

## Feasibility study of using a Small Satellite constellation to forecast, monitor and mitigate natural and man-made disasters in Chile and similar developing countries.

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### ABSTRACT

The humanitarian and economical effects that disasters have on developing countries might be diminished by using a satellite system. Although this capability has not been largely exploited by developing countries, the current trends on small satellite development encourage them to use the new paradigm possibilities. Today Chile, a developing country with high-frequency and diverse-type of disasters, is facing the problem of forecasting, monitoring and mitigating disasters. This work studies the feasibility of using small satellites to perform this activity. The need of ground-based sensor network in combination with satellite constellation for robustness is also analyzed.

### INTRODUCTION

Every place on earth might suffer from different kinds of natural disasters. No matter the degree of development or economical situation, disasters can affect to everyone in equal form. What really makes a difference is how a country or region is prepared to predict, prevent, monitor and react to disasters. Chile is known for being periodically hit by large earthquakes, holding the infamous record of suffering the largest earthquake ever scientifically recorded in history (1960, Valdivia, M 9.5). In recent years two large events have taken place: Tocopilla (2007, Mw 7.7) and Cobquecura (2010, Mw 8.8). The last one generated a large seaquake that destroyed many coastal towns of the southern country. But many other natural disasters have happened during the last decade. To mention a few, droughts, floods and severe snow storms have constantly hit the entire country due to the “El Niño” and “La Niña” climatological phenomena. Chaitén and Llaima volcanoes erupted in 2008 and 2009 respectively and, to finish this abbreviated list, a large fire burned more than 17600 ha (~ 43.500 acres) of Torres del Paine national park in 2011-2012.<sup>1</sup>

It is crucial for developing and developed countries to generate effective ways to prepare for and to face these events, not only for economical reasons but also to avoid human losses. The 2010 seaquake took the life of many people due to the general confusion after the

event and the contradictory data available to take a good decision on whether to declare or not a tsunami alert on the potentially affected areas. Satellite monitoring seems a good alternative to help with the problem. However, due to economical and technological constraints, this solution is not generally considered by developing countries.

The rise of pico- and nano-satellite standards opens an accessible and expedient option for many countries. In addition, the increment on commercially available payload components brings the opportunity of customizing satellites to particular needs, as well as arranging constellations with distributed remote sensing capabilities.

This paper is organized as follows. We first present a summary of disasters in Chile. Then we comment on satellite technology that can be used to sense most of the reviewed disasters. We provide examples of how CubeSats can be used to retrieve some important disaster critical variables. We finalize with a discussion about constellation of pico- and femto-satellites and the conclusion of our work.

### SUMMARY OF DISASTERS IN CHILE

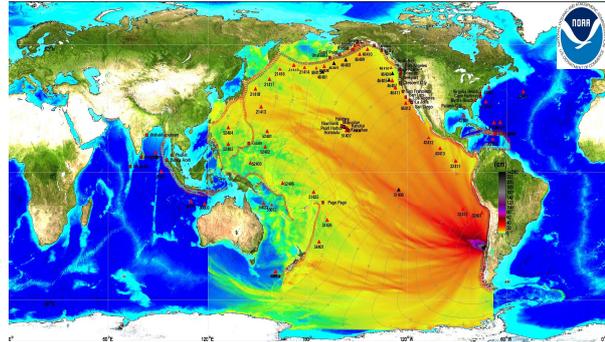
The location and the characteristics of its territory make of Chile a country with a long history of natural disasters. The more frequents are: earthquakes and

seaquakes; drought and intense and concentrated precipitations, which produce floods and landslides; and volcanic eruptions. The earthquakes and tsunamis are the most relevant in terms of casualties and economic losses (see Tables 1, 2, and 3). The hydro-meteorological events have also a large impact over the economy of the country based mainly on its high frequency of occurrence, although the casualties are much less than those produced by earthquakes. There are also other natural disasters important for the life and economy of Chile however their impact and frequency has less effects compared with earthquakes and hydro-meteorological events.

