NOTES AND CORRESPONDENCE

A Study of Delays in Making Tide Gauge Data Available to Tsunami Warning Centers

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ABSTRACT

This short note provides conclusions of a study of the various factors that determine the delay between tsunami arrival at a tide gauge station and data being made available at tsunami warning centers. The various delays involved include those associated with the tide gauge hardware and measurement methods and with the form of telemetry employed. It is shown that the most widely used form of telemetry in existing tsunami networks (meteorological satellite data collection platforms) can be improved upon significantly with the use of modern telemetry alternatives [notably Inmarsat's Broadband Global Area Network (BGAN)], enabling faster, more frequent, more secure, and higher bandwidth transmissions of tide gauge data.

1. Introduction

The Sumatra tsunami of 26 December 2004 was observed around the world and resulted in the loss of many lives (Titov et al. 2005; Woodworth et al. 2005; IOC 2006a). It alerted many countries, even those in areas where tsunamis are relatively rare, to potential tsunami risk, and over the following months a number of international study groups were established and proposals constructed with the aim of building regional warning systems (e.g., Kerridge 2005; EC 2005; IOC 2006a,b,c).

In many cases, such as the Sumatra event, a warning of a tsunami is provided by a seismic signal. However, even in such cases, verification of the actual existence of a tsunami is required by means of one or more different kinds of ocean, coastal, and space-based instrumentation so that a full alert can be made. In other cases, when a seismic signal is absent (e.g., due to a landslide without a preceding earthquake), then the ocean and other instrumentation can become the primary warning mechanism, and tsunami signals have to be separable from the spectra of ocean signals in the instrumental data.

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A number of reports have summarized the range of instrumentation capable of detecting tsunamis (e.g., Kerridge 2005). Ocean instrumentation includes deep pressure sensors [e.g., the Deep-ocean Assessment and Reporting of Tsunamis (DART) moorings of the Pacific and, more recently, the Indian Ocean warning systems], shallow-water pressure sensors (e.g., shallow versions of the DART system, or pressure transducers attached to undersea cables), and current meters. Coastal instrumentation includes conventional tide gauges, offshore tide gauges [e.g., on oil platforms or with the use of global positioning system (GPS) receivers on buoys] and high-frequency (HF) radars. Space-based instrumentation includes the use of various kinds of satellite altimetry (e.g., Song et al. 2005) and GPS reflection off the sea surface from low earth orbiters.

Although the range of possible suitable instrumentation is wide, it is clear that a major component of a tsunami warning system will be provided by tide gauges. Agencies currently use different types of tide gauge (float, radar, acoustic, etc.), most of which have been designed for the measurement of tides, storm surges, and long-term sea level change (see Aarup et al. 2006 for a review). However, for the measurement of tsunamis, one requires sensors capable of sampling sea level as rapidly as possible and which stand a good chance of surviving a major earthquake or tsunami event. Pressure sensors installed below low tide are clearly the most suitable, although, as regards sampling

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at least, some frequency-modulated continuous-wave (FMCW) radar gauges are capable of providing equivalent sampling to pressure sensors and could be an acceptable alternative. Following the Sumatra tsunami, the Global Sea Level Observing System (GLOSS) program of the Intergovernmental Oceanographic Commission (IOC) defined a "baseline tide gauge specification," which is being followed for new installations in Africa and the Indian Ocean (Aarup et al. 2006). This consists of a conventional "sea level" gauge (e.g., acoustic or radar), together with a pressure "tsunami" gauge. The requirement is for the two sets of data to be transmitted regularly to warning centers and sea level data banks.

It is clear that tide gauge measurements of tsunamis are needed from as near the tsunami source as possible, up to the coastlines for which warning is required; that is, one needs as complete as possible a set of "far field" information. If the distance between the far-field gauge and coastline is large, then a warning system will, in principle, have the tsunami travel time between the two points in which to issue an alert. However, in many regions (e.g., Mediterranean, North Sea, Caribbean) the travel time could be short and it is important that no other major delays are introduced in between tsunami measurement and receipt of data by warning centers.

