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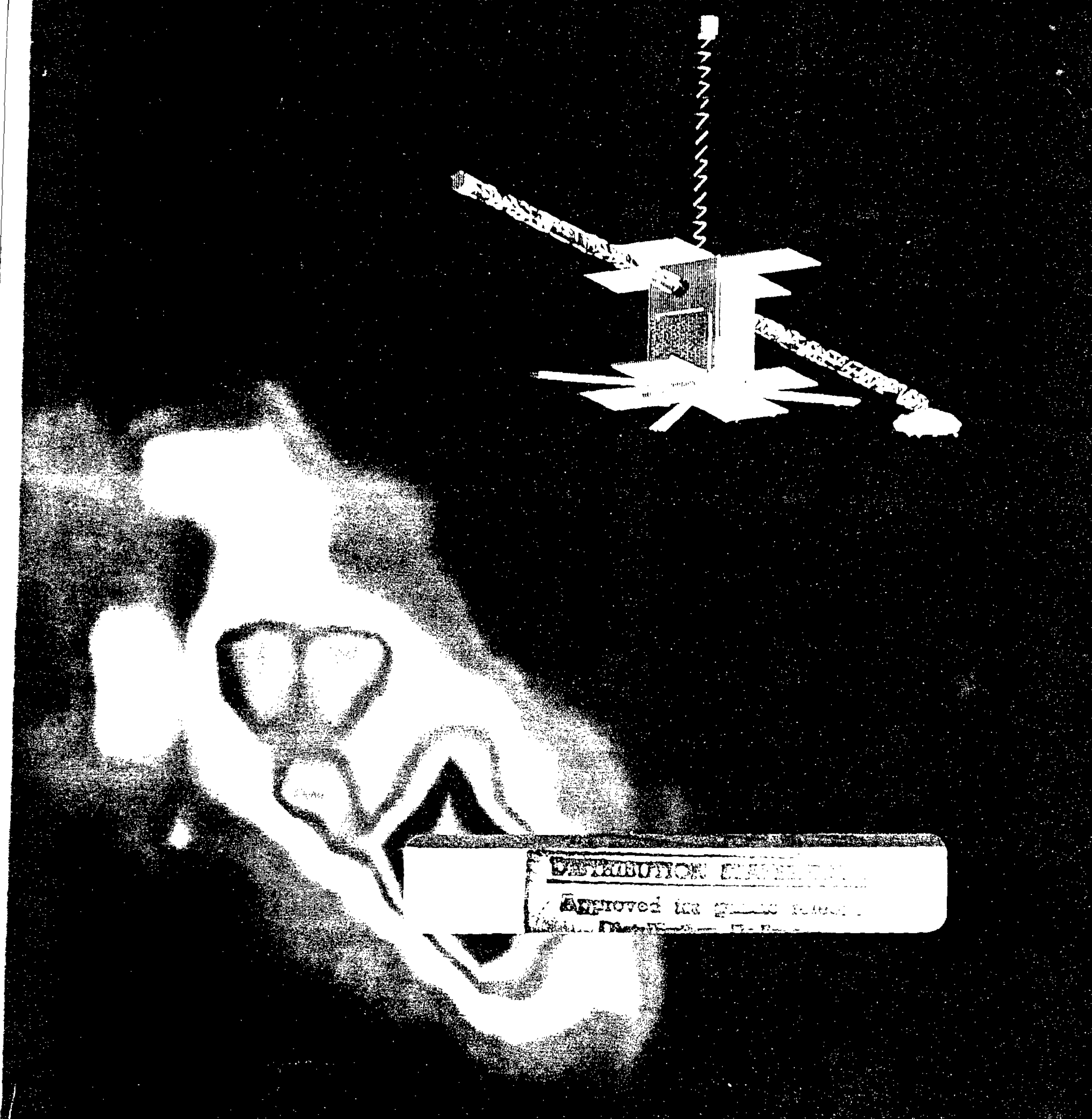

LACE

on the cover

Top:

The Low-Power Atmospheric Compensation Experiment (LACE) satellite

Computer image:

The core of a rocket plume as observed by the Ultraviolet Plume Instrument (UVPI) aboard the LACE satellite is shown in the 260- to 280-nm band. The image was formed from the average contribution, after background subtraction, from each picture element in 72 frames collected over a 3.4-s time span. The image shown is a 32- by 32-picture element array enhanced by smoothing interpolation. The plume intensity is shown in false color, with white representing the highest intensity. Exposure time for each frame was 1/30 s. The range is 450 km. The image covers a 180- by 140-m area at the rocket plume. The rocket is moving toward the lower right and has a velocity component out of the image toward the viewer.

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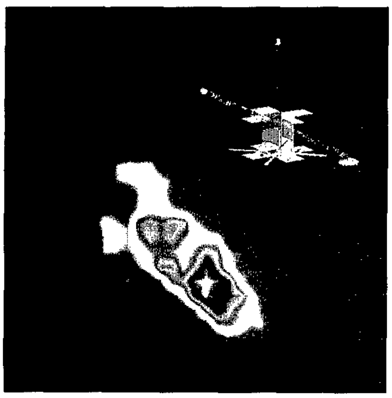


This publication describes the outstanding efforts and technical achievements of the LACE Program from its inception in 1985 through its launch from Cape Canaveral on 14 February 1990 to its operation in orbit. It is dedicated to the LACE team members – the managers, specialists, and family members – who have made the LACE Program 100% successful.

U4333

a brief history of the LACE Program

Donald M Horan

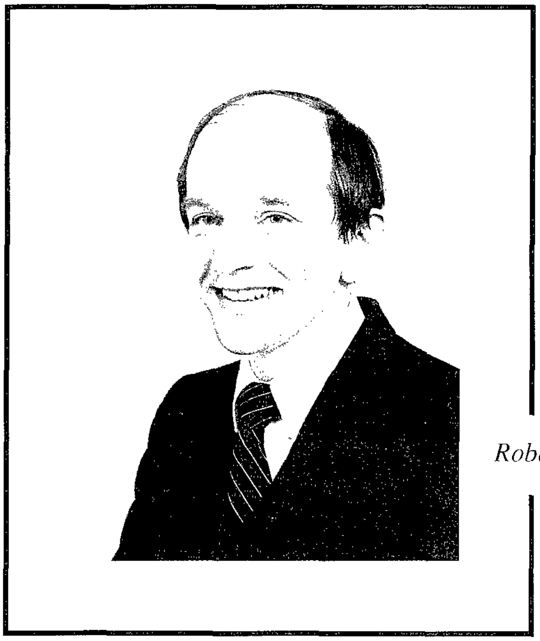
Since its inception in 1985, the LACE Program has encountered many changes. These changes were largely driven by the Strategic Defense Initiative Organization's (SDIO) desire to take advantage of the latest technology as well as a need to adapt to budgetary changes. As a result, the LACE Program has faced many challenges over the years.

The project began as a simple, spaceborne target with a single sensor to characterize a laser beam emitted from a ground-based laser site. Next, the Program was expanded to a few sensors to characterize the laser beam and modify NASA's Long Duration Exposure Facility (LDEF) as a host vehicle. With the Challenger accident and the ensuing hiatus in shuttle launches, the shuttle-launched LDEF was no longer available to carry the LACE target board into space. Therefore, in June 1986, it was decided that LACE would be a full satellite itself instead of a set of sensors on a host satellite. By 1987, the simple, spaceborne target had evolved into three separate sensor arrays with a total of 210 sensors capable of characterizing ground-based laser beams with continuous wave or pulsed emission in the visible, UV, and IR bands. Also, SDIO began discussing the addition of an instrument to take video images of rocket plumes by their UV emission. By April 1987, a request for proposals for the Ultraviolet Plume Instrument (UVPI) had been sent out. Based on the responses, a decision was made to add the UVPI to the LACE satellite. Over the next several months, the launch vehicle was changed from a Delta rocket, to an Atlas, to a Titan, and then back to a Delta. At this point, the Air Force's Relay Mirror Experiment (RME) satellite was added to the LACE satellite for launch. Each major change required a reevaluation of all of the concepts and decisions that had preceded it.

On 14 February 1990, the LACE satellite was launched from Cape Canaveral. The "simple, spaceborne target" has proved that techniques to compensate for atmospheric distortion of laser beams actually work. The UVPI has been successful on all four of its opportunities to make video images of the UV emission from rocket plumes.

Donald M. Horan
Chief Scientist
Director of Operations

a salute to the LACE Team



Robert E. Palma, Jr.

This publication describes the outstanding efforts and technical achievements of the LACE Program. These achievements represent the development and operation of state-of-the-art systems across many disciplines. The systems' development and their subsequent operation were challenges of high order in all areas – technical performance, cost, and schedule.

The disciplines involved in LACE covered nearly every activity typically associated with defense technology. Our program employed many scientists, engineers, managers, quality assurance specialists, technicians, mechanics, assemblers, program assistants, budget analysts, security specialists, legal experts, contracting and procurement specialists, construction and transportation operators and clerical, secretarial, and management assistant staffs. This team provided the Program with its ideas, its energy, its resourcefulness, and its dedication. The team worked until the job was done – until the job was *right.* To each of you, I salute you and say a heartfelt thank you. It was a great pleasure and privilege to work with you.

I also want to express my gratitude and appreciation to many who served but didn't hold a "picture badge" – the family members and friends who supported our efforts. You made this program possible by your understanding, sacrifices, and concern. With your constant support, we were able to overcome all obstacles.

As of May 1991, the LACE Program was 100% successful. I am deeply proud to have had the privilege of being your program manager. Truly, I was but a reflection of the collective consciousness of all of you.