### **Earthquakes and Seaquakes**

Chile is one of the most seismically active places in the world. The entire coast of Chile (about 4000 km) is above the trench formed by the subduction of the Nazca and Pacific plates, fact that guarantees the occurrence of powerful and continuous events over Chile. Each year many earthquakes occur at the boundary where the plates meet or within a plate, and occasionally these events can be extremely large.

The history of Chile is full of powerful earthquakes and seaquakes. A magnitude 8.5 subduction earthquake was well recorded in the northern part of the country, in 1922. In 1960, the south part of Chile experienced a 9.5 magnitude earthquake, the most violent earthquake ever recorded. This earthquake also generated a seaquake (see Figure 1) that put underwater part of the city of Valdivia. That part of the city remains underwater until present days<sup>2</sup>. The effects of the tsunami were felt in places as remote as Hawaii and Japan, where 61 and 140 people died, respectively, due to the wave generated in Chile<sup>3</sup>. In 1985, a magnitude 8.5 earthquake hit the central part of Chile devastating Santiago and many other cities. The last large event struck Chile on February 27, 2010. The magnitude 8.8 earthquake was the fifth strongest earthquake ever recorded. More than 12.5 million people experienced severe or violent shaking due to the earthquake or were affected by the resulting tsunami. The Chilean government has reported over 500 deaths by the earthquake/tsunami. The subsequent tsunami was responsible for 124 of the total deaths. Direct economic damage is close to US\$30 billion, or 18 percent of Chile's annual production<sup>4</sup>.



**Figure 1: Forecasting of the propagation of seaquake caused by Chile's 2010 Earthquake (Cobquecura, Mw 8.8, 2010). A darker zone means a larger wave (NOAA / PMEL / Center for Tsunami Research, Source: <http://nctr.pmel.noaa.gov/>).**

### **Hydro- meteorological Events**

The large extension of Chile and its different climates produces a large variety of extreme meteorological events. Many of the hydro-meteorological disasters in Chile are related to rain, storm surges and snow. The precipitations and their associated natural process are produced in winter time where their intensity and frequency are higher almost along the whole territory. Intense and concentrated rainfall frequently triggers a set of processes, such as: overflows resulting in floods, flooding, landslides and mudslides. In the coastal areas of Chile surges can be generated by storms in the Pacific Ocean. In the mountain areas is common to get extreme snow storms which produces avalanches, town isolation and animal deaths. All these processes can be enhanced by the "Niño" phenomenon.

Although there are many events to report such as: the floods and mudslides of 1984 and 1992 in Santiago, the flood in San Pedro de Atacama Area in 2001, The flood and landslide this past April (2012) in Punta Arenas, we are going to present data from the 2006 event located in the south of Chile. The year 2006 was an especially rainy year in central Chile. In the city of Concepción the peak of rainfall amount within the accumulated 24 hours window had the value of 106.6 millimeters, resulting in severe swollen rivers and flooding. It was reported 296,397 people affected by the storm. 51,206 people lost their houses and 3,158 needed a shelter during the storm period. 33,077 houses suffered minor damages, 2,334 houses suffered major damages and 600 homes were destroyed<sup>5</sup>. In the town of Chiguayante 10 fatalities were reported, while two people died in the city of Chillan. This has been one of the most important events in the Region in recent decades but has not been the most intense<sup>6</sup>.

### Volcanic Activity and Fires

Chile has more than 2,000 volcanoes, with about 500 considered geologically active and about 60 with eruptive record, including two of the most active in South America: Villarrica and Llaima. 50% of the continental territory is exposed in some way to the effects of volcanic eruptions. Energy infrastructure, communications and key industries to the national economy present high vulnerabilities to volcano eruptions<sup>7</sup>.