This report discusses the various delays implied by different tide gauge technologies and telemetry methods, and by the need to detect a tsunami in the gauge data. It considers a state-of-the-art form of telemetry, a satellite-based system independent of vulnerable telephone or Internet infrastructure, that appears to provide an ideal complement to the IOC baseline tide gauge. Our recommendation is for tsunami warning networks to consider adoption of such technology in place of, or in addition to, existing methods.

2. Delays in measurement and telemetry

Although there are many different types of tide gauges employed to measure tides, surges, and longer-time-scale sea level variability, they can be divided into two main types: those that provide spot (instantaneous) measurements of sea level at time intervals T, and those that integrate (average) over intervals T. Spot measurements have the disadvantage that they will sample the instantaneous wave/swell field and therefore tend to be noisy. An advantage of integrations (averages) over T is that noise in the sea level record due to waves will be reduced. However, a disadvantage is that there will be an average delay $T/2$ for the measurement to become available. Values of T of several tens of seconds or less could result in both spot or average sea level values containing contributions from wind waves and swell.

For the purpose of this report, we have adopted a value of T of 1 min, which is suitable for monitoring at most locations (Kilonsky 2006; Leonard 2006), except perhaps for the much shorter (e.g., several minutes) period tsunamis in embayments or inlets caused by landslides. Table 1 provides an overview of present tide gauge technologies and how they might have to be modified or complemented for tsunami purposes following the recommendations of Aarup et al. (2006). The last column is of particular importance if existing tide gauge infrastructure is to be employed to form the basis of a tsunami warning system; otherwise, the tsunami community would be faced with developing an entirely new network of pressure-based sea level stations. In practice, one expects a future station to be equipped with both "sea level" and "tsunami" capability.

Table 2 gives a corresponding overview of delays in the telemetry of tide gauge data using several presently available methods. The Pacific and Indian Ocean tsunami warning networks have been constructed around the meteorological satellite [e.g., Meteosat or Geostationary Operational Environmental Satellite (GOES)] data collection platform (DCP) system (www.eumetsat.int/Home/Main/Access_to_Data/Data_Collection_and_Retransmission/index.htm). This enables sea level measurements (either spot or integrated and whatever value of T) to be stored for transmission every 15 min. Consequently, data can be 15 min old before they reach a warning center. Although meteorological satellites have the advantage of being free of charge for tsunami warning purposes, it is clear that their present transmission frequency will be unacceptable in many cases. We understand that the constraints on more frequent sampling are due to the lack of availability of transmission slots, and that there is a possibility of more frequent transmissions in the future.

An example of an alternative to the DCP is the Orbcomm satellite system (www.orbcomm.com). This system enables emails (or "globalgrams") containing tide gauge data to be sent from almost any location around the world to a number of centers. However, there is a considerable variation in the delay for messages to be received, depending upon the accessibility of satellites in the constellation and on their ability to forward messages via regional gateways. While modest delay (e.g., 30 min) might be acceptable for some forms of operational oceanography (e.g., storm surge model verification), it would clearly be unacceptable for tsunami warning. In addition, the receipt of the emails would be dependent on the reliability of a number of service providers and even on the Internet itself.

A more ideal form of telemetry is to have an "always

TABLE 1. Examples of sea level recording.

Type of gauge	Typical recording method	Normal sampling period (T) for tides, surges, and MSL	Sampling period (T) required for tsunami detection	Modifications/additions to tide gauge infrastructure for tsunami detection
Float	Spot measurements at time intervals T with shaft encoder or potentiometer, or integrations (averages) over time intervals T	1, 6, 15 min (for example)	1 min or less (see, e.g., Kilonsky 2006)*	Add an ancillary pressure sensor either inside or outside the stilling well**
Pressure	Spot measurements or integrations (averages)	As above	As above	Add a second pressure sensor
Radar (e.g., OTT Kalesto)	Integrations (averages)	As above	As above*	Add an ancillary pressure sensor
Acoustic (e.g., Aquatrak)	Average of 181 one-second measurements every 6 min	6 min	As above*	Acoustic gauges such as the Aquatrak are usually equipped with an ancillary pressure sensor

* A float gauge requires a stilling well so the maximum and minimum sea levels it can record are limited in the event of a large tsunami. Also, while we understand that there is no reason why the Aquatrak sensor should not be able to transmit and receive acoustic ranging pulses at 1 Hz, it also requires a stilling well and sounding tube. A similar remark can be made concerning radar gauges if the tsunami level exceeds the height of the sensor.

