AIRBORNE VISIBLE LASER OPTICAL COMMUNICATION EXPERIMENT

J. L. RANDALL
Astrionics Laboratory
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center Alabama

Summary A series of optical communication experiments between a high altitude aircraft at 18.3 km (60,000 ft) and a ground station are planned by NASA in the summer of 1972. The basic concept is that an optical tracker and transmitter will be located in each terminal. The aircraft transceiver consists of a 5-mW HeNe laser transmitter with a 30-megabit (Mbit) modulator. The ground station beacon is an argon laser operating at 488 mn. A separate pulsed laser radar is used for initial acquisition. The objective of the experiment is to obtain engineering data on the precision tracking and communication system performance at both terminals. Atmospheric effects on the system performance are of prime importance.

Introduction In support of the overall communications program of NASA's Office of Aeronautics and Space Technology, the George C. Marshall Space Flight Center (MSFC) is planning a series of optical communication experiments between a high altitude aircraft package and a ground terminal located at MSFC on Madkin Mountain. Each communication terminal will consist of an optical tracking system with image motion compensation and a laser transmitter with a modulator. Thus each terminal will track on the laser beam of the other end and transmit information or commands to the other via its laser beam. This project is the airborne visible laser optical communication experiment (ALVOC). The experiments are intended to perform three functions: (1) to provide engineering data needed for the evaluation of techniques of optical communications and for future systems, (2) to collect scientific data on the propagation of visible wavelength radiation through the atmosphere, and (3) to demonstrate the feasibility of optical communication and tracking techniques for aircraft-to-ground and satellite-to-ground links.

Several groups are involved in this project. The MSFC Astrionics Laboratory is responsible for the overall project, including experiment definition and operation. This laboratory has also performed integration and checkout of the entire Madkin Mountain optical communications site. ITT Aerospace built the airborne optical communication package (AOCP), the ground-based acquisition aid (GBAA), and the ground checkout equipment (GCE). The AOCP consists basically of the fine tracking system and the HeNe laser transmitter and modulator. The GBAA is a pulsed argon laser radar operating at 514 nm. which is used during initial acquisition. The GCE is a portable system to allow complete checkout of the aircraft package after installation in the aircraft just prior to flight. The Chrysler Corporation Space Division has been responsible for the coarse pointing gimbal mirror, flight computer, and all aircraft system integration and control functions. This also includes all aircraft modification and testing.

The aircraft being used in this experiment is an Air Force RB-57F. The desired aircraft flight path is a circular path at 18.3 km (60,000 ft) altitude in a 12.2 km (40,000 ft) radius. The circular path is desired to obtain data at a constant slant range, which will allow for more meaningful data reduction. The modified RB-57F will enter the optical acquisition area of the GRAA from the south on a line 12.2 km (40,000 ft) west of the ground terminal at an altitude of 18.3 km (60,000 ft). When the aircraft is due west of the ground terminal, it will begin a right turn to enter a circular path centered around the ground terminal. During the experiment, aircraft will be tracked by the GBAA and a microwave radar. Information from these two radar systems will provide data that can be used to keep the aircraft in the desired flight path. Alternate constant range flight patterns may also be selected as dictated by performance characteristics and experiment requirements. The RB-57F will fly out of Ellington AFB, Houston, Texas, and will have approximately 4 hours over MSFC with a 1-hour flight time each way from Houston, Texas, to Huntsville, Alabama.

Description of Equipment The experimental system consists of both the airborne package and the Madkin Mountain ground station. Both the airborne package and the ground station have transceivers so that data on both uplink and downlink propagation can be obtained. The airborne transceiver has a 5-mW HeNe laser operating at 632.8 nm. An electro-optic modulator with a modulation index of 0.65 is used to send a 30-Mbit/s data rate. Communication performance of the downlink will be evaluated by sending a 31-bit psuedo random word over and over. A bit error rate detector on the ground will generate the same word on the ground, synchronize the received and generated word, and compare errors bit for bit. The number of errors will be accumulated for 330 μs (10^4 bits) and recorded. Both baseband and the approximately 2-MHz component of the psuedo random word will be recorded for downlink scintillation data.

