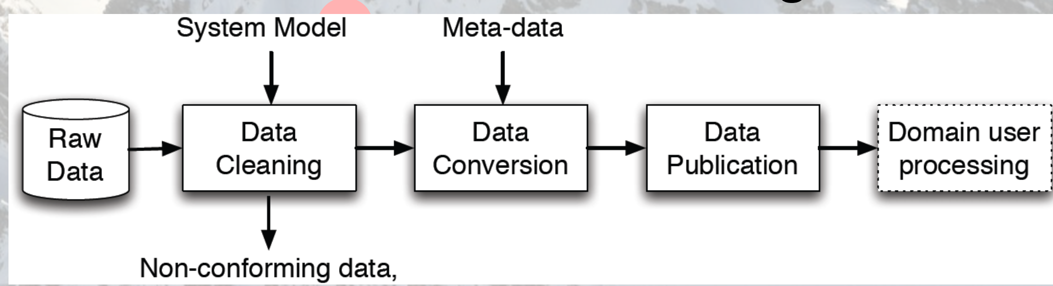


More Data Anomalies

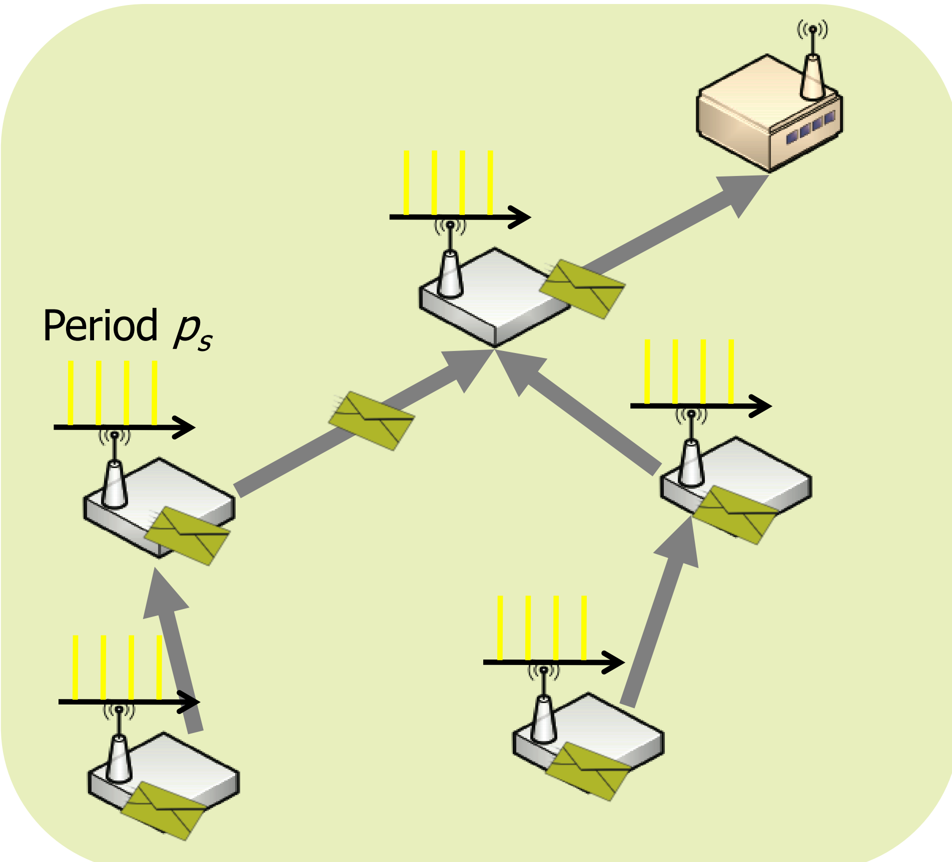


Data is not Correct-by-Design

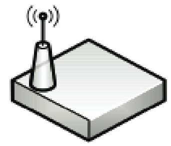
- Artifacts observed
  - Packet duplicates
  - Packet loss
  - Wrong ordering
  - Variations in received vs. expected packet rates
- Matches with findings of other researchers
  - Average of 6.5% packet duplicates [Barrenetxea, SenSys2008]
  - Up to 20% of lost packets [Barrenetxea, IPSN2008]
- Necessitates further data cleaning/validation



