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Galileo Optical Experiment (GOPEX) Optical Train: Design and Validation at the Table Mountain Facility

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The Galileo Optical Experiment (GOPEX) has demonstrated the first laser communications uplink to a deep space vehicle. This article describes the optical design and validation tests performed at the Table Mountain Facility (TMF) transmitter site. The system used a 0.6-m telescope and an optical system at coudé focus to produce the uplink beam. The optical system used a pulsed neodymium:yttrium-aluminum-garnet (Nd:Yag) laser and beam diverger optics to produce the required optical output. In order to validate the optical design, a number of uplinks were performed on Earth-orbiting satellites (e.g., Lageos 1 and 2).

I. Introduction

The Galileo Optical Experiment (GOPEX) performed a deep-space optical uplink with the Galileo satellite during its second flyby of Earth (December 9–16, 1992) [1]. The uplink was performed using transmitter sites at the Table Mountain Facility (TMF), Wrightwood, California, and the Starfire Optical Range (SOR), Albuquerque, New Mexico.

The requirements for the laser transmitter at the TMF site were that a pulsed-doubled neodymium:yttrium-aluminum-garnet (Nd:Yag) laser ($\lambda = 532$ nm) be used as the optical source. The pulses were to be 14 nsec wide, with a maximum energy of 250 mJ. The 0.6-m telescope was used to point the laser at Galileo and transmit the laser beam. The output beam was to have a divergence of 110 μ rad during days 1–4 of the uplink schedule and a divergence of 60 μ rad during days 5–8. In addition, the boresighting between the laser and the telescope had to

be better than 10 μ rad. This article describes the optical design of the GOPEX optical train, the alignment procedure, and the results of the tests performed to validate the system.

The optical design utilized a two-lens system to produce the correct beam divergence. An alignment and boresight procedure was developed and verified through range tests and uplinks to Earth-orbiting satellites. A number of point and shoot experiments were performed on Agessai and Lageos 1 to demonstrate boresighting of the laser with the telescope. In addition, satellite-tracking uplinks were performed on Lageos 1 and 2 and Etalon. All tests were successful and produced returns from the satellites.

During GOPEX, the optical train was aligned and verified every night prior to the uplink time. The beam divergence and laser output power were measured. GOPEX successfully produced uplink data on six of the seven days

of the experiment. Inclement weather prevented laser uplinks on day 4.

II. Optical Train Design

Figure 1 shows a schematic of the GOPEX optical train used at the TMF site. The design used the focal plane iris as the reference point for the entire optical system. During nominal operations, the telescope would be calibrated by focusing a star at the center of the iris. The laser beam would, in turn, be centered on the iris, which would guarantee boresighting of the laser beam with the pointing of the telescope. The output beam divergence would be varied by changing the size of the laser beam at the plane of the iris.

The 0.6-m telescope was used in an off-axis configuration. The laser beam uses only a 15-cm-diameter portion of the primary mirror and exits the telescope unvignetted by the secondary. To accomplish this, the laser beam was incident into the telescope at an angle with respect to its optical axis.

The optical train was subdivided into five components: the laser, the beam diverger, the laser diagnostic system, the charge-coupled device (CCD) acquisition system, and the satellite return system.

A. Laser System

The laser was a pulsed-doubled Nd:Yag laser emitting at a wavelength of 532 nm and capable of producing 14-nsec pulses at 15 and 30 Hz. The average laser output at 30 Hz was 6 W. A more complete description of the laser can be found in [2].

B. Beam Diverger System

Beam diverger optics were used to convert the raw laser beam output to a beam which exits the telescope at the appropriate divergence. GOPEX required output beam divergences of 110 and 60 μrad ± 10 percent. These requirements translated to requirements of beam diameter size at the focal plane of 3.36 mm and 1.84 mm, respectively.

The beam diverger also had a requirement that the beam divergence at the focal plane reference iris be approximately 4 μrad . The focal plane divergence was chosen as a compromise between beam vignetting and the power density on the telescope optics. The beam divergence was made as large as possible in order to maximize the beam size and hence minimize the power density at the

coudé and telescope optics. However, divergences larger than about 4 μrad would result in the laser beam being vignetted by either the edge of the telescope or the secondary mirror.

Based on measurements of the output laser parameters made by Big Sky Corporation, the optical system was designed to meet the GOPEX requirements. The beam diverger design for both the 110- and the 60- μrad configurations consists of two lenses: a plano-convex and a plano-concave lens. Key elements of the output from the Code V optical design are given in Table 1.¹ The Code V output for the beam diverger optical design is given in Appendix A.

All lenses were purchased from CVI Laser Corporation. The part numbers of the lenses and specifications for the two configurations are given in Table 1. The plano-convex lens was antireflection coated at 532 nm. Because the plano-concave lenses continually suffered damage during initial testing, it was recommended that these lenses be used uncoated.² A series of experiments verified that the uncoated surfaces were capable of withstanding the laser energies at both 110- and 60- μrad configurations. In addition, it was determined that laser light reflected from the surface of the plano-concave lens would not focus at or near the plano-convex lens.

