Data Collection, Communications and Processing in the Sumatran GPS Array (SuGAr)

Ian Vince McLoughlin, Kai Juan Wong, Su Lim Tan

***Abstract*—The Sumatran GPS array spans approximately 1300 km along the West coast of Sumatra, Indonesia. Almost 40 monitoring stations periodically collect high accuracy continuous GPS readings, and convey these to a central server for post-processing in Singapore. Solutions from the array data are used to provide precise measurements of the deformation of the earth's surface over large distances: in effect allowing the tracking of tectonic movements, and aiding in the understanding of seismic events in this highly active area of the earth's crust. Invaluable SuGAr-provided scientific data has been published over recent years, however this paper will discuss the communications and computer engineering architecture and evolution of this large sensing network, rather than the tectonic meaning of the data.**

***Index Terms*—GPS, sensing network, satellite communications, tectonic movement.**

I. Introduction

THE Sumatran GPS array (SuGAr) was initiated by Professor Kerry Sieh and colleagues at the California Institute of Technology (CalTech) Tectonics Observatory (TO) in 2002. During that year, six permanent continuous GPS (cGPS) monitoring stations were installed along the Sumatran plate boundary (in effect between the Sunda trench and the Great Sumatran Fault - see Fig. 1). The devastating Aceh-Andaman earthquake on Boxing Day 2004 [1], which caused massive tidal waves and damage, killing thousands around the Indian Ocean, provided fresh impetus to monitor, study, and eventually understand the scientific processes at work in this area.

In time, the network expanded to 24 monitoring sites, serviced through a ground station in Batam, Indonesia, and has seen great use in monitoring earthquakes in the region, including in 2005 [2], 2007 [3], 2008, 2009 and 2010. By 2008, the existing network was transferred to the control of the authors with the mandate to modernise, expand and improve the system. This paper first describes the legacy SuGAr network in Section II, discusses considerations for improvement in Section III. The performance of this system is analysed and conclusions drawn in Section IV. To date, although SuGAr has provided the base data for a number of scientific papers, its technical detail and design have not been discussed in the literature. It should also be noted at this point that SuGAr is still expanding (the recent extent of the network is shown in Fig. 1): it is currently operational and monitoring high quality high rate data.

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II. The Legacy SuGAr Network

A. Monitoring stations

Monitoring stations comprise a permanently-mounted sealed metal cabinet and a separate tripod-mounted GPS antenna. The GPS antenna, either an Ashtech Choke Ring or a Trimble Zephyr, is located on a welded metal structure approximately 2m high: a tripod with centre pole, drilled at least ½m into solid bedrock and secured with fast-curing epoxy. A feed wire connects the active antenna to a GPS receiver mounted inside the cabinet, located several metres away. Almost all of the original SuGAr sites contained Ashtech Micro-Z GPS receivers, set to record one GPS reading every two minutes (the highest sampling rate for this device is 15s, which has been selected on rare occasions), leading to approximately 100kBytes to 1MByte of data recorded per day. Operating power for the receiver is around 8W, including the active antenna.

A lockable steel cabinet at each site, approximately 1.5m tall and 60cm on other sides contains two 12v lead-acid gel cells of up to 90Ah capacity. One or two solar panels of 75W to 90W capacity are located on top of, or near to, each cabinet. Fig. 2 clearly shows a cabinet with solar panel, and a separate GPS antenna tripod.

