Friendly Reflections

Monitoring Water Level with GNSS

Alejandro Egido and Marco Caparrini

WHY IS THE SKY BLUE? This is an age-old question, interesting to anyone with a curiosity about his or her surroundings. But what has it got to do with global navigation satellite systems? Believe it or not, there is a connection.

Some of you might remember the explanation of the sky's color from your Physics 101 course but to bring everyone up to the same level, let's review. Everything we see is the result of the interaction of light and matter. And by matter, we mean the atoms, molecules, and particles making up matter. Light causes matter to vibrate. And vibrating matter (due to its electrical charges) in turn emits light, which combines with the original light. But matter not only re-emits light in the forward direction, it re-emits light in all other directions. This is called scattering.

INNOVATION INSIGHTS with Richard Langley

Scattered signals reveal characteristics of their source.

Now, the light from the sun includes all colors and so if we look directly at the sun when it is high in the sky (don't try this at home), it looks white or slightly yellowish. We are seeing the light propagating directly toward our eyes. When we look at the sky away from the sun, we are seeing scattered light. And this scattered light is predominantly blue. Why? It turns out that scattering is proportional to the fourth power of frequency. Light that is of a higher frequency, say a factor of two, is sixteen times more intensely scattered. So, blue light, which has about twice the frequency of light from the red end of the visible spectrum, is scattered much more than red light. Violet light is scattered even more but our eyes are not as sensitive to violet light as they are to blue light. Hence the sky looks blue.

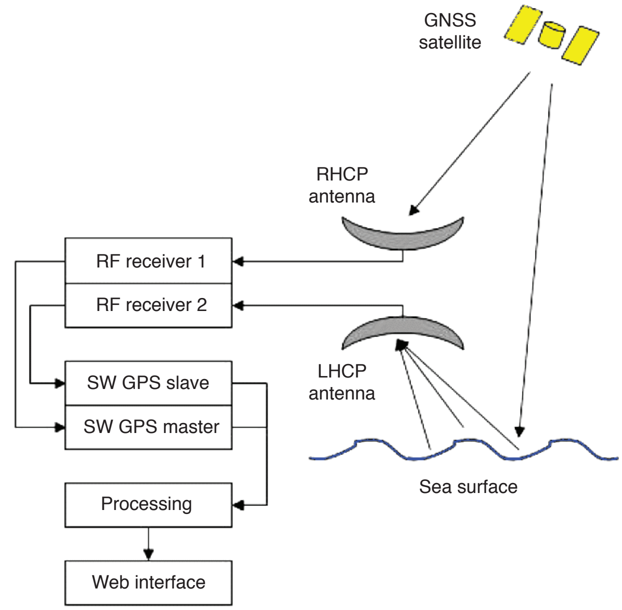
So what has this got to do with GNSS? As we know, for the best positioning and navigation results, we need the satellite signals to travel along a direct path to the receiver's antenna. There may be slight changes in the speed and direction of propagation of these direct-path signals caused by the interaction of the electromagnetic waves with the matter making up the ionosphere and the neutral atmosphere, but these are readily accounted for in the position fixes.

However, once they reach the Earth's surface, the signals can be reflected by buildings, vegetation, the ground, water surfaces, and so on. The signals are actually being scattered by the matter they encounter. A receiver can selectively acquire the scattered signals and the resulting measurements can be interpreted to reveal certain characteristics of the source of the scattering.

In this month's column, we learn about the design and application of a GNSS instrument that uses scattered signals for monitoring the level and roughness of inland and coastal water surfaces–yet one more use of GNSS signals for the betterment of planet Earth.

Lakes and water reservoirs are the world's most important sources of accessible fresh water. Despite its paramount importance — not only for a large variety of human activities, but also for the sustainability of ecosystems — fresh water is already scarce in many regions. The problem is envisaged to become worse in the coming decade. In addition, in climatological studies surface water storage is a critical element of the water cycle since the analyses integrate all hydrologic processes (precipitation, runoff, evapotranspiration, and so on) over a given basin; and for hydroelectric companies, it is the main parameter to be kept under observation for efficient energy production. All of these concerns make the monitoring of fresh water resources a prime activity for a wide variety of stakeholders including governments, climate research organizations, and hydroelectric production companies.

