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Spence, Harlan E., Prof.
Petschek, Harry E., Dr.

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Boston University
Center for Space Physics
725 Commonwealth Avenue
Boston MA, 02215

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14. ABSTRACT
Under the task of nanosatellite mission design, we developed a mission concept that enables hundreds of one-kilogram spacecraft to be placed into orbit with a single mothership. We performed trade studies to arrive at a positive feasibility assessment. The results of that study were described in two publications. Second, under the task of spacecraft design, we developed nanosatellite designs needed to enable constellation missions. Design studies were conducted and subsystems prototyped, including a spin-table and launcher concept for a small stack of nanosatellites. Engineering design studies of this work appeared in the refereed literature. Instruments to be flown on such a small craft have been specified and then developed as part of a related AF SBIR effort. Undergraduate students (>100 in the Aerospace Engineering, Mechanical Engineering, and Electrical and Computer Engineering departments) played an enormous role in the mission and spacecraft definitions of the Constellation Pathfinder project. In addition to five publications, numerous invited and contributed presentations of these studies have been presented at national and international meetings.

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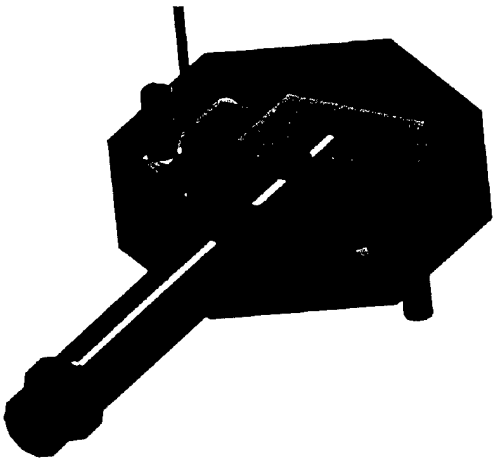
a. REPORT	b. ABSTRACT	c. THIS PAGE			Harlan E. Spence
U	U	U	UU	8	19b. TELEPHONE NUMBER *(include area code)* 617-353-7412

FINAL REPORT
FOR AFOSR GRANT NO. F49620-99-1-0249

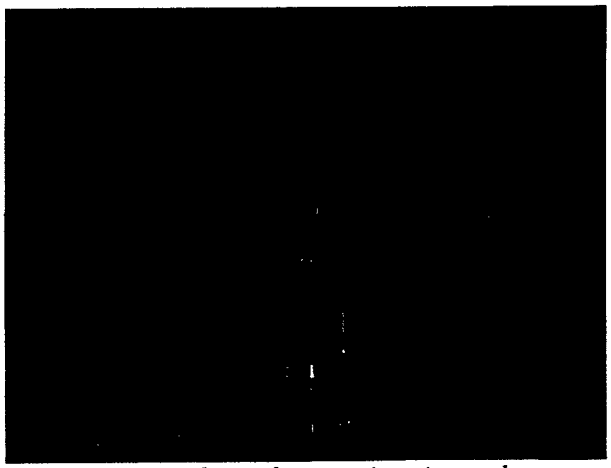
CONSTELLATION PATHFINDER:
A UNIVERSITY NANOSATELLITE PROJECT

Principal Investigator: Harlan E. Spence
Associate Professor of Astronomy
Center for Space Physics and
Department of Astronomy
Boston University
725 Commonwealth Avenue
Boston, MA 02215

E-mail: spence@bu.edu
Phone: (617) 353-7412
Fax: (617) 353-6463



Nanosatellite design concept needed to enable a nanosatellite constellation such as the Magnetospheric Mapping Mission.



