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FINAL REPORT
CONTRACT NAS8-20833 PHASE II

CONSTRUCTION AND TESTING OF A SCANNING LASER RADAR (SLR)

TO NASA
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA 35812

PREPARED BY
TERRY FLOM
H. DEAN COOMBES
DECEMBER 1971

GILFILLAN/SAN FERNANDO, CALIFORNIA
FINAL REPORT
TO
NASA
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ITT GILFILLAN
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San Fernando, California 91342
FOREWORD

This document is the final report for Phase II of Contract NAS8-20833, "Construction and Testing of a Scanning Laser Radar." The program was sponsored by the Marshall Space Flight Center of the National Aeronautical and Space Administration, Huntsville, Alabama. The technical representatives for NASA were J. A. Dunkin, D. O. Lowrey, and C. L. Wyman.

This contract was performed by the International Telephone and Telegraph Corporation, San Fernando, California. The work was performed in the Advanced Engineering Development Department of ITT Gilfillan under T. P. Dixon (Director), and L. G. Cardone (Associate Director). The project engineers were H. D. Coombes and T. E. Flom. Principal contributors were L. Cardone, D. Coombes, T. Flom, J. Priebe, L. Rosenberg, H. Sarrafian, R. Schmidt, S. Valdes, and D. Weaver.
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1.0 INTRODUCTION

This is the final report for Phase II of NASA contract NAS8-20833, "Construction and Testing of a Scanning Laser Radar". Phase I pertained primarily to constructing breadboards of portions of the Scanning Laser Radar in order to prove the feasibility of certain range and scan techniques. The Phase II, reported here, describes the construction and testing of a laboratory prototype of a complete Scanning Laser Radar system. The Scanning Laser Radar was developed to acquire and track cooperative targets (i.e., targets that have corner cube reflectors) for future spaceborne applications such as the rendezvous and docking of two spacecraft. The Scanning Laser Radar was constructed to acquire and track targets anywhere in a $30^\circ \times 30^\circ$ field-of-view without the aid of mechanical gimbals. The system is relatively small, lightweight, low power consuming, and operates at room temperature without cooling.

The Scanning Laser Radar overall system is described in section 2.0 of this report. Block diagrams and photos of the hardware are included with the system description. Detailed descriptions of all the subsystems that make up the Scanning Laser Radar system are included in section 3.0. Block diagrams, photos, and detailed optical and electronic schematics are used to help describe such subsystem hardware as the laser, beam steerer, receiver optics and detector, control and processing electronics, visual data displays, and the equipment used on the target. Tests were performed on the Scanning Laser Radar to determine its acquisition and tracking performance and to determine its range and angle accuracies while tracking a moving target. The tests and test results are described in section 4.0.
2.0 SYSTEM DESCRIPTION

2.1 General

The Scanning Laser Radar (SLR) described in this report has been developed for future spaceborne applications. At present, the greatest need for spaceborne radars is as an accurate guidance aid for spacecraft that are performing rendezvous and docking maneuvers. Laser radar systems are presently being considered for use on future spacecraft such as the NASA space shuttle, space station, space tug, and the RAM (Research Application Module).

Since use of the Scanning Laser Radar is directed toward future spaceborne applications it was important that it be relatively small, lightweight, and low-power consuming. The radar built takes up less than 1.5 cubic feet, weighs approximately 40 pounds, and requires about 50 watts prime power. All the SLR data outputs are in a digital format that allows for straightforward transmission into a vehicle guidance computer or visual instrument panel. No mechanical gimbals are used in the radar and almost all the electronic components are digital type integrated circuits. The entire system operates at room temperature without cooling.