The ground station transceiver transmits a 250-mW argon beam to the aircraft. The uplink beacon is modulated to a 10-MHz subcarrier frequency to send up commands. Both baseband and the 10-MHz component will be recorded for uplink scintillation data. The ground station has a pulsed laser radar that performs initial acquisition of the aircraft by tracking corner reflectors on the bottom of the aircraft. A backup visual acquisition and tracking system, consisting of three television cameras and three monitors, is also provided at the ground terminal.

Ground terminal   A block diagram of the ground terminal is shown in figure 1. The primary receiving and transmitting optics consist of a 61-cm (24-in.) Cassegrainian telescope with the experimental transceiver package located at its Coudé focus. Figure 2 shows the 61-cm (24-in.) Coudé telescope with transceiver package. The incoming 632.8-nm beam from the airborne He-Ne laser passes through a wavelength selective beam splitter to separate it from the 488-nm uplink beam. It is then directed through a system of optics to a tracking detector, a communications detector, and a background detector. The tracking detector is a quadrant photomultiplier that provides fine pointing signals to a piezoelectric-driven beam steerer for fine pointing. These signals, along with the output of the angle encoders on the telescope mount, are also fed into an SCC 4700 computer which performs the necessary coordinate transformations and generates signals to drive the polar equatorial telescope mount to keep the incoming signal in the center of the beam steerer range. The communications detector is a photomultiplier tube whose output provides the wide bandwidth downlink communications channel. The output of the communications channel is routed to the control console and to the communications electronics where it is decoded and applied to the bit error detector during the bit error rate test and to the recorder. The background detector is a photomultiplier that records the background intensity in a narrow bandpass at 700 mn. This information is correlated to degradation of the communication performance. The command tone transmitter allows the selection of tone sequences which are applied as modulation to the uplink laser in the transceiver. These tone sequences, when received and decoded at the airborne terminal, perform control functions over the aircraft package such as increase or decrease beam divergence, receiver attenuation, and selection of downlink modulation. The telescope control console provides manual control functions for the telescope as well as visual and electrical telescope position information. The computer interface provides digital-to-analog and analog -to-digital conversions as required for the various computer input/output lines. The video monitor provides an alpha-numeric readout of experimental status. The uplink laser beam is generated by an argon laser which passes through a modulator and beam steerer and out through the telescope. The beam steerer is driven by the computer to direct the uplink beam directly back along the incoming beam.

The GBAA with the control console is shown in figure 3. The radar transceiver is rigidly attached and boresighted to the telescope. During the acquisition phase of the experiment, the GBAA will operate in a search mode, putting up a 10-deg wide radar fence in the direction the aircraft is to enter the acquisition area. When the aircraft enters the radar fence, reflections from retroflectors attached to the underside of the aircraft will be received by the GBAA. On receiving reflections from the retroflectors, the GBAA will enter a track mode and provide pointing information through the computer to the telescope mount. These pointing errors will be used to refine the telescope position until the transceiver system acquires track of the downlink laser, beam. When the transceiver enters the track mode, it will provide the pointing errors. The GBAA will continue to track the aircraft and will provide range and aircraft position information while the transceiver is in the track mode. To assist the aircraft pilot in maintaining the aircraft on the desired circular flight path, the position information from the GRAA will be compared to a computed desired flight path in the computer. A signal representing the difference between the desired and actual flight paths will be routed to the command tone transmitter where an audio tone representing this difference will be generated and used to modulate the uplink laser beam. When the tone is detected and decoded at the aircraft, it will be used to generate a positive or negative dc: voltage which will drive a pilot’s direction indicator informing the pilot of the magnitude and direction of the flight path error. The GBAA control panel provides for control of the GBAA and visual tracking data readouts and furnishes electrical outputs to the computer.

Also rigidly attached and boresighted to the telescope are three television (TV) cameras; each has a different field of view (FOV) and its own monitor. When used with the joystick telescope control, these cameras provide a means of visually acquiring and tracking the aircraft. When displaced, the joystick applies electrical signals to the computer which influences telescope drive rates proportional to the amount and direction of joystick displacement. By manual manipulation of the joystick, the telescope can be pointed so that the aircraft is in the FOV of a 30-deg FOV camera. When the aircraft is centered on the 30-deg FOV TV monitor, it will be in the FOV of a 10-deg FOV camera; and when centered on the 10-deg FOV monitor, it will be in the FOV of the 1-deg FOV camera. When the aircraft is centered on the I-deg FOV monitor and remains centered, telescope drive rates will be adjusted to the proper value for short term tracking of the aircraft and for laser beam acquisition. Tables 1 and 2 list some of the principal ground terminal parameters and ranges of parameters which can be varied.

