Studying the Ionosphere with Langmuir Probes with an Application to Seismic Monitoring

Final Report, ASEN 5168: Remote Sensing

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ABSTRACT

It has been detected that there are distinct ionospheric anomalies located over areas of seismic activity. There is supporting evidence that electromagnetic emissions propagate from the ground causing these disturbances and other such phenomena such as earthquake lights and magnetic aberrations. A Langmuir probe instrument is proposed to fly within the inonosphere and actively detect total electron count and plasma temperature. The instrument has ample flight heritage on sounding rockets and a handful of missions in orbit allowing for high confidence in performance. Building the instrument would cost an estimated 16.3 million dollars and contain a mass of 39 kilograms. A near circular orbit ranging from 200-500 kilometers at an inclination angle of 50˚ is required. The results would be correlated with seismic activity and other instruments studying in similar areas. The results will determine if ionospheric monitoring is a reliable and accurate way to predict seismic activity. The lessons learned will be used to develop the next generation satellite which will continue this research to a stronger degree.

Nomenclature

DEMETER	=	Detection of Electro-Magnetic Emission Transmitted from Earthquake Regions (satellite)
EOL	=	End of Life
BOL	=	Beginning of Life
TEC	=	Total Electron Count

I. Introduction / Background

Earthquakes are natural phenomenon which has baffled human kind for thousands of years. The human race has used both mythical and scientific rationales to predict and understand the cause for these ground tremors. Although at the present time there is a much better understanding as to the cause of earthquakes, the ability to predict when and where a severe earthquake will occur is still not possible. To add to the complexity of these events, other phenomena have been known to compliment earthquakes such as magnetic disturbances and aurora borealis. In addition, "earthquake lights" (characterized as luminous glows lasting several seconds) have been periodically recorded dating back to ancient Greek writings and were first captured on camera during the Japaneese Matsushiro earthquake of 1965. Figure 1 shows the intensity and beauty of this effect. Several hypotheses have been developed to determine the cause of this occurrence however the lack of scientific data has kept the debate unresolved. Extensive studies have been performed to measure aberrations within the ionosphere and magnetosphere to determine the possible causes for these effects. The results show a buildup of electromagnetic radiation over localized regions in the ELF/VLF/LF ranges. There are hundreds of papers/studies which measure this phenomenon. Of particular interest are the data collected by the DEMETER satellite (Detection of Electro-Magnetic Emission Transmitted from Earthquake

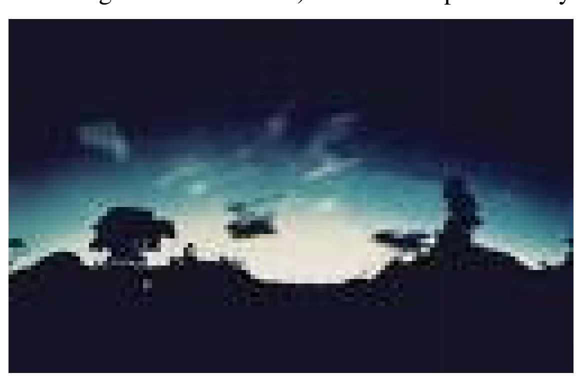


Figure 1: Earth Quake Lights, Japan

Regions), a French campaign launched in 2004. The satellite had a package of low frequency detectors, an ionospheric instrument package and a high precision magnetometer. The data analysis shows evidence that there is a measurable increase in low frequency electromagnetic emissions over long periods of time near earthquake hotspots. Several earthquakes which have occurred during the DEMETER mission have been successfully identified as regions of high level of activity over the course of an earthquake period[1 2]. In addition, several statistical studies performed on a magnetometer located in close proximity to an 8.0 (Richter scale) earthquake off the cost of Guam in 1993. The study showed that there was a significant magnetic disturbance that built up in the weeks prior to the earthquake and that the data suggests that the anomalies were not related to disturbances occurring within the geomagnetic system[3]. The understanding for the electromagnetic emission phenomenon is becoming better understood. A recent a study performed by Friedemann Freund of San Jose State University made a discovery that rocks when stressed are able to hold an electric potential by adapting variable electro-conductivity[4]. This is caused by the breakdown bonds between atoms liberating p-holes. Although the measured electric potential in stressed rock samples is extremely small, the large stresses and the shear size of earth's crust may be powerful enough to interfere with the ionosphere and localized magnetic field and possibly explaining the "earthquake lights" phenomenon recorded over the last thousands of years.

Although the idea that an earthquake can be identified by measuring the changes in low frequency electromagnetic emissions, there are significant issues which need to be identified before an accurate prediction can be determined. Perhaps the largest issue is that the ionosphere and magnetosphere are a highly dynamic system caused by terrestrial weather and Van Allen radiation belt irregularities and solar storms. This causes noise within the measurements which quickly saturates the range of the detectors. As a result of this, to the authors knowledge there has yet to be a successful prediction of an earthquake via electromagnetic phenomenon but only post analysis results taking long periods of time to compile. In fact, all of the studies relating earthquakes to abnormal electromagnetic emissions have been after-the-fact and would have likely remained unanalyzed if not for the seismic data. One final note is that the measured regions of abnormal electromagnetic emissions have had a tendency to be offset from the earthquake epicenter causing additional uncertainty in prediction models. This is likely due to errors in measurement, noise and that high regions of tectonic stress are not necessarily coupled with an earthquake epicenter.

From this knowledge, it is proposed that the work performed by the DEMETER satellite be enhanced by looking at the long-duration effects on the ionosphere which are caused by these electromagnetic earthquake anomalies. The goal is to quantify the effects of earthquake-related electromagnetic emissions on the ionosphere. This is done by using the Langmuir probe concept to actively measure plasma temperature and density within the satellite orbit.