Robert E. Palma, Jr.
Program Manager
and Chief Engineer

the Systems Engineering and Core Management Team

J. Dan Penn
Project Manager

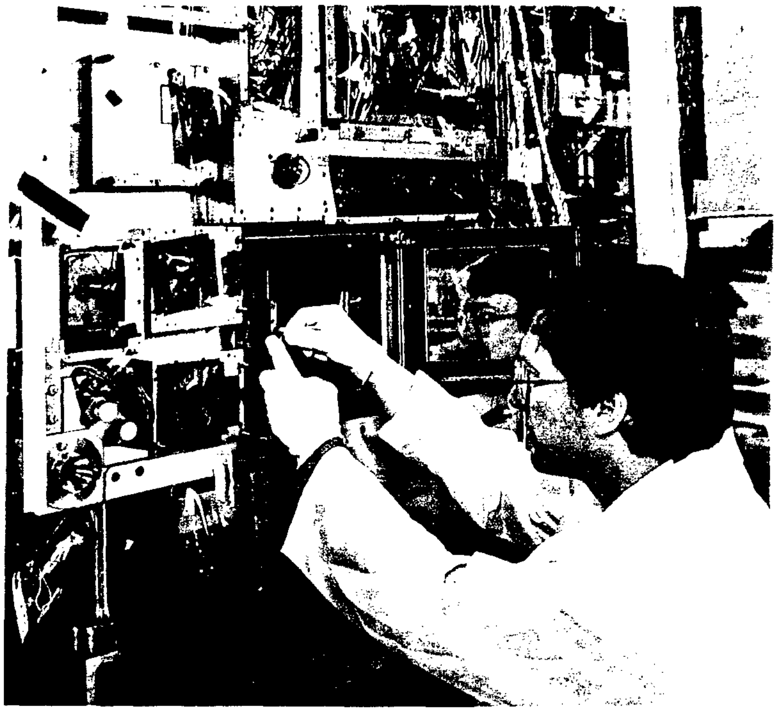
Paul A. Regeon
Electrical Interface Manager

John P. Schaub
Mechanical Systems and Launch Vehicle Integration Manager

William B. Adkins
Mechanical Interface Manager

"White Hats" is the name given to the LACE satellite management team by Robert Palma, Program Manager and Chief Engineer. The Team members, who were brought together from different branches of the Naval Center for Space Technology to design and build the satellite, were completely responsible for the area assigned to them and, as a team, made the major decisions. From the left – J. Dan Penn, Project Manager; William B. Adkins, Mechanical Interface Manager; Robert E. Palma, Program Manager and Chief Engineer; Paul A. Regeon, Electrical Interface Manager; John P. Schaub, Mechanical Systems and Launch Vehicle Integration Manager; and Donald M. Horan, Chief Scientist and Director of Operations.

developing the LACE subsystems hardware



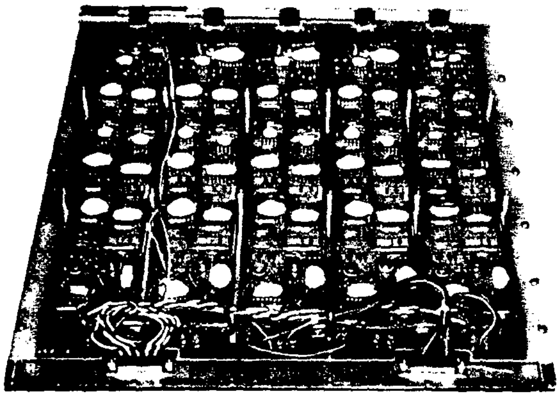
Adjustment of gimballed mirror of UVPI

The original purpose of the LACE satellite was to design the sensor array subsystem (SAS) experiment to measure the intensity of laser emissions over the 4- by 4-m target board on the LACE satellite. The SAS consists of three sensor arrays with 210 sensors and a leading retroreflector array comprising 252 cornercube retroreflectors. The SAS can measure laser emissions in the visible, UV, or IR bands from continuous-wave or pulsed lasers. All of the SAS sensors were carefully calibrated before launch and were built to match the requirements and characteristics of specific ground-based lasers. The visible sensor array is capable of taking 4000 samples-per-second from each of its 85 sensors.

The UVPI was added to the LACE satellite after the satellite's design had been completed and fabrication had begun. The UVPI consists of two video cameras that look through a 10-cm-diameter telescope that in turn looks through an aperture in the bottom of the satellite. A gimballed mirror allows the UVPI to see rocket plumes within a 50 half-angle cone. Filters in the camera systems limit sensitivity to the UV and short-wavelength visible band. One camera has a larger field-of-view to find and lock onto a target; a narrower field-of-view camera with four selectable UV filters is then used to make video images of rocket plumes and background phenomena.

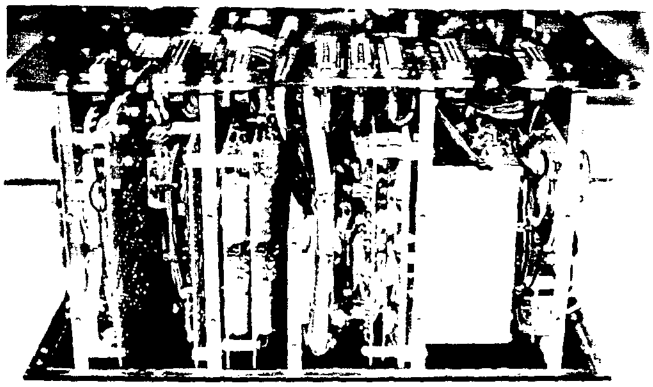
The following subsystems and experiments are also on the LACE satellite:

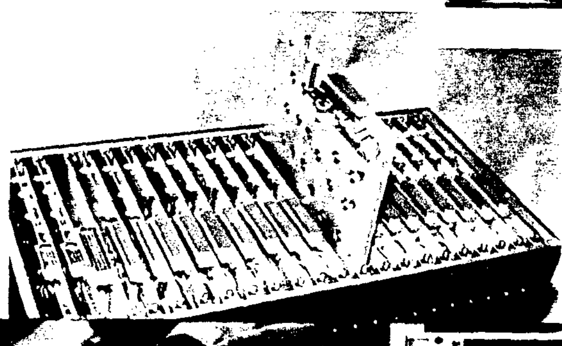
- electrical power subsystem,
- telemetry and tracking subsystem,
- radio frequency subsystem,
- attitude control subsystem,
- mechanism subsystem,



Sensor slice from the central array of the SAS

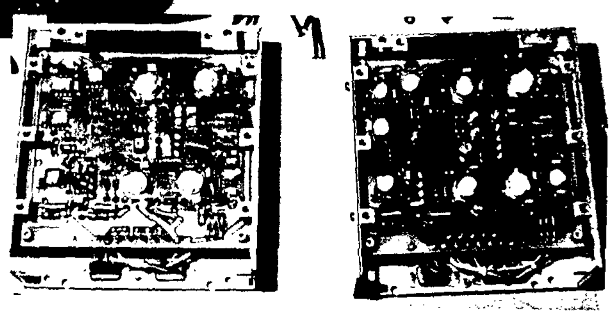
The inside of the EPS





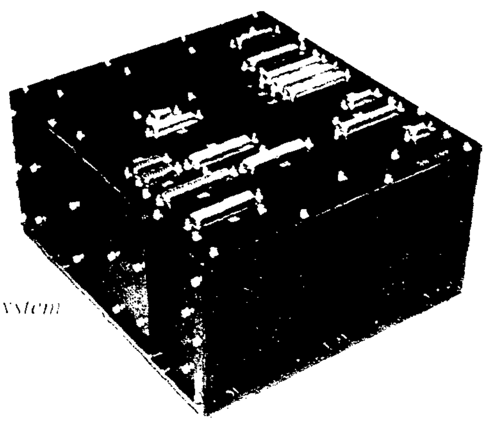
The detector signal processor

Cornercube retroreflector ready to be mounted on the retroreflector array



Visible and pulsed sensor boxes from the SAS

- control electronics subsystem,
- ordnance control subsystem,
- thermal control subsystem,
- structures subsystem,
- radiation detection experiment, and
- Army background experiment.



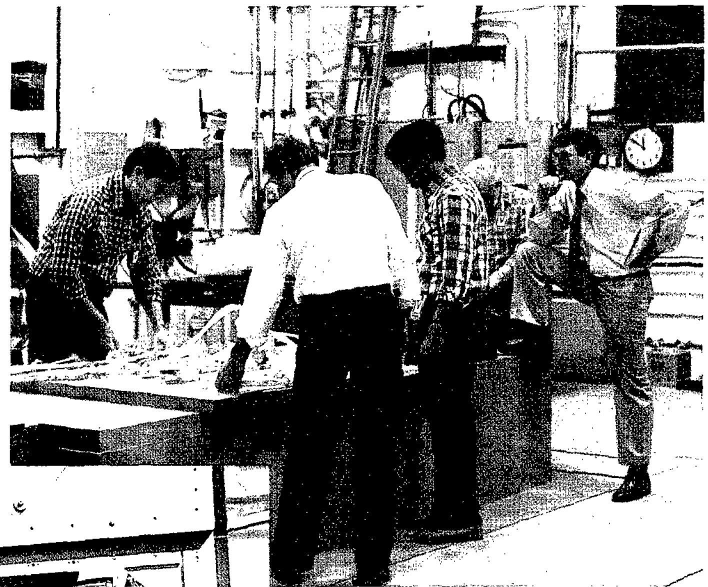
Electrical power system (EPS) regulator

building the LACE satellite

The beginnings of LACE

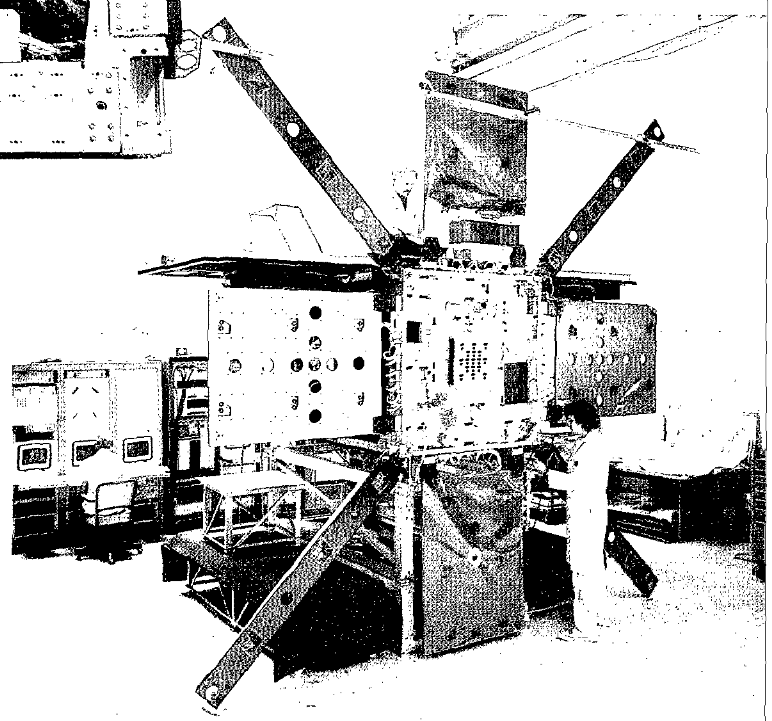
Building the LACE satellite posed several unique challenges. One of these was to repeatedly extend or retract a 150-foot boom in space and know its position to within 6 inches. The LACE satellite uses three of these booms. One boom keeps the sensors pointed toward the Earth, one has the retroreflector array mounted on its end, and the third is used to balance the retroreflector array boom. The retroflector and balance booms have to be moved at the same time (in opposite directions) to keep the satellite's moment-of-inertia constant. These booms are expected to be moved 125 times during the 30-month mission of the satellite. NRL designed and built a special control system that uses a motor to control the extension and retraction of the booms in space.

