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AIRBORNE 2 COLOR RANGING EXPERIMENT

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ABSTRACT

Horizontal variations in the atmospheric refractivity are a limiting error source for many precise laser and radio space geodetic techniques[1-7]. This experiment was designed to directly measure horizontal variations in atmospheric refractivity, for the first time, by using 2 color laser ranging measurements to an aircraft. The 2 color laser system at the Goddard Optical Research Facility (GORF) ranged to a cooperative laser target package on a T-39 aircraft. Circular patterns which extended from the southern edge of the Washington D.C. Beltway to the southern edge of Baltimore, MD were flown counter clockwise around Greenbelt, MD. Successful acquisition, tracking and ranging for 21 circular paths were achieved on three flights in August 1992, resulting in over 20,000 two color ranging measurements.

INTRODUCTION

Atmospheric refractivity is a limiting error source in precise satellite laser ranging (SLR). Several models have been developed to correct SLR measurements for the increased optical path length caused by atmospheric refraction[1-3,8,9]. The first three formulas assume that atmospheric refraction is spherically symmetric, and require surface meterological data at the laser ranging site. A higher order model developed by Gardner [8,9] can, in principle compensate for spatially varying atmospheric refraction by utilizing pressure and temperature measurements at many locations near the laser ranging site. However, this model depends on the surface measurements being strongly correlated to atmospheric density at higher altitudes.

A more accurate method for determining the atmospheric correction is to directly measure the atmospheric dispersion with a two color laser ranging system[4-7]. In the two color ranging approach, the single color range and the differential delay between the two colors is measured. Due to atmospheric dispersion, the differential delay is proportional to the path-integrated atmospheric density, and therefore it can be used to estimate the atmospheric correction. In 1980, Abshire proposed to measure the magnitude of the horizontal gradients in atmospheric refraction by making dual color ranging measurements to an aircraft equipped with a retroreflector. We have developed and successfully carried out such an airborne two color ranging experiment. We expect that data from this experiment will improve our knowledge of gradients in the refractivity, and could contribute towards improving atmospheric models.

APPROACH

Our experiment utilized Goddard's 2 color ranging system at the 1.2 meter (m) telescope facility with a cooperative laser target package on a T-39 aircraft. A simplified diagram of the experiment is shown in Figure 1. The ground-based laser system tracked and ranged to the aircraft as it circled Greenbelt, MD. With this circular flight pattern, the aircraft passed partially over two major cities, Washington D.C. and Baltimore, and land near the Chesapeake bay. It is likely that variations in the terrain temperatures will cause horizontal gradients in the air density directly above, which could be measured by the experiment.

The initial step in the experiment is to acquire the aircraft's approximate location. A realtime GPS data relay link was developed for this purpose. A GPS receiver on the T-39 relayed the aircraft position every 3 seconds through an RF digital packet link to the ground telescope. The telescope's tracking program then determined the pointing angles to the aircraft by extrapolating the aircraft's position from the GPS data.

Once acquired, we closed an automatic tracking loop by using a CCD camera and frame grabber which commanded the 1.2 m telescope to automatically track the aircraft's 810 nm laser diode beacon. The aircraft target package was manually pointed to the ground from inside the aircraft by viewing the ground beacon which was modulated at 5 Hz.

To determine the optical path length we measured the range to the aircraft at 355 nm with a 20 psec resolution laser ranging system. For the differential delay measurement, we used a streak camera-based receiver which recorded the reflected 355 & 532 nm pulses within a 1.2 nanosecond (nsec) time window.

AIRCRAFT INSTRUMENTATION

Figure 2 shows the T-39 aircraft based at (Wallops Flight Facility) used in this experiment, along with the flight crew. The T-39 is a two engine, 4 passenger, jet aircraft capable of maintaining 12 kilometer (km) altitude. The three science flights were limited to 6 - 7 km altitudes due to high cirrus clouds near 7 km. The target package was located beneath the nadir port of the aircraft just aft of the air brake.

On the aircraft we used a combination of laser and electro-optic instrumentation for pointing the target package with two radio transceivers for data and voice communications to the ground laser facility. A photograph of the target configuration is shown in Figure 3. The target package consisted of a cube corner array (CCA), a laser diode beacon and a CCD camera with a narrow bandpass filter. The package was secured to a commercial pan and tilt camera mount and was controlled with a joystick inside the aircraft. The entire package was protected by an aluminum enclosure which incorporated a 1/4" thick quartz window to transmit the optical signals at 355, 532 and 810 nm. This window was tilted ~3°, with respect to the aircraft nadir, so that the beams would transmit through at right angles to the window. We used baffles on both the laser diode beacon and the CCD camera to reduce scattering of the laser beacon from the window into the camera. The baffles extended close to the enclosure window. The target package components and parameters are listed in Table 1.

We used several techniques to control the target package's temperature. To avoid condensation on optical surfaces, tape heaters were attached to the inner walls of the CCA housing and around the filter adaptor tube on the CCD camera. Resistive heaters were installed on the back mounting plate of the target package. An AD590 temperature sensor was placed on the filter adapter of the CCD camera. The sensor indicated that at 7 km altitude the target package stayed at 10°C for the flight duration. Dry nitrogen was flushed into the target enclosure before takeoff and during ascent, descent and landing to displace water vapor, which could condense on cold optical surfaces.

The target package could be pointed in azimuth ±5° from port, parallel to the left wing and in elevation +5° to -15° from horizontal. The operator who moved the target package via joystick could instruct the pilots to adjust aircraft attitude if the ground beacon was moving outside of the CCD camera's 10° field of view (FOV). This was necessary particularly in azimuth during flights with strong cross winds.