II. The Plasma Physics Connection & Langmuir Probe Theory

Ionospheric Science

The ionosphere is a large region of the upper atmosphere ranging from 100 to 1000km and contains atoms mainly consisting of O_2, N_2 and O. This layer is known to be very energetic as these atoms absorb solar radiation causing them to become ionized. As a result the atoms transition into the plasma state (ons and free elections) and become susceptible to electromagnetic fields. The ionosphere is also contained at the bottom of the magnetosphere which has a further effect on energizing the particles when trapped radiation is brought down the magnetic lines. Finally the speed of the atoms (near escape velocity) adds to the energy levels of the particles upon collisions. This layer of the atmosphere is very sensitive to aberrations seen during solar storms, and seasonal changes causing it to be not well understood[5]. In addition several known occurrences exist such as a stronger concentration of ionization at the magnetic equator in the region of interest which is coupled with wind patterns/trends. It has been observed that earthquake phenomenon in addition has an effect on the activity within the ionosphere. As a study performed by Ruzhin using radio waves propagation noticed specific trends which occurred: "*Before separate low-latitude earthquakes with magnitudes of M>5.5 a steady (5-10 days prior to event) ionosphere modification at and above the main peak looking like funnel-shaped 10-20 % reduction of the*

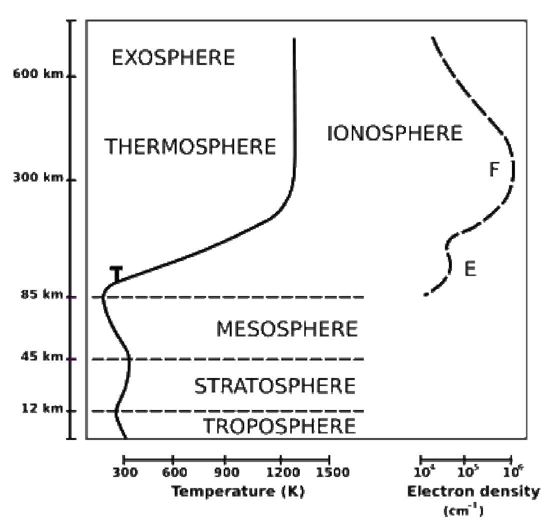


Figure 2: Atmospheric Layout

electron density in comparison with an ambient background level and simulated values was observed[6].” Other studies have used GPS signals to find waves of plasma particles over earthquake regions. *“The greatest plasma frequency in the atmosphere observed...reveals three clear precursors at 1, 3 and 4 days prior to the earthquake[7]”* [Chi-Chi earthquake, R=7.7, September 20th, 1999]. Figure 3 below shows the change in total electron count (TEC) over the course of several days prior to this earthquake collected by measuring short wave fadeouts in GPS signals. The figure shows normal conditions of TEC (upper left corner) and how the change in TEC over several days occurred prior to the earthquake. In addition to TEC count, the ionosphere electron temperature has been observed to increase during earthquake periods. This has been measured by the Indian SROSS-C2 satellite using a Retarded Potential Analyzer. The results found that during several near flybys of earthquake epicenters had an increase of 1.2 times the normal day average ion temperature[8].

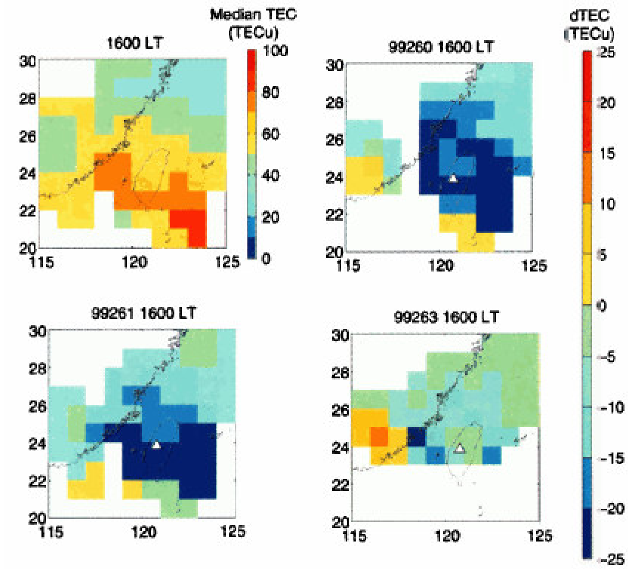


Figure 4 Total electron count prior to the Chi-Chi earthquake[7] (09-20-99) collected by measuring short wave fadeouts in GPS signals. Moving across starting with the upper left corner: 1) represents a 15 day average plot prior to the earthquake period 2) the TEC ionospheric hole four days prior to the event, 3) 2 days prior to the event, 4) 1 day prior to the event7.

Science/Mission Goals

-To characterize variability of total electron count and plasma temperature in the ionosphere.

-To understand the correlation between variations in the ionosphere and global seismic activity.

-To determine the need of research within the field of earthquake detection and enhance the science requirements for a potential large-scale follow-on mission.

Science Requirements

In order to detect these ionospheric anomalies, the F2 region of the atmosphere shall be measured. The average temperature of the ionosphere at this altitude is 1200˚K. To cover the expected change in temperature during the earthquake anomalies as well as seasonal variations, a factor of 3 will be implied for the higher bound and a factor of 1.5 will be applied for the lower bound. This puts the measuring electron temperature range to 800˚K =< Temperature =< 3600˚K. In addition, the average electron density (total electron count) will be measured. The average density within the F_2 layer is 10e5-10e6 electrons/cm^3. Based on the analysis, it can be seen that the minimum sensitivity of 0.01 TEC decrease variability needs to be applied. Therefore this instrument shall measure a range of 10e2=<TEC=<10e7 electrons/cm^3.

Langmuir Probe Theory

Plasma is an unstable state of matter which causes it to be difficult to detect. Upon brining a sensor into contact with plasma, the matter quickly recaptures an electron reducing the energy state and returning into a rarified gas. The Langmuir probe is a novel concept which actively measures plasma by bringing a series of charged materials into close proximity to the matter. As a result, the attraction or repulsion of ions to the electrode causes a shift in the response current. The characterized current-voltage relationship (as seen in Figure 4) is then used to determine the electron saturation and plasma potential. In addition, by periodically varying the initial electrode voltage, the total electron count can be measured. To support the electrode, the typical Langmuir probe is suspended on a boom from a sounding rocket or satellite and sometimes implies a spin

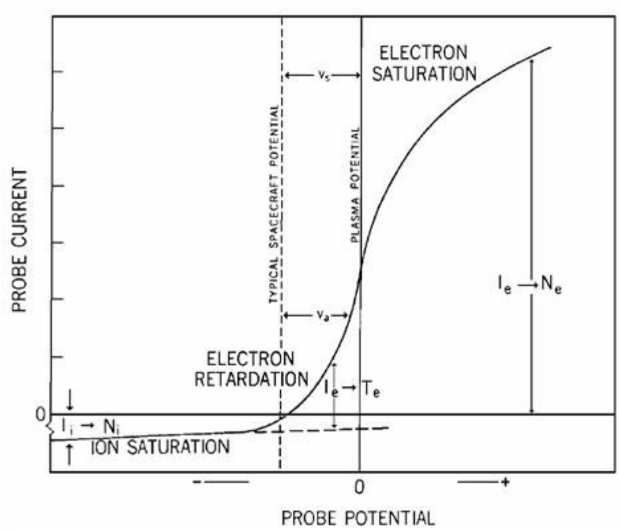


Figure 3: Current-Voltage Relationship for Langmuir Probes.

on the spacecraft to allow for a greater swath distance during sampling. One large problem for the Langmuir probe instrument is that spacecrafts generally gain a charge while in orbit from free electrons. This charge can affect the star-ground (zero reference point) which the instrument uses as a basis for measurements. To counter this, the instrument often has a twin boom without a charged electrode. This allows the spacecraft to calculate the predicted shift in the basis potential due since the electrode has a known surface area.

