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

(Status report as of June 22th, 2017)

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Background

In 2009, the GLOSS program convened a workshop on "*Precision Observations of Vertical Land Motion at Tide Gauges*" before its XIth 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 was the first operational system 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 XIIth 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 (IOC, 2012).

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 third status report of the SONEL GNSS at tide gauges data center since its inception in GLOSS. Most of the illustrations herein are extracted from the Internet portal of SONEL and continuously updated versions can be viewed at www.sonel.org.

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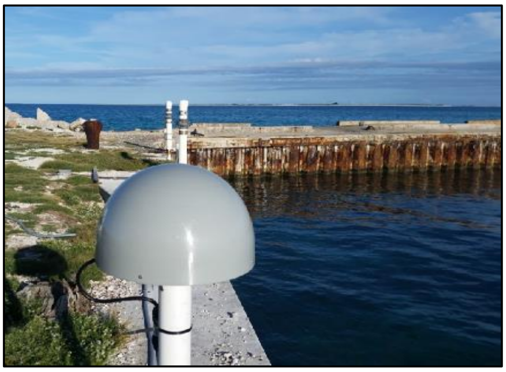
Fort de France (GLOSS 338)


Midway Island (GLOSS 106)

Examples of GLOSS Core Network stations newly equiped with continuous GNSS

I- GNSS data holdings at SONEL

1. Global status overview

SONEL has currently identified 806 tide gauge sites for which a GNSS station is nearby (within 15km), or from the other point of view 954 GNSS stations that are nearby a tide gauge site (Figure 1). Among these GNSS stations **558 are active at 557 tide gauge sites** (a data file was successfully retrieved within the last 30 days, in green on Figure 1), 166 are dormant (no data for the last 30 days, in orange on Figure 1), and 124 are decommissioned (red cross on Figure 1). It should be noted that 106 GNSS stations have no data available (in blue on Figure 1), mostly because of military or commercial restrictions. Note that all the values in this report correspond to the status on 22 of June 2017. As of June 2017, the SONEL data assembly center contains more than 4,000,000 daily station files of GNSS measurements in RINEX format, **contributed by over 170 different organizations.**

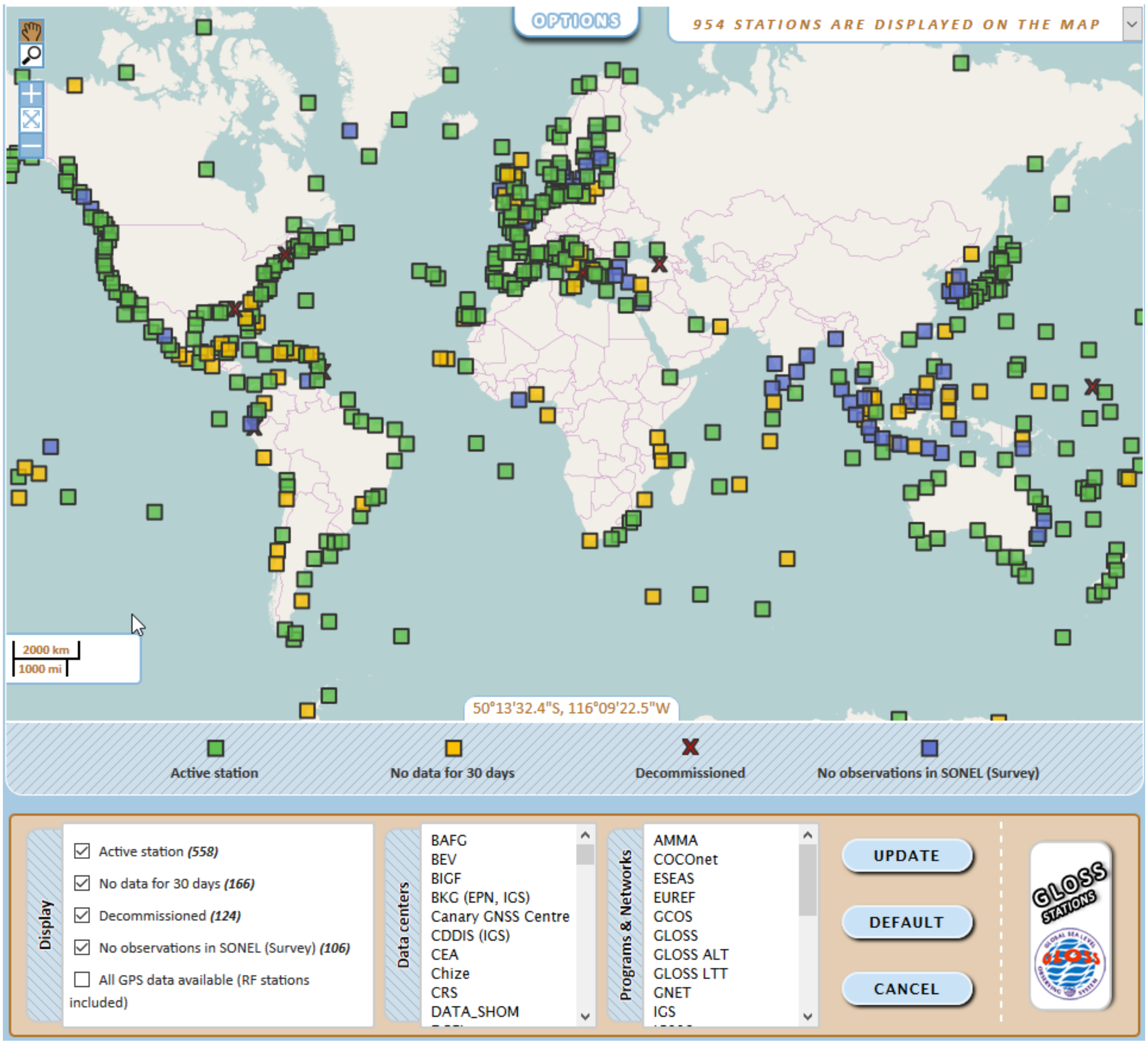


Figure 1: Status of the GNSS@TG data available on SONEL
http://www.sonel.org/-GPS-.html

Since the 14th session of the GLOSS Group of Experts meeting in October 2015, 15 new GNSS stations nearby a GLOSS Core Network tide gauge have been identified and their data collected into SONEL. Among these, some are replacing a decommissioned GNSS station (2) or supplementing an existing one (12). Only one GLOSS Core Network tide gauge out of the above 15 did not have any GNSS in 2015 (at Midway Island tide gauge, GLOSS ID: 106; the permanent GPS is operated by the NOAA). It should be noted that data are available in SONEL for all the 15 new GNSS stations at GLOSS sites. (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 676 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 essential in the GNSS data analysis to ensure the realization of a stable geocentric reference frame over the entire data span.

