Long-term monitoring with spring-based gravimeters

Tilt-control benefits
&
Application to the Rochefort Underground Laboratory (Belgium)

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Monitoring gravimeters

The iGrav#002
(Photo N. Le Moigne)

Superconducting gravimeters (SGs)

Noise : ~3 nm/s²/√Hz *i.e* **1 nm/s²** signals observed after **1-minute** filtering

✓ **Drift**: small and linear over a decade (*Van Camp & Francis, 2007*)

X *Size, weight, helium* compressor needed

Teh gPhoneX #32
(Photo O. Francis)

Spring-based gravimeters

The gPhoneX (Micro-g LaCoste Inc., 2013)

Noise: **< 3 nm/s²** after **1-hour** filtering

X **Drift**: high, non-linear and variable

✓ Total weight: less than 60kg, 1m² needed

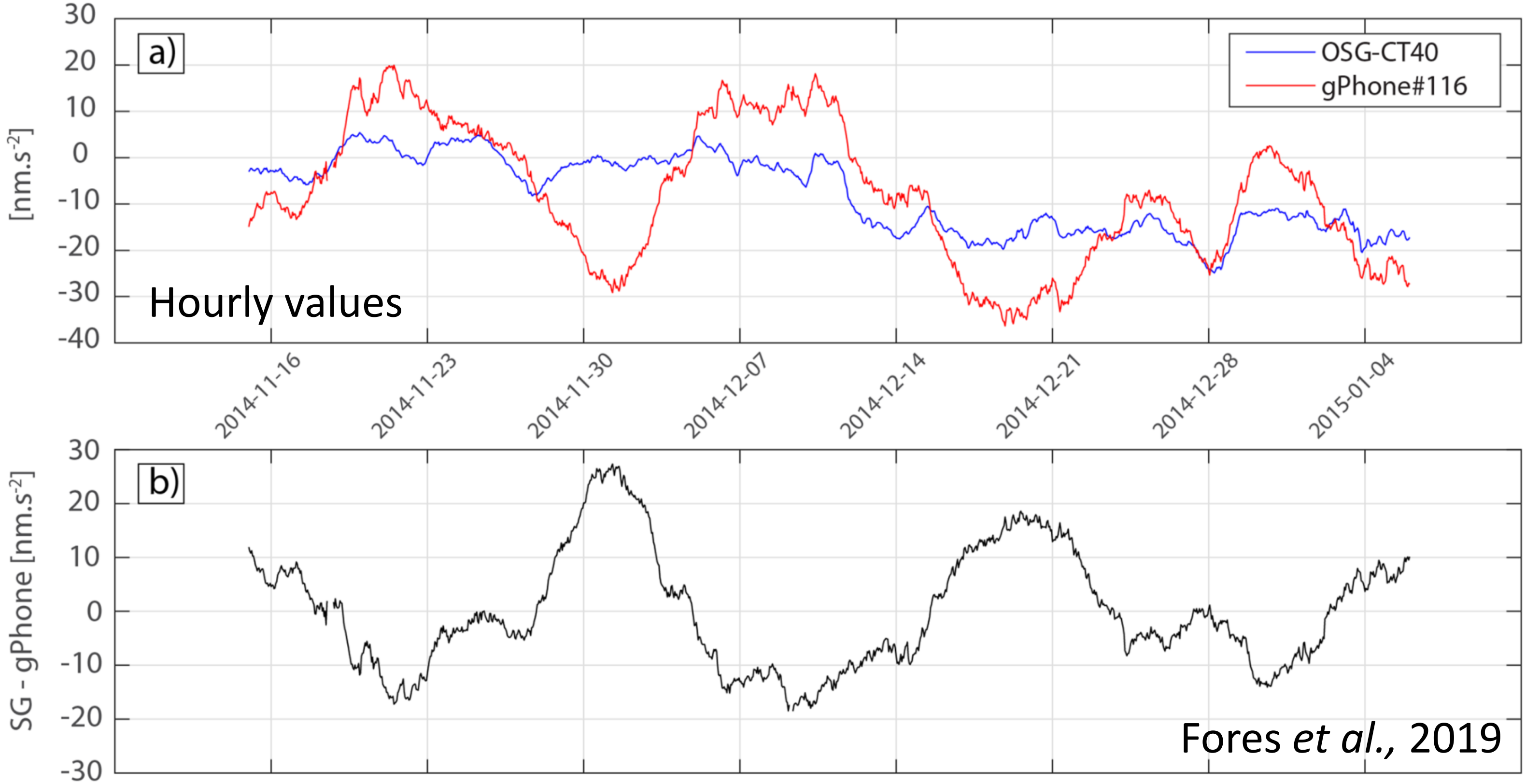
→ Both are relative instruments. **SGs** have the best precision and **are much more stable.**

→ Despite the size reduction of the new *iGrav* SGs (Warburton *et al.* 2011), they remain restricted to specific sites and more expensive than spring gravimeters.

→ The *GphoneX* is precise enough for many kinds of studies; but its instability (induced by its high and no-linear drift) prevents its use for long term monitoring.

Tilt-uncontrolled gPhoneXs

53 days of tilt-uncontrolled gPhoneX versus SG in Luxembourg



- gPhoneX drift corrected with a 3rd degree polynomial function
- **Tilting of max. 180 µrad, corrected in post-processing, re-leveled every month**
- **Differences up to 30 nm/s²** after two weeks between the SG and the gPhoneX
- Other examples in Literature (e.g. Riccardi *et al.* 2011)

→ No matter the degree of the drift correction applied, gPhoneXs are not suited for long term monitoring

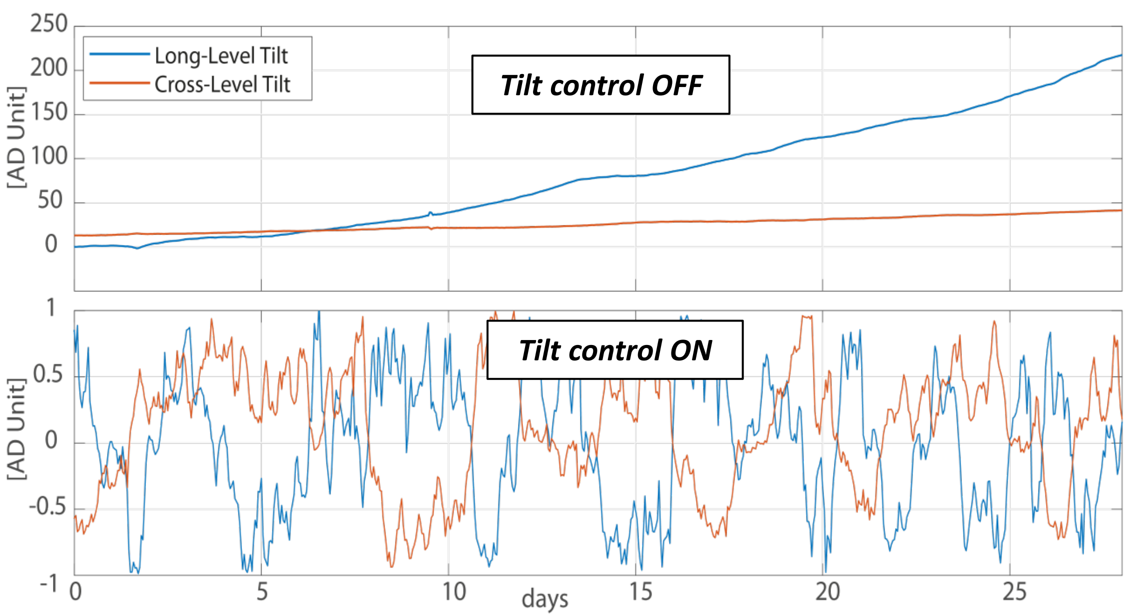
The gPhoneX Tilt-Control Platform

The gPhone tilting over time **is not** actively controlled **, unlike for the SGs**

→ Is tilting the origin of the gPhoneX lack of stability ?

