Using Nanosats as a Proof of Concept for Space Science Missions: QuakeSat as an Operational Example

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ABSTRACT: Several previous satellites (Cosmos 1809 and Aureol-3) had detected anomalous extremely low frequency (ELF) magnetic field signals prior to and after large earthquakes around the early 90's. There were questions regarding signal levels, signal structure, frequency ranges, timing, and the ambient noise environment that made it difficult to specify larger science satellites to thoroughly test the theory that ELF might be a precursor signal to large earthquakes. An inexpensive nanosat (QuakeSat) was built, launched in June 2003, and flown to help determine the design parameters and values needed to build a research satellite for this mission.

INTRODUCTION

Costs and budgets are important factors regarding the development of any satellite system. Commercial satellite systems develop their funding out of cost vs. benefits and cost vs. return models. Established areas of scientific study, such as radio astronomy or planetary exploration, have limits on their budgets, but new and/or yet unproven ideas/areas of scientific study are under even greater pressure to reduce costs and obtain funding. “We don’t support that area of study”, or “If you can prove this, we’d be interested in funding further research”, are common phrases heard while developing funding for these areas of research.

What one needs is a low cost way of getting a foot in the door, a way to collect at least some data on a topic that would support the development of follow on systems. A low cost way of determining if there is any there, there.

QuakeFinder, LLC found itself in this exact position 2 and ½ years ago.

OUR QUESTION

In October of 1989, the San Francisco Bay Area was hit by a large 7.1 magnitude earthquake, centered in the Santa Cruz mountains, 60 miles south of San Francisco. The earthquake caused significant damage, killing 63, injuring 3757, causing nearly $6 billion in property damage (the most costly natural disaster in the US up to that time) and disrupting the transportation infrastructure of the area for months.

Stanford researcher Dr. Tony Fraser-Smith, was conducting ELF research in the area and happened to have a sensor station less than 5 miles from the earthquakes epicenter. Post the recovery of the data recorded by this sensor station, Dr Fraser-Smith was surprised to see a large increase in the local ELF signals under 1Hz, in both the weeks leading up to the earthquake and in the months following[1].

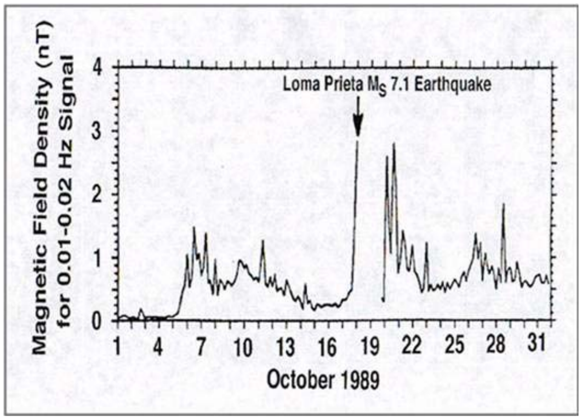

Figure 1. Dr Tony Fraser Smith's ELF Data

Based on this and other research, QuakeFinder, LLC was launched in 2001 with the aim of first proving this correlation, thru the collection of other examples of these signals, pre and post earthquakes, if successful there was the possible commercial exploitation of this data in the form of an earthquake warning system.

QuakeFinder has since established a network of over 30 sensors throughout California with 25 more currently under deployment. These ground sensor stations have been strategically placed along primary California earthquake fault lines. However, with a coverage radius of 10 miles it will take between 200 and 300 to cover California completely.

This is a huge expense for a yet, unproven method of detection. In addition, there are many unanswered questions regarding the best detection techniques (frequencies, required sensitivities, best orientations of the sensor, best additional secondary sensors, etc.).

In addition, large earthquakes do not happen everyday in California, in fact decades can go by before the next large earthquake in California. This has been a problem for earthquake researchers for some time. Where will the next earthquake occur, so that the necessary array of sensors can be placed, this data is needed to develop the models required to be able to reasonably predict where and when the next earthquake will occur. A great chicken and egg question.

ADDITONAL DATA COLLECTION OPTIONS

What we needed was a way to look for these signals world wide. A ground sensor network was out of the question, because of cost. However, maybe this or other related signals could be detected from space. Further investigation indicated several previous satellites (Cosmos 1809[2] and Aureol-3[3]), not originally designed to detect these signals, have detected ELF signals that might have been associated with earthquakes in the early 90's. Could a satellite, specifically designed for this mission, detect and correlate these signals? That was our question.

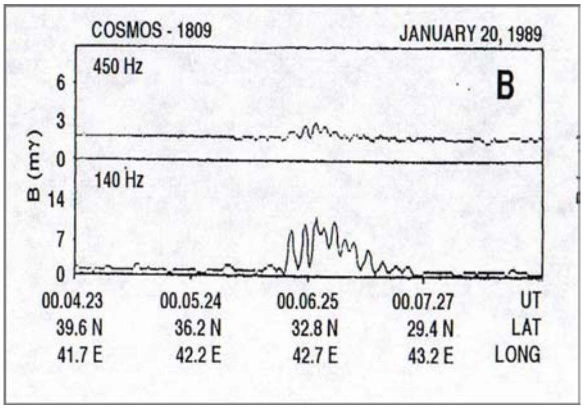

Figure 2. Cosmos 1809's ELF Data

A polar orbiting satellite has global coverage on the order of once or twice a week (depending on the orbit specifics and the data collection envelope). If these ELF signals could be seen from orbit on this same time scale, then the signals should be present for one or two collections before an earthquake and at least a half a dozen afterwards.

