Ground Vibration Monitoring at CERN as Part of the International Seismic Network

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with contributions of many people from integration, civil engineering team, IT…

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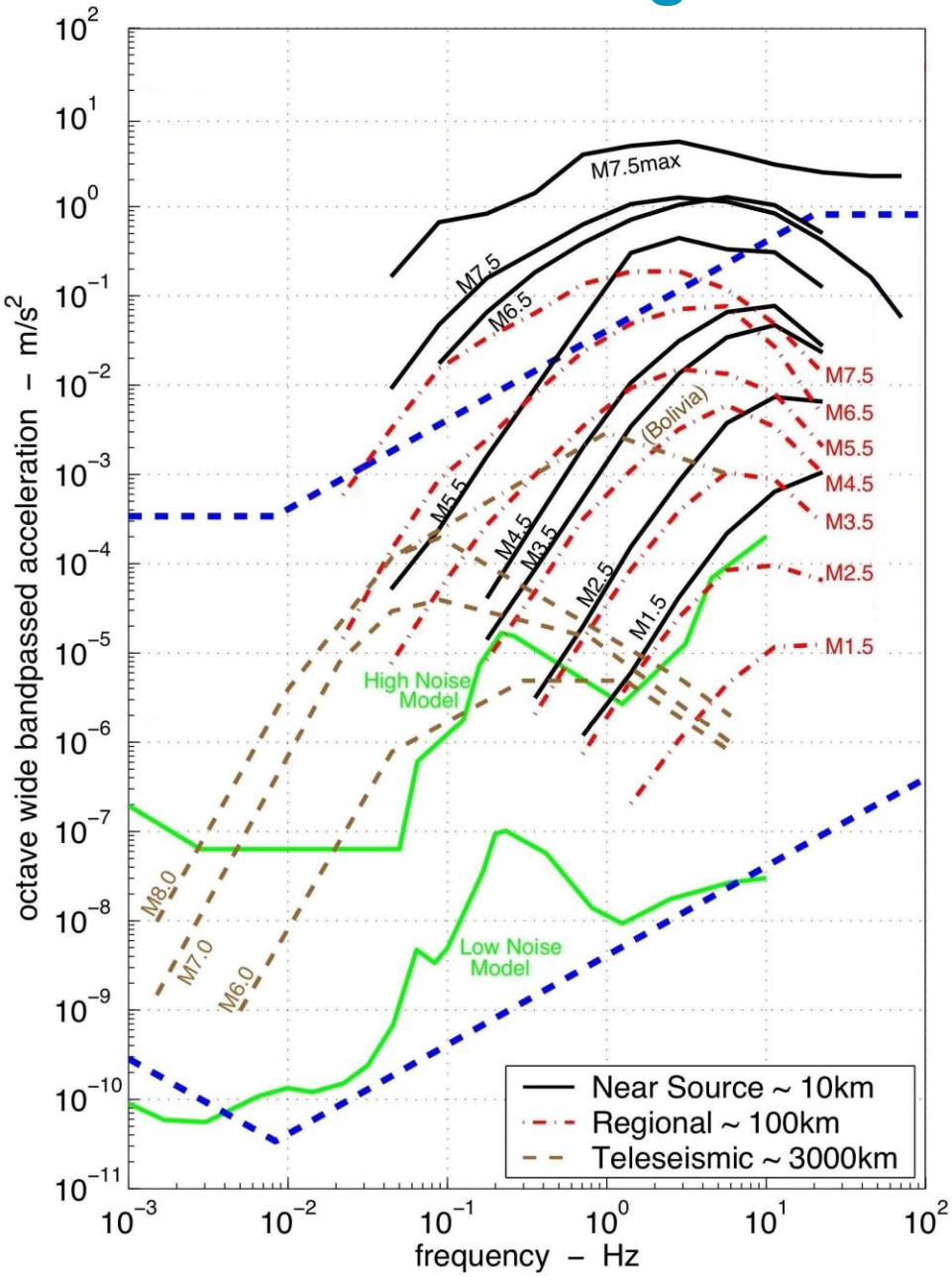
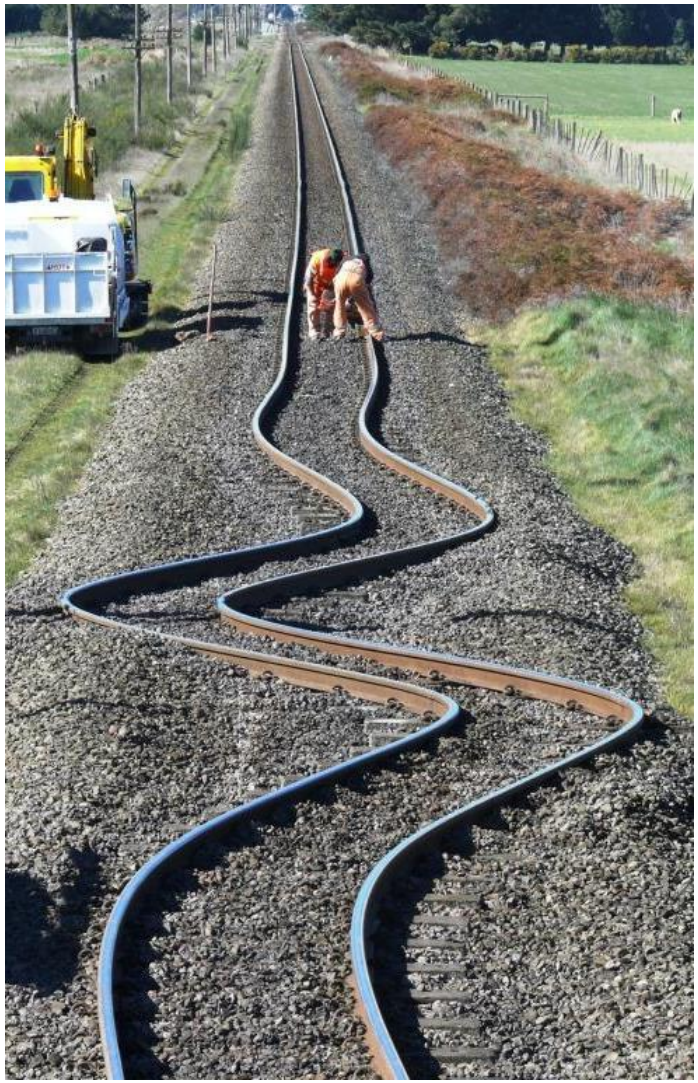
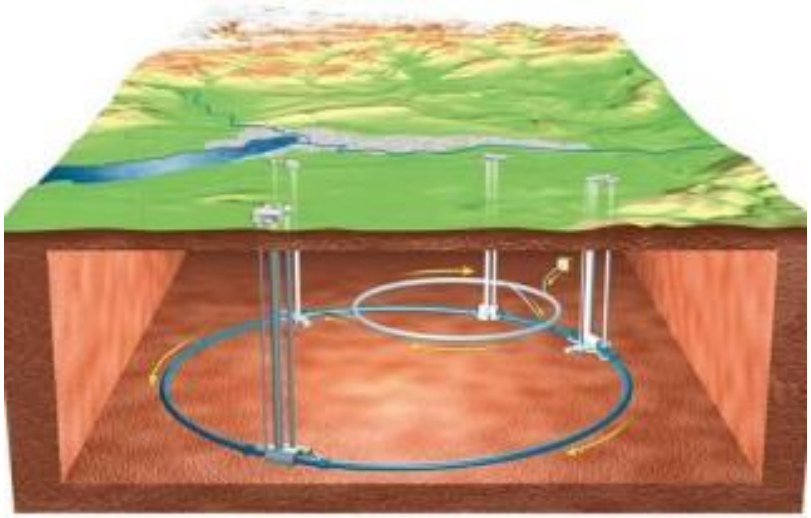
Background knowledge



