Center for Research on Experimental Satellite Technology: A position paper

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Executive Summary

The creation of a technology Center of Excellence, which will enable new science discoveries by developing an innovative and integrative infrastructure for a dramatic increase of observations from space, is advocated. The *Center for Research on Experimental Satellite Technology* (CREST) will develop open standards, technologies and processes necessary for scientific missions that require observations from small orbiting platforms, thereby creating a new class of science missions. In five years CREST will develop key technologies, extend the performance of others and validate their readiness for astrophysical flight missions as well as enable space-based studies in other disciplines such as, planetary studies, remote sensing, solar physics and space physics. To ensure a high probability of success, CREST will articulate a process for developing low-cost space-flight missions that will be based on successful past experiences. It will also incorporate the best practices used in the modern networked community during the design, development as well as test and integration phases. In the end, CREST will enable a long list of scientific discoveries, flight-test key technologies, and train generations of experimentalists who will lead major missions of the future.

A number of sample science experiments that could immediately take advantage of CREST-class astrophysics missions have been identified. They range from the study of fundamental problems in astrophysics to quick response missions for studying comets or supernovae. By enabling a low-cost and high-frequency option for space-based missions, CREST will revolutionize astrophysics from space.

The Center will include universities, industry partners and government entities. Besides specifying the best practices for developing small scientific satellite missions, this team will also conduct a study of geographically distributed organizations with distinctly diverse work cultures. The core members are ready to make a sea change in scientific space exploration in the 21st century and invite others to join the team.

Overview

Early in the 20th century, automobiles appeared as extraordinary vehicles – and now they are part of life everywhere. Late in the 20th century, internet and portable phones appeared as innovations – and now are omnipresent requirements. At mid-century, the first satellites were launched into space – and now some 50 years later – "making a satellite" remains in the domain of highly infrequent events. Why do all universities, government laboratories and similar organizations not have their own research satellites? Why is the work force capable of doing so remarkably small? Why do highly focused science objectives that require just a glimpse from space never get a chance to fly? The *Center for Research on Experimental Satellite Technology* (CREST) will attempt nothing short of making mini satellites for research (following the Moretto and Robinson, 2008 classification) as available as a small plane. Flowing from such a technological innovation will be an array of science achievements spanning the full scope of astrophysics and by extension to other disciplines needing space-based observations.

The engineering and scientific infrastructure for an aerospace society is still in its adolescence due mainly to independently set goals that result in case-by-case unique solutions. This did not occur with computers, cell phones and GPS; they can all connect to each other. CREST will do the same for satellite technologists, scientists, educators, students, and American society. Once successful, a possible proliferation of these satellites will become the (happy) problem to solve, not their rarity as we have today.

Historically, there have been two primary impediments to placing a science experiment in orbit – high launch costs (Space Studies Board, 2000) and the high cost of spacecraft systems and related processes. The first problem appears to have been addressed through the availability of several low-cost (< $10M) launch opportunities. CREST will address the second.

Lowest-cost orbital space science missions – NSF sponsored CUBESATs – are approximately 1Kg in mass and cost approximately $100K+ for the *science payload* and the *spacecraft* (which together forms a *satellite* or *observatory*). CREST will complement the expensive missions which are "too large to fail" and the CUBESATs and suborbital programs (Figure 1). We will do so while deliberately involving students in meaningful roles and creating an environment of spaceflight mission development that encourages experimentation and innovation. CREST will do for the astrophysics community what CUBESAT has done for undergraduates, and together they will provide a roadmap to "domesticate" scientific satellites.

The CREST program will achieve this feat by replacing the current one-of-a-kind satellites (*craft-class*) into a customizable *commodity-class* (like the DELL™ computers). We will demonstrate that our efforts will shorten the development time of these missions so that students could be involved from experiment design to data analysis. It would therefore become the national model for hands-on training for these participants and will leave an important legacy in developing a scientifically and technically competent workforce.

America's space enterprise is facing alarming problems as the graying workforce of the 1960's moves rapidly towards retirement. Our national security, economic health, and environmental sustainability increasingly rely on knowledge collected by on-orbit platforms, but the nation has failed to develop a new pool of scientists and engineers who can serve this need. It seems likely that in addition to the countries in Europe, India, China and Japan will soon close our historical lead in space. At the same time, the competition for talented young people is growing. Today's *Gen Net* students and their faculty from the *Baby Boom* are increasingly engaged in new methods of learning in a digital age. To meet these challenges, the current classroom practices must change, and the value of "out-of-class" experiences must be acknowledged. CREST will aggressively seek new ways to engage students in critical scientific and engineering knowledge while persuasively guiding their education to keep them in the field.