The tilt-control platform developed in Luxembourg:

- 2 piezoelectric legs
- Maximum deviation: ± 1 AD unit = ±0.6 μrad



The platform designed by Francis and Klein

Note: Since then, Micro-g designed its own platform with thermo-controlled legs. The same precision is achieved on the tilt control, so the results presented hereafter are expected to be the same.

1st part: comparisons in the WULG and GEK (Fores *et al.* 2019)

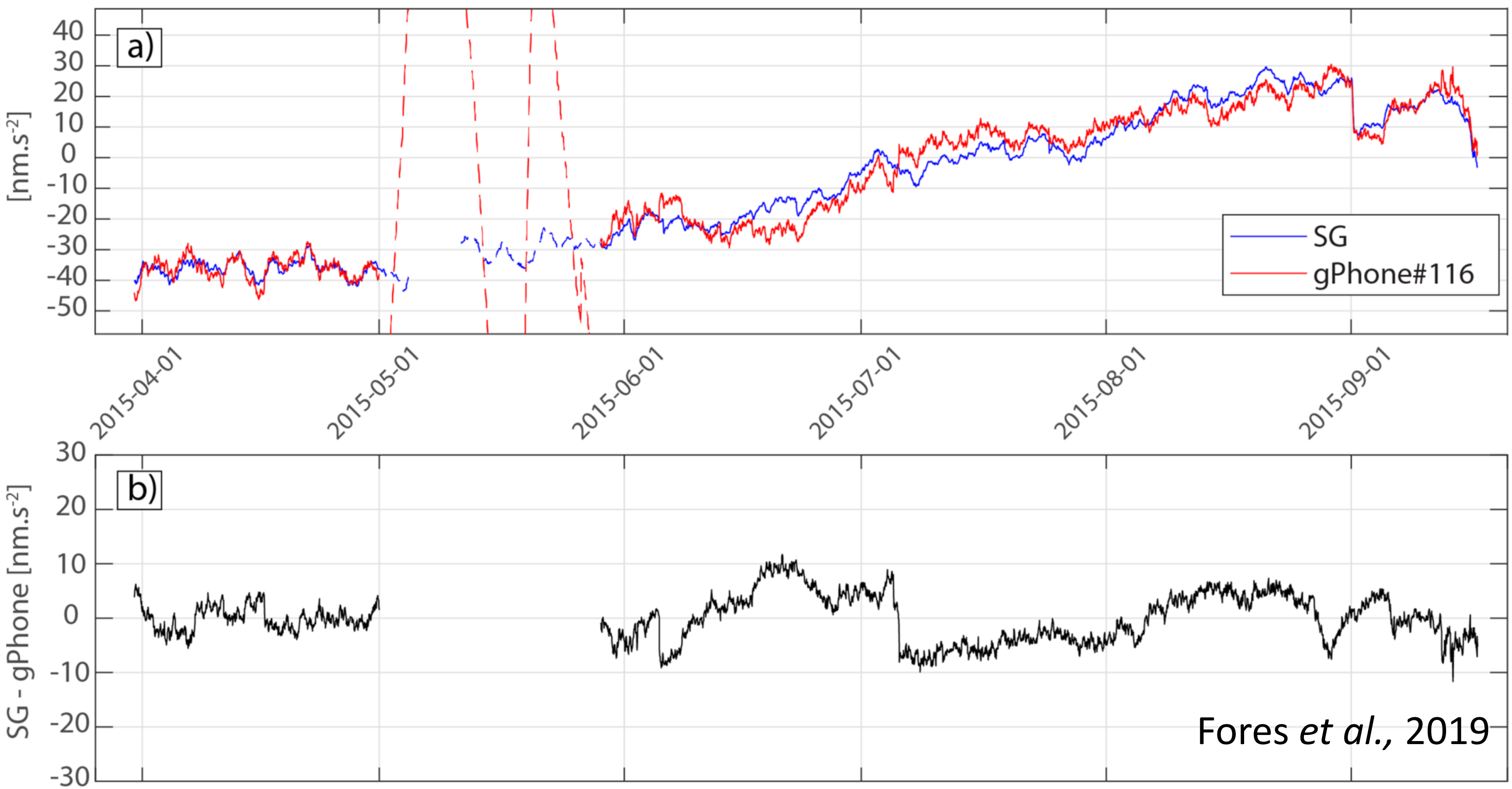
Two observatories operating **superconducting gravimeters (SGs)** and tilt-controlled **gPhoneXs** **simultaneously**

The WULG (Luxembourg) *Walferdange Underground Laboratory for Geodynamics*	**The GEK (France)** *Geodesy in Karstic Environment*
Quiet site, ~100 m below the surface	Quiet site, isolated on the Larzac plateau
OSG-CT040 Superconducting Gravimeter since 2003 (*Lampitelli & Francis, 2010*)	iGrav#002 Superconducting Gravimeter since 2011 (*Fores et al., 2017)*
Tilt-controlled gPhone: 112 days	Tilt-controlled gPhone: **almost a year**
Gravity residuals amplitude: ~ 60 $nm.s^{-2}$ (mainly hydrological signal)	Gravity residuals amplitude: > 150 $nm.s^{-2}$ (mainly hydrological signal)

→ **Comparisons** between tilt-control gPhoneXs and SGs (the references)