Table 1. Ground Terminal Parameters and Variable

Telescope

- 0.61 -m diameter
- Coudé focus f/30
- 10 deg/s angular velocity
- 3 deg/s^2 angular acceleration
- Axle position readout - 0.3 arc sec resolution
- Computer controlled

Optical Transceiver

- Cw argon beacon
    - Wavelength - 488 nm

- Beacon power - 0 to 250 mW
- Beacon divergence - collimated to 200 arc sec
- Modulated at 10.7 MHz for command of aircraft package

Tracking detector

- Quadrant photomultiplier - EMR Photoelectric Co.
- FOV - 0 to 180 arc sec
- Attenuation - 0, 0.5, 1, 3 optical density (any combination)

Image motion beam steerer control loop

- Bandwidth - 20 Hz

Communication detector
- Type - photomultiplier, RCA 8644, S-20 surface
- FOV - 0 to 180 arc sec
- Receiver aperture - 60, 40, 20 10, 5, 2.5 cm
- Receiver bandwidth - $\Delta\lambda = 1.25$ nm

Background detector

- Type - photomultiplier, RCA 8644, S-2 surface
- FOV - 0 to 180 arc sec
- Receiver aperture - 60, 40, 20, 10, 5, 2.5 cm

Communications electronics

- Uplink command (10.7 -MHz subcarrier)
- Downlink 30-Mbit communication

    - Bit error rate detector
    - TV video decoder
    - Aircraft package telemetry decoder

SCC 4700 computer -control f unctions

- Telescope mount control
    - GBAA input
    - Transceiver input
    - Manual input

- Data acquisition for recording
- Experiment status and display
  - Aircraft position
  - Tracking system status
  - Communication status
- Housekeeping control function
  - Dome control
  - Sun protection

Table 2. GBAA System Parameters

Receiver optics assembly

    Lens - 65 mm f/0.75 21-deg FOV
    Filter - 514.5-nm bandpass
    Protective shutter - interference

Receiver sensor

    Image dissector - F4012-S-20

Target tracker

    Acquisition scan - 128 - 0.08 deg steps = 10 deg. total field
    Track scan - ±16 steps, elevation and azimuth

Readout and control

    Elevation error - ±5 deg
    Azimuth error - ±5 deg
    Search -track mode - automatic switching

Beam steerer

    Power drive amplifier - ±5 V
    Transmitter/receiver track - adjustable

Piezoelectric deflection - ±40 minutes
Deflection from transmitter optics - 10 deg x 10 deg deflection

Transmitter

Laser type - argon ion
Wavelength - 514.5 nm
Pulsed driver - 1 kHz pulse repetition rate, 15 μs pulse width
Peak power - 2 W

Aircraft terminal A block diagram of the aircraft terminal is shown in figure 4. This package is shock mounted to the RB-57F aircraft frame to isolate aircraft vibration. Figure 5 shows the aircraft optical package. The flight computer and associated electronics are located in a canister shown in figure 6. Uplink and downlink laser beams pass through a 68-cm optical window located on the lower portion of the aircraft. Flights with and without the window are planned.

Once the GBAA has acquired the aircraft corner reflectors and is tracking, the upcoming cw argon laser of 488 nm will illuminate the aircraft. The gimbaled mirror of the aircraft package is manually pointed in the general direction of the group terminal by the aircraft crew using a drift site TV camera which is slaved to the gimbaled mirror. This will allow the 488-nm radiation to enter the 5 deg x 5 deg FOV of the TV tracker which will acquire and lock onto the beam. Angle error information is provided to the computer which provides a drive signal to the gimbal mirror. This will allow the uplink radiation to enter the 0.5 deg x 0.5 deg acquisition FOV of the image dissector which acquires and locks onto the beam.

