ELF Magnetic Field Monitoring of the San Simeon M6.4 quake from both QuakeSat and a Ground Network

Thomas Bleier* CEO QuakeFinder LLC
tbleier@quakefinder.com 250 Cambridge Ave, Palo Alto, Ca. USA 95306 (650) 473-9870
Clark Dunson Data Analyst QuakeFinder LLC
cdunson@quakefinder.com 250 Cambridge Ave, Palo Alto, Ca. USA 95306 (650) 814-4258

Abstract:
This paper addresses a case study of the Dec. 22 2004, M6.4 San Simeon earthquake in California, and compares both space and ground ELF signatures. Preliminary results of the satellite collections showed unique signals prior to and after the San Simeon quake, as well as several other large world-wide quakes. Ground collections were inconclusive since the closest 4 sensors of the available 35 sensors were located more than 60 km and 2 parallel fault traces away from the San Simeon quake epicenter.

1. Introduction

QuakeFinder LLC, in collaboration with Stanford University, launched a 4.5 kg nanosatellite called QuakeSat (Fig 1) into an 840 km circular, sun-synchronous orbit on June 30 2003. In addition to the student teaching goals, the satellite was a prototype for a research satellite to study whether Extremely-Low-Frequency (ELF) magnetic field disturbances occurred before or after large earthquakes. QuakeSat's single-axis search coil magnetometer and ELF receiver had a frequency response of 1-1000 Hz in 4 bands.

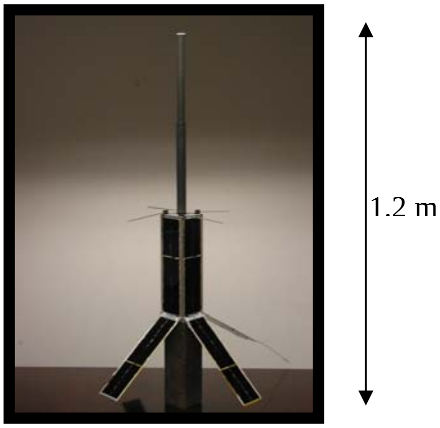

Fig. 1 QuakeSat

The overall data gathering strategy also included a ground component, namely a network of 35 three-axis magnetometer sensors, deployed every 30 km along major faults (e.g. San Andreas) in California. The frequency response of these ELF receivers is 0.1 to 4 Hz and they have an estimated detection radius of 15 km. Both the space and ground-based systems are designed to record time series data, with the objective of determining whether or not earthquake-related ELF signals exist, and if so, to characterize them in both time and frequency being careful to distinguish them from the many other magnetic signals present in space and near the ground.

2. Background:

There have been several reports of ground[1] and satellite-based[2] observations of ELF magnetic field disturbances prior to and after large earthquakes. There is at least one case where near simultaneous observations from ground and satellite collections were made, i.e. Spitak Armenia M 6.9 in 1989.[2] The number of total ELF observations has been small, and after each set of observations was made, there was typically a conclusion that "more data was needed" to prove the statistical significance of the EM signals, and specifically, the ELF disturbances near earthquakes.

During the 1990's there were several significant earthquakes in California (Big Bear, Landers, Northridge, and Hector Mine). Stanford (A. Fraser-Smith) [1] and Berkeley (F. Morrison) had a few ELF/ULF monitors in California (Corralitos, Table Mt., Hollister, Parkfield, and Hayward). None of these appeared to be close enough to the quakes to detect any significant signals, indicating that the detection region of seismogenic electromagnetic signals is small (possibly, a few km depending on magnitude).