To better understand the general performance requirements that are imposed upon a radar system to be used for rendezvous and docking applications the basic radar and target geometry associated with rendezvous and docking maneuvers is briefly discussed here. The first sequence in rendezvous and docking (rendezvous search) will set the limits on the maximum target range for the radar. Generally, two space vehicles will be inserted into coplanar orbits that will necessitate that the on-board radar have a range capability of 20–75 nautical miles. Another important consideration directly affecting the radar design is the relative target ephemeris (bounds of the relative location of the target
at a given time), because the range to the target and the target search cone will directly affect the power required by a given radar system, the acquisition time, and the background characteristics. After the target has been acquired the line-of-sight range and angles between the chaser and target vehicles are measured. The accuracy of these long range measurements will affect the fuel requirements of rendezvous closure because any navigation errors incurred will require additional fuel during corrective maneuvers. The docking sequence requires the on-board radar to measure the relative angular positions between the docking ports. This is normally accomplished at a relatively close range (100 - 500 feet). The on-board radar must continuously measure the line-of-sight angles between the two docking ports to a precision that will allow the respective vehicle or vehicles to maneuver such that the line-of-sight angles are nulled. The line-of-sight geometry for docking is shown in Figure 2-1. These line-of-sight angles must be nulled usually to approximately ±5°, or less, for successful and easy mating of the docking adaptors. Another measurement that is critical to a successful docking is the range measurement, and also the range-rate and angle rates must be continuously and accurately calculated or measured so that the contact velocities can be carefully controlled prior to and at docking contact. Numerous mechanical considerations enter into the determination of impact velocities, however, a maximum range-rate of 1 foot/sec or less is a representative value for the last 25 feet prior to docking contact. The Scanning Laser Radar described here was tested with moving targets and the angle accuracy was approximately 0.06 degrees (3σ) and the range accuracy was 5 centimeters (3σ).

The system configuration of the SLR built and described here has an active receiver on the target for the purpose of measuring the relative orientation or attitude of the target (the α angles shown in Figure 2-1). The system configuration of the SLR for Phase III of contract NAS8-23973 will not have
Null all Line-of-Sight Angles
($\alpha_X$, $\alpha_Y$, $\alpha_{XT}$, $\alpha_{YT}$, $\phi$) $\rightarrow 0$

Final Docking Closure

$Z_T$

Line-of-Sight

$\phi$ relative roll

Target Vehicle

EXAMPLE OF GEOMETRY FOR DOCKING

FIGURE 2-1

2-3
an active receiver on the target, only passive corner cube reflectors. The
target's relative attitude will be obtained by measuring the range and angles
to three corner cube reflectors and then geometrically calculating the rela-
tive target attitude.

Two experimental prototypes of a spaceborne laser radar system have been
developed for NASA by International Telephone and Telegraph Corporation
over the last several years. Both systems were designed for cooperative
target applications. The first generation system was completed in 1967
(contract NAS8-11673) and it experimentally demonstrated the basic feasibility
and the advantages of using laser radar in rendezvous and docking operations.
The first generation system was successfully tested in rendezvous and docking
simulators, however the laser system configuration was limited by the state-
of-the-art components available in 1965-67. The second generation system,
reported on here, was completed in 1971. New or improved lasers, beam
steerers, detectors, optical components, high speed digital logic, and associated
new scan and ranging techniques have been incorporated in the second gener-
ation system. This system uses the scan technique whereby a narrow laser
transmitter beam and an equally narrow receiver instantaneous field-of-view
are synchronously scanned over a relatively larger field-of-view without the
use of mechanical gimbals. This system shall be referred to herein as the
Scanning Laser Radar.
2.2 System Hardware Description

The Scanning Laser Radar is a line-of-sight acquisition and tracking system that will determine the relative location of a target by measuring the line-of-sight range to the target, and the pitch and yaw line-of-sight angles. The range-rate and angle-rates are determined by differentiating the range and angle measurements. A system block diagram of the present experimental prototype of the Scanning Laser Radar is shown in Figure 2-2. For this system configuration, one vehicle will have a radar transmitter-receiver and the other vehicle (the target) will have only a reflector-receiver. The radar transmitter-receiver will be used to determine the line-of-sight range (R) and the line-of-sight angles ($\theta_x$, $\theta_y$) to the target vehicle and the receiver on the target will be used to determine the target orientation or relative target attitude ($\alpha_{xt}$, $\alpha_{yt}$). If it is necessary to have all the radar data on one vehicle, then the respective data will have to be telemetered from one vehicle to the other vehicle.

Photos of the Scanning Laser Radar hardware are shown on Figure 2-3. The target reflector-receiver is in the upper left corner and the basic radar equipment is located in the lower right of the figure. A data display for the basic radar data is also shown. A breakdown and description of this hardware is discussed in the following paragraphs.
TARGET REFLECTOR-RECEIVER

RECEIVER ELECTRONICS

IMAGE DISSECTOR

REC. OPTICS

CORNER CUBE REFLECTOR

RELATIVE TARGET ATTITUDE (α ANGLES)

LINE-OF-SIGHT FROM RADAR TO TARGET (θ ANGLES)

SYNCHRONOUSLY SCANNED TRANSMITTER-RECEIVER

IMAGE DISSECTOR

REC. OPTICS

TRANSMITTER-RECEIVER ELECTRONICS

BASIC BLOCK DIAGRAM - SCANNING LASER RADAR (TRANSMITTER-RECEIVER AND TARGET REFLECTOR-RECEIVER)