Another challenge was to design the retroreflector array used to bounce a laser beam back to Earth for satellite tracking and atmospheric distortion measurements while, at the same time, conduct SAS experiments. The retroreflector array is made up of 252 cornercube retroreflectors whose placement required careful modeling and analysis. The cornercube retroreflectors had to be precisely placed to permit retroreflection from any azimuthal direction when the satellite was at elevation angles greater than 45 from a ground based laser site.



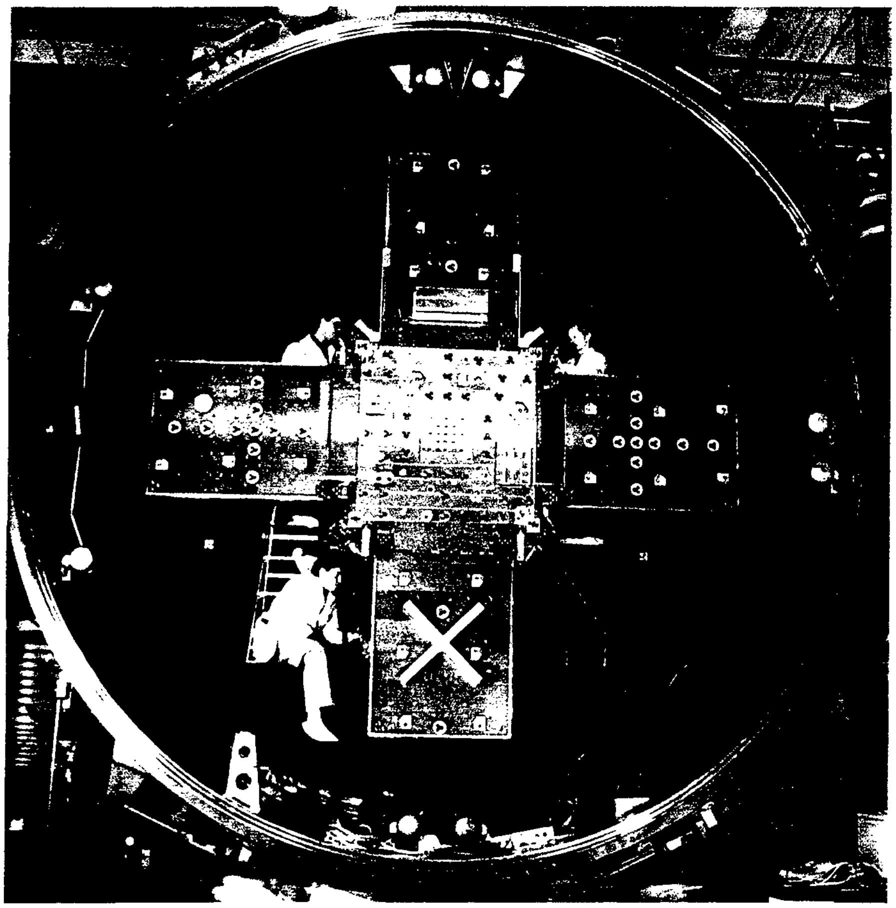
Developing the wiring harness

Installing LACE internal components



The SAS target board takes shape

testing and calibrating the LACE satellite



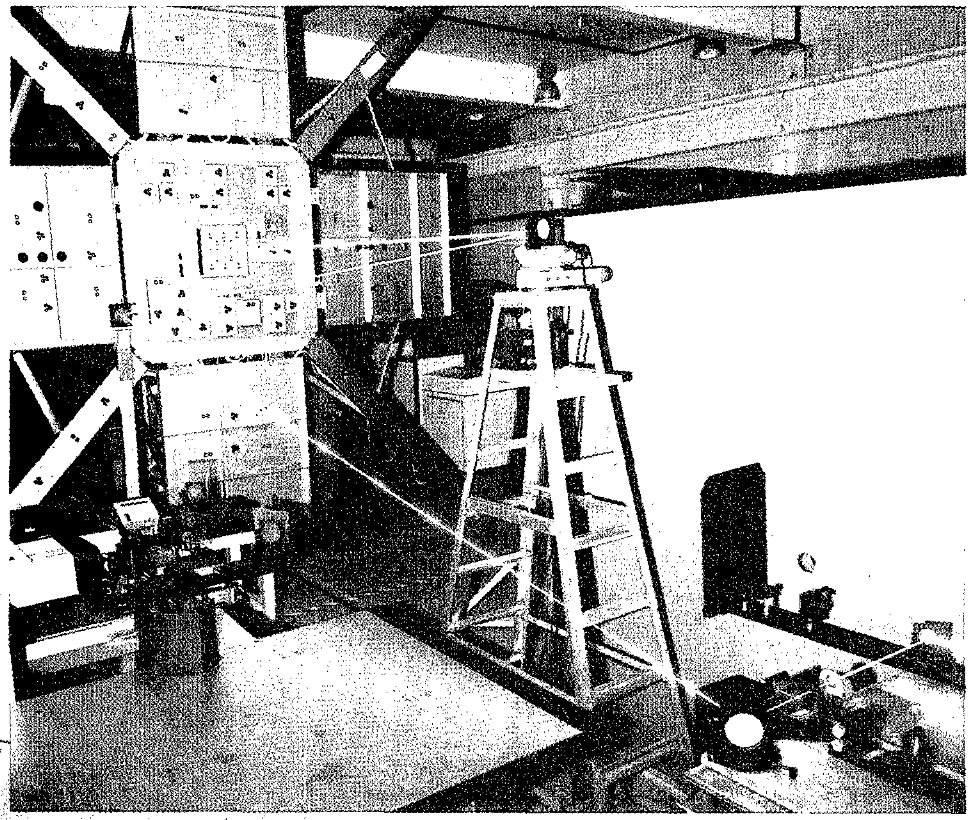
Preparing for thermal vacuum testing

Before the LACE satellite could be flown, it underwent a variety of tests on the individual components and the system as a whole. NRL maintains special facilities to perform thermal-vacuum and vibroacoustic environmental tests. These test chambers are able to simulate the two environments the satellite must withstand. The thermal-vacuum chamber simulates the operational environment of space, and the vibroacoustic chamber simulates the launch environment.

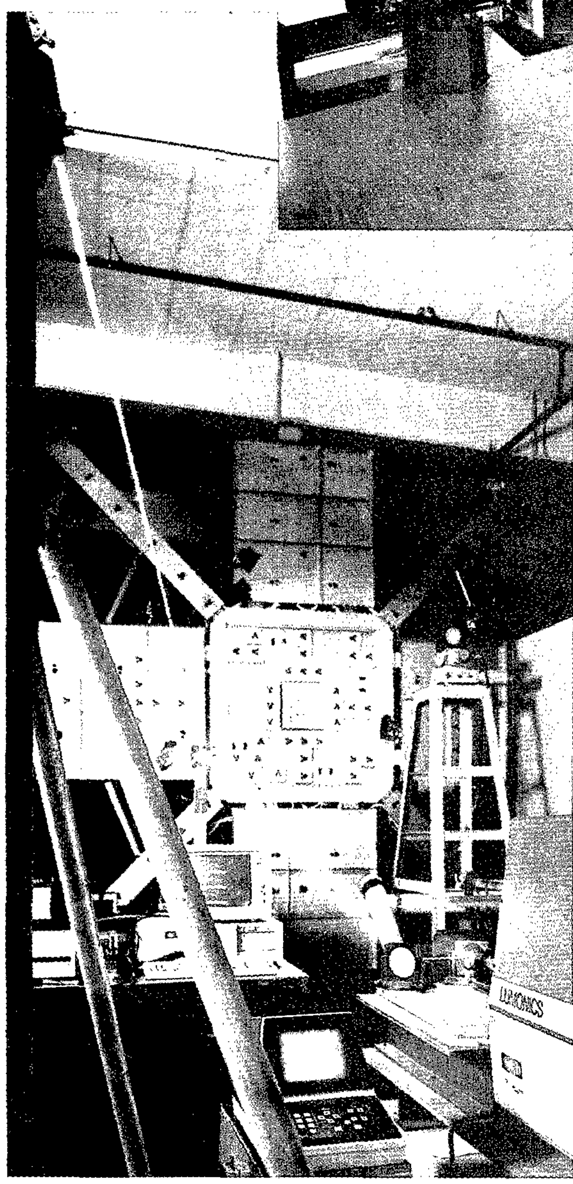
The SAS created a special calibration challenge for the LACE satellite. The sensors had to be calibrated and tested under a wide variety of conditions. To test the individual sensors, special fixtures were built so that each sensor was positioned and handled identically. This special fixturing allowed each sensor to be illuminated by the same portion of the laser beam to reduce the effects of beam nonuniformity.

Other types of testing

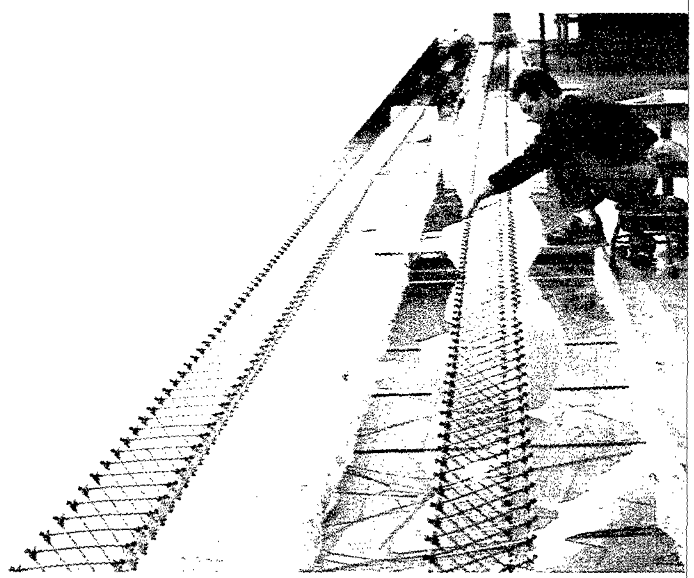
- electromagnetic interference
- electromagnetic compatibility
- vibration tables
- vacuum chambers



