UC/LANL Consortium for Micro-Satellite and Instrument Development

Main Objective: This three-year Campus-Laboratory-Collaboration Project develops a UC/LANL capability of designing and building space environment micro-satellites for future space missions. This includes development of miniature instrumentation for plasma, magnetic, and electric field measurements and the integration of these instruments directly into a micro/nano-satellite bus. The UC/LANL team will be led by researchers in UCLA's Institute of Geophysics and Planetary Physics, and will include researchers within the California Nanotechnology Institute (UCLA and UCSB), the UC-Berkeley Space Science Laboratory and LANL's Center for Space Science and Exploration. The CLC grant creates an interdisciplinary UC/LANL consortium that integrates education with cutting-edge space research and puts UC among the ranks of the few University-based spacecraft and instrumentation facilities worldwide. This consortium will develop further collaborations with NASA, aerospace companies, and other Universities to help solve some of the taunting tasks of designing, fabricating, and analyzing data from large constellations of satellites. The immediate goal of this consortium is to develop a micro/nano satellite with an integrated space environment experiment suite built with significant student support. The consortium will leverage existing external instrument and mission development funding to achieve this goal. Though this proposal describes specific space physics science objectives, the consortium resources can be used for Earth observing, ionospheric, or deep space missions.

1. Scientific Motivation

Several current and future NASA science missions will fly multiple spacecraft including Space Technology-5 (ST-5), Magnetospheric Multi-Scale, and Magnetospheric Constellation. These missions require small, low-cost, low-mass spacecraft. Currently a typical spacecraft has a mass on the order of 1000 kg. Satellites with masses of 100 kg are now being built and are referred to as micro-satellites. Tests are underway on the next smaller class of satellites of the order 10 kg called nanosats. This push to smaller spacecraft is driven by the desire to fly constellations of spacecraft in order to resolve temporal and spatial ambiguities inherent in single satellite missions and/or provide more complete coverage of space.

The Magnetospheric Constellation mission proposes to fly 50 to 100 spacecraft. In order to fly large numbers of spacecraft the spacecraft need to be small to minimize launch costs. A launch vehicle can cost from $40 to $150 million. There are a multitude of challenges in designing small spacecraft for scientific missions including communication, propulsion, miniaturation of instrumentation, power, and deployment. While advances in microelectronics and MEMs (Micro Electro Mechanical Systems) abound, driven by consumer demands in the areas of cellular telephony, computers, and medical physics, these have not found their way into satellites.

In addition, how to organize, store, and visualize data taken simultaneously from several instruments in different regions is a significant problem for future missions.

One of themes of space science is understanding the Sun-Earth Connection. Namely how does variability on the Sun influence the Earth's space environment. This system is composed of several different plasma regimes often separated by sharp boundaries though highly coupled by complex current systems. It is the goal of space physics to understand these boundaries and the coupling between them.

1.1 Scientific Rationale: Boundary Regions

The first two decades of space exploration provided a detailed but qualitative picture of the structure and dynamics of the magnetosphere. The magnetopause, bow shock and tail were mapped [*Cahill and Patel*, 1967; *Holzer et al*., 1966; *Ness*, 1965] using single satellites of the Explorer and OGO series. The polar cusp was discovered at both high altitudes [*Frank*, 1971]] and low [*Heikkila and Winningham*, 1971]. The control of magnetospheric dynamics by the interplanetary magnetic field was revealed in the erosion of the magnetopause [*Aubry et al*., 1970]; episodic expansions and contractions of the plasma sheet [*Russell et al*., 1971] and the control of the magnetospheric substorm [*McPherron et al*., 1973].

The year 1977 brought the launch of the first co-orbiting satellites ISEE 1 and 2 and the ability to measure motions and derive scale lengths. The velocity and thickness of the bow shock were measured for the first time [*Russell and Greenstadt*, 1979]. The acceleration of plasma due to reconnection at the magnetopause was revealed [*Paschmann et al*., 1979] proving the efficacy and reality of this long-proposed mechanism. The wave modes responsible for many upstream waves were identified [*Hoppe and Russell*, 1983] and new previously unexpected phenomena were found such as the still controversial, slow-mode standing wave [*Song et al*., 1992]. Some phenomena could not be probed adequately even with two spacecraft. The flux transfer event [*Russell and Elphic*, 1979] is associated with a moving magnetic tube. Mirror mode waves in the sheath also have a very localized structure [*Southwood and Kivelson*, 1993].