The science, technology and work-force development benefits of small satellite missions have recently been articulated (Gruntman, 2007; Moretto and Robinson, 2008; Baker and Worden, 2008, http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=420). It has been convincingly argued that these missions are a cost-effective way of conducting science from space in many disciplines and, with their rapid turn-around time, can incorporate state-of-the-art technology, which current SMEX or larger programs cannot. When one considers the combined value of science return, technology maturing and training of the next generation of space scientists, technologists and managers, the CREST program could rightfully be viewed as, with apologies to the overused commercial, priceless.

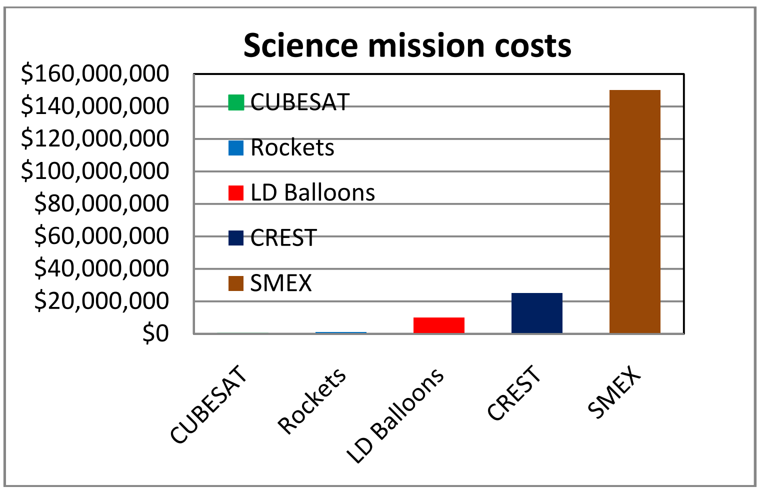

Figure 1: A preliminary estimate for the total cost of a mini satellite mission (including launch) following the approach outlined here. It assumed that the instrument complexity is similar to those designed, developed and flown on sounding rockets, and the integration and test activities and mission assurance program are similar to what is used by commercial, CREST-class launch providers. This exercise revealed that our proposed plans are well-placed between the CUBESATs, the suborbital program and the smallest of the NASA orbital science missions – the Small Explorers (SMEX).

At the end of five years, we envision several important products such as:

- Articulation of standards for spacecraft bus of this class, their major subsystems and their interfaces to each other and to the science payload.
- Maturation of technology that are beneficial to astrophysics and other science missions through suborbital flight tests
- Development of a list of quality subsystems and their capabilities similar to the Sounding Rocket Handbook
- Compilation of a listing of the best practices and processes that lead to a quality CREST-class missions (similar to the GSFC GOLD rules)
- Specification of artificial intelligence (AI) based conformal design tools that could be used by the science PIs to design their spaceflight hardware
- A study of science and technology collaboration for a distributed organization and recommendation for similar activities across science disciplines

Objectives

Many questions from a wide range of science disciplines, from astrophysics to space physics, from microgravity to remote sensing, could be answered by observations from small satellites in Low Earth Orbit (LEO). Moretto and Robinson (2008) have listed 18 possible "shovel ready" missions concerning Space Weather issues alone that could be conducted from small satellites at LEO (see their Table 1) (They defined small satellites as those that cost $100M, take 2 – 3 years to develop and have 250 – 750 Kg mass). These focused experiments could be developed by university researchers at a cost that is significantly lower than the present norm.

For the astrophysics missions envisaged here, a mass between 100 and 250 kg is contemplated. Moretto and Robinson would characterize these as *Mini* satellites with price tag of $50 – 75 M and a development time of approximately two years. *CREST will develop standards, technology and processes to lower the total cost of these missions to $25 M or less*.

Historically, a major obstacle to low-cost space-based science missions has been launch cost. However, in the past decade, tremendous efforts by the space industry and government support have lowered the launch cost tremendously (Table 1). With such affordable launch costs, it is not difficult to imagine a total mission cost of about $25 M for future astrophysics mini satellite missions.

