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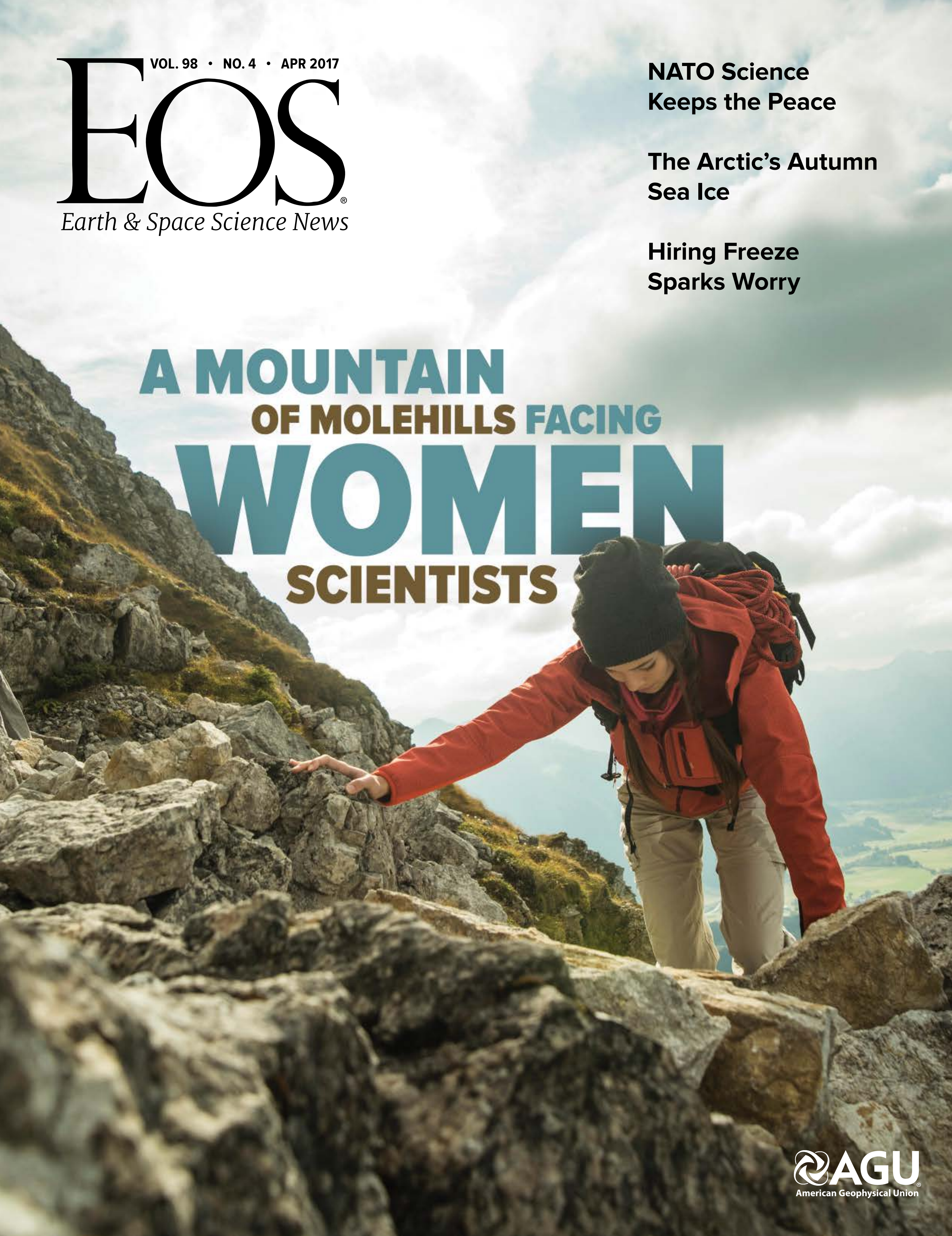

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Why We Must Tie Satellite Positioning to Tide Gauge Data

An acoustic tide gauge monitors the harbor at Burnie on the northern coast of Tasmania, Australia. To its right, a special pillar has a GNSS receiver on top.

Many types of geophysical and environmental studies rely on accurate measurements of sea and land levels and knowledge of how they vary between locations and over time. Sea levels, however, can be particularly complicated to measure.