BU Undergraduate engineering students demonstrating their design of a nanosatellite spin table/launcher. (Spring 2001)

AFOSR Grant No. F49620-99-1-0249
(BU Grant # 20-325-3975-5)
Overall Period of Performance: 5/1/99-4/30/02

Executive Summary of Research

This report describes the efforts accomplished during the grant's period of performance, covering the period of 1 May 1999 to 30 April 2002, of an AFOSR University Nanosatellite grant. We have met the goals set forth in the proposed research objectives. The results of several studies have been published in the refereed engineering and scientific literature. In addition, numerous invited and contributed presentations of these studies have been presented at national and international meetings during the performance period. These studies are summarized below in two main areas and then major accomplishments within the four reporting periods are identified thereafter:

- **Nanosatellite Mission Design** – We developed a mission concept that could allow for hundreds of one kilogram spacecraft to be placed into orbit with a single mothership. In our initial work, we had explored the use of laser communication as an enabling technology for communications. We quickly dismissed this as too immature a technology. Fortunately, standard RF communications was a very suitable replacement. We explored a large number of issues in mission design to arrive at a positive feasibility assessment. The results of that study were incorporated into missions studies describing related types of constellation concepts (**Angelopoulos and Spence, 1999; Fennell et al., 2000**).

- **Nanosatellite Spacecraft Design** – We have used the funding to move rapidly forward with the nanosatellite design needed to envision any large constellation. Design studies have been conducted and prototyping of subsystems have been accomplished, including a spin-table and launcher concept for a small stack of nanosatellites. Engineering design studies of this work have appeared in the refereed literature (**Rayburn et al., 1999; Luu et al, 1999**). Derivative designs have been developed for a low-altitude version of the basic spacecraft. Also, as part of the nanosatellite development, instruments that could be flown on such a small craft have been considered and in some cases early development is now underway (**Galica et al., 2001**). As our AF funding was expiring, we secured additional NASA funds to continue our design efforts into the prototype stage.

Student Involvement

Undergraduate students have played an enormous role in the mission and spacecraft definitions of the Constellation Pathfinder project. I have had nearly 100 students involved since the beginning of the project, some through direct employment, but most through a senior design coursework in our College of Engineering (in the Aerospace Engineering, Mechanical Engineering, and Electrical and Computer Engineering departments). This opportunity to be involved in designing a "real" mission provided an outstanding learning experience, in many cases propelling top students off to graduate school in Aerospace Engineering or into top positions straight from their BS degrees. This level of student involvement was exceptional and may be as important a "deliverable" as the engineering and science development of the Constellation Pathfinder spacecraft itself.

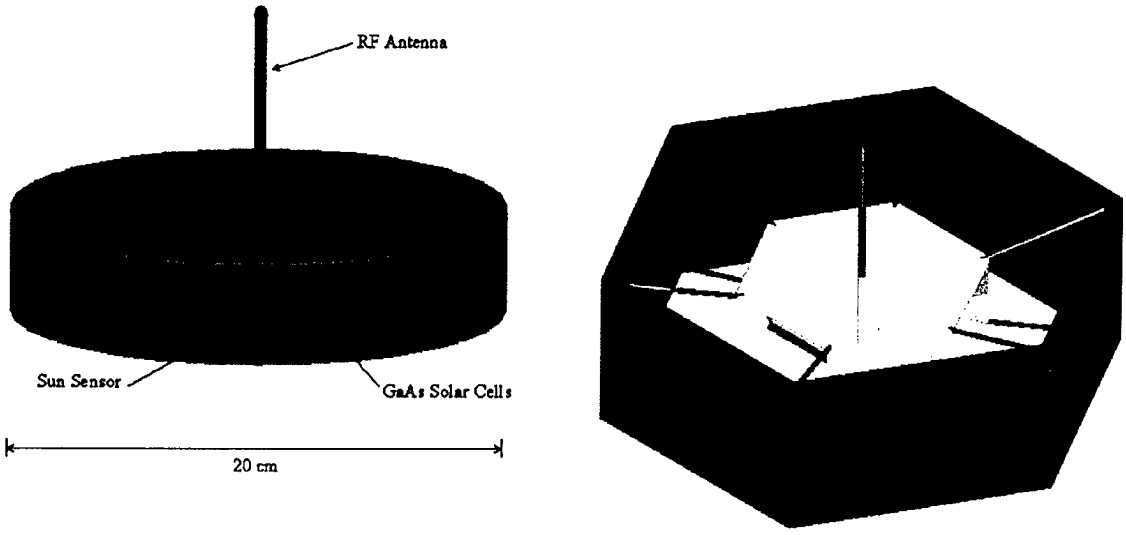
List of Inventions

No inventions were developed as a result of this research effort for the entire performance period covered in this report.