Table 1: Several Low-cost launch options are now available for small science satellite missions (data from Moretto and Robinson, 2008 and Baker and Worden, 2008).

Organization / launcher	Capability / cost	Comments
Sandia Natl. Lab. / Super Strypi	300 kg to LEO/$9M	First launch: 2009
Orbital / Minotaur 1	500 kg to LEO/$20M	First launch: 2006
Air Launch / QuickReach	635 kg to LEO / $5M	Under development
SpaceX / falcon 1	670 kg to LEO / $7M	First launch: 2008
Ride share using ESPA-ring / various	Up to six 180 kg to LEO / "few million dollars"	First launch: 2007
Ride share aboard ISC Kosmotras / Dnepr	Total capability 4500 kg to LEO / Variable	First launch: 1999

Recently conducted science missions of the Mini satellite class were called Student Explorer Demonstration Initiative (STEDI) and University-class explorers (UNEX). They demonstrated that this class of missions is capable of delivering excellent science at a fraction of the cost of SMEX class missions with somewhat higher risk. Three such missions have been launched – CHIPS (http://chips.ssl.berkeley.edu/), SNOE (http://lasp.colorado.edu/snoe/), and TERRIERS (http://www.bu.edu/satellite/). Of those, TERRIERS suffered a bus failure shortly after launch; SNOE conducted over 5 years of scientific measurements resulting in over 15 peer-reviewed and many more conference proceedings and abstracts totaling over 70 publications (see: http://lasp.colorado.edu/snoe/publications/journals.html). Finally, the CHIPS observations have demonstrated that the local area of the galaxy is not emitting radiation in the expected manner. To date, these observation defy a coherent explanation (see Hurwitz et al. 2005); they will likely reshape our view of the structure and dynamics of the galaxy.

The three UNEX/STEDI missions have been conducted for a total cost (for all three missions) of around $65M (assuming $15M average launch cost per mission). This has resulted in two highly successful missions and one failure – a 66% success rate. Contrast this with the SMEX program with a cost of $150M per mission and achieves a success rate of about 90% (nine successful SMEX-es and one failure – WIRE; SPIDR was cancelled). These data could be arguably interpreted as a cost of about $167M per successful SMEX mission vs. $33M per successful UNEX mission. Furthermore, one might expect the UNEX success rate to rise as our experience with such systems increases and more vendors gear up to meet this market.

Straw man Astrophysics Flight Missions

To demonstrate the diversity of astrophysics topics that could be studied from mini satellites, we describe below several viable missions. Some missions will yield classic discovery-mode science while others will need observation of unexpected phenomena that require quick response (the target of opportunity). The latter are not included in the following list.

An all-sky UV survey

In the early 70's the TD-1 satellite made an all-sky survey of the sky at ultraviolet wavelengths. Despite considerable advances in detector technology and electronics since that time, no comprehensive UV surveys have been completed. The MSX mission (Mill et al. 1994) attempted such a survey but the ultraviolet data are not generally available. The Berkeley group surveyed the sky shortward of 1750Å at low spatial resolution (http://adsabs.harvard.edu/abs/2006ApJ...644L.159E , Morales et al. 1998) on two different internal missions. While the GALEX/SMEX mission has surveyed a large number of targets, an UV all-sky survey such as that is available in many other electromagnetic bands is still missing. These data show that the UV sky is scientifically ripe for further study with more modern technology.

Bright star planetary transit search

Observations with the HETE-2 optical cameras (http://space.mit.edu/HETE/) have shown that it is possible to observe stars at sufficient precision from a low-cost spacecraft to detect planetary transits. These observations have led to the proposal of the TESS small explorer (http://web.mit.edu/newsoffice/2008/tess-0603.html), which currently awaits selection decision. A similar, somewhat less capable, mission is possible at a significantly lower cost.

Pencil beam cosmology survey

In recent years several missions have been proposed to detect the ultraviolet emission from the intergalactic medium. None of those missions have reached fruition. While a UNEX class mission cannot hope to achieve the sensitivity or sky coverage of those missions, a modest, yet scientifically significant, pencil beam survey could be attempted. For example, UV spectral imagers could map outflow morphology and velocity field, locate where outflows deposit their energy, measure physical conditions in outflows and analyze conditions for winds and fountains, and correlate with properties of underlying galaxies and surroundings for a handful of nearby galaxies. Furthermore the contributions of such a mission to the characterization of Galactic emissions and emission from Milky Way halo or z=0 Local Group would be significant.