The downlink laser is a Spectra Physics HeNe laser with a 5-mW output. The modulator is driven at a 30-Mbit/s rate. Three basic types of information can be placed on the downlink: a 31-bit psuedo random word transmitted at a 970-kHz rate, a TV video picture, and AOCP telemetry. All data in the aircraft are recorded on an Ampex AR1700 flight recorder but the same data can be telemetered to ground over the 30-Mbit/s link for in-flight analysis on the ground. A separate detector monitors uplink scintillation. The scintillation detector has an aperture control to vary the effective receiver aperture diameter.

Table 3 gives the basic parameters of the aircraft package.

Test Measurements As previously mentioned, two of the main objectives of this experiment are to collect data on the propagation of visible wavelength radiation through the atmosphere and to provide engineering data on system performance for reference on future systems.

The principal measurements to be made are:

1. Scintillation
2. Angle of arrival fluctuations
3. Bit error rate
4. Atmospheric attenuation
5. Engineering measurements of pointing and tracking precision

In addition, several supporting experiments are to be performed during aircraft tests. These include collection of meteorological data and microthermal fluctuation measurements of the temperature structure constant C_T versus altitude during a flight experiment.

A brief discussion of each of the principal measurelmnts follows.

Scintillation Of all aspects of the effects of atmospheric turbulence on optical propagation, none has been more thoroughly investigated than scintillation. Even though extensive studies have been made, some doubt still remains as to whether the existing data adequately confirm the theoretical predictions. The accuracy of the log-normal distribution of the intensity fluctuations, particularly for long path lengths and/or conditions of deep scintillation, has been questioned. Recently, some doubt has been cast on the ability of the accepted theory to predict correctly the reduction in the scintillation by very large receiving apertures. Furthermore, most of the previous experimental studies have been limited to near horizontal paths in the lower atmosphere. Ground-to-satellite optical communications systems will operate over near vertical paths through all levels of the atmosphere. Since upper atmospheric conditions are quite different from those near the ground, it is important that direct verification of the theoretical predictions be obtained over paths which approximate as closely as possible those that will be encountered in an operational communications system. AVLOC will closely simulate a satellite-to-ground link (or, of course, an aircraft-to-ground link) and differ from a ground-based experiment in three important respects. First, the propagation paths will be nearly vertical (20-deg zenith angle); second, the path will pass through essentially the entire atmosphere; and third, the apparent wind caused by aircraft motion will not be encountered in a ground-based experiment.

Table 3. Aircraft Package Parameters and Variables

Optics	
Receiver diameter	10 cm
Transmit diameter	3 cm
Transmitter	
Laser	Helium neon
Laser wavelength	632 nm
Laser power	5 mW
Modulator	
Modulator type	Transverse field
Data rate	30 Mbit/s
Swing voltage	±23 V
Modulation index	65%
Tracking receiver	
Sensitive wavelength	488 nm
Search FOV	0.5 deg x 0.5 deg
Detector type	F 4012 image dissector
Quantum efficiency	17%
Acquisition receiver	
TV camera	
Acquisition FOV	5 deg x 5 deg
Controlled parameters	
Transmit beam divergence	5-205 arc sec
Receive path attenuation	
Scintillation aperture	10 and 1 cm
Flight control computer	SPC-16
Pointing and control system	
Beam steerer-image dissector control loop bandwidth*	150 Hz
Gimbal mirror control loop bandwidth*	10 Hz
Gimbal mirror platform	Modified Aeroflex
Downlink communication	
Bit error rate	
TV video	
Aircraft telemetry	

*Phase lag less than 45 deg

Because of the ambiguity in existing data and the important role of scintillation in limiting the performance of practical laser communications systems, AVLOC will include a careful analysis of the scintillation for both uplink and downlink propagation. The quantities to be measured will include the probability distribution function of the amplitude fluctuations, the power spectral density, the log amplitude variance, the effect of aperture averaging (downlink), and the effect of transmitter aperture size (uplink). Special attention will be given to differences in uplink and downlink propagation and to variations with aircraft altitude.

The uplink scintillation measurements will consist of monitoring intensity fluctuations of the 514.5-nm ground-based argon laser. To facilitate instrumentation of the detection and recording system, the laser will be modulated at 10 MHz. Since the correlation distance (r_o) for the uplink scintillation is expected to be very large, aperture averaging will not be observable. The airborne receiver will therefore be provided with only two aperture stops, the full aperture (10 cm) and a small off -center stop (about 10 mm) which will make the receiver effectively a point detector. The availability of the larger aperture will allow a convenient check on the assumption that uplink aperture averaging is unimportant.