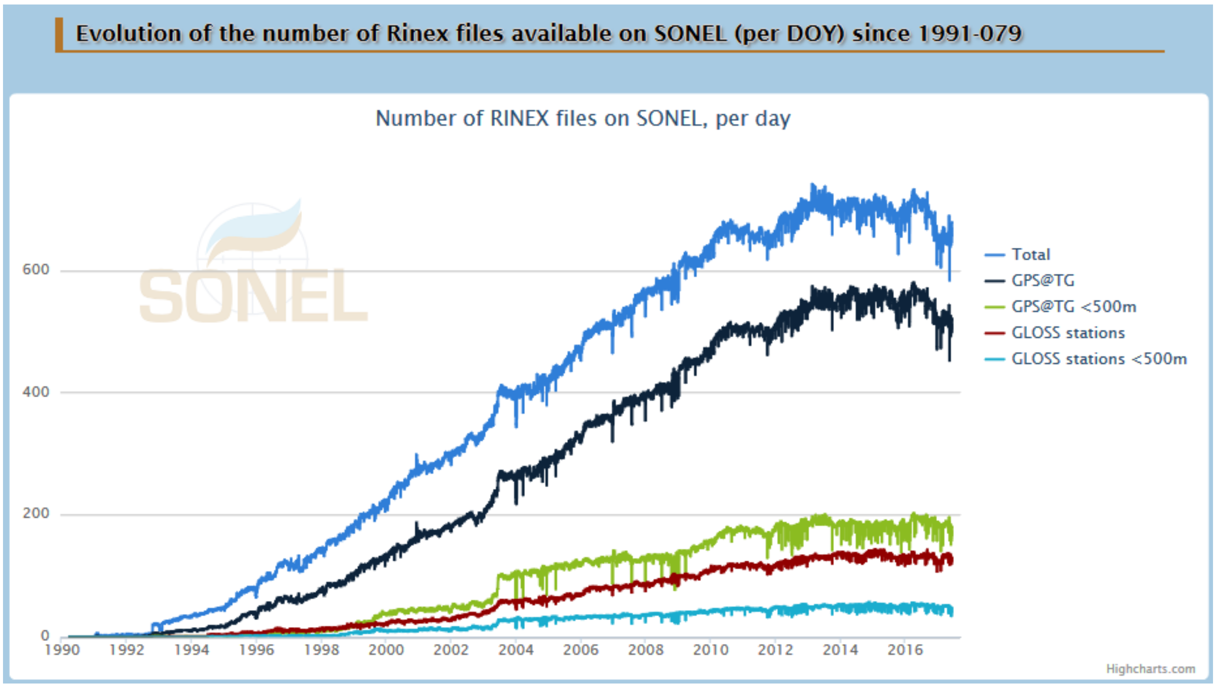


Figure 2: Evolution of the GNSS stations operational (providing data to SONEL)
http://www.sonel.org/-GPS-.html?lang=en

2. GLOSS Core Network status overview

According to the latest version of the GLOSS station handbook (http://www.gloss-sealevel.org/station_handbook/stations/#.VflnKpePv0F), the GLOSS core network comprises 290 tide gauge sites. Figure 3 shows that **212 of these stations are nearby one or more GNSS stations** (this corresponds to 332 GNSS stations nearby a GLOSS tide gauge site). The 75 tide gauges for which no GNSS station has been found in the vicinity are in white on Figure 3. For 21 stations, a GNSS station has been identified but the data are currently not available (in blue on Figure 3, see also Table 1).

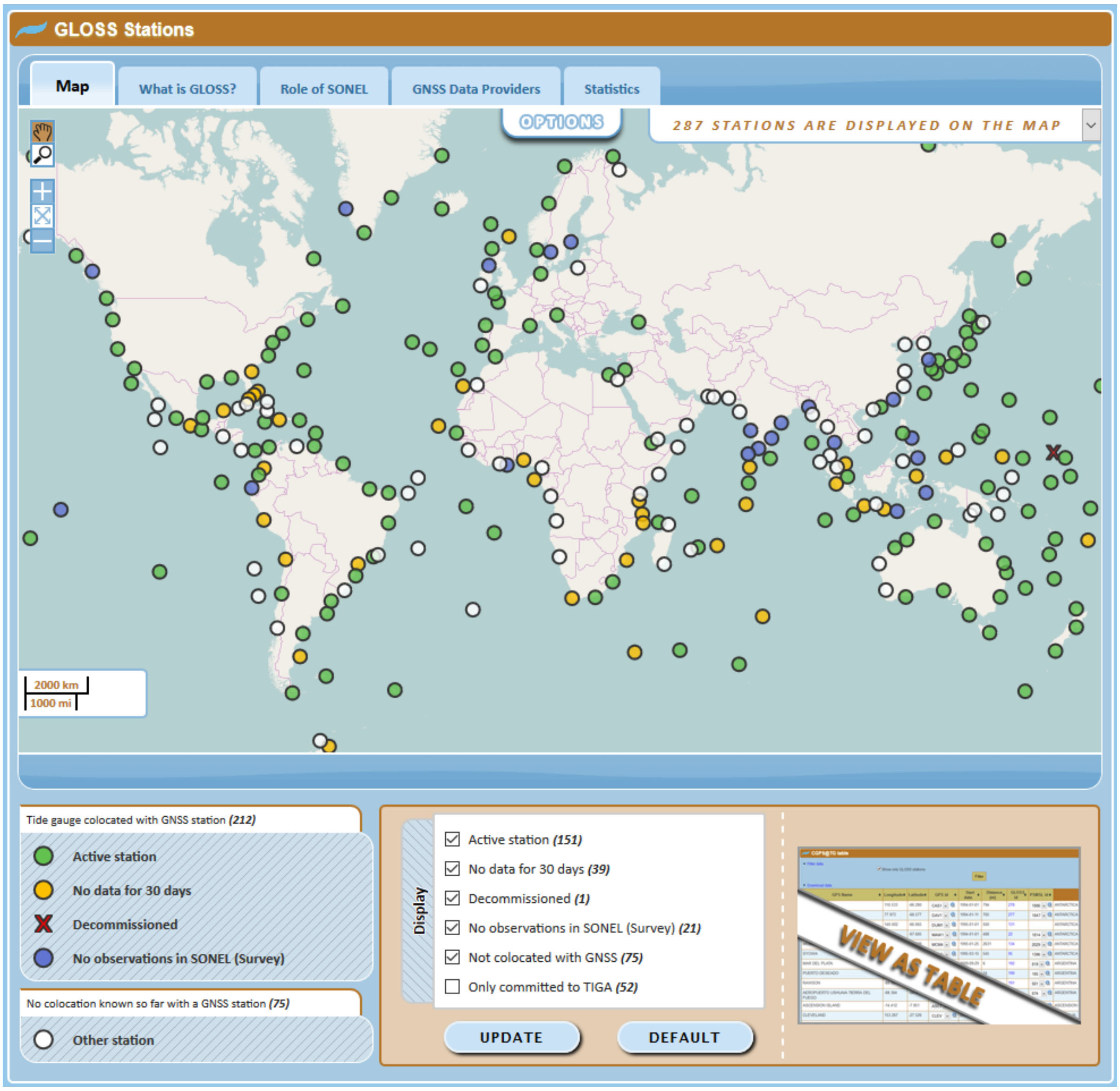


Figure 3: Status of the GLOSS tide gauge network with a GNSS station nearby
http://www.sonel.org/-GLOSS,81-.html?lang=en

GLOSS tide gauge	Country	GPS acronym
Prince Rupert	Canada	BCPR
Xiamen	China	Unknown
La Libertad	Ecuador	SALN, SEEC
Nuku-Hiva	French Polynesia	Unknown
Takoradi	Ghana	TKTG, TADI
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
Stockholm Stupi	Sweden	STH0
Goteborg – Torshamnen	Sweden	Unknown
Ko Lak	Thailand	Unknown
Legaspi	Philippines	PLEG
Davao Gulf	Philippines	PDAV

Pusan	South Korea	PUSW
Godthab	Denmark/Greenland	NUUK
Chittagong	Bangladesh	Unknown

Table 1: GLOSS stations (21) for which a continuous GNSS station has been identified nearby but its data are currently not available

It is worth reminding here that, beyond the formal commitment to the GLOSS program, there is a clear interest to distribute the GNSS measurements freely. Deriving accurate vertical velocities from GNSS measurements is still a challenge in Geodesy. Thus, the GLOSS implementation plan (IOC, 2012) 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 will enable confrontation of the products from current state-of-the-art GNSS data analysis strategies, and hopefully advances to ultimately obtain vertical velocities at tide gauges that are robust and reliable.