FIGURE 2-2

2-6
TARGET
(REFLECTOR-RECEIVER)

SCANNING LASER RADAR
TRANSMITTER-RECEIVER
AND ELECTRONICS

SLR
DATA DISPLAY

PHOTO'S OF SCANNING LASER RADAR HARDWARE
FIGURE 2-3
2-7
The primary equipment in this prototype of the Scanning Laser Radar is the radar transmitter-receiver and its associated electronics. The target equipment plays an important but secondary role. A block diagram of the radar transmitter-receiver and electronics is shown in Figure 2-4 and photos of this equipment are shown in Figure 2-5. This Scanning Laser Radar will scan a 0.1° x 0.1° transmitter beam and receiver instantaneous field-of-view synchronously over a 30° x 30° field-of-view. A raster scan is used for target acquisition and a cross scan about the target is used for target tracking. A 1 KHz PRF and scan rate is used.

To effectively search for and locate a target using a narrow laser beam, a scanning system is needed to rapidly scan the transmitted beam and the receiver field-of-view. A scan technique that steers or points a narrow laser beam synchronously with an equally narrow receiver field-of-view (FOV) will provide a laser radar system with the maximum efficiency with regard to transmitter-receiver beam geometry. If the transmitted laser beam is larger than the receiver FOV all the laser energy outside the receiver FOV will be lost. If the transmitted laser beam is smaller than the receiver FOV, then the sky background noise and the receiver detector dark current noise will be larger, thus reducing the signal-to-noise ratio of the radar system. There are various ways to implement the synchronous scan technique. The synchronously scanned transmitter-receiver chosen here performs the scanning functions electronically without the use of mechanical gimbals. A piezoelectrically driven mirror in the transmitter and an electromagnetic deflection coil in the receiver are the electronic elements that control the transmitter-receiver scan.
TRANSMITTER
BEAM STEERER
LASER
TARGET

1
1
I

SYSTEM POWER

BEAM STEERER DRIVER
LASER DRIVER & PICK OFF

PIEZOELECTRICALLY DRIVEN MIRROR

PHOTOMULTIPLIER

ELECTROMAGNETIC DEFLECTION COIL

RECEIVER OPTICS
SCANNING OPTICAL DETECTOR (IMAGE DISSECTOR)

RECEIVER DEFLECTION DRIVER
PREAMP & AGC

THRESHOLD CIRCUIT

ANGLE TRACKER
RANGE & TIMING

RADAR DATA OUTPUTS

TO BEAM STEERER & RECEIVER DEFLECTION DRIVER

DATA DISPLAY

TO LASER DRIVER & PICKOFF
EXTERNAL COMPUTER

BLOCK DIAGRAM OF THE SLR TRANSMITTER-RECEIVER AND ELECTRONICS
FIGURE 2-4
BEAMSTEERER

SLR ELECTRONICS

SLR TRANSMITTER-RECEIVER

RECEIVER OPTICS

SCANNING OPTICAL DETECTOR (IMAGE DISSECTOR)

SINGLE MODE GaAs LASER

PHOTO'S OF SCANNING LASER RADAR (TRANSMITTER-RECEIVER AND ELECTRONICS)

FIGURE 2-5

2-10
As shown in the block diagram (Figure 2-4) and in the photo's (Figure 2-5) the major subsystems in the radar are; the single mode Gallium Arsenide (GaAs) laser, the piezoelectric beam steerer, the receiver optics, and the scanning optical detector (image dissector). A detailed description of each of these major subsystems is included in section 3.0, Subsystem Descriptions. An illustrative and descriptive look at the major portions of the electronic hardware associated with the radar is shown in Figure 2-6. The basic functions for the major electronic circuit boards or components are briefly described in the figure and quantitative data on the total number of integrated circuits and discrete components is listed. A detailed description of the radar electronics is also included in section 3.0.