The flight crew consisted of two pilots and two science team members. One person pointed the target and communicated with the pilots, while the other operated the GPS control software and maintained radio communication with the ground ranging site. The GPS receiver was used to receive the aircraft's lattitude, longitude, altitude and time. The GPS receiver relayed its information to the flight computer via a RS232 port, as well as to the packet radio. The packet information was transmitted in bursts every 3 seconds. The flight computer allowed the operator to verify that at least four satellites were in the receivers FOV and that the GPS data being sent was correct. An aircraft LORAN unit was used as a backup to initialize the GPS receiver in the event of a computer crash.

The ground packet radio receiver relayed the aircraft's position to the DEC PDP 11/24 computer. This mount control computer pointed the 1.2 m telescope to the aircraft. While flying the circular pattern, the pilots used a TACAN transceiver which gave them slant range to GORF where another TACAN transceiver was located.

GROUND-BASED RANGING & TRACKING INSTRUMENTATION

The airborne two color laser ranging experiment was one of several projects which have used Goddard's 1.2 m telescope ranging & tracking facility. This facility was developed for satellite laser ranging. We tried to design the aircraft experiment to minimize the impact to the ongoing satellite ranging program, so that only slight system modifications were made to convert from satellite mode to aircraft mode. A simplified block diagram of the system is shown in Figure 4, with system parameters given in Table 2.

For the aircraft experiments the Nd:YAG laser was operated at 10 mJ at 355 nm and 0.3 mJ at 532 nm to avoid damaging the telescope optics. The laser was housed about 10 meters from the base of the telescope. Figure 5 shows the laser transmitter and two color optics. The experimenters area is located at the base of the telescope near the telescope focal plane. This area contains the range receiver electronics, aft optics and streak camera. The aft optics for the aircraft configuration is shown in Figure 6. The laser output is directed through a hole in the 45° bifurcated mirror through the telescope and to the aircraft.

The ranging operation can be described by referring to Figure 4. A start diode samples the outgoing laser pulse to initiate the time interval measurement sequence. The aircraft return pulses are then reflected at the 45° birfurcated mirror and into the aft optics receiver. In the receiver a small percentage of the return is split and detected by the MCP photomultiplier tube. This generates the stop signal for the time-of-flight measurement as well as the pre-trigger for the streak camera.

The majority of the received signal was then separated into 532 nm and 355 nm paths by a dichroic mirror and bandpass filters. Each color was focussed into a fiber optic delay line. The optical delay was required to allow pre-triggering the streak camera with respect to the optical pulse's arrival time. The delay fiber bundle was composed of 27 fused silica fibers with 100 μm core for each color which were round at the input side and formed into a single row at the output side. The signals were then imaged onto the streak camera photocathode by the streak camera's input lens. The streak camera's 1.2 ns sweep speed setting was calibrated and used to achieve ~4 psec/pixel resolution. During pre-flight tests the detection threshold for optical pulses transmitted through the fiber optic cable to the streak camera was measured to be 6,600 photoelectrons at 355 nm and 4,200 photoelectrons at 532 nm.

At the transmitter, an optical delay was added to the 532 nm pulses to allow both 532 and 355 nm received pulses to be recorded within the 1.2 ns sweep window. The 532 nm pulse was delayed with respect to the 355 nm pulse by using a total internal reflection (TIR) cube corner mounted on a computer controlled linear motor stage. This time offset was used to compensate for the additional ~2.7 nsec round trip atmospheric delay at 355 nm. Each streak camera waveform pair was digitized to 256 time pixels by 8 bits amplitude and was recorded on hard disk. The streak camera waveforms were stored on the PDP LSI 11/23 at a 2 Hz rate. Each file consisted of the optical waveform pair, the 355 nm time-of-flight measurement, the transmitter 532 nm delay setting, telescope azimuth and elevation angles, and other relevant tracking information.

The aircraft was acquired by using the GPS measured aircraft positions which were relayed to the tracking computer. Every 20 msec, the computer tracking program extrapolated the aircraft's present angular position from the three most recent GPS data points and directed the mount to that angular location. GPS tracking was usually sufficiently accurate to keep the aircraft position within the CCD camera's ~0.3° FOV. The tracking loop was closed by reading an X-Y digitizer which determined the angular offset of the aircraft's 810 nm laser diode beacon within the CCD FOV. In this mode the mount was driven so that the beacon's angular position stayed within the center of the CCD FOV. Optical background from bright stars, the moon and other aircraft were suppressed with a 5 nm FWHM bandpass filter in front of the tracking camera. The telescope was able to track the aircraft to a precision of ~200 microradians, and successfully tracked the aircraft across the face of a full moon.

STREAK CAMERA CALIBRATION

When making two color ranging measurements at 532 and 355 nm, the differential delay is ~1/12 the 532 nm delay. The differential delay must be measured to better than 5 psec for 1 cm single color corrections[10,11]. The streak camera's sweep speed had to be carefully calibrated to permit this accuracy.

The first step involved finding the zero delay setting in the transmitter. A cube corner was placed in the optical path in front of the telescope to avoid any atmospheric effects. Then the transmitter's 532 nm delay was adjusted to a position where the 532 and 355 nm pulses arrived at the streak camera simultaneously. This was denoted the zero reference position. Next an optical delay of 100 picoseconds was set at the transmitter. Each waveform pair was smoothed and peak positions were computed along with the difference between the peaks. The 100 psec optical delay setting was then divided by the peak difference (in pixels) to yield an inverse velocity measurement. This dt/dx value (psec/pixel) was then plotted at the x position which was at the midpoint of the two peaks.

This process was repeated several hundred times as the pulse pairs were moved across the streak camera window. The coefficients for the sweep speed were computed as the best fit to the inverse velocity versus midpoint plot as shown in Figure 7. To check the calibration, and to process the flight data, the time difference between the 355 and 532 nm pulses were computed by integrating the inverse velocity profile [5]. The calibration was checked by displacing the TIR cube corner to other known values for comparison with calculated optical delays. The system's calibration was tested either before or after each aircraft experiment, and agreement was typically ~4 psec.