Following these highly successful missions, the next step was to resolve spatial gradients, since a pair of spacecraft can only resolve one component of a gradient, along the spacecraft separation vector. To address this problem ESA with some assistance from NASA developed the four-spacecraft Cluster mission that has now been launched. However the separation of these spacecraft is too large to address the major issues raised by the ISEE 1 and 2 spacecraft [*Russell*, 2000]. Thus, NASA's Magnetosphere Multiscale Mission (MMS) is planned to have much smaller separations, down to 10 km. Both Cluster and MMS use an approximately tetrahedral configuration, which allows us to directly calculate the curl of the magnetic field, that is, the current density. This is an essential measurement in understanding the electrodynamics of different parts of the magnetosphere. Currents are the means by which stresses are communicated from one part of the magnetosphere to another, and also to the ionosphere, where the closure currents can induce significant perturbations on the ground. In the future, missions such as Draco may involve 50 to 100 spacecraft.

ST5 is a precursor mission to the multi-spacecraft missions such as Draco. The ST5 mission involves three spacecraft flying in a close configuration (~ 100 km separation) in a 200x35,790 km elliptical orbit as shown in Figure 1.3. The spacecraft will each be instrumented with a UCLA-built fluxgate magnetometer to measure the magnetic field in the region of space where the ring current flows. An energetic particle experiment is also proposed to fly on this mission. This current, carried by energetic particles, couples to the ionosphere through field-aligned currents. Measuring the particles and the magnetic field together, and determining their gradients will provide significant new insights as to their interrelationship, as well as their variability during different levels of magnetospheric activity.

1.2 Scientific Rationale: Current Systems

The earliest observations of low-altitude field-aligned currents (FACs) flowing into the ionosphere from the magnetosphere were by *Zmuda et al*. [1966], as measured by satellite 1963-38C at 1100 km altitude. *Cummings and Dessler* [1967] presented a convincing argument that the disturbances could best be attributed to field-aligned currents, and not waves. *Zmuda and Armstrong* [1974a,b] showed that the currents lie in two concentric circles roughly co-located with the auroral oval. *Iijima and Potemra* [1976] named these currents Region 1 and Region 2. During intervals of intense geomagnetic activity the ionospheric currents can induce strong signals that can have catastrophic effects on electrified systems on Earth [*Le and Russell, 1993; Boteler et al.,* 1998]. Thus understanding the variability and structure of currents within the magnetosphere is an essential aspect of furthering our ability to predict space weather.

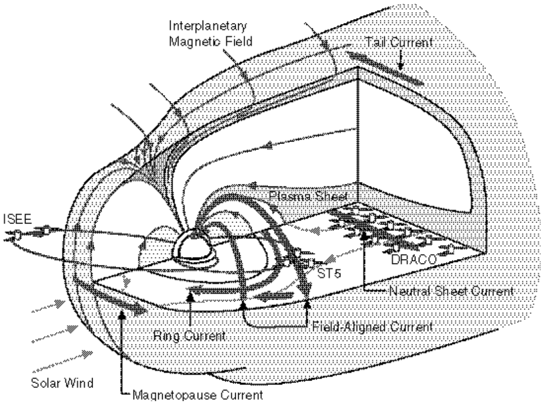

Figure 1.1 Summary of constellation missions within Earth's magnetosphere, showing the ISEE orbit, ST5 and a Draco-like mission.

FACs often show a high degree of temporal and spatial variability. Single spacecraft can help identify regions within which such variability occurs, but they cannot resolve time versus space. For example, they cannot address the evolution of FACs as a function of altitude, such as whether the fine structure of FACs is due to increasing filamentation at different altitudes, or is inherently part of the generation mechanism. These types of question can only be addressed through constellations of spacecraft, with close constellations addressing temporal versus spatial variations, and larger constellations addressing questions of field-aligned current mapping.