During the last three decades, the volcanic activity in Chile, although it has existed, has not reached the dangerous levels of the past. This does not mean that the danger is less; in 1971 the eruption of Villarrica volcano generated a mudflow that buried the town of Coñaripe, killing more than 20 people (not including the missing). In 2008 the Llaima volcano eruption maintained a slow and lengthy process which facilitated the evacuation of nearby villages. Instead, the Chaiten volcano eruption in May 2008 was sudden and explosive that forced the evacuation of the city within hours. 500 hectares of native forest were devastated by the eruption of the Chaiten volcano. Relocation of the village would cost \$300 M, for this reason the government ruled out this option.

Some of the effects produced by the eruption of a volcano are similar to those produced by a wild fire (see Figure 2). High temperatures in summer produce big fires in areas with large forests. This risk increases with the climatic phenomenon called la Niña. In summer 2011-2012, a large fire struck “Torres del Paine” national park causing a huge damage in the ecosystem and also in the tourism.



**Figure 2:** Ash cloud emitted by Chaiten volcano covering part of Argentina’s territory. Picture taken by MODIS satellite, May, 2008 (EOSDIS/NASA, Source: <http://rapidfire.sci.gsfc.nasa.gov/>)

**Table 1: Disaster types and number of victims in Chile for the period 1900-2009. (Source: EM-DAT, 2010).**

Disaster type	Victims number	%
Earthquake and Tsunami	54,373	97.03
Floods	1,040	1.86
Storms	267	0.48
Landslides	229	0.41
Volcanoes	110	0.20
Wild fires	10	0.02
Extreme Temperatures	8	0.01
Drought	0	0.00
TOTAL	56,037	100.00

**Table 2: Main natural disasters in Chile for the period 1900-2009 based on the number of people affected. (Source: EM-DAT, 2010. ONEMI, 2009).**

Rank	Disaster	Date	People Affected
1	Earthquake and Tsunami	02/27/2010	2,671,556
2	Earthquake	07/08/1971	2,348,973
3	Earthquake and Tsunami	05/22/1960	2,003,000
4	Earthquake	03/03/1985	979,792
5	Flood	07/1965	375,000
6	Storm	07/1984	242,345
7	Flood	05/24/2002	221,842
8	Flood	06/12/2000	139,667
9	Drought	08/1968	120,000
10	Flood	07/17/1987	116,364

**Table 3: Main natural disasters in Chile for the period 1900-2009 based on economical impact. (Source: EM-DAT, 2010).**

Rank	Disaster	Date	Thousand of USD
1	Earthquake and Tsunami	02/27/2010	30,000,000
2	Earthquake	03/03/1985	1,500,000
3	Earthquake	01/24/1939	920,000
4	Earthquake and Tsunami	05/22/1960	550,000
5	Earthquake	95/06/1953	500,000
6	Wild fire	01/02/1999	280,000
7	Earthquake	07/08/1971	236,400
8	Earthquake	03/28/1965	235,000
9	Drought	01/1991	200,000
10	Flood	05/24/2002	200,000

## SPACE TECHNOLOGY FOR PREVENTION, MONITORING AND MITIGATION OF DISASTER EFFECTS

### *Remote imaging*

Remote imaging is the most used way to obtain information about a disaster but its application is related to monitoring more than any other action (e.g. Figure 3). Without any other kind of additional sensor, remote imaging only serves to see, in most of the cases, the effects of a disaster. There are many examples for this: Damage after an earthquake or/and a seaquake, flooded and snow covered areas after a storm, movement of an ash cloud after a volcano eruption, deforestation, etc. There are only a few examples in which imaging enables the capacity to prevent disaster, as for example, big storms and tornadoes early formation and their possible consequences on land near to the path of this phenomena.

This feature also suffers of hard constraints to be efficiently applicable. The first one is the resolution required by the particular application and the second one is related to inherent technology restrictions: Imaging in visible spectra cannot be used at night and when the target objective is not clear (cloud, ash, dust storms, etc).