C. Laser Diagnostic System

A laser diagnostic system was used to determine the shape of the laser beams at various parts of the optical train. The Big Sky Software Corporation Beam Code Laser Diagnostic System was used. The optical train was set up so that the laser beam at the focal plane iris was monitored. A CVI Laser Corporation concave mirror with a focal length of 2 m was used in the diagnostic system. The divergence and spot size were measured by moving the focusing mirror into one of two locations (labeled A and B in Fig. 1). Location A imaged the focal plane onto the beam-monitoring CCD. The magnification factor was determined by measuring the distances between the principal planes and the focusing mirror with a tape measure. Location B was chosen one focal length away from the monitoring CCD and was used to measure the laser beam divergence.

¹ M. Chrisp, "GOPEX Beam Diverger Optical Design," JPL Interoffice Memorandum OSG 92-46 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 26, 1992, and "GOPEX Redesign Beam Divergers," JPL Interoffice Memorandum 92-138 (internal document), Jet Propulsion Laboratory, Pasadena, California, September 29, 1992.

² G. Al Jumaily, "High Power Lenses for GOPEX," JPL Interoffice Memorandum OSG 92-142 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 26, 1992.

In addition to monitoring the laser beam, the diagnostic system was used to boresight the laser beam with the telescope. The alignment procedure is described in Section III.

D. The Vision Acquisition Systems

The visual acquisition system was used to center a calibration star at the center of the focal plane iris thereby calibrating the telescope to the laser-uplink system. This system consisted of a pick-off mirror to divert the starlight beam into the visual acquisition arm, lens, and eyepiece. The lens and eyepiece were aligned with the line of sight of the telescope and adjusted so that the observer would focus on the plane of the iris. This was important so that the position of the focal plane of the telescope would automatically be collocated with the plane of the iris. During laser uplink, the pick-off mirror would be flipped up to allow the laser beam to enter the telescope.

The CCD acquisition system was used to acquire star images and measure the seeing condition during GOPEX. The system used a Photometrics Star I Camera to perform the image acquisition. A flat mirror was manually placed to pick off the starlight which is normally used for the visual acquisition system and redirect it to the entrance of the camera. A 70- to 210-mm camera lens with a 4-cm extender tube was used to reimage the focal plane iris onto the CCD. The stellar image fell on an approximately 5×5 pixel array. Stellar targets of visual magnitude 4-6 were picked for the seeing measurement so that the integration time was in the 1- to 3-sec range. The long integration times served to average out the speckle caused by the atmosphere.

E. Satellite Return System

The satellite return system was only used during the precursor experiments. Laser uplinks to Earth-orbiting satellites were detected by a two-part transmit and receive (T/R) switch (Fig. 2).

The transmission side consisted of a rotating chopper blade and a light-emitting diode (LED). The chopper blade (labeled A) had a dielectric coating with a maximum reflection at 532 nm, which reflected the return signal from the satellite into the receiver side. In addition, the chopper blade had a 1-cm hole to allow transmission of the outgoing laser pulse through the chopper wheel. The wheel was rotated at 30 Hz. An LED (labeled F) which illuminated a smaller 5-mm hole in the chopper blade and a photodetector in the chopper motor (labeled A) was used to produce a synchronization signal. This signal was fed into the chopper motor driver (labeled D) and then into a

delay generator (labeled E) which was then used to control the synchronization between the laser firing time and the position of the 1-cm hole in the chopper blade.

The returned laser beam was reflected by the chopper into the receiver side of the T/R switch where the signal was routed by fold mirrors (labeled B) to a photomultiplier tube (PMT; labeled C). The output of the PMT was then connected to a DSA 602A Digitizing Signal Analyzer for storage of the return pulse.

The signal analyzer was configured to detect only the laser return pulse. The trigger of the analyzer was enabled by the outgoing laser pulse. The trigger delay offset was set at the minimum transit time of the laser, which guaranteed that the analyzer would not interpret scattered light from the outgoing pulse as satellite returns. The trigger level was set so that the frequency of dark events was approximately one per second, which minimized the chance that a dark event would trigger the analyzer prior to the actual satellite return. The satellite returns were stored in the internal memory of the analyzer and later transferred to floppy disks and used to produce hard copies (see Figs. 3-6).

III. Optical Alignment Procedure

The following is the alignment procedure for the 60- μ rad configuration. The alignment for the 110- μ rad configuration is similar, with the addition of the fold mirrors (M2 and M3) :

- (1) The laser output was optimized for pulse energy and beam spatial profile (Gaussian shape) using the Big Sky Corporation's diagnostic system.
- (2) The focal plane iris was stopped down and the visual acquisition system was aligned. The lens (L3), eyepiece, and the flip mirror (M4) were moved so that the observer could focus on the focal plane iris.
- (3) An aperture target board was placed at the output of the coude tube. This was used to align the laser beam with the optical axis of the telescope
- (4) A low-power raw laser beam was aligned to both the center of the focal plane iris and the coude target. The tilt and position of mirror M1 were adjusted so that the light reflected from the telescope secondary was centered on the coude target.
- (5) A sheet of white paper was placed on the dome, and the edges of the telescope tube and secondary mirror were marked on the paper.