On average, there are typically between 50 and 70 large earthquakes world wide each year. This, in concert with the global coverage of a satellite, increases the likelihood of being in the right place at the right time. Exactly what we needed.

There are still many unanswered questions regarding detection of these signals from space (best frequency bands, required sensitivities, best orientations of the sensor, best additional secondary sensors, etc.). To cover all these parameters on a first mission, the cost was preliminarily put at $85 million in 1996.

After getting the previously mentioned answers, we decided we needed to come up with an option that would allow us to start the research effort, to begin to understand the nature of these signals, for a lot less. A whole lot less, almost 2 orders of magnitude less.

And with that the QuakeSat concept currently on orbit was born.

MAXIMIZING DEVELOPMENT PARTNERSHIPS

In order to do our mission, for around 2 orders of magnitude less cost, we were going to have to get smaller, a lot smaller. In addition, we would want to exploit COTS type solutions for as much of our development as possible.

We are fortunate to be located near several significant sources of development partnerships; universities and industry. QuakeFinder, LLC is located only miles from where Dr. Tony Frazier-Smith, had started this research at Stanford University. In addition, Stanford Professor Bob Twiggs, had just recently started developing his CubeSat concept. Could we tap into these and other partnerships?

NANOSAT ENABLERS

NanoSats, satellites in the 1 to 10kg range, can currently be developed for between $10K and $1million. This is possible because of several key attributes; small size and simplicity and the use of ground based COTS products for large parts of the system.

Launch costs for nanosats have also come down. Since the end of the cold war, former Soviet ICBMs have been refurbished by the Russians for use as launch vehicles. Nanosats have been launched on Dnepr and Euroket launch vehicles for around $40K per kilogram. US and ESA launches may also become possible for small sats through the use of the ESPA ring or by one of DARPA’s Falcon Class launch vehicles

Although the reduction in cost for nanosats is hugely important, the vast increase in the performance of COTS based micro electronics has allowed nanosats to be considered for real science missions. 100+ MHz PCs with up to a Gigabyte of storage can now be easily packaged into a nanosat. Future on-board processing will allow for even greater data collection as the overall downlink rate is still somewhat limited.

QUAKESAT

An early look into possible QuakeSat designs lead us to believe that at current technology levels it was unlikely that we would be able to get the level of performance required from just a 10x10x10 cm cube, ie a CubeSat. The sensitivity of our magnetometers is a function of length and number of coil windings. Our ground station magnetometers are just under 30 cm long and with a HyMu-80 core and we were unlikely to find or develop a way to fit it into a CubeSat, but maybe a triple CubeSat.

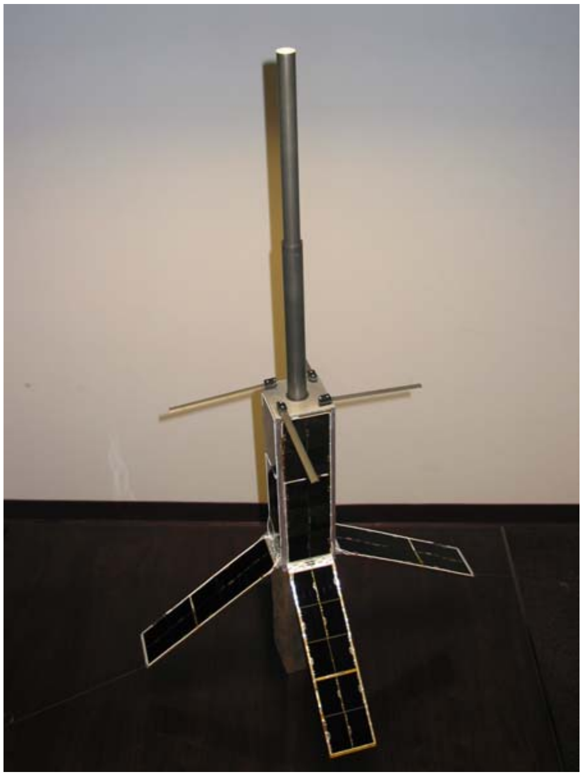

Figure 3. QuakeSat on display before shipping for launch

QuakeSat, weighing under 5kg and under 150cm fully deployed, carries a single axis, AC magnetometer as its primary instrument. A secondary E field sensor is also carried.

Table 1. QuakeSat Payload Parameters

Item	Description
Magnetometer	Search coil (induction) type
Specs	Two 25,000 turn co-axial coils + cal coil
	Low noise preamp with negative resistance circuit (GSFC)
Sensitivity	10pT noise floor
Dynamic Range	80-100db (low and high gain mode) 16 bit A-to-D

Mode 1 Bandwidth	.5 to 10 HZ @ 50 samples/sec
Mode 2 Bandwidth	10 to 150 HZ @ 500 samples/sec
Mode 3 Bandwidth	10 to 1000 HZ @ 3000 samples/sec
Mode 4 Bandwidth	140Hz (127 to 153 Hz pass band (E and B field) @ 500samples/sec
Mode 1 Collection Limit	100 minutes continuous
Mode 2 Collection Limit	10 minutes continuous
Mode 3 Collection Limit	100 seconds continuous
Mode 4 Collection Limit	30 seconds continuous
E Field Antenna	2 wire dipole antenna, .6 meter separation
Power Load	.6 to 2.2 watts depending on filters selected

QuakeSat's magnetometer has a theoretical sensitivity or noise floor of 10pT. Four filter bandwidths cover the frequency range from 1 to 1000Hz. Sampling rates of up to 3000 have been collected, with most collections using a Mode 2 type collection, 10-150hz @ 500 samples per second.