Such constellations would have been invaluable in the work of *Lotko et al.* [1998] who found field-aligned current structures with widths of the order 10 km at 4000 km altitude with data from the Fast Auroral Snapshot (FAST) Explorer. These widths are comparable to ion Larmor radii and electron skin depths. At these scale lengths Alfvén waves can maintain parallel electric fields, thereby generating aurora. UCLA supplied the magnetometer for FAST. Currently to calculate currents with single spacecraft like FAST, we have to assume that the currents are stationary in time and space, and are sheet-like. Neither of these assumptions are likely to hold for small-scale structures, but these assumptions are necessary with observations from only one spacecraft.

Field-aligned current density in the auroral region often shows oscillatory structure at both high and low latitudes. Is this spatial or is it temporal? Are the currents (and associated particle distributions) sheet-like or filamentary? We need constellations of spacecraft for the answers to these questions.

2. Magnetometer Instrument

The UCLA fluxgate magnetometer has been employed in state-of-the-art investigations of magnetospheric and solar system magnetic fields for over 35 years. During this time the accuracy and precision of the magnetometer has grown even as its mass, size and power decreased. In this section we review the heritage of the UCLA flux gate design and describe the development plans that this CLC consortium will support.

2.1 Missions with UCLA Magnetometers

UCLA has a long history of supplying science-grade magnetometers, as shown in Figure 2.1. All of these magnetometers were successful and built on the design efforts of its predecessors.

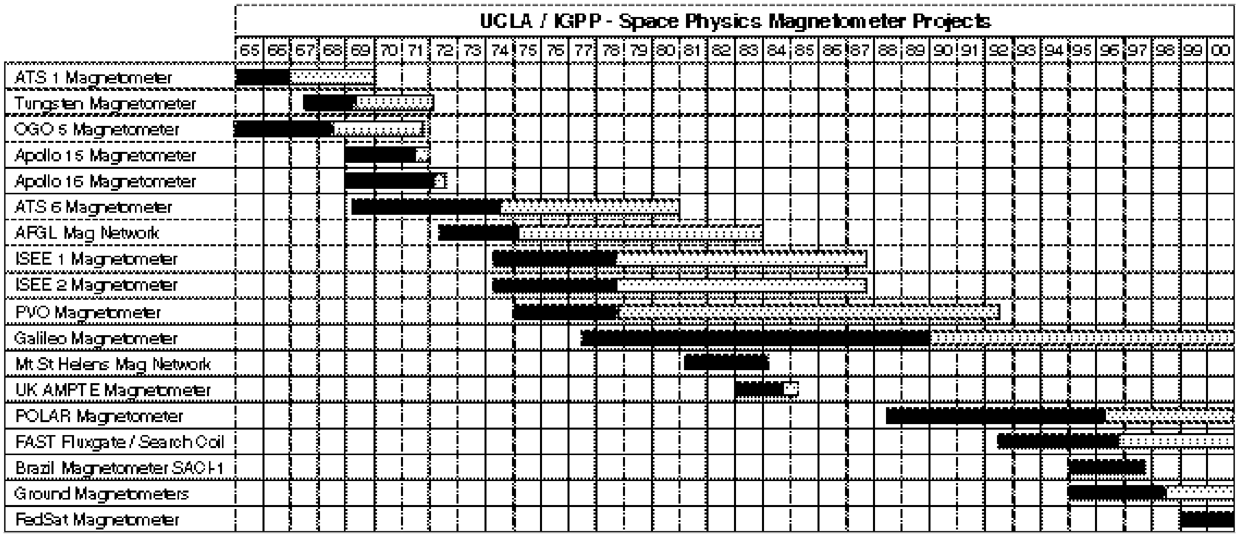

Figure 2.1 Spaceflight and ground-based magnetometer programs at UCLA over the last 35 years summarize the accomplishments of the group. Dark bars show fabrication and light bars operational phases.

Table 2.2 shows that mass of the basic UCLA magnetometer continued to shrink even as it grew more precise and accurate. The CLC proposal will help continue this trend as well as to integrate the magnetometer instrument and data into a coherent experiment suite for advanced space environment monitoring.

Table 2.2 Modern components and continued improvements have lowered the mass of the UCLA basic circuitry.