This laser radar was built to operate against a cooperative target. A block diagram of the target reflector-receiver and associated electronics is shown in Figure 2-7 and a photo of the equipment is shown in Figure 2-8. The key component on the target is the corner cube reflector. It redirects the incoming radar beam back to the radar with only a negligible loss in power. The return signal coming from a corner cube reflector is generally $1 \times 10^6$ times greater than the return signal obtained from a lambertian surface for most radar applications. The rest of the target equipment, the receiver and electronics are used to measure the incoming direction of the radar beam (the target's relative attitude with respect to the radar). The target receiver and electronics uses almost the same components found in the radar with the major exception that it has no ranging circuitry. The target scans a $0.1^\circ$ instantaneous field-of-view over a $30^\circ$ FOV, and will acquire and track the radar beam anywhere in the $30^\circ$ FOV. The corner cube reflector can redirect beams over approximately a $60^\circ$ FOV. An illustrative and descriptive look at the major portions of the target electronics
BLOCK DIAGRAM OF THE TARGET REFLECTOR—RECEIVER AND ELECTRONICS

FIGURE 2-7

2-13
hardware is shown in Figure 2-9. The basic functions for the major electronic circuit boards or components are briefly described in the figure and quantitative data on the total number of integrated circuits and discrete components is listed. A detailed description of the target electronics is included in section 3.0.

After completion of the Scanning Laser Radar hardware field tests were performed to determine some of the pertinent performance characteristics under dynamic conditions with a moving target. A summary of this performance data is shown in Table 2-1 and a detailed description of the tests and test results is included in section 4.0. Table 2-2 shows the size, weight, and power characteristics for this Scanning Laser Radar.
<table>
<thead>
<tr>
<th>LOCATION MARKER</th>
<th>DESCRIPTION</th>
<th>IC'S &amp; DISCRETE COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (OS1)</td>
<td>RECEIVER, Post Amplifier and Acc Generator, Power Converter for Preamplifier -56V to 1.5V</td>
<td>4/65</td>
</tr>
<tr>
<td>2 (OS1)</td>
<td>IMAGE DISSECTOR, HIGH VOLTAGE AND PREAMPLIFIER</td>
<td>2/69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CIRCUIT BOARD</th>
<th>DESCRIPTION</th>
<th>IC'S &amp; DISCRETE COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (TT1)</td>
<td>MASTER OSCILLATOR, MASTER TIME COUNTER, TRACK CONTROL COUNTER, POSITION AND VELOCITY COUNTERS</td>
<td>102/50</td>
</tr>
<tr>
<td>#2 (TT2)</td>
<td>TRACK AND ACQUISITION COUNTERS &amp; CONTROLS, ANGLE SHIFT REGISTER</td>
<td>91/5</td>
</tr>
<tr>
<td>#3 (TT3)</td>
<td>DIGITAL TO ANALOG CONVERTERS, DEFLECTION COIL DRIVERS</td>
<td>8/56 PLUS 2 D/A CONVERTER MODULES</td>
</tr>
<tr>
<td>#4 (TT4)</td>
<td>POWER CONVERTERS -56V TO -250V, +15V, -15V, +5V, AND FOCUS REGULATOR</td>
<td>1/11 4 MODULAR P.S.</td>
</tr>
</tbody>
</table>

ILLUSTRATIVE LAYOUT OF THE TARGET REFLECTOR - RECEIVER ELECTRONICS
FIGURE 2.9
## TABLE 2-1

**SUMMARY OF THE SCANNING LASER RADAR PERFORMANCE DATA**

(Obtained during dynamic tests with moving targets)

<table>
<thead>
<tr>
<th></th>
<th>Range Accuracy $(3\sigma)$</th>
<th>Angle Accuracy $(3\sigma)$</th>
<th>Max. Tracking-rates</th>
<th>Max. Acquisition-rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pm 5$ centimeters for $R&lt;50$ meters</td>
<td>$\pm 0.06$ degrees over $30^\circ \times 30^\circ$ FOV</td>
<td>0.9 degrees/second</td>
<td>0.17 to 0.25 degrees/second</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.01%$ of $R$ for $R&gt;50$ meters</td>
<td>(15.7 readings per second)</td>
<td>1,000 meters/second (estimated)</td>
<td>(depending upon direction of target trajectory)</td>
</tr>
<tr>
<td></td>
<td>(10 smoothed readings per second)</td>
<td></td>
<td>1,000 meters/second (estimated)</td>
<td>1,000 meters/second (estimated)</td>
</tr>
</tbody>
</table>