- (6) The coudé target was removed and mirror M1 was adjusted to allow the laser beam to pass through the center of the focal plane iris and produce a spot on the dome paper, which is roughly centered between the telescope edge markings.
- (7) The plano-convex lens (L1) was placed in its designed position and adjusted in centering and tilt by using the light reflected backwards from the surface of the lens.
- (8) The plano-concave lens (L2) was placed in its designed position and also adjusted using back reflections.
- (9) The laser-beam-monitoring system was then adjusted by focusing the focal plane iris onto the diagnostic CCD.
- (10) The plano-concave lens was adjusted slightly so that the beam was centered on the iris. Then the beam diameter was measured and adjusted by either moving lens M5 or both lenses as a unit.
- (11) The laser beam divergence at the focal plane was controlled by changing the spacing between the convex and concave lens. The beam diameter at the focal plane was adjusted by varying the distance from the concave lens and the focal plane. With these two degrees of freedom, it was possible to meet the GOPEX requirement.
- (12) The laser beam output was then checked at the dome target to make sure there was no vignetting by the telescope edges.

IV. Optical System Boresight Tests

A. Range Test

Numerous range tests were used to verify the optical design and the alignment procedure. In these tests, a target was positioned on an adjoining slope (distance = 2.5 km). The target had a flashlight in its center. The telescope was focussed and centered on the telescope using the visual acquisition system. The laser was turned on and the laser beam pattern on the target was recorded on videotape. Both the laser beam diameter and centering on the target were studied.

B. Cross Hair Test

The cross hair test was used to verify the boresight of the optical system without the use of an external target. Instead, the cross hairs of the finder scope were used to determine the system's pointing accuracy.

The cross hair test was conducted as follows:

- (1) A relatively bright star was centered on the center of the focal plane iris.
- (2) The cross hair of the 0.6-m telescope's finder scope was then centered on the same star.
- (3) Laser pulses were fired and the pointing of the laser with respect to the cross hair was checked to determine boresight.
- (4) Adjustments were made to the optical system (with Beamcode) if the boresight was found to be in error.

V. Precursor Experiments

Prior to the GOPEX encounter, numerous precursor experiments were performed to test laser uplinks to Earth-orbiting satellites. This section summarizes the results of these tests.

A. Agessal Point and Shoot Experiments

The first laser return experiments were performed on the Agessal satellite. This was a low altitude satellite which travelled horizon to horizon in about 15 minutes. Because of this rapid velocity, satellite tracking using the TMO 0.6-m telescope could not be done. Consequently, an uplink experiment was performed that consisted of pointing the laser at a point on the satellite track and waiting for a return as the satellite crossed the beam. In order to guarantee at least one returned pulse, a 30-Hz pulse repetition rate and a 300- μ rad beam diameter were chosen to be used. This output beam divergence was implemented by moving the 110- μ rad lens pair away from the focal plane iris (see Fig. 2).

The experiment consisted of finding the closest *Fifth Fundamental Catalogue* star to a particular point in the satellite track (typically the middle of the track) and calibrating the telescope on that star. At a time close to when the satellite would cross that point in the track, the telescope was off-pointed to the predicted satellite location and the laser was fired. At the time the satellite crossed the laser beam, a return pulse would be observed.

Two experiments were performed on October 1 and 6. Both resulted in successful returns from Agessal. Figure 3(a) shows the satellite return on October 1. The return shows a typical output from a Q-switched laser, which is distinctly different from a photomultiplier dark event, as shown in Fig. 3(b). Figure 4 shows two returns obtained on October 6. The satellite return on this date was markedly larger than in the previous experiment. This

was attributed to the shorter time (~ 5 sec) between the pointing of the telescope and the time of laser firing. In the first experiment, the delay between pointing and firing was approximately 2 minutes, which allowed the pointing of the telescope to drift significantly.

B. Lageos 1 Point-and-Shoot Experiment

An experiment similar to the Agessai experiments was performed on the Lageos 1 satellite on November 1. Lageos is a higher flying satellite and traverses horizon to horizon in about 30 minutes. For this experiment, the output beam divergence was decreased to $110 \mu\text{rad}$, with a repetition rate of 30 Hz. The laser was shot at the satellite at three different positions in its track. For all three shots, a laser return was observed. Figure 5 shows the laser returns for the different satellite positions.