Sea level measurements at the coast require the use of tide gauges (sometimes called sea level recorders). Tide gauges measure changes in sea level relative to the land on which they are located, but that land can never be considered stable. Although we might not perceive it in our day-to-day experience, a range of natural geophysical factors (e.g., abrupt changes due to earthquakes or gradual changes due to glacial isostatic adjustment) and human activities (e.g., groundwater extraction) will cause vertical land movements and so complicate the sea level measurements needed for research.

To account for land influences on sea levels, scientists pair tide gauges with Global Navigation Satellite System (GNSS) positioning sensors, of which GPS instruments are the best known [*Intergovernmental Oceanographic Commission,* 2016]. These sensors measure the elevation of the land surface relative to the center of Earth. Unfortunately, positioning sensors are often located some distance away from tide gauges, making it difficult for researchers to know whether the vertical movement of the land is the same at both locations.

Making the Ties

Tide gauges measure the level of the sea relative to the height of "benchmarks," located in the solid rock or sometimes on buildings on nearby land. In turn, the height of these benchmarks, which geodesists sometimes call "stations," can be measured relative to the center of Earth using advanced geodetic techniques such as the GNSS/GPS equipment.

In an ideal but uncommon situation, the GNSS equipment is attached directly to the tide gauge or located nearby (see, e.g., the photo above). In these cases, data from a given tide gauge and the corresponding GNSS equipment refer back to the same benchmark.

However, tide gauges and GNSS equipment are more commonly separated by distances of several meters to a kilometer or more. In these cases, the relative heights of the various marks must be measured by means of conventional spirit leveling in a procedure called "making a tie." When the distance between marks is short, this procedure can be performed in a short time. However, when the marks are some distance apart, a more exten-

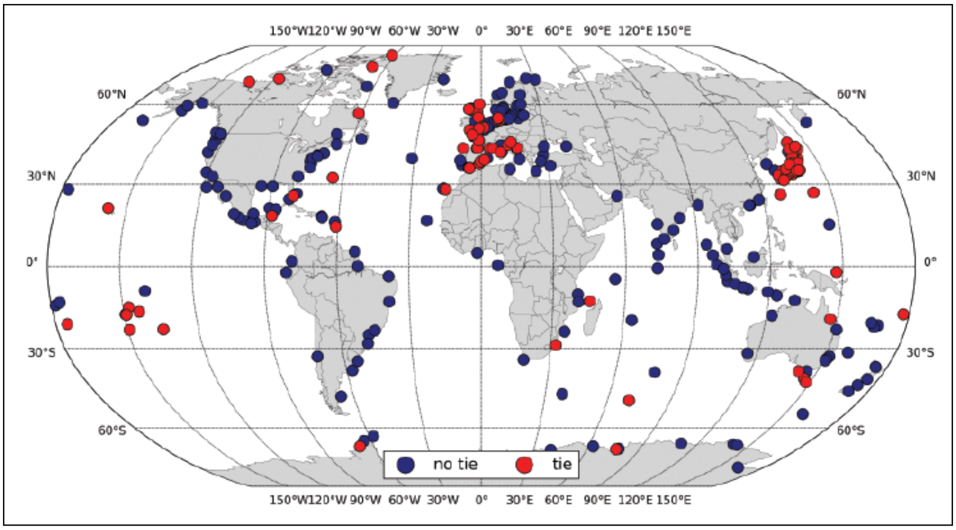

Fig. 1. Locations of permanent GNSS stations near tide gauges (closer than 1 kilometer) that have data in SONEL. Sites where local ties between tide gauge and GNSS have been made and the information is included in the data bank are shown in red. Sites lacking such information are shown in blue.

sive leveling exercise is necessary, which can require a greater commitment of staff time.

Missing Information on Ties

Such ties are essential, yet they are not made at many tide gauges around the world, primarily because tide gauges and GNSS equipment are operated by different national agencies. These agencies do not accept making the ties as being their responsibility, in spite of this issue being raised with them many times by international sea level and GNSS programs, including the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC).

Figure 1 illustrates the problem. It shows tide gauge locations around the world for which a permanent GNSS station nearby (closer than 1 kilometer) has been identified in the Système d'Observation du Niveau des Eaux Littorales (SONEL) data bank at the University of La Rochelle in La Rochelle, France. SONEL is the official data bank for GNSS information for the GLOSS program. The map shows in blue that there are many sites for which information on ties is unavailable. In fact, this map underestimates the overall problem because sites are shown in red here if a tie has been made just once, rather than at regular intervals (e.g., annually) as required by GLOSS.