Figure 4 highlights the information on distance between the tide gauge and the closest GNSS antenna. This information is important as the likelihood of leveling links between the instruments 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 tide gauge. This issue was first discussed by Bevis *et al*. (2002), and most recently by Gill *et al*. (2015). As highlighted by Gill *et al*. (2015), the leveling error can potentially become a significant part of the total error budget at distances longer than 1000 m, thus stations more than one kilometer away should not be considered as “co-located” in the practical sense. For the 124 GLOSS tide gauges with a GNSS antenna less than 1000 m distant, 62 are within 100 m.

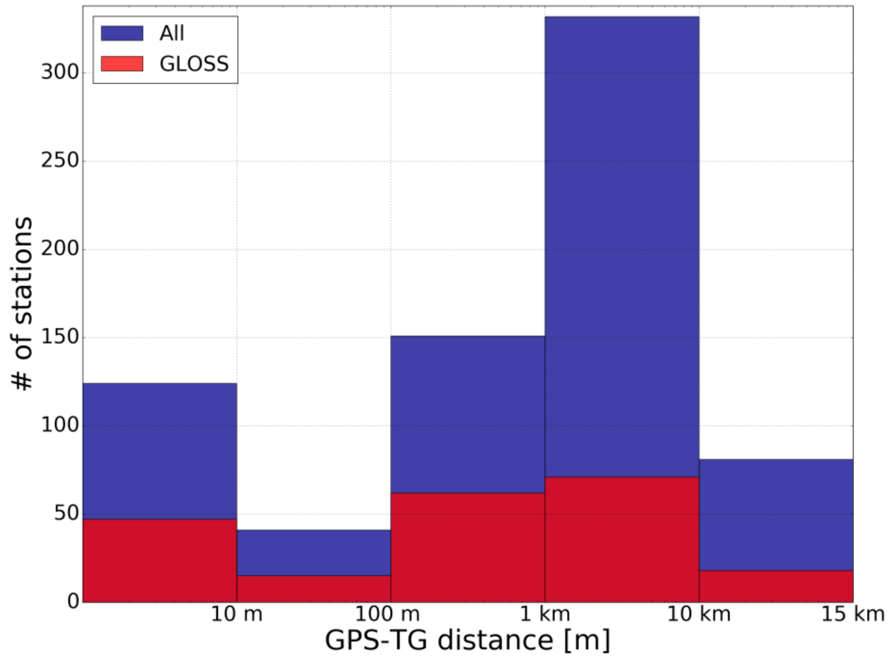


Figure 4: GNSS antenna distance from the tide gauge.

Appendix 1 provides a list of the GLOSS Core Network sites with some relevant information on the data availability related to the GNSS stations nearby, and the leveling connections of the GNSS antenna and tide gauge benchmarks.

The distribution of the number of GPS stations against their record length or against a minimum record length are shown in Figure 5 and 6, respectively. The record length is calculated as the difference between the last and the first data file available, without considering gaps. The information on large data gaps is stored and available on the SONEL website. The GPS record length is a critical factor in order to derive an accurate vertical velocity. According to Santamaría-Gómez and Mémin (2015) **a minimum record length of a decade** (without gaps) is required in certain tropical areas to mitigate the impact of interannual loading land deformation in the secular vertical velocity estimates. As an obvious consequence, it is highly recommended to install a permanent GNSS station at the tide gauge as soon as possible, and **to change the GPS equipment only when it is strictly necessary** (to avoid interruption and offsets in the time series that can bias the velocity estimate).

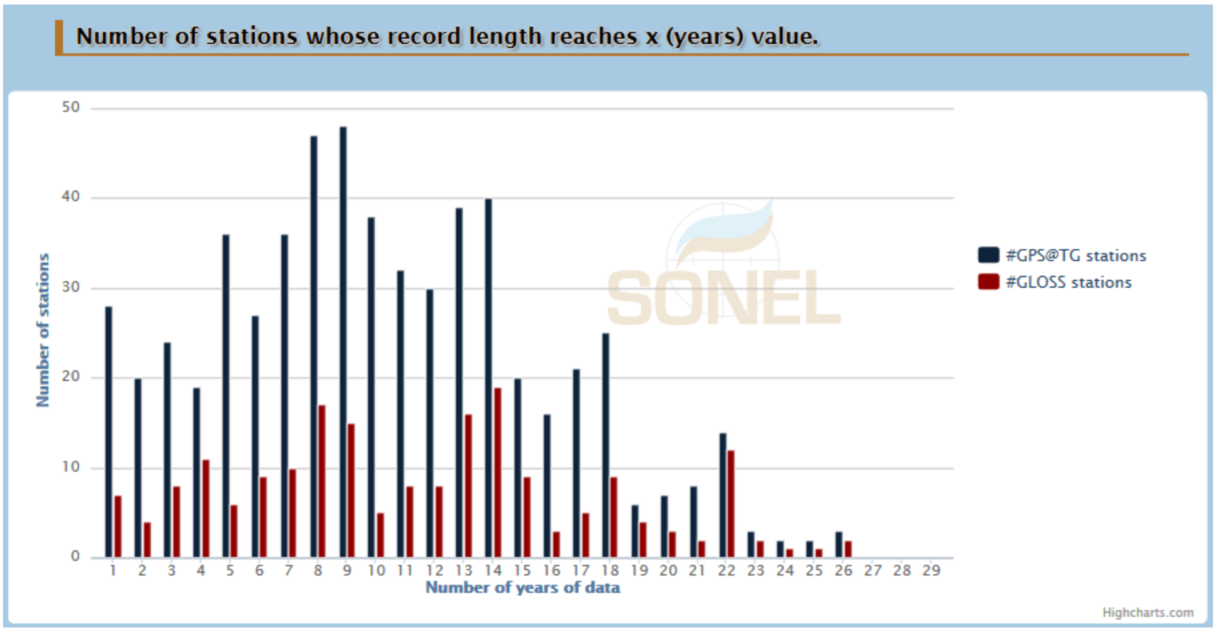


Figure 5: Number of stations whose record length reaches a given number X of years of data.

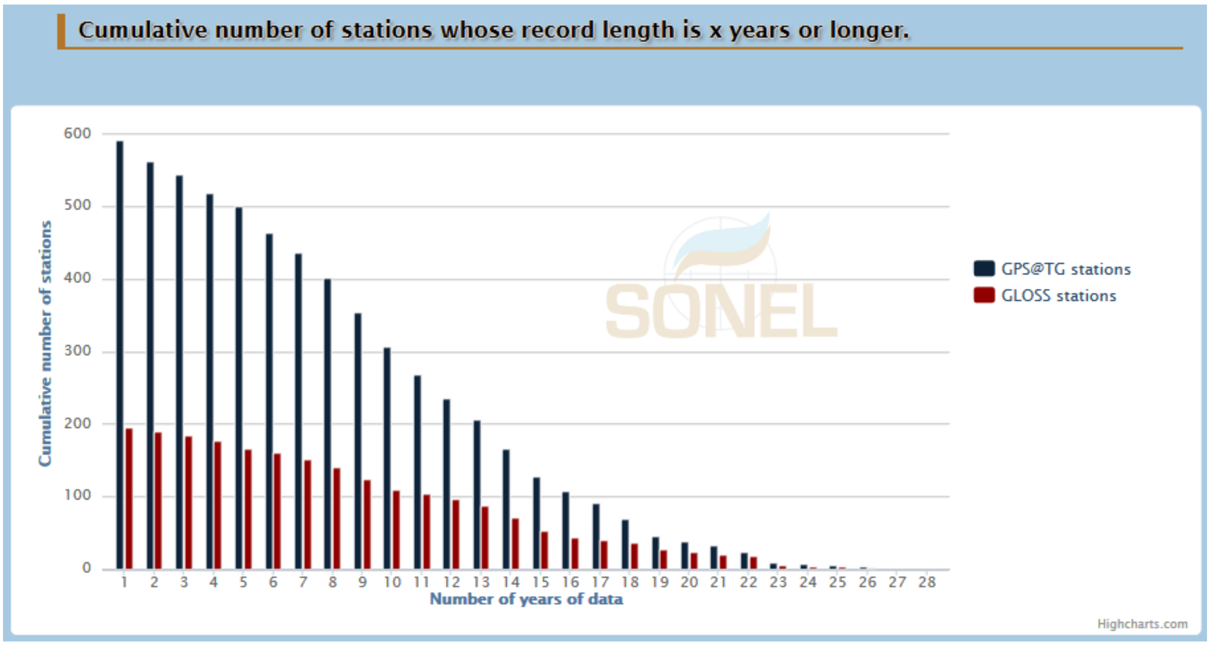


Figure 6: Cumulative number of stations whose record length is X years or longer.