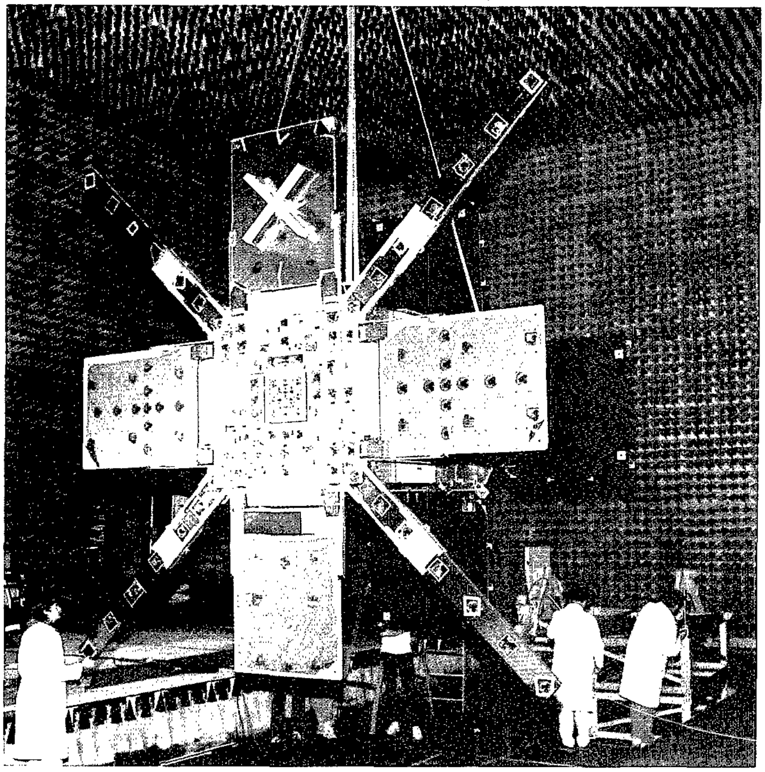
Testing individual sensors on the central sensor array of the SAS



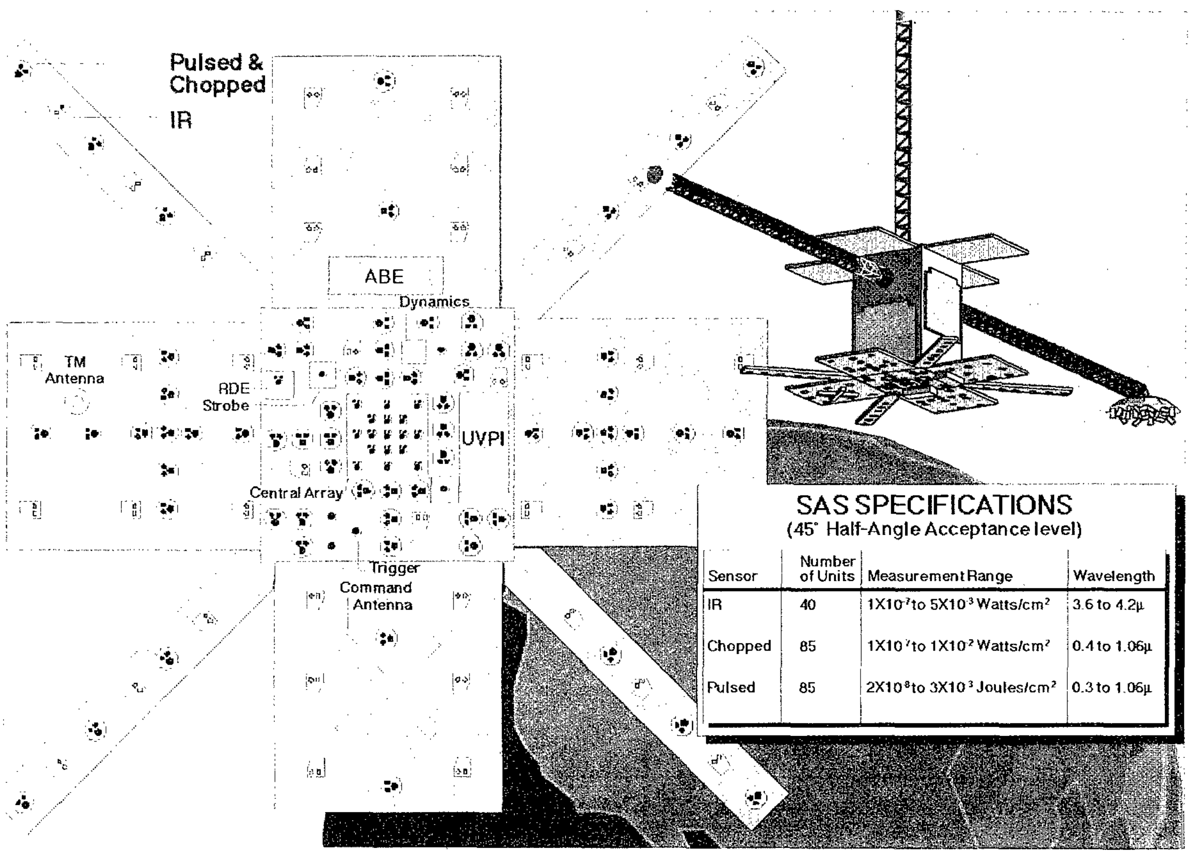
Flood beam testing of SAS



LACE booms during "water tray" testing



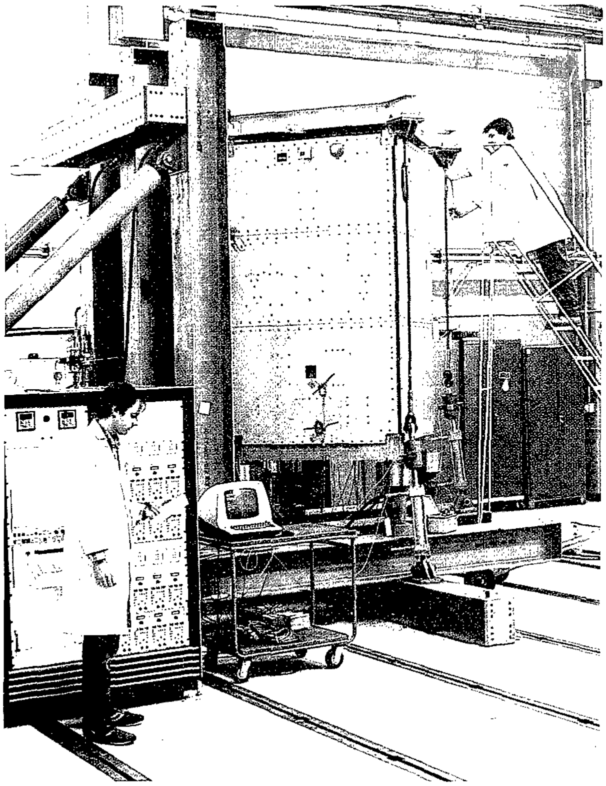
LACE satellite in the anechoic chamber at the Patuxent River Naval Air Test Center



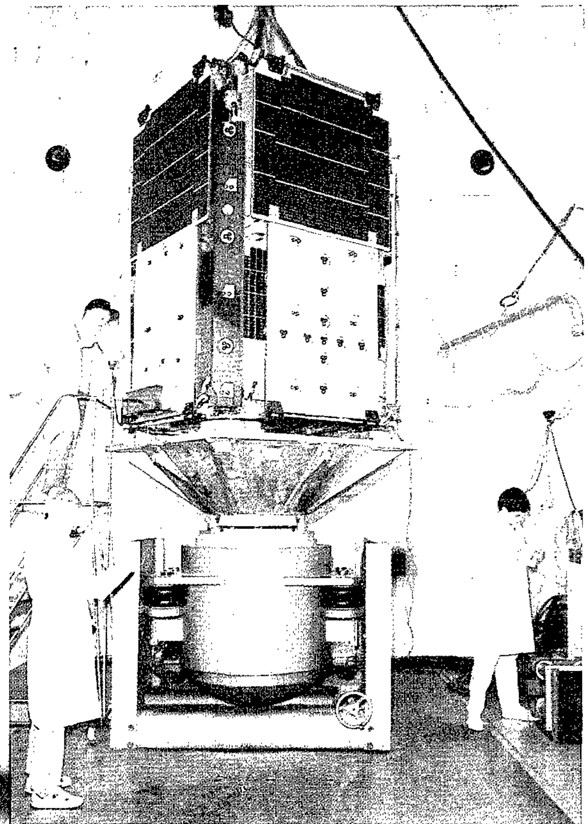
SAS SPECIFICATIONS
(45° Half-Angle Acceptance level)

Sensor	Number of Units	Measurement Range	Wavelength
IR	40	$1X10^{-7}$ to $5X10^{-3}$ Watts/cm^2	3.6 to 4.2µ
Chopped	85	$1X10^{-7}$ to $1X10^{-2}$ Watts/cm^2	0.4 to 1.06µ
Pulsed	85	$2X10^{8}$ to $3X10^{3}$ Joules/cm^2	0.3 to 1.06µ