The downlink system will consist of a 632.8-nm HeNe laser and a 61-cm (24-in.) diameter receiving telescope which will be fitted with a continuously variable aperture stop. Two schemes for measuring the downlink scintillation will be used. The first will consist of measuring the intensity fluctuations of the unmodulated laser while the second will utilize a 30-MHz modulation. When the second method is used, the laser will be pulse code modulated (PCM) at 30 Mbit/s with a pseudo random code. The code to be used will be symmetrical in the sense that it will contain an equal number of zeros and ones. The resulting modulation will therefore contain a high 30-MHz component which can be extracted and recorded. In this way a direct comparison between scintillation and bit error rate will be available.

The principal problems that might be encountered in collecting the scintillation data are assuring that the detection and recording systems have sufficient linearity and dynamic range. Care must also be taken to eliminate system noise and the effects of pointing errors. Initial estimates indicate that a dynamic range of 60 dB will be required to obtain reliable scintillation data. Design calculations indicate that this dynamic range can be obtained; nevertheless, a careful check of the dynamic range, linearity, and signal-to-noise ratio of the system wi be ma prior to each flight.

Beam wander and tracking errors should not affect the scintillation measurements. For the uplink the pointing error in the telescope mount will be on the order of I arc sec while the minimum beam divergence will be 20 arc sec. Assuming a Gaussian beam, this pointing error will cause an apparent scintillation of 0.25 percent which is entirely negligible. The downlink pointing errors will be slightly greater but greater beam divergence will also be used so that the apparent scintillation will be of the same order of magnitude as the uplink. For both uplink and downlink measurements, sufficient power is available to allow wider beam divergence if necessary to reduce this effect.

Angle of arrival fluctuations   Atmospheric turbulence causes phase fluctuations which are manifested at the receiver as a tilt of the incoming wavefront and as a wavefront distortion. Of these two effects the former is approximately 40 times as large as the latter. The tilt or apparent angle of arrival fluctuations will be measured for both uplink and downlink propagation. The measurements will be made by summing the output from the angle encoders on the tracking mounts and the error signal generated by the tracking servo to give the instantaneous apparent angle of arrival for the incoming wave. The signal will then be passed through a high pass filter to eliminate angular variations resulting from true tracking of the aircraft, jitter caused by random motion of the aircraft, and jitter caused by pointing errors in the telescope mount, all of which should occur at frequencies below the atmospherically induced fluctuations. Quantities to be investigated will include the variance of the angle of arrival fluctuations, their probability density function, aperture averaging effects, and dependence on range and zenith angle.

Bit error rate   The bit error rate for a 30-Mbit/s PCM communications system will be measured by transmitting a 31-bit pseudo random word on the downlink beam. The received word will be compared bit by bit with an identical word generated at the receiver and the bit error rate will be recorded. Quantities to be investigated will include mean bit error rate; correlation of the bit error rate and scintillation; and dependence of the bit error rate on range, receiver aperture and transmitted power, and beam divergence. By varying the transmitted power and/or beam divergence, the received: power and therefore the signal-to-noise ratio may be adjusted as necessary.

Atmospheric attenuation   The atmospheric attenuation of both uplink and downlink beams will be measured by monitoring the output power of both transmitters and computing the total received power at each receiver. Clear air attenuation and measurements will be made during each flight. Aerosol scattering from rain and fog will be measured if the opportunity arises. Transmission through clouds will also be measured.

Engineering measurements of pointing and tracking precision   The measurements described previously are intended to yield fundamental information concerning turbulence in the atmosphere and its effects on wave propagation as well as to provide critical data needed to design future optical communications systems for satellite-to-ground or aircraft-to-ground links. The angle of arrival and bit error rate measurement will also provide engineering data for the evaluation of a state-of-the-art communication system and analysis of the feasibility of a more advanced system. Other measurements will be conducted to provide additional engineering data for system performance analysis. These measurements will include:

Tracking accuracy - This is the most important engineering measurement of the experiment.

Signal-to-noise ratio of voice and/or command channels (uplink).

Determination of maximum acquisition range with the GBAA.