Coastal management is also a wide-ranging issue with large social and economic impacts. Care of our coasts includes dealing with threats such as storm surges and flooding, coastal erosion, and conflicting land-use issues. Coastal areas support the greatest concentration of living resources and people on the planet. In the past few decades, these regions have experienced a population density increase, which is envisioned to grow steadily. Furthermore, conflicts between commercial interests, recreational activities, infrastructure development, environment conservation, and exploitation of natural resources will become increasingly important and contentious. In fact, the coastal zone is a peculiar environment in which terrestrial, oceanic, atmospheric, and human inputs of energy and matter converge. Storm surges and coastal flooding events have caused considerable damage and economic loss on European coasts in par-



▲ **FIGURE 1** Basic operation of Oceanpal and the principle of GNSS-R-based sea-surface monitoring. Right-hand and left-hand circularly polarized antennas feed signals to radio frequency (RF) receiver front-ends that, in turn, feed software (SW) receiver back-ends and subsequent processing algorithms.

ticular. Such events, possibly linked to the world climate change, are expected to get worse in the near future, due to sea level rise and storm activity.

So, close monitoring of both inland waters and coastal regions is necessary for the well being of the planet. And since the need is so pervasive, monitoring systems should be characterized by a relatively low cost, low maintenance, and easy deployment, to serve the widest possible user community. We have developed a patent-pending solution using signals from global navigation satellite systems (GNSS).

Called Oceanpal, our monitoring system exploits reflected GNSS signals as signals of opportunity for passive remote sensing of the Earth's water surfaces. These multipath signals are usually considered to be nuisance signals since they reduce the accuracy of GNSS positioning applications. But for monitoring various processes affecting the Earth's surface, they are very beneficial. The technique is known as GNSS reflectometry (GNSS-R), and during the past decade, its use as a technique for Earth observation purposes has taken root.

GNSS-R is basically a bistatic radar technique. While most radar systems, such as those used for monitoring air space and harbor approaches and for weather forecasting, combine the radar transmitter and receiver at the same site — so-called monostatic radar — bistatic systems use transmitters and receivers separated by a considerable distance. Such systems have been used for studying certain atmospheric phenomena and for military applications where simple line-of-sight reflections from the target of interest are inadequate or insufficient.

The concept of bistatic radar can be extended to satellite signals. Since some of the signal transmitted by a satellite gets reflected off the Earth's surface, detecting this reflected signal by a separate passive receiver would provide some information about the reflecting surface. While any satellite signal could be used in principle, GPS (and other GNSS) turn out to be particularly useful. The concept of using GPS signal reflections was initially proposed in 1993 by Manuel Martín-Neira, working at the European Space Agency's European Space Research and Technology Centre in Noordwijk, The Netherlands. Since then, the technique has been successfully implemented by an increasing number of researchers.

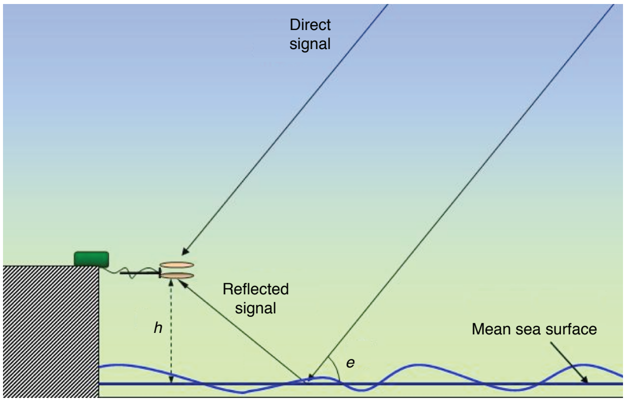
We could list several reasons for the continuous growing interest in GNSS as a remote sensing tool, but two main ones stand out: first, the global availability and stability of GNSS signals enables their use as reliable signals of opportunity; and second, GNSS makes use of L-band radiation, which is highly interactive with the natural scattering medium but relatively impervious to atmospheric conditions. Moreover, the passive nature of this concept allows for the production of cost- and resource-effective instruments.

Navigation signals are sensitive to a wide variety of geophysical parameters including topography, surface roughness, surface moisture, ionospheric electron content, tropospheric water vapor, water salinity, and vegetation. Research targeting related geophysical applications has been ongoing for many years, and the first pre-operational services exploiting reflected GNSS signals are now available. In fact, while the scientific community is waiting for a dedicated GNSS-R space mission to confirm the theoretical predictions about the characteristics of reflected signals observed from space, ground-based and airborne sensors have already been developed and validated for a number of applications.