Mission Name	Ranges [nT]	Cadence [Hz]	Mass [g]	Area [in^2]
ISEE	8000, 556	4, 16	500	100
Galileo	16,000, 512, 32	0.05, 3, 32	500	100
Polar	47,000, 5700, 700	8.3, 100	400	70
FAST	64,000	Up to 512	350	60
FedSat	60,000	10,100	200	35

2.2. ST5 Magnetometer Design

UCLA's ST5 fluxgate magnetometer is the product of a long series of successful spaceflight magnetometers. The sensors are boom mounted and have no active components. Drive, sense and feedback signals travel along the boom cable between the sensors and the electronics board on the spacecraft. The electronics generates the fluxgate drive signal, detects the second harmonic of this signal, nulls the field surrounding the sensor, and provides a digital reading of the current needed to null each of the sensors. This signal is then sent to the telemetry system. There is no microprocessor in this simple design. The magnetometer has two commandable ranges, 64,000 and 1000 nT.

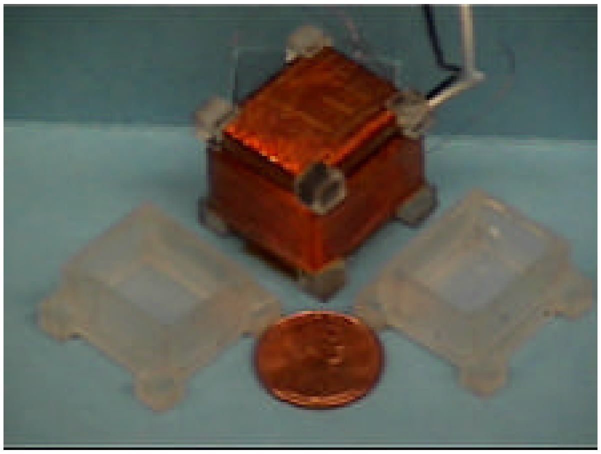

Figure 2.3 The 3-axis ring-core fluxgate sensor fabricated by UCLA with a penny in the foreground for comparison.

2.3 Ground-Based Magnetometers

Deployment of UCLA's precision, low-cost, ground-based magnetometer for studying ionospheric and magnetospheric currents was a very important development in magnetometry at UCLA. This magnetometer can measure less than 0.1 nT in the full Earth's field with precision GPS timing control .UCLA has built and installed over 30 of these devices building ten at a time and testing them five at a time at its San Gabriel test site. These magnetometers are now operating from the Canadian arctic to the equator.

3. Magnetometer Development Goals

The discussion in the previous section indicates how far we have taken the design of the analog fluxgate magnetometer. To further reduce the mass and power characteristics of the magnetometer beyond those of ST5 requires a departure from this design path. The three areas that can be developed are: first, sensor design; second, electronics unit design; and third, multi-instrument integration.

Significantly, changing the sensor design is not an option. As discussed earlier, the feedback-compensated fluxgate magnetometer is a highly linear sensor, with extremely low intrinsic noise characteristics and offset stability. Other technologies, such as magneto-resistive sensors tend to have higher intrinsic noise levels, and are subject to significant offset drifts, especially if the sensor is power cycled. Thus any sensor development should be evolutionary, and based on the fluxgate principle.

Changing the design of the electronics unit can result in substantial savings. Reducing the amount of analog circuitry in the instrument is the most promising approach. This will reduce the power of the magnetometer (400 mW for ST5), but most affect mass and board size. We expect at least a factor of two decrease in board area, with the corresponding reduction in mass. We also expect that moving to a digital design will improve the thermal characteristics of the magnetometer, with less variation in gain and offset as a function of temperature. The basic characteristics of the digital fluxgate magnetometer are shown in Table 2.

Range	64,000 nT
Resolution	±0.1 nT
Sensor Mass	75 g
E/U board size	10.4x10.4x2 cm
E/U board mass	100 g
Power	250 mW

Table 2. Basic Characteristics of the digital fluxgate magnetometer.

The last area of improvement is to integrate the magnetometer with other instruments on board the spacecraft. Since any space-based magnetometry effort requires both precise timing and position information, the prime candidate for integration with a magnetometer is a GPS receiver. We have already integrated a GPS receiver with a magnetometer in our ground-based system, but in that case GPS was used only for timing purposes. The value of such an integrated instrument is significant. Not only will the instrument function in a "stand-alone" capability, but it could also serve as a system resource for other experiments on board a spacecraft. The integrated system will provide timing to other instruments, guaranteeing synchronicity both within the spacecraft and also with other spacecraft and ground-based observations. In addition, experiments such as particle detectors will have direct access to the magnetometer data through the same interface for determination of pitch angle, etc.