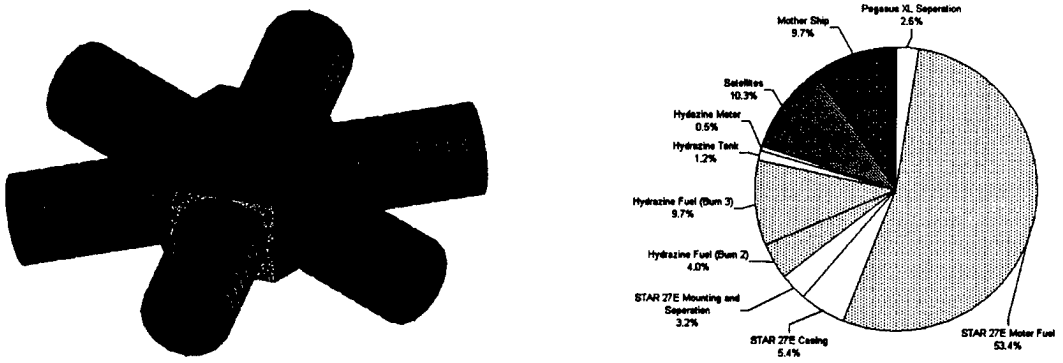
Reporting Period Accomplishments

1) 05/01/99 - 08/31/99

- **Completed preliminary design of Constellation Pathfinder nanosatellite based on earlier conceptual design.** This project represented the first step from our conceptual design toward a robust preliminary engineering design. In the process, we validated the assessment that the mission could be achieved in a very small, resource-limited package (1 kg, 1 W) and developed resource allocation tables for each of the major components of the spacecraft. Preliminary thermal and vibration studies demonstrated that the preliminary design was within the guidelines of even a rather harsh launch and orbital environment. This study also began the task of identifying critical design paths (thermal, communications, power). *(Study involved one senior Aerospace Engineering undergraduate.)*



Conceptual (left) and preliminary (right) designs of Constellation Pathfinder

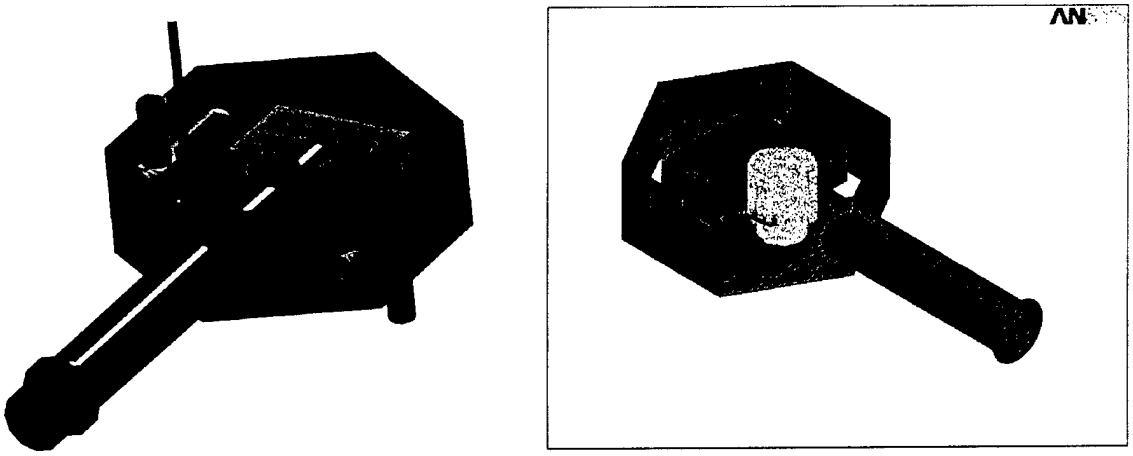


Preliminary design of mother ship concept (left) and mission resource allocations (right)