The calculations required to determine the plasma temperature and electron count are complex and beyond the scope of this report. The top level equations can be seen in equations 1 and 2 below. Equation 1 is used to calculate the plasma temperature (Te) where Φ is the potential drop across the electrodes (Debye sheath), k_B is Boltzmann's constant, and m_e is the mass of an electron. The final variable v_e is the average velocity of the incoming electrons which were able to overcome the potential drop of the two adjacent electrodes (sheath). Upon calculating the plasma temperature the electron density (en_e) can be determined as seen in equation 2 where $J^{saturation}$ of the electron is (determined empirically by varying the voltage-current relationship (as seen in Figure 4), γ_e is the adiabatic coefficient for elections (commonly set to 3) and T_i is the temperature of the ions (if not known can be assumed to be equivalent to T_e.

$$v_e = \left(\sqrt{\frac{k_B T_e}{2\pi m_e}}\right) e^{\frac{\Phi}{k_B T_e}} \quad (1) \qquad j_{electron}^{saturation} = en_e \sqrt{k_B(\gamma_e T_e + T_i)/m_e} \quad (2)$$

III. Instrument Design

Probe Design

The Langmuir probe instrument has an extended history on sounding rockets and a few orbiting missions. From these heritage instruments, there are several different design options for the probe itself. The simplest design is the "Singe Probe" concept in which an electrode is attached to the end of a boom projected out from the spacecraft. The electrode has a buffer insulator material which mechanically holds the electrode to the boom. In addition there is an insulated wire that protrudes along the length of the boom and attaches to the inside of the electrode. It is critical that the radius of the probe is far smaller than the length to ensure the Langmuir cylindrical theory equations can be used. This design can be seen in figure 5 below and shows an exterior (top) and cut away view (bottom). The second concept is similar to the "Single Probe" concept however has two electrodes each separated by a buffer insulating material. This design allows for more flexibility and various spacecraft modes which can gather TEC count, Plasma temperature and a voltage bias simultaneously. In addition, this probe can set a bias between the two electrodes and back out additional details such as ion temperature (beyond the scope of this paper). This design has been drawn in Figure 6 below. The final probe choice is the "Spherical Probe" concept in which an insulated sphere placed on the end of the spacecraft boom. The sphere has a series of electrodes which perform a similar task to the "Double Probe" concept however is not able to determine the spacecraft voltage bias. This design also has the capability to determine the ram direction of the plasma particles and is a relatively new concept with limited flight heritage. This design has been drawn in Figure 7 below.

A trade study was performed to determine which probe configurations would best suit the scientific requirements. The results show that there are benefits for having both a single probe and double probe projected out on separate spacecraft booms. This allows for greater flexibility for on-orbit adjustments, instrument sensitivity and a higher reliability/knowledge of instrument performance (in terms of heritage). The spherical probe adds complexity in manufacturing and analysis which is not necessary based on the science requirements. Materials selected for the probe are: Titanium-Nitride for the electrodes which has flight heritage on the Cassini orbiter, delrin plastic for the insulator material which is commonly used in space and Aluminum for the spacecraft boom (connected to the spacecraft star ground). The length of the booms will be required to be a minimum of 18 inches from the spacecraft edge and size of the electrodes are required to be 50mm in length and 5mm in diameter based on the successes of previous missions and theoretical calculations[9] [10]. Probe dimensions are difficult to determine in that it is hard to control a smaller electrode, however too large and it disturbs the plasma field[11]

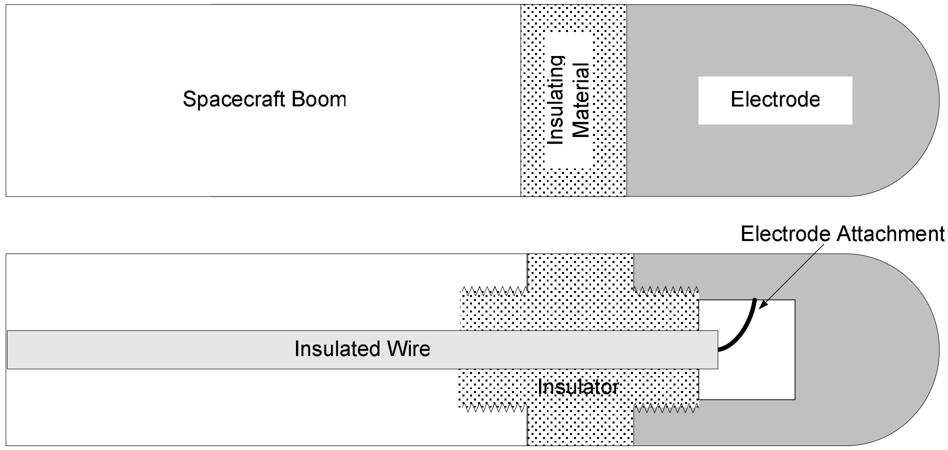


Figure 5: "Single Probe" Concept (exterior and cut out view)