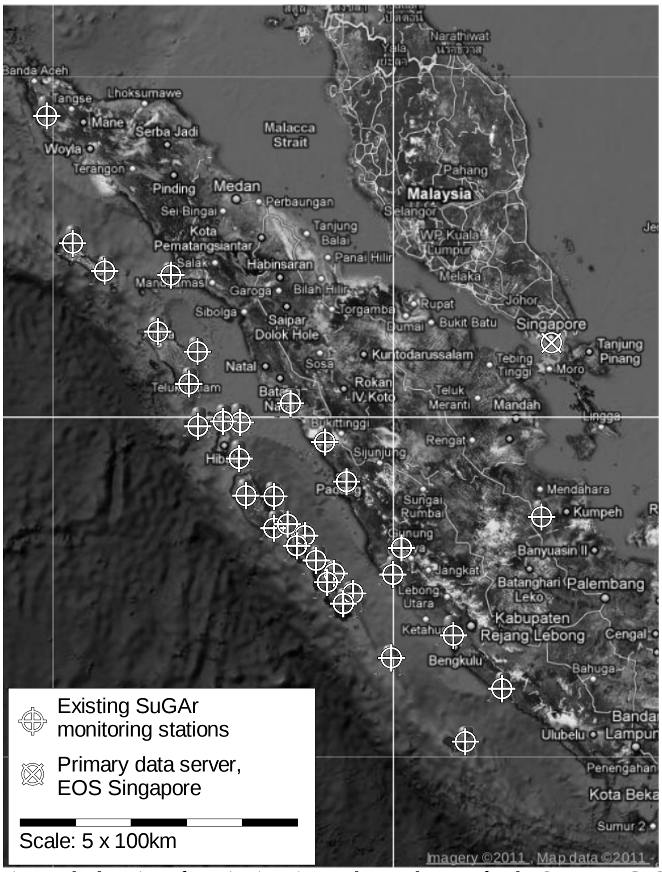

Fig. 1. The location of monitoring sites and central server for the Sumatran GPS array (SuGAr), spanning more than 1000km of known tectonic faults.

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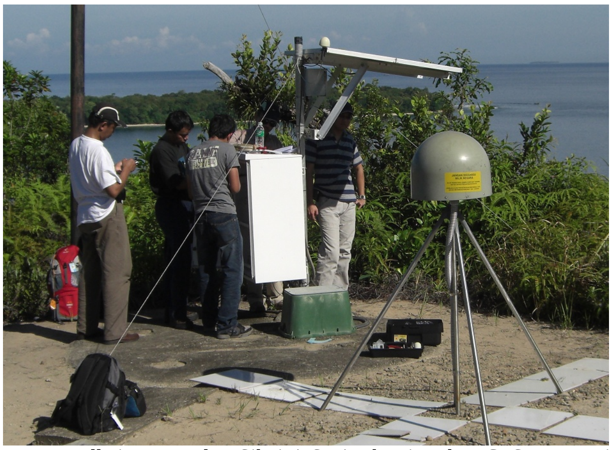

Fig. 2. Installation on Pulau Sikui (PSKI), showing the cGPS antenna in its radome mounted on a tripod (foreground), and the instrument cabinet with solar panel on top.

Apart from communications links (discussed in subsection IIB), cabinets also contain an electrical timer, which is used to periodically reset the power to various systems in an attempt to enhance reliability – but could also be used to turn off all electrical power to various subsystems during the times they are not being used.

B. Communications system

SuGAr was designed from the first, to make use of satellite communications. Only two of the sites were located within convenient reach of urban settlements, none were within GPRS or cellular coverage range (although two have recently been included in Indonesia's ever-expanding GSM and GPRS cellular network), and only one was placed within a few kilometres of land-line telephony. This differs from the few other large-scale GPS monitoring systems which tend to rely upon land-line communications [4], or denser systems than can rely upon line-of-sight radio [5]. In fact, in SuGAr, only two or three sites are within line-of-sight of others (and in areas of frequent seismic activity, reliance upon critically aligned antennas could be problematic). Hence SuGAr, from the first, incorporated satellite communications, making use of the Garuda-1 geostationary satellite, located at 123º East, which provides the Asian cellular satellite system (ACeS) service. ACeS is a GSM-like single satellite data service that covers most of South-East Asia with 140 spot beams [6]. A modified radio modem was developed specifically for SuGAr - and since marketed to other customers - the FR190G - derived from the Ericsson R190 unit, which itself closely resembles an SH888 GSM handset, and consumes up to 20W of power when active, although average consumption can be a lot lower. ACeS does not require a precisely aligned antenna; an advantage for areas subject to frequent seismic shaking.