** Of all technologies suitable for tsunami monitoring, pressure sensors are not only the most robust but are the most appropriate for rapid sampling.

on" communication such as can be provided by various forms of telephone modem or Internet technology. In these cases, there need be no significant delay between transmission and receipt of messages. However, a potential risk remains due to the local vulnerability of the telephone or Internet networks in the event of a major disaster.

The advent of Inmarsat's Broadband Global Area Network (BGAN) has made "always on" technology available almost anywhere on the earth's surface (www.inmarsat.com). BGAN is a satellite broadband system that employs highly portable terminals, of similar size to a laptop computer. The BGAN units provide bidirectional Internet Protocol (IP) data streams of up to 492 kbps as well as Voice Over IP (VOIP) telephony and Short Message Service (SMS) text messaging (see next section). A major advantage of BGAN from a tsunami warning point of view is that it does not have to depend on local telephone or Internet infrastructure.

Most tide gauge data from the Pacific and Indian Ocean tsunami warning systems are transmitted using DCPs and are routed to national and international agencies using the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO). This system was established originally for the international exchange of meteorological information. Messages are usually routed via meteorological agency nodes that decide whether to send them onward to other interested parties such as warning centers (WMO 2004; C. Little 2006, personal communication). The speed with which messages are transmitted depends on their priority. Priority 1 messages, which include warnings (e.g., of tsunamis), are transmitted around the world in seconds. Priority 2 messages, which include

TABLE 2. Examples of delays in data transmission.

Meteosat DCP connection to gauge datalogger	Orbcomm email message from gauge datalogger	Terrestrial or satellite telephone modem connection to gauge datalogger	Terrestrial or satellite Internet (e.g., BGAN) connection to gauge datalogger	Satellite SMS (e.g., BGAN) message from gauge datalogger to a second BGAN terminal
15 min, e.g., fifteen 1-min samples every 15 min	Minutes to hours	Seconds*	Seconds*	Seconds*

* Or more realistically, five 1-min samples every 5 min.

TABLE 3. Delays in tide gauge data flow due to the GTS.

Delay from tide gauge to GTS (other than that in Table 2)	Seconds
Delay for GTS to make tide gauge data and/or detected tsunami alert visible to a warning center via a meteorological agency node	Seconds − minutes

TABLE 4. Other delays in tsunami detection from tide gauge data.

Delay for detection software to identify a tsunami signal (redundant if previous seismic alert)	A large fraction of one tsunami period τ (e.g., 5 min)*

* Delay for tsunami detection would be much reduced if there had been a previous seismic alert. Otherwise, an alert has to be provided by analysis of the sea level time series.

meteorological data, could take seconds to minutes. Lower-priority messages, which contain high-volume satellite data and administration information, could take longer depending on the demands on the system. One expects the delays in the routing of tide gauge data at priority 2 to be of the order of tens of seconds or at most minutes (Table 3). The additional delays due to the GTS are not relevant if a tide gauge center functions also as the warning center, and they would not apply if telemetry such as BGAN SMS was adopted (see next section).

There are many other forms of telemetry suitable for transmission of tide gauge data, and Aarup et al. (2006) contains a comprehensive list of the various technologies.

In the absence of a seismic warning, one has to rely on automated analysis of far-field tide gauge data (or of other forms of ocean and coastal instrumentation) to flag the possible presence of a tsunami. Software for the detection of tsunamis in bottom pressure data has been employed for several years in the DART systems, and algorithms for use with coastal tide gauge data are presently under construction and being tested with the use of historical and simulated tide gauge records of tsunamis (e.g., as part of the EU TRANSFER program; B. Perez 2006, personal communication). The DART software makes use of the rate of change of bottom pressure to flag the possible existence of a tsunami, within a background bottom pressure signal considerably less noisy than that of a typical coastal sea level time series. It is difficult to see how an unambiguous tsunami alert could be provided from noisy coastal data in a time significantly shorter than a large fraction of the tsunami period (Table 4).