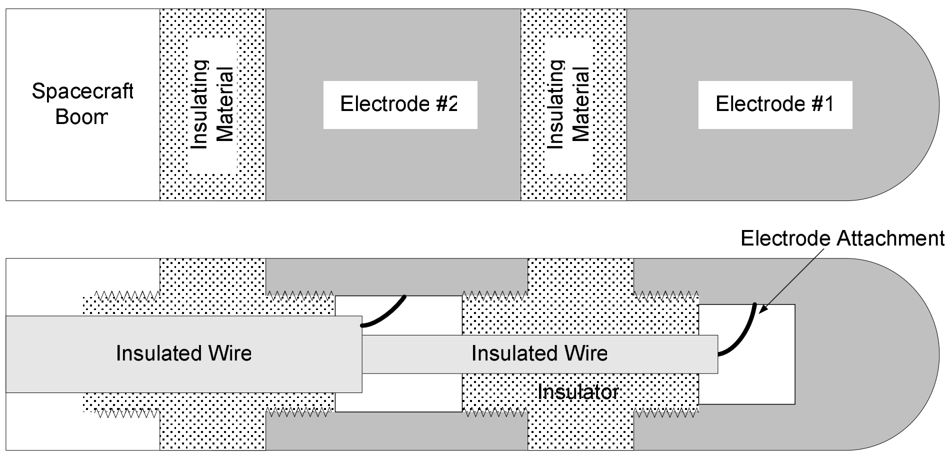


Figure 6: "Double Probe" Concept (exterior and cut out view)

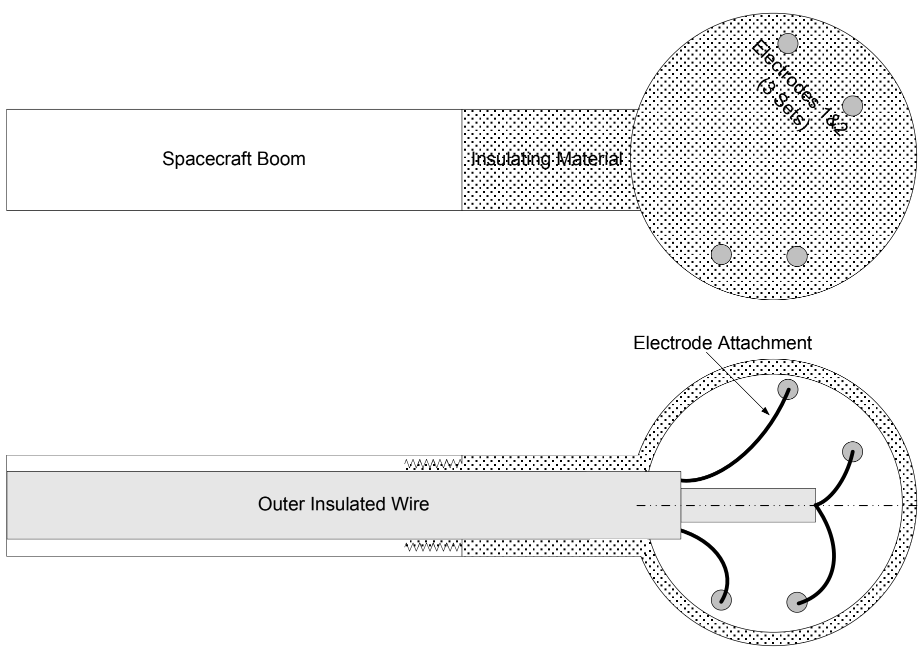


Figure 7: "Spherical Probe" Concept (exterior and cut out view)

Instrument Bus

The instrument module will need to contain several components which are unique to this spacecraft**:** processing electronics, a voltage controller, and a mechanical system capable of deploying the probes away from the spacecraft bus. The electronics will consist of a central processor computer which will command the voltage controller, the deployment of the booms and monitor the thermal status of the instrument components. The computer will also gather the raw data from the probes, preprocess and then encode the data prior to being sent to the spacecraft bus. The voltage controller will regulate and supply the probes with the correct voltage. There will be a separate voltage controller for each electrode. Finally, there will be a mechanical arm which will remain stowed during launch to protect the instruments. Upon spacecraft commissioning, the instrument central processor computer will send a command to deploy both booms. Upon completion a mechanical lock will become engaged to ensure that boom is rigidly connected reducing the risk for jitter.

The instrument will nominally maintain a voltage of 5 (3σ) on a maximum of two electrodes simultaneously. This result corresponds to a minimum current of 400mA to control the voltage controller. The probe will sample the electrodes at 1kHz to determine the I-V relationship and perform a full sweep over the current range every 0.5 seconds[12]. The raw data will be sent to the instrument preprocessor where the electron density and plasma temperature are calculated. These values are then transferred onto the spacecraft bus and stored until it can be downloaded. Periodically once an hour, the instrument will record all the data points sampled over the 0.5 second I-V relationship and send it to the spacecraft bus to be down-linked to the ground. This data will be used as a check point to ensure that the instrument is correctly counting TEC and plasma temperature. The instrument will have the ability to increase/decrease the frequency of full sweeps (nominally set at 0.5 seconds) from the ground to get better recordings when requested from the science team.

Instrument Budgets

Four budgets (Mass, Power, Data Rate, Cost & Schedule) were generated to define the instrument requirements and the effects it will have on the satellite bus, launch vehicle and mission classification (based on cost). These budgets do not reflect the requirements and costs of the launch vehicle, launch integration or the spacecraft (power supply, communications, mission operations...etc).

The mass budget is difficult to determine and as a result, heuristic data was used from [Wertz][13]. The total mass equates to 39 kilograms which is a very small instrument for a dedicated launch vehicle. For this reason it is more likely that this instrument would be well complimented with a secondary payload. The power budget has a maximum power draw of 35 watts during the boom deployment. This action however is over a short period and only occurs during the commissioning phase. As a result, it is more accurate to assume that the continuous power draw during science gathering mode will be 30 watts and will be supplied by the spacecraft. The data rate of the Langmuir will nominally be ~3kb/s[14] however must be designed for a maximum data rate of 34 kb/s. The fiscal budget shown in Figure 9 below first calculates preliminary workforces cost to design, build and integrate the Langmuir probe instrument over a three year period. In addition, factors such as materials, traveling and specialized testing facilities (plasma chamber, vibration table, thermal vacuum chamber, electromagnetic interference facility) were included. The total cost is estimated to be 16.3 million dollars over three years. Finally, an early schedule for building the instrument has been created and shown in Figure 10 below. The time of three years was chosen as this is a typical allotment of time given to instrument builders of a non-heritage design. The three years includes all instrument calibration and testing allowing to be immediately installed onto the spacecraft bus upon delivery and ready for launch upon completion of spacecraft level testing.