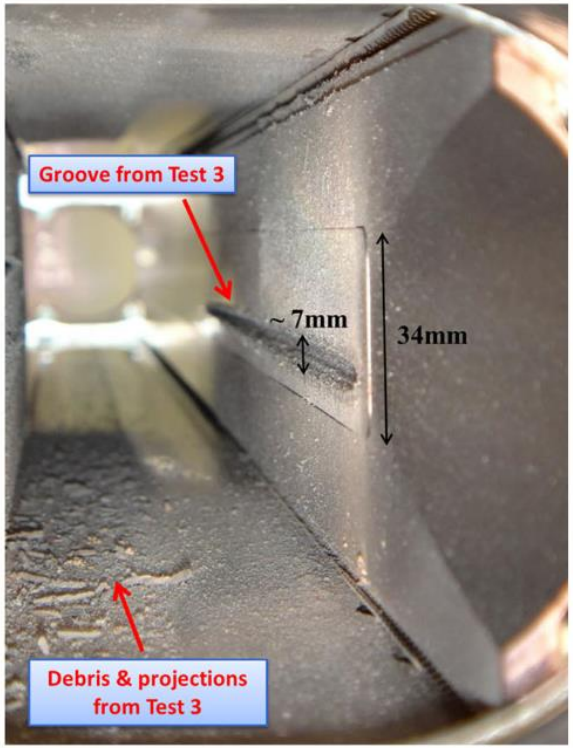


LHC

- The Large Hadron Collider (LHC) : A 27km ring

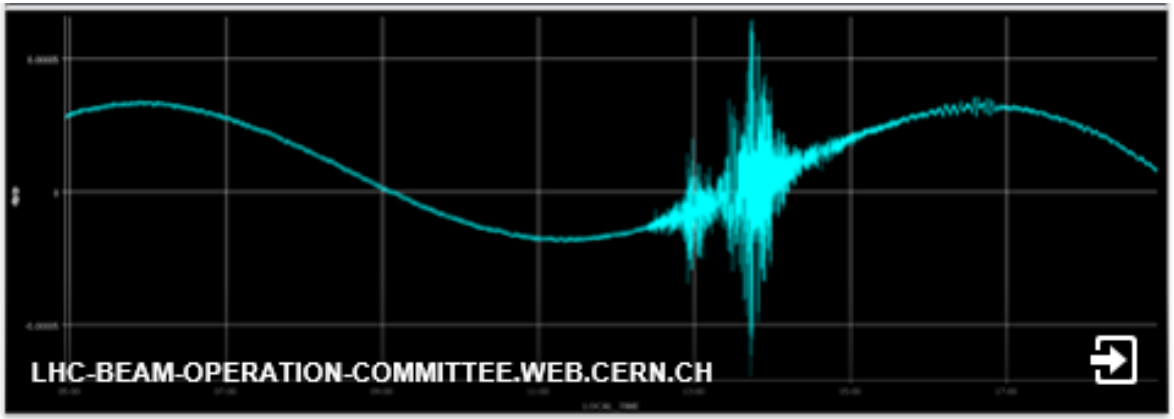


The energy of a 200m long fast train at 155 km/hour corresponds to the energy of 360 MJ stored in one LHC beam



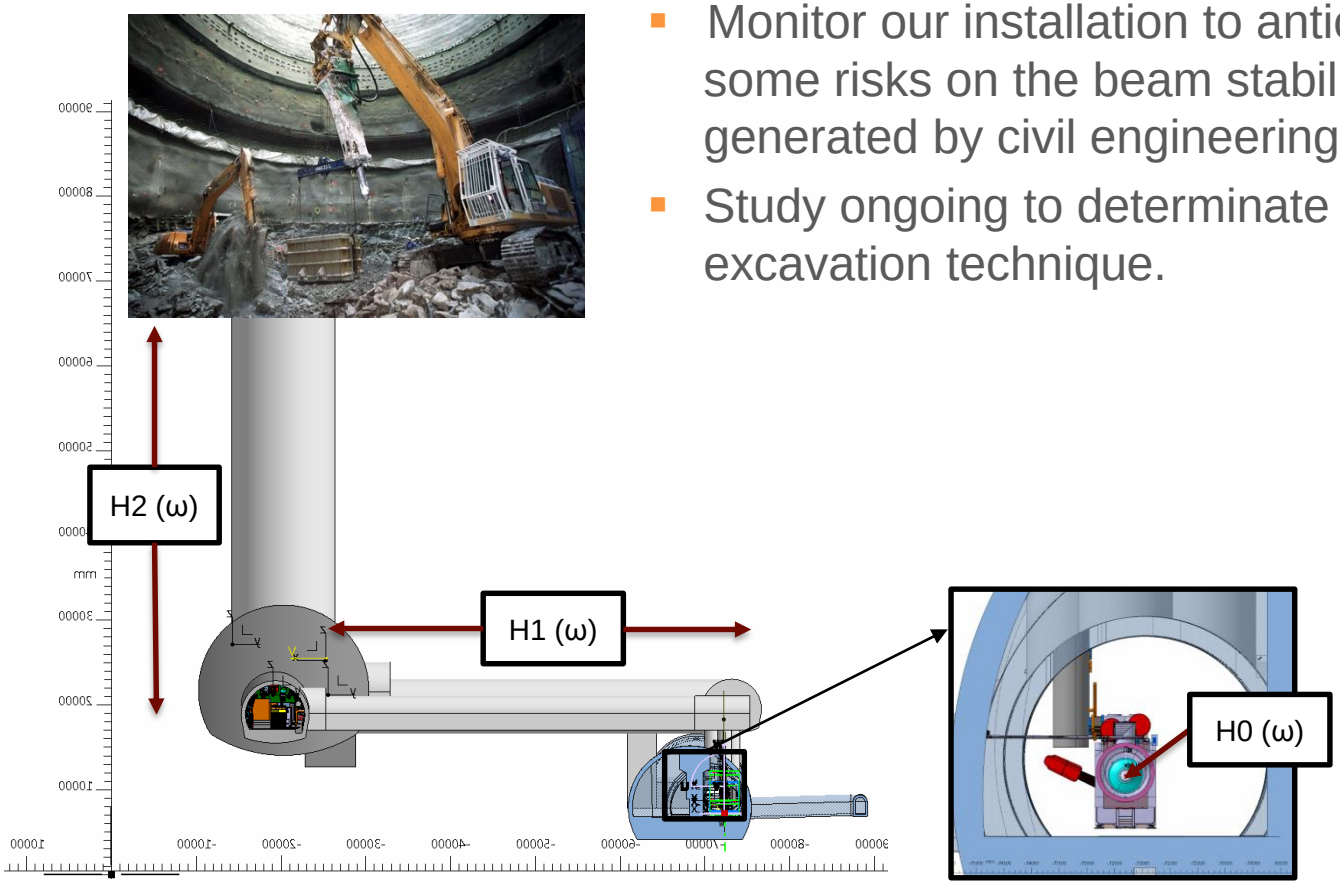
Motivations

- Continuous LHC monitoring
  - Beam sizes around 1 mm during injection, 0,25 mm at top energy
  - Stability of the magnetic field center (depending LHC operation):
    - Safe conditions : < 5 µm
    - Unstable conditions : 5 to 20 µm
  - Beam abort : > 20 µm



Motivations

- HL-LHC Civil engineering activities



- Monitor our installation to anticipate some risks on the beam stability generated by civil engineering activities.
- Study ongoing to determinate the best excavation technique.

Motivations

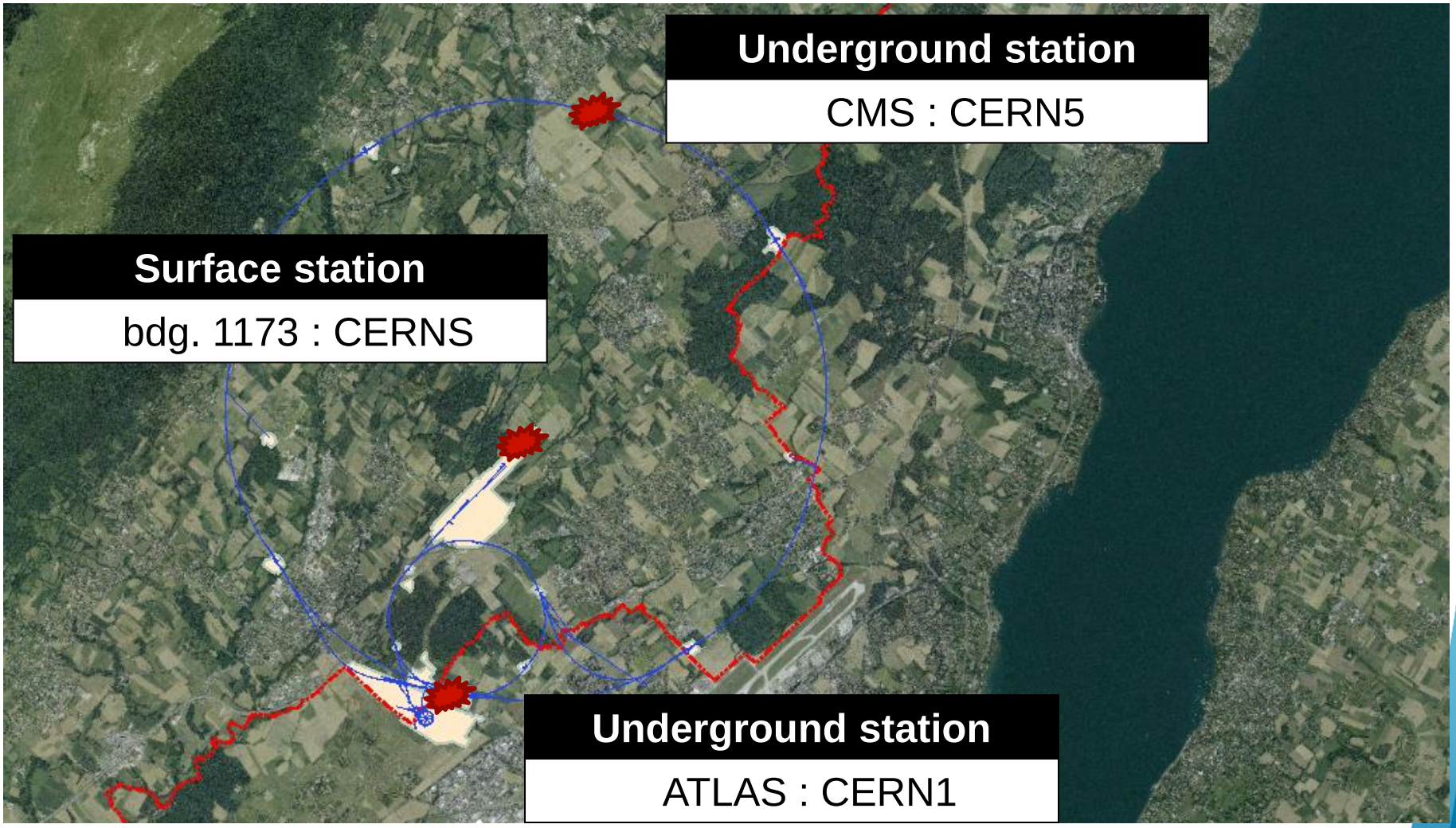
- Geneva Program “Géothermie 2020”
  - Evaluate effects of the micro-seismicity induced by the geo-thermal exploitation on CERN installations.
  - Study by the engineering company Resonance mandated by SIG (Services Industriels de Genève)