In addition, a number of cross mode collections have been made, high data rate sampling, cal signal sampling, etc all in an effort to better understand and characterize the noise in our collections. The noise has been somewhat higher than expected before launch and lessons learned here will be incorporated into our following satellites.

Table 2. QuakeSat Satellite Parameters

Item	Description
Orbit	840km circular, sun-synch, Dawn-dusk
Size	150 x 80 x 80 cm (Deployed) 35 x 11 x 11 cm (Stowed)
Weight	~4.5 kg
Power (Batteries)	2 Li Ion batteries (3.0AmpHr total) (Failed open circuit Jan24 and Jan 28 respectfully.)
Power (Solar Arrays)	12 solar panels (4 body fixed and 4 double sided deployable) 10 triple junction GaAs cells per panel, dual string. ave 14 watts BOL
Power Load: (CPU, Receiver. and Power. Boards)	3.6 watts continuous
Power Load (Transmitter)	1-1.4 watts depending on bus voltage
Communication	436.675 MHz half duplex, 9600 baud
Attitude Control	Passive magnetic stabilization, (Likely not maintaining pre-launched planned attitude.)
Attitude Determination	12 solar array currents primary, IR and temperature Sensors secondary. (Mux with primary channels failed at launch.)
On Board Computer	Prometheus PC-104, down clocked to 66MHz, 32 RAM
A to D	16channel, 16bits up to 3000 samples/sec
Storage	128 MB Flash, up to 64 MB available for data collection.

Orbit

QuakeSat flies a nearly circular, sun–synchronous, dawn-dusk orbit at approximately 840km. The circular, sun synchronous part of our orbit is fine for our type of mission, however the dawn-dusk portion would not have been our choice. While great for power collection, the "flying the terminator" aspect has QuakeSat over its target during the most turbulent time of the day for the ionosphere.

Power

QuakeSat power is provided by 12 solar panels, 4 fixed body mounted along the long axis and 4 double sided wings attached in a wind mill fashion off the end, opposite the magnetometer boom. Each panel consists of 10 triple junction GaAs cells in two strings.

QuakeSat uses two Li Ion battery packs for energy storage, a total of 3.0 Amp Hrs. The batteries provided total system power during the short eclipse period in the month following launch and supplemental power during ground contacts.

Both battery packs failed in late January after approximately 7 and ½ months of operations. We never operationally stressed the batteries with respect to their Depth of Discharge/Cycling, but we were running them very hot for about 2 months before the failure.

Since the battery failures, QuakeSat's link margin and therefore its throughput is down. The instantaneous power available without the batteries is no longer able to provide full power to the radio and sometimes not even enough to power the rest of the satellite.

Attitude Control

QuakeSat's attitude control system is passive and consists of four 10 x .6 x .6 cm Alnico magnets, aligned along the boom axis, with 2 31 x 1.25 x.6 cm Hysteresis rods for damping. Our hope was to fly along the magnetic field lines, rotating through 720 degrees per orbit.

Attitude determination was to be done with current sensors from the 12 solar panels, each one acting as a coarse sun sensors. The Mux containing most of the on-board current measurements failed before the first TLM contact (likely during or before launch). With that failure, our attitude sensors, not planned for this use, became a wide angle (30deg) light sensor, solar array bus voltage and on-board temperature sensors (both internal and external).

These sensors are not ideal for attitude determination and so we have only a crude model of our attitude. QuakeSat attitude is not magnetic field line following, more likely nadir pointing with a wide wobble.

On-Board Computer & Vehicle Flight Software

QuakeSat uses a Diamond Systems Prometheus PC-104 CPU with a built in 16 channel, 16-bit A/D converter. We run a Diamond Systems provided Linux OS.

QuakeSat's Vehicle Flight Software (VFS) was under 10,000 lines of code, some of that was already written device drivers (ie AX.25, modem, etc.).

The simple software architecture is outlined as follows:

- Device driver: hardware timers, payload board controller
- Executive program: receive a command, send a response (1 packet up/down)
- Worker program (reads in a time-tagged sequence of commands and executes them). This allowed multi-day planned collections.
- Beacon program (send beacons: alive health/status).
- File upload/download standalone programs PFS/PFR (with integrated hole management to fill in missed packets).
- Heartbeat generation program to tell the watchdog board all is working

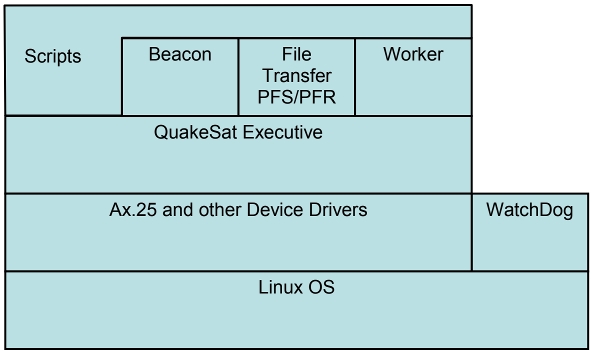

Figure 4. QuakeSat Software Architecture

DESIGNING AND BUILDING FOR OPERATIONS

Building and launching QuakeSat would be of little use if we couldn't fly it and collect the data we were looking for. We needed to be able to fly it, task it to collect the data we were looking for, maximize the amount of data we could collect during our short mission and analyze the data we did collect.