Comparison in the WULG

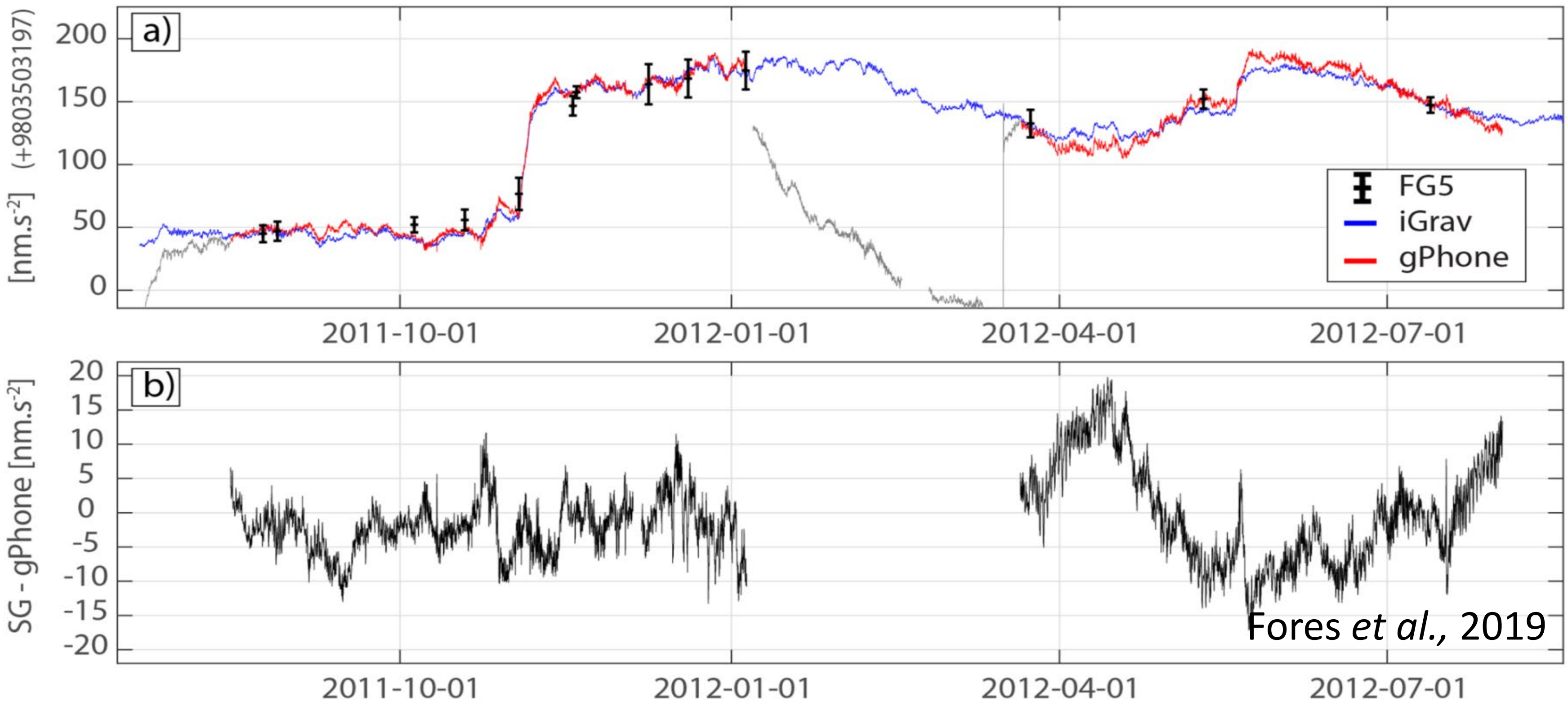
(32 +) 112 days with tilt-control



gPhoneX drift corrected with a 3rd degree polynomial

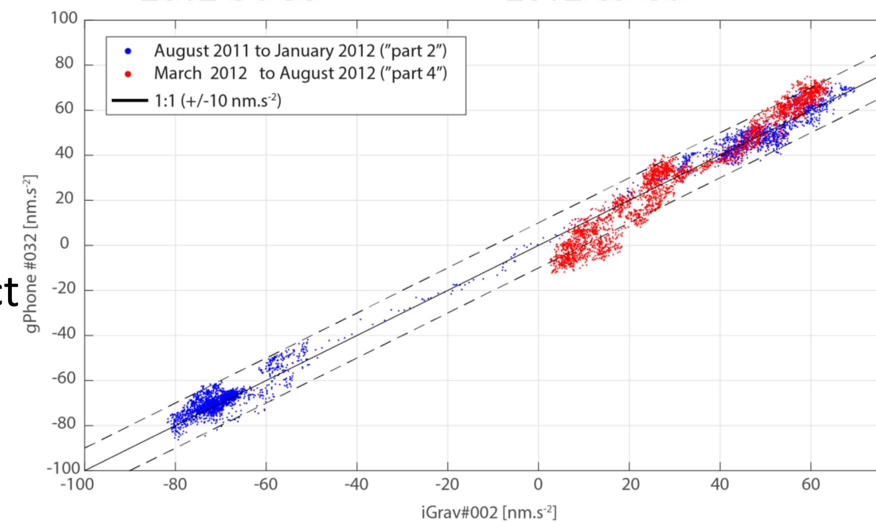
→ Hourly **differences** between the SG and the gPhone **are maintained below 10 nm.s^{-2} (1 µgal) !**

Comparison in the GEK



- **276 days** (over 354) with the tilt-control on.
- One discarded period, **but :**
  - **no offsets** were applied
  - **no human** intervention
  - a **unique 3rd degree** polynomial to correct the drift of the whole time series

→ **Hourly differences maintained below 10 nm.s^{-2}**



1st part Conclusions & Recommendations

CONCLUSIONS

- ✓ gPhoneX **stability** is greatly **improved** by an **active tilt control**
- ✓ **Differences** between gPhoneX and SG hourly values are below 10 nm/s^2 over one year and do not increase with time
  → Long-term stability of 10 nm/s^2
- ✓ gPhoneXs are stable and precise enough for long-term monitoring such as hydrological monitoring
  → 10nm/s^2 represents a 2.5 mm slab of water

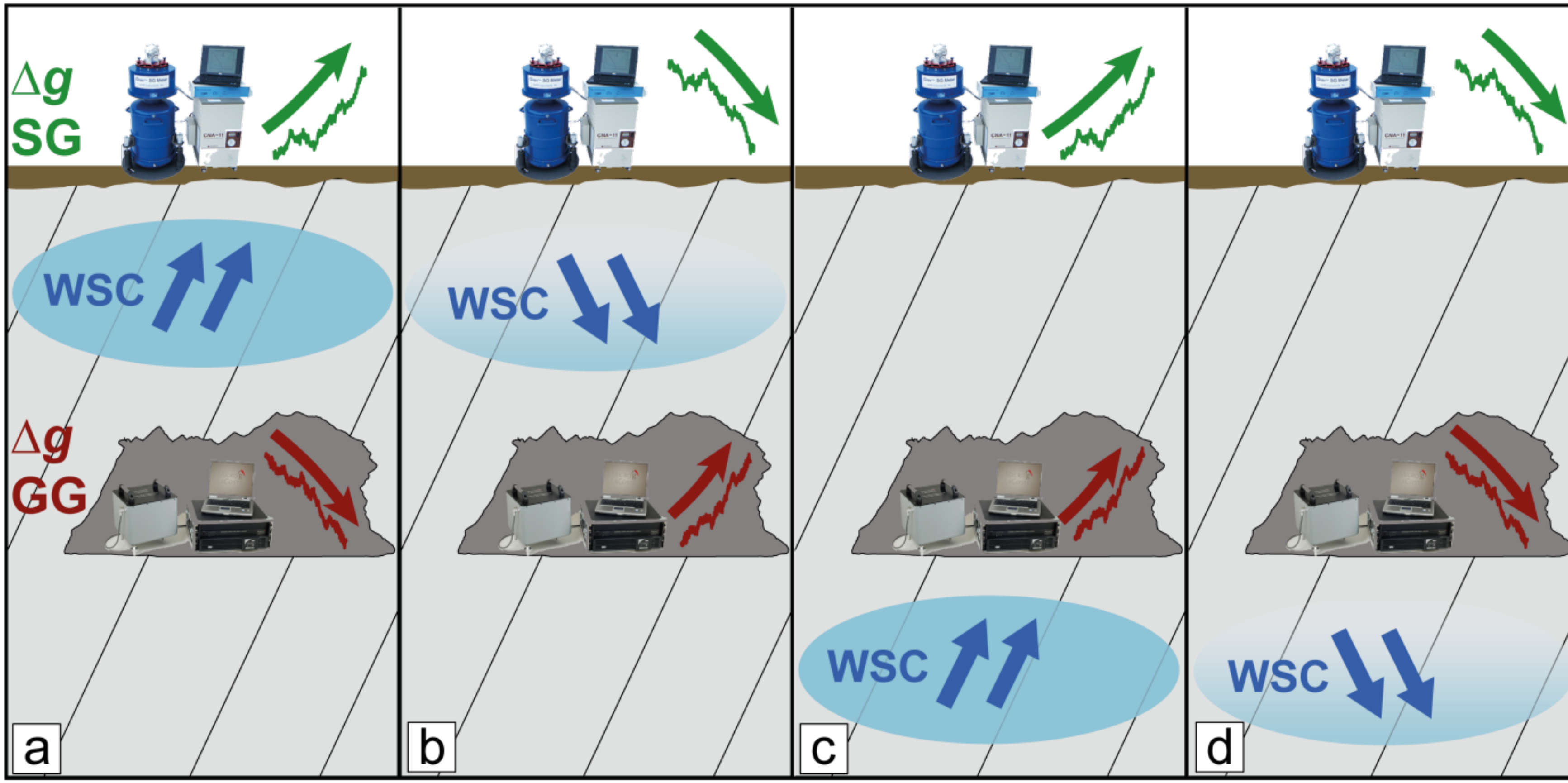
RECOMMENDATIONS

- Active tilt control
- Do not consider the initial relaxation period after the first installation. The drift decreases over time and tends to become linear.
- Equip the installation with an UPS system to avoid power shortages.