SUMMARY:

On the evenings of August 5, 6 and 7, 1992 we conducted a two color ranging experiment to an aircraft. Each ranging experiment lasted about 2.5 hours as the aircraft circled the ranging system at an altitude of 6 to 7 km and a slant range of 20 to 25 km. This resulted in 7 to 8 full rotations around the ranging site per flight. About 6,000 to 8,000 two color laser ranging measurements were recorded on each flight. In total 30 Mbytes of calibrated 2 color ranging data were collected.

An example of a waveform pair from 8/05/92 is illustrated in Figure 8. Both smoothed and raw data for the green and UV are shown. The waveforms are smoothed for analysis by convolving with a raised cosine pulse. Most of the waveforms had pulse widths wider than the transmitter. Some pulse broadening was caused by modal dispersion in the multimode fiber delay lines. Additional broadening on some signals may be due to saturation of the streak camera. However, in most cases, the sharp leading edges of the optical pulses were preserved in the waveforms. Our work to date shows that timing to the pulse's leading edges appears to have the least timing jitter.

We are currently in the process of normalizing the data for varied range and elevation angle as well as optimizing our method for calculating the differential delay between the 2 color pulses. These results will be compared to atmospheric models[3,8,9] and published upon completion.

ACKNOWLEDGEMENTS

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Table 1. Aircraft Instrumentation Parameters

1. Cube Corner Array Target	23 element array, 2.5 cm cube corners, 5 arc second accuracy, UV coated, R=78% @355 nm.
2. Laser Diode Beacon	SDL-2460 AlGaAs Array, 780 mW at 810 nm, 7° azimuth by 8° elevation divergence.
3. CCD Camera	Philips model 56471 camera, 25 mm lens, f/0.7, 10° FOV, Bandpass Filter: 810 ± 2.5 nm.
4. Pan & Tilt Camera Mount	VICON model V353APTV variable speed drive system and tilt controller, 8" by 12.75" mounting plate
5. GPS Receiver	Motorola EagleVIII, 4-channel, simultaneous L_1 C/A code carrier tracking, <25 m spherical error probability.
6. Packet Radio Controller	AEA, Inc. Model PK-87 Controller ICOM IC-37A FM Transceiver 217.55 MHz, 25 Watt.
7. Minicomputer	Compaq 386 for GPS data control and display.
8. Voice Radio	ICOM IC3SAT FM Transceiver 219.45 MHz, 5 Watt.

Table 2. Two Color Laser Ranging Aircraft Experiment System Parameters

1. Laser Transmitter	Continuum PY62 Cavity Dumped, mode-locked, Nd:YAG System: 355 nm: 10 mJ, 150 μrad 532 nm: 0.3 mJ, 300 μrad Pulsewidth: 30 psec FWHM.
2. Telescope	1.2 meter diameter, f/28 Cassegrain.
3. Detectors:	
PMT	ITT F4128, Microchannel Plate.
Streak Camera	Hammamatsu model C1370, 2 psec resolution, 256 elements by 8 bit digitization.
4. Time Interval Unit	Hewlett Packard HP5370, 20 psec resolution.
5. Minicomputers:	DEC PDP 11/24, Pointing. DEC LSI 11/23, Tracking, Streak Camera.

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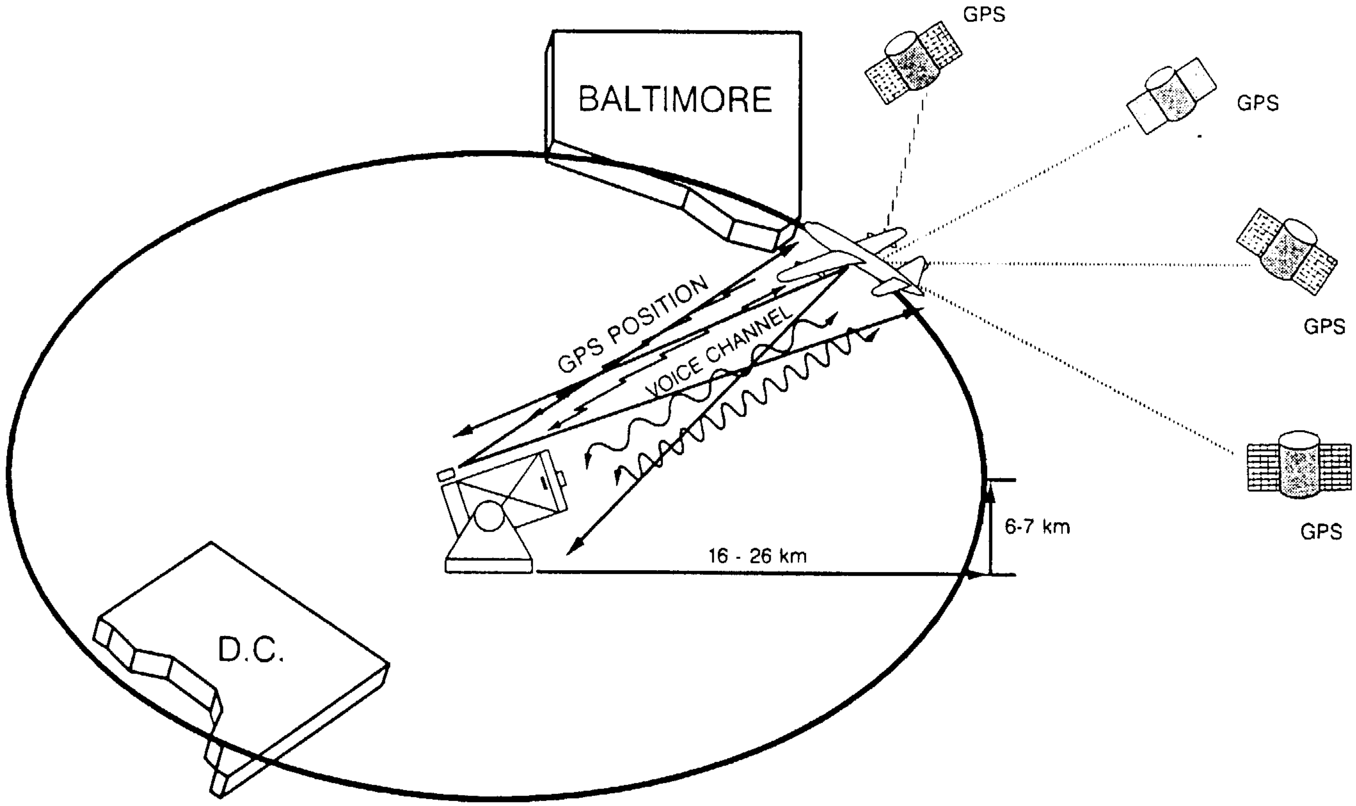