System Model

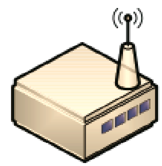


- Dynamic multi-hop tree topology
- Unidirectional links



Sensor Node Functions

- Periodic data sampling
- Packet sequence numbers
- Data forwarding queue
- Local clock with bounded drift



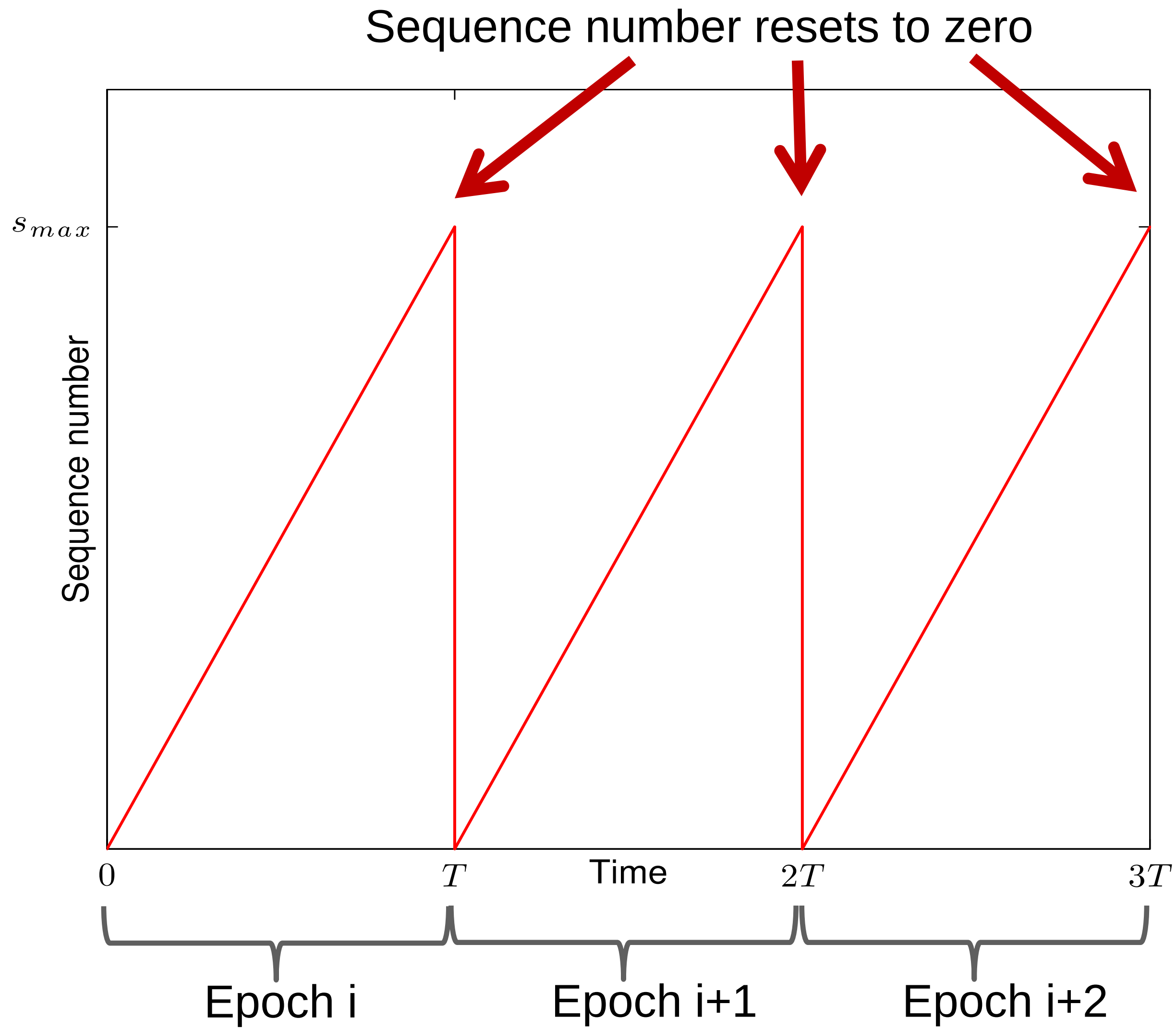
Base Station

- Sink of WSN data collection tree
- Synchronized to GMT clock
- Forwards data to database server

- At the sink the accumulated sojourn times are used to calculate the "generation time" of each packet
- Sequence numbers used to check ordering

Idea: Separation of Data into Epochs

- **Epoch**: Packets generated between two consecutive resets of the sequence number belong to same epoch
- **Epoch Index**: Epochs are identified by a monotonically increasing integer value.