2nd part: practical application in the Rochefort Cave Laboratory (RCL, Belgium)

One iGrav Superconducting Gravimeter at the surface (buried 1m)

One tilt-controlled gPhoneX in a cave 35m below the surface

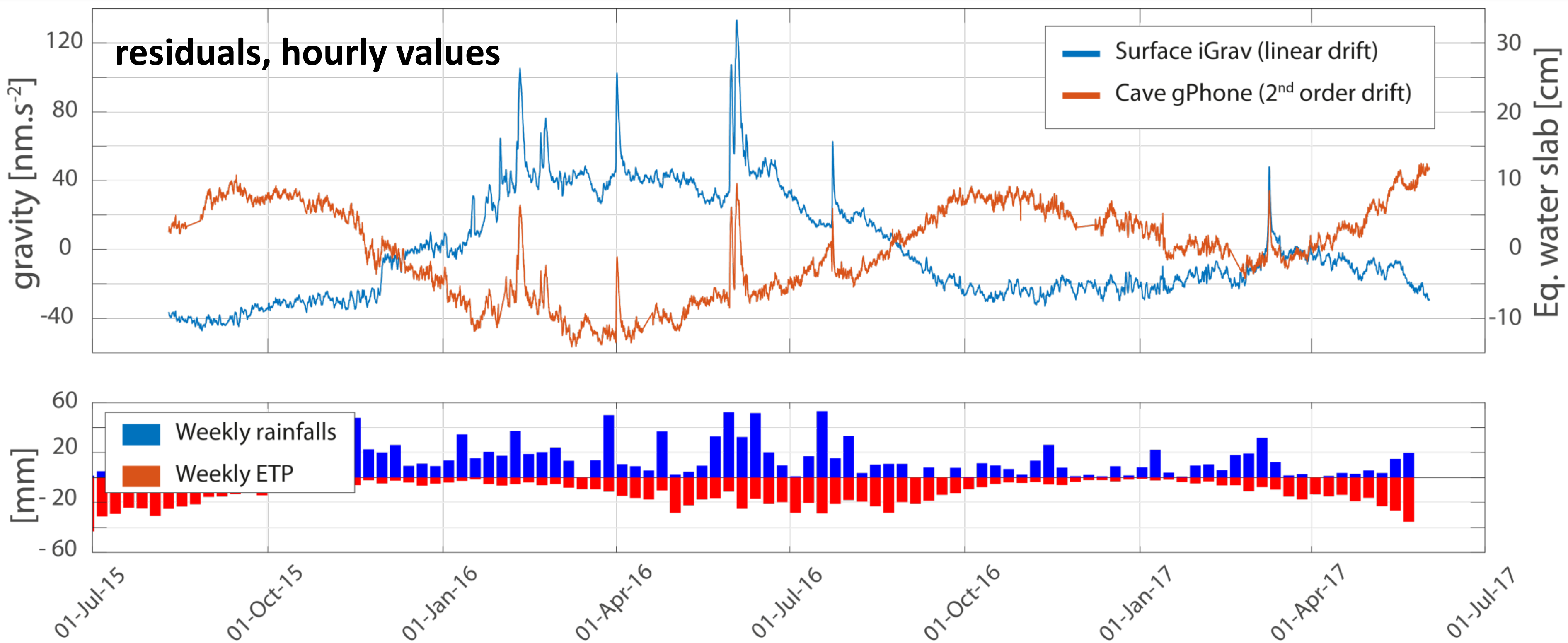


Watlet, 2017

In-cave installation thanks to the gPhoneX size

Hydrological interpretation based on the comparison of two precise time series

The RCL two-years time series



<u>**Direct information** on water locations & fluxes</u>

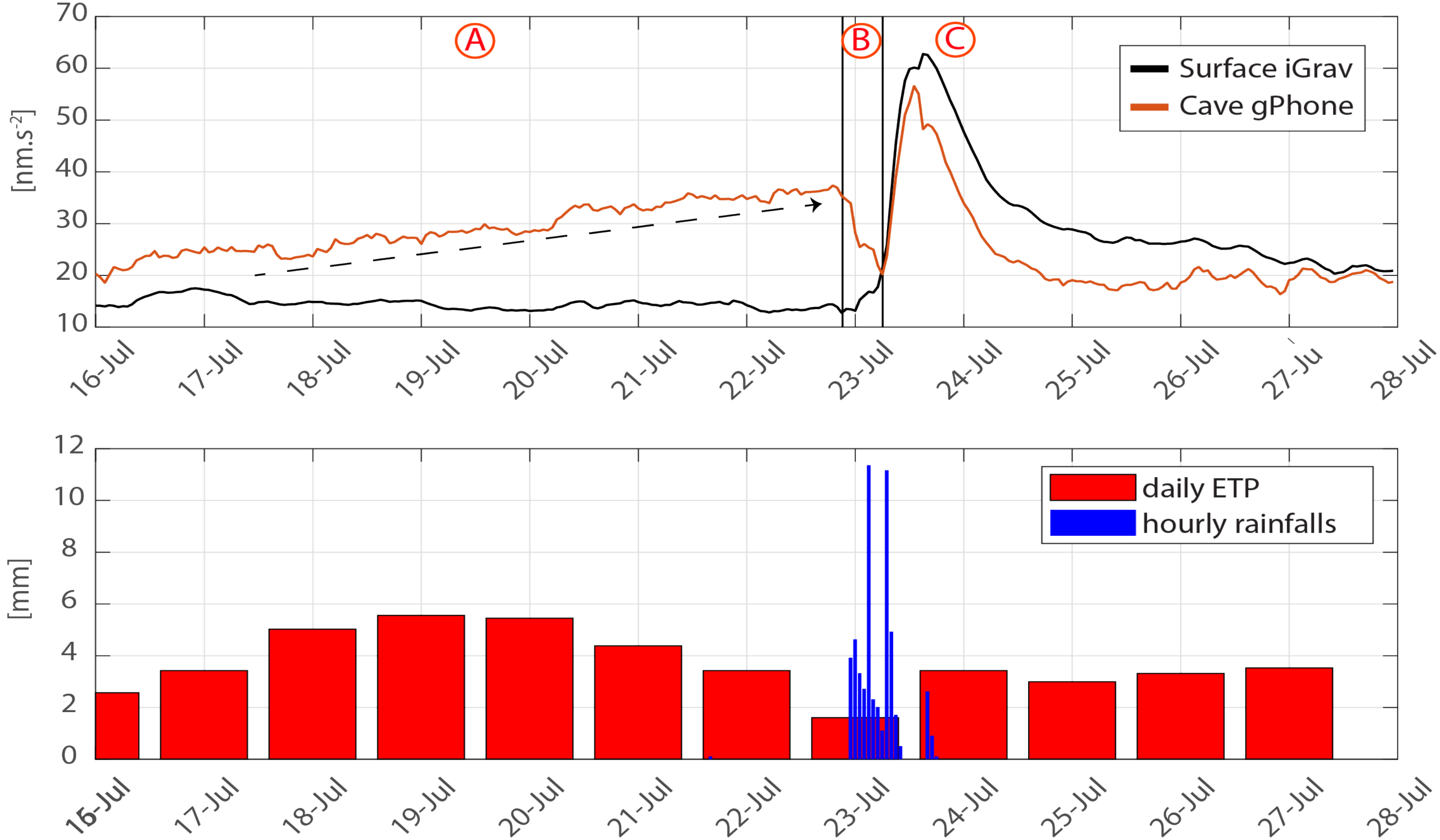
Long-term signal (matrix saturation changes) + floods peaks signals (karstic flooded conduits)

Long-term signal:

- **1-year period signal** (extrema in April and October): classical signature in Western Europe
- **Coherence** with meteorological data: **surface gravity ↗** after rainfalls and **↘** when dry
- **Anti-correlation** between the two gravimeters (r= **-0.93** after low-pass filtering)