Expected earthquakes	During the stimulation period	During the stationary phase	Expected cold mass movements
Magnitude 2	Several per week	A few per month	~1-10 µm
Magnitude 3	A few per month	2 to 3 per year	~10-100 µm

- Need for a seismic network
  - Measuring near source earthquakes to better know the region seismicity
  - Integrated into the worldwide seismic network

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

Requirements



Requirements

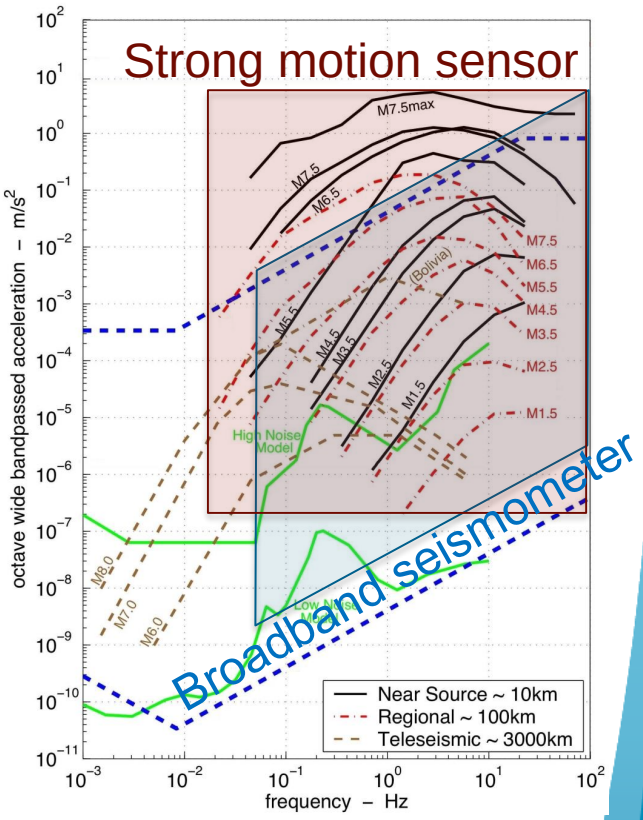
	Needs for a common station	Specific needs for CERN
	Geothermal exploitation, SED	HL-LHC excavation
Min amplitude	LHC ground motion	LHC ground motion
Max amplitude	20 m/s^2	20 m/s^2
Min frequency	1/30 Hz	1 Hz
Max frequency	20 Hz	100 Hz
Timestamp precision	~ 1 ms	~ 10 ms
Data latency	10 s	1 min
Data format	MiniSEED	ASCII
Data transmitted to	SED servers	CERN servers, LHC database
Other needs	Available 24/7	Independent systems with same software and hardware

- Due to different needs, it was easier to develop a solution internally

Hardware proposal

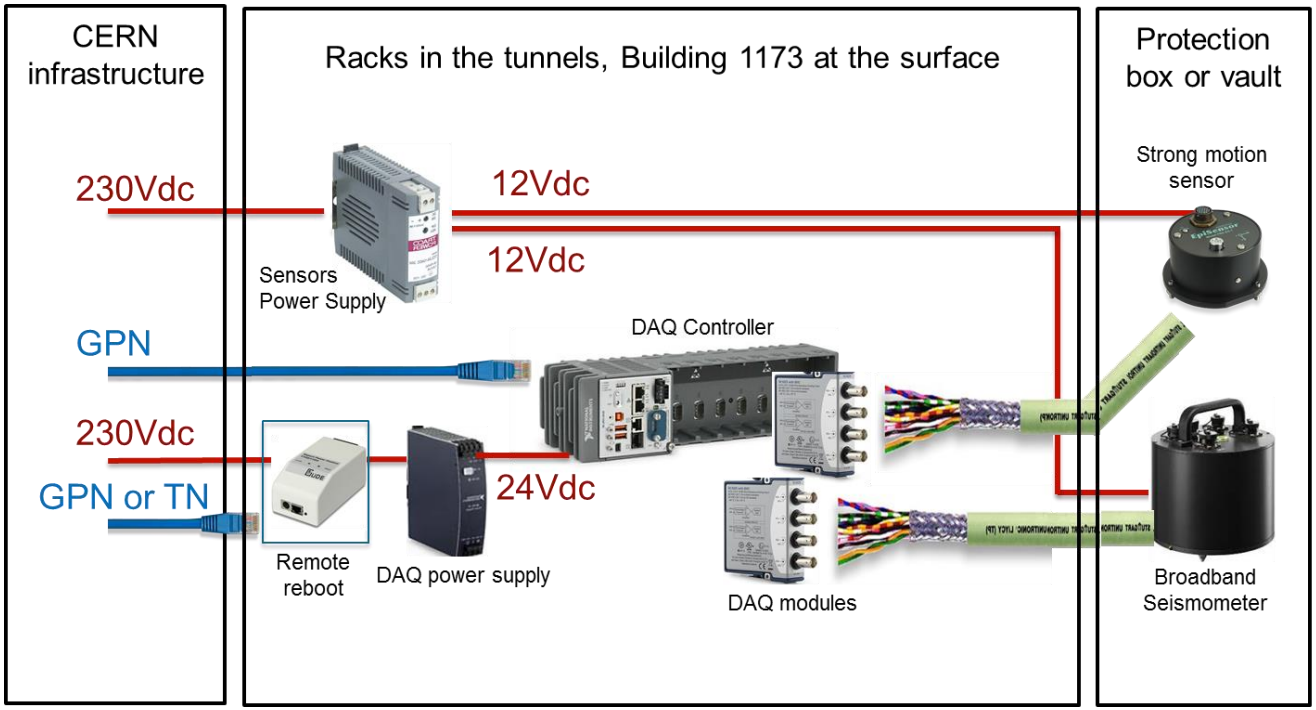
- Sensors

Model	Guralp 6T	Guralp 40T	Kinemetrics EpiSensor ES-T
Output	Velocity	Velocity	Acceleration
Triaxial	Yes	Yes	Yes
Frequency range	30s to 100Hz	60s to 100Hz	DC to 200Hz
Sensitivity	2000 V/(m/s)	800 V/(m/s)	2,5 V/g
Analog/digital	both	both	Analog +-5V differential
Noise	172 dB	172 dB	155 dB
Power supply [V]	10 to 36V	10 to 36V	12V
LHC Ground motion level	Yes	Yes	No
Threshold level for earthquake	≈ M3 @10km	≈ M3,5 @10km	M 7,5 @10km



With a 10V, 24 bits ADC

Hardware proposal



- NI CompactRIO 9035 (1 GB RAM, 2 cores)
  with NI C-series 9239 (+/-10V, 24bits, fs = 1.6 to 50kHz, 70uV noise)
- Linux Real Time
- NTP timing source at CERN (<1ms accuracy)
- GPN connection
- Remote reboot: GUDE Expert power control 1103

Software proposal

Raw data

SED and worldwide seismic databases

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

MiniSEED Files : Standard for Exchange of Earthquake Data (time domain)