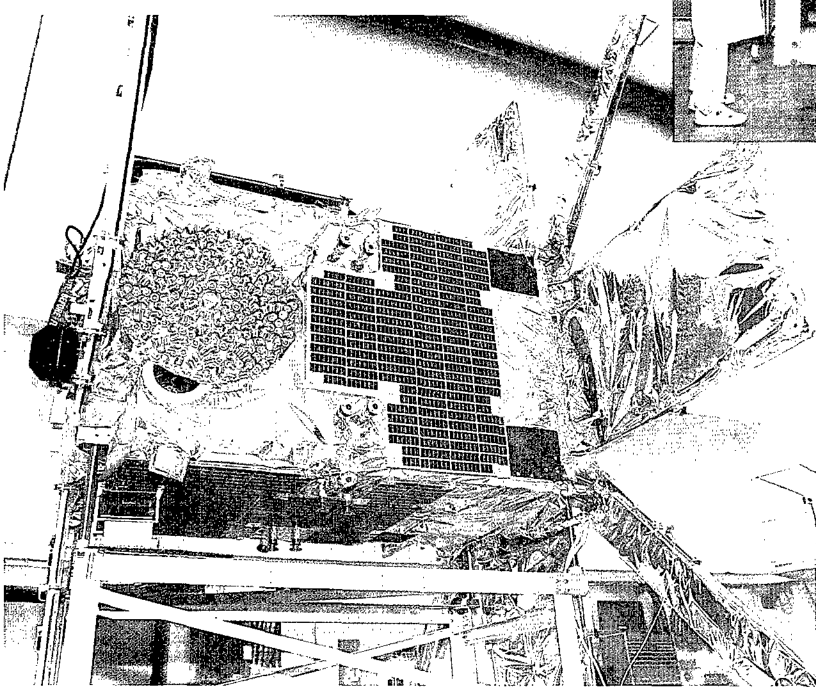
Details of the sensor array subsystem



Load testing on the LACE qualification model

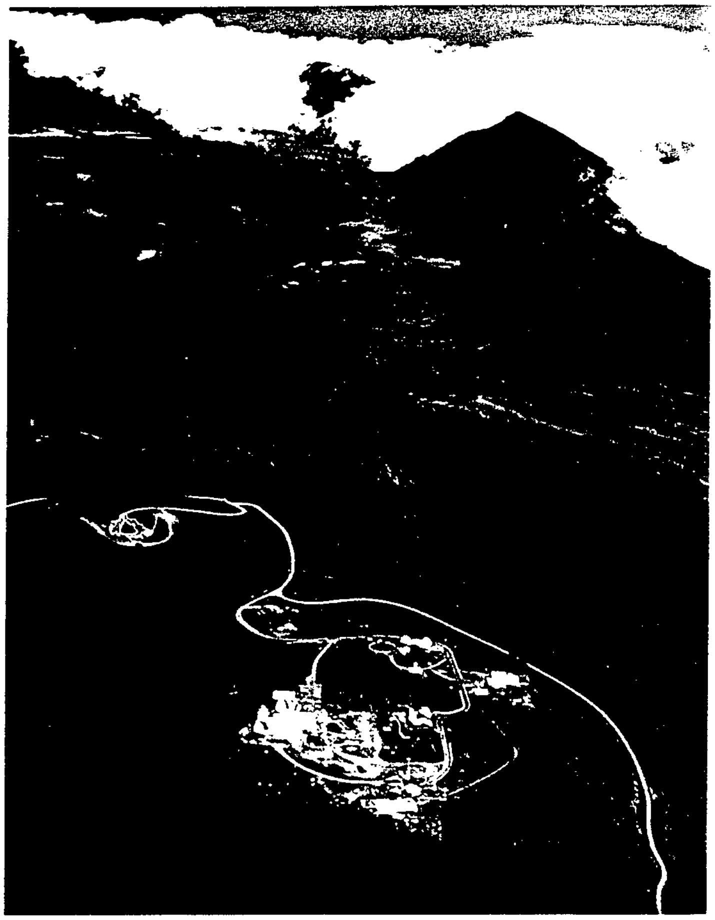


Vibroacoustic testing



LACE side view showing retroreflector array and body-mounted solar panels

LACE satellite ground support



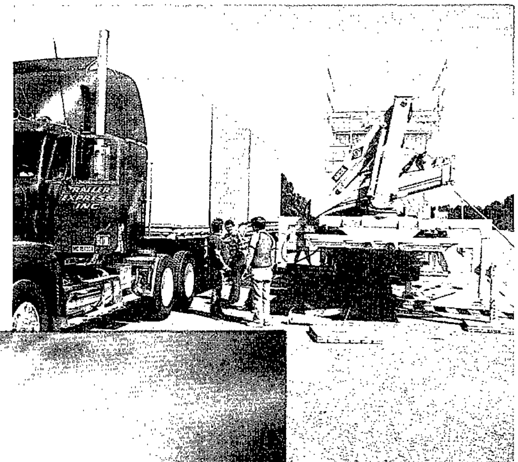
Laser site for SAS testing at Mount Haleakala, Maui, Hawaii

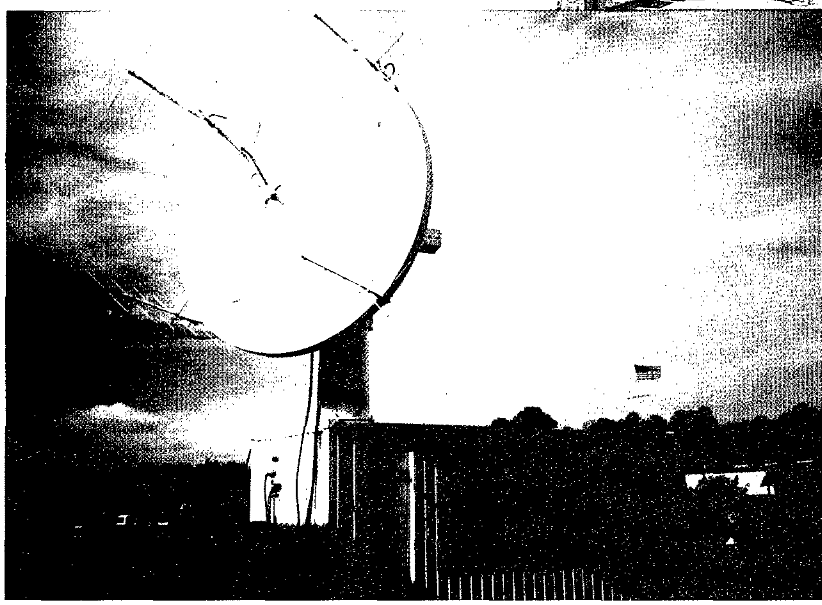
Because real-time SAS data are required at a ground-based laser site during each test, movable mission support centers are required to provide real-time spacecraft control, to receive experimental data from the satellite, and to serve as data and voice links between the experimenter's facilities and the LACE Operations Control Facility located in Alexandria, Virginia. NRL designed and built two transportable ground stations (TGSs) for this purpose. The TGSs allow the experimenters to review the data and assess the progress of the experiments in real time. This timeliness is critical because of a 2-minute time frame that exists to conduct the experiment. Timing and timeliness are also critical in UVPI experiments. The satellite-borne UVPI has to acquire the rocket and take images during the rocket-burn phase that lasts only 1 to 2 minutes.

Ground Station Locations

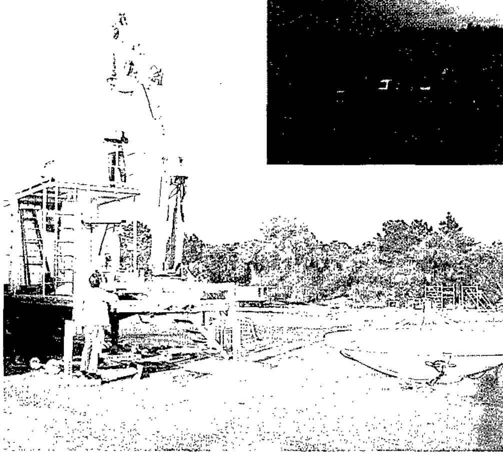
- Hawaii
- Maryland
- California
- Florida