→ **Seasonal water storage between** the two gravimeters

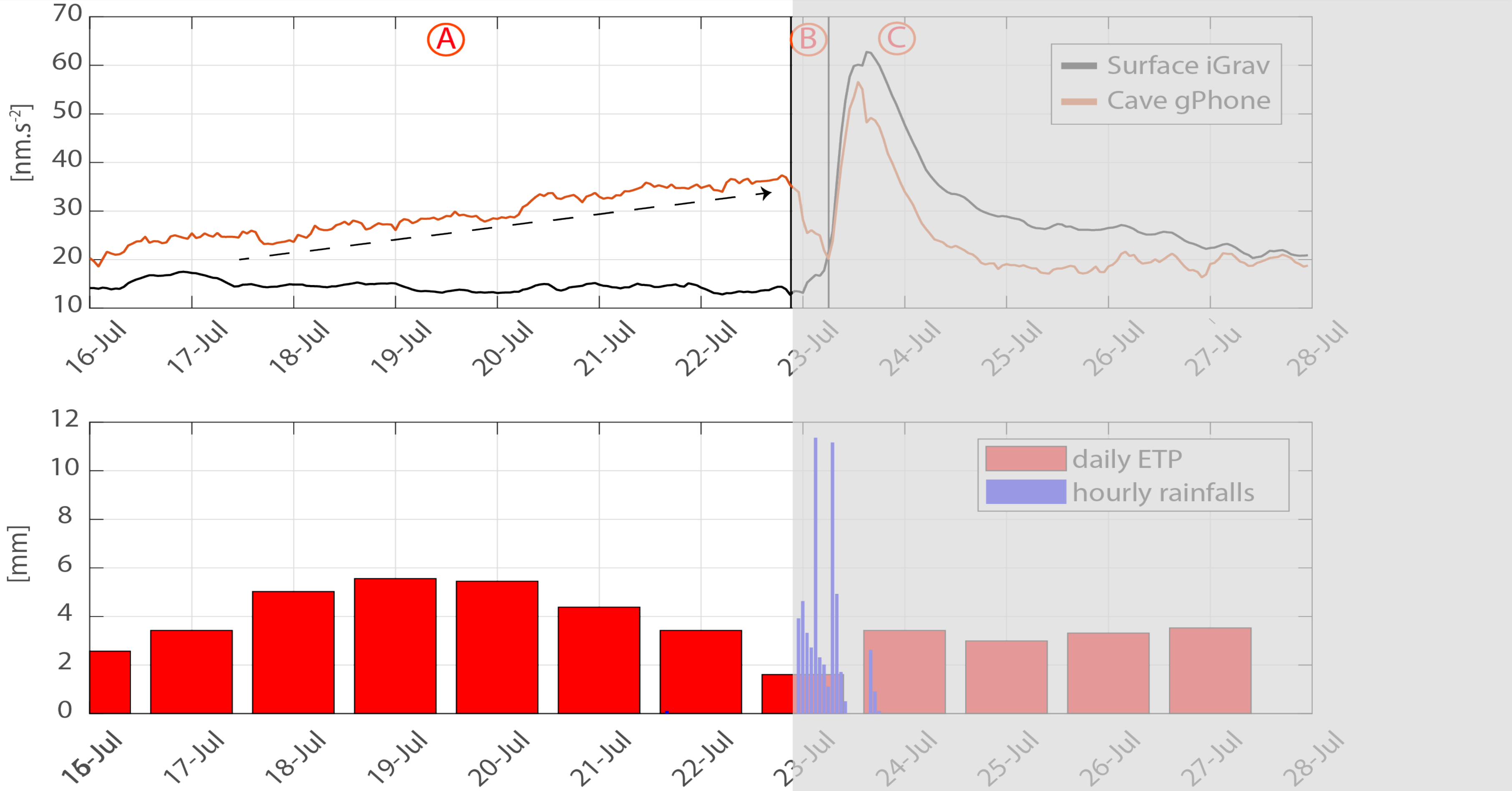
2-weeks zoom



gPhoneX hourly residuals compares well with SG ones

Examples of signals cross-interpretation

2-weeks zoom



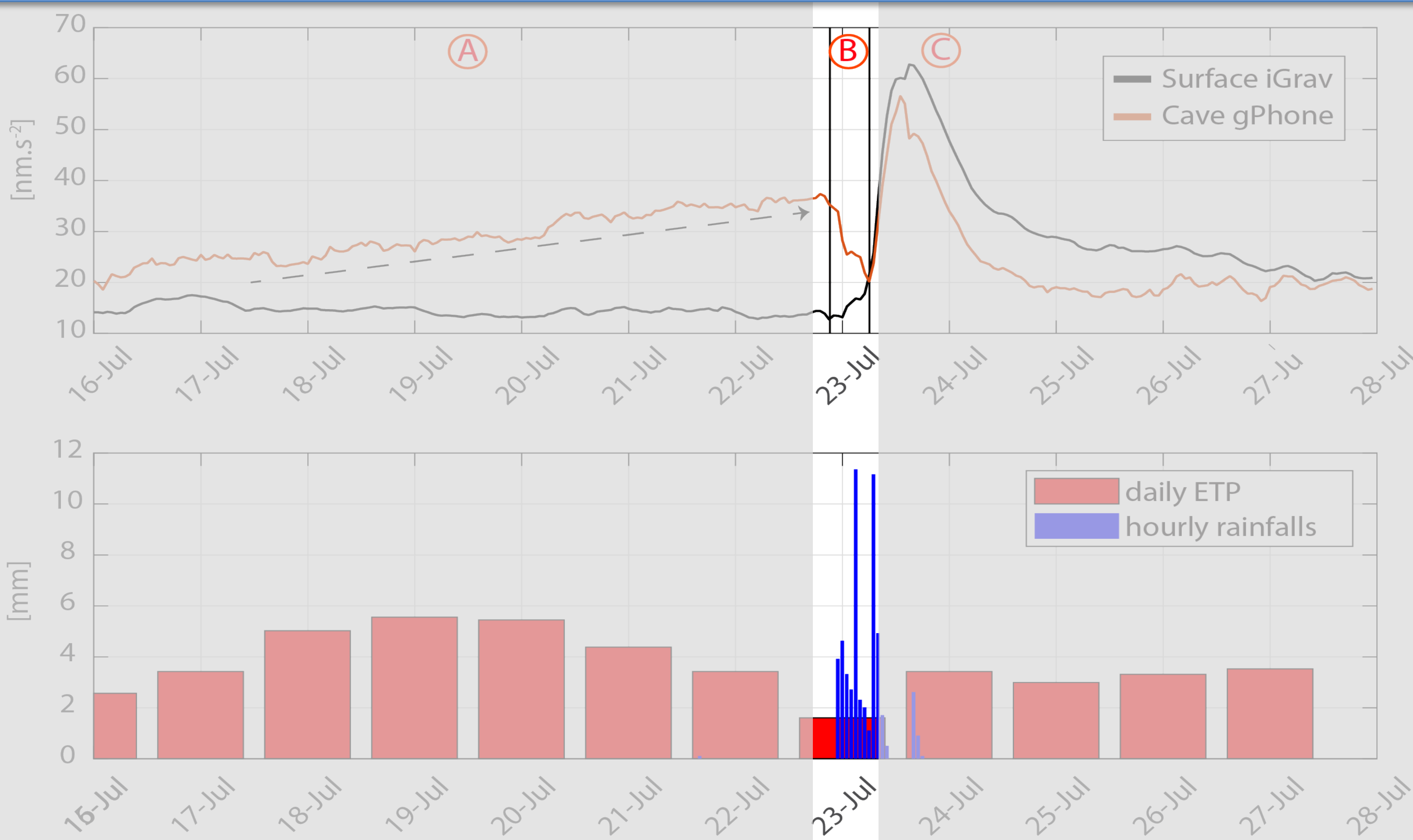
(A) steady surface signal – cave signal increase – dry period

