Progress Report on the GNSS at Tide Gauge Activities: SONEL Data Holdings & Tools to access the data

(Status report as of October 11th, 2013)

Prepared by M. Gravelle, E. Prouteau, G. Wöppelmann

With contributions from M. Guichard, A. Matthews, C. Poitevin, A. Santamaria-Gomez, M. Tamisiea, P. Tiphaneau, S. Williams

Background

In 2009, the GLOSS program convened a workshop on "*Precision Observations of Vertical Land Motion at Tide Gauges*" before its Xth Group of Experts meeting. The main objective was to review the geodetic methods that could provide a means to accurately express the tide gauge data in the same geocentric reference frame as the satellite altimetry data, and to monitor the vertical land movements that are recorded by the tide gauges at the sub-millimeter per year precision level, hence enabling their separation from the climatic signals. One of the main conclusions of the workshop was that the Global Positioning System (GPS) had reached the maturity to address these issues, provided continuous GPS observations were carried out at the tide gauge and were made available to the groups that have the knowledge and experience to analyze the data using the state-of-the art data analysis strategies, models and corrections. Most of these groups are committed to the International GNSS service (IGS) working group named TIGA. (Note that GPS is one of the several Global Navigation Satellite Systems (GNSS) available today).

Another important conclusion from the mentioned workshop was that the GLOSS program should designate a dedicated "GNSS at tide gauge" data assembly center. To further examine this issue of a dedicated data center, a follow up meeting was organized at the University of Hawaii Sea Level Center (UHSLC) in 2010. The proposal of the SONEL data center, which has been acting as primary data center for the TIGA since 2001 was retained, and finally adopted at the XIth GLOSS Group of Experts meeting in 2011. The GLOSS Implementation Plan released in 2012 recognizes that data center as an associated infrastructure, along with the other dedicated data centers of the program such as the UHSLC or the PSMSL.

Consistently, the GLOSS implementation plan calls for the important upgrade of its core network sea level stations with continuous GNSS stations, and that their observations be provided to its dedicated data assembly center (SONEL), so that the observations and generated products be public and free to anyone in line with the IOC/UNESCO Oceanographic Data Exchange Policy.

This report is the first status report of the SONEL GNSS at tide gauges data center since its inception in GLOSS. It has been prepared with the contributions from colleagues of the PSMSL, as an important effort has been accomplished in the interoperation of the respective databases, achieving useful merged information and combined scientific products. Most of the illustrations herein are extracted from the Internet portal of SONEL: www.sonel.org.

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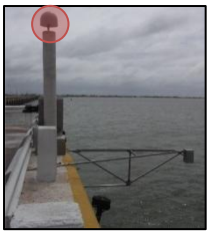

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I- GNSS data holdings at SONEL

1. Global status overview

SONEL has currently identified 593 tide gauge sites for which a GNSS station is nearby (within 15km), or from the other point of view 724 GNSS stations that are nearby a tide gauge site (Figure 1). Among these GNSS stations **411 are active** at 367 tide gauges (a data file was successfully retrieved within the last 30 days, in green on Status of the GNSS@TG data available on SONELFigure 1: Status of the GNSS@TG data available on SONEL), 120 are dormant (no data for the last 30 days, in orange on Figure 1) at 113 tide gauges, and 89 are decommissioned (red cross on Figure 1) at 75 tide gauges. It should be noted that 104 GNSS stations have no data available (in blue on Figure 1) at 100 tide gauges, mostly because of military or commercial restrictions. Note that all the values in this report correspond to the status on 11 October 2013.

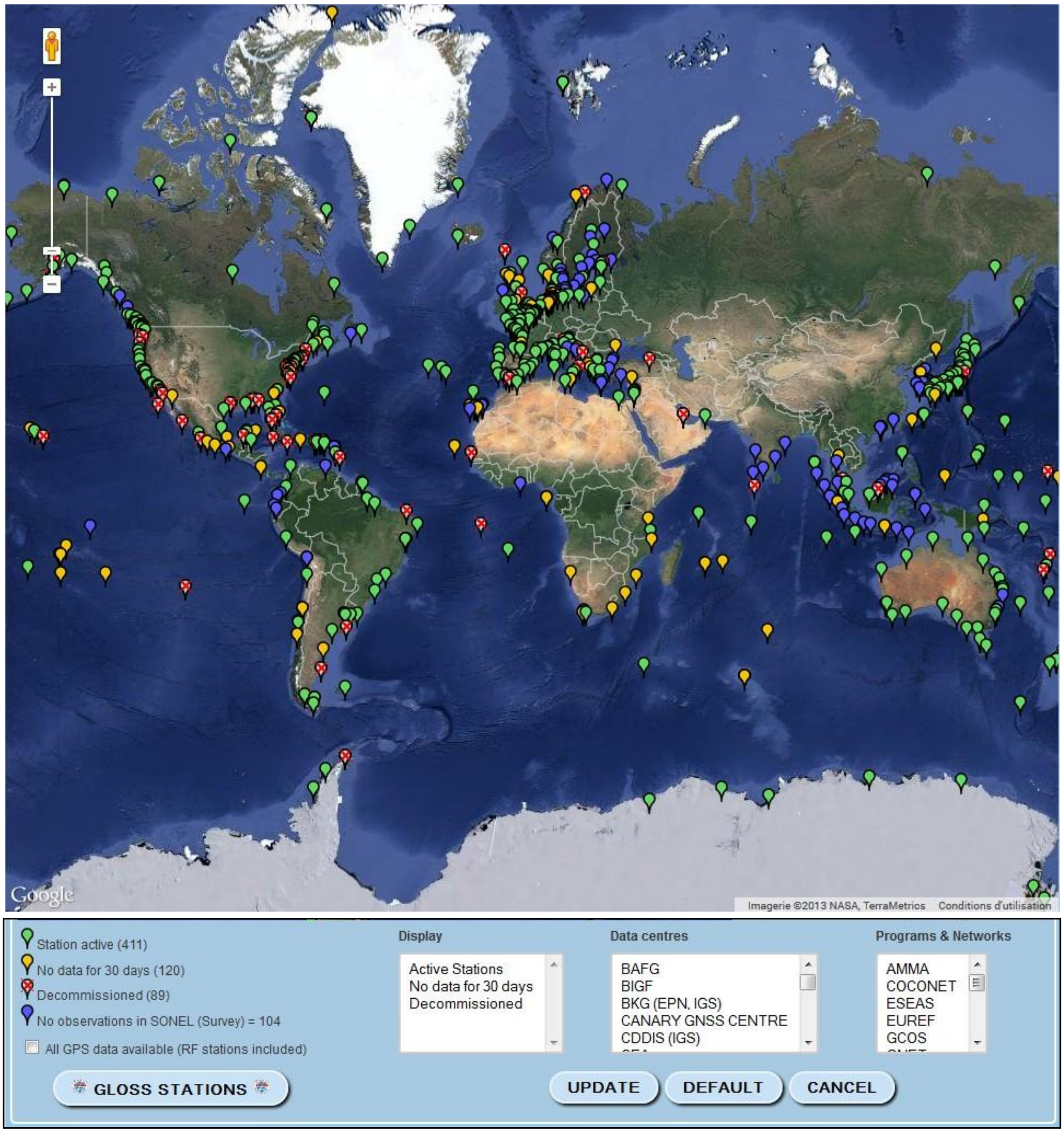

Figure 1: Status of the GNSS@TG data available on SONEL
http://www.sonel.org/-GPS-.html

Since the 12th session of the GLOSS Group of Experts meeting in November 2011, 61 new GNSS stations nearby 47 GLOSS Core Network tide gauges have been identified and their data collected in to SONEL. Among these, some are replacing a decommissioned GNSS station or supplementing it. Only 18 GLOSS Core Network tide gauges out of the above 47 did not have any GNSS in 2011 (for two of these 18 tide gauges, the GNSS observations are not accessible). (Note that by GNSS it is meant a continuous GNSS station). Most of the GNSS stations are currently GPS, even though other satellite constellations may be recorded as well such as GLONASS or Galileo.