Figure 1. The 1.2 meter 2 color ranging facility centrally located in the flight pattern tracks and ranges to the aircraft. Coarse tracking is accomplished with GPS and fine tracking utilizes the diverging laser diode beacon on the aircraft. 2 color ranging is represented by the two sinusoidal bidirectional lines. The jagged lines imply radio transmission. The aircraft is able to point the cube corner target by tracking the ground laser diode beacon.

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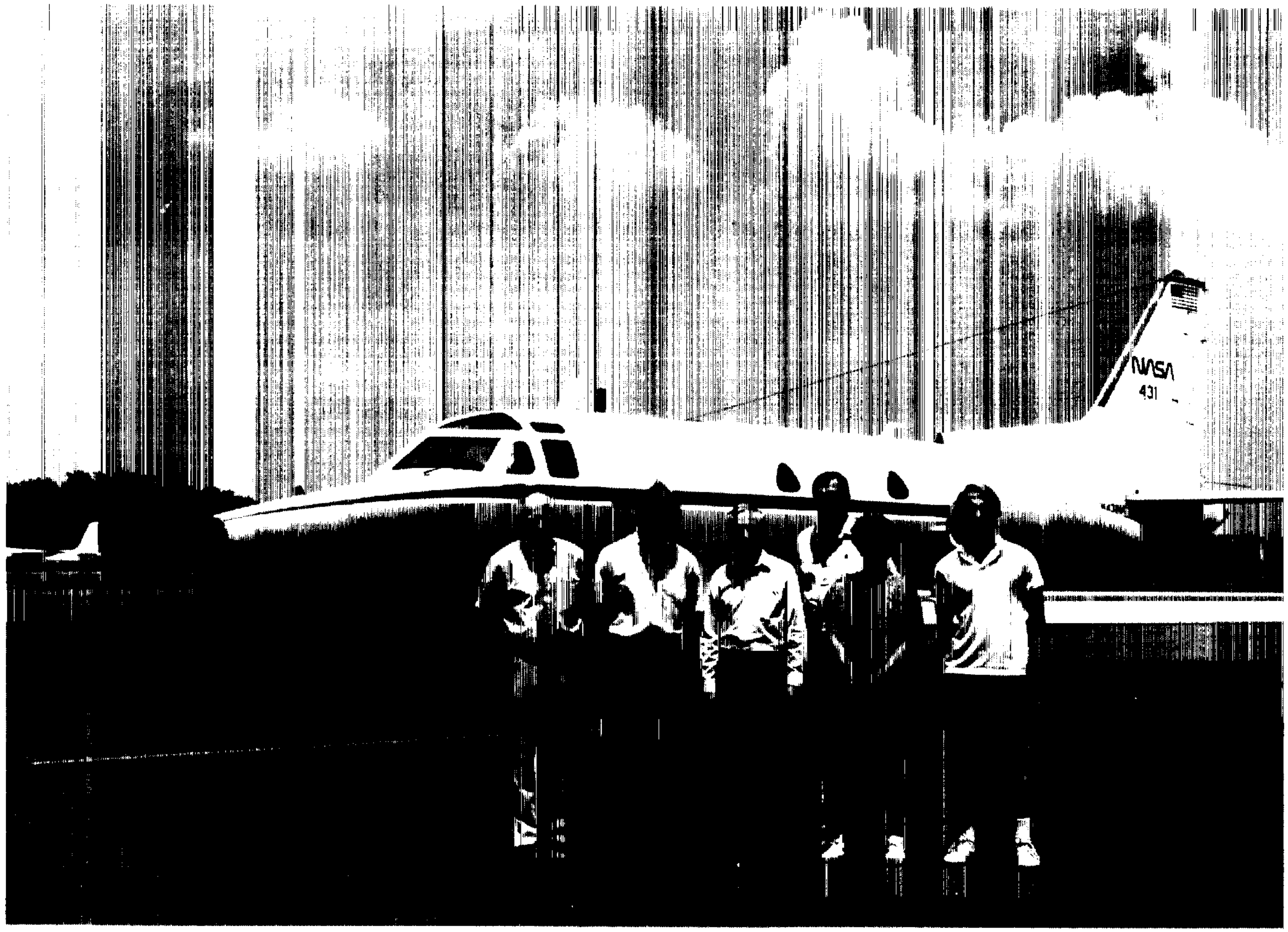

Figure 2. NASA T-39 aircraft and airborne 2 color laser ranging flight crew at Wallops Flight Facility.