C. Lageos 1 and 2 Tracking Experiment

A set of satellite tracking experiments was performed on November 2. In this set of experiments, laser pulses were uplinked as the telescope was set to track the satellites along its path. A $110\text{-}\mu\text{rad}$ beam divergence and a 15-Hz repetition rate were used. A description of the setup for the tracking experiment follows:

- (1) Satellite predict files were obtained for both point-ahead and non-point-ahead files. The point-ahead file was to be used for laser uplink and the non-point-ahead file was to be used for visual acquisition.
- (2) The satellite track was divided into four sections. The first and third sections used the non-point-ahead file, and the second and fourth sections used the point-ahead file. This merged satellite file was used to control the telescope pointing.
- (3) The telescope mount was calibrated along the satellite track using the LEARN command in the telescope control software. During this procedure, numerous stars close to the track path were found and the offset from the mount pointing was recorded in the program.
- (4) The satellite was visually acquired during the first section of the track and centered on the focal plane iris. Because the satellites only showed up as sporadic glints of light, two people (J. Young and B. Hornaday) were needed for visual acquisition: one to visually search for the satellite in the finder scope and the second to acquire it in the coudé room.
- (5) Before the second section of the track began, the laser beam would begin firing and the uplink returns would be observed and recorded on the storage scope.

- (6) The visual acquisition procedure was repeated for the third section of the track and the laser was uplinked during the fourth section of the track.

On November 2, tracking laser uplinks were performed on both Lageos 1 and 2. Since both satellites were passing over at the same time, it was decided that tracking would be performed on only half of the Lageos 1 track and about three-quarters of the Lageos 2 track. In all cases, successful returns from both satellites were observed. Figure 6 shows a small sample of the many pulse returns from the two satellites.

D. Etalon Tracking Experiment

On November 30, a $60\text{-}\mu\text{rad}$ divergence beam with a 15-Hz repetition rate was used to track the satellite Etalon. This satellite took approximately 2.5 hours to traverse from horizon to horizon. Again the track was divided into four parts with two acquisition and uplink pairs. This experiment was performed after the internal dry run that had been performed earlier that night. Successful returns were obtained from Etalon. It was noted that the signal was sporadic; for some of the time the returns were strong and continuous, followed by a period where there were no returns, followed again by a strong series of returns. This was attributed to wobble in the pointing of the telescope, which was corroborated during the visual acquisition phase where the satellite was observed to wobble in the field as the telescope tracked.

VI. Galileo Encounter Support

During Galileo encounter, the optical train was checked every night and the beam parameters were measured. The checks included measuring the output laser power and beam divergence. In addition, boresighting of the laser beam with the telescope was checked using both a range test and a cross hair test.

As described previously, the range test involved firing the laser beam at a target located on a slope facing TMF. This test was performed on day 1 and day 5 of the experiment. The beam pointing and shape were checked to see if they were qualitatively within the specifications for that night's experiment. Range tests for the other nights were not done since the optical system had not been reconfigured.

On most nights, no problems were encountered and no adjustments to the optical system were made during the time of the experiment. However, during day 3, when

the repetition rate for the 110- μ rad configuration was increased from 15 to 30 Hz, laser damage was observed on the coudé turning mirror. In this situation, the mirror was rotated to an undamaged section of the mirror just prior to the time for Galileo uplink. By the end of the experiment, evidence of laser damage was found on the turning mirror. Day 4 experiments were cancelled at the TMO site due to unfavorable weather conditions.

VII. Conclusion

The optical design and alignment procedures for the GOPEX optical train at TMF have been presented. The results for the first optical uplink to a deep space satellite were very successful. This was due, in part, to an extensive verification process that used uplinks to Earth-orbiting satellites and range tests to validate the performance of the optical train.

Acknowledgments

The authors would like to recognize Michael Chrisp and Ghanim Al-Jumaily for their contributions to the optical design. Thanks also to Kevin Masters, William Hornaday, Jim Young, Garrett Okamoto, and Ron Dotson for their contributions during GOPEX and the precursor experiments. The contributions of Jim Lesh, Keith Wilson, and Tsun-Yee Yan, as well as the Table Mountain Facility staff, including Dan Sidwell and Pam Glatfelter, are also gratefully acknowledged.

References

- [1] K. E. Wilson and J. R. Lesh, "An Overview of the Galileo Optical Experiment (GOPEX)," *The Telecommunication and Data Acquisition Progress Report 42-114*, vol. April-July 1993, Jet Propulsion Laboratory, Pasadena, California, pp. 192-204, August 15, 1993.
- [2] G. Okamoto and K. Masters, "GOPEX Laser Transmission and Monitoring Systems," *The Telecommunication and Data Acquisition Progress Report 42-114*, vol. April-July 1993, Jet Propulsion Laboratory, Pasadena, California, pp. 248-254, August 15, 1993.

Table 1. Optical design parameters.