3. Ground-Based Collections:

QuakeFinder was formed in 1999 with the specific purpose of conducting simultaneous space and ground observations at ELF frequencies in California to collect more ELF data. The ground strategy was to develop a simple and inexpensive 3-axis magnetometer and ELF receiver, and to deploy the monitors every 30 km along the major faults in California. This part of the project started as an industry-funded educational outreach project in which Stellar Solutions (parent company of QuakeFinder) and the State of California sponsored

35 ELF "kits" that were distributed to physics classes at various high schools, located near major faults. These kits included a 3-axis magnetometer with a sensitivity of 10 pT/root Hz at 1 Hz, and had a bandwidth of 0.5-4 Hz to remove power line hum and Schumann Resonance noise. In 2004, NASA sponsored 20 more sites (upgraded with GPS, air conductivity sensors, and satellite phones). (See Fig. 2). The initial network was installed in Northern and Central California, and the NASA units were deployed in the southern California desert area that coincided with the Keilis-Borok prediction[4] of a large quake in the greater Mojave Desert area during the summer of 2004). (Fig. 3).

Fig. 2 QF 1003N

Fig. 3 QF Ground Network (9/04)

4. Case Study: San Simeon M6.4 quake 12/22/03

On Dec. 22, 2003, a M6.5 quake struck the central California coastal area near Paso Robles and Hearst Castle. The epicenter was approx. 60 km from 3 QuakeFinder sites (Parkfield, Coalinga, and Shandon) and a single Berkeley site (PKD) at Parkfield. These sites were deployed along the major fault (San Andreas), but unfortunately, two faults and 60 km away from the epicenter. This is four times the expected range of the QF sensors. Only minor disturbances were seen in the data from these four sensors. Any earthquake signals, similar to those detected by Fraser-Smith et al, could not be detected, and may have been masked by the diurnal (solar) variations seen on the Berkeley PKD unit.

Fig.4 San Simeon Quake - monitor locations

5. Space-Based Collections

This project also included a space-based ELF collection capability to simultaneously detect and record signals from space along with the ground sensors, discussed above.

QuakeFinder LLC collaborated with Stanford Univ. (including students from Lockheed Martin) in 2001-2003 to build, launch, and operate a 4.5 kg, 1 m long nanosatellite called "QuakeSat". QuakeSat was designed to be an inexpensive, proof-of–concept nanosatellite, which was built with commercial-off-the-shelf parts. This spacecraft has a single axis magnetometer and small E-field dipole antenna. QuakeSat records ELF magnetic field data in the 1-1000 Hz range in 4 bands (1-10 Hz, 10-150 Hz, 130-150 Hz, and 10-1000 Hz.), one band at a time. This choice of bandwidth was influenced by Cosmos 1809 which had detected signals in the 140 Hz channel, and Aureol 3, which had detected similar signals during 1989 and the early 1990's[2,3]. The QuakeSat band was expanded to 10-1000 Hz, and collected raw time series to determine if there were any unique time-series signatures that could lead to more focused collection strategies in future missions. QuakeSat was launched on June 30, 2003, and has been collecting since July 2003.

The spacecraft had successfully collected over 1500 data files until Jan '04 when the unexpected loss of its Li Ion batteries reduced the operational capacity of the mission. Solar panels continued to provide limited power in the dawn-dusk orbit, but reduced power reserves make downloads are more difficult now.

The collection strategy was to collect signals over areas of high earthquake probability by selectively operating the magnetometer as the spacecraft crossed the "target areas". (See Fig 5).

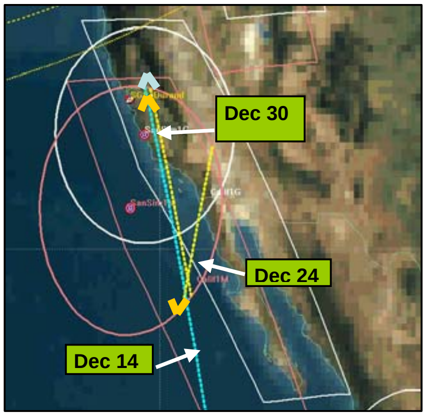

Fig. 5 Target areas with "magnetic offsets"