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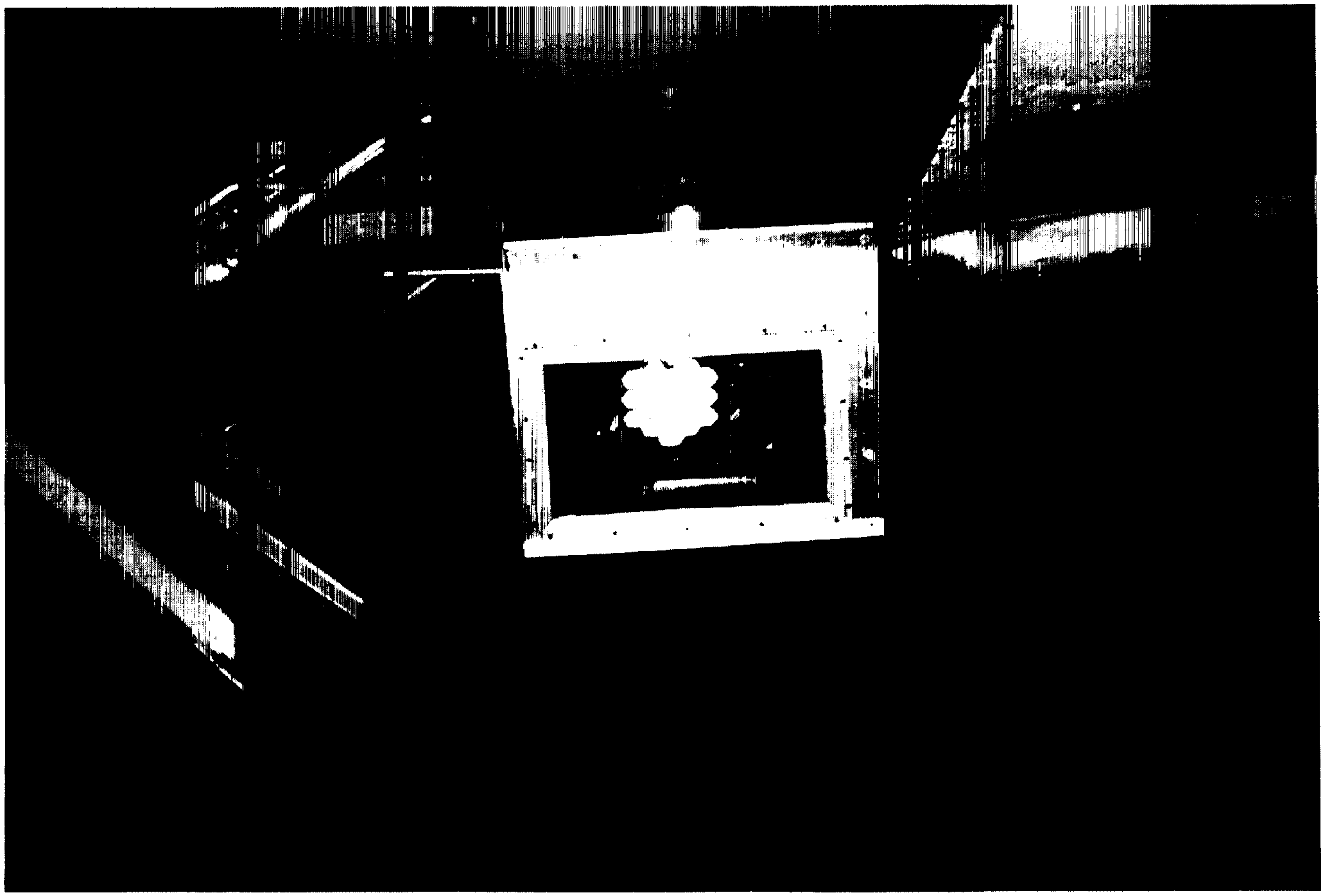

Figure 3. Aft of the T-39 airbrake is the protective enclosure and target package which is mated to the nadir port of the aircraft. The package assembly consists of a cube corner array, and a 1 Watt laser diode beacon above a CCD camera with 25 mm lens and bandpass filter. A pan & tilt mount (not visible) can point the target ± 5° in azimuth and +5° to -15° in elevation .