Our development goals are therefore divided into three areas: digital magnetometer development, sensor development and integration with a GPS receiver.

3.1 Digital Magnetometer

The basic principle of the next generation fluxgate magnetometer is to integrate the sensor directly into the analog to digital conversion stage. There are several design challenges involved.

Figure 3.1. Output from a breadboard test of the digital magnetometer, showing the ability to resolve a 5 nT triangular signal when set to a 50,000 nT range.

First, the digital filter must have the appropriate frequency characteristics. Second, the feedback elements of the circuit, which include the digital filter, require careful engineering. Third, the magnetometer must achieve accuracies to the 20 bit level for a resolving power of ±0.1 nT in a field of 64,000 nT. Again, there is a significant design challenge in achieving this accuracy with the desired linearity across the full dynamic range.

We have performed breadboard testing of the new magnetometer design, and the results of the test are shown in Figure 3.1. To perform this test we used elements from our ground-based system, such as sensor assemblies, and the ground system to control the magnetometer and acquire the data. Clearly the magnetometer can resolve the 5 nT signal, but there is some noise at about the 1 nT level. Understanding and minimizing this noise is one of the goals of the development effort.

3.2 GPS Integration

The mass, size, power, and cost of space-borne GPS systems, while still high in comparison to other small spacecraft components, is beginning to enter the region where very constrained projects can consider their use. We have compared Motorola's space-qualified Monarch and Viceroy space-borne GPS receivers and JHU/APL's GPS receiver that is currently at the engineering model stage. JHU/APL's receivers are factor 5-10 lower mass, 7-50 times lower volume, and consume 4.0 W. Clearly, JHU/APL and other organizations are making significant progress in reducing the resources necessary to implement these GPS systems on small spacecraft. However, small spacecraft demand very highly integrated solutions where multiple components share common resources.

	Motorola		
	Monarch	Viceroy	JHU/APL
Mass	3.4 kg	1.2 kg	0.35 kg
Size	20.3x18.9x14.0 cm	20.3x18.9x14.0 cm	two 10.4x10.4 cm boards
Volume	5371 cm^3	862 cm^3	110 cm^3
Power	25 W	4.7 W	4.0 W

Table 3. Space-borne GPS receivers.

The integrated magnetometer-GPS receiver module will provide precise magnetic field data along with accurate position and timing information. The use of GPS obviates the need for extensive flight dynamics analysis. By the same token, precise timing is essential for synchronizing observations on a single spacecraft. For example Sun pulse timing using the same clock is essential if measurements are acquired on a spinning spacecraft. Any attempt to synchronize with other spacecraft or ground observations is also made much easier when using a common clock, as provided by GPS. Last, magnetic field data are often considered to be a service to other experiments, and as such falls into the same category as the clock pulse shared by all experiments on a spacecraft. The magnetometer is therefore clearly the primary candidate for integration with a GPS receiver.

3. Electric Field Instrument

Direct measurements of the electric field with wires or stacers are crucial components of operational, upcoming and planned missions. Electric field measurements provide the DC, 3 dimensional electic field, which, in combination with the magnetic field, gives the plasma flow assuming plasma drifts are small. Departures from the value of the plasma flow computed simultaneously by a plasma instrument provide information on the ion drifts (essentially the ion pressure gradient term, or Hall term in Ohm's law). Electric field instruments are able to provide measurement of parallel electric fields along field lines. Finally, electric field instruments can measure plasma waves which are crucial for understanding instabilities leading to energy exchange between space plasmas of different origin (solar wind, magnetosphere, ionosphere). Typically electric field measurements employ wire or stacer booms to deploy a spherical sensor away from the spacecraft body.

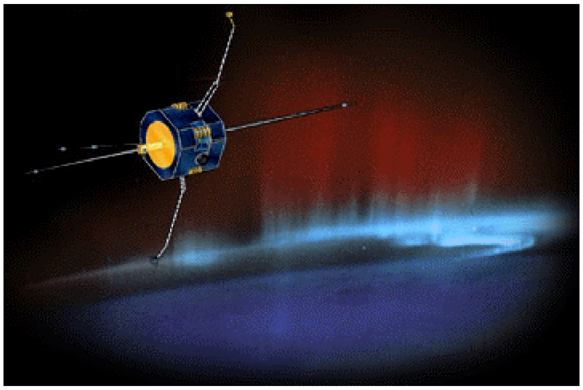

Fig. 3.1 The FAST spacecraft showing traditional massive electric field booms.