Table 5 provides an indicative summary of the information in the preceding tables. If a warning center had been alerted to the possible presence of a tsunami by a seismic alarm, then, if one takes as an example the most practical form of telemetry in which five 1-min samples are transmitted every 5 min, an overall delay of the order of 7 min between tsunami arrival at a tide gauge station and verification of the tsunami's existence would result. If this delay was considered unacceptably large, then transmissions could be made every minute, reducing the overall delay to just several minutes. If there were no prior seismic signal, then the time following tsunami arrival needed to detect the tsunami signal in the tide gauge record would be several minutes longer, depending on the tsunami period and a range of algorithm-dependent parameters (e.g., tsunami amplitude relative to ambient noise).

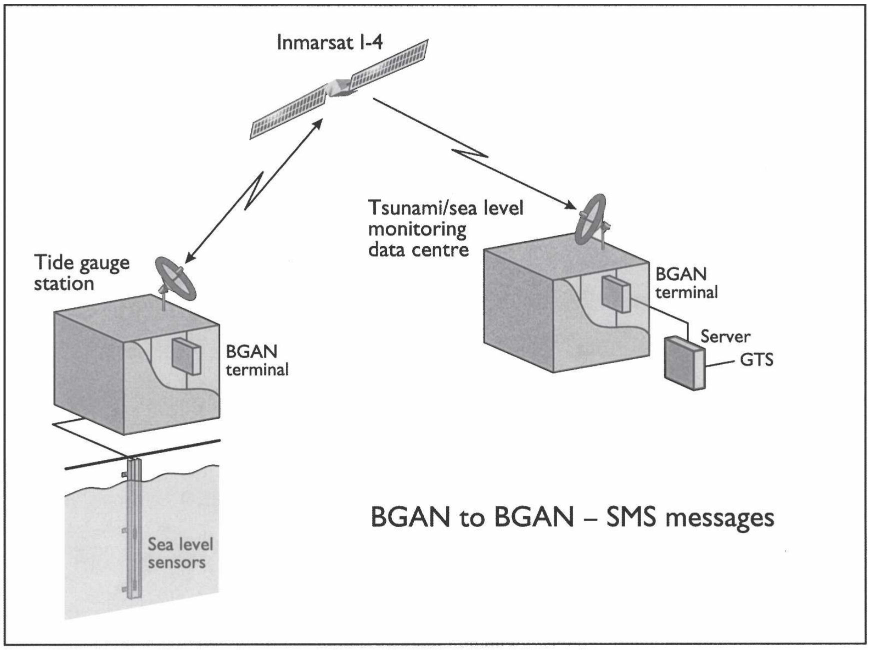
3. BGAN and its SMS messaging system

The Proudman Oceanographic Laboratory (POL) has been working with colleagues at IOC and within the Ocean Data and Information Network for Africa (ODINAFRICA) collaboration to install up to a dozen new baseline tide gauges in Africa and in the western Indian Ocean. All installations include an OTT Kalesto radar tide gauge, pressure sensors, Logosens datalogger, and Meteosat DCP (Woodworth and Smith 2003; Aarup et al. 2006). Meanwhile, POL has been developing a low-power Linux-based embedded system that can control the radar and pressure sensors and can communicate through a BGAN terminal. Technical information of the system development is given in Holgate et al. (2007).

Communication from the embedded system through BGAN can be made in several ways. In one method, the BGAN terminal in effect provides the system with an IP address, by means of which communication across the Internet (either public Internet or dedicated line) with established protocols (email, ftp, ssh, etc.)

TABLE 5. Total delay: indicative summary.