Imaging resolution requirements have been stated to be between tens of meters to one kilometer<sup>9</sup> in order to be used as an effective disaster monitoring tool. For nano-satellites this is commonly an easy requirement to achieve. There are many examples of this, but the closest example for Chile is the SSOT satellite, the third LEO satellite of Chile, that has a camera with resolution of 1.54 meters in panchromatic and 5.4 meters in multispectral band<sup>10</sup>

### *Radars*

The second problem of remote imaging can be solved using radars (like SAR) and LiDARs to extend the capabilities to anytime any weather condition imaging and also to add a third dimension, height of the object or area sensed, which turns this technology to be applied most for topographic applications. One obvious example of application for this very useful feature is sea level monitoring and the subsequent early seaquake detection.



**Figure 3: Chuquicamata copper mine. First picture taken by Chilean satellite SSOT (Sistema satelital de observación terrestre), December, 19, 2011. (SSOT/GOS/FACH, Source: <http://www.fach.cl>).**

The requirements for this kind of technologies are more complex and hard to implement even for nano-satellites. SAR requires high power in order to achieve a good performance. Ultra-capacitors can be an alternative to use SAR (or any other high power device) in very shorts amounts of time<sup>11</sup>. LiDAR are even more complicated because they also need high power and additionally need cooling systems to work with photodiodes in noisy environments. Temperatures of tens of Kelvin are needed to operate this technology and the most commonly used element to do that are Stirling cooling engines. A new approach using most modern Peltiers can enable the use of LiDAR in very small spacecrafts. Optimization of heat distribution along the satellite is also relevant to keep the efficiency of those devices<sup>45</sup>.

### *IR and bolometers*

If the capability to observe other spectra is added, space technology expands its capacity to prevent and predict events in many other areas than meteorology. In addition to the clear application of local and global weather forecasting, different IR subbands, in particular, the 3 - 4  $\mu\text{m}$  band, could be used to sense the radiation from the earth surface and then estimate the temperature of land, enabling the capability to prevent possible areas in which a fire can take place (hot spots) and sense the behavior of fires once they started. BIRD nano-satellite is a very good example of this technology, achieving resolutions of 0.1 K<sup>12</sup>. Also, recent research opens the possibility to predict low depth earthquakes near to ocean measuring the quantity of water vapor produced by heat irradiated due to the collision of tectonic plates<sup>13</sup>. Aerosol sensing is also possible (Despite this is a no disaster precursor) with IR

band together with UV band, this last one is very important to sense ozone and then, to monitor the ozone layer hole and its effect in the land that it covers, mainly, ice melting of Antarctica.

Similarly to LiDAR, infrared sensors require high power and low temperatures to work with reasonable resolution. It might be used a combination of subbands and terrestrial post processing to achieve a similar performance without very high power, size and thermal requirements. One alternative to infrared sensors is the microbolometer which performances poorer but its requirements are much less strict.

#### *Other sensors and concerns*

Ultra- and extremely-low frequencies magnetic sensors is a proven technology carried by nano-satellites like Quakesat<sup>14</sup> for earthquake precursor detection. This sensor technology is mature and can be combined with heat flux/water vapor experiments to achieve more accurate predictions of large events.

With the use of high resolution and narrow field sensors, more complex and accurate attitude determination and control systems are needed. Passive systems like magnetorquers and hysteresis rods cannot be enough for all applications, and therefore, active systems of higher power and size requirements are needed for more complex measurements. Star trackers, reaction wheels, GPS and propulsion systems form a complete suite to determine and control the attitude of a satellite with a few tenths of degrees<sup>15</sup>.

