Jan. 8, 1999

Grant Number NCC 2-471

IN-91
018 286

FINAL REPORT

WORK ON PLANETARY ATMOSPHERES AND PLANETARY ATMOSPHERE PROBES

Alvin Seiff, grantee
P.I.: Peter Lester, Chair, Dept. of Meteorology

On April 1, 1987, Ames Research Center and San Jose State University entered into an agreement to collaborate on Studies of the Atmosphere of Venus and Work on the Atmosphere Structure Experiment of the Galileo Jupiter Entry Probe. This grant terminated on June 30, 1998. This is a summary final report of work accomplished under the grant.

Under this agreement, the grantee worked in the following subject areas:

- Galileo Probe science analysis
- Galileo probe Atmosphere Structure Instrument
- Mars Pathfinder Atmosphere Structure/Meteorology instrument
- Mars Pathfinder data analysis
- Science Definition for future Mars missions
- Viking Lander data analysis
- Winds in Mars atmosphere
- Venus atmospheric dynamics
- Pioneer Venus Probe data analysis
- Pioneer Venus anomaly analysis
- Discovery Venus Probe
- Titan probe instrument design
- Laboratory studies of Titan probe impact phenomena

Collaboration with Ames scientists and engineers included: Dr. Richard E. Young, Mr. Benny Chin, Mr. Charles Sobeck, Mr. John Mihalov, Dr. Robert Haberle, Dr. Chris McKay, Dr. Carol Stoker, and Dr. James Pollack

The work has resulted in over 10 articles published in archive journals, 2 encyclopedia articles, and numerous working papers. The grantee has served as PI of the Galileo (Jupiter) Probe Atmosphere Structure Instrument, as Co-I and consultant to the Huygens (Titan) Probe Atmosphere Structure Instrument Team, as chairman of the Mars Pathfinder Science Advisory Team for the atmosphere structure and meteorology instrument, and as a member of the Discovery Venus Chemical Probe study team, with responsibility for measuring the structure of the atmosphere of Venus during entry and descent.

This final report is organized around the four planets on which there was activity, Jupiter, Mars, Venus, and Titan, with a closing section on Miscellaneous Activities.

<u>The Galileo Probe Atmosphere Structure Experiment</u>: A major objective of the grant was to complete the fabrication, test, and evaluation of the atmosphere structure experiment on the Galileo Probe, and to receive, analyze, and interpret data received from the spacecraft. The grantee was competitively selected to be Principal Investigator of Jupiter's atmosphere structure on the Galileo Probe. His primary motivation was to learn as much as possible about Jupiter's atmosphere by means of a successful atmosphere structure experiment, and to support the needs and schedule of the Galileo Project.

After a number of launch delays, the Flight instrument was shipped to Kennedy Space Center 2 years after the start of this collaboration, on April 14, 1989, at which time it was determined from System level tests of the ASI on the Probe that the instrument was in good working order and ready for flight. The spacecraft was launched on October 18, 1989. Data analysis of test and calibration data taken over a period of years of instrument testing was continued in preparation for the encounter.

The initial instrument checkout in space was performed on October 26, 1989. The data set received by telemetry was thoroughly analyzed, and a report of the findings was transmitted to the Probe Operations Office on Feb. 28, 1990. Key findings reported were that the accelerometer biases had shifted by <1 mg through launch and since calibration at Bell Aerospace in 1983; accelerometer scale factors, evaluated by means of calibration currents, fell on lines of variation with temperature established in laboratory calibrations; pressure sensor offsets, correlated as a function of temperature, fell generally within the limits of several years of ground test data; atmospheric and engineering temperature sensor data were internally consistent within a few tenths of a degree; and the instrument electronics performed all expected functions without any observable fault. Altogether, this checkout was highly encouraging of the prospects of instrument performance, although performed >5 years prior to Jupiter encounter.

Capability of decoding the science data from the Experiment Data Record to be provided at encounter was developed and exercised using the tape recording of the first Cruise Checkout data. A team effort was organized to program the selection and combination of data words defining pressure, temperature, acceleration, turbulence, and engineering quantities; to apply decalibration algorithms to convert readings from digital numbers to physical quantities; and to organize the data into a suitable printout.

A paper on the Galileo Atmosphere Structure Instrument was written and submitted for publication in a special issue of Space Science Reviews. At the Journal editor's request, the grantee reviewed other Probe instrument papers submitted for this special issue.