CERN Users

timber
The LHC Logging System
TIMBER
browsing & data extraction

Power Spectral Density : Ground motion monitoring (frequency domain)

CERN Experts

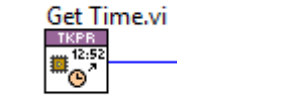
Mechanical Measurement Laboratory

Raw data (time domain)
Power Spectral Density (frequency domain)
Sum Level (time domain)

Technical proposal

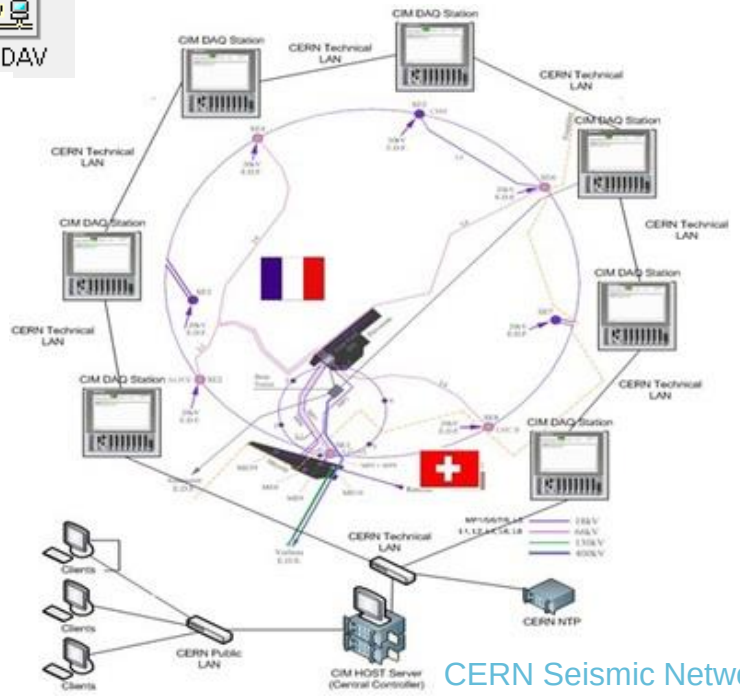
Advantages

- CERN is a LabVIEW Center of excellence
- Huge experience with CompactRIO at CERN
- Timekeeper API
- Sounds and Vibration, HTTP, WebDAV palette from NI
- RADE palette from MTA Team to communicate with CERN infrastructure
- Distributed architecture
- System fulfilling the requirements

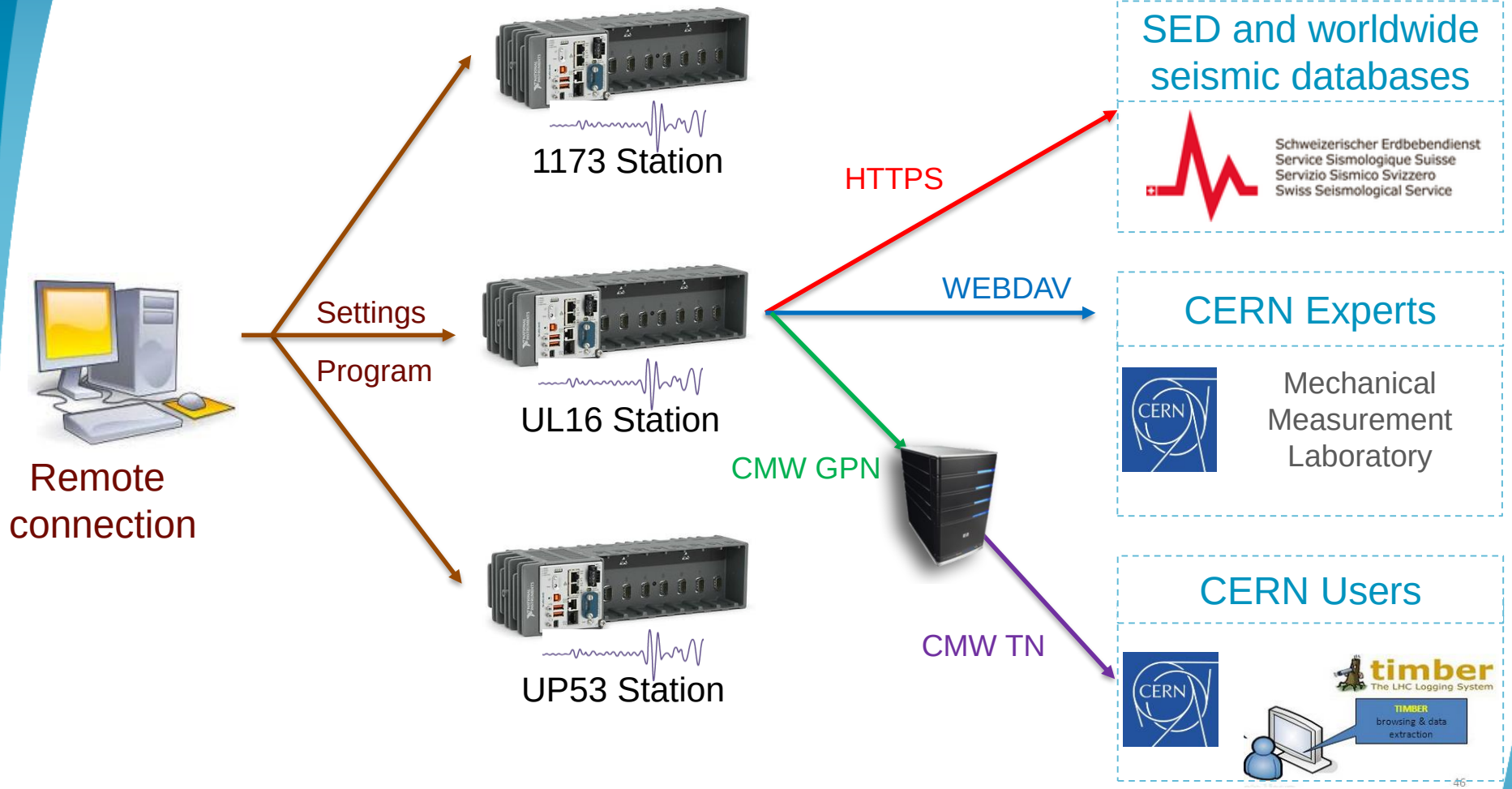


Challenges

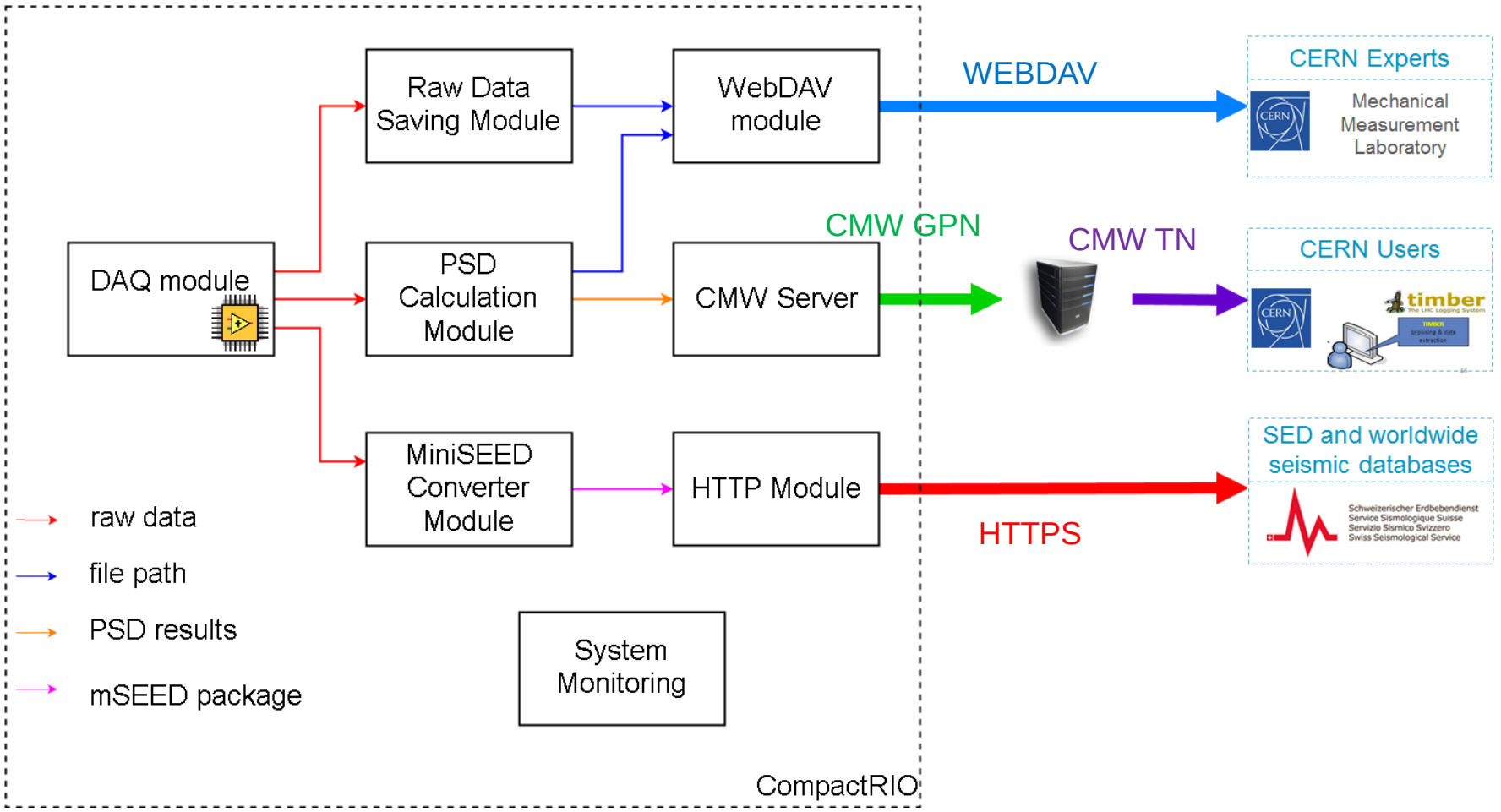
- Manpower cost more important for the development
- Mseed converter to be develop
- Quality of the streaming to SED to be proven
- Non-standard seismic station