The FR190G modem operates at only 2400 baud maximum, however this is sufficient to handle the few hundred kilobytes per day stored at each monitoring site, if downloaded on a daily basis. The Ashtech GPS receivers contain internal memory that can record over a month of data (depending upon recording options, file partitions and sampling rate), in the event of communications loss.

Since ACeS is a cellular system, each site has an international phone number which can be called from any telephone. When this is done, the call would be connected via an exchange in Jakarta, linked to the satellite (via the ACeS Batam ground station), and then a call would be established with the site. Although it is technically possible for each site to initiate a call back, SuGAr adopted a passive solution, whereby each site simply waits for contact, connection, and file retrieval. The communications network is shown diagrammatically in Fig. 3. The multiple links from the Batam site to Garuda-1 indicate the circuit-switched nature of the communications.

C. Central server and software

At the central base station on Batam, four FR190G modems were employed to call, in turn, each site across the SuGAr network, establish communications, and download the collected data. To minimise network traffic loading, this was scheduled between midnight and 4am each day.

When all equipment is operating correctly then this arrangement works well. However when communications is interrupted for any reason, more data needs to be communicated on subsequent days – something that can be clearly clearly on the data availability map in Fig. 4, which plots all data points received from 2003 to 2007.

The central server runs a high reliability operating system (CentOS 5.2 Linux) and makes use of two scheduling and control packages, named *schedg* and *sharc*, written in C++ and Perl, and released by Keith Stark [7]. This software is responsible for periodically contacting remote sites, determining the list of files stored in the GPS receivers at those sites, downloading any files that are not yet resident on the main server, and deleting whatever files have been downloaded during the previous connection session. In fact, both *sharc* and *schedg* are flexible open source tools that can cater for a number of connection arrangements, protocols, and handle several GPS instruments.

Retrieved files, located on the SuGAr server, are backed up, copied to a main server and to partner institutions (typically with a 3 month delay), including one copy to SOPAC (Scripps Orbit and Permanent Array Center) in San Diego, USA. Generally, the received files, one per day per site, are then used by geophysical scientists to derive daily tectonic solutions using large-scale analysis tools such as GAMIT/GLOBK, BERNESE or GIPSY [8].

D. Limitations

The original SuGAr array, whilst innovative for its time, has long since been superseded by technological advances: GPS sampling rates in other networks can now regularly exceed 1Hz, whereas the limit for the Ashtech Micro-Z GPS units is one sample every 15s (even so, the existing

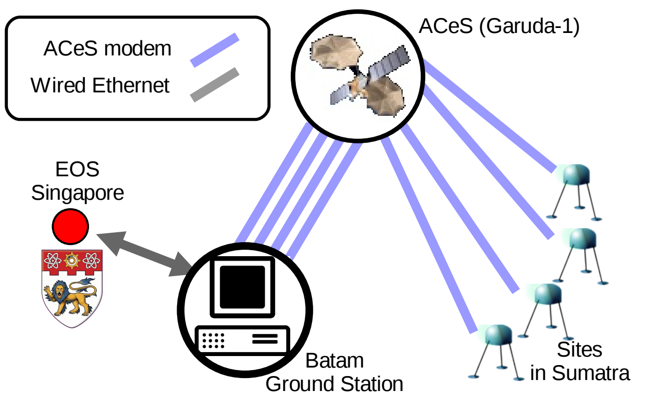

Fig. 3. Showing the SuGAr connectivity arrangements between remote sites and the Batam ground station, then on to Singapore. The central role of the ACeS satellite to network operation is clearly visible.

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Fig. 4. Data availability map from http://eos1.ntu.edu.sg showing SuGAr data files from 2003 to 2007, available for download from the server, for the first 32 installed SuGAr sites (i.e. sites installed up until 2007), listed vertically. A separate point is plotted for each day of each year, running in the horizontal direction, with the shading of the point indicating the amount of collected data, ranging from around 40kBytes (light shading) to almost black (1.9MBytes). Dark records often indicate a problem, such as previous lost communications requiring greater data transfer to catch up later, or may indicate a site configured to store GPS data with a faster sample rate than usual.

network could not cope with such a sample rate at every site). SuGAr also suffered a number of reliability problems including ACeS antenna failure, battery failure and so on. However these problems were dwarfed by the fading abilities of the Garuda-1 satellite itself, which is approaching end of life. As the ACeS satellite transponders and systems gradually fail, the number of working spot beams has diminished, and link reliability has dropped to a point that, at certain times, most calls will fail. During link failure, recorded observations would be kept in the Micro-Z internal memory (maximum 128MByte, but limited to only 100 files).