Communications

Communications with QuakeSat is done over the HAM radio band (436.675 spacecraft transmitter and receiver). We use basic Pacsat protocols. QuakeSat can be seen as just an additional computer on the Internet. While overhead a ground station, the computer can be Pinged and logged into as a typical computer on a typical ground network, but the half duplex radio communication architecture makes this type of communication less time efficient. With contact time limited to under 150minutes per day at maximum, every minute must be wisely used.

For most contacts an automated contact execution script is used to drive our automated ground station. Upon receipt of two QuakeSat beacons the beacon program is terminated and the current memory usage is downloaded. A list of files we would like to download is maintained and ranked in priority order. The next file on the list is requested for download. The status of the download, ie which blocks have been downloaded and which ones still need to be requested or re-requested is maintained in a Holes file, this Holes files accompanies the requested file on the ground until the file has been completely downloaded.

A number of possible satellite states are tracked during this process, as the packet level comm. with QuakeSat can at times be poor to very poor, ie commands can be received and executed on board QuakeSat, but the acknowledged response not received by the automated ground system. In addition, manual contacts are run routinely to load new tasking loads or update scripts or other programs.

Tasking and Targeting

QuakeSat has a unique targeting problem, the path of the ELF signals is not direct line of sight like our radio signal. The exact path is not fully understood or modeled yet, but is a function of ionosphere height and thickness, atmospheric turbulence, signal frequency, signal strength, receiver height. None of these variables are constant for any satellite pass over a target, and even vary during a specific pass.

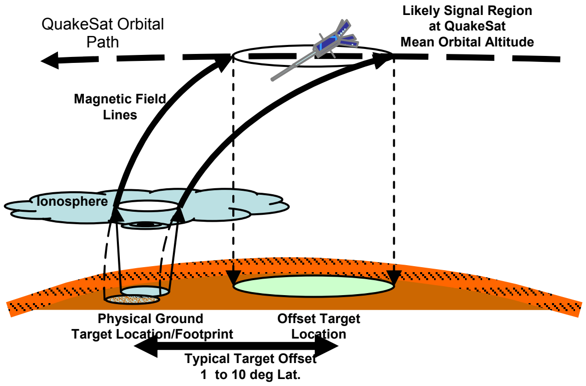

Figure 5. Offset targeting model

Pre-launch, likely earthquake regions were laid out globally and given a related priority. The corner points and centroids of these regions were then propagated along our modeled path to the mean QuakeSat attitude. For point signal sources such as earthquake epicenters, a circular region was made surrounding this point. These points were then projected back down on to the earth's surface to create new offset targets.

QuakeSat accesses to these targets are then calculated using a simple vertical fence model to define collection On and Off times. Collection mode, sample rate and other data is then added to the collection load, which in turn is then uplinked to QuakeSat.

Since download time is a premium, most of our collections are over areas that we might expect a signal to originate from. Should QuakeSat survive its current eclipse period, we plan some additional negative area collections (ie area where we would expect no earthquakes or only noise signals).

Analyzing

In additional to building, launching, tasking and collecting data from QuakeSat we need to analyze the data. To this end we have established our QuakeFinder Data Center. The data center is the repository of all of the QuakeFinder data and analysis tools, both for QuakeSat collected data and our ground sensor network. In addition, other data associated with our analysis is housed under the data center umbrella (ie space weather, ground weather, other university and researcher's sensor data.).

Currently the data center contains a data base repository for the actual raw data, spectrograms and energy plots for each collection, maps showing actually satellite position at the time of signal detection and using our current signal propagation model, the ground location of the likely signal origin (Note: Not all of our detected signals have a ground origin).

Lessons learned during our development process are available at our QuakeSat web site. http://ssdl-delta.stanford.edu/LM-CubeSat/Team4/index.htm. This document[5] covers mainly spacecraft related lessons learned, but also includes some payload related lessons learned.

WHAT HAVE WE DISCOVERED SO FAR

Like all satellite missions, we went through the various phases of operations, Initialization, characterization, full mission ops and end of life mission ops.

We launched on June 30, 2003 and collected our first magnetometer data on July 2, 2003. But by August 27, 2003 we had determined that we were detecting a number of QuakeSat generated signals, and up loaded new collection software to reduce some of this CPU interrupt generated noise. In addition, we had determined our own internal modem, battery charge controller and power supply were also noise sources, but we have been unable to correct this on orbit. By November the second ground station was coming on line and we had a large increase in the volume of data collections. In October and November, we made several corrections to our signal propagation model and therefore updated our targeting model. Finally in December QuakeSat was really humming. On a good day we were getting about 6 MB of uncompressed data down from the satellite.

A total of nearly 2000 magnetometer collections were made of all modes, primarily 10 to 150Hz, roughly 500MB raw binary uncompressed data. The areas targeted were primarily, 1) likely earthquake regions, hoping to catch a signal before an event and 2) significant post earthquake collections in the region surrounding the earthquake. In addition, over a 100 collections were made looking for lightning strikes and several global 1-10Hz surveys were made.