Assembly of the transportable ground station at Malabar, Florida



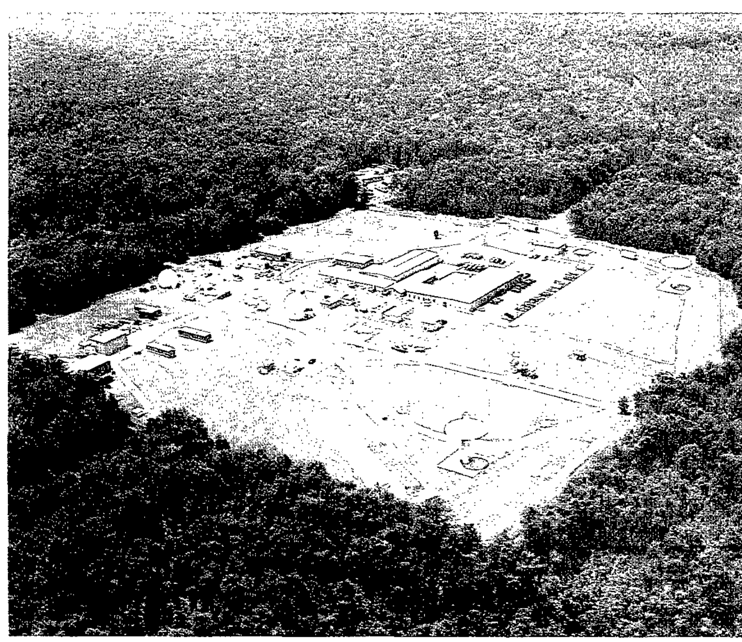


The transportable ground station

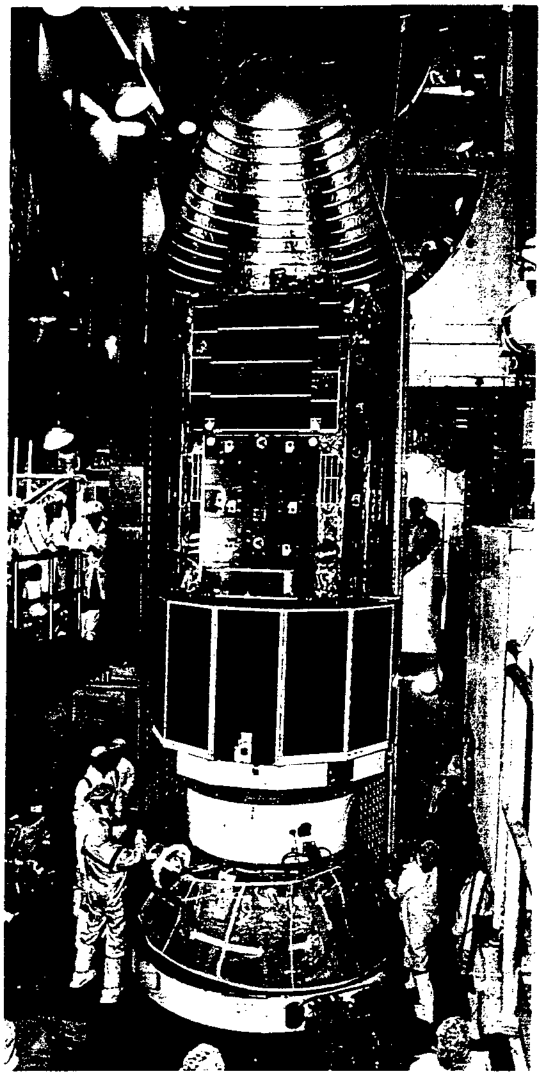


Assembly continues

The permanent ground station at NRL's Maryland facility

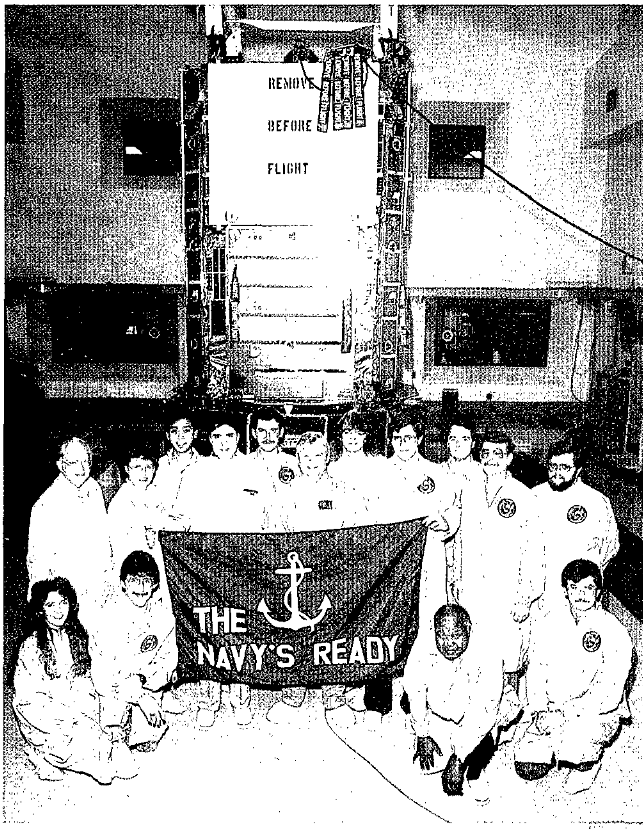


launch vehicle integration

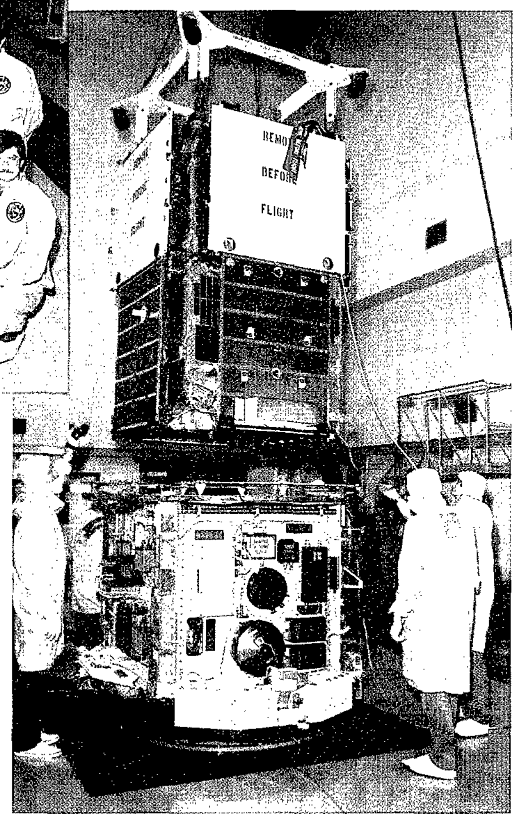


The LACE-RME ensemble with half of the payload fairing in place

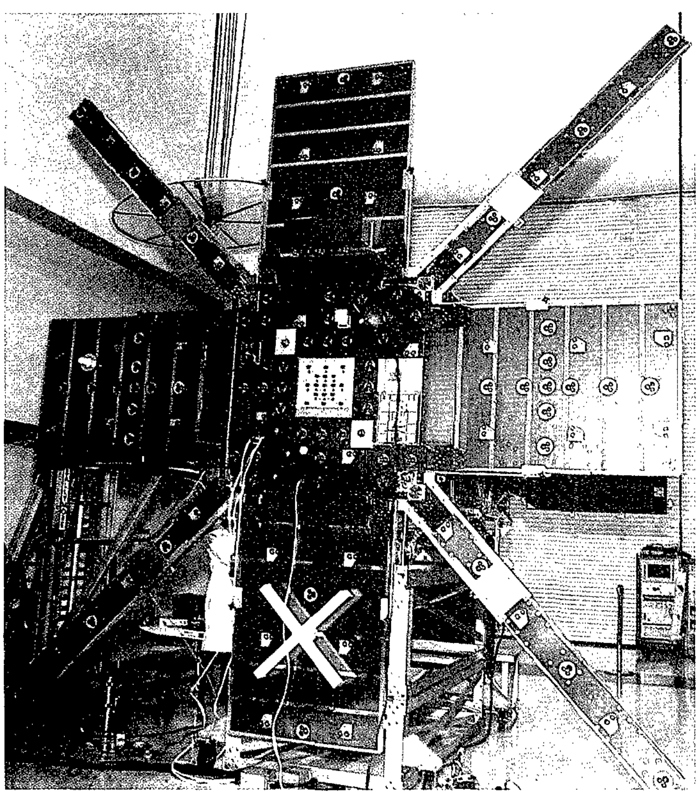
The LACE satellite was shipped to Florida and prepared for integration as a combined payload with the Air Force's Relay Mirror Experiment (RME) in January 1990. Preparation for launch required another complete checkout of the LACE satellite's systems before they were integrated with the RME satellite. Because the LACE satellite was mounted on top of the RME satellite, special electrical and mechanical interfaces were designed. These interfaces allowed the LACE satellite to be monitored during launch and to be released into orbit at the proper time. Once the two satellites were connected, the payload was ready to be placed on top of the Delta launch vehicle.



The Navy's Ready . . .
the LACE-RME ensemble is ready to be mounted on the Delta rocket

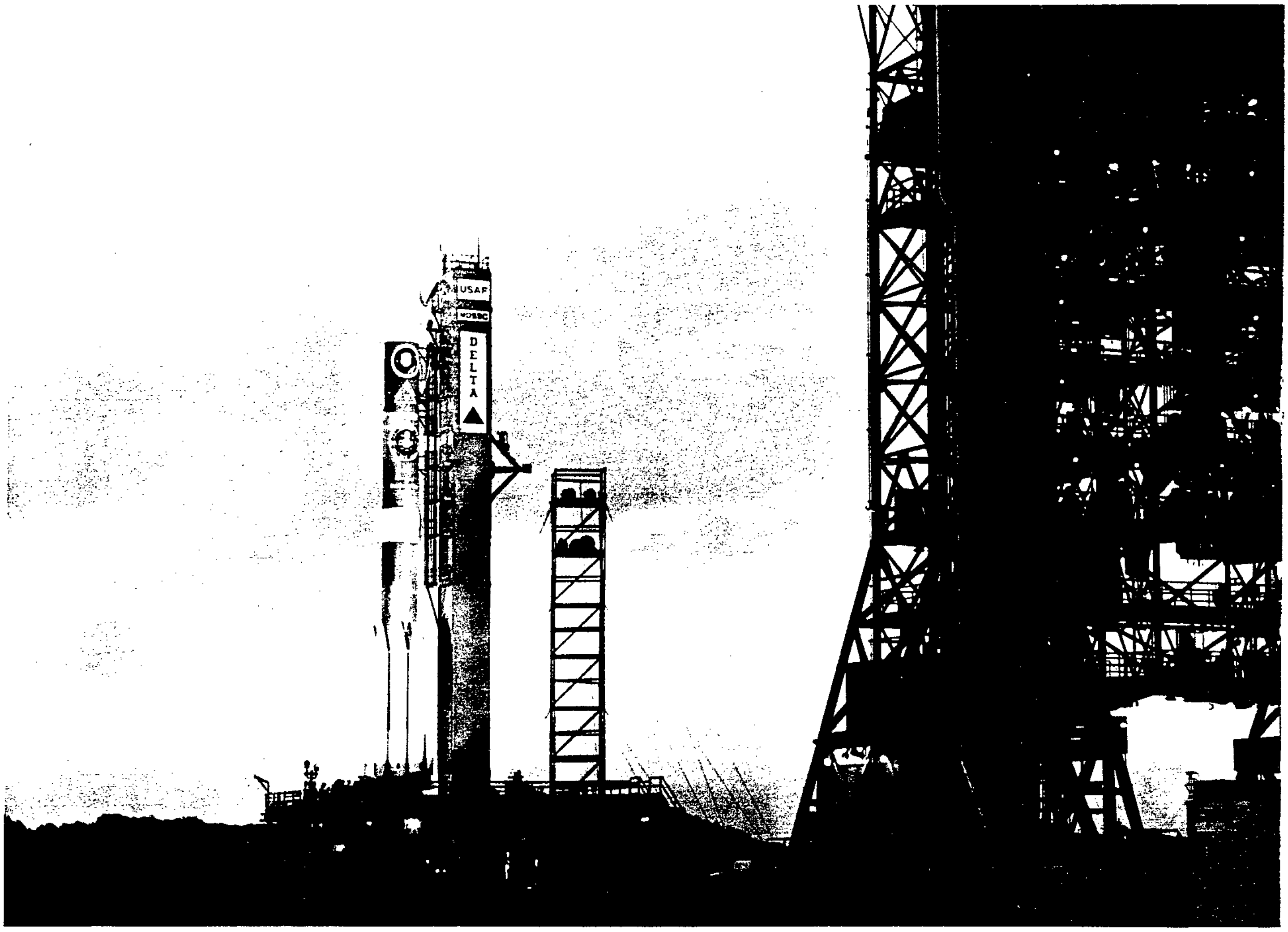


The LACE satellite is lowered onto the RME satellite



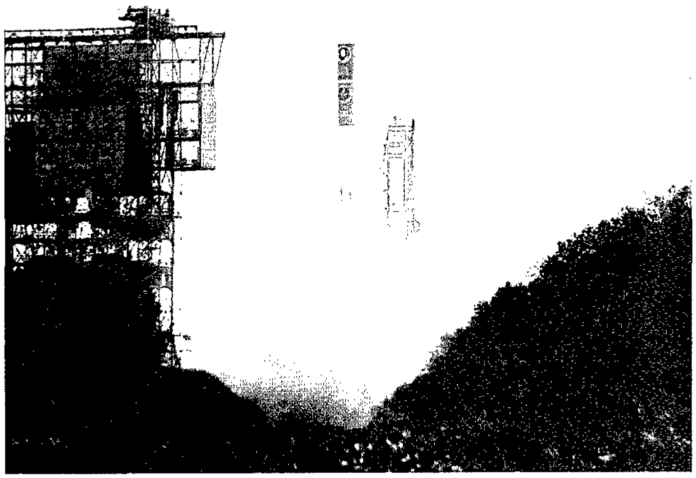
SAS target board with sensors installed

the launch



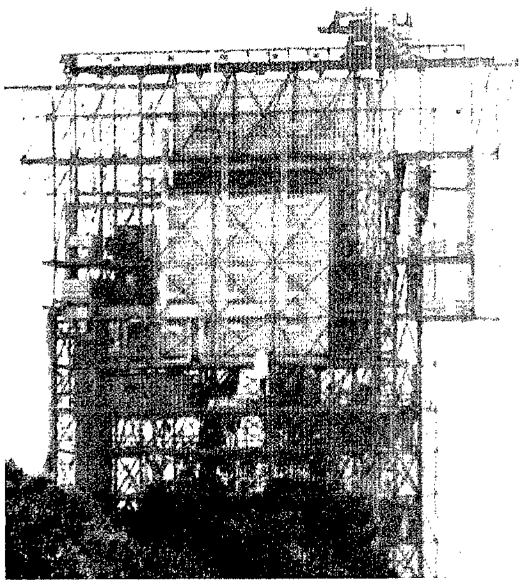
Dawn at Complex 17, Pad B

On 14 February 1990, the LACE-RME ensemble was launched atop a Delta rocket from Complex 17, Pad B, at Cape Canaveral, Florida. At approximately 15 minutes into the mission, the LACE satellite was separated from the Delta launch vehicle at its assigned orbit of 295 nautical miles and began to deploy the LACE sensor arrays, solar panels, and booms. After 60 days of on-orbit checkout, the satellite was ready to begin its 30-month mission. The mission is returning extremely valuable scientific data to researchers on the ground.