Mass Budget	(kg)
Primary Structure	15
Extending Boom	10
Main Computer	10
Voltage Controllers	1.5
Harnesses	2
Thermal	0.5
Total	**39**

Power Budget	(watts)
Langmuir Probe	4
Main Computer	20
Voltage Controllers	6
Boom Deployment	15
Total*	**35**

*worst case power draw during, boom deployment with instrument off

Data Rate Budget	kb/s
Langmuir Probe, nominal	1
Langmuir Probe, fast sam.	32
Calibration Sample, nominal	0.25
Housekeeping, nominal	1
Total*	**34**

*worst case dara rate when Langmuir Probe sweep sample rate is at max.

Figure 8: Projected Langmuir Probe Instrument Mass, Power and Data Rate Budget

Workforce Fiscal Budget	Hr/week		
	Year 1	Year 2	Year 3
Program Manager	40	40	40
Principle Scientist	30	30	30
Systems Engineer	40	40	40
I&T Manager	0	20	40
Mechanical Engineer (3)	120	120	60
Electrical Engineer (2)	80	80	60
Software Engineer (2)	40	80	80
Calibration Engineer	0	40	40
Machinest (2)	20	80	20
Electrical Assembly (2)	20	80	40
Total Yearly Hours	19500	30500	22500
Yearly Workforce Cost*	3900000	6100000	4500000
Total Workforce Cost: 14.5 Million			
*Average salary projected at 200$/hr with overhead			

Total Fiscal Budget	(Millions)
Personnel	14.5
Personnel Travel	0.3
Materials	1.0
Testing Faciliites	0.5
Total	**16.3**

Figure 9: Projected Langmuir Probe Instrument Fiscal Budget

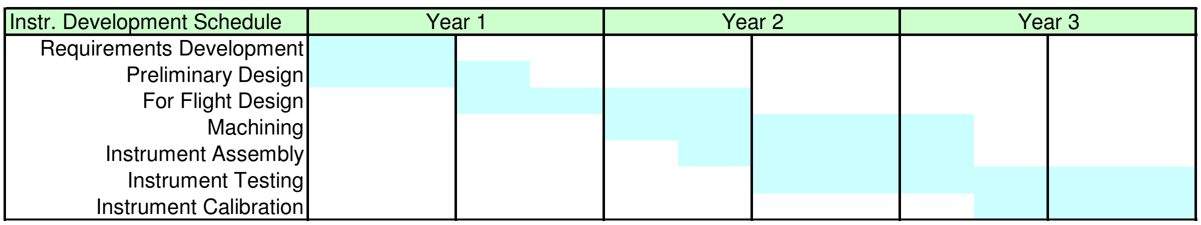


Figure 10: Projected Langmuir Probe Instrument Build Schedule

IV. Spacecraft/Mission Design

Orbit Selection

The ionosphere is defined within the region of 100 to 1000 km. However it can be seen from Figure 2 that the electron density reaches a peak at 350km. Therefore to meet the science requirements, the orbital parameters shall be contained to an altitude of 200 to 500km (EOL). A circular orbit would simplify the science requirements since the variability in TEC and plasma temperature would not be a function of altitude. However, a slightly eccentric orbit is acceptable since density can be backed out by analysis. Figure 11 below shows the acceptable orbital parameters as a function of apogee and perigee. The reason for this allowing this variability is to accommodate requirements of secondary instruments which may be manifested into the mission. In addition, this flexibility allows for satellite perturbation which (typically hard to predict) degrade the orbit while still maintaining mission success. When determining the orbital inclination of the orbit, it is most desirable (from an ionospheric science perspective) to have the smallest inclination as possible. This is because the ionosphere is more predictable at lower latitudes due to the decreased interaction with the magnetosphere. The ionosphere tends to be highly variable near the poles as trapped radiation from the magnetosphere is brought down during solar storms. This non-cyclic occurrence of the varying storms will saturate the variability readings for a finite period of time. By staying away from the poles, it is expected that the frequency, impact and duration of this interference can be reduced. However this conflicts with the goal is for maximized global coverage. Upon analysis of a map showing the earth's tectonic plates, it can be found that the majority of the plate's interactions (earthquake hotspots) that occur on land are located within the latitudes of ±50 degrees. Figure 12 below shows the ground track for (the nominal) 350km orbit at an inclination of 45° over the course of 1 day. It can be seen that the earthquake regions are well covered by this tracking. The grey portions of the ground tracking represent periods for when the earth is in sunlight. The sun-lit portions of the orbit are expected to have less accuracy within the data product since interactions with solar particles will induce noise. Figure 13 shows the ground track for the two orbits within the orbital envelope. It can be seen that the lower orbit (200km) has closer passes over the same location however the difference is trivial compared to the higher orbit (500km). Given that the exact altitude of the orbit is not specified, a thruster system built into the spacecraft used to boost the orbit will not be required. This will save considerable resources throughout all phases of the mission.