II- Data access tools

1. General

SONEL strives to provide user-friendly access to its data holdings by developing web-based interfaces such as clickable maps (e.g., Figure 1). For the last couple of years, the maps have given information on which GNSS stations are near a tide gauge, its activity status, and data availability. 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 center, 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 observation 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 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 to facilitate users own studies. 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 the GNSS vertical velocities, and perhaps more interestingly to demonstrative products like: (i) the combined linear trends from the GNSS and the tide gauge records (relative *versus* geocentric sea level trends), (ii) the combined linear trends from the tide gauge and satellite altimetry data (an unorthodox method of estimating vertical land motion). Both demonstrative products were achieved through stimulating and productive cooperation between the SONEL and the PSMSL teams or between the SONEL and the University of Balearic Islands, respectively. The SONEL report of 2015 to the GLOSS group of experts described the first product. In this report, details are provided on the combination of tide gauge and satellite altimetry data in section II.3.

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 the station, as well as its 'residual' position time series. The term 'residual' refers to the difference between the positions and the linear model at given epochs, typically weekly or daily since the last IGS 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 data base was designed to handle several types of GNSS solutions. First, it can cope with solutions from different analysis centers. This is an interesting feature which enables the user to appraise the level of agreement in the vertical velocities from the various analysis centers at a given station. It provides some additional reliability beyond the formal uncertainties from an individual analysis center solution. Second, SONEL can also handle multiple solutions from a single analysis center. For instance, it may be interesting to update a solution by incorporating new models or corrections (reprocessing), 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

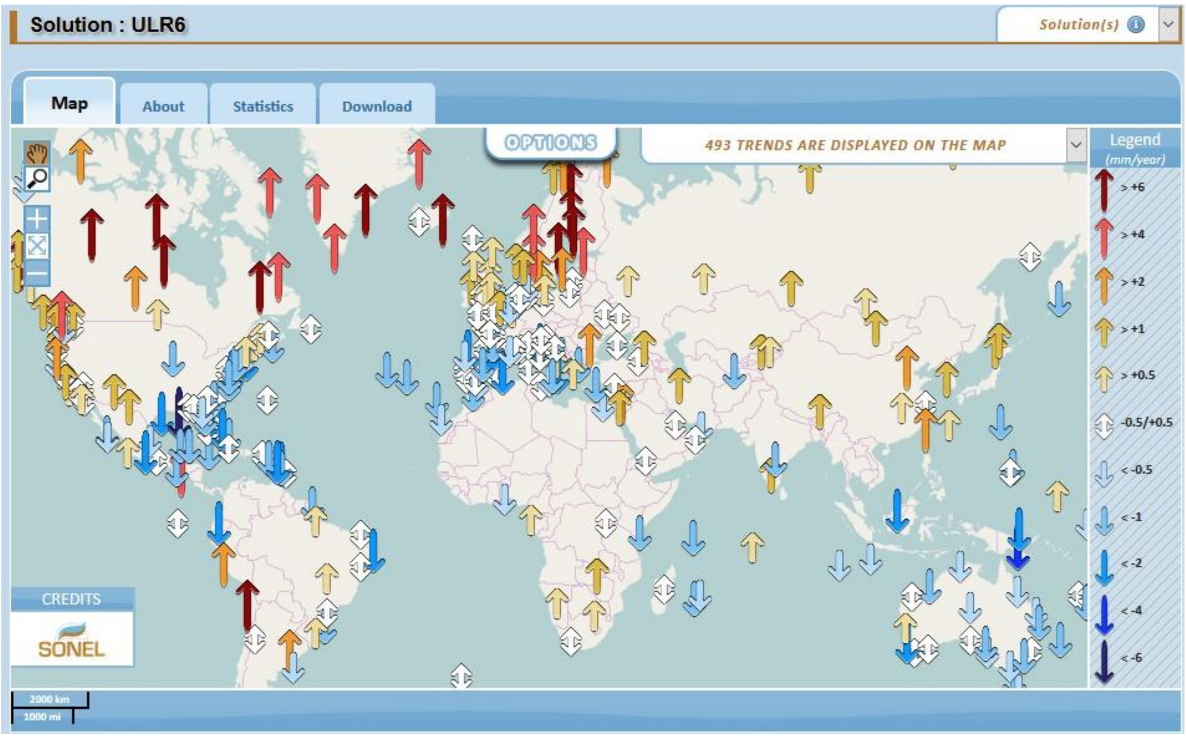


Figure 7: Display on a web-based clickable map of the GNSS vertical velocities from ULR6 solution http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en

Figure 7 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, global solution file in SINEX format, table of estimated discontinuities, etc.).

The SONEL report of 2015 to the GLOSS group experts provided details on the latest GNSS solution available from the University of La Rochelle (Santamaría-Gómez *et al.* 2017). As mentioned previously, SONEL data base was devised to handle other GNSS analysis center solutions, including DORIS solutions, provided the groups are making them available to SONEL (Section III.1).

b) Local specific view (to a particular station)

The 'GNSS solution' data for a specific station can be accessed either through the aforementioned 'GNSS solution' map, or through the former GNSS general information map presented in Section II.1, which describes what observations are available (e.g., 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 8). First, the general information was 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 was 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 can 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.