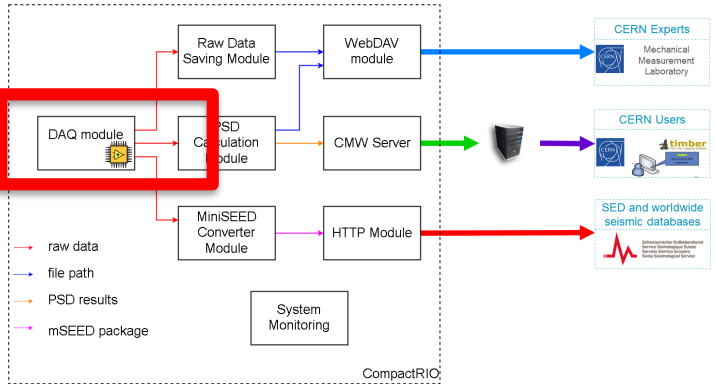
Software architecture



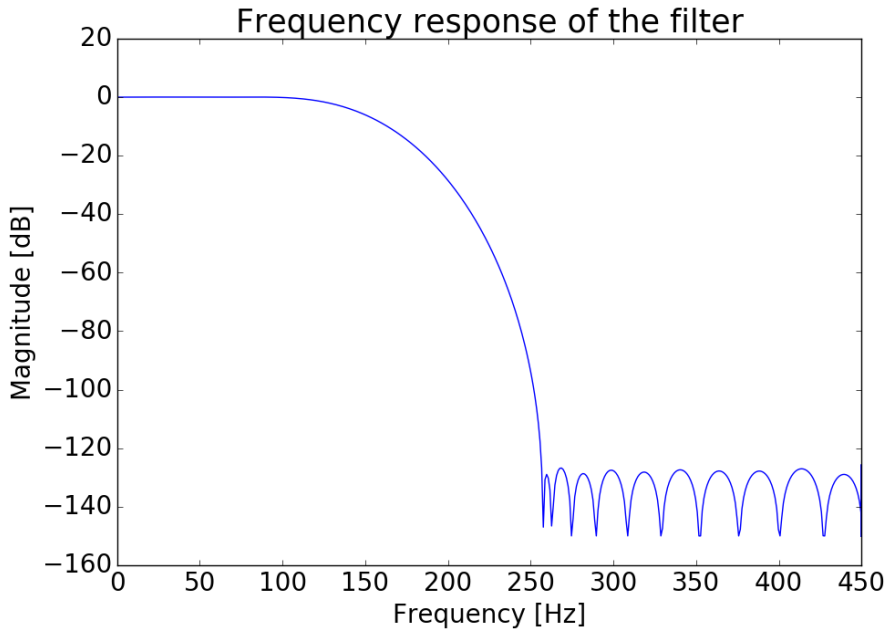
Software architecture



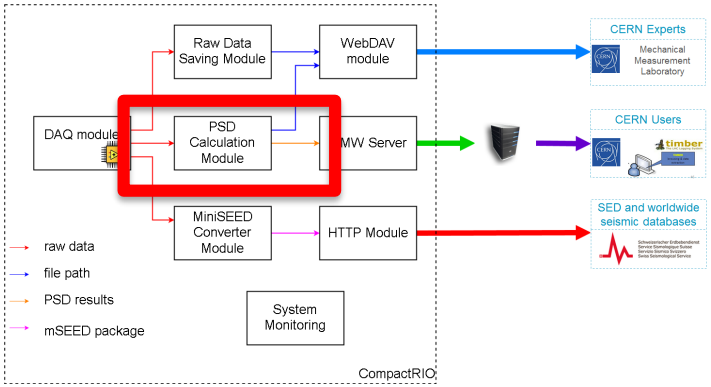
Data Acquisition Module



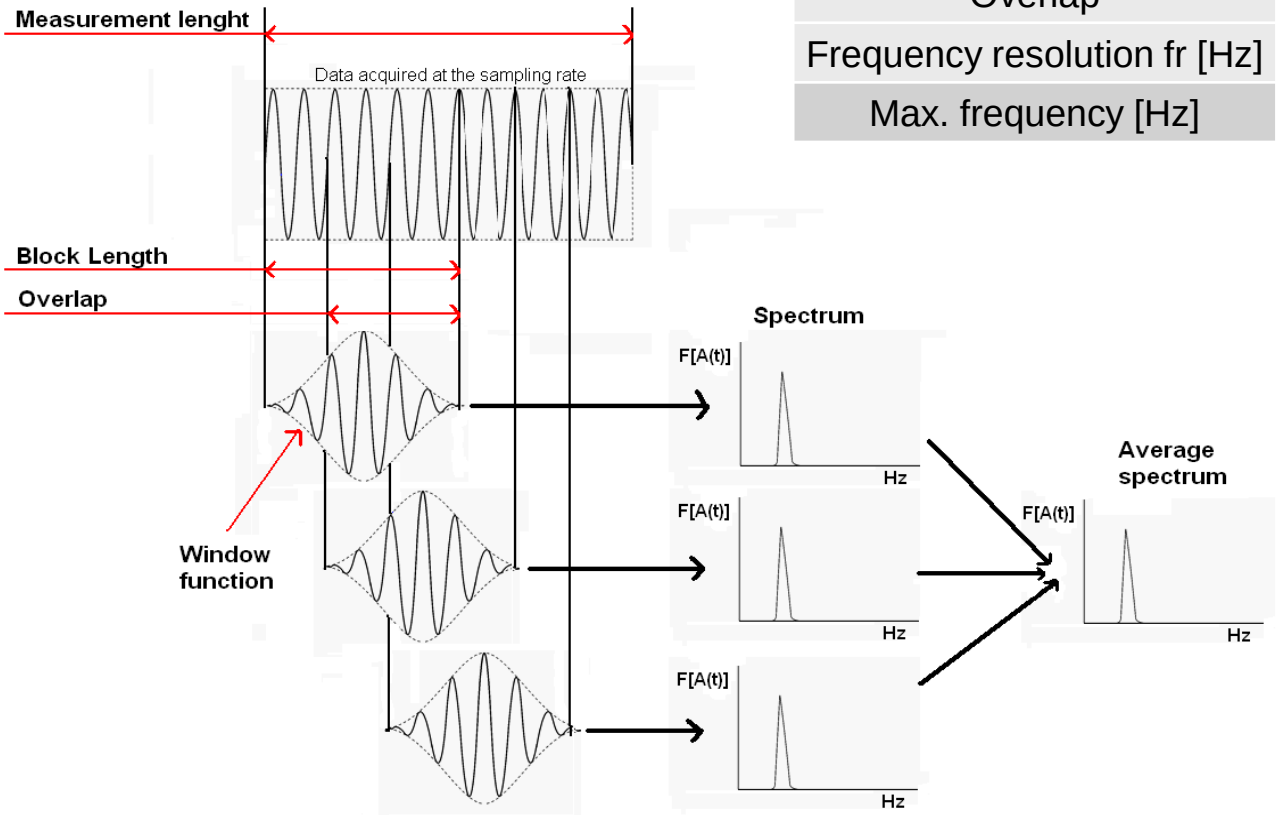
- Read data from DMA
- Keep Timekeeper synchronized
- Down sample and filter from 2kHz to 250Hz
- Sinc filter with Blackman window