Analysis of this complete data set is still underway. We have approximately 25 signal types currently cataloged. Some of these are known or highly likely to be satellite generated, a few we suspect are satellite or satellite environment related. However, a number have a signature that we might expect to see related to an earthquake, wide band frequency and wide time span (ie not impulsive). In addition, we detected aural signals over the polar regions, up to 80Hz and a number of lightning strikes 10-1000Hz.

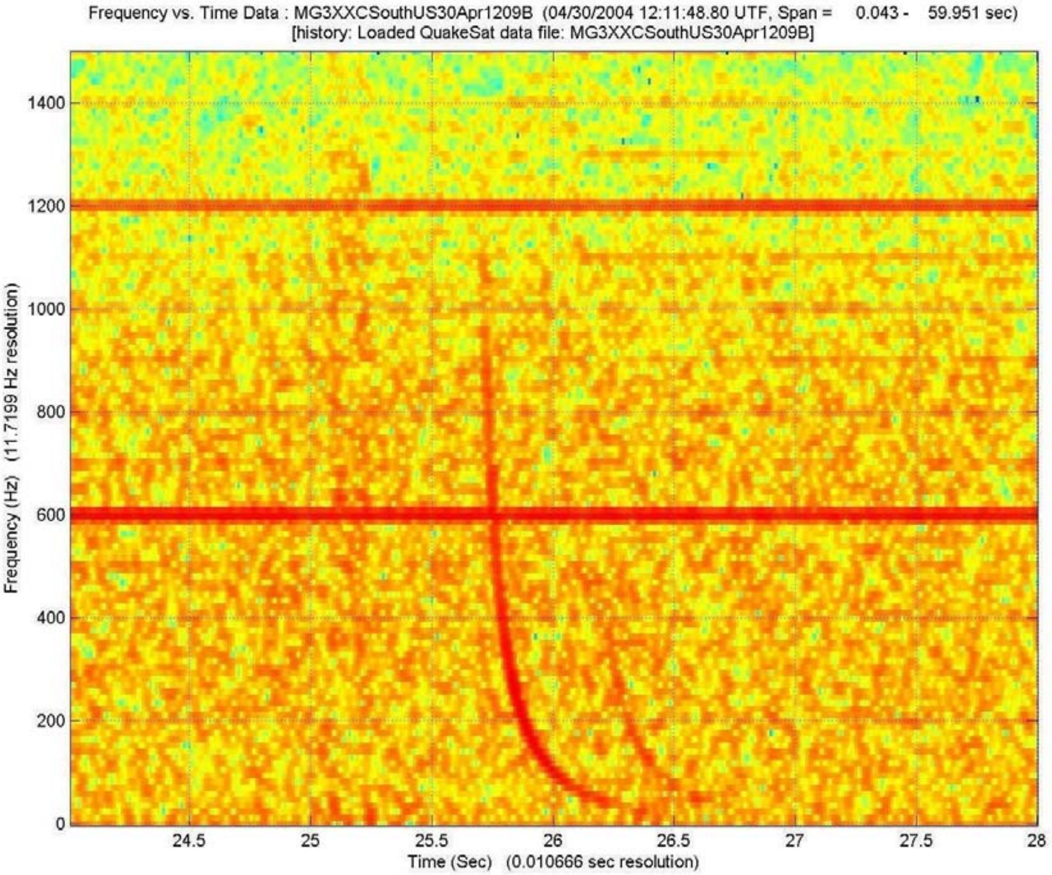

Figure 6. Lightning collection over the southern US.

The signal's propagation path, mentioned before, is still not fully understood. Factors that likely impact the path include ionosphere height, atmospheric disturbances, signal frequency, etc. We are currently investigating this, using detected lightning strikes. Lightning strikes have a powerful, wide frequency pulse. Their impulsive nature allows us to better understand where they are generated and how they are received by QuakeSat. A characteristic J hook shape, (a rear facing J), indicates that the propagation path is different for different frequencies. This type of signal has been detected by many ground based systems. This may prove useful in geo-locating earthquake related signals, by using the difference in time of detection and path to determine multiple eclipses of possible signal origination.

Cosmos 1809 had a narrow band instrument, measuring 140 Hz and 450 Hz (ie creating two vertical planes at 140 and 450 Hz through a time vs frequency vs intensity surface). QuakeSat carried a wider band instrument covering the 10-150Hz and 10-1000Hz bands. While this reduced the overall sensitivity at a specific frequency; it increased the range of frequencies we could look at, creating a 3D view of the signals.