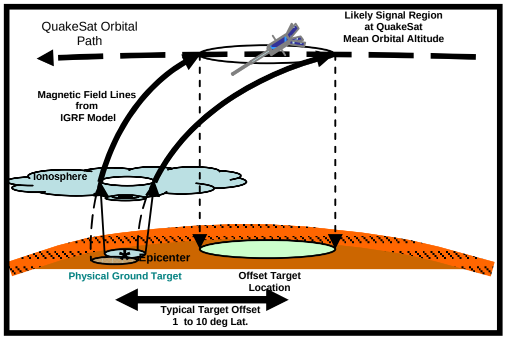

Fig. 6 Magnetic Offset Targeting

Data collections from Cosmos 1809 and Aureol-3 appeared to have a consistent southern offset from the quake epicenters. ELF propagation paths were assumed to follow the magnetic field lines above the ionosphere, and thus the tasking was "offset" to collect earthquake areas (See Fig 5,6).

There have been approximately 2000 collections made to date (Sept 2004), with approximately 6000 "signals" detected. Within that signal set, there were approximately 25 "signal types" identified. The majority of these were self-induced satellite noise (power supplies, battery charge controllers, modem, transmitter, heartbeat, and a 100 Hz CPU generated clock). After these were manually identified and removed, natural signals were also identified (lightning-induced whistlers, polar hiss, elevated noise during the Oct 28-Nov 2 solar storms). The remaining signal set was categorized as "unexplained ELF" signals. Particular interest was given to a series of wideband ELF noise bursts with energy between 10 Hz and 150 Hz, and lasted from 2 sec to 20 sec. See Fig 8.

These ELF bursts are not always present. When they do appear, they can be discriminated from "whistlers" which have a typical "J hook", and are only a few milliseconds wide. (See Fig 9).

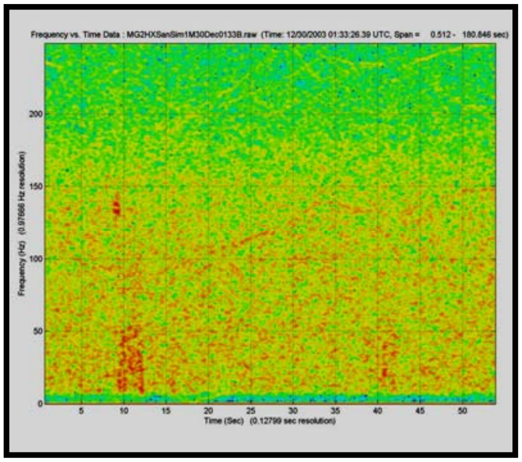

Fig. 8 ELF Burst - San Simeon quake +8 days

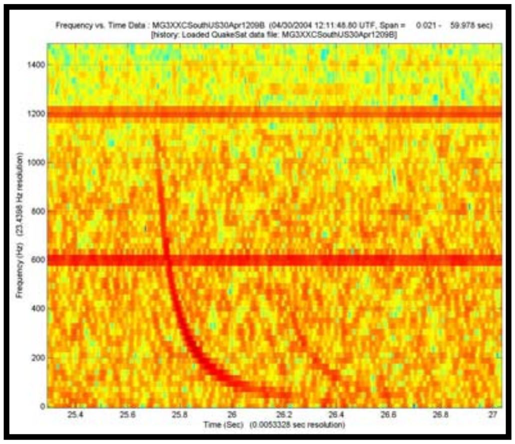

Fig. 9 Lightning-generated whistler 10-1000 Hz

The lightning-generated whistlers also exhibited the typical dispersion effect where higher frequency components arrive at the satellite before the lower frequencies. Fig 8 shows an ELF burst recorded 8 days following the San Simeon quake and also exhibited a slight dispersion, possibly indicating that the signal could have come through the ionosphere. There was no lightning within 2000 km at this time in the US during this collection. These wideband short bursts were observed over a 2 month period prior to San Simeon quake (but not during every pass over the area). We also took several "null sets" of data over the open Pacific at the same northern latitudes and saw none of wideband ELF signatures. The ELF bursts appeared to be sporadic, and even though we did detect similar bursts over several large quake areas, they were not present on every pass over the areas. Figs. 10-13 (10-150 Hz Channel) show similar (and wider) ELF bursts over other large earthquakes in 2003-04.