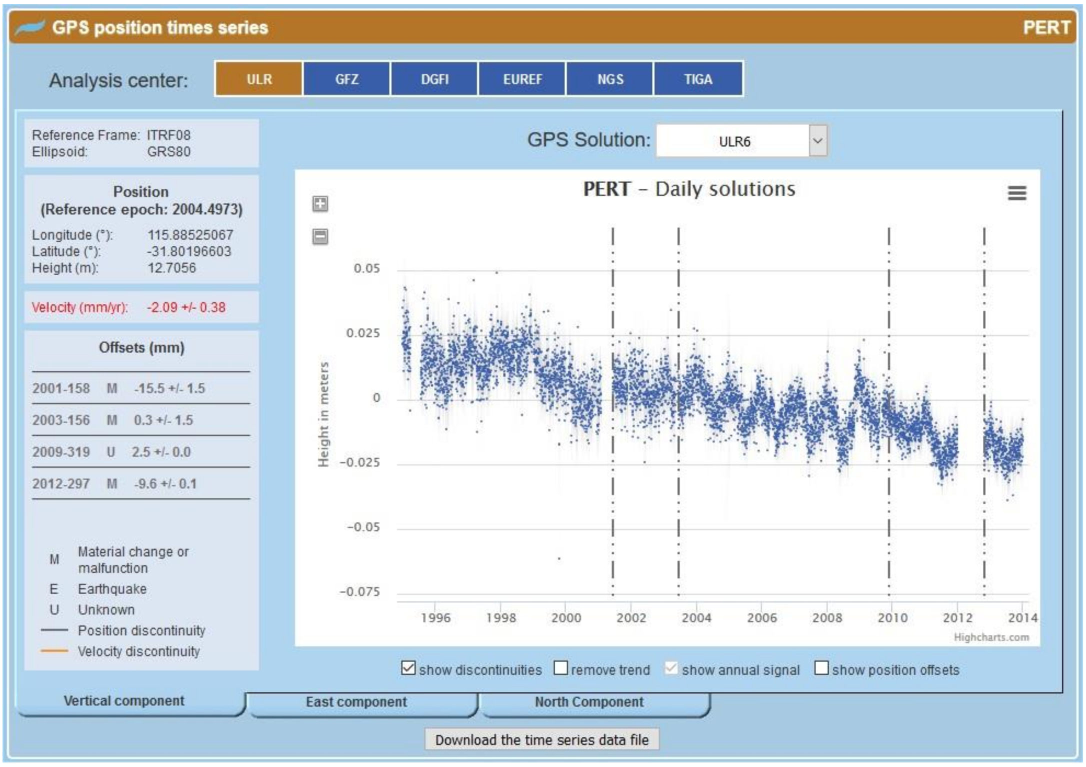


Figure 8: An example of 'GNSS solution' for the PERT station (Perth, Australia).
http://www.sonel.org/spip.php?page=gps&idStation=812

3. Combined product from tide gauge and satellite altimetry data

Combining tide gauge and satellite altimetry data can be useful in many technical and scientific respects, for instance: (i) quality controlling each measurement technique by examining the sea level differences, (ii) learning about oceanic processes whose imprint in sea level is different between off-shore and coastal areas, (iii) estimating vertical land motion at the tide gauge. The latter application is of particular interest since many tide gauges are not co-located with GNSS stations yet. Even though the tide gauges were equipped with continuous GNSS stations, the GNSS results can be subject to many systematic errors that an independent approach can reveal.

The approach consists in subtracting the sea level time series from a tide gauge with an equivalent time series from satellite altimetry. To the extent that both instruments measure identical ocean signals, their difference (U = N – S, Figure 9) is a proxy for the vertical position of the tide gauge. Assuming that the instrumental drifts are negligible, the time series of the sea level differences will then be dominated by vertical land motion at the tide gauge.

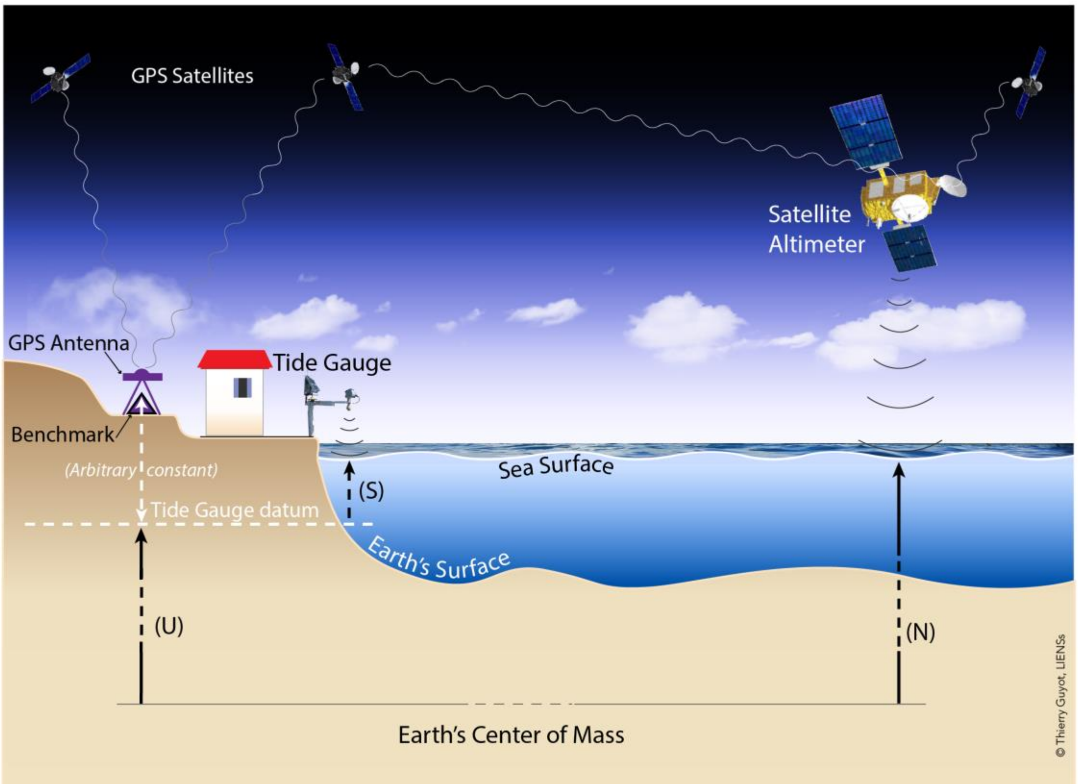


Figure 9: Observational quantities and instruments involved in the combination of tide gauge and satellite altimetry data

This approach was first published by Cazenave *et al*. (1999). SONEL has recently started gaining insight in the details of this approach within a collaborative framework with the University of Balearic Islands. The results were recently made available as a demonstration product on the SONEL website using the AVISO altimetry dataset (http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en, Figure 10). They show an RMS of 1.35 mm/yr (Figure 11) when compared to the ULR6 GNSS solution at 190 common sites. Details can be found in Wöppelmann and Marcos (2016) or on the above webpage ("About" tab). If the users find it useful, SONEL will consider updating the product on a yearly basis as the satellite and tide gauge records lengthen. In addition, other satellite altimetry products from other groups than AVISO will then be a natural development as well.