Six sensors form an orthogonal system of boom-pairs to provide a 3D measurement., for a total experiment weight Wire deployment mechanisms, or stacer mass required for stiffness, cause each sensor to be 1-3.5 kg of 6-21 kg. This is unacceptable for nanosatellites. Despite this difficulty, electric field measurements are important for upcoming space physics missions, including constellation class missions such as the Orion constellation of NASA's Living with a Star program. Other constellation missions that employ electric field measurements are MagCat (MIDEX class proposal), QUATRO (SMEX class proposal), Swarm (a European multisatellite mission proposal) and others. The proposing team is participating in many of the above proposed missions and thus has a vested interest in the success of these and in participation in future constellation class missions. For both the sake of participating in future nanosatellite constellations (such as NASA's Magnetospheric Constellation DRACO) and for improving the funding probability of current proposals that involve electric field measurements, it is important that our team develops a miniature electric field sensor that benefits state of the art mechanical and electronic designs and incorporates lessons learned from the most recent flights. We propose to design, model and prototype a complete 3D electric field instrument suitable for a 20kg nanosatellite that is under 3 kg. We will do so by taking advantage of lessons learned on most recent flights and a number of design changes that are most suitable for nanosats.

1) Thin wire to sphere. On the Cluster II flight the spherical sensors connected to the long 8-wire cable via an ultra-thin wire. This improved the performance (sensitivity) of the measurement by a factor of 10 from previous missions. Effectively the small surface area of the ultra-thin wire prohibited surface-charge photoelectrons from the 8-wire cable to return to the sphere.

2) Wire resize. Measurements taken during the deployment of the Cluster II wires

indicated that the quality of electric field measurement improved drastically at a length of 24m. At small distances the asymmetric photoelectron cloud creates large differences between the spheres that are not due to the ambient electric field. The potential (and its asymmetries) drop with distance as 1/r and the critical distance r0 is proportional to the satellite diameter, a. For a typical nanosatellite a<0.5m and a wire deployment to 6m is expected to provide adequate measurements. We will baseline a 10m wire including margin. The new (smaller) size permits relocation of the preamps at the satellite, rather than at the sphere.

3) Spool and motor redesign and consolidation. Conforming to the high degree of integration expected of nanosatellite design we will consolidate wire spools and motors into a single motor for all four wires, located at the center of the nanosat. A new (lighter) motor and spool design commensurate with the smaller wire length bestows deployment simplicity with further weight savings.

4) Axial boom sensor. The spherical sensor is useful in that it minimizes the effect of satellite potential asymmetry by increasing the sensor area. Since most nanosatellite concepts are expected to have a spin vector along the ecliptic normal and the north-south potential asymmetry is minimal, there is no need for spherical sensors. Rather, as surmised from the Cluster II thin wire, it is important for the sensor to be a long, thin tube. Tubular, thin wall sensors have improved stiffness to weight ratio. A telescopic assembly is envisioned, whereby an axial boom is composed of 3 stacer pieces of decreasing diameter, with the final step being the sensor. A 6 m - long boom can thus be build with stiffness that parallels that of previous designs but with significant weight reduction. The latter comes from the decreasing diameter with distance and from the reduced tip mass.

5) Boom electronics boards consolidation and reduction. The boom electronics boards, performing boom deployment and analog signal processing currently operate with discrete electronics modules. Integration on a single chip and consolidation on a single board, near the spool and motor assembly permits a very high degree of weight reduction. Again, this stems mostly from the new approach of a highly integrated nanosatellite design, that could not be afforded by the distributed subsystem philosophy of classical spacecraft.