## TABLE 2-2

**SIZE, WEIGHT, AND POWER CHARACTERISTICS OF THE SCANNING LASER RADAR**

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>Weight</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmitter-Receiver</td>
<td>6&quot;x9&quot;x21&quot;</td>
<td>32 pounds</td>
<td>40 watts</td>
</tr>
<tr>
<td>Electronics</td>
<td>9&quot;x9&quot;x9&quot;</td>
<td>8 pounds</td>
<td>@23 VDC</td>
</tr>
<tr>
<td>Visual Data Display</td>
<td>4&quot;x9&quot;x9&quot;</td>
<td>4 pounds</td>
<td>10 watts</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver</td>
<td>4&quot;x5&quot;x18&quot;</td>
<td>15 pounds</td>
<td>25 watts</td>
</tr>
<tr>
<td>Electronics</td>
<td>4&quot;x9&quot;x9&quot;</td>
<td>4 pounds</td>
<td>@28 VDC</td>
</tr>
<tr>
<td>Reflector</td>
<td>2 1/2&quot; dia.</td>
<td>1 pound</td>
<td>0</td>
</tr>
</tbody>
</table>

2-17
3.0  SUBSYSTEM DESCRIPTIONS

3.1  General

There are numerous subsystems that make up the Scanning Laser Radar system described in Section 2.0. These subsystems will be described in detail in this section and are the following:

3.2  Single Mode GaAs Laser and Laser Modulator Electronics
3.3  Piezoelectric Beam Steerer and Driver Electronics
3.4  Receiver Optics
3.5  Receiver Detector (Image Dissector)
3.6  Pre-amp, AGC, and Threshold Electronics
3.7  Mode Control Electronics
3.8  Angle Tracker Electronics
3.9  Range and Timing Electronics
3.10 Power Converters
3.11 Target Reflector and Receiver
3.12 Target Electronics
3.13 Radar Data Displays
3.2 Single Mode GaAs Laser and Laser Modulator Electronics

The Scanning Laser Radar is a small, lightweight, low power-consuming laser radar system which is used to acquire and track cooperative-type targets. A pulsed semiconductor laser, which is small, lightweight and will operate at room temperature without cooling, has, therefore, been used as the radiating source. Photos of the laser are shown in Figure 3-1. The particular pulsed semiconductor laser used is a recently developed Gallium Arsenide (GaAs) laser that emits its radiation in a single-mode ($\text{TEM}_{oo}$). Because the single mode beam is essentially diffraction-limited, it enables one to use a beam steering technique that requires relatively small optics. The single mode operation will also enable one to get a far-field radiation pattern that is gaussian-shaped, a highly desirable characteristic for a radar system.

To get single mode operation, a GaAs laser diode is placed in an optical resonator. The GaAs laser diode is a specially fabricated semiconductor p-n diode. All p-n diodes, when forward-biased electrically, emit radiation when holes and electrons combine. In a laser diode a stimulated emission process occurs that amplifies the radiation on the p-n junction axis that is perpendicular to the parallel sides of the diode. A laser diode, without the external optical resonator, emits its radiation in many electro-magnetic modes. When the laser diode is properly aligned inside the optical resonator, the optical resonator will allow only one transverse electromagnetic mode ($\text{TEM}_{oo}$) to oscillate with high gain. The optical resonator components and their respective alignment motions are shown in Figure 3-2, Optical-Mechanical Sketch of the Single Mode GaAs Laser. The Optical resonator essentially consists of a GaAs laser diode that has anti-reflection optical coatings, two lenses, and two flat mirrors; one used as the total reflector and one used as the partial reflector in the optical resonator.
PHOTOS OF SINGLE MODE GaAs LASER

FIGURE 3-1

3-3
<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>DESCRIPTION</th>
<th>MOTION ADJUSTMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TX-RC Baseplate</td>
<td>Fixed (System Reference)</td>
</tr>
<tr>
<td>2A</td>
<td>Interface Baseplate</td>
<td>Fixed (Pinned &amp; clamped to 1)</td>
</tr>
<tr>
<td>2B</td>
<td>Laser Baseplate</td>
<td>Fixed (Pinned &amp; Screwed to 2A)</td>
</tr>
<tr>
<td>3ax</td>
<td>Total Reflector + Lens</td>
<td>x Translation</td>
</tr>
<tr>
<td>3ar</td>
<td>Total Reflector + Lens</td>
<td>x-z Rotation About y</td>
</tr>
<tr>
<td>4 bx</td>
<td>Partial Reflector + Lens</td>
<td>x Translation</td>
</tr>
<tr>
<td>4 br</td>
<td>Partial Reflector + Lens</td>
<td>y-z Rotation About x</td>
</tr>
<tr>
<td>5y</td>
<td>Laser Diode</td>
<td>y Translation</td>
</tr>
<tr>
<td>5r</td>
<td>Laser Diode</td>
<td>y-z Rotation About x</td>
</tr>
<tr>
<td>6y</td>
<td>Aperture Siit</td>
<td>y Translation</td>
</tr>
<tr>
<td>7az</td>
<td>Total Reflector + Lens</td>
<td>z Translation</td>
</tr>
<tr>
<td>7bz</td>
<td>Partial Reflector + Lens</td>
<td>z Translation</td>
</tr>
</tbody>
</table>