- Sequence numbers are unique within an epoch
- Epoch index & sequence number yield packet order



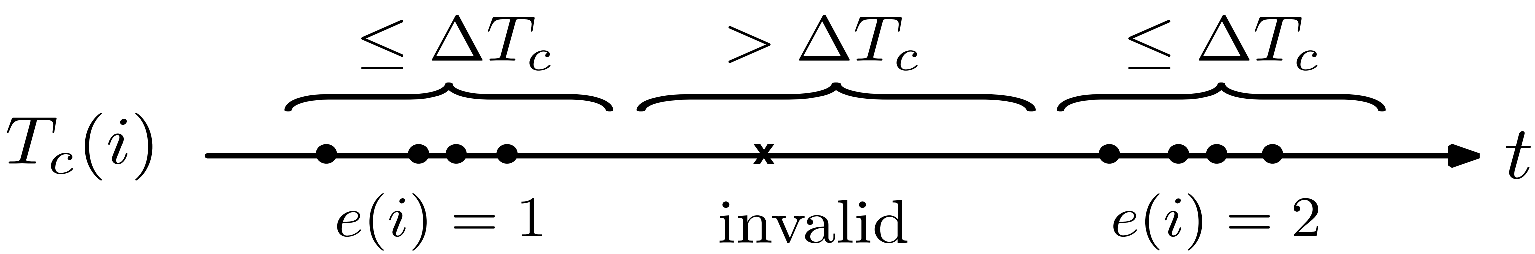
Epoch Assignment in A Nutshell

System generating one packet every **T**:

- For each packet **i** with sequence number **s(i)** generated at $\mathbf{t_g(i)}$, we calculate the "epoch center" $\mathbf{T_C(i)}$:

$$T_c(i) = \tilde{t}_g(i) - s(i) \cdot T$$

- Epoch assignment based on temporal locality of epoch centers of packets belonging to the same epoch



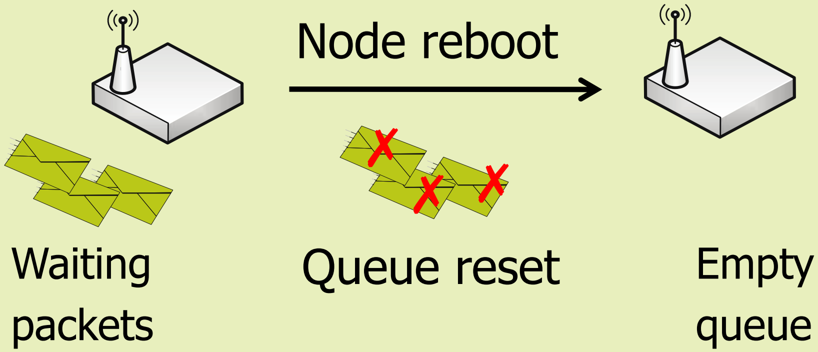
- Bounded ΔT_c

$$\Delta T_c = (s_{max} - 1)(\hat{\rho}T + T - T') + T' + 2\hat{\rho}t_s^{max}$$

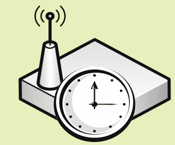
[Keller, IPSN2011]