Source	Delay
Table 1: measurement time	1 min
Table 2: data flow (most practical case)	5 min
Table 3: onward transmission	1 min
Total (assuming seismic alert)	7 min
Total (assuming no seismic alert and tsunami detection by analysis of time series)	Above plus large fraction of τ, e.g., 12 min



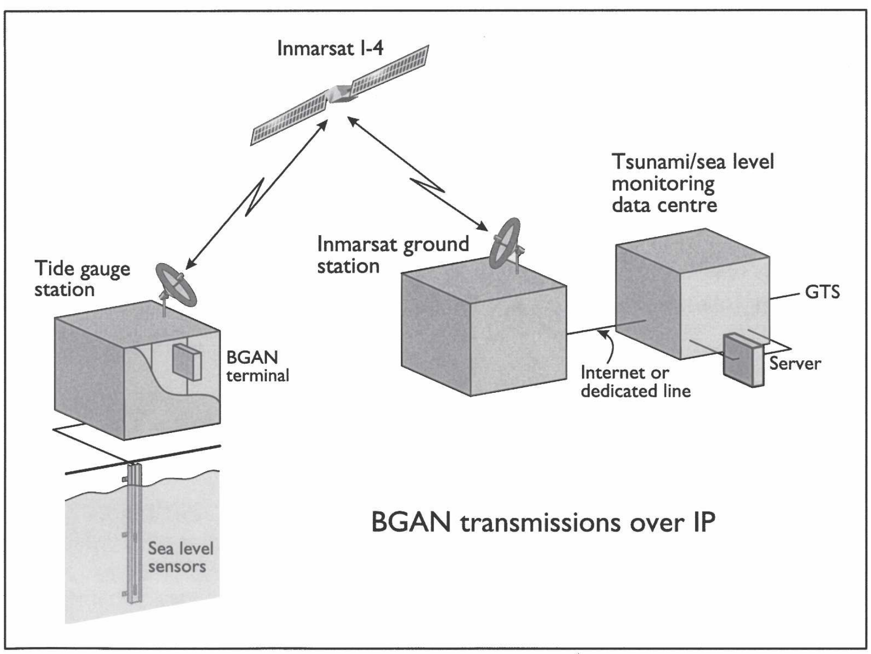


FIG. 1. (top) Schematic of SMS data transfer between a BGAN terminal connected to an embedded system at a tide gauge station and another BGAN terminal at a warning center. (bottom) Schematic of a tide gauge station controlled by an embedded system linked via a BGAN terminal to the Internet (public Internet or dedicated line) and tsunami warning center and onward data distribution via the GTS (an alternative would have a dedicated line to the GTS and onward distribution to warning centers).

can be accomplished (Fig. 1, botttom). In this method, the BGAN technique is conceptually the same as conventional broadband telemetry, but routes its information via a satellite rather than a landline. Using the IP connectivity, full communication is possible with the tide gauges despite their remote locations. This broadband connection provides the ability to diagnose any problems with the gauge remotely and also to reconfigure the system without costly visits into the field.

In an alternative method, the terminal can function as a telephone with SMS capability, such that data can be sent via the satellite either to a telephone capable of receiving SMS messages, or to one or more other BGAN terminals (Fig. 1, top). The latter option is particularly attractive for use in tsunami monitoring and other disaster applications. Once a tide gauge and warning center are both equipped with BGAN terminals, data can pass between them via the Inmarsat satellites irrespective of whether the telephone or Internet infrastructure has been damaged. By keeping the SMS messages entirely within the private BGAN system (i.e., by sending messages from one BGAN terminal to another), data security is maintained (the data never enters a public network) and the delay is only around 2 s since Inmarsat does not employ any message queuing, unlike public domain network operators. Additional advantages of the method are its relatively low cost and that its bandwidth (number of bytes allowed per SMS message) is ideal for the tide gauge sampling described above. In practice, one might expect both BGAN and another form of telemetry (e.g., Meteosat DCP) would be employed to ensure that tide gauge information passed to warning centers by at least one method.