Scientific Requirements

What are the scientific requirements for ties? The first requirement applies to studies of long-term sea level change. Consider a common situation: A well-established tide gauge that has recorded sea level for more than a century is a short distance from a permanent continuous GNSS station that has recorded land levels (ellipsoidal heights) for perhaps as long as 20 years. The rate of change of land movement recorded by the GNSS station can be compared with the rate of sea level change measured by the tide gauge record to understand how much of the record results from movement originating in the ocean or on land.

> Tide gauges and navigational satellite equipment are commonly separated by several meters to a kilometer or more.

In addition, the GNSS rate can be added to the tide gauge rate to obtain a geocentric rate of sea level change that is akin to that measured from space by a satellite radar altimeter. Consequently, the rates recorded by the different techniques can be used to validate each other. For example, altimeter and tide gauge data can provide estimates of land movement that can be compared with those of GNSS data. Similarly, tide gauge and GNSS data can be used to calibrate altimeter measurements.

Researchers have made such comparisons of rates using different techniques for many years [e.g., *Wöppelmann and Marcos*, 2016].

However, an implicit assumption is always that the level of the land on which the tide gauge is located is moving in the same way as the land under the GNSS and that there is no differential movement between them. Such an assumption may be reasonable where the two sensors are not far apart and are located within the same parcel of land.

However, it becomes more problematic when the two sensors are farther apart, when they are installed on dissimilar substrates (e.g., the GNSS is installed on hard rock and the tide gauge is on a nearby piece of reclaimed land), or when measurements are compared over a long period of time. When ties can be made and repeated at regular intervals, these assumptions become unnecessary.

A Worldwide Height System

A second scientific requirement for ties comes from worldwide height system unification (WHSU), in which the geodetic community is moving toward the use of the geoid (a model of an equipotential surface of Earth's gravity field) as a datum, or geodetic reference level, that represents "zero" instead of the many national reference levels presently in use.

One of the oceanographic components of WHSU involves validating geoid models by comparing the mean dynamic topography (MDT) observed at tide gauges (the difference between the local mean sea level and the geoid) with the MDT values obtained from ocean models [*Woodworth et. al.*, 2012]. In this case, we need to know the mean sea level (MSL), expressed as an ellipsoidal height by means of a leveling connection, or "tie," between the tide gauge benchmark and other marks (stations) nearby at which either continuous or episodic (campaign) GNSS measurements have been made.

Falling Between the Cracks

Why has it been so difficult to make the ties and include them in sea level and GNSS data banks?

One reason might be a lack of scientific appreciation for the importance of this activity. Most researchers consider only the rates of change of sea and land levels, measured by the tide gauge and GNSS, respectively, to be important. They seem to be happy enough to assume that the intervening land is relatively stable, so the same land movements occur at both locations, but this assumption cannot be made in long-term studies, for example, within the context of validating new satellite radar altimetry missions aimed at climate sea level applications. Scientists engaged in the relatively new field of WHSU are also disadvantaged by the lack of ties.

However, the main difficulty in making ties on a regular basis has been practical, rather than scientific, and has to do with the way that tide gauge and GNSS measurements are organized and funded in many countries. Tide gauges are usually operated by port authorities or agencies concerned with flood warning, and they may have little contact with the geodetic agencies that operate GNSS equipment. Thus, the ties often fall between the organizational cracks.

Sometimes international programs of organizations such as IOC, the International Hydrographic Organization, and the International Association of Geodesy make appeals to the various agencies responsible for collecting sea and land level data. However, in our experience, national agencies have taken little notice of such international recommendations. In addition, proposals that these organizations have developed for a coordinated international measurement program for ties have not been moved forward by national agencies.

This lack of coordination has been a frustrating situation so far. That's why we believe it is essential for yet another attempt to be made to break down these cultural walls and for the various national and international organizations to redouble their efforts. Without regularly repeated ties, their sea level and geodetic programs will be unsuccessful in the long term.

> National and international organizations must redouble their efforts toward a coordinated measurement program for ties.

Advice on measurement requirements, techniques, and formats for sending information to the data centers is readily available from the Permanent Service for Mean Sea Level (see http://www.psmsl.org) and SONEL. We hope that more information on ties will become available and be included in data banks alongside the sea level and GNSS data. This information will benefit future researchers of global sea level change, surveyors and geodesists concerned with WHSU, and those concerned with many other practical applications.

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