Measurement of frequency of loss of track and time to reacquire. From these measurements, total system dead time caused by loss of track can be established.

Ability of the system to operate through fog, rain, and clouds. These measurements will be, of necessity , those of opportunity because of the inability to predict local weather conditions accurately.

A subjective evaluation of real-time television transmission (downlink).

Conclusions The AVLOC program is scheduled for completion of field tests in April 1972, and flight experiments are to begin in May-June 1972. Results of the field and flight tests will be given in the presentation at the International Telemetering Conference on October 10-12, 1972.

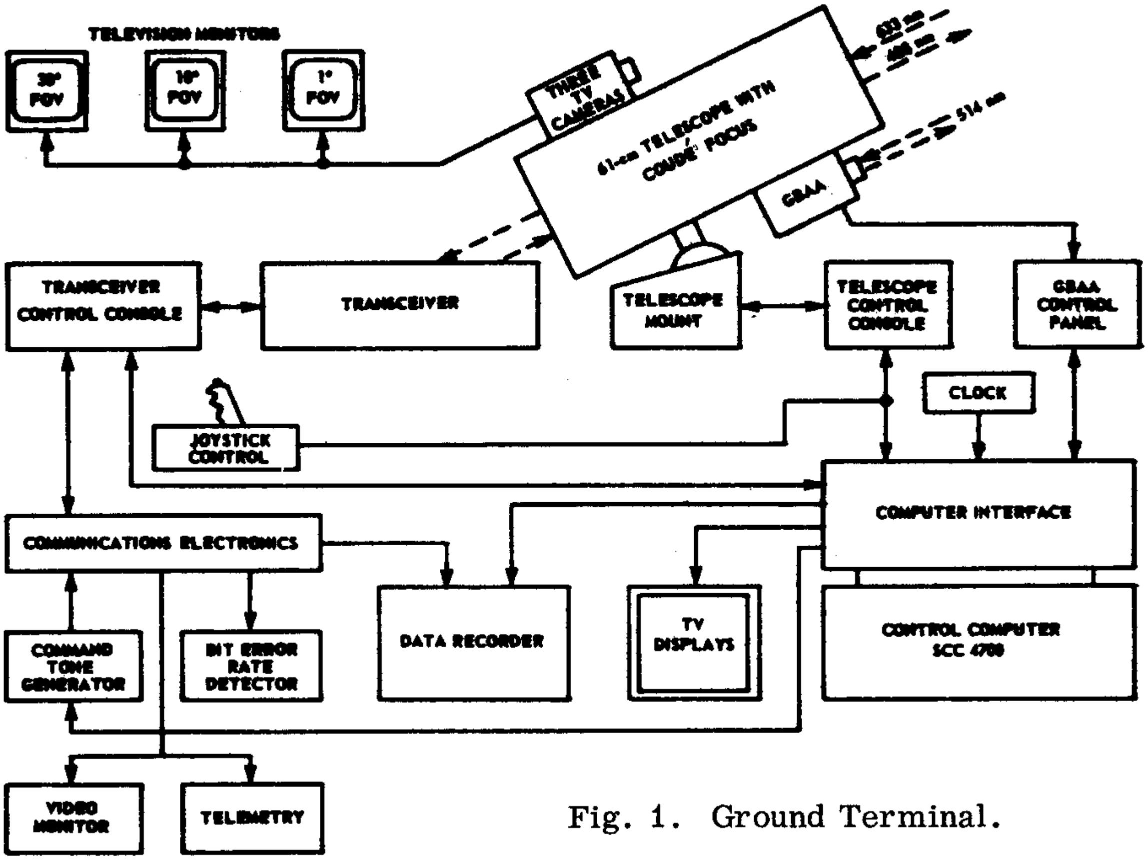

Fig. 1. Ground Terminal.