Sources of Error included in ΔT_c

Data Loss



Clock Drift $\rho \in [-\hat{\rho}; +\hat{\rho}]$



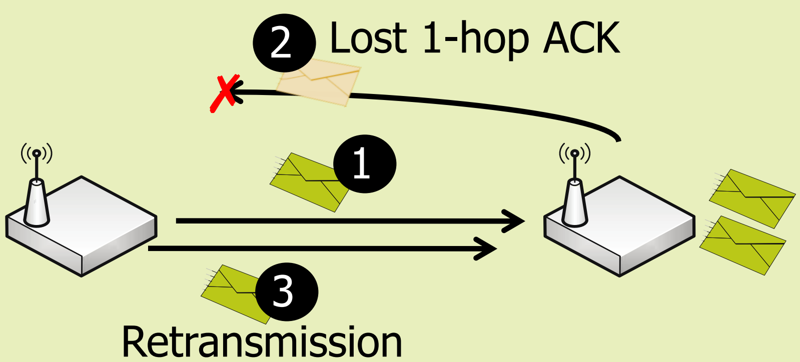
Directly affects measurement of

- Sampling period T
- Contribution to elapsed time t_e

Indirectly leading to inconsistencies

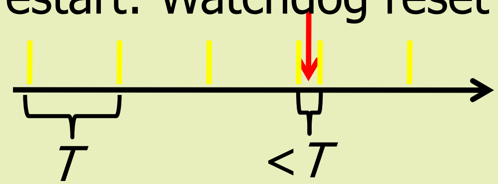
- Time stamp order t_p vs. order of packet generation s

Packet Duplicates



Node Restarts

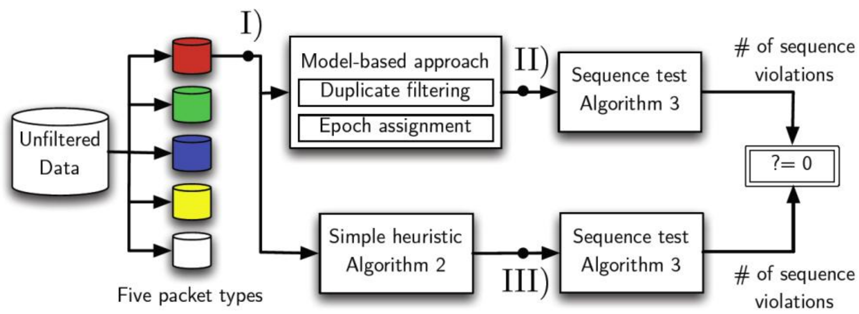
- Cold restart: Power cycle
- Warm restart: Watchdog reset