6) Hinged radials. One problem that is anticipated from the new design is the poor Izz/Ixx ratio that stems from the reduced length and tip-mass of the wire sensors. This problem has been dealt with and addressed for the MMS mission (Pankow and Ullrich, 2000). We will evaluate this problem for 20kg, 0.5m diameter nanosatellites spinning at 10-20 RPM. The solution entails increasing the "effective" spacecraft diameter by adding a small stacer (or carbon epoxy) boom at the base of the wire. The wire is hinged on the stacer and the satellite becomes more stiff to nutation and tip-off. The weight penalty from this addition is expected to be small and will depend on spin rate, choice of hinge boom, length and stiffness desired, etc.

Sensor Mass Breakdown:

Component	Mass
Wire: 10m X 6g/m X 4 wires	240g
Sphere sensors: 60g X 4	240g
Preamps: 80g X 4	320g
Boom Electronics Board	200g
Deployment (spool, motor, etc)	1000g
Axials: 500g x 2	1000g

4. Plasma Analyzer Heritage

5. Micro/Nano Satellite System

Specifics of Research Objectives: This proposal seeks to develop a UC/LANL consortium to develop small spacecraft and instrumentation to enable space scientists within the UC system to successfully compete for future NASA missions. Collaboration with faculty and students in the Earth and Space Sciences, Atmospheric Sciences, and Physics and Astronomy departments, the California Nanotechnology Institute and Mechanical and Aerospace Engineering departments will make this a truly interdisciplinary collaboration. Space scientists and engineers routinely work together at Los Alamos National Laboratory where the "group" structure fosters close working relationships between the technologists and the scientists. This new UC/LANL consortium will allow engineering and science faculty the opportunity similarly to work closely together across department, college and campus boundaries. The consortium will provide students the opportunity to work on real-life, hands-on space science missions and will strengthen UCLA's and UC-Berkeley's space science activities immeasurably. The consortium takes advantages of the existing strengths of the different member institutions and combines them in order to develop a complete repertoire of capabilities needed to build small space science satellites.

Education Objectives: In particular we will utilize the experience of LANL in building small spacecraft but incorporate a strong educational component at the graduate, undergraduate, and pre-college level. Specifically in addition to the traditional graduate and senior undergraduate involvement we will partner with UCLA's Graduate School of Education's Project X to involve science teachers in urban school districts into the research program. A summer science teacher fellowship program and workshop will involve pre-college urban school district teachers directly into the research objectives of the consortium. In addition the consortium strengthens the educational exchange between the UC campuses and LANL and utilizes LANL's technical strengths (computational resources for data visualization for example) in both UC research and UC's teaching mission.

Consortium Members Roles: This consortium will develop small sensors and spacecraft for space environment monitoring. The UCLA magnetometry group develops low-mass and volume flux gate magnetometers and tests small commercial chip-based magnetometers for their suitability for space missions. Faculty within the California Nanotechnology Institute will work with scientists at LANL developing MEMS, which have the potential to be utilized as plasma diagnostics. Faculty at UC-Berkeley, UCLA and LANL provide expertise in developing multiple spacecraft missions in order for the consortiums efforts to be focused on developing mission concepts. Students and faculty at UC-Berkeley develop small lightweight electric field booms. Partnerships with NASA JPL and commercial aerospace companies that have been developed in the past will continue to be fostered by the consortium.

Future Funding: The consortium is well poised to respond to future NASA opportunities to participate in space missions in a wide range of disciplines including earth observing (atmospheric and oceanography), geospace physics, planetary physics, and astronomy. The timing of this CLC initiative is excellent for responding to these future opportunities. UCLA, UC-Berkeley and LANL have a long history of participating in NASA missions and have developed plasma, magnetic, and electric field sensors on scores of spacecraft including for the upcoming ST-5 microsatellite mission. The consortium strengthens both LANL's and UC's ability to compete for spacecraft missions by teaming a Minority Institution (UCLA) with the technical and intellectual strengths of LANL.

Management Structure: The consortium is managed by the PI at UCLA who has overall financial and scientific responsibility. He works closely with the other academic faculty to foster collaboration and interdisciplinary research. An advisory team of co-investigators from the different UC campus programs and departments, and LANL scientists ensures close collaboration. This proposal funds 4 graduate students and 3 post-doctoral fellows. A winter quarter planning workshop of all the participants is held at UCLA each year to coordinate activities and to share opportunities. It is planned to have all the students and faculty in residence at LANL for at least part of the summer each year to integrate the research efforts of the different teams.

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