Apart from the GPS and communications link problems, SuGAr has long attracted the attention of other scientists, many of whom have requested the sites to co-host various sensors: weather stations, tilt meters, accelerometers (for seismic measurements), gas sensors, tide gauges (for sites close to the shore) and digital cameras. The site cabinet architecture, communications system arrangement, power budget and ACeS bandwidth preclude any of these. In fact, much legacy SuGAr network hardware has been superseded by lower power, more reliably and capable alternatives, the common eventual fate of many pioneering systems.

One notable operational difficulty has been that the system communications is marginal, taking 53 minutes to download a one-day record from one site over modem. If, for any reason, the download does not proceed for one day (the white areas in Fig. 2 show such times), then the system will need to consume extra time the next day to catch up with downloading, or suffer data loss. This has a potential knock-on effect to other sites, since they will in turn have less available download time. When two failures happen in close succession, the system can become so backed up that it is unable to recover – necessitating manual intervention.

Finally, although ACeS is a relatively low cost cellular system, call costs in data mode – especially for the length of time needed to download data each night during high error periods – become high. The system average is well over $1000 per month.

III. Improvements

With the process of transferring SuGAr from the CalTech team to the Earth Observatory of Singapore in 2008, the opportunity was taken by the authors to design improvements to the network. Fig. 5 shows a diagram of the improved SuGAr system architecture, indicating the number of possibilities now supported for data transfer and the redundant central server sites.

A number of new equipment and system choices were made, as discussed in the following subsections.

A. Improvement to site installations

Sites now utilise the Trimble NetRS GPS receiver, either with the Zephyr or choke ring antenna. The NetRS is capable of sampling at up to 10Hz with very high accuracy, and is naturally a network-centric device, supporting HTTP, HTTPS and FTP. Internal memory is also much larger, and the NetRS can natively support additional sensing packages, such as the Trimble meteorological sensor. Including the antenna, the NetRS power consumption has been found to be less than half that of the Ashtech Micro-Z units, at less than 4W.
For the SuGAr network, all sites have been or will soon be upgraded to use Trimble NetRS, and provided with a small