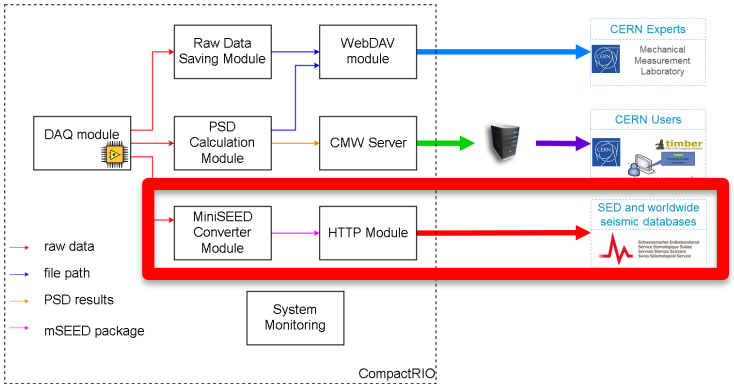
PSD Module



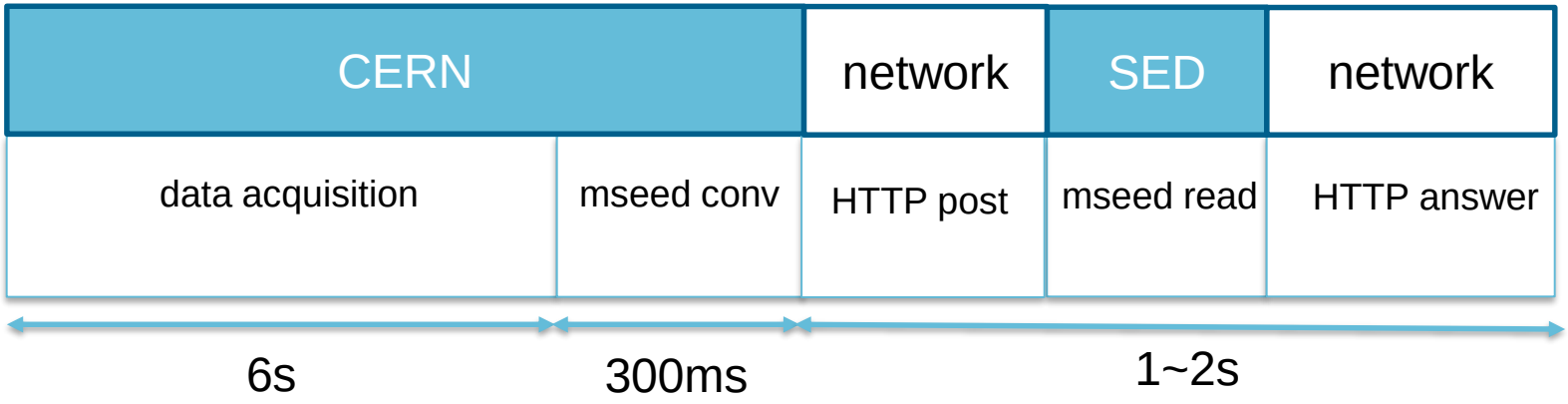
Parameter [unit]	Value
Representation	Quadratic RMS [m^2/Hz]
Window	Hanning
Block length	64s
Overlap	66.60%
Frequency resolution fr [Hz]	0.015625
Max. frequency [Hz]	97.7



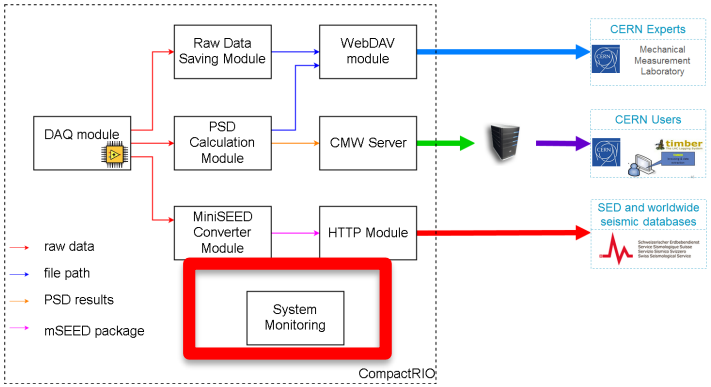
MiniSEED Converter & HTTP Module



- Build MiniSEED header (timestamp, sequence number, station name…)
- Send package to SED
- Handle SED server reboot, network disconnection
- Objective: 10s latency



System Monitoring Module



- Monitor CPU/RAM usage
  - Maximum CPU peak at 50%

    Average CPU ~ 10%
  - About 50% of the 1GB RAM available
- Monitor VI states
- Monitor number of elements in queue and RT fifo
- Send “alive” message to an other machine
- Monitor NTP synchronization

NTP report :

	remote	refid	st	t	when	poll	reach	delay	offset	jitter
*	[redacted]		2	u	556	1024	377	0.301	-0.071	0.025
+	[redacted]		2	u	397	1024	377	0.302	-0.091	0.038
+	[redacted]		3	u	47	1024	377	0.335	-0.062	0.038

NTP server

seconds

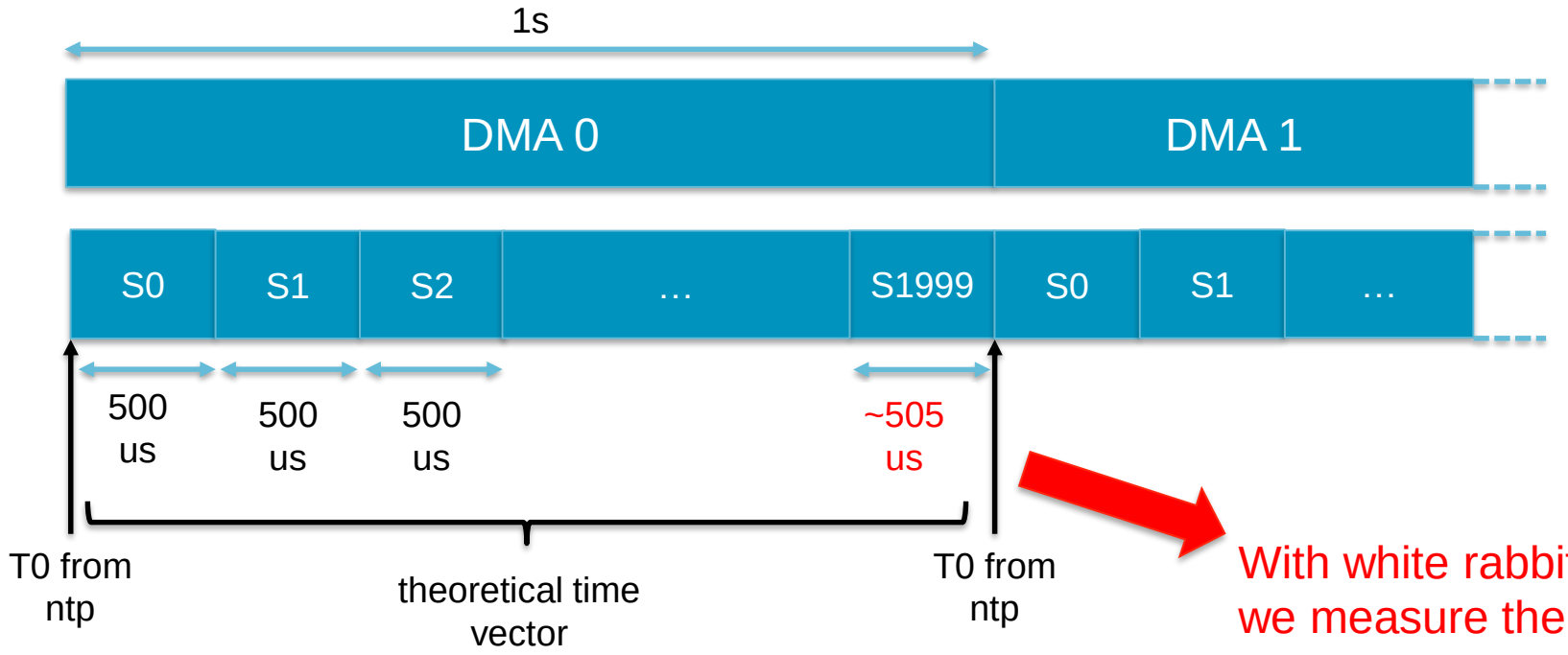
Octal code

milliseconds

The timing challenge

- Problem with SED :

The 2kHz on-board clock is not perfect. The gap between the timestamp of sample 1999 of DMA 0 and sample 0 of DMA 1 had to be reduced below 1us to fulfil SED requirements