Beam divergence, μrad	Convex	Concave	Lens spacing, mm	Distance to focal plane, mm
110	PLCX-25.4/128.8-UV	PLCC-25.4/77.3-UV	84.70	75.00
80	PLCX-25.4/128.8-UV	PLCC-25.4/38.6-UV	186.23	71.54

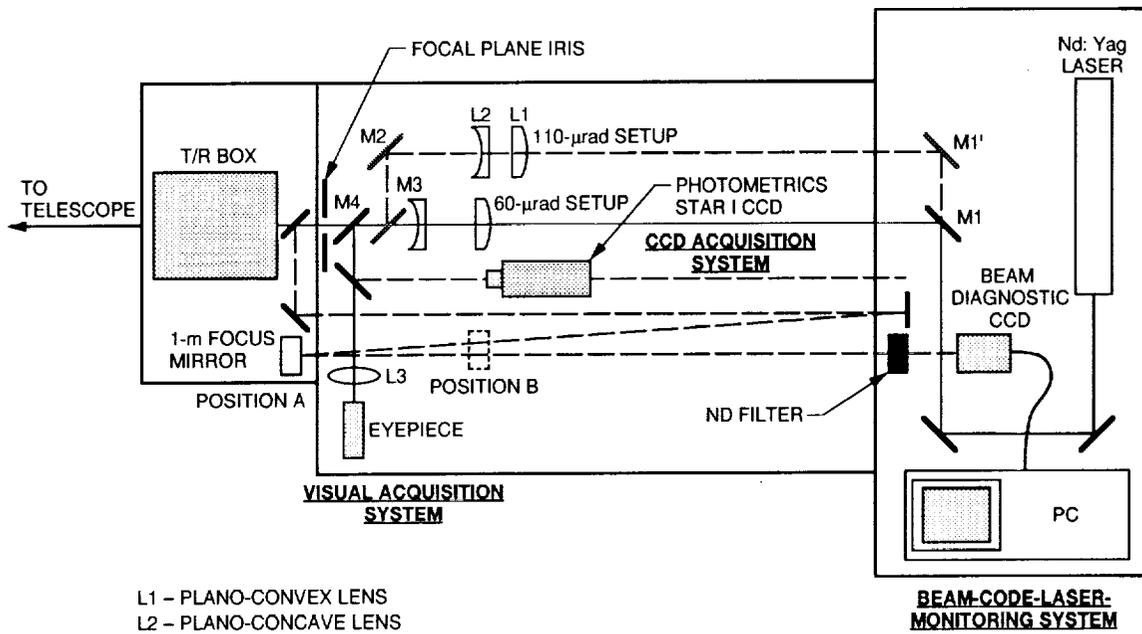


Fig. 1. GOPEX Optical System layout.

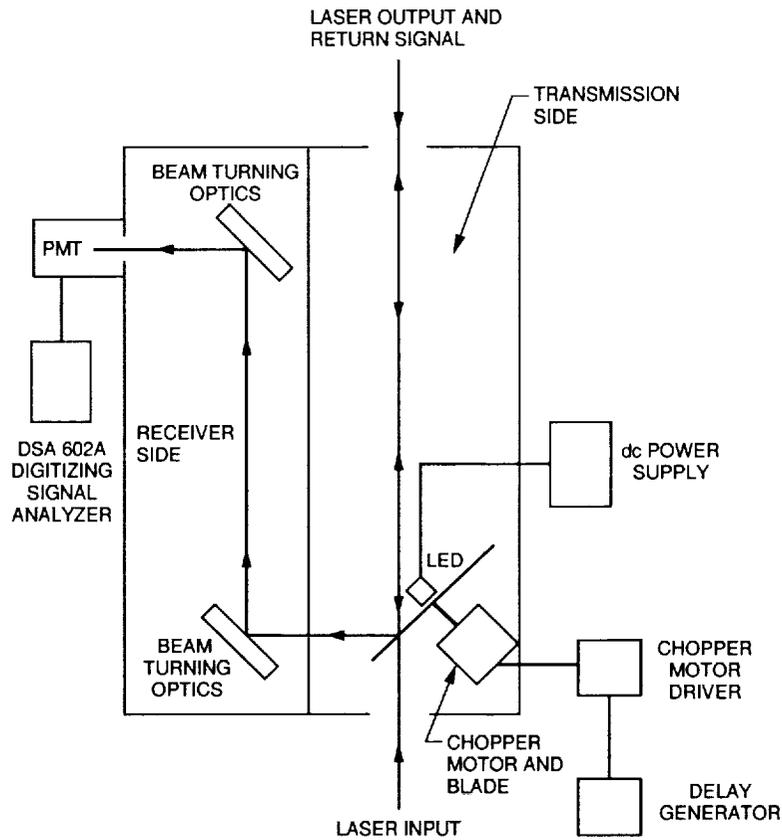


Fig. 2. Transmit/Receive switch.