Figure 2 shows the evolution of the number of daily GNSS data files, which informs on the number of GNSS stations actually operational. As many as 620 stations are reported (Total curve, in blue), which includes both the GNSS at tide gauges and the reference frame stations. The latter reference frame stations are important in the GNSS data analysis to ensure the realization of a stable geocentric reference frame over the entire data span.

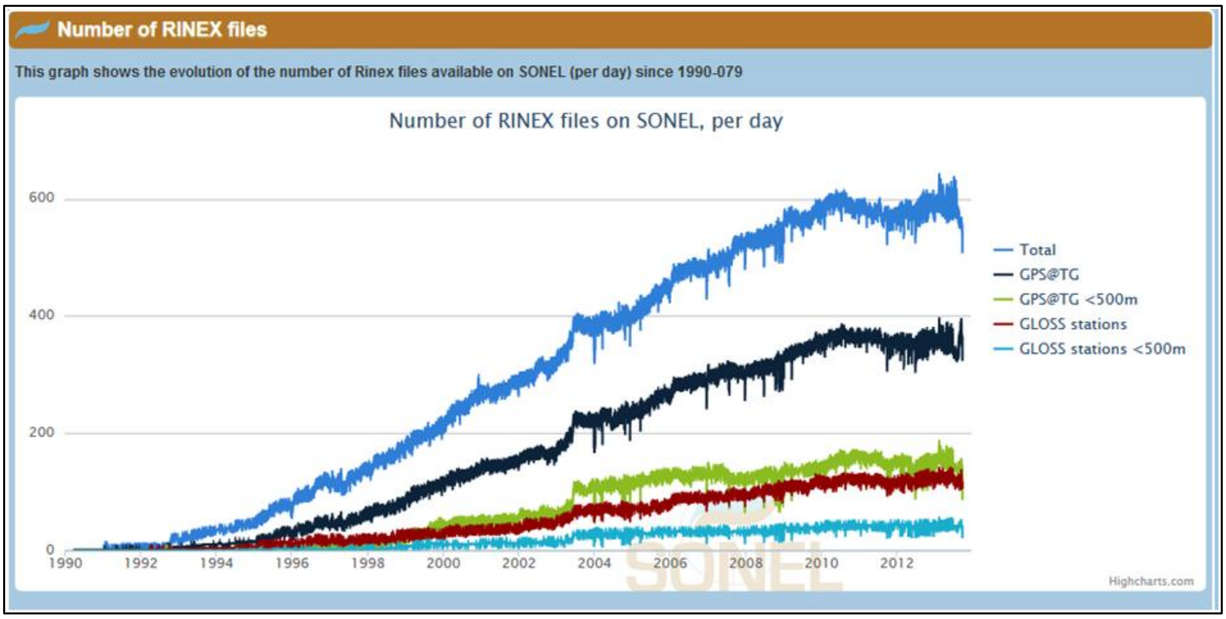

Figure 2: Evolution of the GNSS stations operational (providing data to SONEL)
http://www.sonel.org/What-GPS-data.html

2. GLOSS Core Network status overview

The GLOSS core network comprises 289 tide gauge sites. Figure 3 shows that **191 of these stations are nearby one or more GNSS stations** (this corresponds to 273 GNSS stations nearby a GLOSS tide gauge site). The 98 tide gauges for which no GNSS station has been found in the vicinity are in white on Figure 2. For 19 stations, a GNSS station has been identified but the data are currently not available (in blue on Figure 2, see also Table 1).

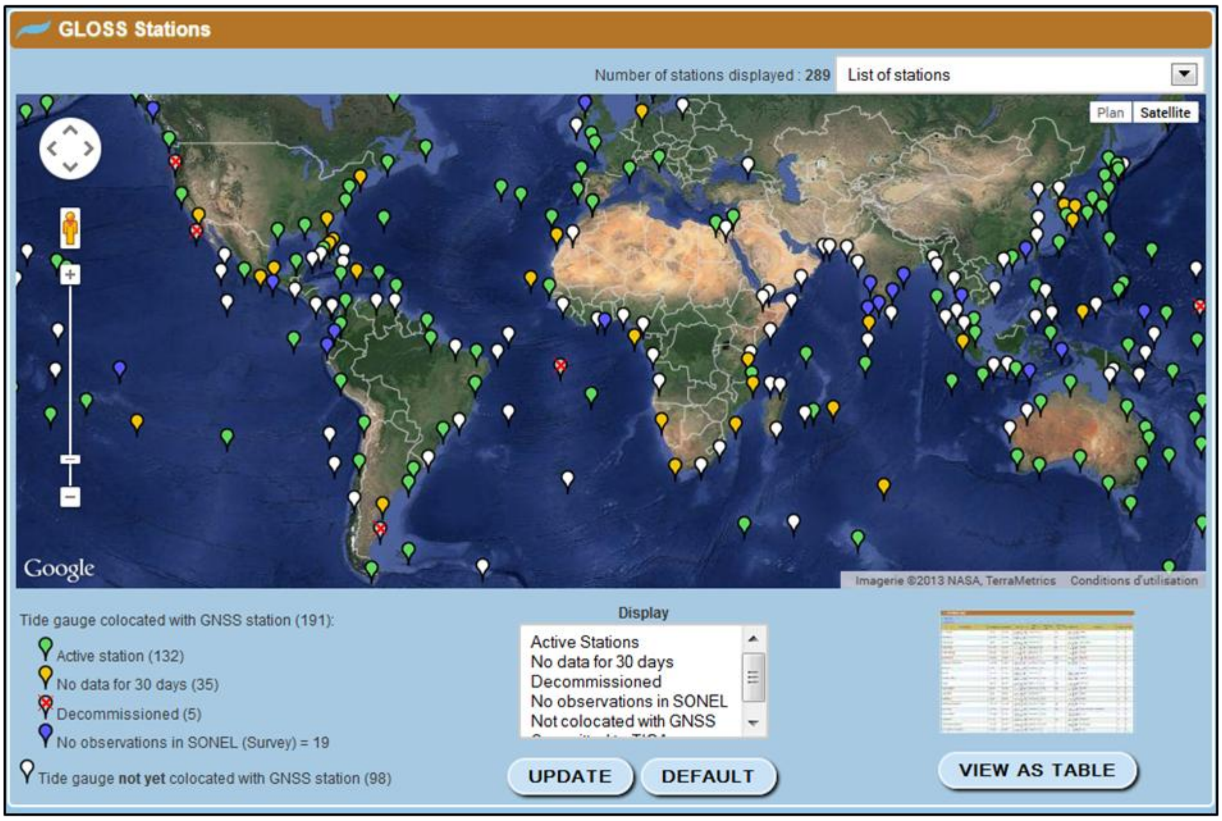

Figure 3: Status of the GLOSS tide gauge network with a GNSS station nearby
http://www.sonel.org/-GLOSS,81-.html?lang=en

GLOSS tide gauge	Country	GPS acronym
Prince Rupert	Canada	BCPR
Xiamen	China	Unknown
Tumaco	Colombia	TUMA
La Libertad	Ecuador	SALN
Chuuk	Federated States of Micronesia	TRUK
Nuku-Hiva	French Polynesia	Unknown
Takoradi	Ghana	TKTG
Cochin	India	Unknown
Chennai / Madras	India	Unknown
Marmagao	India	Unknown
Minicoy	India	Unknown
Vishakhapatnam	India	VISA
Ambon	Indonesia	CAMB
Waikelo	Indonesia	WAIK
Malin head	Ireland	Unknown
Puerto Angel	Mexico	OXUM
Stockholm Stupi	Sweden	STH0
Goteborg – Torshamnen	Sweden	Unknown
Ko Lak	Thailand	Unknown

Table 1: GLOSS stations for which a continuous GNSS station has been identified nearby but its data are currently not available

Figure 4 is similar to Figure 2 but focusing on GLOSS tide gauge sites. (Note that several GNSS stations may be nearby a GLOSS station).