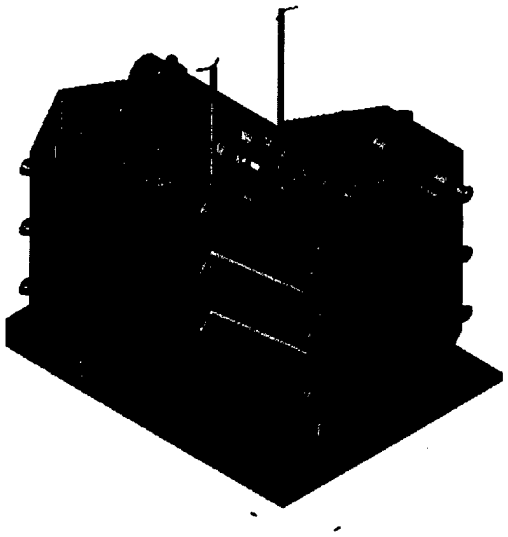
- **Completed trade study of primary science instrument, a 3-axis vector fluxgate magnetometer from MAGSON.** This project was to research and identify possible flight magnetometers. We investigated several COTS magnetometers that had the requisite low-resource requirements of the project (low mass, low power, low volume, low cost). Several vendors provided prototype magnetometers and these were subjected to environmental tests in our laboratory test chambers (thermal and magnetic). Based on these initial tests, we discovered that COTS general-purpose magnetometers would not be suitable. We identified another non-US vendor who we would describe as part research-oriented and part commercially-motivated. This company, MAGSON, has excellent past history for developing small, cheap, but highly capable magnetometers that fit our requirements. We worked with their engineers to define a magnetometer suited for Constellation Pathfinder. While somewhat more expensive per unit than the truly COTS instruments, this important component of our mission has been successfully identified.

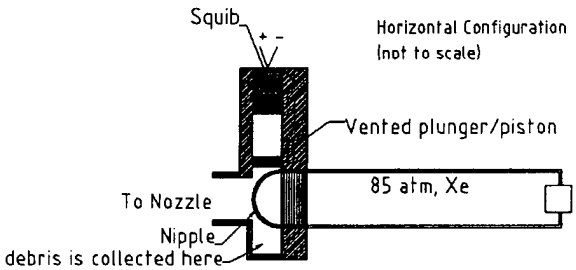
(2) <u>09/01/99 - 08/31/00</u>

- **Completed preliminary design of Constellation Pathfinder nanosatellite.** *This 146-page report outlines the mission concept, the science instrument payload, and includes systems analyses and design of the configuration and layout, structural design, thermal design including full eclipse analyses, communications, launch environment analyses, release mechanism trade studies, flight dynamics, and nutation damping.* This was our first complete end-to-end design effort on the nanosatellite using such tools as, for example, STK and ANSYS for sophisticated communications and thermal modeling.. *(Study involved four senior Aerospace Engineering undergraduates.)*



Rendering of Constellation Pathfinder (left) and nodal analysis using ANSYS (right)