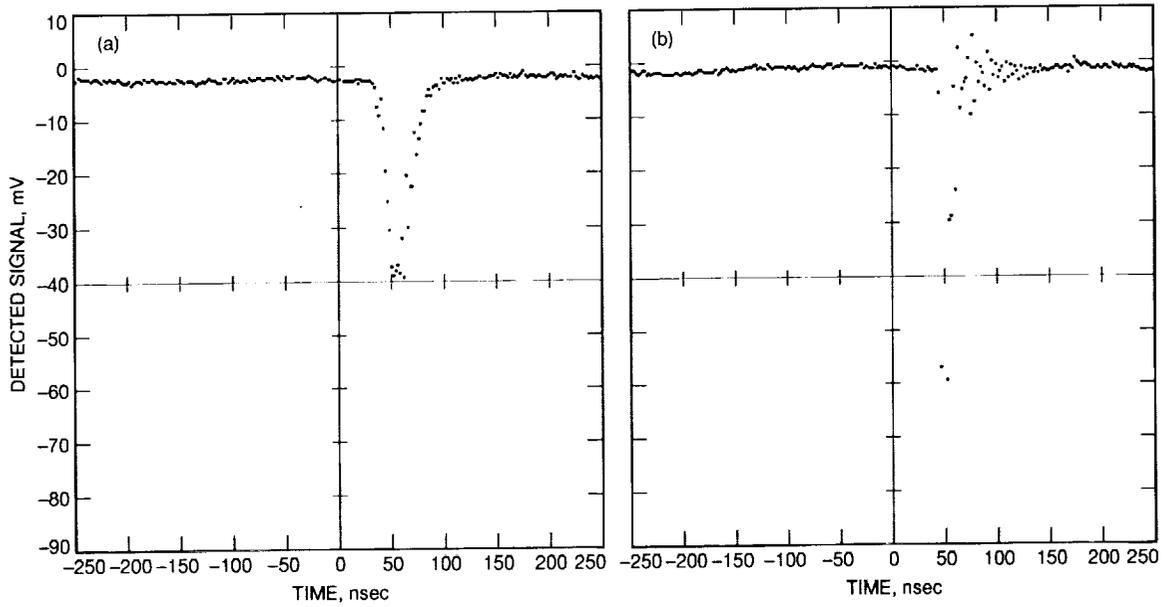


Fig. 3. Agessal Point and Shoot Experiment I (October 1, 1992): (a) Satellite return and (b) Photon detector dark event.

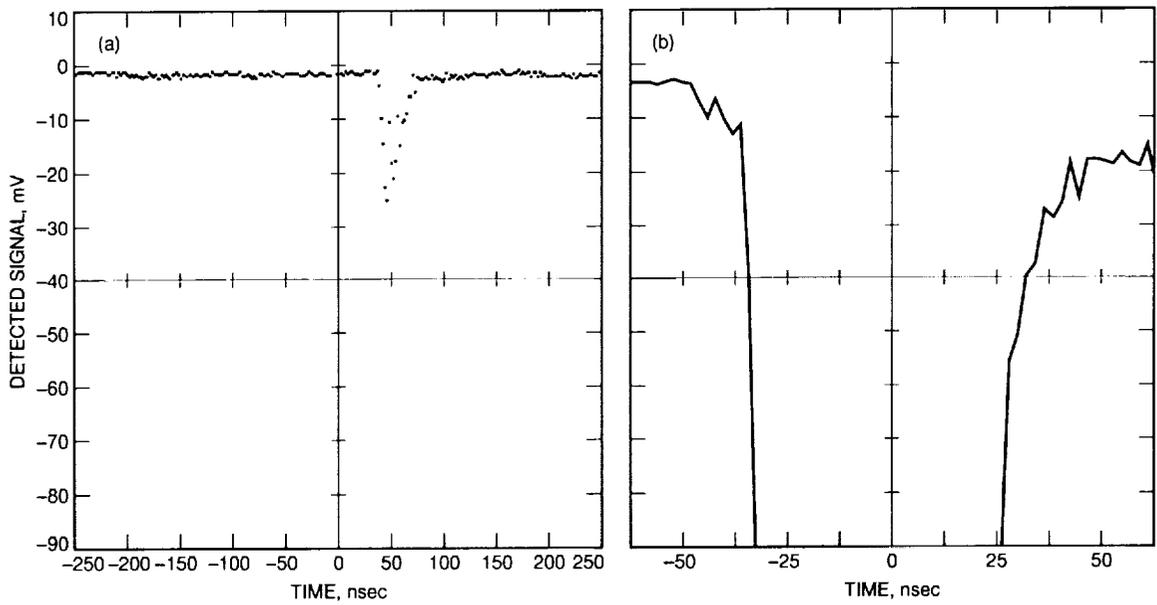


Fig. 4. Agessal Point and Shoot Experiment II (October 7, 1992): (a) Agessal return, highest point and (b) Agessal return, descending point.