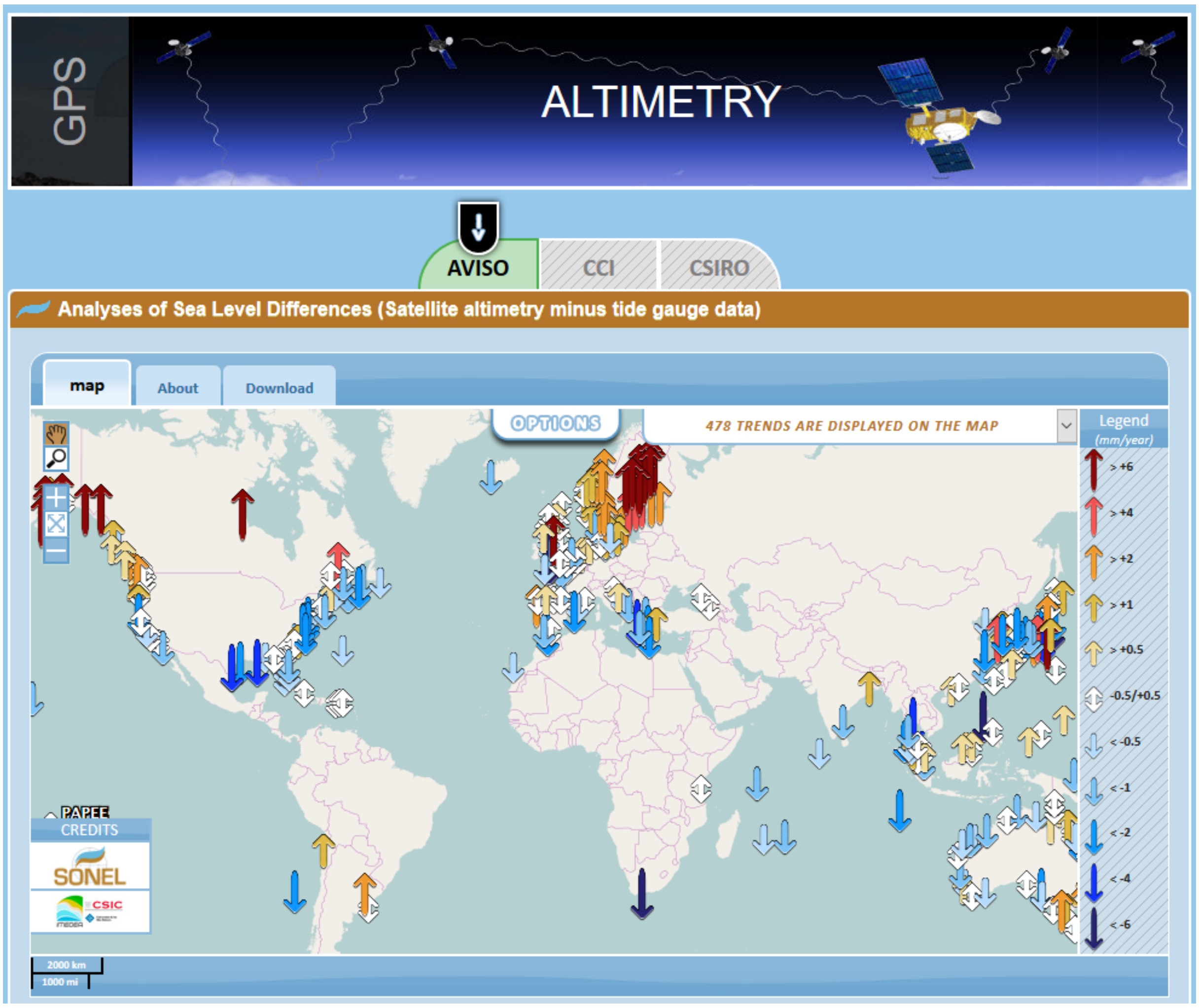


Figure 10: Vertical velocities estimated at 478 PSMSL sites using the combination of tide gauge and satellite altimetry data
http://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en

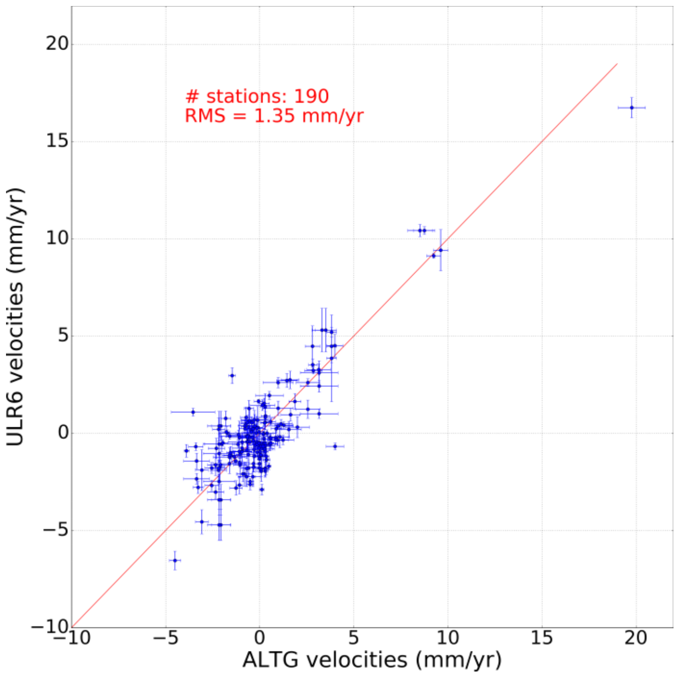


Figure 11: Comparison between vertical velocities obtained from the two independent approaches (satellite altimetry minus tide gauge data and GNSS solution from ULR6)

The tools to access the results from the combination of tide gauge and satellite altimetry data are similar to those in place for the GNSS results. For instance, dedicated station web pages were created to display the sea level time series from satellite altimetry and PSMSL tide gauges along with the corresponding differenced time series (Figure 12).

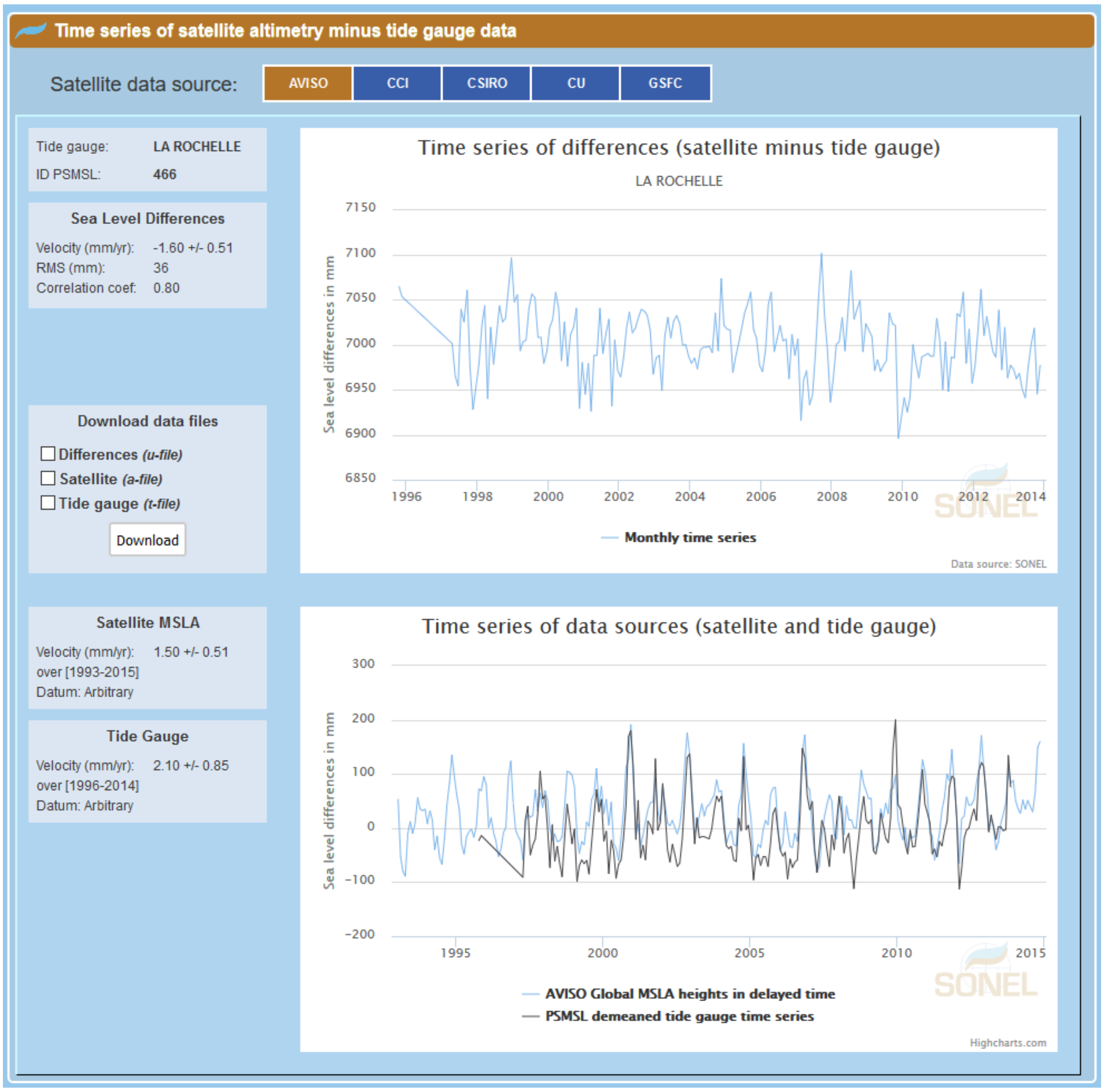


Figure 12: Example of SONEL station webpage showing the combination of AVISO satellite altimetry data and PSMSL tide gauge monthly time series at La Rochelle http://www.sonel.org/?page=altimetrie&psmslId=466

III- Future work

1. 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, 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 8 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 in 2016 with the CLS group at the OSTST meeting. 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.