Figure 2 demonstrates the compact nature of a baseline system equipped with BGAN. It shows an OTT Kalesto radar tide gauge at Liverpool connected to a Hughes regional BGAN (RBGAN) terminal on a nearby wall. (RBGAN was a predecessor to BGAN with similar functionality but which is to be replaced by BGAN itself. Note that terminals are available from manufacturers other than Hughes.) The terminal is also connected through the embedded system to subsurface pressure sensors. Holgate et al. (2007) have demonstrated that such a baseline system with BGAN can be constructed and operated successfully.

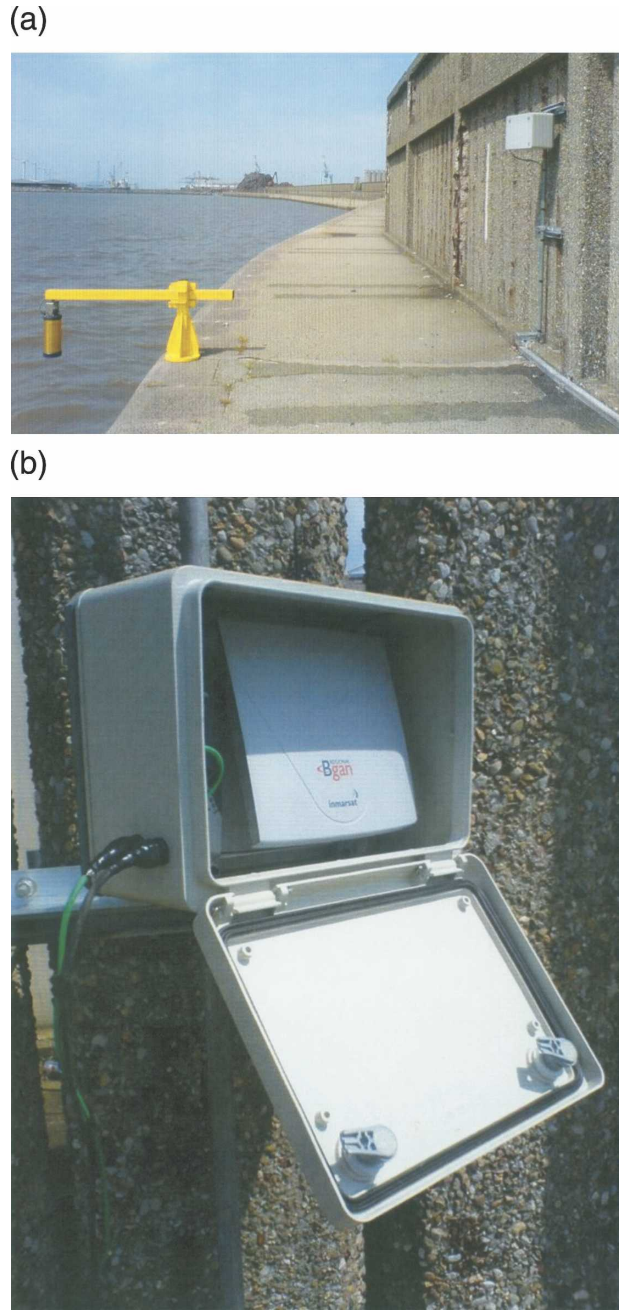


FIG. 2. (a) A radar tide gauge installed at Liverpool communicating via an Inmarsat RBGAN or BGAN terminal. (b) The terminal can be mounted on a nearby post or wall and is approximately the size of a laptop computer.

4. Conclusions

This paper has described where possible delays can occur in the measurement of tsunamis by coastal tide gauges and in the onward transmission of the data to warning centers. It has emphasized the importance of pressure sensors for tsunami measurement, alongside the several other forms of tide gauge technology employed to monitor tides, surges, and long-term sea level change. It has presented some of the advantages and disadvantages of different forms of telemetry, and has made a special case for Inmarsat BGAN SMS telemetry, which is an already-available and relatively inexpensive technology with the advantage of not being dependent on regional telephone or Internet infrastructure in the event of a major disaster. It may have particular application for Mediterranean and other coastlines (e.g., Indonesia, Thailand) where tsunami travel times are much shorter than they are on average in the Pacific, and where the established DCP and GTS-based telemetry are unsuitable.

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