The **iGrav is blind** to the **first 4-m** because **of the topography and its buried position** (Watlet *et al.*, 2020)

Σ_AET = 32 mm *i.e.* 13.5 nm.s^{-2} (1-D relation)

→ **Evaporation** signal, masked on the iGrav (**'sun umbrella' effect**) and seen by the gPhoneX

2-weeks zoom



(B) Surface signal **slight increase** – **Cave** signal **sharp decrease – Heavy rainfalls**

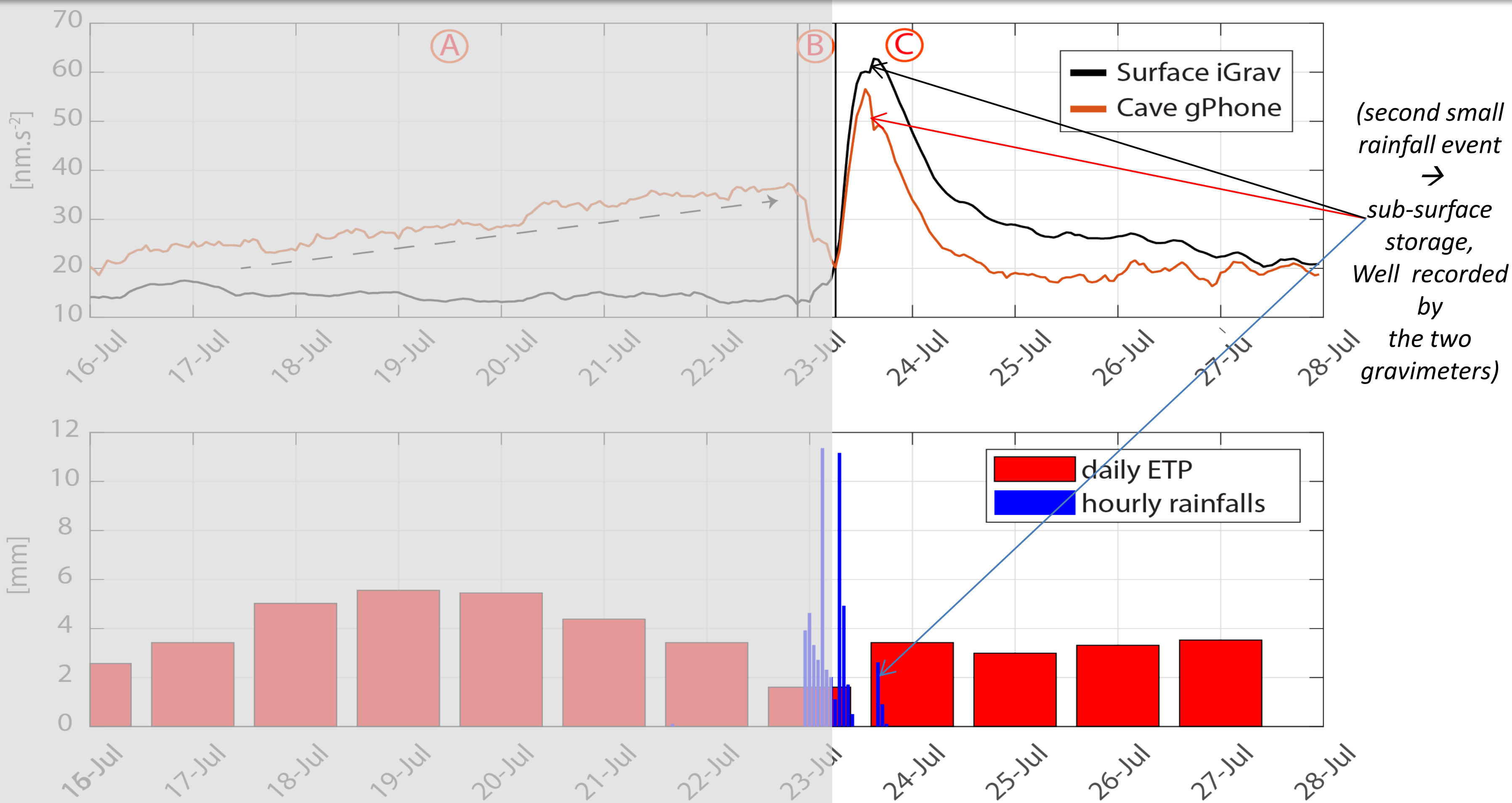
→ Rainfalls watering the first meters (dry after the dry past weeks)

→ Partly masked on the iGrav (**'umbrella' effect**); seen by the gPhoneX

More on the mask effect on gravity: Deville *et al.* (2013)

Note: the mask varies with soil moisture conditions (Fores *et al.*, 2017; Reich *et al.*, 2019)

2-weeks zoom



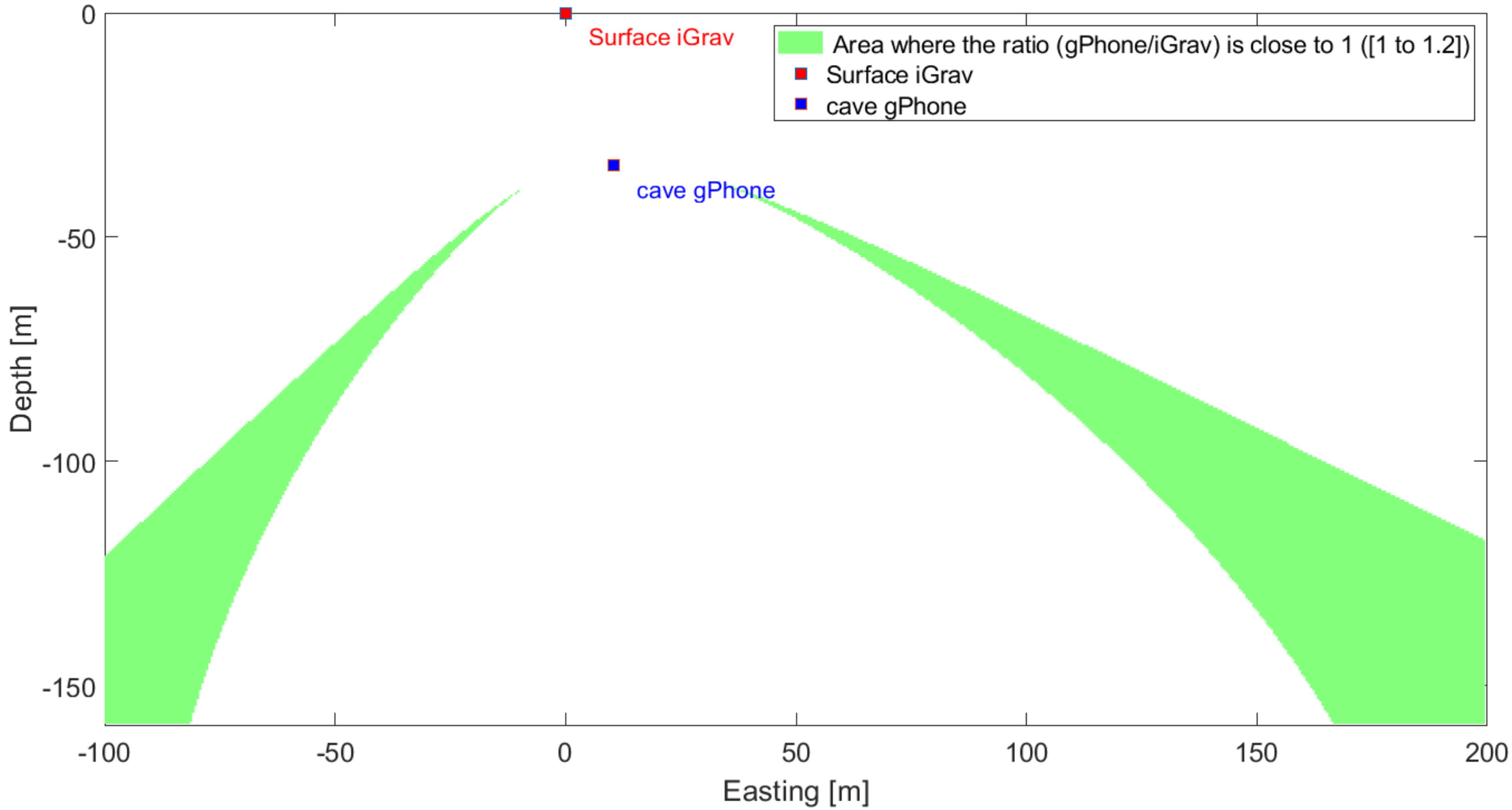
(C) Sharp increase followed by **exponential decrease (both gravimeters)**