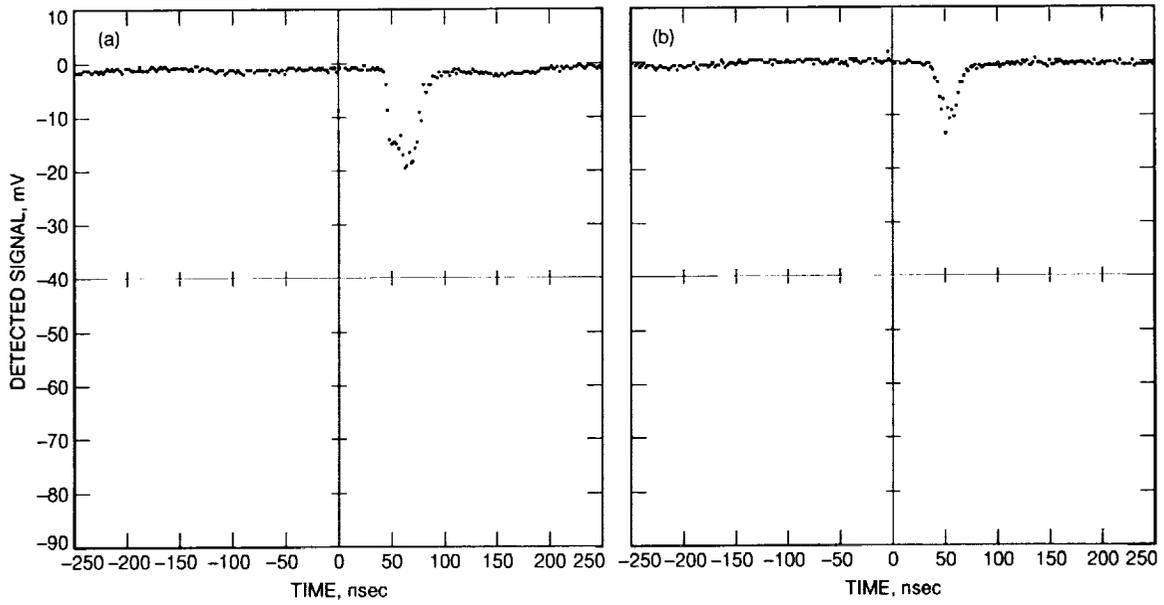


Fig. 5. Lageos Point and Shoot Experiment (November 1, 1992): (a) Lageos return, highest point and (b) Lageos return, descending point.

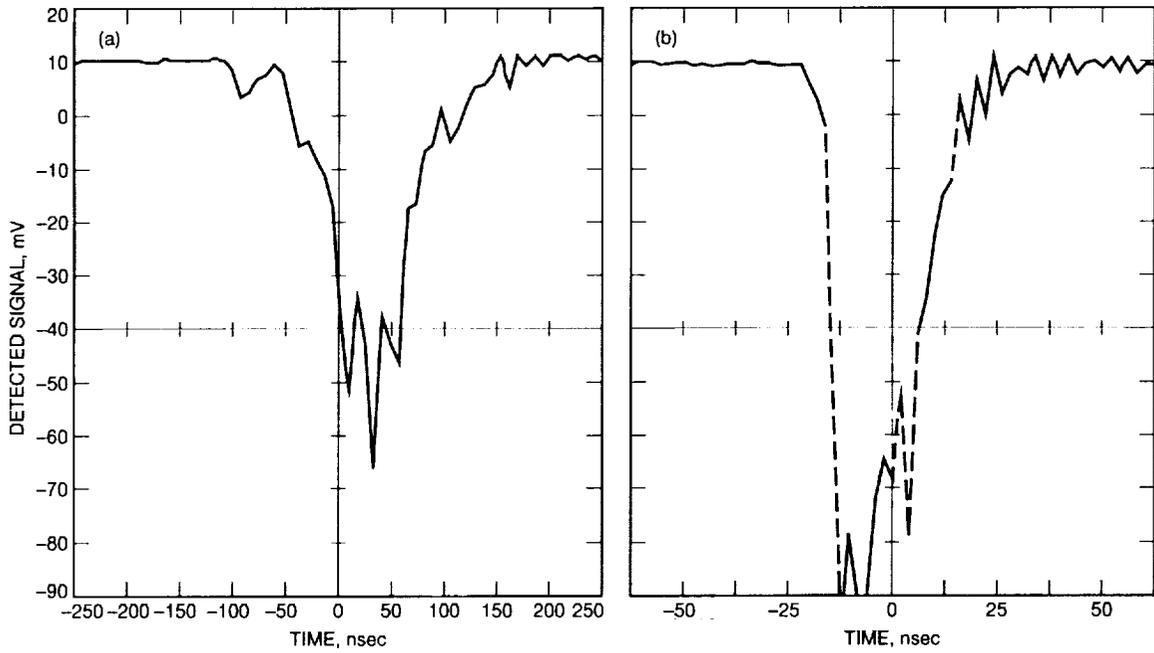


Fig. 6. Satellite returns from Lageos Tracking Experiment (November 2, 1992): (a) Lageos 1 uplink and (b) Lageos 2 uplink.