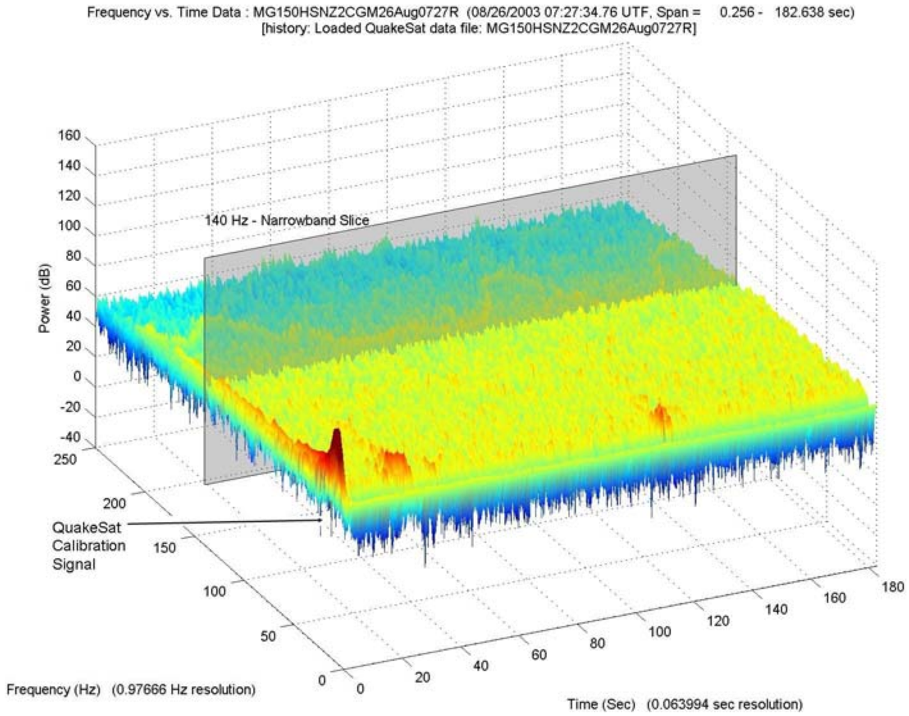

Figure 7. A 10-150Hz collection over New Zealand with a 140Hz narrowband slice for illustration purposes

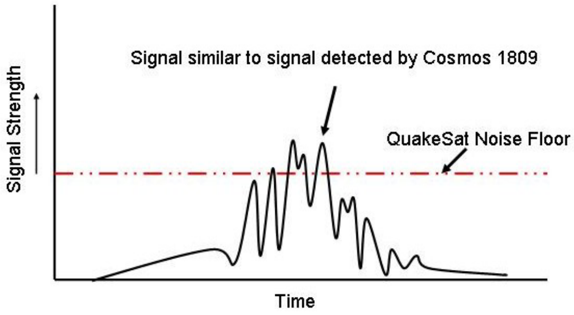

Figure 8. Likely QuakeSat sensitivity overlain on a "Cosmos 1809-like" data curve

We currently believe that the wide band bursts of energy we have seen a number of times, may be the peaks of the signals similar to the ones Cosmos 1809 detected over Spitak-Armenia. We saw these over a broad range of frequencies up to about 150Hz.

We suspected that these earthquake signals were likely broad band and one of the missions of QuakeSat was to determine how broad and what frequency(ies) might be best.

Signals of this or similar type were seen immediately following the August 21 2003, 7.2M South Island NZ quake, the December 22, 2003 6.5M San Simeon CA quake, and the December 1,2003 6.0M Kazakhstan-Xinjiang Border Region earthquake.