Calibration data were carefully taken for all experiment sensors and accumulated over a period of 10 years The data were analyzed, fitted with algorithms, and summarized in a calibration report for use in analyzing and interpreting data returned from Jupiter's atmosphere. The sensors included were the primary science pressure, temperature, and acceleration sensors, and the supporting engineering temperature sensors. This report was distributed to experiment coinvestigators and to the Probe Project Office.

The second cruise checkout was performed as the spacecraft flew by Earth on Nov. 20, 1992. Analysis and interpretation of the test data showed the instrument to be operating properly and repeating values seen in the Dec., 1990 checkout to within ± 1 or 2 counts.

During 1993 and 94, preparations for analysis of the data of the Atmosphere Structure experiment made important progress. Work was completed to decode the Experiment Data Record from a magnetic tape on which the experiment data were to be delivered to the ASI Team. A second computer program to convert the digital numbers received (in counts) to physical quantities (temperatures, pressures, accelerations) was nearly completed. The PI provided the decalibration algorithms and guided and interacted with coinvestigator D.B. Kirk of the University of Oregon in this work.

Prior to the final cruise checkout, which occurred 8 months before encounter and about 3 months before the probe separated from the orbiter on July 10 of 1995, the grantee negotiated with the Project to obtain telemetry of checkout data from the Probe. (The Project Office had taken the position that no instrument data were to be returned to Earth from this checkout, over the strenuous objection of the PI.) The grantee wrote a number of letters of justification stressing the importance of returning these data. In January, the Project agreed to collect and transmit to Earth data from the ASI taken at that time. These data were used to establish which accelerometer was to be primary for the critical entry period, and in Descent, and defined the offset shifts which had occurred since Nov., 1992, thereby contributing to the accuracy of the measurements of the atmosphere.

Laboratory tests were performed with the flight spare temperature sensor to define the thermal conductivity errors to be expected when the sensing head is exposed to the cold atmosphere (~100K, minimum) while its mounting pad is on the shelf inside the spacecraft at 223 to 390 K. These data established that the conduction error was small, and furthermore, established a quantitative basis for its correction.

As the Galileo Mission moved toward encounter in early 1995, emphasis and share of the grantee's time devoted to it increased. In the final Cruise Checkout, an "Abbreviated System Functional Test" was performed in space near the orbit of Jupiter on March 16, 1995. Analysis of this checkout showed the Atmosphere Structure Experiment to be in good health and showing generally excellent stability of the electronics and sensor calibrations after 5 years in space.

Another key event was an ASI Team meeting convened by the grantee on Feb. 13, 1995, which brought together the 9 individuals participating in this experiment to define status, identify work remaining to be done, and assign tasks. (Two Ames scientists, Richard E. Young and John Mihalov, were members of this Team.) This meeting clearly energized the Team's activity, and brought people into participation who had not been active previously. The data decommutation and decalibration program had been successfully completed in the past year and was tested with one of the Cruise data sets. Work was started on the trajectory reconstruction programs which extended those used on the Pioneer Venus mission to include: 1) massive heat shield ablation leading to important mass loss during entry; and 2) rapid planet rotation, which introduces terms in the motion equations not needed on Venus. An approach was invented to represent the mass loss as a function of time, initially based on the theoretical analysis of ablation used to design the heat shield. A gravitational model for Jupiter was identified and adopted. The approach to defining atmospheric mean molecular weight in the descent period was redeveloped, and its accuracy estimated. (This objective would be abandoned if strong vertical flows were encountered, and be replaced by the objective of defining the vertical flows.) The atmospheric lapse rates to be expected were reviewed, and the instrument's capability for defining them was analyzed. The effect of moisture in the water clouds on atmospheric lapse rate was quantified. The effect of atomic and molecular spin configurations of hydrogen (ortho and para) was reviewed based on literature publications. The above were representative of Galileo work activities.

From July through November, 1995, the grantee led the Atmosphere Structure experiment team effort to prepare for the encounter and receipt of data. Work included interpreting and organizing calibration data, selecting values for key constants for the Probe and for the planet, devising analysis strategies and finishing the programs to read data from project files, preparing data analysis programs, and participating in science team meetings in anticipation of the data return.