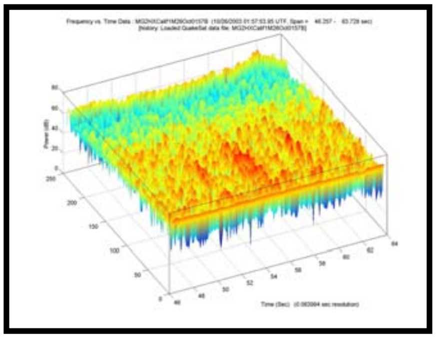

Fig. 10 San Simeon   M6.4   -56 days (prior)

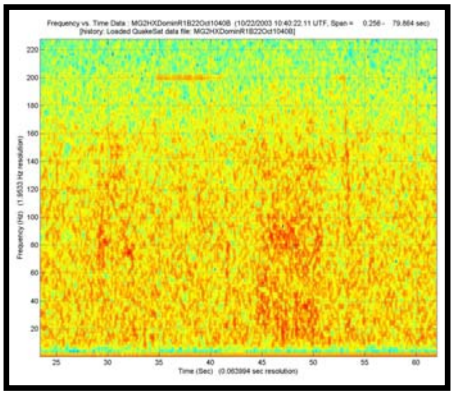

Fig. 11 Dominican Republic M6.5 +31 days

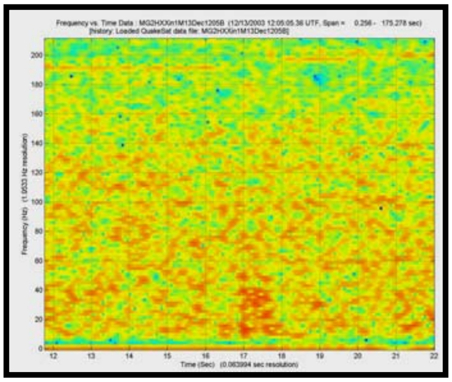

Fig. 12 Xin China M6.0 +12 days

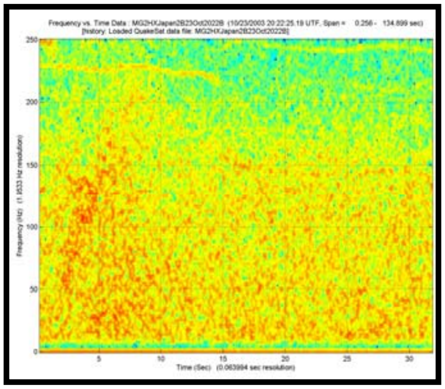

Fig. 13 Honshu Japan M7.0 -8 days

These limited collections do not constitute a comprehensive set of statistics, but one of the main purposes of QuakeSat was to identify unusual signal patterns (frequency and amplitude) over multiple earthquake areas that could be used to create a "matched filter" on future flights.

We are now in the process of analyzing the remaining QuakeSat data with this type of "matched filter" to identify all locations for these ELF bursts. We also plan to analyze DEMETER data to see if these same patterns exist over future quakes using their more sensitive magnetometers.

6. Conclusions:

Ground-based monitors have the advantage of collecting data over limited areas 24 hr/7 days a week, and potentially provide more accurate location capability. However, based on empirical experience with our magnetometers, the sensors must be located within 15 km the epicenter of a large quake (M6+). At this writing, the only large quake (M6.5 San Simeon) that occurred was 60 km from our closest monitoring stations, the epicenter was on a different fault system, and therefore we did not observe any significant signals. QuakeFinder elected to use smaller, less sensitive (and less expensive) ground monitors in order to install more systems thus increasing the probability of being closer to earthquake epicenters.

Satellites may be able to sense unusual patterns (ELF bursts) over a larger set of worldwide quakes and therefore provide some "wide area warning". QuakeSat did detect ELF bursts over 8 earthquake areas in 12 months. These bursts may be unique to earthquake areas, but it is important to collect more data using different and more sensitive instruments such as those on DEMETER and a future QuakeSat II (circa 2007) to confirm these findings.

7. References:

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