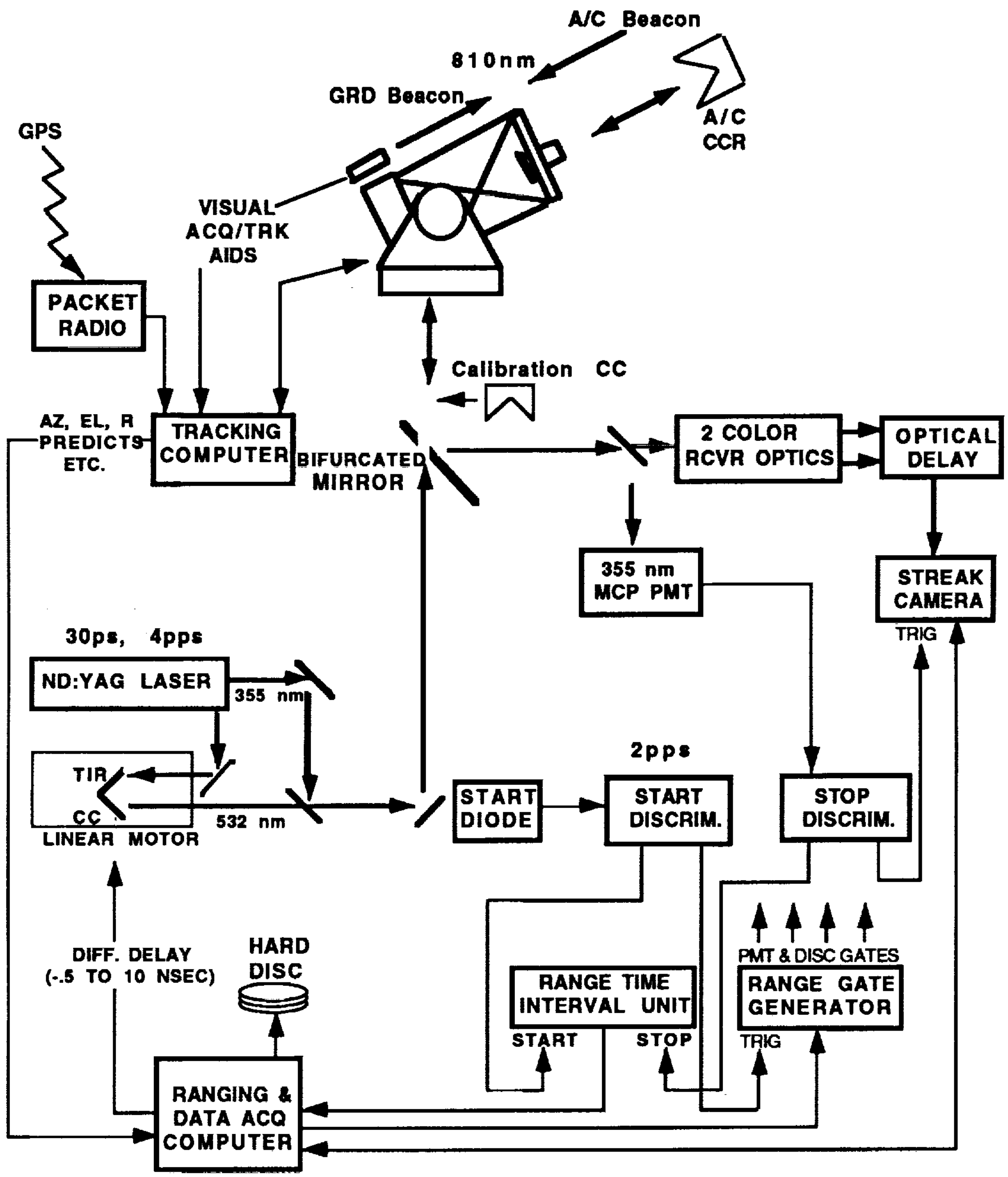

Figure 4. Simple block diagram of 1.2 m ranging and tracking facility in Greenbelt, MD. Thick lines represent optical signals while thin lines indicate electrical signals. The system operated at 2 Hz (or pps). Single color range was measured at 355 nm with conventional time of flight instrumentation. Differential time between the 355 and 532 nm pulses was measured with a streak camera based receiver. System calibration was performed by inserting a corner cube in front of the telescope and setting known delay in the 532 nm path with the TIR cube corner (cc).

A/C = aircraft, ACQ = acquisition, DISCRIM. = discriminator,
MCP PMT = microchannel plate photomultiplier tube, TRK = Tracking

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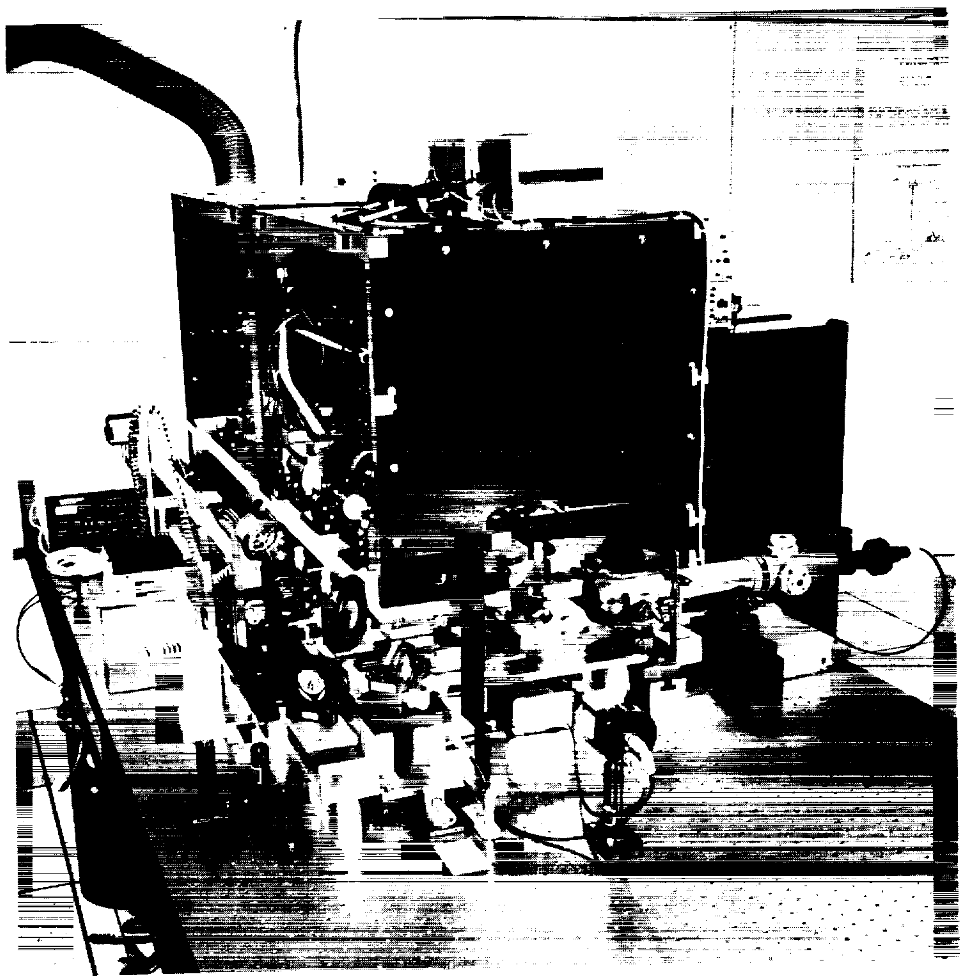

Figure 5. Laser clean room housing the 30 ps Continuum PY62 cavity dumped, mode-locked, doubled and tripled Nd:YAG laser. This system has two amplifier stages. The TIR cube corner variable delay in the green path is shown on the left side of the optical table. Alignment and two color optics are located outside of the primary, plexiglass, laser housing.