On Dec. 7, 1995, the Galileo Probe encountered the planet Jupiter. From earliest receipt of fragmentary data in December through May, 1996, analysis and interpretation were furiously ongoing. The interpretation was complicated by probe internal temperatures and temperature rates well outside the bounds specified in advance. The pressure data required corrections, and to develop a basis for those corrections, complex laboratory tests of flight spare instruments were designed, planned, and performed.

Early contributions of the experiment were: To define the basic structure of the deep atmosphere to a depth of >22 bars, where temperature was 429 K, as lying close to the dry adiabat. Definition of the stability of the atmosphere at altitudes below the 5 bar level, where the atmosphere was unexpectedly found to be stable, with important implications for the planetary dynamics. Definition of the upper atmosphere profiles of density, pressure, and temperature to an altitude of 1000 km (1 nanobar), showing thermosphere temperature reaching 900 K, and densities at this level 100 X those anticipated. Indication independent of the Doppler radio tracking of wind velocities at altitudes below the 3 bar level as constant and ~200 m/s. These contributions all became more quantitative and better supported with further analysis.

Invited papers were presented at the Lunar and Planetary Science Meeting in Houston on March 18, and at the American Geophysical Union in Baltimore on May 19. A quick-look article on experiment results was prepared for *Science*, and published in the May 10, 1996 issue. Seminars were given at the California Academy of Science in March, at Varian Associates in February, and for the Astronomy Club of Santa Cruz in April.

In 1996 and 1997, the major task was to refine, verify, and extend the analysis of data. The grantee, as Principle Investigator of the experiment, performed analysis, led the effort. The experiment returned to Earth the first and only *in-situ* sounding of the atmosphere below the 1-bar level and above the 10 mb level. In the middle and upper atmospheres, it yielded data of quality comparable to the best information available in Earth's similar regions. Work included organizing and interpreting the data, devising strategies and approaches for dealing with problems, such as the response of instruments operating outside their design ranges, preparing data analysis programs, and organizing and conducting science team meetings in which the preliminary results were reviewed, their scientific significance discussed, and means of improving the analysis were proposed and responsibilities delegated.

From earliest receipt of fragmentary data in December, 1995, through the end of 1997, analysis and interpretation were continuously ongoing. It was verified that the corrected data indicated a dry adiabatic atmosphere within measurement accuracy. Pressure, temperature, and altitude as functions of time were communicated to other Probe investigators to provide a common framework of depth in the atmosphere at which their individual observations applied.

Definition of the upper atmosphere profiles of density, pressure, and temperature to an altitude of 1000 km, showed thermosphere temperature reaching 900 K at the level where pressure was one-billionth of an atmosphere. (Such high temperatures in the upper atmosphere of a planet 5X the distance from the sun as Earth required explanation.) Discovery of gravity waves propagating in the middle and upper atmospheres, and the discovery by coinvestigators, that these waves were the likely source of upper atmosphere heating. (This explanation has subsequently been challenged.) Measurement of wind velocities at altitudes from 0.5 to 22 bars which indicated, independent of the Doppler radio tracking, wind velocities increasing with depth down to the 4 bar level, and constant at ~250 m/s below that to at least the 17 bar level. Detection of a tenuous ammonia cloud, previously unidentified, existing at the edge of the nearly cloud-free "hot spot" region where the Probe descended.

Invited papers were prepared for presentation at the international COSPAR meeting in England in July, and at the American Geophysical Union in San Francisco in December. An article on middle and upper atmosphere results was published in the April 4, 1997 issue of *Science*.. A paper on winds measured by the accelerometers in the deep atmosphere was published in *Nature*. Invited talks and/or seminars were given for the California Academy of Sciences in March, Ames/Stanford Summer University Fellows Program at Asilomar in July, for the Astronomy Clubs of Santa Cruz and of Foothill College in August, and at the Department of Meteorology, San Jose State University, in May.

Four publications of results of the experiment have included three cited above and a fourth, comprehensive article in JGR--Planets for Sept. 25, 1998.

Mars Atmospheric Research and Projects: As an outgrowth of the grantee's past work in measuring the structure of Mars' atmosphere during entry and descent of the two Viking Landers, he was asked to participate in four areas of renewed Mars activity: 1) As a member of the Mars Atmosphere Working Group. 2) As a participant in the Mars Exobiology Instrument Workshop. 3) As a contributor to planning the NASA Mars Global Network. 4) In a similar role on the Soviet-French Mars 94 Mission planning.