Astroseismology/reverberation mapping/Doppler imaging

The MOST satellite (http://www.astro.ubc.ca/MOST/) has demonstrated that the scientific return from long time baseline, high precision photometry is considerable. The science topic that can be addressed with a modest increase in the effective area and/or a change in the bandpass include reverberation mapping of stellar disks, astroseismology, Doppler imaging of chromospheres, etc.

VHF astronomy/interferometry

Radio astronomy at wavelengths longer than the ionospheric cutoff is not possible from the ground because of absorption in the ionosphere. Any mission to observe such radiation would, by its very nature, be quite speculative. A low cost satellite would be an ideal platform for such a mission. Furthermore, with the advent of GPS, it is possible to use a multi spacecraft mission for VLBI observations at these wavelengths.

X-Ray Astrophysics

Four reflection, grazing incidence X-ray have been suggested for SMEX and/or MIDEX missions (Szentgyorgyi et al., 1994). A recent design included the Diffuse Intergalactic Oxygen Surveyor Mission (DIOS) which will measure diffuse soft X-rays originating from the warm-hot intergalactic medium (Tawara et al., 2005). These missions could be scaled back to fit the CREST-class missions for pencil-beam probing. Other possibilities include studies of X-ray occultation by Kuiper Belt Objects as well as all-sky transient monitoring.

Example of a non-astrophysics mission

As an example of another capability afforded by CREST, we consider a small satellite mission to study the atmospheric region between 130 km and 200 km. This is the region around the Earth where the magnetosphere connects to the lower region of the ionosphere, which overlaps the base of the thermosphere. Experimentally, this region of the upper atmosphere cannot be reached by airplanes or balloons; sounding rockets cannot probe it for any extended period of time. Satellites operating in this altitude regime return to the Earth only after a few days due to the strong atmospheric drag. As a result, this near-space is poorly understood and is called the *ignorosphere*. A CREST-class mission can contribute much needed in-situ data, such as neutral winds and electric fields. While the lifetime of a satellite without any orbit maintenance in this regime may be only a few days, 35-years of advancement in technology and global coverage from only one satellite will return sufficient high quality of data to merit *several* Ph. D. and masters level dissertations. A few-days observations may not be cost-effective for major satellite missions, CREST, with its unique combination of cutting-edge science, technology and educational objectives, is the ideal vehicle to address this important space physics question.

The above are examples of science that will be enabled by CREST. It is possible to list many other missions of similar scope in astrophysics as well as in other disciplines that require a short observation period, multiple satellites or some combination. While the value of missions like these is generally acknowledged, the current rate of about one $100–300 M mission every couple of years and occasional $1–5 B ones, cannot support such a broad range of experiments or accept the risk inherent in the more speculative – and thus more interesting – explorations. CREST will make a new tool available to the science community to make discoveries, develop new observational approaches and provide a training ground for the next generation of space explorers. This will be the legacy of CREST.

CREST Implementation plans: Integrative Innovation

Unlike the risk-averse large science missions, our approach will include the infusion of advanced spacecraft technology such as power or communication systems or the use of new technology in structures and components that are *designed for demise* (D4D – see for example, ses.gsfc.nasa.gov/ses_data_2003/031007_Hull_presentation.ppt). Working as a university-industry-government team, we will validate this new approach through prototyping, vigorous testing (including suborbital flights) and summarize the findings as standards. To make this transition smooth, our team includes industry partners with direct experience with standards and standard spacecraft bus.

In most satellite missions the science instruments have the least flight heritage. Many of the spacecraft bus components are well developed and can be procured commercially. Thus, the task of satellite design and building often is that of system integration around a central processor with all subsystems (e.g., attitude control or command and data handling) and the science instruments acting as input/output devices. We will use conformal design tools (see below), to articulate a new methodology for the development and implementation of CREST-class missions.

Technology infusion

We plan to investigate how the capabilities of an instrument could be significantly improved with selected infusion of technology. Boston University (BU) has revolutionized ground-based planetary studies which started with a simple rhetorical question: *If Galileo had owned a CCD* (Baumgardner and Mendillo 1993). By replacing the eye with a sensitive CCD in the back of a 10-cm dia telescope (which is only slightly larger than the telescope Galileo had used and smaller than most amateur telescopes), the team discovered the largest object in the solar system – the Jovian Magneto-nebula (Mendillo et al., 1990). The team has since discovered sodium tails on Mercury and the Moon and a third (sodium) tail on a comet! None of these discoveries could have been made had we stayed on the path of increasingly larger diameter telescopes.