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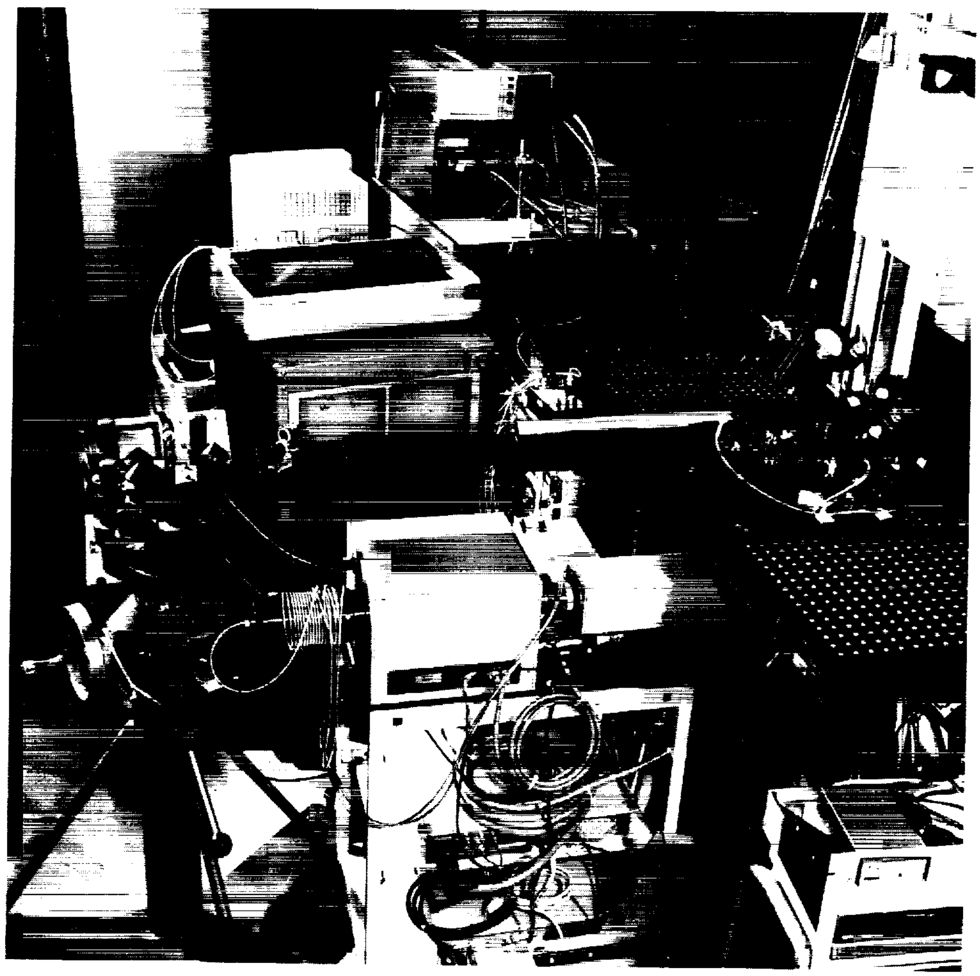

Figure 6. Receiver electronics including MCP PMT, Hammamatsu model 1730 streak camera, fiber optic delay lines, two color aft optics fastened to small breadboard at the base of the 1.2 m telescope.