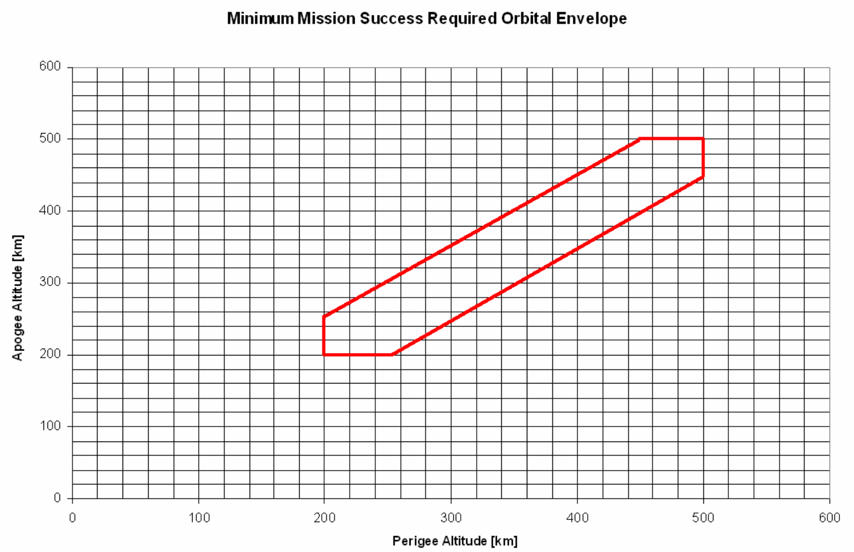


Figure 11: Orbital envelope based on science requirements

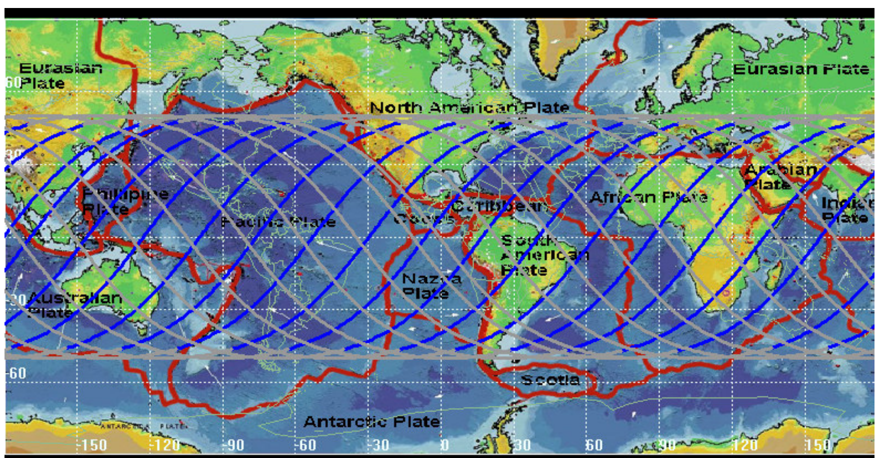


Figure 12: Ground track for the Langmuir Probes when at 350km.
Grey trackings are represent when the spacecraft is over sunlit earth

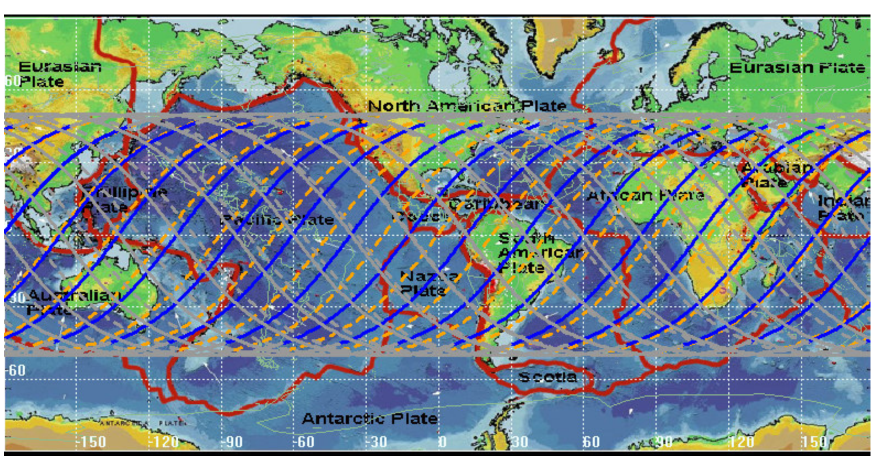
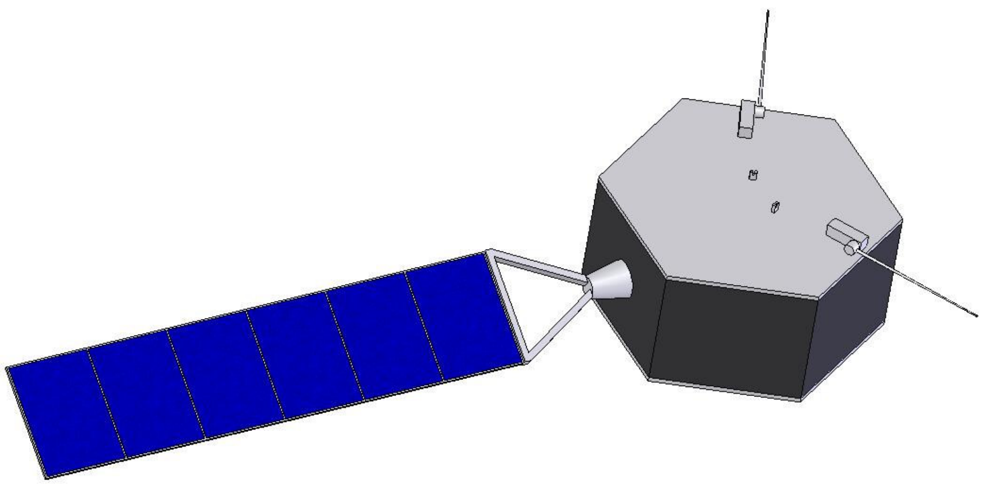


Figure 13: Ground Track for the Langmuir Probes when at 200 km (orange) and 500km (blue) representing orbital envelope. Grey trackings are represent when the spacecraft is over sunlit earth

V. Spacecraft Considerations

Spacecraft Design

The supporting spacecraft has been designed to be simplistic and expandable as the possibility of having a secondary or third instrument is likely. The spacecraft bus layout of a simple hexagonal prism roughly one meter across and 0.5 meters high. The Langmuir probe instrument sensors will be located on one of the hexagonal (top) surface of the bus with the launch adaptor located on the opposite (bottom side). The spacecraft subsystem components will be located inside the bus as well as the instrument electronics as a form of protection from the space environment hazards. The two Langmuir probes will extrude outside of the spacecraft from the top hexagonal surface at a respective angle of 120° from each other. The solar array panels will be projected on a third boom which will complete the 120° symmetry with the Langmuir probes. This setup was configured so that the probes are not blocked by either the spacecraft or the solar panels while on orbit. The Langmuir probes in the stowed configuration will be locked down and resting on the top hexagonal surface during launch. The solar arrays will wrap around the hexagonal bus structure when in the stowed configuration during launch (see Figure 19 below). The interior components of the spacecraft will be housed in independent containers to reduce electromagnetic interference.