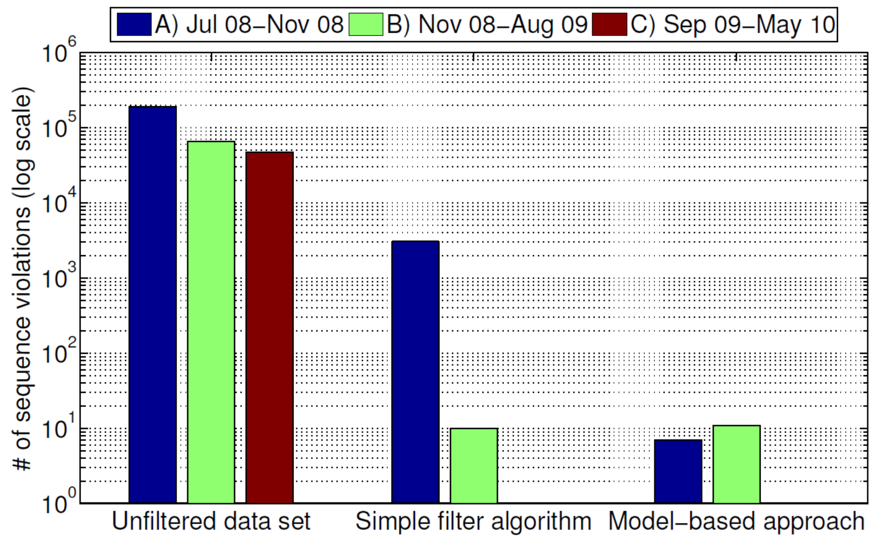


- Shortens packet period
- Resets/rolls over certain counters

Model-based Data Validation Case Study

Evaluation Methodology





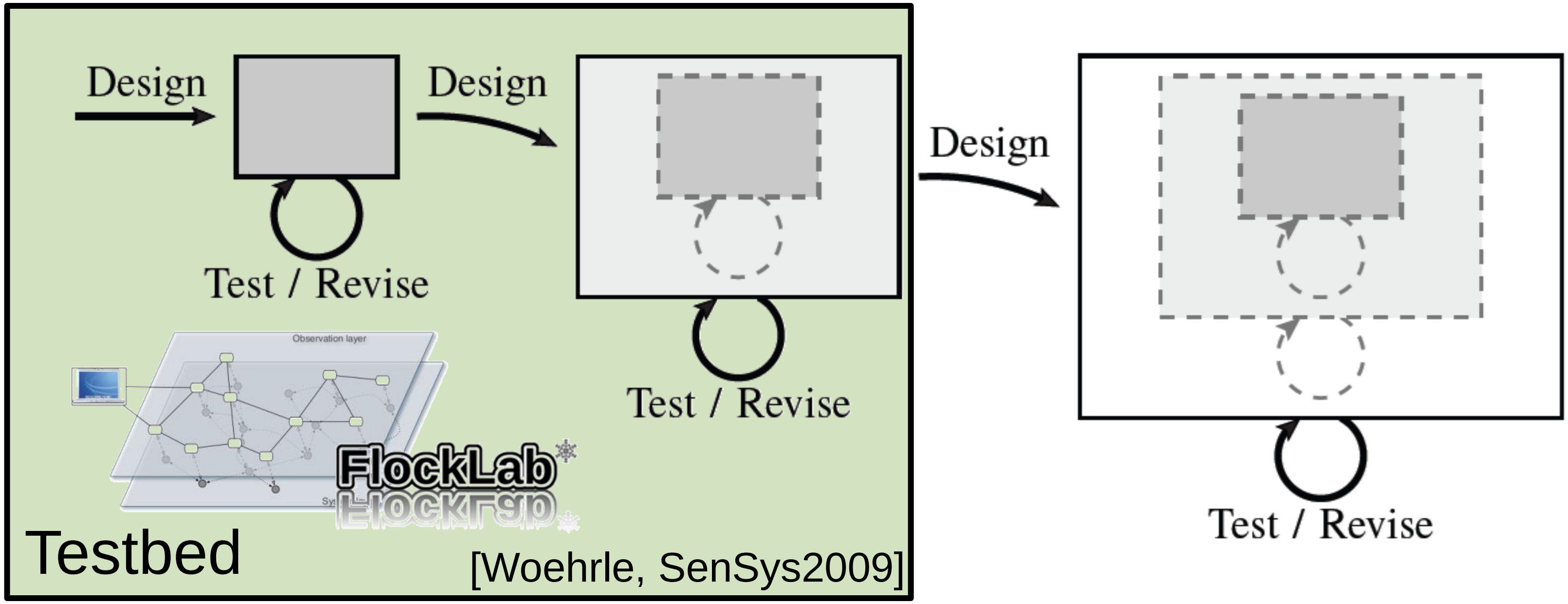
- Reconstruction of correct temporal order
- Validation of correct system function
- Domain user primarily interested in "correct" data