A very common effect of a disaster is the collapse of terrestrial communications links either by rupture of physical lines or due to excessive calls. In fact, during the February 27 of 2010 earthquake the communication system in Chile collapsed even for the emergency team<sup>16</sup>. All service providers, both landline and wireless services, experienced extensive setbacks due to commercial power outages, unanchored equipment failures, building failures, and loss of reserve power in most distributed network facilities. For Chile and other developing countries is imperative a reliable backup or emergency communication system to react fast and properly to disasters. Nano- and pico-satellites could be useful to achieve this goal using proven transmitters in several missions. The main constraint is not related to hardware, but it is related to the ephemeral coverage that these Low orbit satellites have with a fixed ground station. Small satellites constellation and formation arise as feasible solutions, but with this also appears the enormous difficulties to deploy, coordinate and operate a large number of spacecrafts.

## **CUBESAT TECHNOLOGY FOR DISASTERS**

In this section is explored the CubeSat capabilities to measure some of the variables of interest for monitoring as well as for predicting disasters in Chile. Examples of developed or under development CubeSats to measure some of the variables of interest are presented in Table 4. We focus in *Imaging* for all kind of disasters, *Atmospheric Temperature and Humidity*, *Land and Sea Temperature* for weather as well as a possible precursor of earthquakes<sup>13</sup>. *Magnetic Filed* has also been pointed as a possible precursor of earthquake so that its feasibility is also analyzed. *Ocean altimetry* and *snow and ice cover* measurements are also analyzed. The analysis of this section is based on the work of Selva and Krejci, 2012<sup>15</sup>.

The CubeSat standard was created by collaboration between Calpoly and Stanford. A (1U) CubeSat measures 10x10x10 cm<sup>3</sup> and shall weigh no more than 1.33kg. Power consumption does not exceed a few Watts, and available data rates cannot overcome 1Mbps. CubeSats are designed, built, tested, and launched by universities at a price between \$50,000 and \$200,000. Some CubeSat payloads include GNSS receivers, CCD cameras, etc. Extended options (2U, 3U and 6U<sup>11,38</sup>) of CubeSats are also available.

#### *Imaging*

Many CubeSats have been capable of taking photos of the earth's surface but with less resolution<sup>17</sup> despite CMOS imaging sensors have grown in pixel density reaching resolutions as high as 16 MP. The small focal length distance achievable in very small satellites is the main constraint for earth imaging, problem that can be solved with solutions like PRISM, deployable telescope imager<sup>18</sup>. For pico-satellites, CubeSats in particular, this is a more challenging task and needs, commonly, the use of a larger than 1U CubeSat as MISC suite proposed by Pumpkin Inc.<sup>19</sup> Also the technology developed and implemented in the Lytro camera might offer less attitude control of CubeSats to take a good image. Since this technology allows to changing the focus of the image via software after the image is taken.

Another important constraint for pico-satellites is the low data rates of communication link to download this valuable information.

#### *Atmospheric temperature and humidity fields*

CanX-2 performs water vapor total column measurements in the 1.4 mm spectral line. On-orbit calibration is done actively, through use of five different infrared lasers, and a calibrated standard illumination source<sup>20</sup>.

**Table 4: Example of CubeSats**

CubeSat	Description
QuakeSat	AC magnetometer. Ultra low frequency (ULF) magnetic signals from large (Richter > 6) earthquakes <sup>14</sup>
CanX-2	Atmospheric spectrometer, and GNSS receiver in occultation geometry. 1-km horizontal resolution tropospheric CO <sub>2</sub> total column. Atmospheric humidity and total electron content <sup>39</sup>
Micromas	mm-wave multi-channel radiometer. Hyperspectral microwave atmospheric sounding (vertical profiles of atmospheric temperature and humidity) <sup>40</sup>
Cloud CubeSat	VIS camera NIR camera Polarimeter.. Aerosol and cloud properties <sup>41</sup>
Aalto-1	5–10 nm, 6–20 channel imaging VNIR Fabry–Perot interferometer spectrometer. Aerosol and cloud properties, vegetation measurements, fire monitoring, water monitoring, land use, atmospheric chemistry <sup>42</sup>

Micromas features a hyperspectral millimeter wave atmospheric sounder with 4 channels near the 118 GHz O<sub>2</sub> rotational feature, and 4 channels near the 183 GHz water rotational feature<sup>42</sup>. The combination of these eight channels allows the retrieval of 1 km vertical profiles of atmospheric temperature and humidity with an expected rms error on the order of 1–2 K for temperature and 10–30% for humidity.