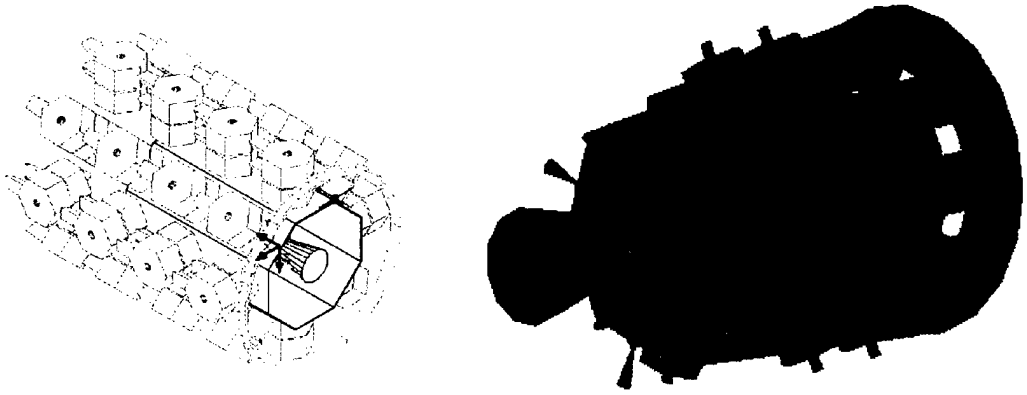


Nanosatellite stacks on mothership launcher platform (right) and release concept (left).

- **Completed preliminary design of Sun Sensor system.** This project was to design and develop an in-house small sun sensor capable of working on a rapidly-spinning nanosatellite. A simple system was designed and prototyped. A parallel trade study was conducted and alternative solutions were found. Ultimately, we decided to go with a micro sun sensor developed for other applications by the Army Research Laboratory. That sensor is now part of our present design. *(Study involved four senior Electrical and Computer Engineering undergraduates.)*

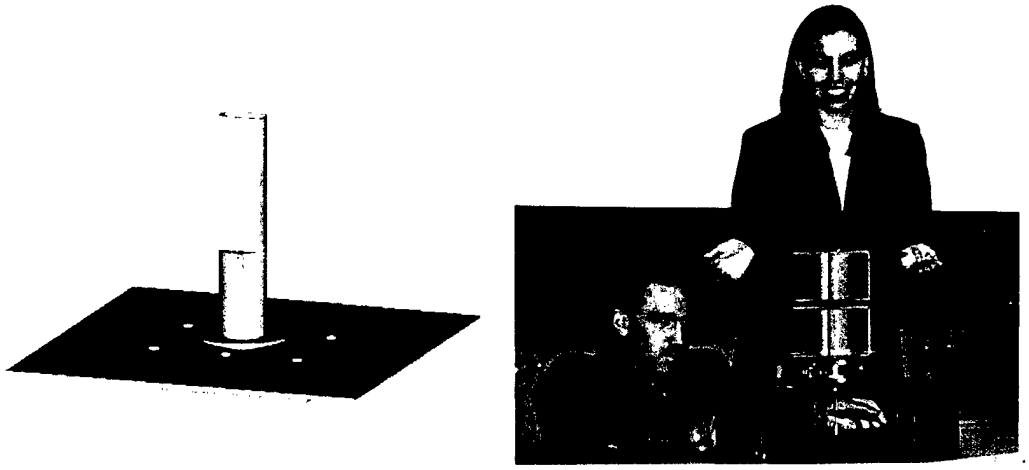
3) **09/01/00 - 08/31/01**

- **Completed preliminary design of Constellation Pathfinder mothership (called "Statulinus").** *This 167-page report outlines the mothership concept, including preliminary engineering trade studies.* The report does an end-to-end mission study of the main spacecraft systems including: propulsion, attitude determination and control, power and thermal, structure, and systems integration. *(Study involved five senior Aerospace Engineering undergraduates.)*



Initial and final preliminary designs of nanosatellite mothership, Statulinus.

- **Completed design of an interface and release mechanism between the Constellation Pathfinder nanosatellite and the mothership Statulinus.** The purpose of this release mechanism is to spin up and then release sequentially a stack of nanosatellites on a larger mothership holding many, many stacks. This mechanical device was designed, fabricated and tested during the reporting period and was designed to be consistent with nanosatellite design and mothership concept. The 98-page report details the design constraints, including cost analysis and failure analysis, as well as engineering drawings that were used in our shop to prototype the design. *(Study involved three senior Mechanical Engineering undergraduates).*



Drawing of launcher prototype (lef) and test of prototype launch table (right).

Aerospace and mechanical engineering senior undergraduates involved in "Statulinus" study and launcher spin-table prototype (see in right of foreground of left picture.)