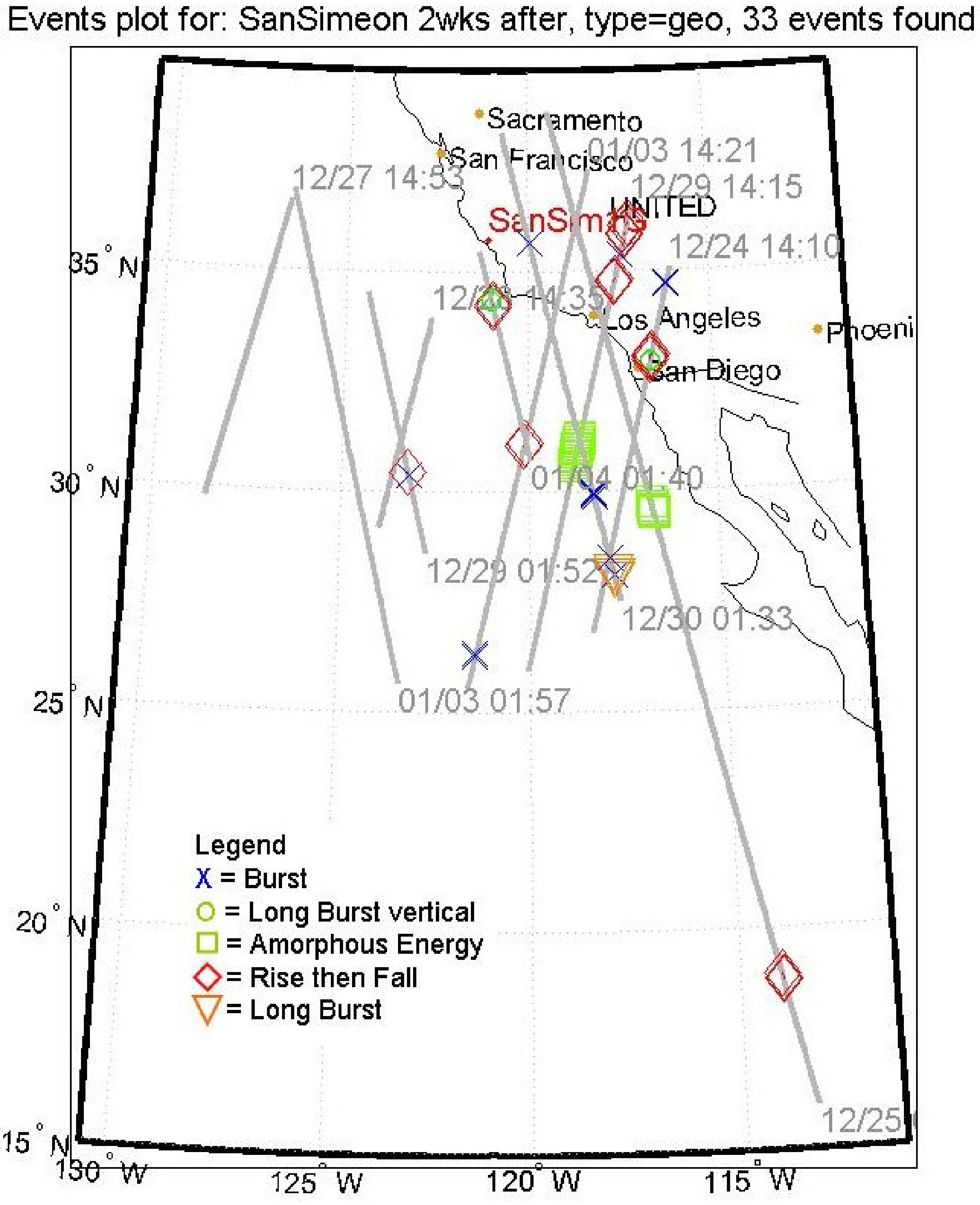

Figure 9 QuakeSat collections during the 2 week post the San Simeon earthquake.

Our analysis of the data collected to date is on going, future collections are still possible even though QuakeSat is no longer at full operational capability. The QuakeSat noise floor was higher than expected, and the dawn dusk nature of our orbit has us flying over our targets while the ionosphere is in a turbulent transition period between night and day, these are likely reasons why we have seen only a few signals

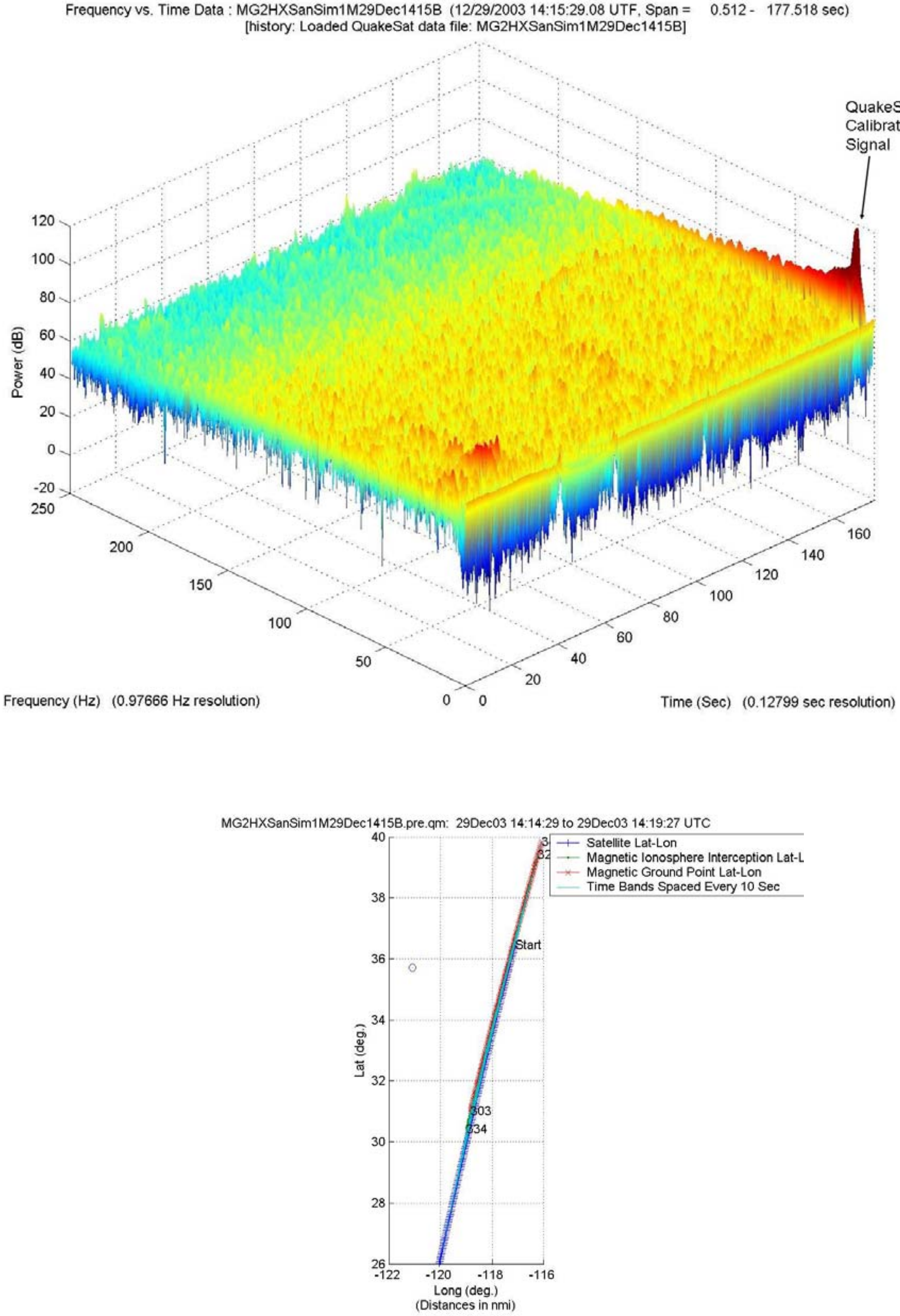

Figure 10 Early morning collection over San Simeon (Dec 29 2003)