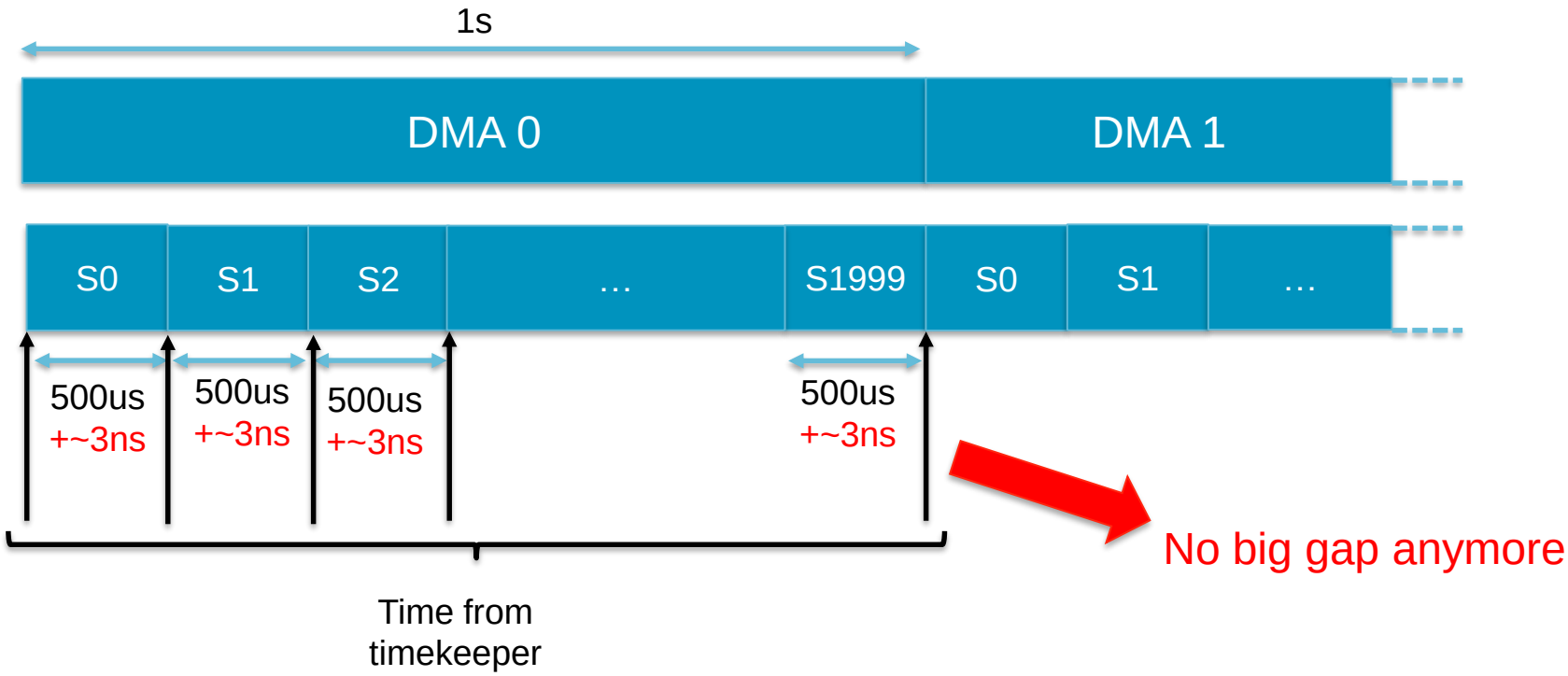
With white rabbit, we measure the loop speed at ~500.003 us

http://www.ohwr.org/projects/white-rabbit/wiki

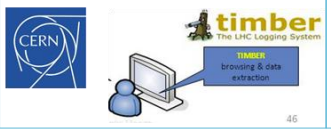
The timing challenge

- Solution :

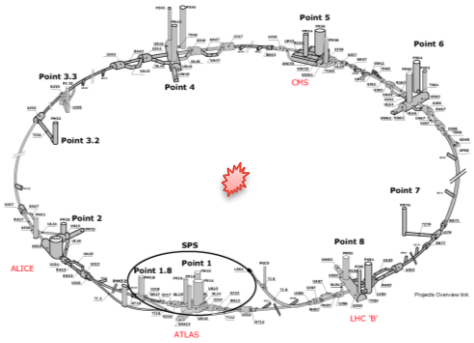
  The timekeeper API to timestamp every sample on the FPGA



Software Robustness

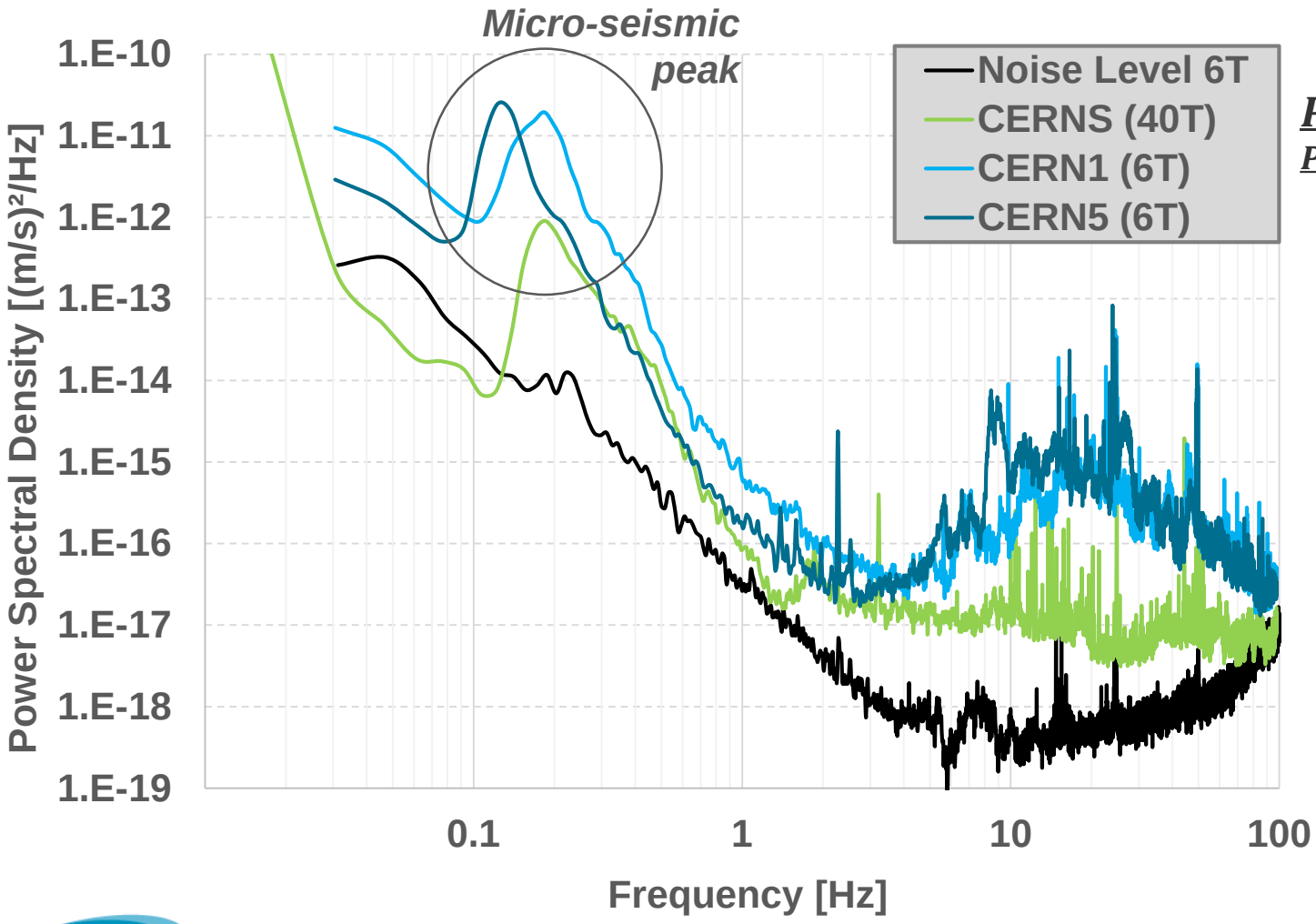
Problem	CompactRIO reaction
CERN Users 	Sends warning and keeps streaming
SED and worldwide seismic databases 	Stores MiniSEED files on USB drive, sends it when SED is back
CERN Experts Mechanical Measurement Laboratory	Stores experts files on USB drive
	Stores everything on USB drive
	Automatic restart

Installation



Stations performance

- Ground motion measurements versus position



PSD

Power Spectral Density

$$\phi_w = \frac{\left(\overline{S_w^2}\right)}{fr}$$

$\overline{S_w}$: average magnitude of FFT spectrum [rms]