Counter	A) Jul 08-Nov 08	B) Nov 08-Aug 09	C) Sep 09-May 10
Accepted packets	632,058 (59.4%)	2,110,855 (96.8%)	2,579,444 (95.4%)
Discarded packets	432,826 (40.6%)	69,829 (3.2%)	124,554 (4.6%)
Packet duplicates	4,020 (0.4%)	69,422 (3.2%)	44,601 (1.7%)
$t_s(i) > t_s^{\max}$	0 (0.0%)	0 (0.0%)	0 (0.0%)
Failed epoch assignment	235,927 (22.2%)	277 (0.0%)	2,466 (0.1%)
Invalid interval $t_g^{u,l}(i)$	192,879 (18.1%)	130 (0.0%)	77,487 (2.9%)
Total packets	1,064,884 (100.0%)	2,180,684 (100.0%)	2,703,998 (100%)

[Keller, IPSN2011]

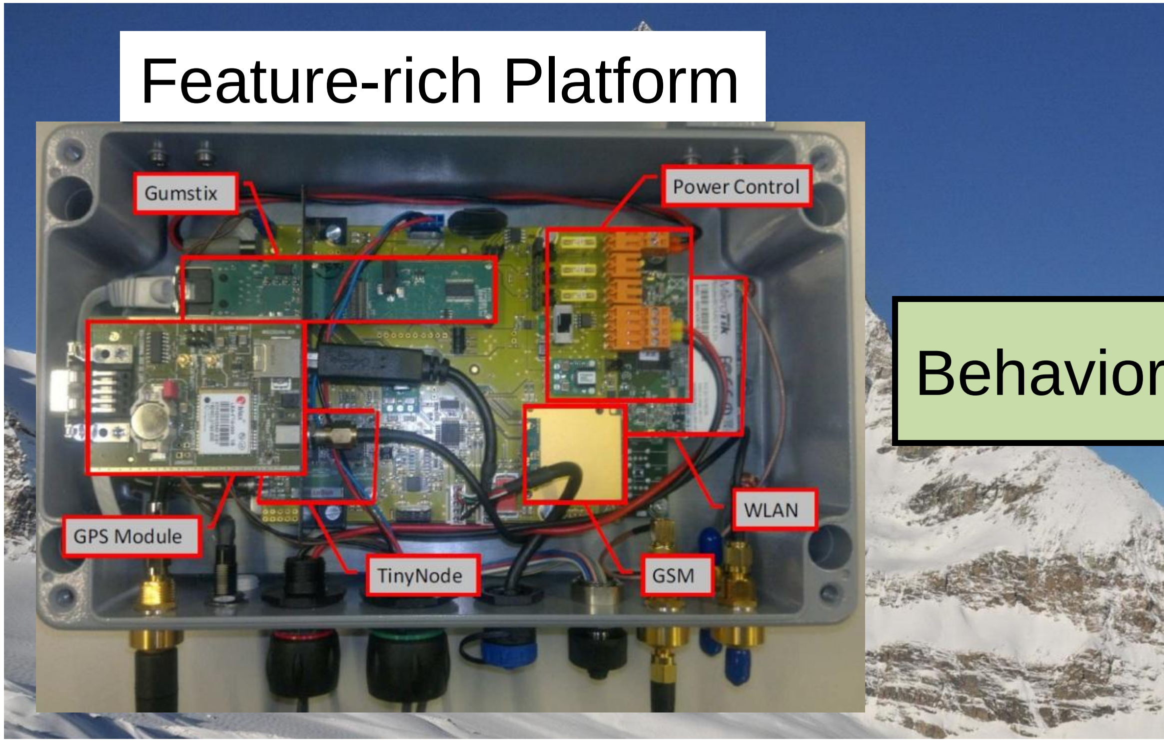
Challenge: The Design Approach

- Traditional iterative design approach: waterfall-model
- Repeated for individual system layers