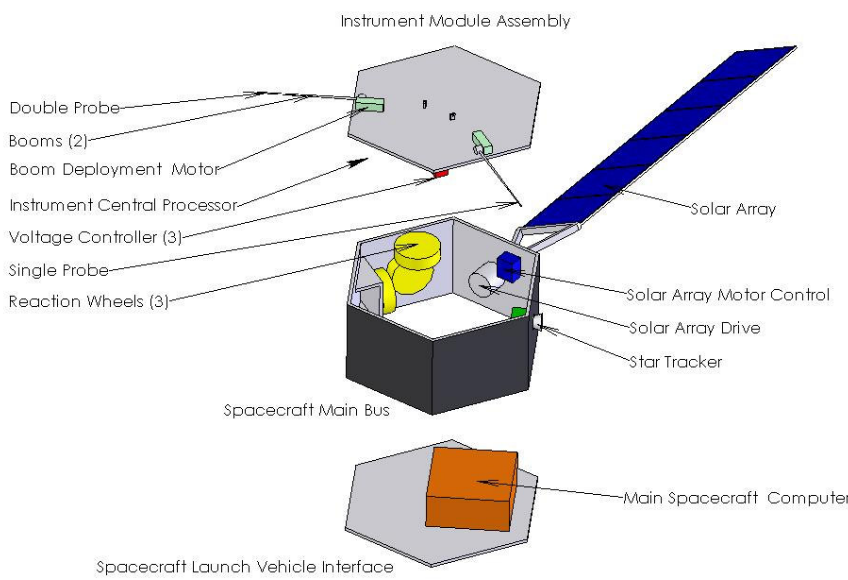


Figure 14: The Langmuir Probe Instrument & Spacecraft (Concept)
Exterior View (top), exploded view (bottom)

Spacecraft Subsystems

The scope of this paper is not to design the entire spacecraft, however there are several important requirements that the instrument will imply onto the spacecraft and are discussed below:

Power: The instrument will require a continuous supply of 30 watts to maintain power during the science mode. During the boom deployment mode the instrument will require 35 watts of power for a period lasting 15 minutes. The solar array therefore needs to be sized (with margin) to accommodate this power draw in addition to the spacecraft electronics. Given the low inclination orbit, the spacecraft batteries need to be sized to enable power to the spacecraft while in shadow with a full duty cycle not to exceed 60% depth of discharge.

Command & Data Handling: The CD&H system will be relatively simple system commonly seen on small spacecraft. The main requirements for this are that the maximum data rate the computer will accept is 34kb/s. The spacecraft shall have the storage capability to record a 6kb/s nominally of continuous data over a 48 hour period. This period is considered to be the worst case duration if th ground station misses two consecutive opportunities to downlink data. The total storage size this requires (worst case) ~1.040 Gb with. Upon storing all of the raw data for down-linking, this capacity will allow for a minimum of 8.5 hours of recorded data. The transmitter shall be capable of downloading all of this data within two ground station passes.

Attitude Control: For instrument operations, it is critical that the electrodes are extruded from the spacecraft in the direction perpendicular to the orbital velocity vector (see Figure 15). This allows for incoming plasma / electrons to interact with the electrodes without being effected by the spacecraft itself. A spin about the spacecraft central axis for attitude stabilization is acceptable as long as the axis as along the orbital velocity vector. Fortunately the spacecraft will have fairly loose requirements related to the attitude allowing for a simplistic system. In order to ensure that the probes remain outside the required separation from electrode to spacecraft center, the half cone-angle required upon the attitude system is 8˚. This was calculated by simple geometry and the instrument requirements discussed above. Depending on cost and performance components such as star trackers and torque rods should fulfill these requirements well.

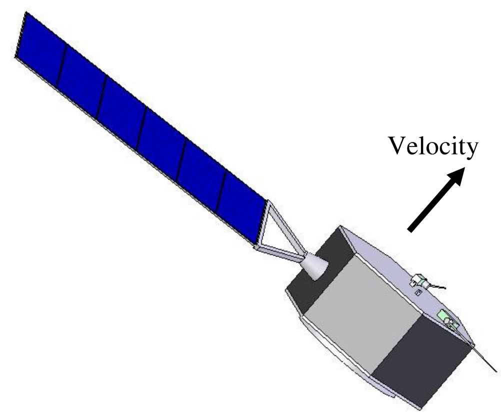


Figure 15: Spacecraft with velocity vector shown

VI. Integration & Testing

Calibration

The calibration and parameterization for this study is based on a report put together by [Mausbach][10] which is an extensive study to determine the most accurate way to measure a single cylindrical Langmuir probe. Laframboise's Algorithm (equation 3) is used to calibrate the instrument since a generalized root function is a good approximation and allows for flexibility in matching the expected I-R curve. In the algorithm seen below, *a* is an amplitude scaling factor while *b* sets the zero point and *c* is the power of the root function.

$$f(x) = a(b+x)^c \qquad (3)$$

To perform the calibration, a plasma source and a relative environment needs to be created. This requires a complex system in which an anodic crucible with evaporating copper melt arcs current to a cathode molybdenum cylinder. From there an electric field (along with several other components) is induced to force the plasma down the length of the chamber. The plasma fills the entire volume of the chamber and returns to a rarafied gas at the chamber walls. Thus a chamber large enough is required to ensure that this is does not effect the calibration. The Langmuir probe is located a significant distance away from the plasma source (>50 times the probe radius) to ensure that the plasma is properly characterized and in near normalized velocity to the probe. The number of ions and the plasma temperature is characterized by the electronics at the source. From there, prorogation equations can be used to determine the TEC at the Langmuir probe source, (see Figure 16 below for a diagram of the chamber). Several studies have been performed to determine the statistical average temperature of the plasma created within the chamber in addition to alternative and more reliable methods; however they go beyond the scope of this report.

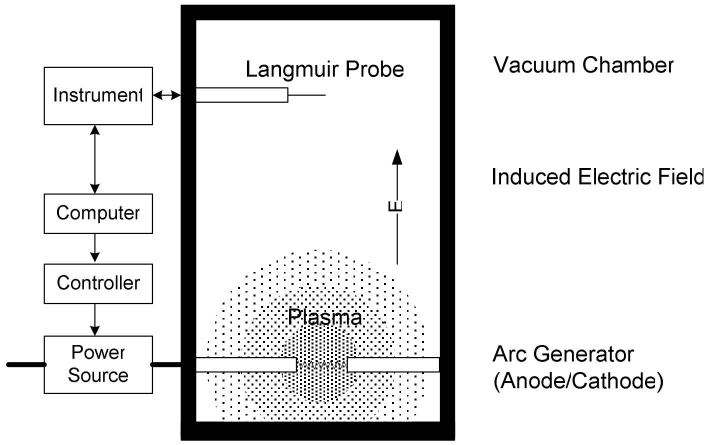


Figure 16: Example of a Plasma Source Calibrator

<u>Testing</u>

Interlaced during calibration, various parts of the spacecraft will be put together and tested starting at the component level and building up to the full system level. Tests at the smaller level might be attributed to boom deployment tests, electrical grounding of wire harnesses, software, recoverability from a single event upset, etc. Upon the completion of the integration, a series of tests should be performed to ensure that the spacecraft is ready for spaceflight: vibration test, “bakeout” cleaning, thermal vacuum test, electromagnetic interference test, end-to-end software test, and a 5-day-operations test. These can be performed in various orders based on needs of the calibration team or the availability of the test facilities. It is critical to note that at the system level testing, the instrument should be configured as it will see for flight. This is to ensure that the results you see on the ground will be reproduced during the mission, removing additional variables of uncertainty.