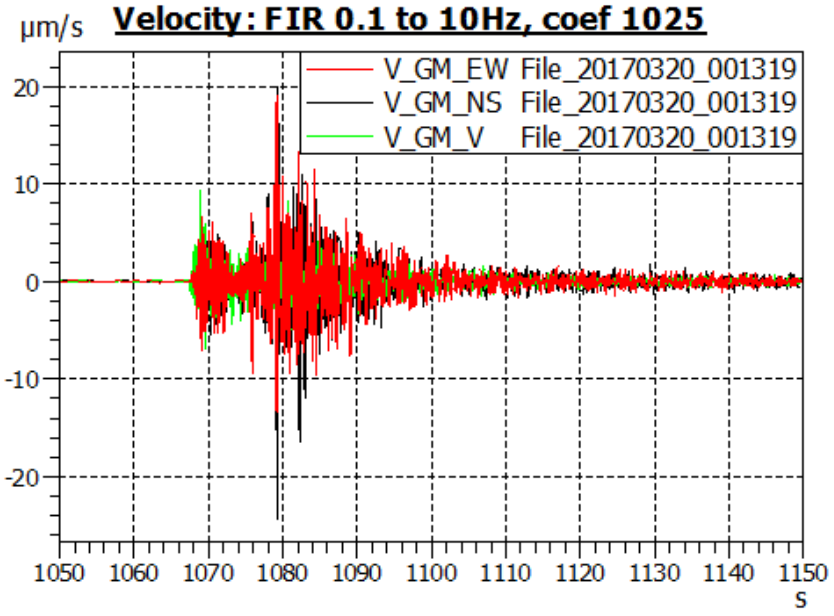
fr: *Frequency resolution*

Stations performance

- Recorded earthquakes

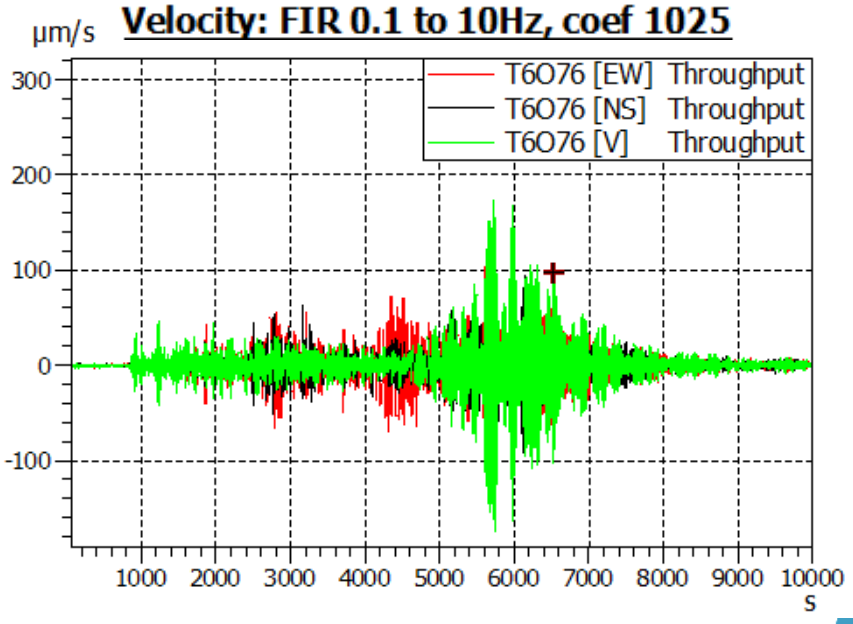
M 3.3 - FRANCE - 2017-03-20 00:30:54 UTC

- Magnitude **ML 3.3**
- Region **FRANCE**
- Date time **2017-03-20 00:30:54.7 UTC**
- Location **46.04 N ; 6.91 E**
- Depth **4 km**



M 7.9 - SOUTH ISLAND OF NEW ZEALAND - 2016-11-13 11:02:58 UTC

- Magnitude **Mw 7.9**
- Region **SOUTH ISLAND OF NEW ZEALAND**
- Date time **2016-11-13 11:02:58.4 UTC**
- Location **42.69 S ; 172.97 E**
- Depth **10 km**



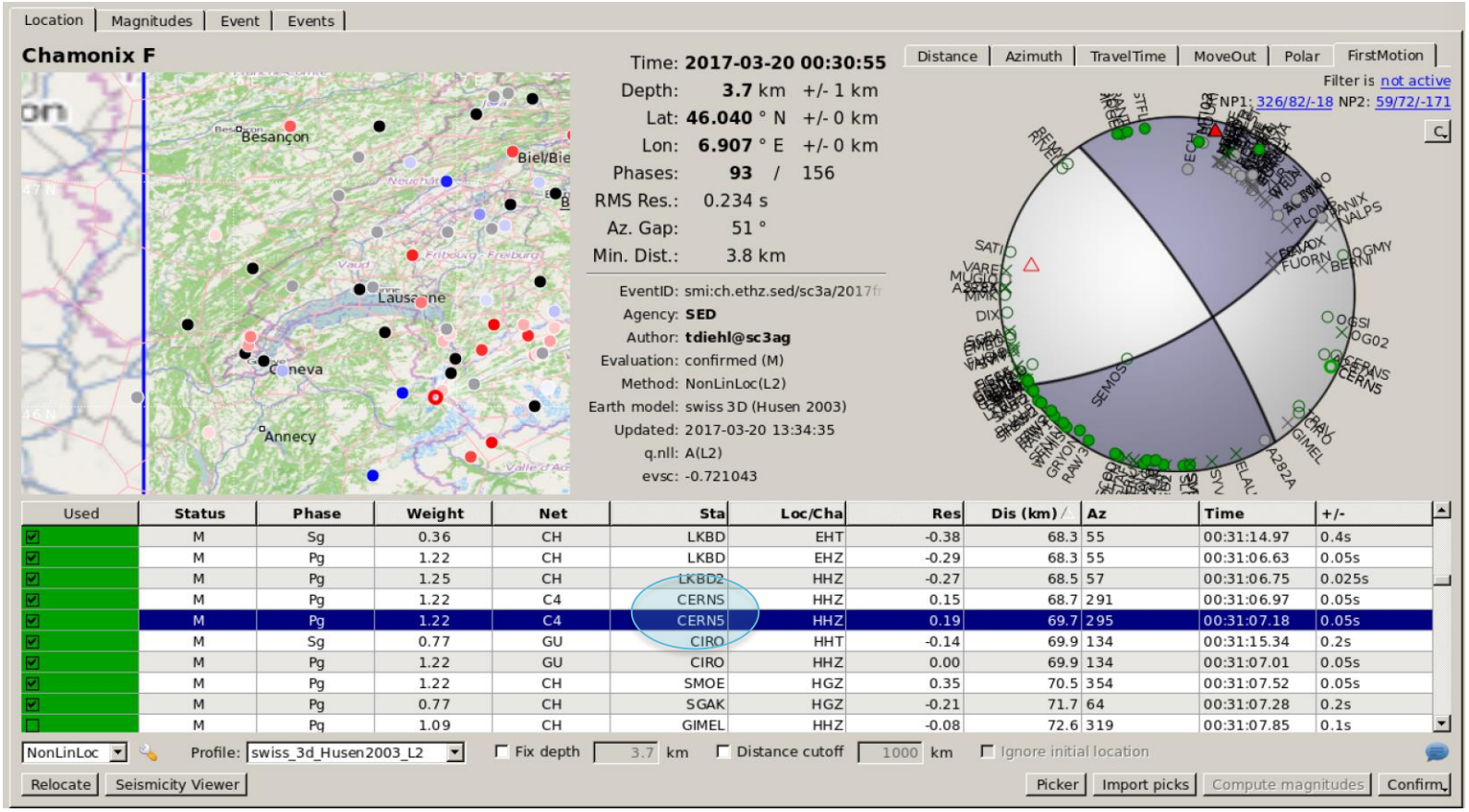
Conclusion

- The seismic network already permits to:
  - Monitor the LHC ground motion
  - Track earthquakes on a wide range of amplitude

- It satisfied successfully the needs of SED and CERN
  - System compliant with LHC tunnel and CERN network
  - Standard format files for seismologists

- SED is doing some regular checking on CERN stations as for their own stations, CERN is maintaining the stations.

Conclusion



"CERN stations fully integrated in network, expect to operate like any other SED station, and included permanent archive"

"CERN stations now used in all earthquake related products"

Dr. John Clinton, Director of Seismic Networks and Head of the Earthquake Monitoring section at the SED

Future of the project

- Further calculations will be implemented in order to set a warning trigger during the excavation.
- A further collaboration will permit to get a warning in case of large earthquake.
- The possibility of sending the data with a 2s latency could allow to add the stations into the fast triggering system and forecast the earthquakes arrival.
- The CompactRIO is not using all of its CPU and RAM: The available slots can be used for future developments.
- The price of a future station is estimated to 27 000 CHF.

Thank you!

Questions