The grantee was appointed to the Science Definition Team of the Mesur (Mars Environmental Survey) probe network mission and the Mesur Pathfinder mission. The function of this team was to define the science goals and priorities of planned Mars missions, which included meteorology goals. This activity became an international forum, with representatives from the European Space Agency (which was planning a parallel mission), from Japan, and from Russia (which had the Mars '94 mission in preparation). The grantee helped establish Team recommendations, wrote and reviewed letters stating the Team conclusions, etc..

These involvements and interaction with Ames colleague Dr. Robert Haberle led to a return to analysis of the Viking Lander parachute descent data to refine and improve the definition of winds between 1.5 and 4 km altitude at the two entry sites. These data, the first in-situ data on winds in Mars atmosphere above the 1.6 meter level, show some very interesting results. The wind magnitudes recorded were 20 m/s at 23^{o}N latitude in early summer, and 8 m/s at 48^{o}N latitude in summer. The wind vectors were found to rotate slowly with altitude, the final directions agreeing with landed measurements by the Meteorology instrument at 23^{o}N, but differing from landed wind direction at 48^{o}N. The lower latitude data were taken in late afternoon, and indications are that they are within the boundary layer. The higher latitude data were taken at 9AM, and were above the boundary layer, estimated theoretically to be 1 km thick at that local time.

A paper was written on winds in the atmosphere of Mars at the 1.5 to 3.5 km level and submitted to the Journal of Geophysical Research--Planets. The paper was published in JGR-Planets (98, no. E4, 7461-7474). These are the first in-situ data on winds in Mars atmosphere above the 1.6 meter level. Wind magnitudes at both the Viking 1 and Viking 2 sites were not well predicted by the Ames Mars GCM which was subsequently, improved to bring about agreement with the data.

Another topic addressed was the variability of the structure of Mars atmosphere, which is known to vary with season, latitude, hemisphere, and dust loading of the atmosphere. The collected data on atmosphere structure were studied, and considered in relation to theoretical understanding. It was concluded that winter hemisphere temperatures were affected in the lower 30 km by the seasonal changes in ground temperature, but that the upper level temperatures were less affected. This topic was of importance to missions which use the atmosphere to decelerate the spacecraft and Mars orbital injection (manned missions and some heavy unmanned missions).

In Sept., 1993, the grantee was asked to chair the Science Advisory Team for a combined atmosphere structure and meteorology instrument (ASI/MET) on the Mars Pathfinder lander mission, the first approved Discovery mission. For a period of about 20 months, this responsibility became the major focus of the grantee's work, involving frequent meetings, presentations, and response to difficult Project Office technical questions. At the same time, work on the MESUR Science Definition Team (of which the grantee was a member) came to an end. The original concept was to distribute 20 long-lived probes over the planet to serve as meteorology and seismology stations and to study the geology and geochemistry at each location. It was determined that that mission as conceived could not be accomplished within the cost guidelines. The Pathfinder mission was an outgrowth of this activity. One of the recommendations of the Science Definition Team was that Pathfinder carry an ASI/MET instrument.

Pathfinder was in the formative state during 1994, 95. The Science Advisory Team was formed to advise the Project at JPL on an instrument to measure the structure of the atmosphere during entry and descent and the meteorology at the landing site for 30 days after landing. The detailed design and fabrication of the instrument, identified by the acronym ASI/MET, was the responsibility of an instrument group within JPL. The SAT met 4 times formally, but it functioned almost daily by way of e-mail and telephone interactions among Team members and Project personnel. Because of SAT activity, the instrument flown to Mars went well beyond what was originally planned by the Project. It had a deployable meteorology mast, whereas it began minimally as a thermocouple mounted on the antenna mast, and a pressure guage. The MET mast had 3 temperature sensors at different heights to measure the near-surface profile in the boundary layer, and included a wind sensor at the tip of the mast. The wind sensor design met the constraints of simplicity and minimum impact on lander systems. It was conceived, developed, and tested by the grantee and coworkers at Ames. The design and fabrication of conceptual wind sensors and their experimental evaluation in the Mars Wind Tunnel was a major effort. The test data were analyzed and graphically presented to the Project to show evidence of wind measuring sensitivity in both magnitude and direction. The Team also advised on instrument calibration approaches, data sampling routines on the surface of Mars within the spacecraft limitations on data capacity and power, etc.. Calibration studies of the wind sensor showed sensitivity to wind speeds up to ~40 m/s, and to wind direction through 360^{o}. A report of these results was prepared and delived to the Project.