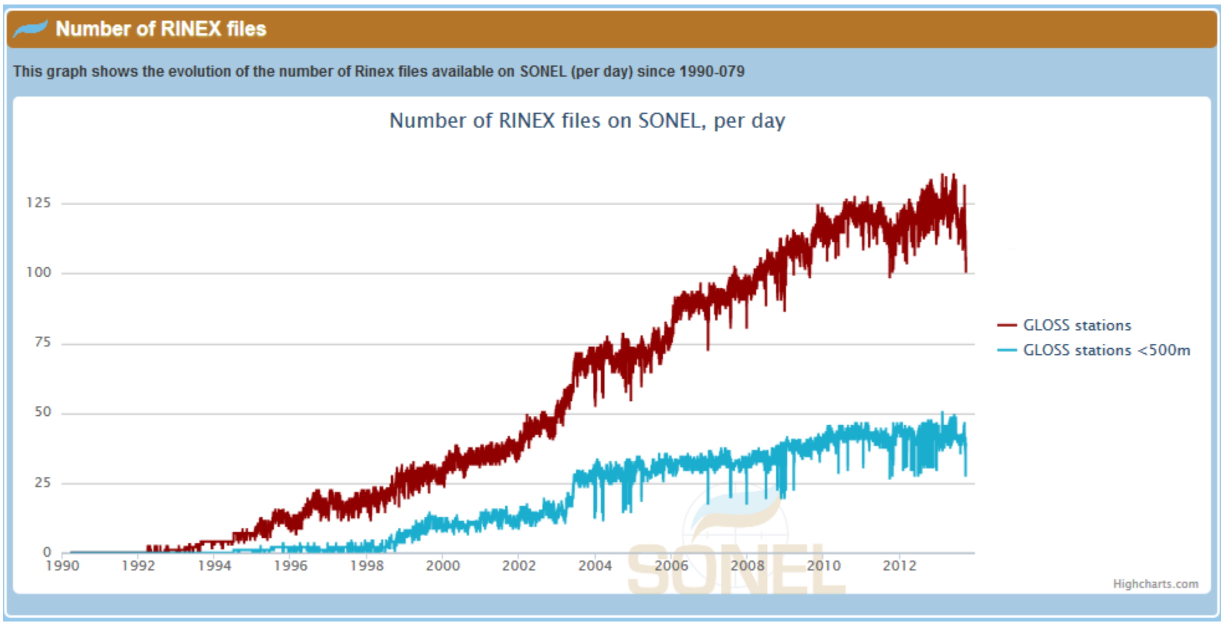

Figure 4: Evolution of the GNSS stations operational (providing data to SONEL) nearby a GLOSS site http://www.sonel.org/GNSS-data-at-or-nearby-GLOSS-Core.html

Figure 5 highlights the information on distance between the GNSS antenna and the tide gauge. This information is important as the likelihood to get the geodetic link between both instruments by leveling decreases with distance (resources, expertise…), and thus raises the question of usefulness of the distant GNSS antennas to monitor the vertical land movements at the very tide gauge.

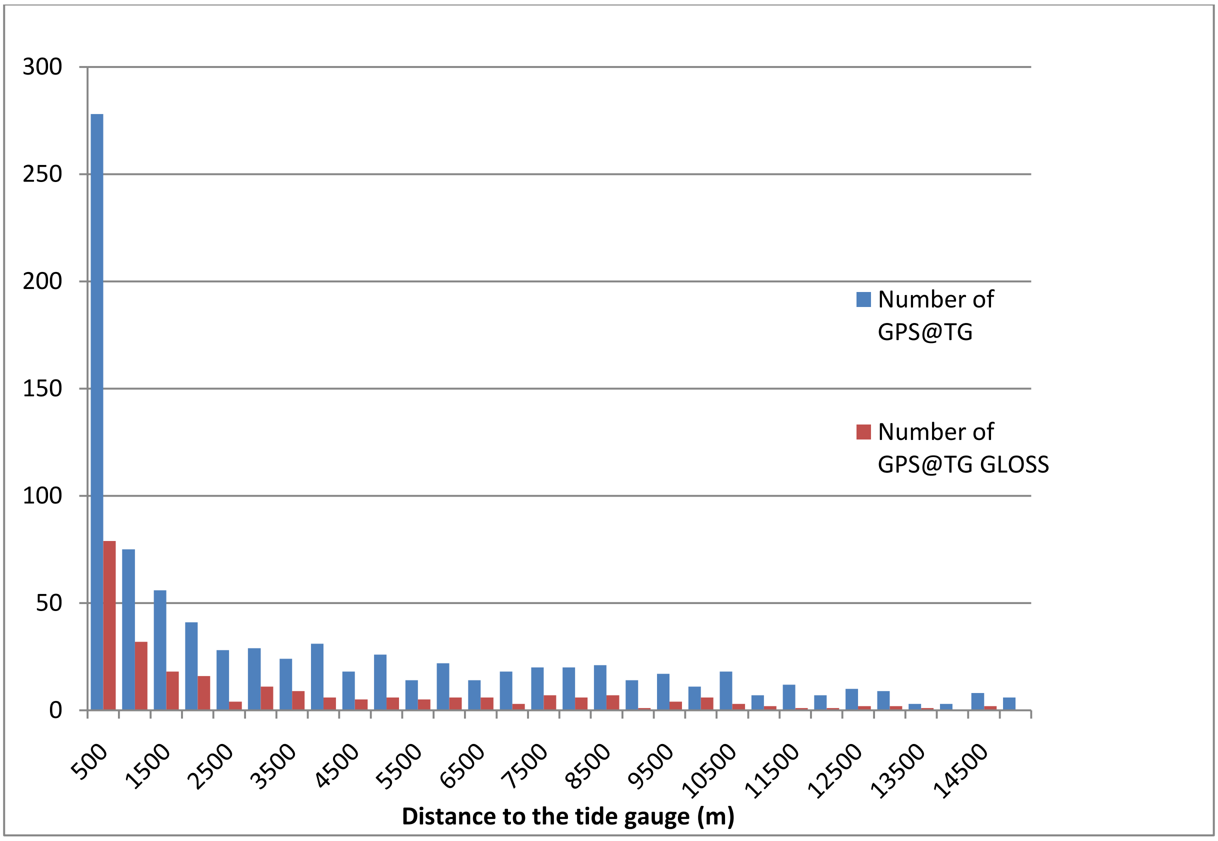

Figure 5: GNSS antenna distance to the tide gauge

For the 111 GLOSS tide gauges with a GNSS antenna less than 1000 m distant, 55 are within 100 m and 56 are between 100 m and 1000 m.

3. TIGA and COCOnet status overview

There are 119 GNSS stations at tide gauges that are committed to the TIGA working group of the International GNSS service (IGS). As of October 2013, 92 GNSS stations are operational (green in Figure 1), 12 are decommissioned (red crosses) and the rest are likely active or dormant (orange). Some of the latter stations (dormant) have not provided data for more than one year: Rawson (RWSN) in *Argentina*, Freeport (FREE) in *Bahamas*, Palmeira (TGCV) in *Cape Verde*, Dunedin (DUNT) and Littleton (LYTT) in *New Zealand*, Malakal (PALA) in *Palau*, Puerto de la Luz (PLUZ) in *Spain*, Richards Bay (RBAY) and Simon's town (SIMO) in *South Africa*, and Aberdeen (ABER) in *UK*.