The GNSS-R research area that has been most thoroughly investigated concerns the reflection of navigation signals from water surfaces, given the highly reflective nature of water. However, from water the interest has now moved towards ice and land applications, more specifically to the detection of sea ice and the monitoring of soil moisture. Recently, GNSS-R has also been proposed as a possible tool to monitor vegetation. This article focuses on the presentation of the Oceanpal sensor, and the description of the altimetry algorithms for monitoring the levels of sea (coastal) and inland waters.

Our Instrument

As mentioned above, Oceanpal is a GNSS-R-based sensor designed for operational monitoring of coastal and inland waters. The instrument comprises three subsystems: a radio frequency (RF) section, an intermediate frequency (IF) section, and a data-processing section. The RF section features a pair of low gain L-band antennas. A right-hand circularly polarized (RHCP) zenith-facing antenna collects the direct GNSS signals while a left-hand circularly polarized (LHCP) nadir-facing antenna collects the sea- or lake-surface reflected GNSS signals. (On reflection, the signals become predominantly LHCP.) Data bursts of some



▲ **FIGURE 2**. The geometry of GNSS signal reflections for altimetry applications.

minutes' duration are acquired from each antenna using two GPS L1 receivers (front ends) that down-convert the signals to IF. Within the IF sections, the signals are one-bit sampled and stored on a hard disk.

These direct and reflected raw data are then fed into the processing section of the instrument, where a pair of software GNSS receivers detects and tracks the available signals in the direct channel (which works as a master) and blindly despreads the reflected signals in the reflected (slave) channel. The result of this processing is a set of direct and reflected electromagnetic field time series for each satellite in view, plus some ancillary information, such as the satellite pseudorandom noise code (PRN) numbers and GPS time references, among others. The architecture described above is shown in **FIGURE 1**.

The data products provided by Oceanpal are so-called "Level-2" or derived products, namely the significant wave height (a statistical measure of trough-to-crest wave height), and the height of the nadir antenna over the mean level of the water surface under observation. To make this data available for the user in a friendly way, the observations are uploaded to a web server and displayed on a web page.

Oceanpal requires low maintenance compared to its competitors. Standard oceanographic buoys, which use accelerometers and a magnetic compass, or GPS buoys, featuring a conventional GPS receiver, are in contact with water, which implies costly infrastructures and frequent maintenance operations. Pressure sensors and air bubblers, commonly used to monitor the level of water reservoirs, also require frequent maintenance because of sediment accumulation. Compared to the alternatives, our sensor is a less costly and lower maintenance solution.

GNSS-R Altimetry Algorithms

The inland-water/sea-level monitoring is based on the estimation of the height of the Oceanpal antennas above the water/sea surface. This height is retrieved by the comparison of the delay (in time or distance) between the reflected and the direct signals. The reflection geometry is shown in **FIGURE 2**. Such a delay can be estimated using either the PRN code or the carrier phase of the incoming signals. The phase-based estimation provides more precise values, but it is only available for calm water surfaces where coherent constructive scattering (specular reflection) is predominant. In the case of rougher surfaces, the reflected signal's coherency is lost, and therefore the code-based algorithm must be used.

The basic equation that links the delay of arrival of both signals with the height of the antennas over the surface as a function of time (t) can be written as equation (1):

$$\tau(t) = 2 \cdot h \cdot \sin e(t) + b \tag{1}$$

where τ represents the lapse between the time of arrival of the reflected and the direct signals (as determined using either phase or code measurements), h is the height to be estimated, e is the elevation angle of the satellite considered, and b is the system bias, which is considered unknown but constant during every estimation. Solving a linear system with many such equations for different satellites over, say, one minute provides the sought estimation of h (and b).