#### *Cloud properties, liquid water, and precipitation*

The Cloud CubeSat will provide measurements of cloud particle size and optical thickness. Polarimetric or multi-angular measurements such as the ones taken by POLDER or APS are particularly important to obtain information about cloud particle size, shape, and composition. For instance, multi-angular measurements are more effective than multi-polarization measurements to infer information about cloud particle shape. In particular multi-angular and multi-polarization can also be used to estimate aerosols, however in this case multi-polarization measurements are more effective for aerosol shape estimation.

On the other hand, passive microwave measurements have successfully been used to recover liquid water and precipitation inside clouds. Thus, Micromas will also provide some useful precipitation measurements. However, the accuracy of this measurement is not as high as the one obtained with active instruments, i.e., cloud profiling and rain radars using the 94 GHz band. Furthermore, CanX-2 features a GNSS receiver in occultation mode<sup>21</sup>. Part of the signal received by GNSS occultation receivers is due to hydrometeors and

therefore at least theoretically, retrievals of cloud liquid water should be possible using CanX- 2 data<sup>22</sup>.

#### *Surface temperature*

Land and ocean temperature measurements might be used to predict earthquake since some anomalous temperatures have been measured nearby the earthquake epicenters even days before the occurrence of a big event. Land temperature measurements can be used to predict and monitor wild fires; nevertheless a high resolution imaging device is required to perform this activity.

Although no CubeSats have performed surface temperature measurements, current uncooled or thermoelectrically cooled microbolometers can measure radiance with reasonable accuracy at medium spatial resolution in the desired spectral regions (8–12 μm)<sup>23,24</sup>.

An alternative approach to measure surface temperature is to use a multispectral or hyperspectral microwave passive sounding instrument that includes transparent channels, e.g., AMSU<sup>25</sup>. A similar approach could be utilized with a CubeSat like Micromas, though the utility of this measurement has yet to be demonstrated.

Ocean surface temperature is a key parameter to study ocean thermohaline circulation. The techniques for measuring ocean surface temperatures are very similar to those mentioned for land surface temperature. High radiometric accuracy passive measurements in a transparent band of the thermal infrared region of the spectrum are required. Therefore, both microbolometers, and to a lesser extent millimeter wave sounders appear as viable options for retrieval of ocean surface temperature from CubeSats.

#### *Ocean Altimetry*

Ocean altimetry measurements with accuracies on the order of a few centimeters provide useful information for ocean current determination, sea level height, as well as bathymetry. Typically, ocean altimetry has been accomplished through real aperture radar altimeter such as ERS/RA, Envisat/RA-2<sup>26</sup>, or Topex/Poseidon<sup>27</sup>.

Although there has been some effort from industry to miniaturize Ka-band radar altimeters<sup>28</sup>, the miniaturization accomplished so far is not yet compatible with the CubeSat standard. So far the option to explore is the use of reflected GNSS signals as exposed before for the case of land topography, with the additional benefit that GNSS reflectometry has better sensitivity over ocean than over land because the ocean is dark in the microwave regions<sup>29</sup>. The

expected accuracies would be on the order of 10 cm, far from the 2–3 cm achieved by state-of-the-art altimeters<sup>29</sup>. Therefore, these sensors could be used for coarse spatial resolution measurements of sea level height, but probably not for finer measurements, unless the loss of accuracy is compensated by averaging out many samples in time, coming from a populated network of sensors. Another interesting possibility would be to use a disaggregation scheme in which the coarse frequent measurement from the CubeSat constellation is combined with a sparse, higher spatial resolution measurement to yield a data product with relatively good temporal and spatial resolution, similarly to what has been proposed for the SMOS mission<sup>35</sup>. A strategy based on a disaggregation scheme can be used in other applications as well: CubeSat-based architectures provide frequent low spatial resolution data, which can be complementary to sparser high resolution dataset achieved by larger sensors.