- **Completed modification of nanosatellite design to incorporate collapsible magnetometer boom** in order to provide higher packing factor of nanosatellites onto mother ship. Fixed booms made deployment difficult. Extensible boom facilitates in design more nanosatellites per mothership. Booms deploy after spin

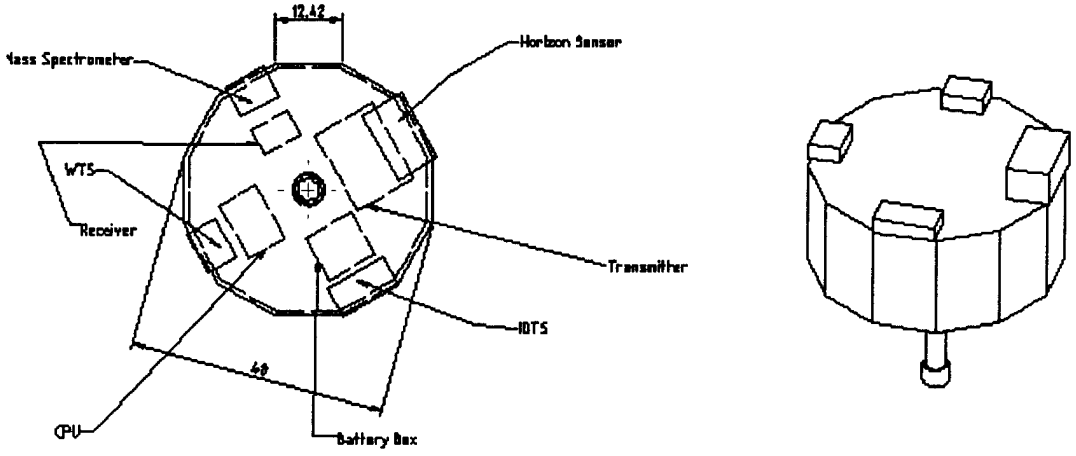
up of nanosatellite through centrifugal forces. Working prototype of boom completed in our machine shop after re-engineering study.

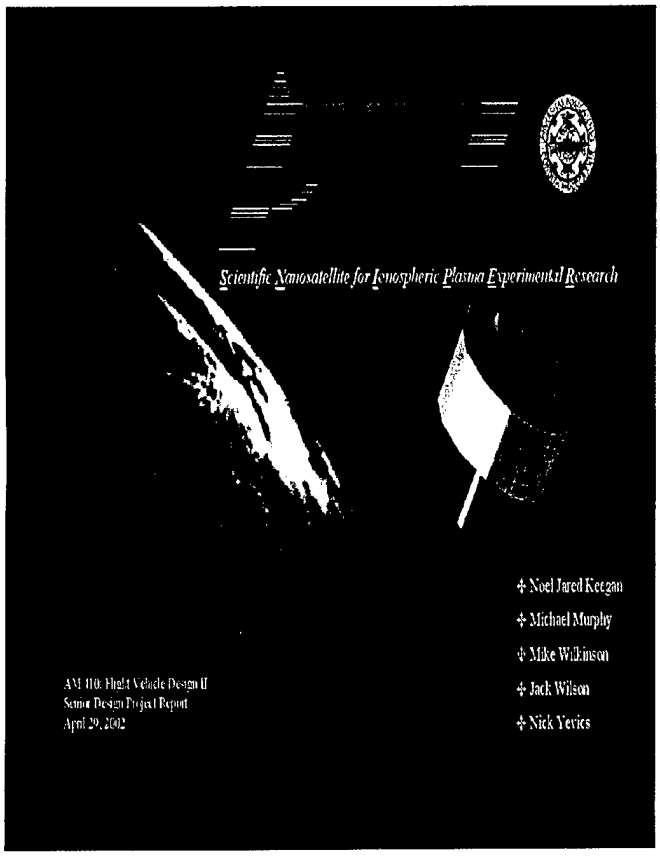
- **Completed development of prototype RF transceiver based on COTS system and power system.** The RF is deemed to be the tall pole in the tent, and is an item that we will need to purchase from an external vendor. We developed a working prototype of the type of RF system we will eventually use and established a link between the two transceiver boards at the target frequency (415 MHz). We also designed and breadboarded a power system using solar cells, power conditioning circuitry, and NiCd batteries for backup power. (Study involved twelve senior Electrical and Computer Engineering undergraduates.)