Measuring the Level of a Water Reservoir

As mentioned before, when the water surface is sufficiently flat, the coherency of the reflected signal is maintained, thus its phase can be used to retrieve estimates of the height of the antennas over the surface. This algorithm is the so-called phase altimetry algorithm. The basic observable for this algorithm is the interferometric complex field *(ICF)*, defined as the ratio between the reflected and direct complex correlation waveform peaks:

$$ICF(t) = \frac{P_R(t)}{P_D(t)} \tag{2}$$

where P_R and P_D represent the time series of waveform peaks for the reflected and direct signals, respectively. In computing this ratio, adverse propagation effects such as the extra delay induced by the ionosphere and troposphere cancel out. Measuring the phase of the *ICF*, ϕ_{ICF}^{PRN}, one is then considering the phase single difference, $\phi_D^{PRN} - \phi_R^{PRN}$, between the reflected and direct signals as given in equation (3):

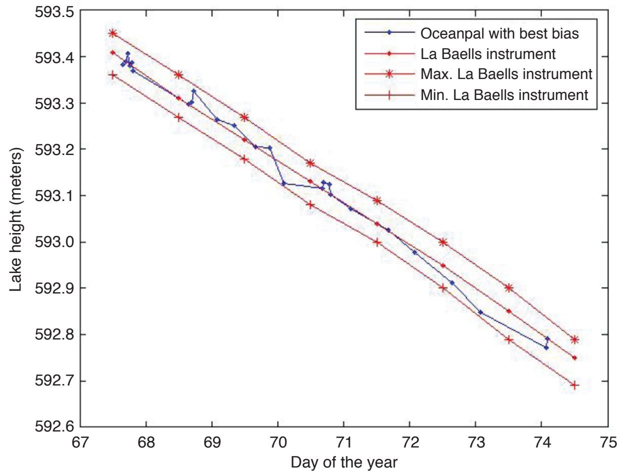
$$\begin{aligned}\phi_{ICF}^{PRN}(t) &= \phi_D^{PRN}(t) - \phi_R^{PRN}(t) \\ &= k \cdot D(t) + noise_\phi - N_{D-R}^{PRN}\end{aligned} \tag{3}$$

where k is the wave number of the GPS carrier frequency (the reciprocal of the wavelength), $noise_\phi$ is the noise present in the *ICF* phase and N_{D-R}^{PRN} is the unknown integer cycle ambiguity. D is the excess path of the reflected with respect to the direct signal, which can be directly linked to the height of the antennas over the surface. In order to solve for the cycle ambiguities, phase double differences among satellites are calculated, and by means of an ambiguity resolution algorithm (we use the null-space method developed by Manuel Martín-Neira and colleagues) the unknown phase-cycle ambiguities can be determined. It is then a straightforward procedure to work out the excess path of the reflected signals to finally deduce the height of the antennas over the water surface.

La Baells Experiment. An experimental campaign was carried out with an Oceanpal instrument at the La Baells water reservoir (near Berga in Catalonia, Spain) in cooperation with the Catalan Water Agency. This experiment was designed to study the feasibility of accurate altimetry measurements at lakes and reservoirs using our technique.

Within this campaign, one week of data was gathered early in March 2008 to compare the Oceanpal GNSS-R phase-altimetry measurements with those from the La Baells in-situ sensor (a water bubbler known to have centimeter-level accuracy). The results from this campaign are shown in **FIGURE 3**. After referencing the measurements to the antennas' position with respect to the mean water level, the accuracy obtained from the Oceanpal measurements with respect to the ground truth (the water bubbler) was better than 2 centimeters (after a five-minute integration time).

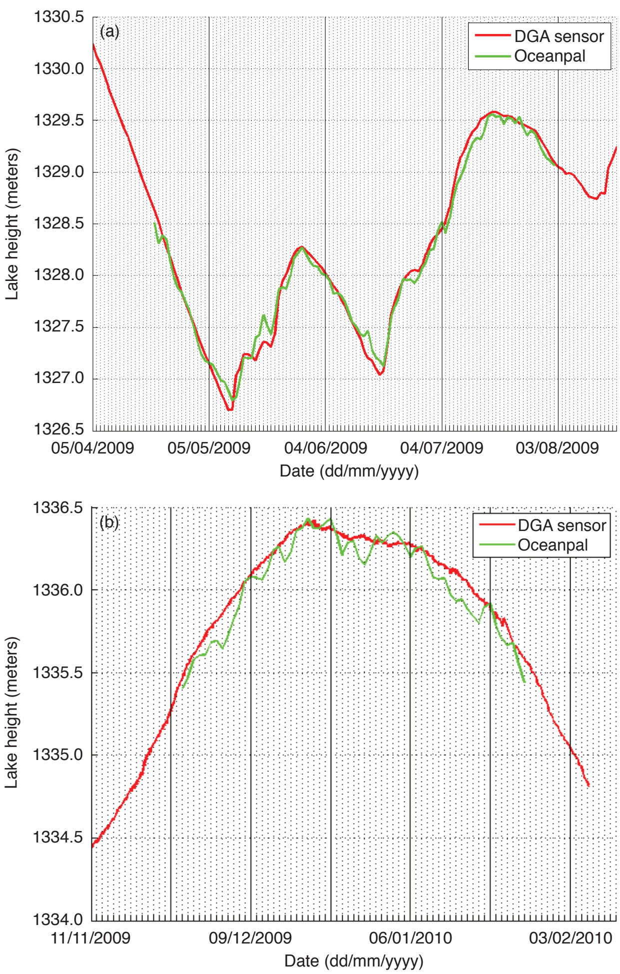
Despite the fact that the phase altimetry algorithm is precise, it requires the simultaneous observation of several reflections from different satellites to converge and accurately solve for the phase ambiguities. However, this cannot be done for all scenarios, and in these situations the conventional phase altimetry algorithm cannot be applied.