On-board decision making software tools have been used to plan, execute tasks based on predetermined goals, detect, analyze, and respond to science events, and to downlink only the highest value science data (see for example, http://ai.jpl.nasa.gov/public/projects/ase/). The development, refinement and application of tools for optimal flight and mission operations will be investigated and incorporated by CREST, if appropriate.

To be competitive, CREST must employ innovative tools and latest technology and/or mature tools to a high *Technology Readiness Level* (TRL), and still be cost effective. CREST could be used as a vehicle to advance the TRL of these and other technologies and/or validated them.

While all subsystems will be open for evaluation and research, we discuss below another enabling technology effort.

Before launch, all space-bound experiments undergo rigorous tests. We anticipate future missions using the CREST model to be geographically distributed. To prepare for this scenario, we will develop a scheme for an *internet based Horizontal Test (FlatSat)*, which will allow the test of subsystems developed at different partner institutions to connect to the rest of the system through the internet, thus eliminating the need for travel. Essentially this is analogous to flying Ethernet™ on the satellite. Because we plan to adopt this technology, we will also investigate how to effectively incorporate the spacecraft bus modules with the instrument(s) such that they could communicate using both wired and wireless protocols. A wireless spacecraft subsystem, another technology to be introduced, will minimize the mass and cost of wire harnesses.

Conformal Design Technology

Study of many satellites indicates that there is as much as 30% empty space inside the satellite, often as small disconnected volumes. We will build the spacecraft bus conformally around the science instruments using Artificial Intelligence tools to perform multimodality reasoning:

- **Goals** that include minimum mass, minimum volume, minimum wiring harnesses and maximal use of industry standard interfaces, Ethernet, USB or Spacewire.
- **Constraint**s in a satellite design include making the individual parts pack into the minimum volume and shape while not violating electromagnetic or other constraints.
- **Satisficing** involves design for static assemblability, testing and repair but also operational control of the satellite in orbit (e.g., a cryogenic sensor must be shaded from direct sunlight).

Since the availability of such tools could be a key enabler for science missions from many disciplines and all classes, it will be a key thrust of our effort.

Development of Open Standards for Science Missions

To meet the needs of the science and technical investigations described above, we will first develop an open standard for CREST-class satellite missions. They will include specifications (mechanical, electrical and data interfaces) for key spacecraft subsystems such as power, telemetry, and attitude control, so that an optimized mission could be developed.

It is reasonable to ask how our efforts compare to other standards that are being developed by NASA or the Department of Defense's *Operationally Responsive Space* (ORS). NASA's lower priority for a small satellite program gave birth to NSF's CUBESAT initiative described above. The *Integrated Systems Engineering Team* (ISET) has published a comprehensive set of standards (http://projects.nrl.navy.mil/standardbus/). Our partner MSI is involved in ISET. Another partner, Ball, is heading the *Space Test Program*'s (STP) *Standard Interface Vehicle* (STP-SIV) (http://www.ballaerospace.com/page.jsp?page=126). All CREST-class missions should meet the straw man requirements shown in Table 2 once such a program become routine.

Research on Practices and Processes for Mission Assurance

We will create a catalog of subsystems similar to what is used in the sounding rocket community (http://fulcrum.gi.alaska.edu/hex/documents/Wallops_Info%5CSounding_Rocket_Handbook_July2001.pdf), so the prospective science missions will have ready choices. In addition, we will produce a standard of practices and process similar to the Goddard Open Learning Design (called GOLD rules, see http://snebulos.mit.edu/projects/reference/NASA-Generic/GSFC-STD-1000.pdf) describing, for example, the number, timing and types of reviews, and allowable components consistent with the level of acceptable risk. Together, they will be the playbook for CREST-class missions. There will also be provisions for timely adjustments in the future.