Regarding the Continuously operating Caribbean GPS observational network (COCOnet; http://coconet.unavco.org), 20 GNSS stations have been identified nearby a tide gauge since the last GLOSS group of experts meeting. All of them are providing daily files of observations, except Mona Island (MOPR) in Puerto Rico, which stopped reporting data on 24 August 2011. It should be mentioned that one of these COCOnet stations (CN12) is nearby a GLOSS tide gauge (Port Royal in Jamaica, GLOSS Id. 210).

II- New tools to access the data

1. General

SONEL strives to provide user-friendly access to its data holdings by developing web-based interfaces such as clickable maps. This has been the case for a couple of years, for instance, to inform what GNSS station is nearby a tide gauge (Figure 1) with details on whether it is active or not, and whether it provides observations or not. Some display options on the subset of stations can be chosen on the panel just below the map (checkboxes). For instance, what data is retrieved from a specific data centre, or whether the station belongs to a particular network or program? The selection options could be further developed upon request, if the users express a particular interest.

The station symbols on the maps are usually clickable to show basic details such as name, latitude, longitude, and a link that leads the user to a full page of details. For each station, one may learn whether SONEL has collected data files of observations, what is the first and latest data available on SONEL, but also one can display a detailed calendar to see and retrieve the daily file of observations in RINEX format by clicking on a specific day on the calendar table. The user may also find what tide gauge is nearby and if there are other tide gauges or GNSS stations, in which case a link can lead to the co-located station information web-page. If leveling data is available between the GNSS antenna and the tide gauge, a link to that information is also available as well.

Furthermore, if the observations of that station have been processed by at least one analysis center contributing a *'GNSS solution'* to SONEL, the GNSS position time series may be viewed and downloaded in ASCII file format. In this respect, the SONEL team has been working since the last GLOSS Group of Experts meeting in 2011, to provide new web-based features to manipulate and display those time series (de-trended, annual cycle removed, etc.). The SONEL team has also been working on extending the web-based clickable maps to enable a comprehensive view and a simple access to some relevant products like: (i) the GNSS vertical velocities (section III.2), and perhaps more interestingly, (ii) the combined linear trends from the GNSS and the tide gauge records (section III.3). The latter objective has been achieved through a stimulating and productive cooperation between the SONEL and the PSMSL teams.

2. GNSS solutions

First, it may be helpful to clarify what is meant here by a *'GNSS solution'*. Here, for a set of stations, it consists of the average station position and velocity, which are valid over the input observation time span of each station, as well as its (residual) position time series. Residual means the difference between the position and the linear model at given epochs, typically weekly though the IGS is moving to daily for its next reprocessing campaign. The linear model may include offsets, in which case their values are estimated as well in the same adjustment run. Each solution is expressed in a specific geocentric reference frame (the most accurate and stable at the moment of the solution release).

SONEL is able to handle several GNSS solutions, either from a given analysis center (solution updates from a complete reprocessing of the entire data span) when significant progress has been recognized, for instance, by using new models or corrections, or from different analysis centers as long as these comply with the up-to-date IGS-agreed international recommendations (see http://acc.igs.org/reprocess.html).

a) Global comprehensive view

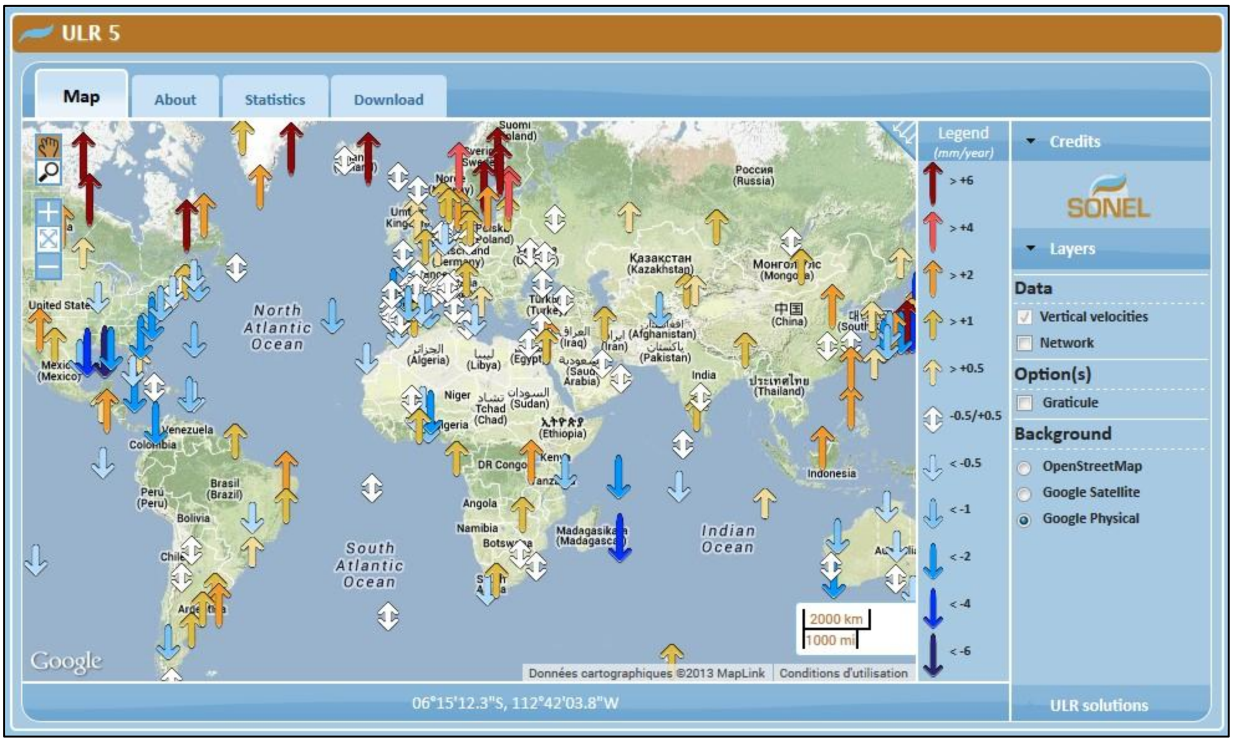

Figure 6: Display on a web-based clickable map of the GNSS vertical velocities from ULR5 solution http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en

Figure 6 shows the newly developed GNSS solution webpage: http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en, which displays a clickable map with the GNSS vertical velocities of a given *'GNSS solution'*. The upward arrows indicate land uplift, whereas the downward arrows indicate subsidence. Double-end arrows indicate velocities within -0.5 to +0.5 mm/year.

The arrows are clickable to obtain a small popup window with the station name, its vertical velocity, the associated time span, data completeness, and a link to the station web-page with full information on the station and its 'GNSS solutions' (see next section).

The detailed description of a given 'GNSS solution' is split into "tabs" to reduce the amount of information displayed in a single web-page. The default-selected tab corresponds to the vertical velocity map of the network of processed stations for which a robust vertical velocity has been estimated. The tab called "About" gives technical details on how the solution was processed (main features of the analysis strategy) and in which geocentric reference frame it is expressed. Another tab called "Statistics" provides common statistics and graphs for the solution. Finally, the tab called "Download" gives comprehensive access to download the GNSS solution files (table of all the vertical velocities that were estimated, station position time series files assembled in a .zip file, SINEX file, table of estimated discontinuities, etc.).

This new facility of making available a 'GNSS solution' is currently available for the ULR analysis center solutions (ULR4 and ULR5 solutions). As mentioned previously, SONEL can handle other GNSS analysis center solutions, including DORIS solutions (Section IV).

b) Local specific view (to a particular station)

The 'GNSS solution' data for a specific station can be accessed either through the above new 'GNSS solution' map, or through the former GNSS general information map presented in Section II.1, which describes what observations are available (Figure 1). Note that a GNSS station webpage can also be accessed directly by using the GNSS acronym in the "Search" facility on the left-hand panel that is available from any page on the SONEL website.