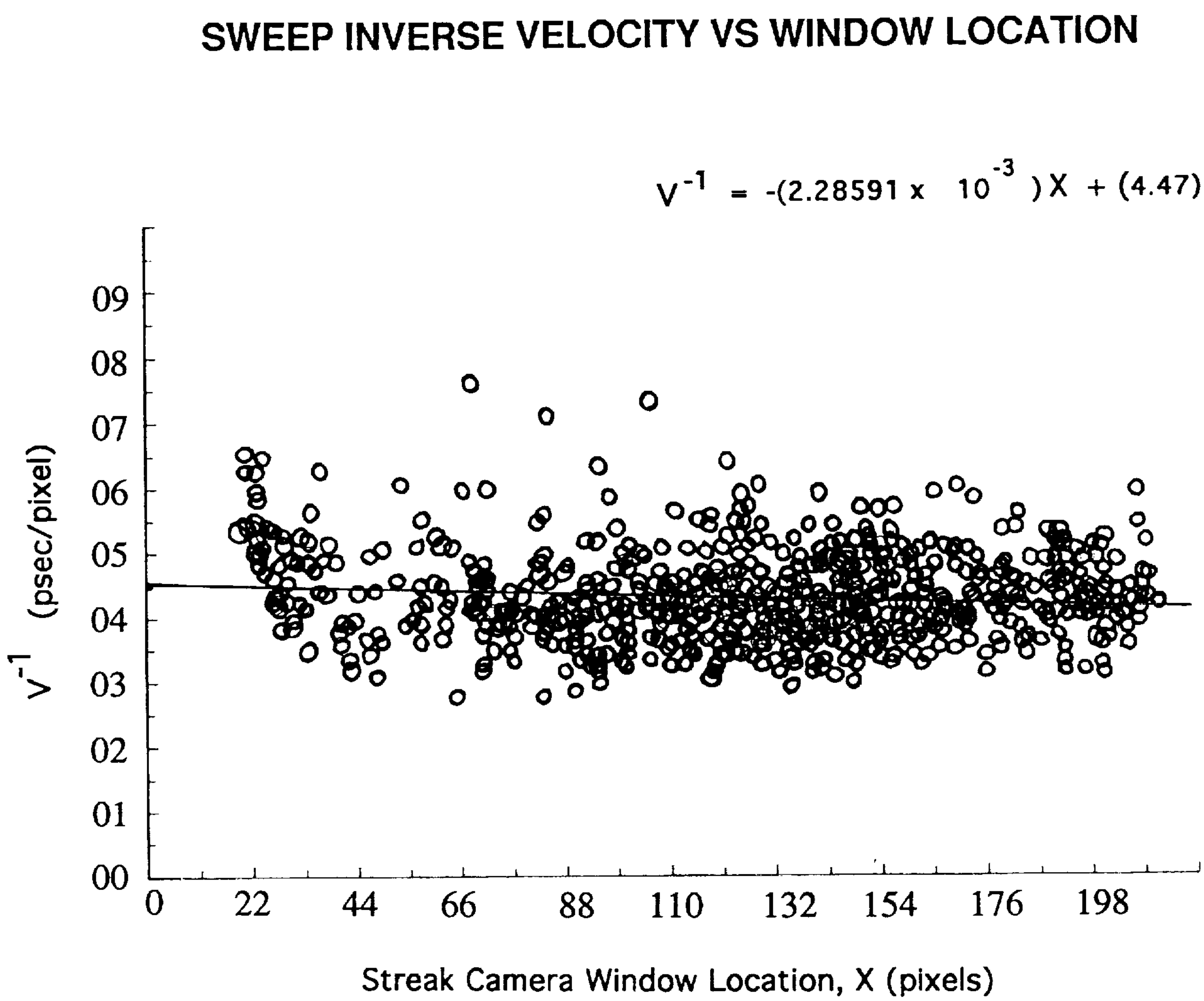

Figure 7. Streak camera sweep speed calibration for 2nsec sweep using data taken 3/24/92. The linear fit using 100 data points is displayed in the upper right hand corner of the plot. The units of inverse velocity are psec/pixel.

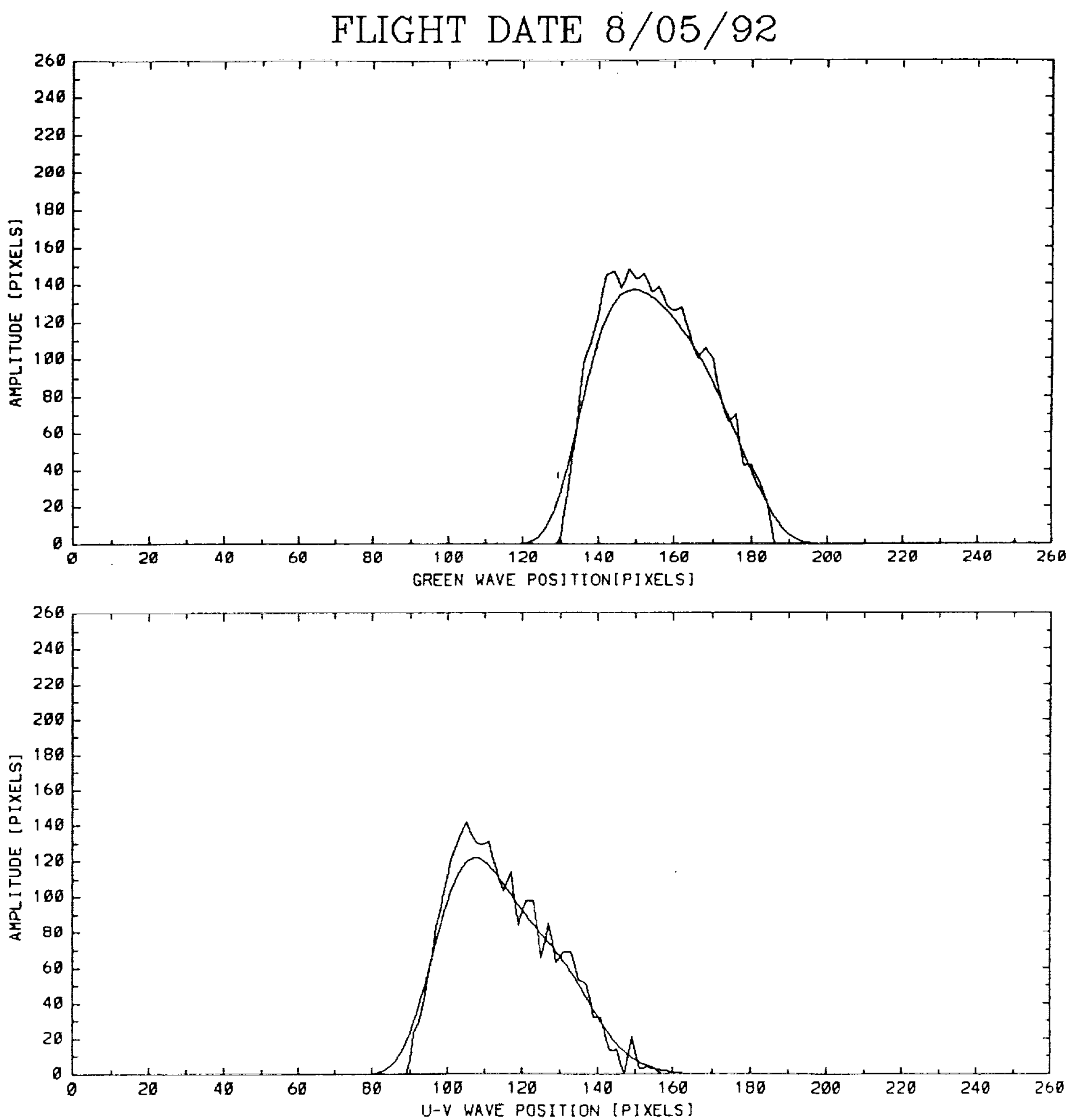

Figure 8. Two color waveform pair recorded by Hammamatsu model C1370 Streak Camera. Each waveform is shown in both raw and smoothed form. The horizontal scale factor is about 4.2 ps/pixel determined by calibration. For this pulse pair, the differential delay (including the optical delay set in the 532 nm path) was 2.667 nsec.