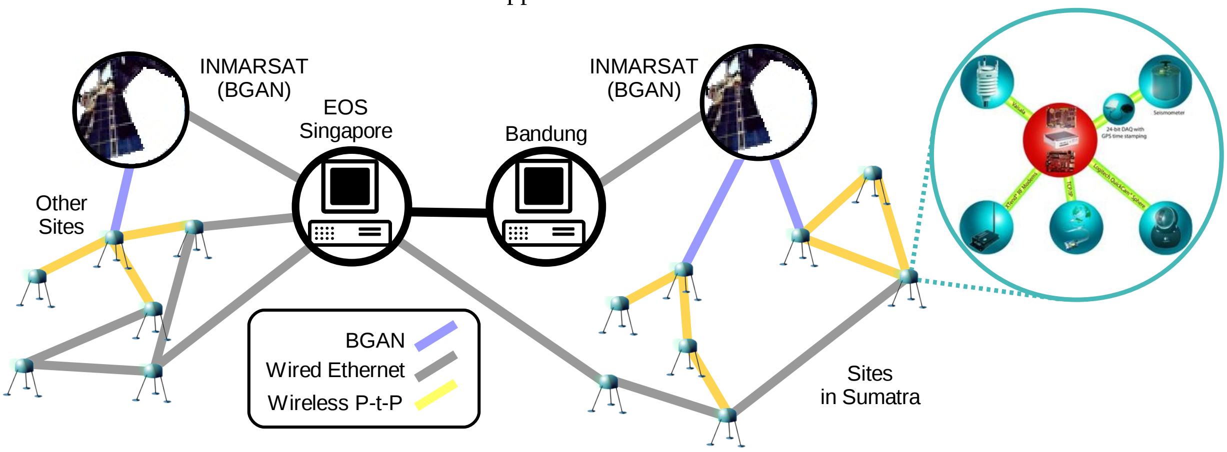

Fig. 5. Connection diagram, showing the improved SuGAr architecture which makes use of redundant backup servers in Bandung, Indonesia, and Singapore,. with multiple communications links including INMARSAT BGAN, wired Ethernet and medium-range point-to-point wireless linking. Detail of the sensors and services supported by each node (apart from cGPS) is shown in the inset, top right. Sensors and services shown, clockwise from top right include seismometer, steerable camera, web server, point-to-point RF modems (supporting sensors located nearby, such as tide gauges), and integrated weather sensors.

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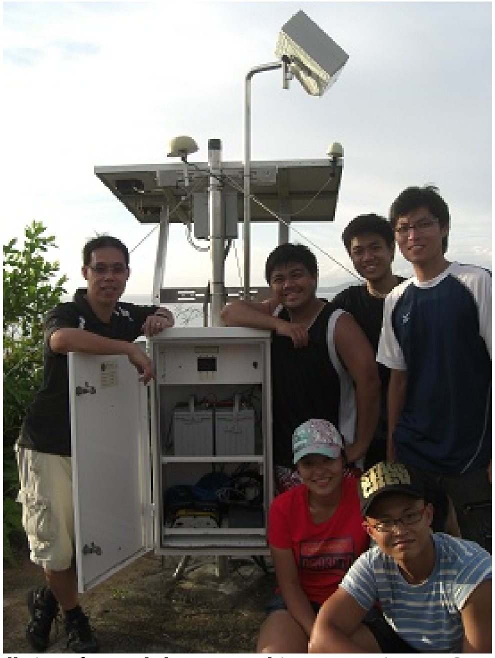

Fig. 6. Installation of upgraded sensors and instrumentation at PSKI, August 2009, showing view of cabinet internals, and the student team led by Prof. Steven Wong (left).

network switch to allow the connection of other IP-aware instruments (examples that have been deployed by the authors include steerable digital cameras, meteorological packages, and seismometers, shown in Fig.5). Fig. 6 shows an upgrade and experimental package installation on Pulau Sikuai (PSKI), off the West coast of Sumatra, Indonesia. Note the solar panel (background), BGAN antenna box (tallest structure), weather sensor (small dome), and cabinet containing two batteries.

Apart from the upgrades already mentioned, research has been conducted in the idea of incorporating a small embedded control computer at each site. Adding another active component would normally reduce reliability, but in this case, intelligent supervisory and backup facilities were targeted to increase overall reliability. Apart from supervisory monitoring, and transmitting telemetry on the state of the site, the embedded computer has been used successfully for compressing the data to be communicated [9].

Several embedded computer tests were made, and the software ported to successively lower power hardware: a 1.6GHz Intel-Atom based PC/104 system drawing 12W of electrical power, an 800MHz-1.6GHz generic Atom module drawing 9W, an SiS 550 x586 running at 200 MHz (5W), a Vortex86 at 800MHz (2.5W) and a 200MHz ARM9-based system consuming less than 1W of electrical power. Price has also reduced during this refinement from $1000 to less than $200. All systems have been found reliable in field testing at Mayon volcano in the Philippines (as part of a seismic monitoring network), and the last two are now being installed in several SuGAr nodes.

B. Improvements to system communications

Since ACeS is nearing end-of-life, several other communications systems were considered. The nature of SuGAr – widely scattered, in rural areas and across many uninhabited islands, means that terrestrial communications methods are, at best, able to support only a small subset of the network, thus satellite communications is still preferred for the bulk of data transfer.