▲ **FIGURE 3**. Results of a one-week campaign at the La Baells water reservoir near Berga, Spain, in March 2008. Lake height in meters with respect to mean sea level.

Lake Laja Experiment. A case where we couldn't use the phase approach was project Hydro. This was an initiative developed

▲ **FIGURE 4**. The Oceanpal installation at Lake Laja, Chile.



▲ **FIGURE 5**. A comparison of measurements of Lake Laja's water level by Oceanpal and a water bubbler sensor operated by Dirección General de Aguas (DGA) for two periods of time corresponding to (a) the austral winter (from late April 2009 until early August 2009) and (b) the austral summer (from late November 2009 until late January 2010).

by our organization in collaboration with Pontificia Universidad Católica de Chile (the Pontifical Catholic University of Chile) and funded by ENDESA (Empresa Nacional de Electricidad S.A.), one of the world's largest electricity companies. An Oceanpal instrument was installed at Lake Laja, in the Biobío Region, Chile, a water reservoir managed by ENDESA Chile. The Hydro project aims to use remote sensing assets to predict and monitor water flow in the Laja River basin. For that, having precise measurements of Lake Laja's level is a must.

The instrument was installed on the shore of the lake as seen in **FIGURE 4**. However, the high variability of the lake's level, more than 10 meters in one year, and the abruptness of the terrain, results in the number of observed reflections from the water surface being quite low. This is especially the case when the level of the lake is low. In this situation, the number of different GPS satellites observed per hour was calculated to be fewer than two for more than 45 percent of the time, and fewer than three for more than 85 percent of the time. Given this scarcity of reflections, we could not use the phase altimetry algorithm as described above.

We developed a new phase altimetry algorithm, which considers the interferometric phase evolution over time. The resulting relative phase parameter can be linked to the height of the antennas over the water surface by means of the same geometrical relationship as before. Despite the fact that measuring a relative phase increases the measurement noise with respect to the case in which an absolute phase is used, the phase ambiguity and the bias between the direct and reflected receiving channels do not need to be calculated, thus reducing the complexity of the algorithm and its convergence requirements. A Kalman filter is used to smooth the inherently noisy behavior of the relative phase.

The Oceanpal measurements were compared to those of a sensor operated by the Dirección General de Aguas (DGA), the Chilean water management agency. An accuracy better than 9 centimeters was achieved in determining the lake's level during the austral winter, when the lake is at its minimum level and therefore the satellites' reflections from the water surface are scarce. The lake level has its maximum during the summer after the melting season. During this period of time, the achieved accuracy of Oceanpal with the new phase algorithm was better than 5 centimeters. A comparison of Oceanpal and DGA's sensor measurements of the water level is shown in **FIGURE 5**.

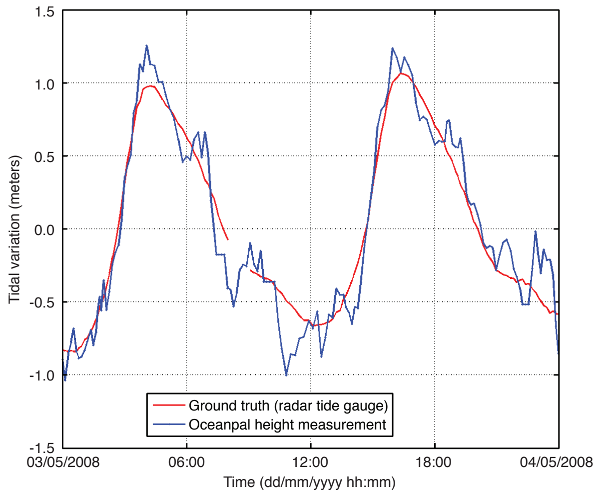
Measuring Sea Level

Sea level is obtained from Oceanpal measurements by means of the code altimetry algorithm due to the inherent roughness of the sea surface. This technique derives altimetric information from the displacement of reflected waveforms with respect to the direct ones. Such a displacement can be directly related to the delay between the direct and reflected signals (the so-called lapse), and is used in a similar way to the phase-based method to extract the altimetry information of the water surface being monitored.