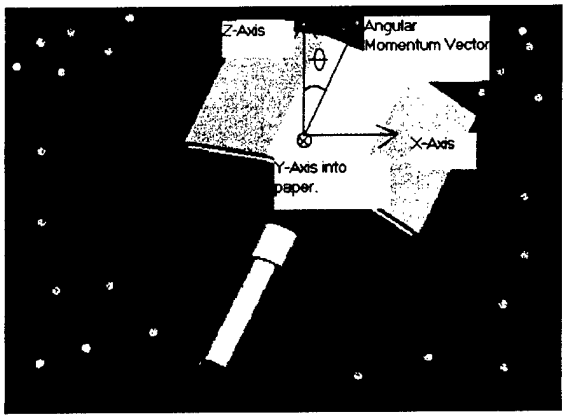
- **Completed end-to-end mission review by professional engineers at The Aerospace Corporation.** In early 2001, The Aerospace Corporation (TAC) conducted an internally-funded reviews of the Constellation Pathfinder nanosatellite and mission concept. Their six-week study reviewed project progress and was aimed at developing a collaborative effort in getting the mission flown through TAC channels (including the possibility of an upcoming STP mission). As a result of the positive feedback from that review, we are moving ahead with discussions with sponsors regarding possible flight opportunities.

4) **09/01/01 - 04/30/02**

- **Completed preliminary design of Constellation Pathfinder's low-altitude derivative (called "Sniper") in collaboration with NASA/GSFC engineerings and scientists.** *This 57-page report outlines the modifications needed to evolve CP to a low-altitude version, including preliminary engineering trade studies.* The report does an end-to-end mission study of the main spacecraft systems including: structures, power system, communications, ACDS, thermal and cost. Engineering drawings, the cover page of their report, and an isometric view of SNIPER is shown below. *(Study involved five senior Aerospace Engineering undergraduates.)*







Publications ***(Italicized authors are BU Undergraduates)***

1. Angelopoulos, V., and **H. E. Spence**, Magnetospheric constellation: past, present, and future, in *The International Solar Terrestrial Physics Program: The Great Observatory for the Sun-Earth Connection*, AGU Geophysical Monograph Volume 109, pp. 247- 262, 1999.

2. Luu, K., M. Martin, M. Stallard, H. Schlossberg, J. Mitola, D. Weidow, R. Blomquist, M. Campbell, C. Hall, E. Hansen, S. Horan, C. Kitts, F. Redd, H. Reed, **H. E. Spence**, and B. Twiggs, University nanosatellite distrubuted satellite capabilities to support TechSat 21, Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites, SSC99-III-3, pp. 1-9, 1999.

3. ***Rayburn, C. D.***, **H. E. Spence**, H. E. Petschek, M. Bellino, J. Vickers, ***M. Murphy***, N. Dennehy, D. Sargent, M. Socha, Constellation Pathfinder: A University Nanosatellite, Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites, SSC99-V-1, pp. 1-9, 1999.

4. Fennell, J. F., **H. E. Spence**, T. E. Moore, and J. Galloway, Magnetospheric constellation missions, Proceedings of the Cluster II Workshop on Multiscale/Multipoint Plasma Measurements, *ESA SP-449*, 2000.

5. Galica, G. E., B. D. Green, F. Scire-Scappuzzo, **H. E. Spence**, J. D. Sullivan, B.K. Dichter, and D.L. Cooke, Scintillator-Based Ring Current Imager for Nanosatellites, Proceedings of the 39th AIAA Aerospace Sciences Meeting, AIAA 2001-0237, 2001.