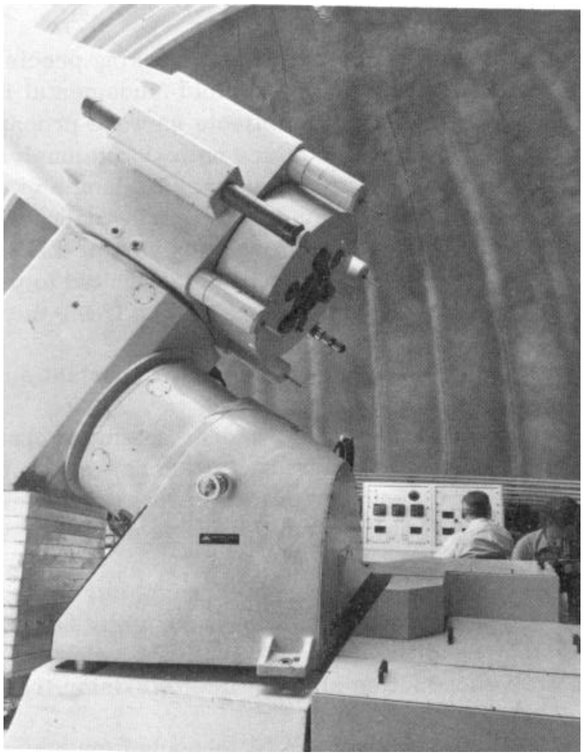

Fig. 2 61-cm Coudé Telescope with Transceiver Package.

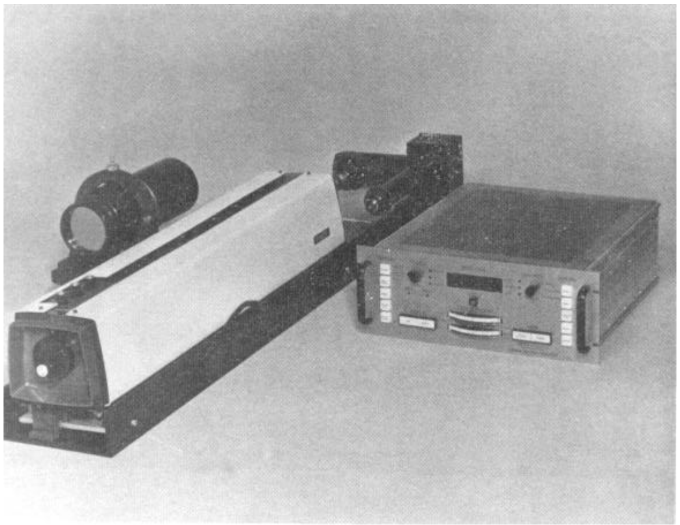

Fig. 3. GBAA with Control Console.