Regarding the approach of combining tide gauge and satellite altimetry data (section II.3), if the users find the demonstration product useful to supplement estimates of vertical land motion where there are still no GNSS stations or to check the level of agreement between the two independent methods, SONEL will consider updating the product on a yearly basis to extend the time series. Satellite altimeter products from other groups than AVISO will be explored as well. This can in turn provide an interesting comparison tool between satellite altimetry data products and groups producing them.

2. New products for satellite altimetry and height system applications

Other combined products can be envisaged, in particular for 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. Consequently, the leveling data between the tide gauge datum (Figure 9) and the GNSS antenna is crucial, and making its data available is an important requirement for GLOSS Core Network stations (IOC, 2012).

In this context, SONEL attempts to gather all the available geodetic connections (mostly leveling results) for the tide gauges and integrate those into its database. A major issue associated with this activity is the access and 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. The activity includes the connections with GNSS antennas but also with nearby DORIS stations (about 30 DORIS stations are nearby a tide gauge).

Figure 13Figure 1 shows that as many as (or as few as) 150 tide gauges have a geodetic link to a GNSS station on SONEL, and 23 tide gauges with a DORIS station. A status of these geodetic connections between tide gauges and GNSS stations available in SONEL was recently published by Woodworth *et al.* (2017), highlighting the varied issues associated with this activity.

Among the 150 tide gauges, 71 belong to the GLOSS Core Network (Figure 14). Even though substantial progress has been made since the last report to the GLOSS group of experts in 2015, these connections are currently known for only 25% of the GNSS co-located GLOSS tide gauges in SONEL (14% in 2015).

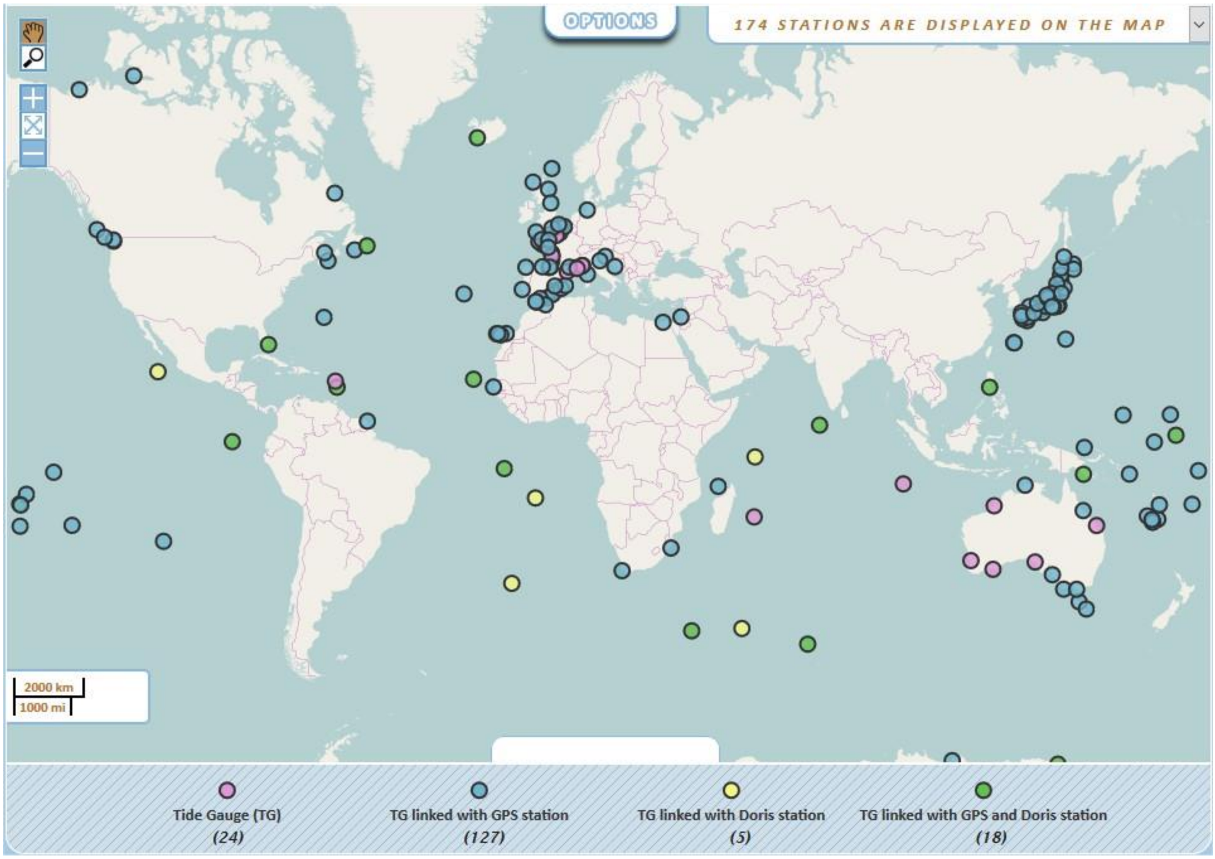


Figure 13: Status of the leveling campaign data at tide gauges stored in SONEL
http://www.sonel.org/-Stability-of-the-datums-.html?lang=en

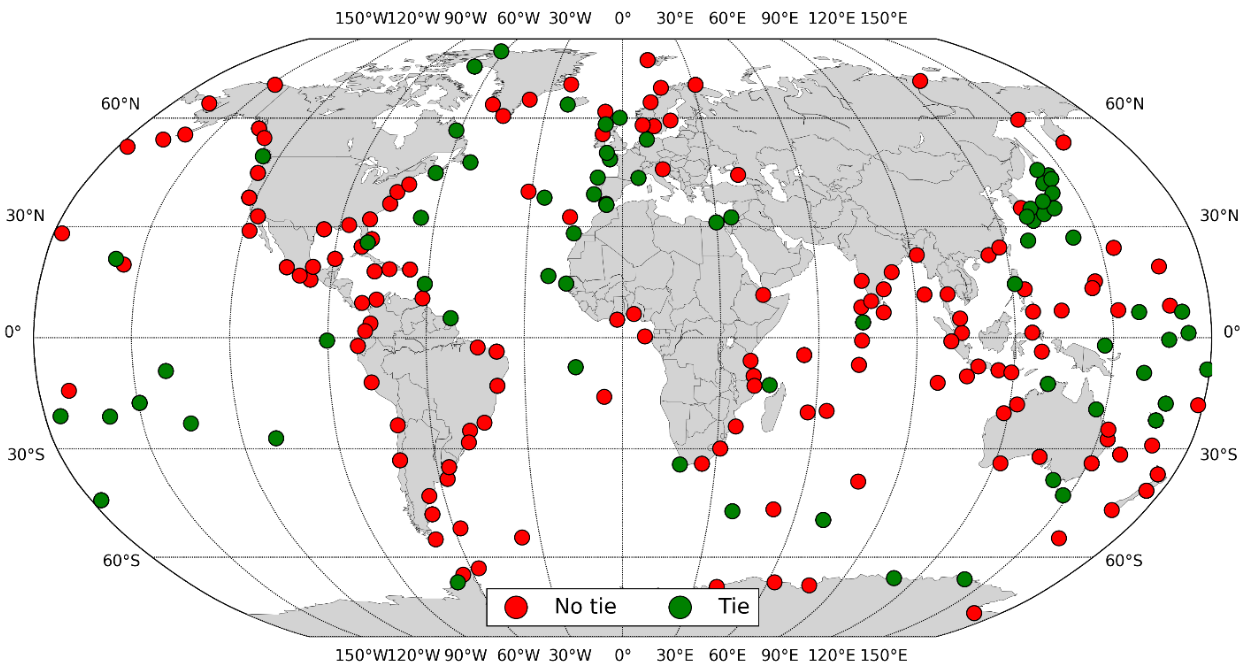


Figure 14: Geodetic ties available (known) in SONEL for the GLOSS Core Network.