- Testbeds are essential but they are an abstraction
  - Sensing is a mock up, environment is hard to create (TCT)

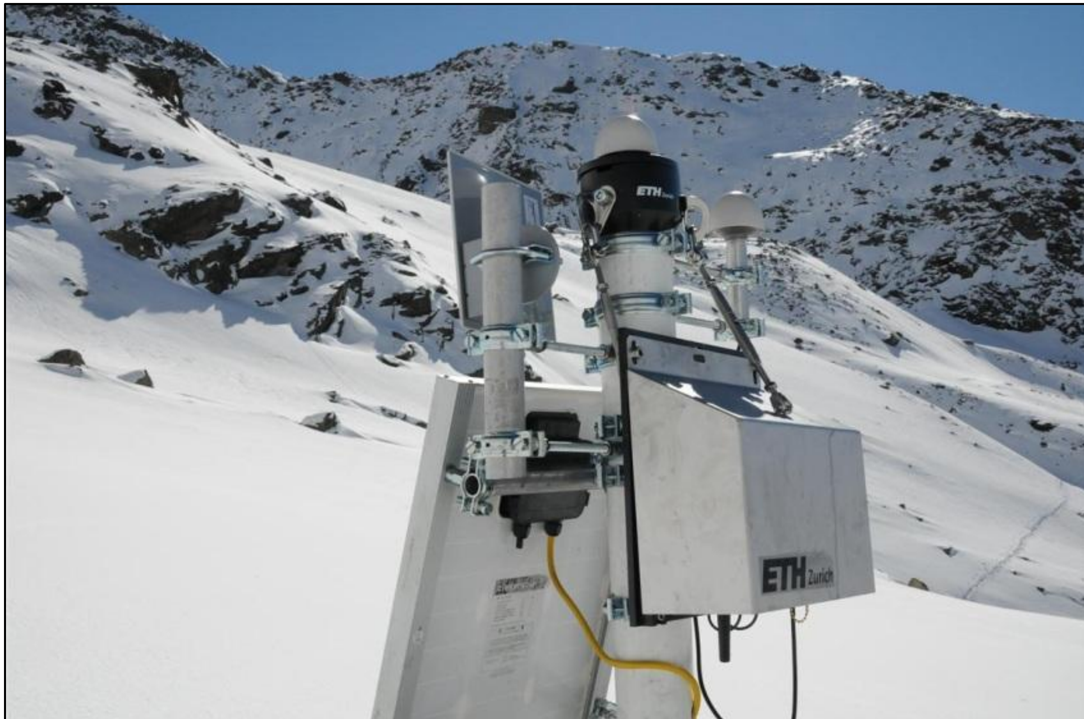
Top-down Approach: In-situ Design & Test