#### *Snow and Sea ice*

No CubeSats have been found that measure snow cover. Although SAR is discarded, there is no apparent reason to discard VNIR spectrometers, or Ka band and millimeter wave passive radiometers, albeit the lower spatial resolution.

Similarly to snow cover, sea ice cover was traditionally measured using passive microwave radiometry. In addition, the utility of millimeter wave measurements up to 157 GHz for retrieval of ice cover was demonstrated on an airborne instrument<sup>30</sup>. Active measurements using SAR have also been proposed and explored. Therefore, as in the case of snow cover, it would in principle be possible to do remote sensing of sea ice from space with CubeSats using millimeter-wave radiometers.

#### *Magnetic field*

Current magnetometers are small and low in power and thus a CubeSat configuration could be designed. A more modern approach is a cluster of satellites flying in formation like ESA's SWARM<sup>31</sup>. In this configuration, satellites flying side by side allow correction of some sources of error. The simplest option for a CubeSat-based measurement of the Earth's magnetic field would be to use currently available flux gate magnetometers like the one used by the Ørsted mission<sup>32</sup>. However, this would require: (1) along boom to separate the magnetometer from the spacecraft; (2) a high accuracy attitude determination and control system.

## SWARM AND CONSTELLATIONS OF CUBESATS

Rapid development and low costs of production make CubeSats a very suitable option for constellations or formations, but not for all the imaginable purposes due to the inherent limitations of the standard.

Low earth orbit, the most frequent orbit for CubeSats, gives only two or, in the best case, three passes per day with connection times (between the satellite and the ground station) of 12 to 15 minutes per pass, again in the best scenario. This is a serious constraint if CubeSats want to be used for disaster monitoring that requires revisiting times of minutes like fire propagation monitoring and earthquake/seaquake damage estimation, even revisiting times of the order of few hours is hard to accomplish. One option to solve this problem is to launch as many CubeSats as needed to achieve a full coverage of the target territory. If we assume that this is a "good" solution, another problem needs to be solved which is related to the distribution of the satellites in space. Launching a bunch of spacecrafts means that you must have a very good attitude control and determination system to maintain the constellation with determined shape, if the application requires it.

On the other hand, a reliable inter-satellite communication system must be implemented to take full advantage of what constellations of CubeSats can offer. There are efforts to adapt the physical layer and the MAC sublayer of the 802.11 IEEE protocol in order to make it usable in space<sup>33</sup>.

Smaller satellites are natural candidates to operate in a swarm mode. PCBsat<sup>34</sup> is a paradigm in which many COTS elements are integrated to a single PCB (PC104 standard) creating a very small and reduced capabilities satellite. Another paradigm is creating a Satellite-on-a-Chip like Cornell's Sprite which first prototype was a satellite on a PCB in a 3.8 by 3.8 cm area, being reduced later to a complete system in a chip of 1 cm by 1 cm<sup>35</sup>. It is clear that the capabilities of this femto-sats (< 1kg) are very reduced: short communication ranges and low data rates, low energy generation and storage (low solar cell density and very small sized batteries) and antenna integration problems (more for satellite-on-a-chip) but this disadvantages are compensated by the very low costs of this devices: USD \$1000 for Satellites-on-a-chip and USD \$300 for PCBsats<sup>35</sup>.

Using constellations or swarms of small satellites will enable the possibility to sense variables like temperature, pressure, humidity, etc. in an ad hoc sensor network fashion, allowing the generation of dynamic 3D maps of in situ measurements.