Despite the fact that the code altimetry algorithm is not as precise as the phase altimetry algorithm, it is not subject to the coherence requirement for the reflected signal. Therefore, it can be applied to rough, dynamic surfaces such as the open ocean and coastal areas. The use of code altimetry in rough water conditions results in a clear observation of tide dynamics but, as expected, with a higher error range compared to situations where phase altimetry can be applied.

Scheveningen Pier Experiment. The performance of the code-based algorithm was tested during an experimental campaign carried out on Scheveningen Pier in Den Haag (The Hague), The Netherlands. An Oceanpal instrument was installed close to a Radac X-band radar tide gauge. **FIGURE 6** shows the tide variation at the installation site estimated by the Radac instrument and by Oceanpal. As can be seen, a good agreement between both estimates is achieved with a standard deviation of the difference of 12 centimeters.

To improve this result, a combination of code and phase estimation is being investigated, involving the alignment of the phase using the code information. The combination of these two parameters may provide the best of both worlds. However, with the signals from modernized GPS and those of the forthcoming Galileo system, the code-ranging precision is envisioned to increase by a factor of four or five, which is expected to impact directly on the precision of the code altimetry algorithm.



▲ **FIGURE 6**. Daily tidal variation at Scheveningen Pier, The Hague, The Netherlands, on May 3-4, 2008, measured by X-band radar and Oceanpal.

Conclusion and Outlook

During the past decade, the scientific community's interest in GNSS-R has grown, leading to the continuous development of new applications and to an increasing relevance in specific market niches. Some of these applications, especially those related to the monitoring of water surfaces, have reached an operational level of maturity, and provide end users with valuable information.

In this brief article, we have described the Oceanpal instrument and outlined its use in altimetric measurements of water surfaces. It was shown that using the phase of reflected signals with respect to that of direct signals, accurate measurements of a lake's level could be obtained. In addition, we overviewed a new algorithm that incorporates the evolution of this phase in time. This algorithm is suitable for low satellite visibility scenarios. For example, using this algorithm, the level of Lake Laja in Chile was determined with an overall accuracy better than 7 centimeters. Such a level of accuracy meets the monitoring requirements necessary for improving the stream-flow prediction in the Laja River basin. We also showed that code altimetry can be successfully used to monitor sea level variations associated with tides, with a demonstrated accuracy of 12 centimeters.

These encouraging results are expected to be further improved with the evolution of GPS, the refurbishment of the Russian GLONASS system, and the deployment of the European Galileo system. First of all, when all three navigation systems are fully deployed, it is calculated that at least 20 navigation satellites will be visible at the same time. A GNSS-R instrument could take advantage of this large number of available signals. In addition, the quality of these signals is expected to be largely improved in terms of signal-to-noise ratio, bandwidth, and ranging precisions, which will in turn improve the performance of GNSS-R altimetry algorithms. As a result, the prospects for GNSS-R altimetry over water surfaces, not only for ground-based systems, but also airborne and even spaceborne systems, are extremely promising.

Manufacturers

The Oceanpal instrument was developed by **Starlab** *(www.starlab.es)*, Barcelona, Spain. The Scheveningen Pier experiment used a **Radac** *(radac.nl)*, Haarlem, The Netherlands, WaveGuide radar level gauge.

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MARCO CAPARRINI received the "Laurea" degree in electronic engineering — remote sensing from the University "La Sapienza" in Rome. He has worked as a research engineer at ESA's European Space Research and Technology Centre in Noordwijk, The Netherlands; at the German Aerospace Center in Oberpfaffenhofen, Germany; and at the Swiss Federal Institute of Technology in Zurich. His main research field is the use of GNSS signals as sources of opportunity for remote sensing of planet Earth, and he is the Starlab manager for the space research and development area.

FURTHER READING

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