A paper on the ASI/MET instrument was prepared and was published in the April 28, 1997 special Pathfinder issue issue of *Journal of Geophysical Research-Planets*. Advisory contact was maintained with the Pathfinder Project and the lead person on the Atmosphere Structure, Meteorology instrument on Pathfinder throughout the year. A proposal to take part in the operational phase of this Mission as a Participating Scientist was prepared, submitted, and accepted. The grantee participated in early data collection phase of the Pathfinder lander and consulted with other ASI/MET Team members on data analysis and interpretation. This work is still ongoing.

<u>Huygens Probe Atmosphere Structure Experiment</u>: Work on an atmosphere structure instrument for the Titan Probe component of the Cassini Mission, designated the Huygens Probe, was funded by a grant extension, dated Dec. 15, 1989. This is a joint European-United States mission to the planet Saturn and its giant moon, Titan. A team of scientists headed by the grant PI was organized in the Space Science Division at Ames Research Center in mid 1989 to begin development of an atmosphere structure instrument for Huygens Probe, with the goal of submitting an experiment proposal . The team identified an objective requiring laboratory development: to discriminate between liquid and solid surfaces on Titan and to determine surface physical properties such as density, strength, and hardness, from impact deceleration traces. Tests were undertaken with scale models, dropped from various heights into sand, to represent the solid planet, and water, to represent the Titan ethane-methane-nitrogen ocean. The data were analyzed to understand the physical processes governing the impact deceleration, and techniques to correlate the a(t) history with surface properties were sought and identified.

In the December, January time period, an experiment proposal was written and submitted to the European Space Agency. The proposed experiment included the atmosphere structure objectives and basic approach of the Galileo Probe experiment now on its way to Jupiter.

The experiments selected to fly on the Huygens Probe were announced Oct. 1, 1990. The winning ASI experiment proposal was by a European team with representatives from Italy, where the PI resides, Finland, Great Britain, France, Germany, and Holland. This selection was influenced by the desire of the European Space Agency, which will fund and have responsibility for the probe, to have major

European science participation. The grantee was immediately invited by the experiment PI to serve as a co-investigator on the experiment.

The grantee served in an advisory role in the design and preparation of the experiment, giving extensive consultation to Italian and British designers of the sensors. Visits were made to the Universities of Padua and Rome in February, 1993, and to the University of Kent and to the European Space Technology Center (ESTEC) in April, 1992, which resulted in many constructive interactions in which the grantee was able to call attention to problems, and discuss solutions. The instrument reached fabrication stage in 1993. Extensive use was also made of e-mail, as well as attendance at Team meetings in Italy, England, and Scotland.

At one point, the Huygens ASI experienced an implementation crisis during the in that it was over the allowed mass. This made it necessary to cut back on the atmospheric electricity aspects of the instrument, but the basic structure instruments were retained intact.

The grantee's activity on the Huygens Probe ASI diminished in 1994, 95, after key decisions on the instrument design had been made. The grantee attended a Project Science Group (PSG) meeting in Pasadena where he interacted with the Probe Scientist and others. He initiated activity at Ames to use CFD to obtain the flow fields and drag coefficient of the entry and descent configurations. He exchanged letters and ideas with the British scientist who is taking lead responsibility for the probe impact measurements and their interpretation. With other e-mail interactions, this was the level of activity possible and necessary to the program.

Venus science activities: The grantee was invited in 1993 to participate in a Discovery Venus Mission, later called the Venus Chemical Probe, by the proposed PI of that mission, Prof. Lawrence Esposito of the University of Colorado. Several meetings were held to define the proposal, and participants collaborated in writing the proposal. The PI made a presentation to the Discovery program workshop in November, where it was well received, and appears likely to be one of the proposals which move forward.

The science objectives of the Venus Chemical Probe were to resolve unanswered questions concerning the minor species chemistry of Venus' atmosphere which control cloud formation, greenhouse effectiveness, and hence thermal structure. The grantee was the structure investigator on this team. Structure parameters measured on the probe establish altitude and pressure levels at which chemical species are measured. The structure experiment also seeks to resolve some issues left unanswered or not completely determined by the four Pioneer Venus Probes, principally the stability of the atmosphere below 12.5 km and the reality of small scale gravity waves in the deep atmosphere. After a competitive selection, this mission was one of ten funded at a low level for a year's design study of the spacecraft and its instrument complement. Before this mission is approved for implementation, it must compete with many others of which only one or two will be selected. The competition was by way of a second, more mature proposal on which the grantee collaborated.