Satellite options include VSAT (very small aperture terminal), Iridium and INMARSAT BGAN (broadband global area network) [10]. VSAT is expensive to install but cheap to operate, however it is considered to be high maintenance in the need to keep dishes clear of animal life and plant growth, and re-align in the very likely event of earth movement. With its relatively high bandwidth, VSAT has been considered for backup communications purposes. Iridium call costs have prevented the widespread use of this satellite technology in such systems, although the physical alignment issues are minimal and power consumption is low. Several BGAN alternatives were tested from, Addvalue, Hughes and Thrane & Thrane [11]

In conclusion, BGAN was chosen for a mixture of price, flexibility, convenience, and providing good bandwidth. BGAN antennas are much less sensitive to misalignment than VSAT, are smaller and less likely to be damaged or displaced and communications costs are much lower than comparable Iridium services.

During deployment tests, it was found that BGAN communications actually required a lower power consumption at 492 kbits/s than FR190G did at 1200 bits/s. BGAN-based communications allowed the more flexible IP-based architecture as shown in Fig.5, as well as supporting the connection of different sensor types.

With the BGAN system, as described, it was found during pre-deployment trails of 3 months that daily connectivity was 100%, and during the first year of deployment that system uptime was over 95%. The small amount of downtime that was experienced was not caused by failure in communications links, but by the periodic time out of the dynamic IP address assignment from the DHCP server.

C. Improvements to back-end data handling

Back-end data handling has been improved through a set of new tools, including a web interface for configuring *sharc*. In addition, sites are now tied into Google maps/Google earth (see Fig. 7), allowing status and latest data to be examined and retrieved. The use of BGAN for communications, and thus more bandwidth plus its all-IP connectivity, has allowed a number of additional services as well as sensors to be accommodated. It is now possible to remotely log into each site using SSL, and either manually or automatically determine status, change operating software and conditions and run diagnostics (as well as

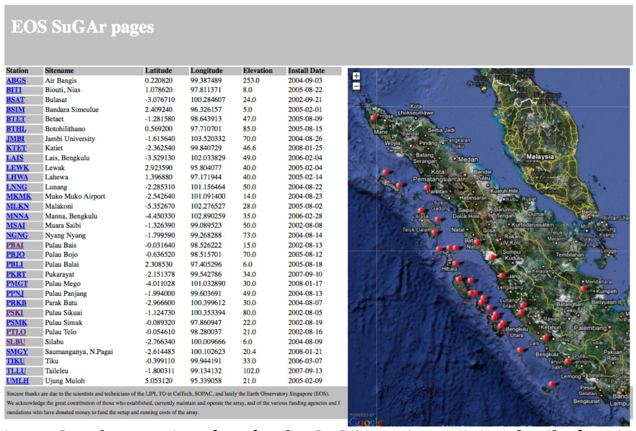

Fig. 7. Google maps interface for the SuGAr stations, giving detail of station equipment, servicing record and downloaded data availability, from http://eos.ntu.edu.sg.

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retrieve or download any files that are required).

At the server side, an identical back-end server system has been installed in the LIPI (Lembaga Ilmu Pengetahuan Indonesia - the Indonesia Institute of Science) headquarters in Bandung. The system is set up so that data mirroring can take place and, as shown in Fig. 4, that the communications load can be shared between the two servers.

IV. Conclusion

The baseline infrastructure described in this paper is flexible enough that it is being used for sites other than SuGAr: in the past year, measurements have been collected from Bangladesh, Nepal and Burma (Myanmar), by the EOS technical team, and stored on the EOS back-end database servers.

System reliability, whilst too early to measure for a complete system, has been seen to be high for all upgraded sites. BGAN communications costs are lower, and reliability much higher than the ACeS-based predecessor, and the higher communications bandwidths have allowed sampling rates to be increased to 15s, and up to 1Hz. Meanwhile, additional weather sensors have been co-located at some test stations, and a web-steerable video surveillance camera trialled.

Thus the new site components and system architecture of SuGAr has been demonstrated to be more scalable, more reliable, more flexible, lower power and lower cost than the original system. SuGAr is currently collecting data, and is online to measure earth movements during future earthquakes near Sumatra; providing more data for tectonic scientists and contributing to better understanding of earth science.

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