![Optical-mechanical sketch of the single-mode GaAs laser](image)

**Figure 3-2**

**Output Beam**

**Junction**

**Laser Diode**

**Slit**

**Aperture**

**Laser Output**

**Partially Reflective Mirror**

**Laser Baseplate 2B**

**Interface Baseplate 2A**

**Transmitter-Receiver Baseplate #1**

**Optical-Mechanical Sketch of the Single-Mode GaAs Laser**
The peak output power of the single GaAs laser (Generation #2) is 0.5 watts in the single mode ($\text{TEM}_{00}$). The wavelength is 0.9040 μmeters with an optical bandwidth of 0.0030 μmeters (30 Å). The laser was developed by IBM.

The laser was pulsed at a 1 KHz pulse repetition frequency (PRF) with a current modulator or driver as shown in Figure 3-3, Schematic of the GaAs Laser Driver and Transmitter Pickoff. The 0.5 watt peak output power from the laser was obtained with approximately 80 amperes peak current from the laser driver. The optical pulses had a rise time of approximately 10 nanoseconds and had a pulse width of approximately 50-100 nanoseconds.

The optical output pulse from the laser was used as the start pulse for each radar range measurement. The transmitter pickoff circuit for detecting the start pulse is shown in the lower half of Figure 3-3.
SCHEMATIC OF GaAs LASER DRIVER & TRANSMITTER PICKOFF
FIGURE 3-3
3.3 Piezoelectric Beam Steerer and Driver Electronics

The beamsteerer subsystem takes a narrow laser beam \(0.1^\circ\) and steers or points it over a relatively large field-of-view \(30^\circ\) without the use of mechanical gimbals. The active deflecting device is a mirror mounted to piezoelectric crystals. When a voltage is applied across a piezoelectric crystal it bends proportional to the applied voltage, which causes the attached mirror to be rotated and the beam striking the mirror is deflected. The laser beam striking the mirror is deflected a known amount by controlling the voltage on the piezoelectric crystal. Calibrated strain gages are attached to precisely monitor the actual bending thus taking care of the off-axis hysteresis in the piezoelectric crystal. With a diffraction-limited beam from the single mode GaAs laser \(\lambda = 0.9 \mu \text{meters}\), and two 0.7 x 1.0 inch piezoelectric-driven mirrors that are both rotated \(0 \pm 0.25\) degrees, one obtains a square raster scan pattern that has better than 300 x 300 resolvable scan elements. For a \(0.1^\circ\) beam and \(30^\circ\) field-of-view a minimum of 300 x 300 scan elements are needed just to cover the full \(30^\circ\) field-of-view. 376 x 376 scan elements are programmed into the SLR acquisition raster scan logic so that a 20% overlap between adjacent scan elements is obtained.

The purpose of the additional optics in the beamsteerer is to amplify the initial beam deflection \(\pm 0.25^\circ\) into a \(\pm 15^\circ\) beam deflection. A number of optical configurations were considered for the beamsteerer. Most of these were refractive, and although suitable, will not be discussed here. A reflective technique was used because it offered:
the lowest cost custom-made system

The highest potential optical transmission

easily calculable performance

alignment in visible light

50% greater raster resolution (or less beamsteerer drive voltage) than required because of the double reflection from each beamsteerer.

Photos of the beamsteerer are shown in Figure 3-4, and a simplified schematic showing the beamsteerer optics and the deflection of a beam in one axis is shown in Figure 3-5. The piezoelectric driven mirrors were developed by GT&E. In Figure 3-5, the output beam from the laser is converged to a small symmetrically-focused spot by the first input lens. The beam then diverges into a cone and reflects off two piezoelectric-driven mirrors; only one is shown in order to simplify the drawing. The beam is then reflected and refocused by a spherical mirror and for a second time the beam reflects off the piezoelectric-driven mirrors. The focal point of the spherical mirror is displaced from the focal point of the first lens because of a small fixed tilt (γ) in the placement of the spherical mirror. Also, the focal point of the spherical mirror is located in the focal plane of a projector lens assembly located at the output of the transmitter beamsteerer. A rotation of the piezoelectric-driven mirrors will result in an angular displacement of the beam and thus cause the beam to be displaced laterally at the focal plane of the spherical mirror. This lateral displacement will be converted and amplified by the projection lens assembly into the final desired off-axis angular deflection at the output of the transmitter. A small rotation (+0.25 degrees) by the piezoelectric-driven mirrors results
PHOTO OF PIEZOELECTRIC BEAMSTEERER
FIGURE 3-4
Piezoelectric Driven Mirror Schematic