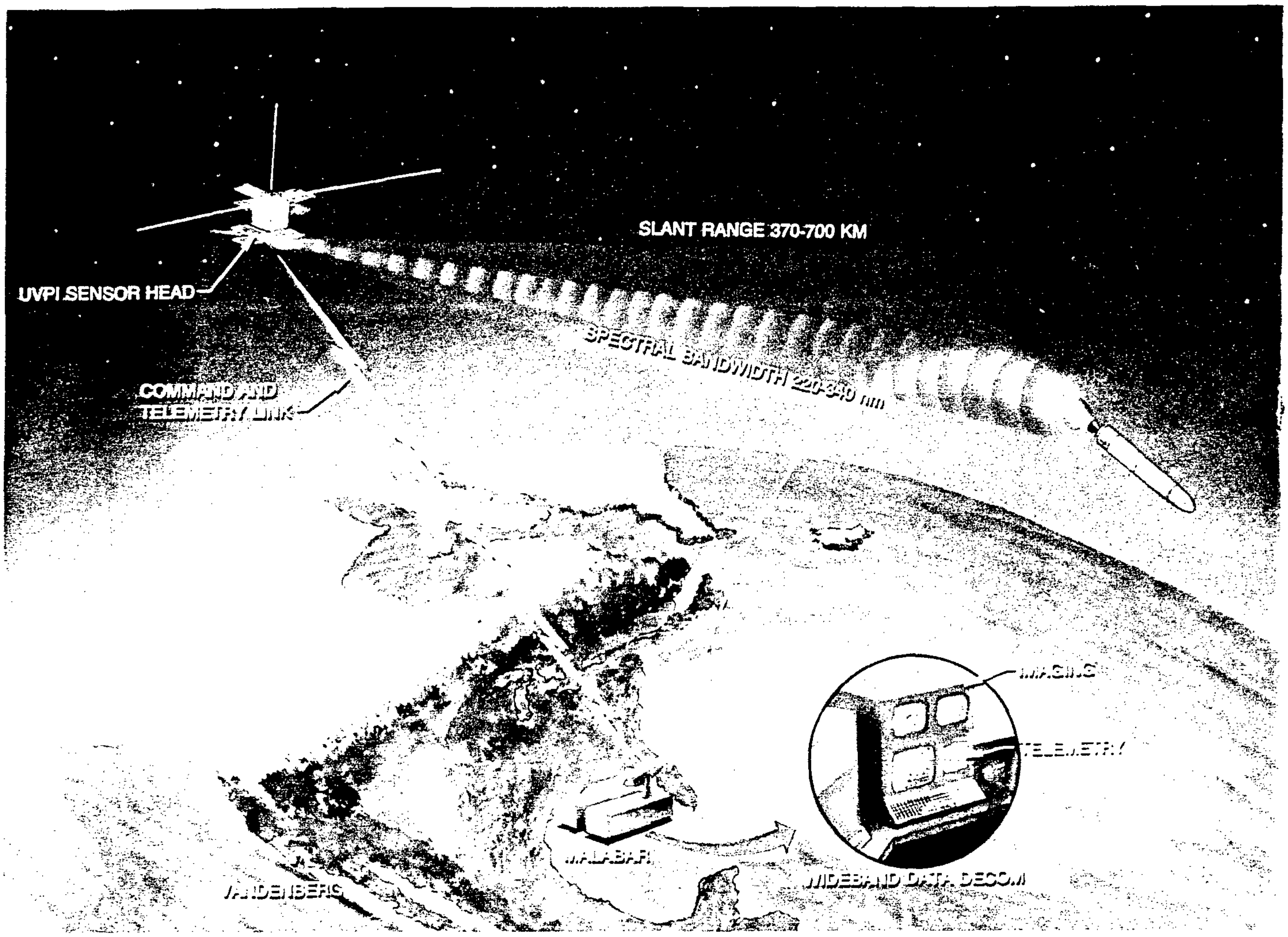


Liftoff!

The rocket pulls away



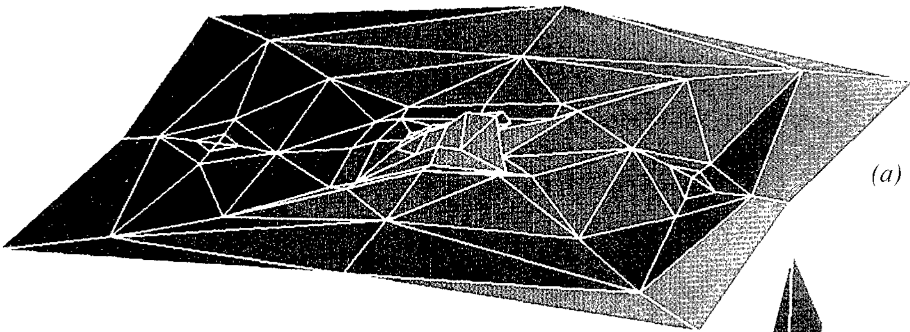
the mission



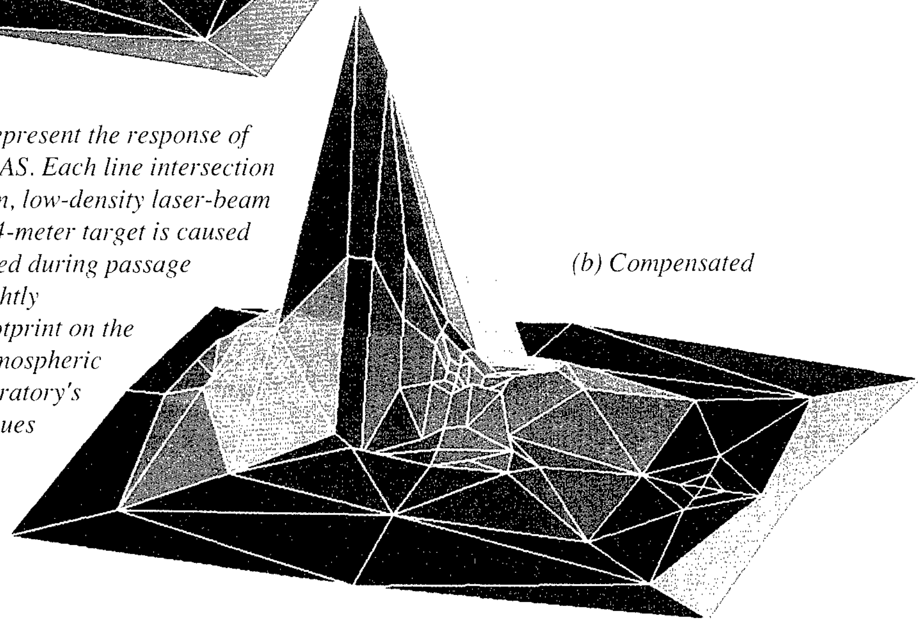
Depiction of a typical UVPI mission.

The UVPI's mission is to obtain images of UV plume emissions from launch vehicles and to measure the UV back-ground emissions as seen from orbit. UVPI has observed four launches in four opportunities.

The SAS's mission is to measure the distributed intensity of laser radiation that is aimed at the spacecraft from various ground stations. These sensors determine the effectiveness of various methods of compensating for the distortion caused by the passage of a laser beam through the atmosphere. The sensors also give measurements of the absolute power received at the spacecraft.



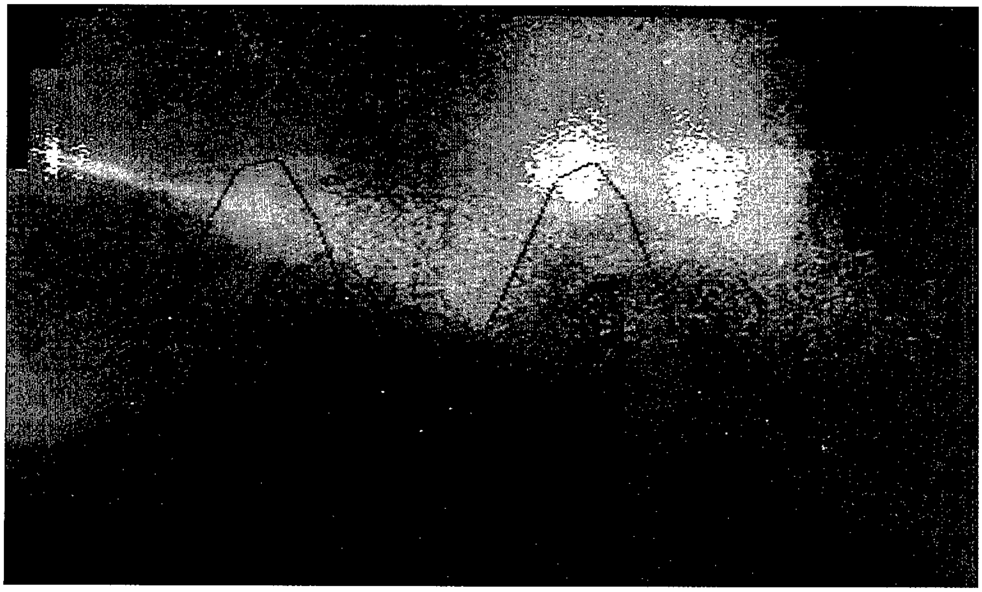
(a) Uncompensated



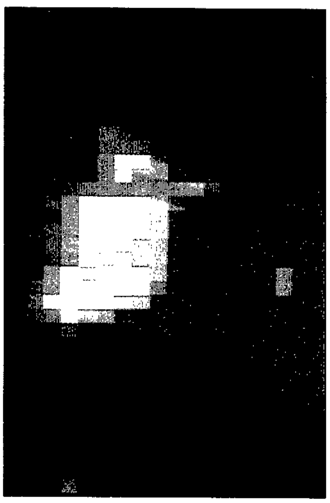
(b) Compensated

These three-dimensional displays represent the response of 85 sensors of the LACE satellite's SAS. Each line intersection represents a sensor: (a) The uniform, low-density laser-beam footprint distributed over the 4- by 4-meter target is caused by uncompensated distortion received during passage through the atmosphere; (b) The tightly concentrated peaked laser beam footprint on the SAS target results from applying atmospheric compensation by MIT/Lincoln Laboratory's Short Wavelength Adaptive Techniques (SWAT) Group. These tests on 30 November 1990 clearly demonstrated that compensation for atmospherically induced distortion on a ground-based laser beam could be performed.

This UVPI image shows the New York City area at night. The image was taken by the tracker camera with a 240- to 450-nm bandpass filter. Since wavelengths shorter than 320 nm are blocked by the ozone layer in the Earth's atmosphere, most of the emission forming this image is between 320 and 450 nm in wavelength.

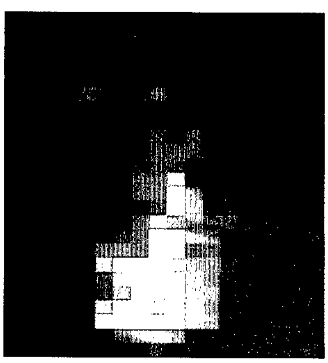


The mosaic shows the southern aurora — aurora australis — in the bandpass of the UVPI tracker camera at 240 to 450 nm. The mosaic is made up of many images. The sinusoidal pattern within the mosaic shows the path traced by the small field-of-view of the UVPI's plume camera.