Whenever a 'GNSS solution' is available for a given station, the individual station webpage will show a "GPS position time series" block of information that otherwise will not appear. This block displays the (residual) position time series, but it has been improved to provide visual tools that support the analysis of the results (Figure 7). First, the general information has been completed (reference frame, ellipsoid, average position and velocity). Second, the graphs are now dynamic, which means that the vertical scale can be adjusted (+/- buttons) and the information on a point of the curve under the cursor (residual, epoch) can be displayed.

In addition, the trend has been added back to the residual position time series (default display). However, the user may choose to remove this trend through a checkbox. The annual signal and the estimated position offsets can be added back for an overall analysis, for instance, to assess the linearity or quality of the results. The horizontal components of the positioning are also accessible. They may provide information of problems that have occurred with the station. The vertical bars on the graphs highlight the dates when a position or velocity discontinuity was estimated. These discontinuities are detailed on the left of the graph frame. Finally, the "Download" button below the graph allows for retrieval of the (residual) position time series corresponding to the user's view of the graph.

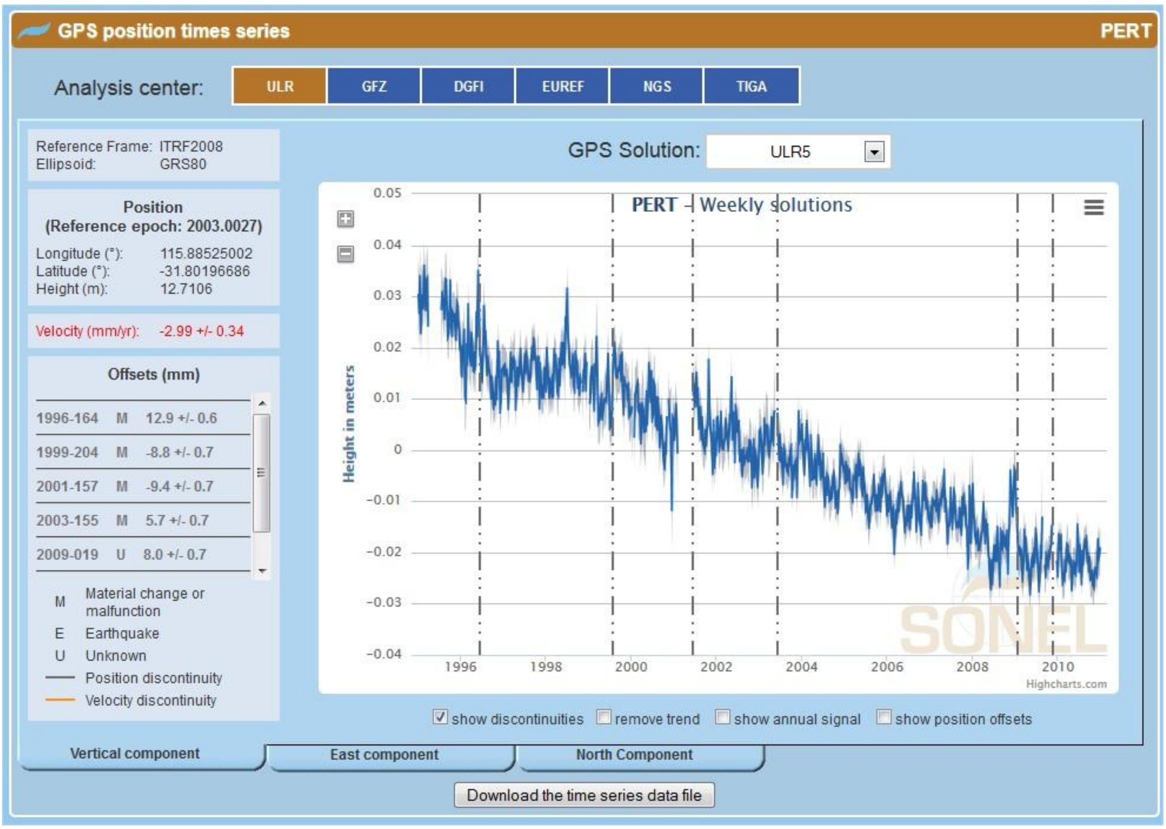

Figure 7: An example of 'GNSS solution' for the PERT station (Perth, Australia).

c) Latest GNSS solution (GPS) and GNSS solutions for GLOSS stations

The latest GNSS solution at tide gauges available on SONEL was released by the University of La Rochelle (ULR) in 2012, and is called ULR5. Any station for which GNSS observations were available in 2011 on SONEL was included. It corresponds to 420 stations for which the entire dataset between 1994.0 and 2010.9 was reprocessed using the most up-to-date models and corrections available at that time. As many as 282 GNSS stations were at or nearby a tide gauge (Figure 8).

Figure 8: Number of processed stations per week
http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en

A minimum of three continuous years without an offset (e.g., due to an equipment change or an earthquake) in the time series were required to estimate a "robust" vertical velocity. This duration is the minimum to limit introducing biases from the seasonal cycles. Ultimately, there were 232 GNSS stations nearby a tide gauge for which a GNSS velocity was estimated. The median uncertainty on the estimated vertical velocities is about 0.3 mm/year (Figure 9). Further details can be found on the SONEL related web-pages.

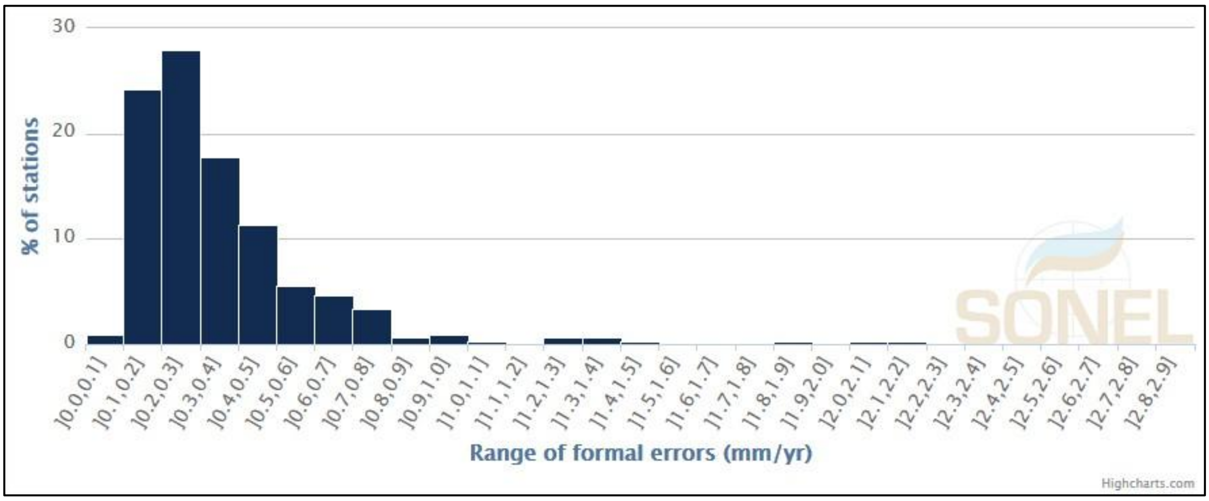

Figure 9: Formal errors on the estimated GNSS vertical velocities
http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en

Figure 10 shows the 80 GLOSS tide gauge sites for which a robust GNSS vertical velocity is available in the ULR5 solution, out of the 114 GLOSS Core Network tide gauges for which a GNSS station had data processed in that solution.