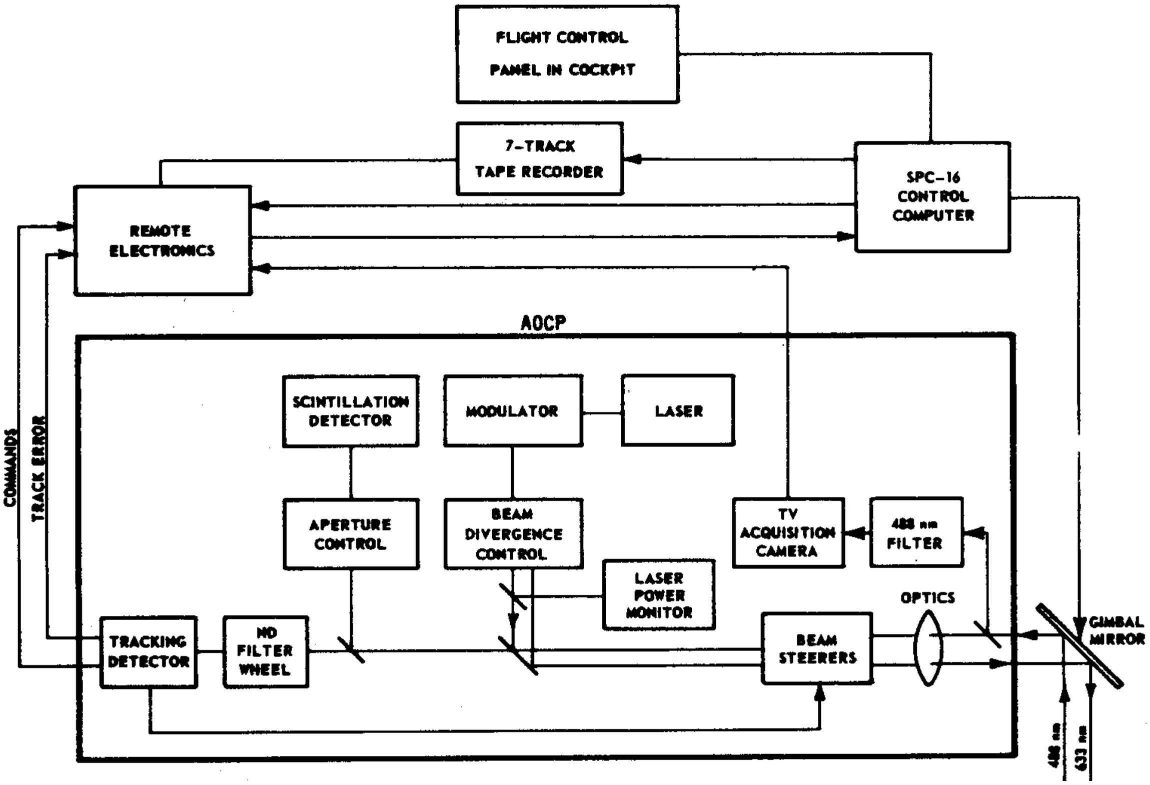

Fig. 4. Aircraft Terminal.

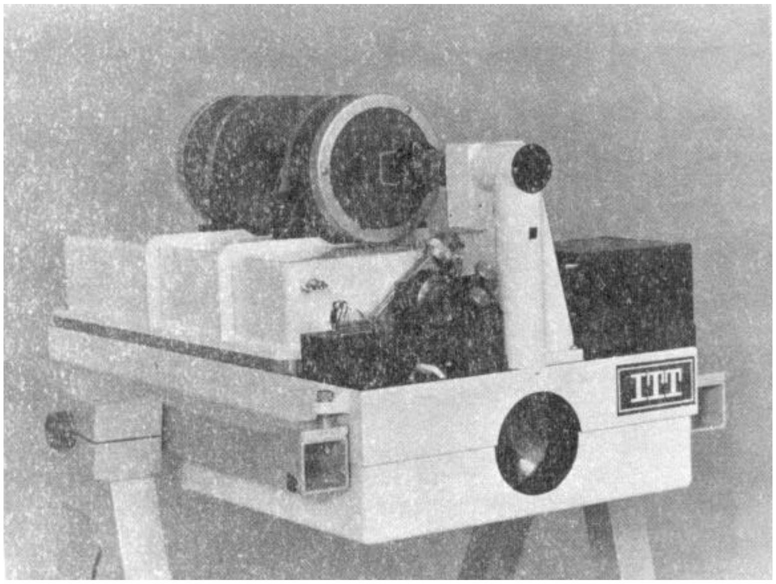

Fig. 5. Aircraft Terminal Pointing and Tracking System.

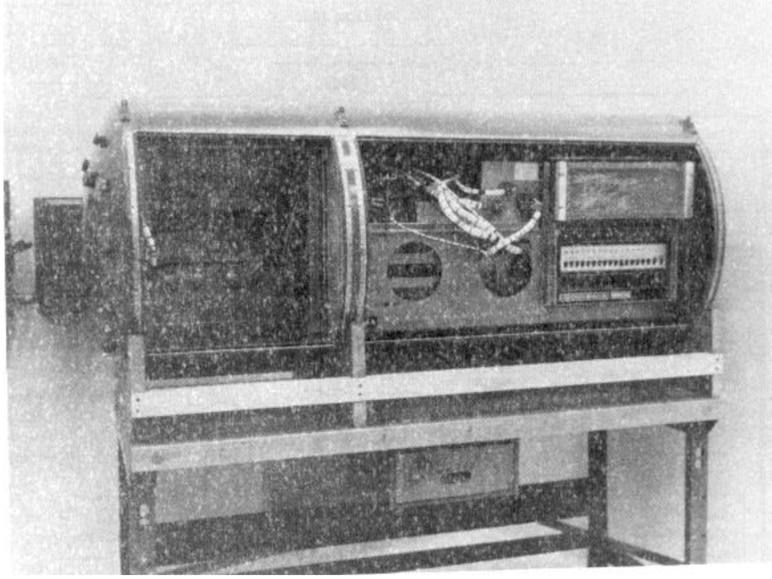

Fig. 6. Flight Canister with Control Computer and Associated Electronicx.