Table 2: Key straw man plans for the proposed CREST-class system retain the necessary functions of expected science missions while eliminating complex, expensive and unnecessary features

ISET Implementation *	CREST Implementation	Rationale
LEO and HEO orbits	LEO orbits only	System simplification; low mission cost
Availability: >99%; Reliability: >85% over mission lifetime (> 1 year)	Reliability: > 85% over mission life (≥ a few weeks)	Consistent with the historic success rate of the sounding rocket program
Mission life: > 12 months	Mission life: > a few weeks	Lowers mission operation cost
Spacecraft mass: < 250 kg	Spacecraft mass: ≤ 250 kg	Design parameter
Orbit Average Power to payload: 400 W (LEO)	Orbit Average Power: ≤300 W (LEO)	Adequate for most astrophysics and other NASA SMD missions
Spacecraft bus-payload interface: defined	Interfaces to subsystems: defined	Allows flexibility and efficiency
0.05° attitude control	0.001° attitude control	Similar to the sounding rocket capabilities
Slew rate of 2° per sec	Slew rate of 0.1° per sec	Adequate for tracking astronomical targets
Expected recurring cost for the Spacecraft Bus: $5M - $25M	Cost for complete mission: ≤$25M	Competetive with current Suborbital Program (see Figure 1)
Practices and process: undefined	To be modeled after GSFC Gold rules	Quality assurance

* ISET data from http://projects.nrl.navy.mil/standardbus/

Collaboration Studies

CREST will use collaborative R&D project team model: "individuals with different perspectives - from different disciplines… working together to accommodate the extraordinary complexity of today's science and engineering challenges". Collaboration will include web-based conferencing, shared document management, and infrequent travel. The project will selectively apply knowledge about what leads to innovation and equity in the for-profit sector to an educational setting. Not only will this project contribute significantly to space science and technology research and education, but this geographically distributed collaboration will also be carefully designed and iteratively modified to contribute to social science understandings of the processes by which cross-cultural project teams build effective relationships. A social network of mentoring approach, which is more suited to the multiple level and reciprocal relationships that occur on project teams (Higgins and Kram, 2001), may be appropriate.

Education and Human Resources Development Plans

CREST will draw upon nearly two decades of experience with team-based entrepreneurial project learning. These efforts include senior capstone design courses in Engineering, student design competitions, NASA sounding rocket student teams, USAF Nanosatellite student teams, Engineering Research Centers' undergraduate discovery labs (*High Tech Tools and Toys Labs*) and similar out-of-class learning (Ruane, 1999, 2001, McNight et al, 2001). Our goals include:

- Engage science/engineering students in service to society, through spacecraft and orbital mission design.
- Involve students in real, important and large-scale challenges related to modeling, design, development, testing, operations, analysis and standards setting.
- Introduce students to the complex engineering systems, modern engineering design tools, and contemporary human organizational structures thereby re-introduce and energize "the joy of discovery" in 21st Century space exploration

Collaborations are planned locally at each partner institution with undergraduate, graduate, and mixed teams, under the mentorship of faculty and research and technical staff. To maximize benefits of collaborations for CREST-class missions, we will conduct studies and recommend best techniques geographically distributed collaboration (sometimes called, *Virtual Organization*, see Cummings et al., 2008). The classroom experience will be buttressed by real-world experience through seminar series, workshops, summer school, internships provided by CREST as well those that could be leveraged (e.g., Space Grant Fellowships). Within CREST we will examine the social networks that arise—at team levels, between teams, and among institutions and disseminate the direct and indirect lessons of CREST.

Management Plan

To implement our vision, we have formed a core consortium of six universities, two research laboratories, three aerospace industry partners and a NASA center. We will mature the standards and needed technologies using sounding rocket flights (NASA WFF is a core member). A preliminary estimate has put the development cost of a CREST-class mission at less than $25M, including launch cost and related mission operations, data analysis and dissemination (Figure 1).

We have carefully assembled a core team and have identified key areas of research and development. The team consists of experienced technologists, problem solvers, educators, managers, and sociologist with decades of in-practice experience. We will develop a membership agreement that encourages the shared use of facilities and jointly sponsor seminar series, workshops, summer schools as well as visiting scientist and teachers' training programs. We will also develop agreement for Intellectual Property rights that are consistent with the accepted norm for such a consortium. Finally, we plan to develop affiliate programs, leverage knowledge transfer (Oakes, 1990) through professional organizations/societies and other industry programs.

Summary

A Technology Center of Excellence to transform small science satellite missions is suggested. It will incorporate open standards, infuse and test state-of-the-art technology, use a virtual organization and develop a blue print for low-cost satellite missions for science exploration while involving students and professionals from a diverse background. CREST will revitalize the enthusiasm in experimental space research that has suffered significantly in recent decades from rare "big satellite missions" and make space accessible to a broad community.

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