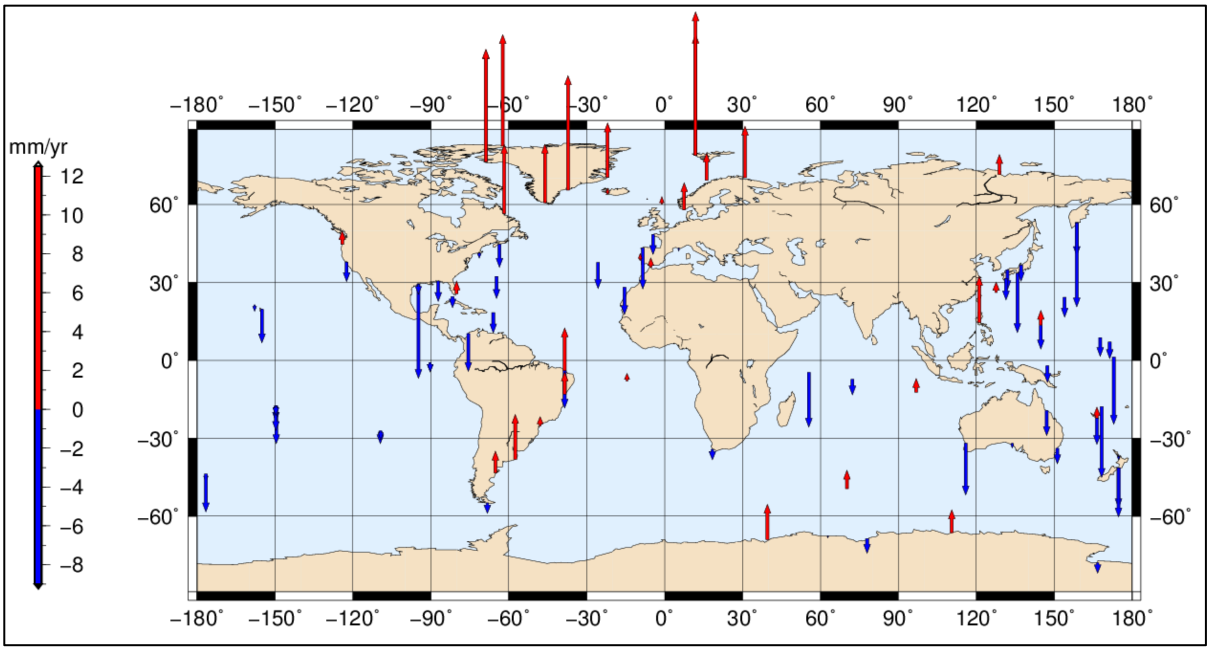

Figure 10: GNSS vertical velocity field of ULR5 solution at the GLOSS tide gauges (80 stations)

3. Combined products (from the PSMSL & SONEL)

In collaboration with the PSMSL, the rates of relative sea level change (RSL) from tide gauges and the vertical land movements (VLM) estimated from the GNSS velocities have been combined to produce rates of absolute (geocentric) sea level change (ASL) following the simple relationship:

$$ASL = RSL + VLM$$

The rates of relative sea level change are provided by the PSMSL (Figure 11). These rates are calculated over a given period using the annual time series from the RLR dataset. The period can be chosen by the user between 1900 and 2011, with a minimum time span of 30 years. The computation requires 70% of data completeness over the chosen period.

The vertical land movements are estimated using the latest GNSS solution available on SONEL (ULR5). Note that two working hypotheses are necessary when using GPS data to correct vertical land movements in tide gauge records. The first requires that the linear vertical land movement estimated from the GPS data is consistent over the multi-decadal to century timescale of the tide gauge record. The second hypothesis requires that the land motion detected by the GPS antenna is consistent with that affecting the tide gauge at the level of a few tenths of a millimeter per year. Both are necessary working hypotheses, which have been discussed extensively in the literature. See for instance Santamaria-Gomez et al. (2012).

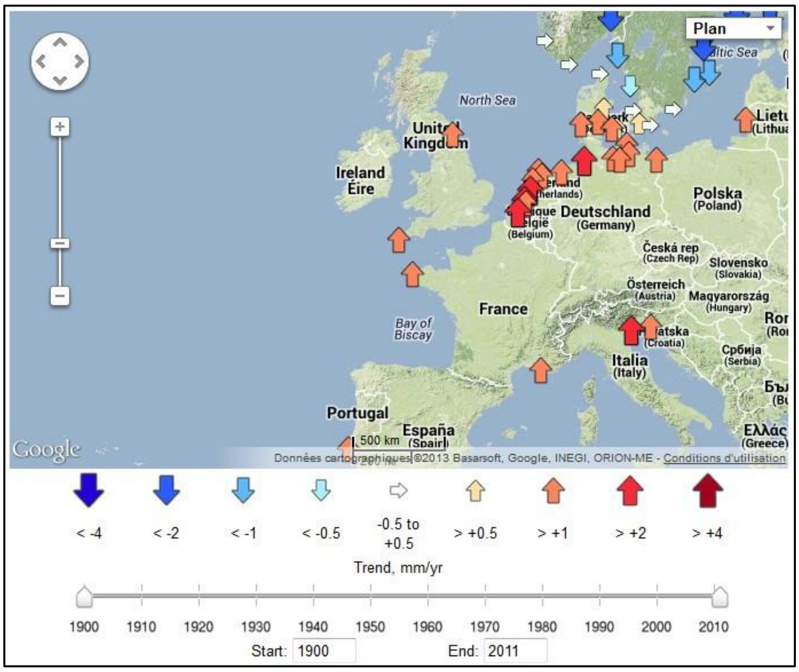

Figure 11: Rates of relative sea level change computed by the PSMSL over a given period
http://www.psmsl.org/products/trends/

Figure 12 displays the results of absolute (geocentric) sea level trends on a clickable map. By default, these are over the 1900-2011 period. The user can then select another period, either by entering the start and end of the period, or by using the scroll time span arrows below.

The sea level change arrows on the map are clickable to obtain a small popup window with the station name and a summary of the data, including, the combined velocity or absolute sea level change, the GNSS and tide gauge linear trends (velocities), the selected time period, and the links to the station web-pages, either at the PSMSL (tide gauge) or at the SONEL (GNSS).

For a selected time period, the user can further select the region of interest (zoom options), and later on download the selected data as a table (.csv format) or as a PDF file, either for the stations in that region or for all the stations in the world for which the computation was performed. Vice-versa, the user can first select the region, and then the time period.

Another option is the possibility to switch from absolute to relative sea level trends, in which case the users is displaying the data computed by the PSMSL, but restricted to the stations for which a nearby robust GNSS velocity is available.

Figure 12: GNSS Absolute (geocentric) sea level trends over the 1900-2011 period
http://www.sonel.org/-Sea-level-trends-.html?lang=en

III-Future work

1. Updated products (GNSS velocities and absolute sea level trends)

As the GNSS data analysis strategies progress, for instance, with new models or corrections, a consistent reprocessing of the entire dataset is mandatory to ensure accurate estimation of vertical velocities at the sub-millimeter per year level. Considering the progress made since 2010, the IGS has launched a reprocessing campaign called "repro2". The ULR data analysis center is participating to "repro2" with the preparation of a tide gauge-oriented solution (ULR6) whose data span will cover the period 1995.0-2012.9.

Considering the low number of GNSS stations very close to or **directly <u>at</u>** GLOSS tide gauges (only 19% are within a 100 meter range, section II.2), the traditional distance criteria between a GNSS antenna and a tide gauge has not been considered in the preparation of the ULR6 solution. Instead, the nearest GNSS station has been searched and included in the reprocessing as long as a plate tectonic boundary or a large extent of water (sea or ocean) is not in between the tide gauge and the GNSS antenna.