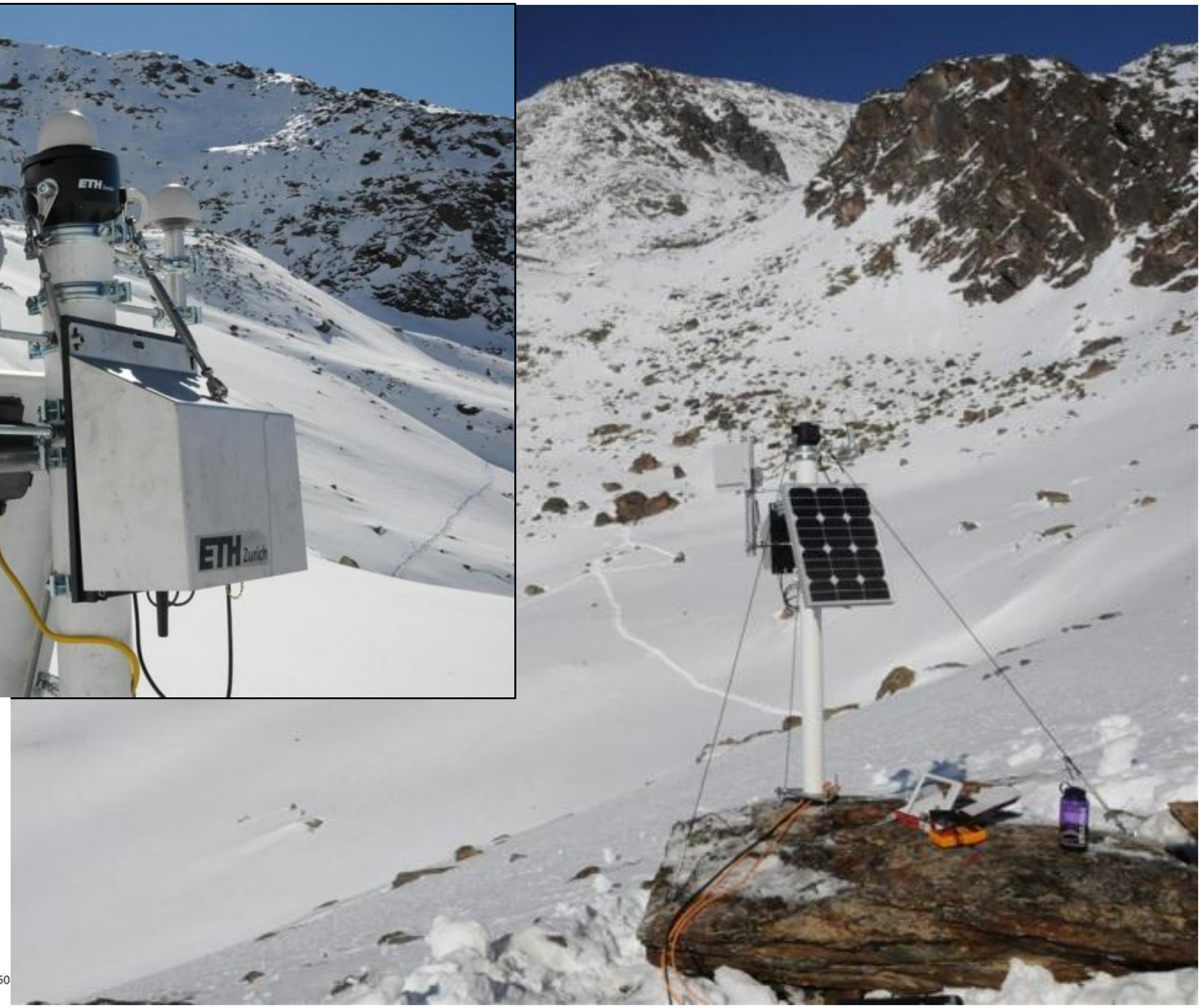


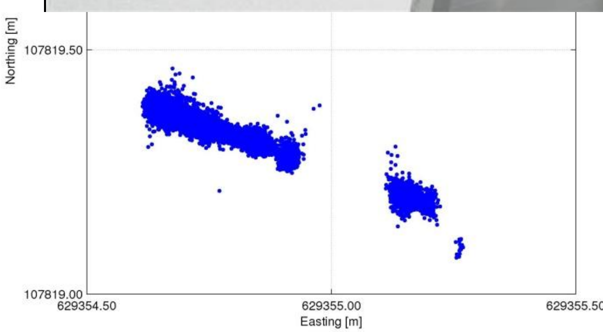
Behavioral Data → Refined Platform Specification

- Flexible in-situ exploration (testbed ≠ real system)
- Real sensor data, real environment
- Integration with live data management (system of systems)

Current Test Deployment in Valais







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