Figure 15 shows that at present the geodetic connection is unknown in SONEL for 116 GLOSS Core Network tide gauges that lie within 1 km distance from a GNSS station. A 1 km distance is a reasonable distance for a leveling campaign, meaning that the potential for a substantial improvement is within reach if tide gauge operators consider including the leveling of the GPS antenna in their next (annual) leveling control.

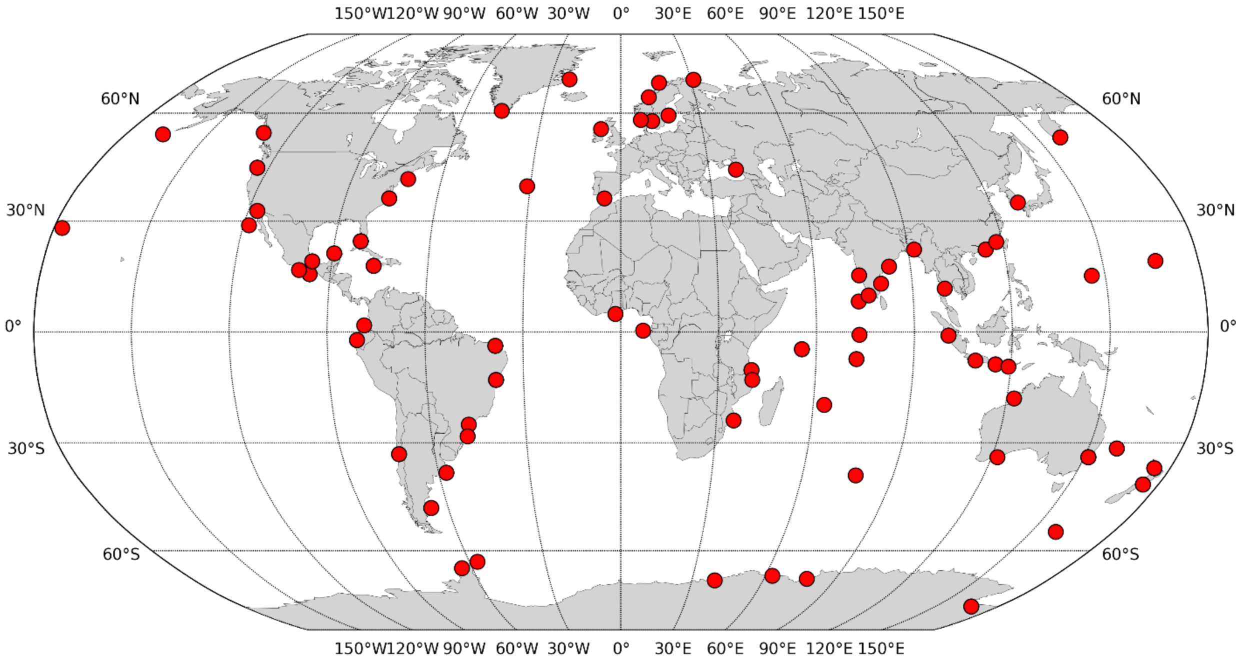


Figure 15: GLOSS tide gauges within 1 km from a nearby GNSS station for which the geodetic tie is not available in SONEL.

3. 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 in sea levels, confrontation with satellite altimetry, vertical datum unification). Only 22% (62 out of 287) 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 (IOC, 2012) 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).

IV- Usage statistics

Accurate usage statistics are extremely difficult to establish, in particular for FTP anonymous servers, which is the case with many data from SONEL. A rough idea can be obtained from the number of files downloaded in June 2017: as many as 950,000 files were downloaded from the SONEL FTP server. Another idea of the importance of the service can be appraised from the number of visits of the SONEL website per month (Figure 16). Figure 16 shows a steady and significant increase of this number of visits.

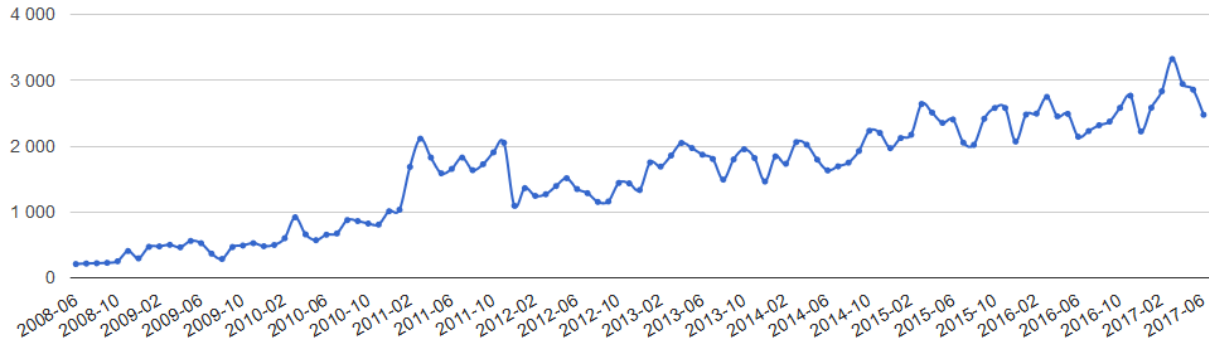


Figure 16: Number of monthly visits of the SONEL website (available at: http://www.sonel.org/-Statistics-.html?lang=en)

It is even more difficult to appraise the number of scientific studies that use data from SONEL. The number of articles published in peer review journals that explicitly quote SONEL (as far as the SONEL team knows) is shown in Figure 17. It certainly represents the tip of the iceberg. From the titles of the articles (a list can be viewed at http://www.sonel.org/-Users-feedback-.html?lang=en), it appears that in addition to sea level, tectonics, atmosphere and geodesy benefit from SONEL data.

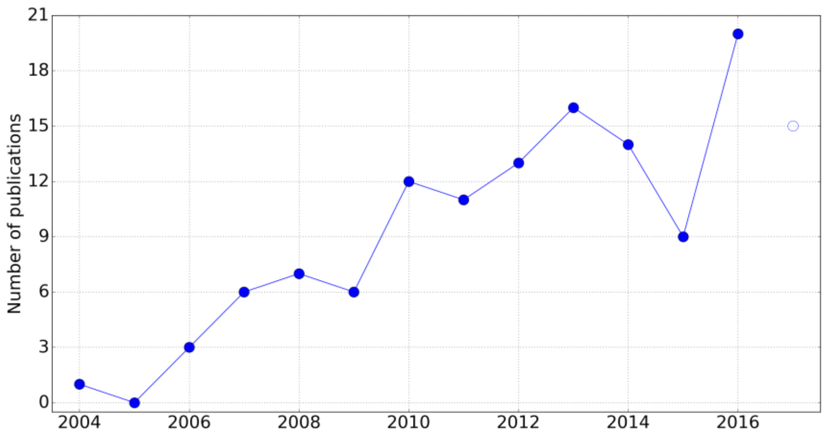


Figure 17: Number of scientific publications using SONEL data (as far as the SONEL team knows)

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