Finally, the ULR6 network comprises 660 GNSS stations, of which 487 are nearby tide gauges (213 are nearby a tide gauge that belongs to the GLOSS core network). In other words, in addition to the 80 GLOSS tide gauges for which a ULR5 robust GNSS velocity is available (Figure 13, green circles), 130 GLOSS tide gauges may get a robust GNSS velocity (Figure 13, purple circles), that is, 73% of the GLOSS core network. Yet, 79 GLOSS tide gauges will remain without any useful GNSS data nearby (Figure 13, black stars). Mostly, because of no GNSS station has been installed.

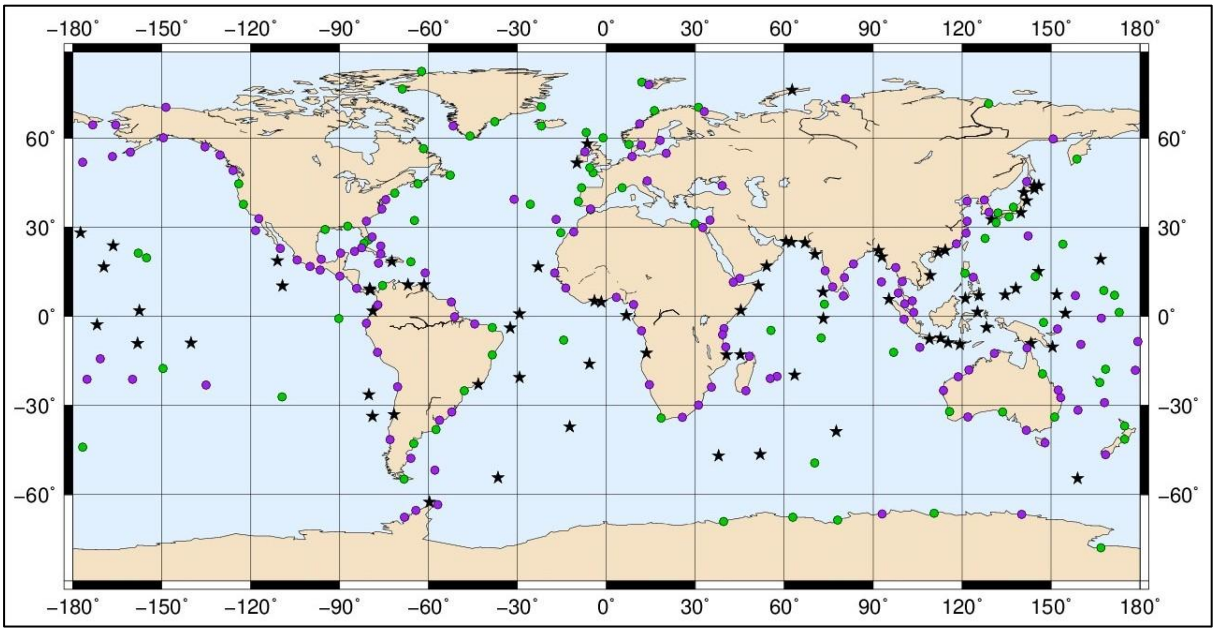

Figure 13: Potential GNSS-corrected GLOSS tide gauges with the forthcoming ULR6 solution. Green circles represent tide gauges with an existing GNSS velocity from ULR5 solution. Purple circles represent the tide gauges for which a GNS velocity is expected in ULR6. Back stars show the tide gauges for which the vertical land movement will remain unknown.

However, these numbers should be considered with extreme caution. First, the 130 new stations for which a ULR6 velocity is expected have been chosen following an *a priori* data quality criteria (minimum length of the time series, data completeness). Thus, if *a posteriori* a discontinuity in the position time series is detected, for instance, due to a change in the equipment (antenna or receiver) or an earthquake, or if the data recorded appear to be corrupted, the estimation of a robust velocity will be hampered. Second, one should keep in mind that the expected increase in the number of GLOSS Core Network stations with a robust GNSS velocity is due to the implicit extension of the distance criteria between the tide gauge and the GNSS antenna (up to 752 km for the Inhambane tide gauge). It is thus a very tentative experiment, assuming that the GNSS antennae are sensing the same vertical land movements as the tide gauges when they are distant!

2. Other vertical velocity solutions (TIGA, DORIS…)

SONEL has been developing its infrastructure to cope with different GNSS solutions, that is, updated solutions from a given analysis center (e.g., previous section), but also solutions from other groups within the GNSS area or from other geodetic methods. That said, only state-of-the art solutions will be considered at the time of submission; the minimum being the adoption of the latest IGS-agreed models and corrections. Figure 7 illustrates how the user may choose a particular solution (the analysis centers displayed are tentative and only serve as an example at this stage). Interestingly, DORIS solutions are envisaged from a recent contact with the CLS group in 2012. The question whether absolute gravity may be provided has been considered as well, even though too few groups have invested on this costly but accurate geodetic method.

3. New products for satellite altimetry and height system applications

The focus of SONEL developments over the past two years has been to implement user-friendly tools (i) to access the GNSS data, and (ii) to determine the combined rates of sea level change (section II) with the PSMSL colleagues. Other combined products can be envisaged, in particular for satellite altimetry applications or geodetic and hydrographic datum connections. For these applications, however, the geodetic connection between the GNSS antenna and the tide gauge is critical. This is also important data for studies of long term trends in sea levels, even though one can make the somewhat reasonable (or not) assumption of local stability when this data is missing.

SONEL attempts to gather all the available geodetic connections (mostly leveling results) for the tide gauges and integrate those into its database. It includes the connections with nearby DORIS stations (about 30 DORIS stations are nearby a tide gauge). Figure 14 shows that as many as (or as few as) 60 tide gauges have a geodetic link to a GNSS station on SONEL, and 5 tide gauges with a DORIS station. Among the 60 tide gauges, 40 belong to the GLOSS network (Figure 15).

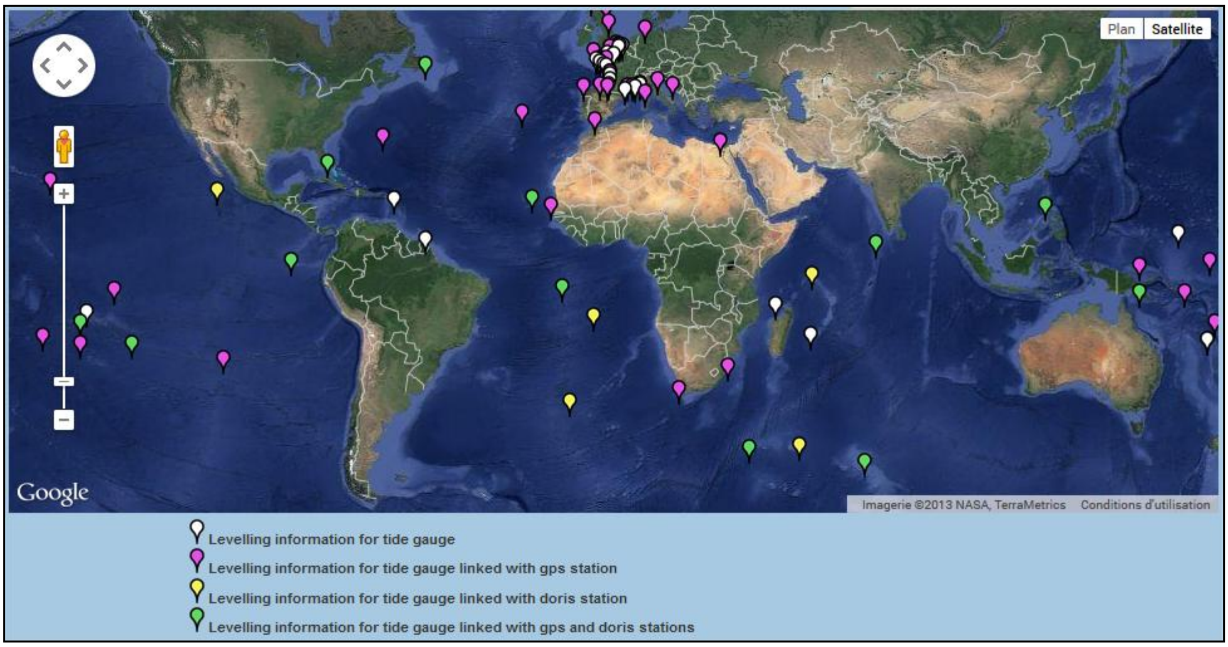

Figure 14: Status of the leveling campaign data at tide gauges stored in SONEL
http://www.sonel.org/-Stability-of-the-datums-.html?lang=en

A major challenge is the analysis of reports from leveling campaigns, focused on linking the tide gauge data reference level (for instance the RLR when the data are retrieved from the PSMSL) and the GNSS antenna reference point. Many of these reports are observing tide gauge benchmarks that are not reported in the PSMSL diagrams showing where the tide gauge reference level or RLR is, or their identification (name) is not the same, making it difficult or impossible to guess if they are actually the same.