Appendix A

Code V Design of Beam Divergers

```

File [MPC.GDPEX]G00D110.LEN(2) has been restored
Lens title: "REDESIGNED 110 MICRORAD SYSTEM 9/28/92"
CODE V> LIS
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REDESIGNED 110 MICRORAD SYSTEM 9/28/92
      RDY          THI          RMD          GLA
> OBJ:          INFINITY      4766.815342
STD:          INFINITY      0.000000
  2:          128.80000      4.000000      SILICA_SPECIAL
  3:          INFINITY      84.704658
  4:          INFINITY      2.300000      SILICA_SPECIAL
  5:          77.30000      0.000000
  6:          INFINITY      75.000000
IMG:          INFINITY      0.000000

SPECIFICATION DATA
NAD          0.00046
DIM          MM
WL          532.00
REF          1
WTW          1
XAN          0.00000
YAN          0.00000
VUY          0.00000
VLY          0.00000

APERTURE DATA/EDGE DEFINITIONS
CA
CIR S1          6.550000

REFRACTIVE INDICES
GLASS CODE          532.00
SILICA_SPECIAL      1.460711

No solves defined in system

INFINITE CONJUGATES
EFL          -2060.3872
BFL          -1404.3365
FFL          3153.5222
FND          -466.4748
AT USED CONJUGATES
RED          -0.2601
FND          -280.7455
OBJ DIS      4766.8153
TT          4932.8200
IMG DIS      75.0000
OAL          91.0047
PARAXIAL IMAGE
HT          0.0000
THI          -868.3498
ANG          0.0000
ENTRANCE PUPIL
DIA          4.4169
THI          0.0000
EXIT PUPIL
DIA          2.8858
THI          -58.1606
CODE V> RSI 1 0 0 0
      RSI 1 0 0 0
REDESIGNED 110 MICRORAD SYSTEM 9/28/92
Position 1, Wavelength = 532.0 NM
      X          Y          Z          TANX          TANY          LENGTH
OBJ          0.00000      0.00000      0.00000      0.00046      0.00000
STD          2.20847      0.00000      0.00000      0.00046      0.00000      0.00000
  2          2.20847      0.00000      0.01894      -0.00509      0.00000      0.01894
  3          2.18820      0.00000      0.00000      -0.00744      0.00000      3.98112
  4          1.55823      0.00000      0.00000      -0.00509      0.00000      84.70700
  5          1.54644      0.00000      0.01547      0.00178      0.00000      2.31550
  6          1.54641      0.00000      0.00000      0.00178      0.00000      -0.01547
IMG          1.68000      0.00000      0.00000      0.00178      0.00000      75.00012
      OPD =          2.813 Waves

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Fig. A-1. A 110- μ rad beam diverger Code V listing.

Appendix B

GOPEX Code V Optical Design

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RES [MPC.GOPEX]G00D60
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LIS
REDESIGNED 60 MICRORAD SYSTEM 9/28/92
      RDY      THI      RMD      GLA
> OBJ:      INFINITY      4668.743625
STO:      INFINITY      0.000000
  2:      128.80000      4.000000      SILICA_SPECIAL
  3:      INFINITY      186.231488
  4:      INFINITY      2.300000      SILICA_SPECIAL
  5:      38.60000      0.000000
  6:      INFINITY      71.544887
IMG:      INFINITY      0.000000

SPECIFICATION DATA
NAD      0.00046
DIM      MM
WL      532.00
REF      1
WTW      1
XAN      0.00000
YAN      0.00000
VUY      0.00000
VLY      0.00000

APERTURE DATA/EDGE DEFINITIONS
CA
CIR S1      6.550000

REFRACTIVE INDICES
GLASS CODE      532.00
SILICA_SPECIAL      1.460711

No solves defined in system

INFINITE CONJUGATES
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BFL      -1423.4322
FFL      14636.2829
FNO      -1033.3016

AT USED CONJUGATES
RED      -0.2316
FNO      -249.8943
OBJ DIS      4668.7436
TT      4932.8200
IMG DIS      71.5449
DAL      192.5315

PARAXIAL IMAGE
HT      0.0000
THI      -388.3650
ANG      0.0000

ENTRANCE PUPIL
DIA      4.3261
THI      0.0000

EXIT PUPIL
DIA      1.3212
THI      -58.1949

CODE V> RSI 1 0 0 0
      RSI 1 0 0 0
REDESIGNED 60 MICRORAD SYSTEM 9/28/92
Position 1, Wavelength = 532.0 NM
      X      Y      Z      TANX      TANY      LENGTH
OBJ      0.00000      0.00000      0.00000      0.00046      0.00000
STO      2.16303      0.00000      0.00000      0.00046      0.00000      0.00000
  2      2.16304      0.00000      0.01816      -0.00498      0.00000      0.01816
  3      2.14321      0.00000      0.00000      -0.00727      0.00000      3.98189
  4      0.78842      0.00000      0.00000      -0.00498      0.00000      186.23642
  5      0.77693      0.00000      0.00782      0.00200      0.00000      2.30785
  6      0.77691      0.00000      0.00000      0.00200      0.00000      -0.00782
IMG      0.92000      0.00000      0.00000      0.00200      0.00000      71.54503
      OPD = 1.729 Waves

```

Fig. B-1. A 60- μ rad beam diverger Code V listing.