DEFLECTED OUTPUT BEAM

SCHEMATIC OF THE BEAM STEERER OPTICS
FIGURE 3-5
in a relatively large beam deflection (+15 degrees) at the output of the projection lens assembly. The projection lens assembly is also used to collimate the output to the desired beamwidth (0.1 degree).

The electronics needed to control the piezoelectric beam deflectors and the strain gage circuitry used to monitor the precise deflection are shown in Figure 3-6 (Schematic of the Beam Deflector Electronics) and Figure 3-7 (Schematic of the Beam Deflector Strain Gage).
NOTE: OP-AMP PIN 4 IS 15V
PIN 7 IS -15V

When mirror moves away from mount, strain gauge output + volts
When mirror moves toward mount, strain gauge output - volts
Max. strain gauge output for 2.40 mm beam deflection

SCHEMATIC OF THE BEAM DEFLECTOR ELECTRONICS
FIGURE 3-6

3-12
SCHEMATIC OF THE BEAM DEFLECTOR STRAIN GAUGE ELECTRONICS
FIGURE 3-7
3.4 Receiver Optics

A multi-element lens is used to collect the energy from the return laser radar signal. The lens focuses the return radar beam to a small spot at the focal plane of the lens. For each return signal the focused spot is uniquely located at one place in the focal plane and this location is directly proportional to a radar-to-target line-of-sight angle. A multi-element lens assembly is used in the SLR receiver because good off-axis resolution and high speed (low f/#) are needed. The Angenieux 50 mm f/1.0 lens used in SLR images the radar's 30° FOV upon the area of the optical detector which has a diameter of 1.0 inches. The high speed f/1.0 permits the largest collecting aperture possible, consistent with high resolution. A narrow band optical filter is also used in the receiver optics in order to filter out light that is not at the same wavelength as the laser. This filter reduces the undesirable background radiation which is potentially a large noise contributor, especially for a sunlit cloud background. The bandwidth of the filter envelope is approximately 200 Å and is centered at the wavelength of the GaAs laser (0.9 micron meters). A 200 Å optical bandwidth is needed for the narrow passband optical filter even though the optical bandwidth of the laser is considerably less than 200 Å. The 200 Å is needed because the filter must pass the return signal ±15° off the boresight axis, and if the filter bandwidth was less than 200 Å the off-axis shift in wavelength would reduce the effective signal transmission severely. Photos of the receivers optics are shown in Figure 3-8 and a schematic of the multi-element lens and narrow band optical filter is shown in Figure 3-9.
PHOTO'S OF RECEIVER OPTICS
FIGURE 3-8

3-15
SCHEMATIC OF THE RECEIVER OPTICS

FIGURE 3-9
3.5 Receiver Detector (Image Dissector)

A scanning optical detector (image dissector) is used to convert the optical (laser) energy to electrical energy and measures the amplitude and angular direction of the return radar signal. An image dissector with a 1.0 inch diameter photocathode (ITT F4011) and a central or instantaneous aperture of 0.0035 inches is used. The 30° radar FOV is imaged onto the 1.0 inch photocathode surface. Therefore, the 0.0035 inch instantaneous aperture will look at a 0.105 degree instantaneous FOV. An S-1 surface for the photocathode is selected in order to detect the GaAs (0.9 micron meters) laser radiation. The S-1 photocathode has a sensitivity of 0.006 amps/watt at 0.9 micron meters. The dark current for the S-1 photocathode is typically $1 \times 10^{-12}$ amps/watt per cm at 25°C. The electrons emitted from the photocathode are deflected and focused magnetically in the F4011. The drive currents into the coils determine the amount of deflection and focusing. The electron gain in the photomultiplier section is set at $1 \times 10^5$. Photo's of the image dissector are shown in figure 3-10. Figure 3-11 shows a general schematic of the image dissector and figure 3-12 shows an outline drawing and detailed schematic of the F4011 image dissector.