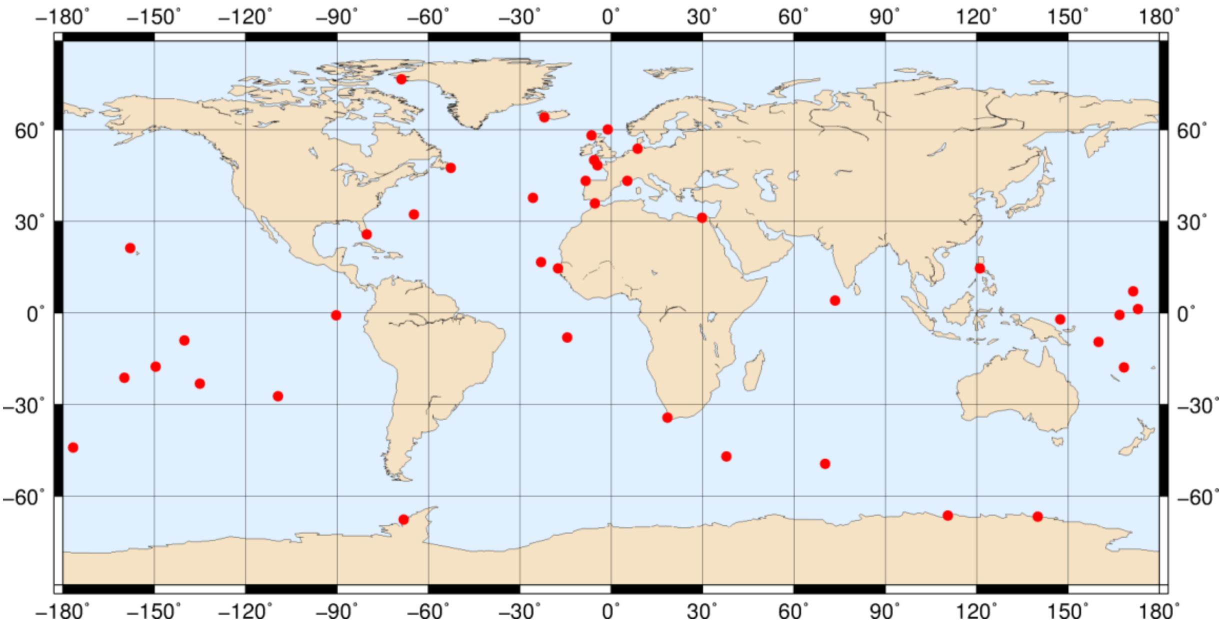

Figure 15: GLOSS tide gauges for which the geodetic connection with the nearby GNSS station is known in SONEL

Figure 16 further highlights the missing geodetic connections. There are currently known for only 10% of the GNSS co-located tide gauges in SONEL. About 200 tide gauges (Figure 16, purple circles) are within 1 km from a GNSS station, but for which the geodetic connection at present is unknown in SONEL.

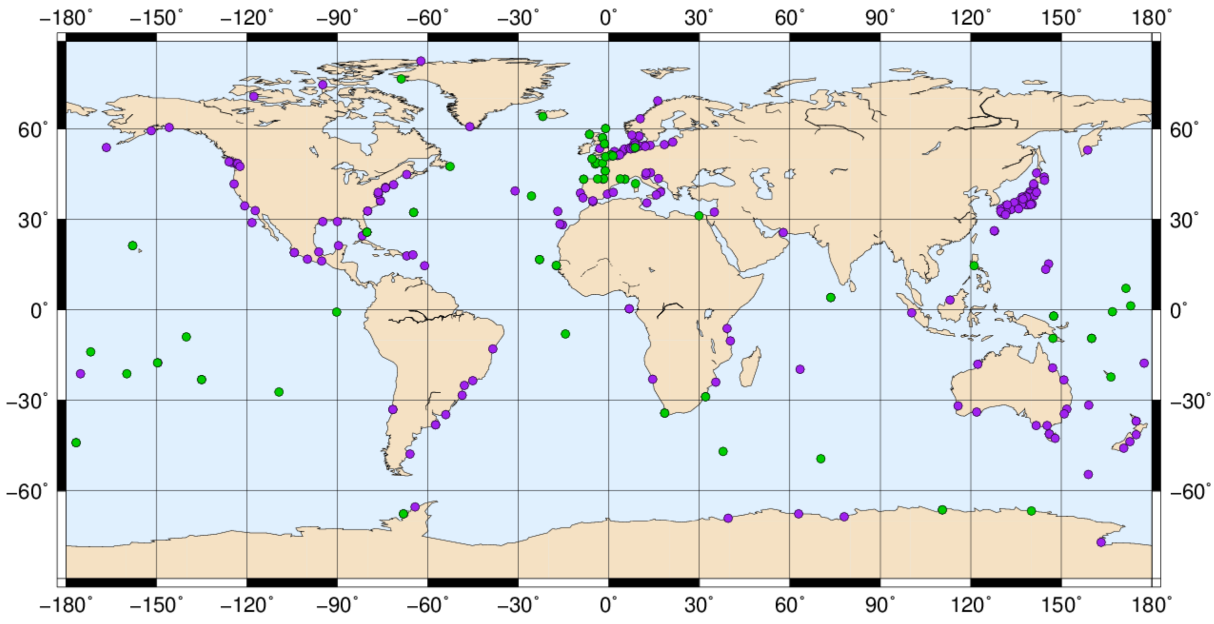

Figure 16: Tide gauges with a known geodetic connection to a GNSS antenna in SONEL (green circles) and tide gauges without that information but within 1000 m from a GNSS antenna (purple circles)

4. Summary of major limitations today

The major limitation for the applications aimed at in GLOSS is certainly the availability of continuous GNSS station at tide gauges (long term trends, satellite altimetry, datum unification). Only 19% (55 out of 289) are co-located at a GLOSS station (at or within 100 m). Progress is still needed in this respect to fulfill the GLOSS Implementation Plan requirements for a core network station.

Another important issue is the free and open access to the relevant GNSS observation following the international guidelines of the IGS/TIGA, that is, daily files in RINEX format with a 30s sampling.

Equally important is the need for updates on the equipment changes or any change of its immediate environment (metadata) as soon as possible by updating the GNSS station log-sheet, which should follow the IGS standards, and to inform the SONEL network station manager, Ing. Elizabeth Prouteau (elizabeth.prouteau@univ-lr.fr).

Last but not least, whenever the GNSS station is not directly installed on the same tide gauge roof or ground, it is necessary to undertake repeated leveling connections for at least five years to assess that the GNSS antenna and tide gauge are not experiencing differential land motions at 0.1-0.2 millimeter per year level. In any case, the availability of the initial connection is critical for satellite altimetry comparisons or calibrations, and vertical reference unifications on land (height systems) and sea (chart datums).

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