- Classic shape of flash flood signals (fast flows in transmissive karstic conduits)
- **Positive** correlation
- ~ same amplitude after correction of the different effect of the soil saturation changes (B), slightly higher on the gPhone (based on 20+ floods)

Flash flood signals origins

Water tables monitored in known caves only **explain a few %** of the **gravity peaks** of the surface signal (*Watlet, 2017*)

→ **<u>Where are the unknown flooded conduits</u>?**



1) ~ **Same amplitude** on both gravimeters and **positive correlation**

→ **Delimitation** of the possible origin of the floods

Flash flood signals origins

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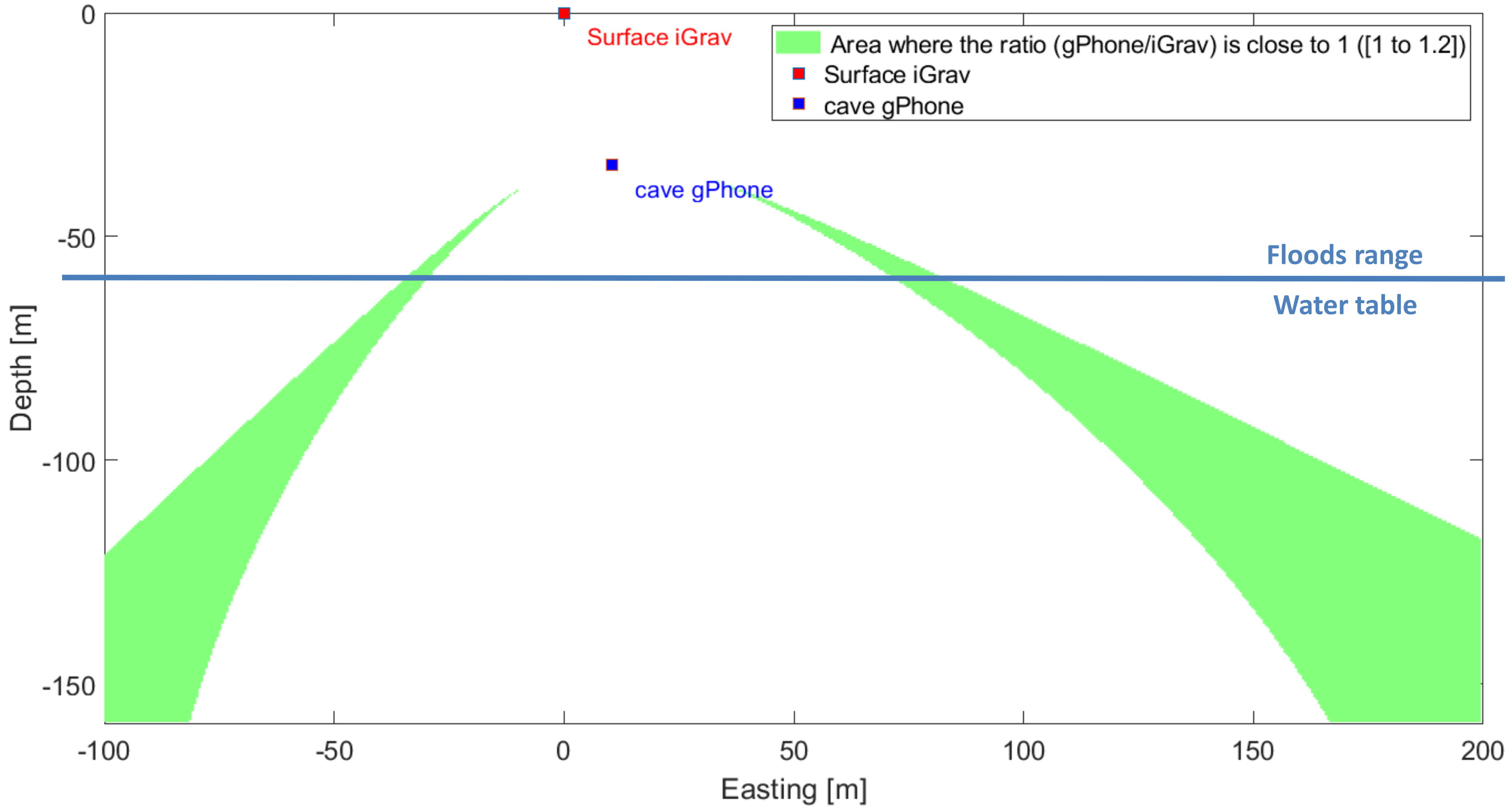
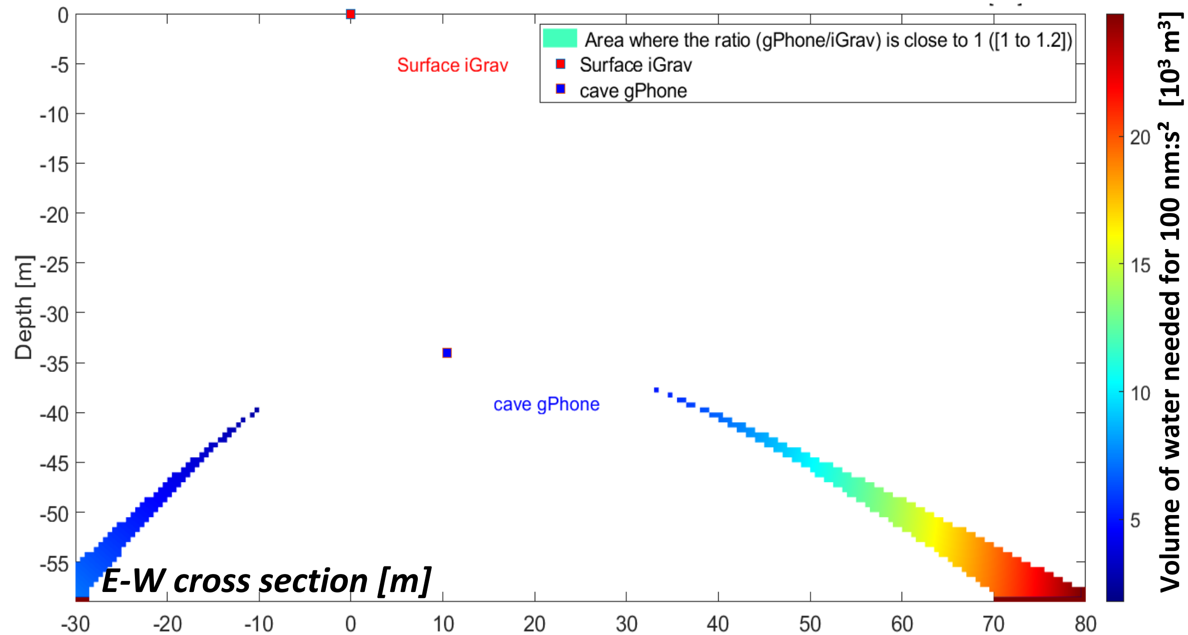


1) **~ Same amplitude** on both gravimeters and **positive correlation**
2) Other information: **geology, topography** and **water table…**