Communications is also an obvious task that can be accomplished by groups of spacecrafts. There are notable examples like the Inmarsat and the Globalstar satellite network, but their complexity and the very high costs make them unable to replicate by developing countries with a non-mature space technology field. Small satellites could provide communication links not only in emergency situations but also could serve to connect rural zones in which ground or cellular networks are difficult to implement due to the geography limitations or excessive costs.

Imaging is another area in which having more than a single satellite could be beneficial. Taking images of a same place but from different angles enables the possibility to create 3D maps of the zone that can be used for many purposes.

Self-reconfigurable space systems can be potentially achieved by exploiting a group of femto-satellites. Research in the field of robotics<sup>42</sup> is showing how self-reconfigurable systems have the capability to adapt function by re-organizing the topology and form of modular systems. So, a satellite can be conceived as a group of modules with the capability to adapt form and function in space.<sup>43</sup>

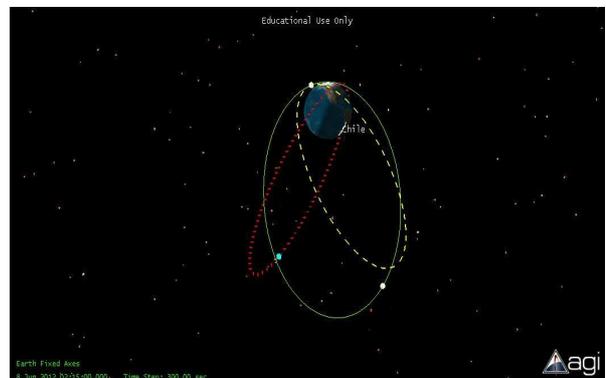
## DISCUSSION

It was clear from the information stated in the summary of catastrophes section that the most important catastrophic events in Chile are the earthquakes both in lives as well as economic damage. The second most important disaster type is that of hydro-meteorological nature although its impact in terms of losses of lives and infrastructure is order of magnitude less than those produced by earthquakes/seaquakes. Recent evidence shows possible relations between Earthquake and geophysical anomalies of total electron content, magnetic field, water vapor and surface temperature. Some of these variables might be used as precursor of earthquakes. Although the accuracy of those possible precursors is still debatable, it is of high relevance for Chile to be able to properly study the validity of these hypotheses. Since a constellation of CubeSats (pico- or nano- satellites) should be used to properly perform this analysis the cost of a project like this, might be prohibited for a developing country as Chile. However, many other countries along the orbit might also take advantage of the constellation; therefore a collaborative approach could be followed. In particular, the new paradigm of a fully open collaborative philosophy<sup>44</sup>, that offers even more advantages than that given by the COST approach, since production can be shared for different countries by using digital building process reducing production times due to fast collaboration between the parties.

A simple example of a possible constellation is the one that uses Molinya-type orbit with three spacecrafts. As can be seen in Figure 4, this formation takes full advantage of Chilean geography. A satellite of this group can perform measurements above the entire Chilean territory two times per pass. This arrangement permits 100% coverage using the ground station located at Santiago's downtown, Chile. The main disadvantage is the larger apogee (~ 26000 km) that makes unfeasible, for example, remote imaging with satellites and also makes difficult to establish high speed link communication. The challenge, therefore, is to find a feasible experiment that could be done with all these constraints.



(a)



(b)

**Figure 4: Constellation formed by three spacecrafts each one following a Molinya-type orbit above Chilean territory. (a) 2D view (b) 3D view.**

## CONCLUSION

This work presents a summary of what might be done to study disasters in Chile and in similar countries. Remote sensing techniques are suggested to study possible precursors of earthquakes. This study might be conducted in a collaborative manner since it is likely that a constellation would be needed. Some of the

variables (e.g. water vapor) to study might be useful for the study of other kind of disasters along the globe. Technology of CubeSats seems also feasible for seaquake monitoring.

### Acknowledgments

We would like to thank to the Faculty of Physical and Mathematical Sciences at the University of Chile for the full support of this work.

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