The proposal was not selected as one of three winning Discovery mission starts in 1994. However, the PI wished to continue the effort and resubmit it in another year. The grantee 's responsibility for an atmosphere structure experiment were continued. A measurement approach for the instrument was identified, and sensor studies were undertaken. The grantee was assisted in this work by John Mihalov of Ames. Three Science Team meetings and monthly telephone conferences with the PI and other coinvestigators were required to consolidate the objectives and approach. In these meetings, each coinvestigator having responsibility for an instrument and an investigation (and hence comparable responsbility to that of a PI on other missions) was asked to report progress and status of the design, as well as problems encountered. This culminated in a second intensive proposal writing activity, which involved mutual editing under an exacting schedule. The proposal was submitted in Dec., 1996. The Discovery Program is highly competitive, with over 30 proposals submitted of which only 6 were selected for further study. The Venus Composition Probe was not selected for continuation.

Another area of research, possibly necessary to success of the Venus Composition Probe, was to try to understand 16 years after it occurred the atmospheric physics or spacecraft design flaw which caused the anomalies which occurred on the four Pioneer Venus Probes at and below the 12.5 km level of the atmosphere of Venus. A Workshop was convened by the grantee to study this problem. The Workshop brought together members of the science teams with instrument and spacecraft designers and outside atmospheric scientists. The Workshop concluded that the most likely hardware cause was insulation failure in the electrical harness outside of the Probe pressure vessels, and recommended further harness testing under better simulated deep atmosphere conditions than those used prior to flight. This was done subsequently at Hughes Aerospace Co. (the Probe contractor), and it was discovered that the shrink tubing material used to cover the external lead connections fails (depolymerizes) at 600K, releasing carbon and HF. This fault is capable of explaining numerous anomalies experienced by the Probes. The importance of the finding is that it permits further Venus probes to be undertaken with confidence that no unknown dangers lie in wait at 12.5 km, provided that suitable harness is selected and thoroughly qualified beforehand. A report of the Workshop and its discovery was prepared and was prepared for publication as NASA Conference Publication 3303, Sept. 28-29, 1993.

In another area of research, arrangement was made for Dr. Julio Magalhaes to collaborate with the grantee under a parallel grant at SJSU Foundation to further analyze the descent data of the Pioneer Venus probes and the Soviet Vega Lander, to evaluate the presence of small scale gravity waves in and below the Venus cloud layer. Small scale gravity waves with wavelength ~1 km.appeared to be present in the the descent velocity data derived from the pressures and temperatures measured in Venus atmosphere below the clouds by the four Pioneer Venus Probes. The temperature and pressure profiles were then analyzed directly by collaborator Julio Magalhaes (an Ames post-doctoral fellow) for the presence of the gravity waves. Small amplitude wavelike temperature oscillations were found in the deep atmosphere, with wavelengths of a few km. These have been identified as gravity waves. Papers presenting the results were given at the annual meeting of the Division of Planetary Science of the American Astronomical Society in November, 94, and at the second conference on Venus held at the University of Arizona in January, 95.

<u>Miscellaneous Activities</u>: The grant PI served as a member of the Science Steering Group of the Aeroassist Flight Experiment mission, an Earth's atmosphere experiment to study the shock layer flow around, heat transfer to, and vehicle response to entry during an aerobraking maneuver high in the Earth's atmosphere. Further goals were to answer questions concerning non-equilibrium flow and

thermal radiation, and heat protection systems required. It was intended to be a precursor to the use of such vehicles in Earth operations of manned spacecraft, and in aerobraking maneuvers to put spacecraft into orbit about the planets. The Science Steering Group's function was to review and advise on proposed experiments for this mission. Meetings of the SSG were held in 1989. The grantee devoted only a few percent of his time to this activity.

The grantee also interacted with Dr. John Anderson, PI for gravity research in the Galileo Orbiter Radio Science Team, on the possibility of evaluating the mass of the asteroid Ida which the spacecraft flew by Ida in Oct., 1993.

The Grantee was honored by the American Institute of Aeronautics and Astronautics by selection as the Von Karman Lecturer for 1990. A lecture was prepared and delivered at the Aerospace Sciences Meeting in January, 1990. A written version of this paper was published by AIAA in one of the archive journals of the Society.