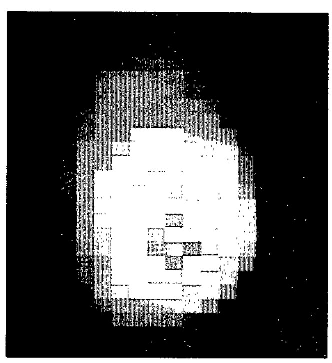


These composite images show emissions from an Orbus solid-fueled rocket plume. Images (a) through (c) show the third stage of the Starbird development launch from Florida on 18 December 1990. The third stage was a solid-fueled Orbus rocket motor that produced 7000 lb of thrust. Image (d), also a solid-fueled Orbus rocket, is from the fourth stage of the launch. The images were made from data obtained while the Orbus was between 55 and 76 km in altitude. Emission is shown in the nanometer band indicated.

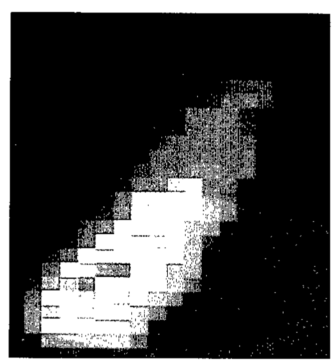
(a) 300- to 320-nm band



(b) 220- to 260-nm band

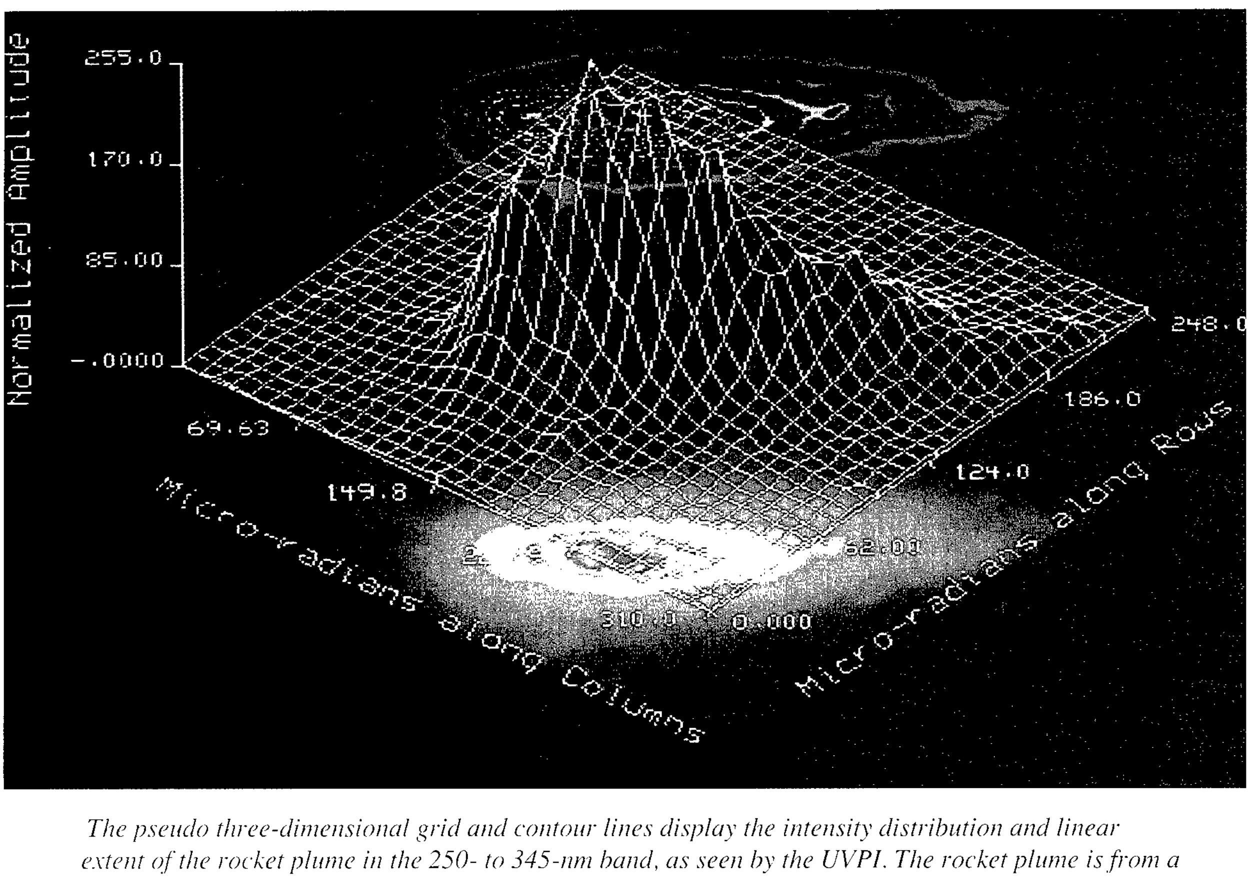


(c) 250- to 345-nm band

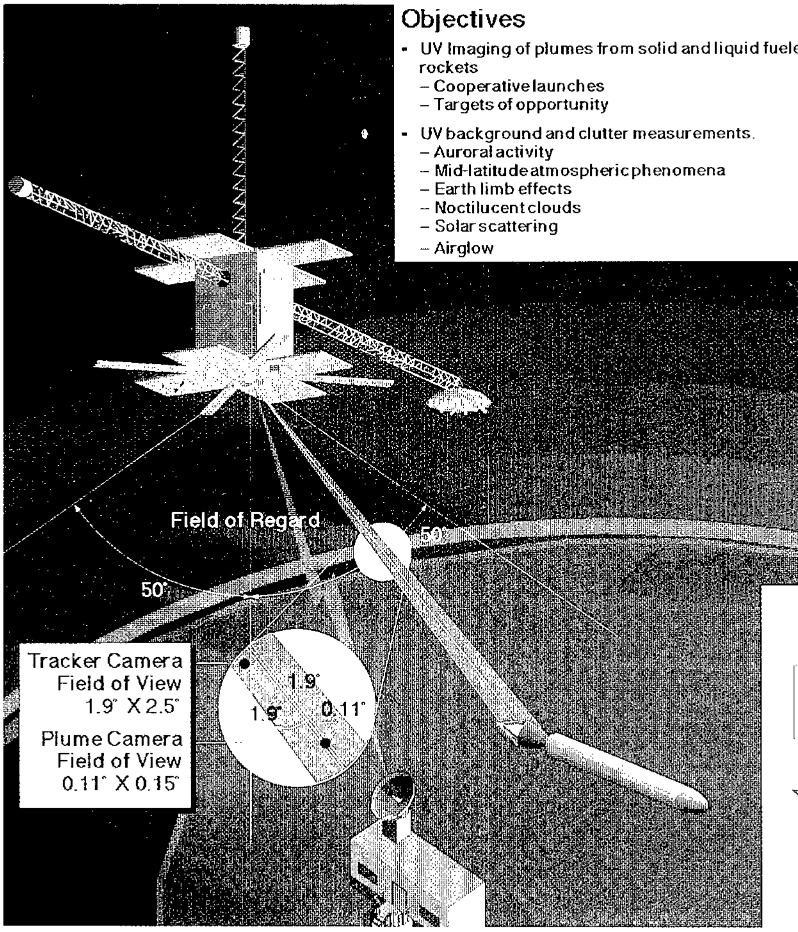


(d) 260- to-280 nm band

The UVPI image shows emission in the 250 to 345 nm band from a solid-fueled Antares rocket, which was the second stage of the STRYPI, launched from Kauai, Hawaii, on 18 February 1991. The Antares produces 20,000 lb of thrust. This image was made when the Antares was at an altitude of approximately 110 km and traveling at nearly 2 km/s.



The pseudo three-dimensional grid and contour lines display the intensity distribution and linear extent of the rocket plume in the 250- to 345-nm band, as seen by the UVPI. The rocket plume is from a solid-fueled Minute Man I, which was the third stage of the Low Cost Launch Vehicle (LCLV) launched on 6 February 1991 from Wallops Island, Virginia.



Objectives

- UV Imaging of plumes from solid and liquid fueled rockets
  - Cooperative launches
  - Targets of opportunity
- UV background and clutter measurements.
  - Auroral activity
  - Mid-latitude atmospheric phenomena
  - Earth limb effects
  - Noctilucent clouds
  - Solar scattering
  - Airglow

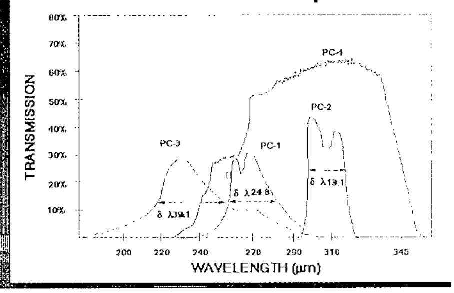
Plume Camera

- 30 Microradian Resolution
- Intensified Charge Coupled Device Technology
- Cesium Telluride Photocathode

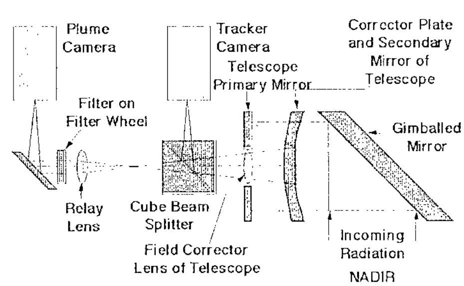
Tracking Camera

- 230 Microradian Resolution
- Intesified Charge Coupled Device Technology
- Bialkali Photocathode
- Single Bandpass, 240 to 450 Nanometers

Plume Camera Response



UVPI Optical Schematic



LACE Ultraviolet Plume Instrument (UVPI)

Space Systems Development Department

Technical Consultant:
Jay Furr

Technical Information Division Production Staff

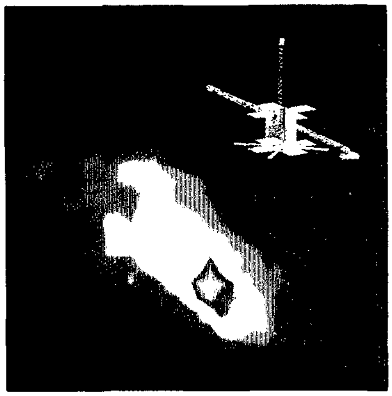
Editor:
Pat Staffieri

Consultant:
Kathleen Parrish

Graphic Design and Layout:
Jan Morrow
Tazewell Rufty
Beba Zevgolis

Reviewed and approved
October 1991

R.E. Eisenhauer, Superintendent
Space Systems Development
Department



Naval Center for Space Technology

The LACE and UVPI were built and are being operated by NRL for the Strategic Defense Initiative Organization