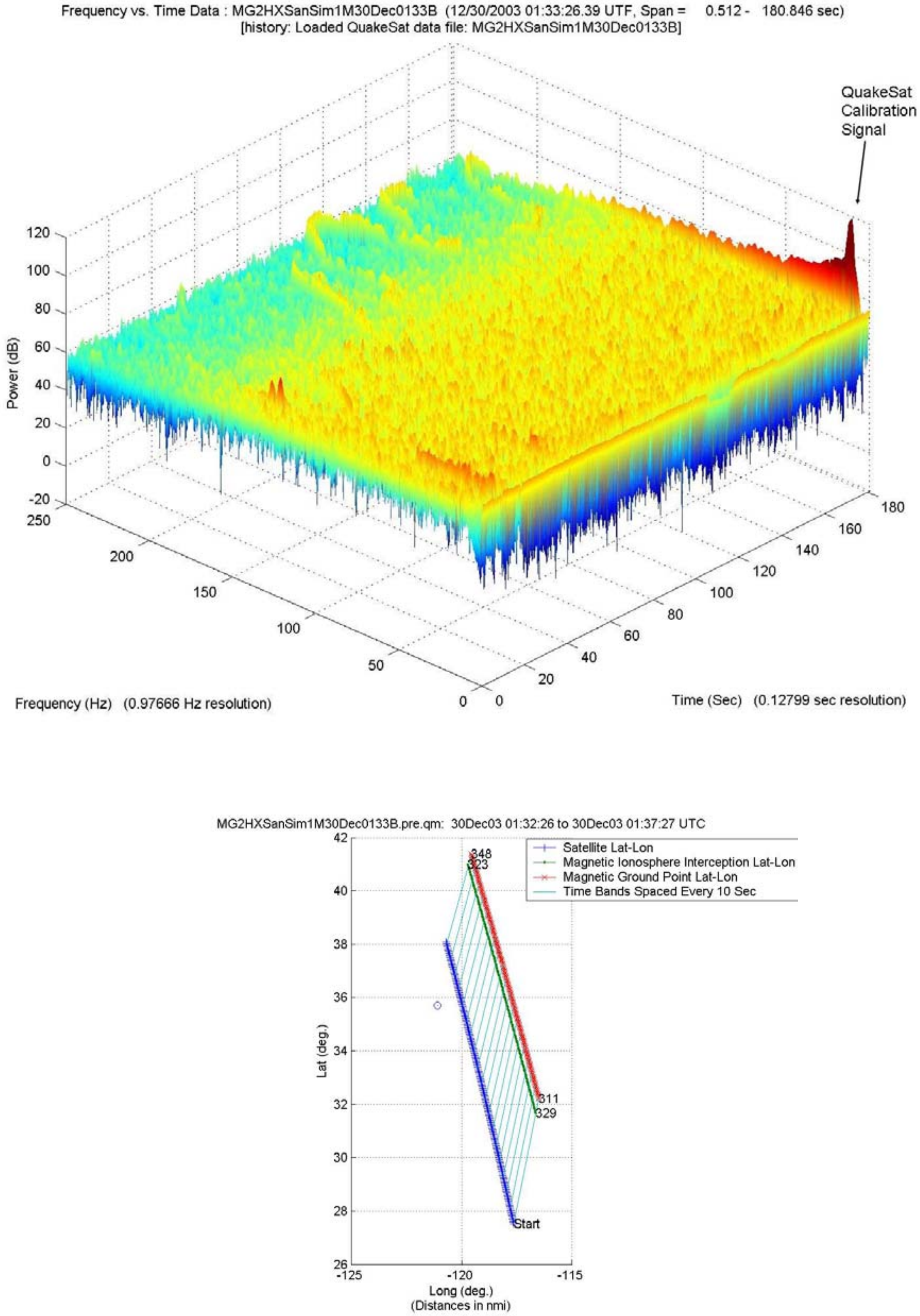

Figure 11 Late afternoon collection over San Simeon (Dec 29 2003)

of the type we believe may be similar to the earthquake signals Cosmos 1809 detected over Spitak-Armenia.

We look forward to applying these lessons to our continuing efforts. QuakeFinder hopes to team with the French DEMETER satellite team, scheduled to launch on June 30th of this year, exactly one year after QuakeSat to further investigate this phenomenon.

In addition, efforts are underway for the preliminary design of QuakeSat 2, a larger, (likely a small microsat) improved version of QuakeSat. Additions include multi-axis magnetometers; reduced satellite noise, increased sensitivity, additional attitude control, higher communication data rate. Launch is still TBD, but likely in early 2006.

SUMMARY
CAN YOU DO SCIENCE FROM A NANOSAT?

Yes, you probably can't answer all your questions on a single nanosat flight, but important insight into the problem and collection of preliminary data can be very important in solving or understanding the complete problem.

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I would also like to thank the small group of individuals on the QuakeSat team (alphabetically): Tom Bleier, Paul Clarke, Jamie Cutler, Louis DeMartini, Clark Dunson, Janine Flagg, Scott Flagg, Lew Franklin, Mary Klenk, Allen Lorenz, Dr. Jeannie Seelbach, Victor Safradin and Eric Tapio, without them the QuakeSat mission would not have been possible.

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For further information on our continuing investigation into this area of science see:

1) www.quakefinder.com
2) www.earthquaketracker.com