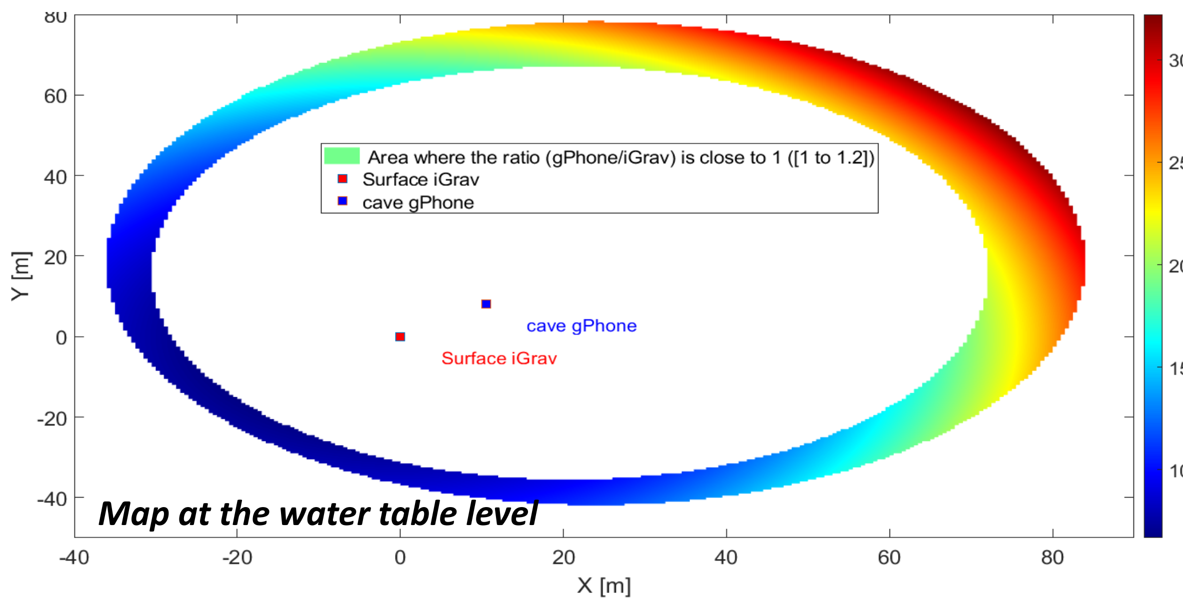
(e.g. ↳ Probably not eastward nor northward)

Flash flood signals origins

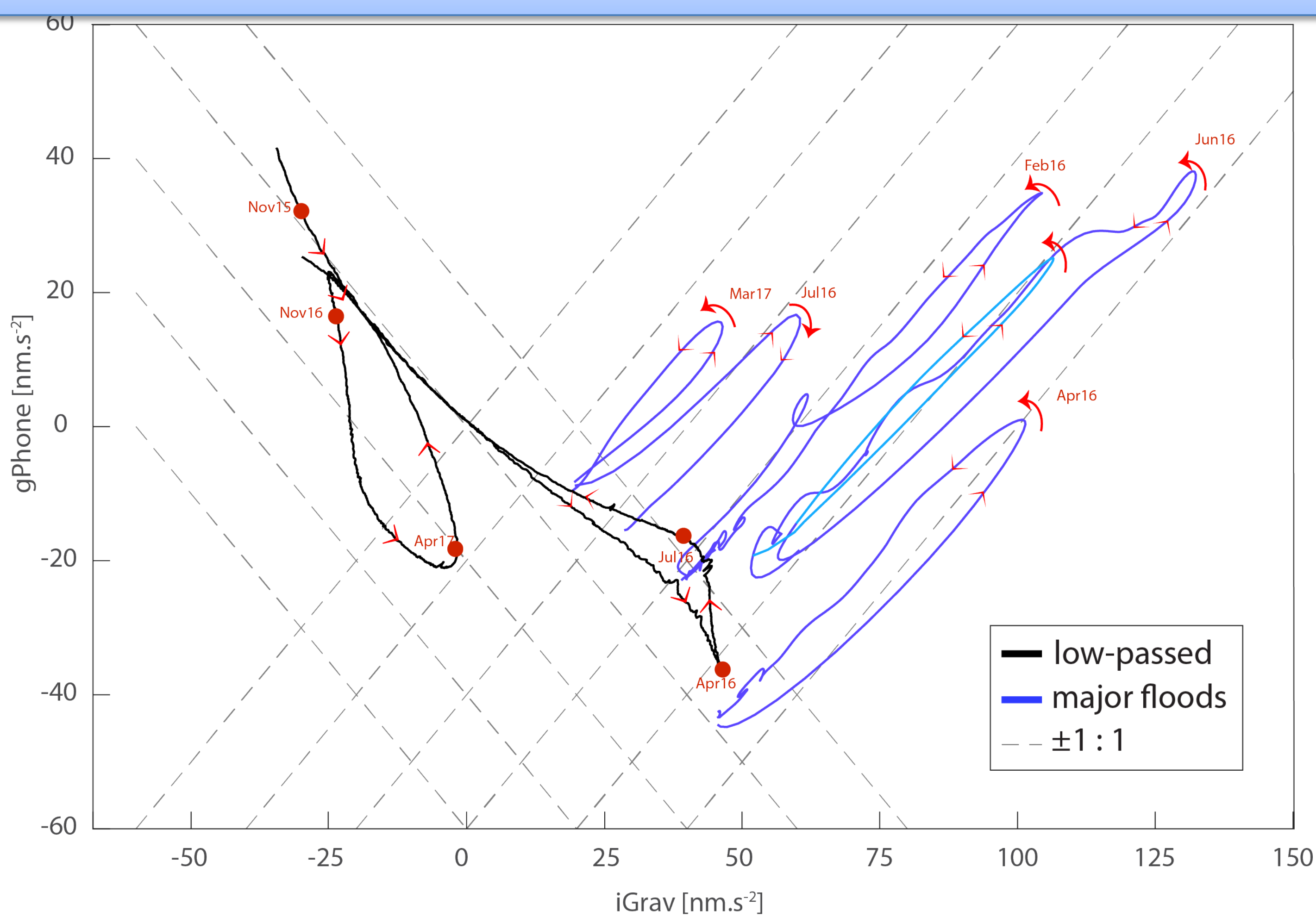


Based on the gravity information :

- Some flooded conduits must cross the colored area
- total volume of karstic conduits in this area: minimum few thousands of cubic meters
- No active conduit should cross the vicinity (~50m) of the gPhone



Recap: where is the water ?



- **Negative correlation** for the long-period **seasonal water** signal
  → matrix saturation changes **between** the two gravimeters (between **4 and 35 meters)**
- **Positive correlation** for the **flash floods peaks**
  → unknown **karstic conduits below** the gPhoneX altitude coming from a demarcated area

(one can note the July 2016 flood "clockwise" exception: summer flood leaving water in previously dry soil, unseen by the iGrav because of the topographic mask effect)

Conclusions

1) Comparisons in **two** low-noise **observatories** with collocated **superconducting gravimeters** and **gPhoneXs spring gravimeters** (considered as perfect references)

→ gPhoneX long term stability better than 10 nm/s²

→ comparable hourly values

2) Validation in a field experiment in Rochefort, where a tilt-controlled gPhone was installed in a cave and a SG in the surface laboratory.

- We showed few examples of cross-interpretations allowed by this surface to depth monitoring
- The precision and stability of the two gravimeters allow to interpret seasonal water changes, flood peaks and detailing very slight signals

✓ **gPhoneXs can be used for long-term monitoring if the tilt is actively controlled**

Next experiment: monitoring karstic temporary lakes near Besançon (France) with a tilt-controlled gPhoneX in a private garage (part of the TRANSKARST project). No collocated SG. Installation: ~~the 10 of april~~ when the lockdown is over.

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