<u>Contamination Control</u>

Fortunately contamination control requirements for this instrument are fairly relaxed in that the system does not contain optical surfaces. However, small debris, oils, and residue left on the spacecraft will outgas on orbit and potentially reform on the electrodes causing unpredictable degradation. In addition the microgravity environment has the potential to move loose foreign objects around the spacecraft potentially shorting circuitry. As a result, requirements will be flowed down on the engineering team to use certified NASA materials with an outgassing specification less than 1% Total Mass Loss (TML) or 0.1% Collectable Volatile Condensable Material (CVCM). In addition, all components will be thoroughly cleaned by NASA certified quality assurance technicians and placed in a class 10,000 cleanroom or less for continued instrument integration and testing. The instrument will be double bagged when removed from a clearnroom for testing or transport.

VII. Alternative Concepts / Design Flexibility

<u>Dual Spacecraft Concept</u>

Given that the instrument mass is well below the typical values seen for launch vehicle payloads[13], it is possible that multiple Langmuir probes / spacecraft systems could be stacked atop each other and released at different times during the launch. This would have a large effect on the science return and analysis (as described in the orbit section below) for a relatively small financial increase. Figure 17 shows how a second spacecraft ground track coverage 180 degrees out of phase from the first and hence doubling the coverage. This would be invaluable to the science team as it would double the resolution surrounding an area of interest. Adding a second instrument is also cost effective as the designs would be finalized and the additional cost required would relate to the technical assembly. Figure 18 shows a predicted budget necessary for a secondary instrument to be 7.2 million which is ~half the cost of a single instrument. Finally, Figure 19 below shows a concept for how multiple spacecrafts would be paired together (in launch configuration: solar cells and booms in the un-deployed state).

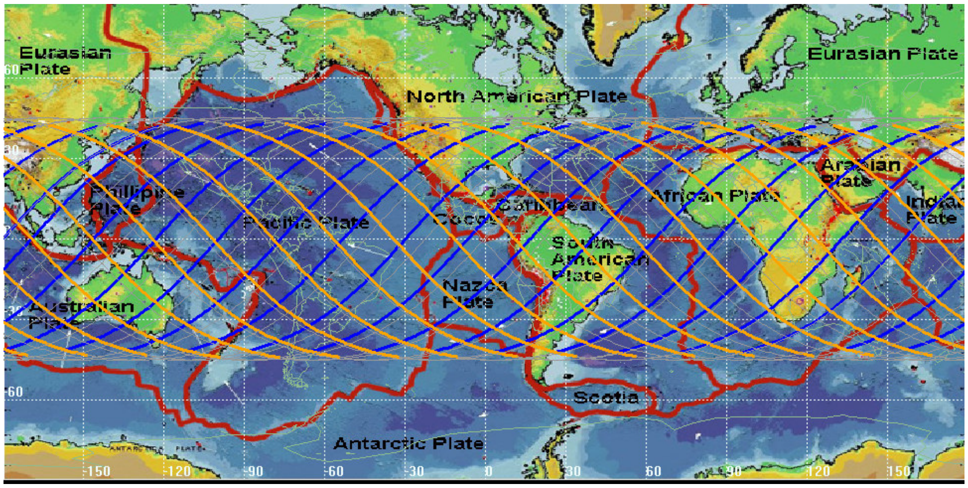


Figure 17: Ground Track with two instruments at 350km (orange) and 500km (blue) Grey trackings are represent when the spacecraft is over sunlit earth

Workforce Fiscal Budget for a Second Langmuir Instrument	Hr/week		
	Year 1	Year 2	Year 3
Program Manager	5	5	5
Principle Scientist	15	15	15
Systems Engineer	0	10	10
I&T Manager	0	10	20
Mechanical Engineer	20	20	20
Electrical Engineer	5	5	5
Software Engineer	5	5	5
Calibration Engineer	0	40	40
Machinest (2)	20	80	20
Electrical Assembly (2)	20	80	40
Total Yearly Hours	4500	13500	9000
Yearly Workforce Cost*	900000	2700000	1800000
Total Workforce Cost: 5.4 Million			
*Average salary projected at 200$/hr with overhead			

Total Fiscal Budget	(Millions)
Personnel	5.4
Personnel Travel	0.3
Materials	1.0
Testing Faciliites	0.5
Total	**7.2**

Figure 18: Projected cost to build a second instrument in tandem

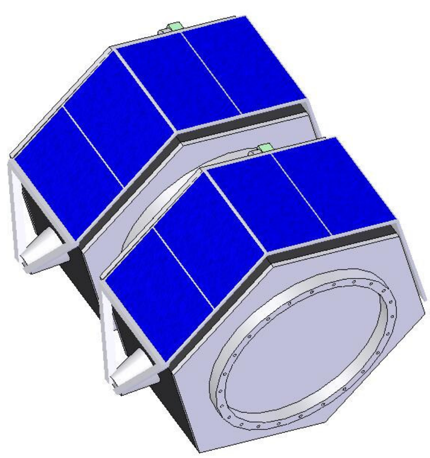


Figure 19: Two Langmuir Probe Spacecraft Nested for a single launch vehicle

VIII. Conclusion

It has been detected that there are distinct ionospheric anomalies located over areas of seismic activity. There is supporting evidence that electromagnetic emissions propagate from the ground causing these disturbances and other such phenomena such as earthquake lights and magnetic aberrations. A Langmuir probe instrument can be built to fly within the inonosphere and actively detect total electron count and plasma temperature. This data could then be correlated with seismic activity and other instruments studying similar data on the ground and on orbit. The results will show if ionospheric monitoring is a reliable and accurate way to predict seismic activity. The lessons learned will be used to develop the next generation satellite which will continue this research to a stronger degree.

Earthquakes are a natural phenomenon which has baffled human kind for millennia causing a desire and need for better understanding. The unpredictability of earthquakes and the impact of their devastation cause a need for new technologies to be explored in hopes that one day, accurate earthquake warnings will be available.

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