After the receiver optics has focused the return signal on the photocathode of the image dissector, the image dissector senses the precise X-Y position of the return signal on the surface of its photocathode, and then determines the angular direction of the incoming beam. Every X and Y position on the photocathode surface is directly proportional to a pitch ($\theta_p$) and yaw ($\theta_y$) line-of-sight angle. The image dissector works like a television picture tube in reverse. A TV picture tube
SLR TRANSMITTER-RECEIVER

RECEIVER OPTICS
SCANNING OPTICAL DETECTOR
(IMAGE DISSECTOR)

F4011 IMAGE DISSECTOR
PHOTO SENSOR
DEFLECTION COIL

FOCUS COIL

PHOTO'S OF THE SCANNING OPTICAL DETECTORS
(IMAGE DISSECTOR)
FIGURE 3-10
3-18
GENERAL SCHEMATIC OF SCANNING OPTICAL DETECTOR
IMAGE DISSECTOR

FIGURE 3-11
Photocathode External Lead Extends 2 Inches Beyond Tube Base .005 x .040 Nickel Ribbon Covered with Mystik No. 7505 Teflon Tape.

F4011 IMAGE DISSECTOR OUTLINE DRAWING AND SCHEMATIC

FIGURE 3-12
has a centrally located aperture that emits electrons and these electrons are directed toward and onto one small spot on the TV screen by an electromagnetic field. The small spot on the TV screen is accurately positioned by controlling the electromagnetic field with a known current. When the electrons hit the small spot on the TV screen, the screen emits photons of light which form one small part of the image the viewer will see. The image dissector operates in the reverse process, the incoming photons of laser light strike one small spot on the screen (photocathode of the image dissector), and then electrons from the small spot are emitted toward the central aperture. By varying the electromagnetic field, the image dissector can effectively scan the surface of the photocathode to determine where the laser spot is located. Two significant advantages are obtained by having the laser return focused to a small spot and then measuring the current from only one small spot on the photocathode. The entire background in the optical field-of-view is imaged on the detector area, therefore, the background noise is a function of the detector area sensed. Since the image dissector senses only a small area, during any given time interval, the background noise is reduced significantly. Also, the dark current noise of an optical detector is proportional to the detector area. Therefore, it is also reduced because only a small area is sensed during any given time interval. It should also be noted that the image dissector is a non-storage device, allowing random or variable scan rates without changes in signal amplitude. The image dissector signal output is a current pulse with approximately the same waveform as the incoming laser pulse. The peak level is in the microampere range. This is terminated into a 50 ohm load and the resulting microvolt signal is amplified to a 3 volt level with a wide bandwidth preamp and postamp.
3.6 Pre-Amplifier, Automatic Gain Control and Threshold Electronics

The radar signal processing circuitry between the image dissector anode and the digital logic consists of a two-stage transistor pre-amplifier, an automatic gain control attenuator, an integrated circuit video amplifier, a two-stage transistor post amplifier and an automatic gain control circuit. These circuits are very well shielded and decoupled from external noise sources and have an overall small signal gain of 50,000. A block diagram of the pre-amp, AGC, and threshold is shown in Figure 3-13 and a detailed schematic of the pre-amp and AGC is shown in Figure 3-14.

The two-stage transistor preamplifier is used to amplify the signal voltage, developed across the anode load by the image dissector anode current, to a level sufficient to operate the attenuator. A 40 MHz bandwidth is required to allow approximately a 10 nanosecond risetime on the return pulse. Amperex A485 transistors are used in the preamplifier because of their high cut-off frequency($f_T$) and low noise characteristics. The gain of the two-stage preamplifier is approximately 30 and the dynamic range of the output is 2.0 mvolts to 3.0 volts.

An automatic gain control system is used in the video amplifier to prevent distortion of the video return pulse and still preserve the large signal-to-noise ratio on strong video returns. The AGC attenuator keeps the signal amplitude nearly constant after the attenuation and has an attenuation range of 60 db. An integrated circuit video amplifier with a gain of 80 is used on the small signal (1.5 mv) after the attenuator to increase the signal level to 0.12 volts. A two-stage
BLOCK DIAGRAM OF PRE-AMP, AGC, & THRESHOLD
FIGURE 3-13
SCHEMATIC OF THE PREAMPLIFIER AND AGC
FIGURE 3-14
transistor post amplifier is then used to increase the video return signal to a 3.6 volt amplitude. This level is compatible with logic level signals and is also used to generate the AGC control voltage. Integrated circuit amplifiers cannot be used here throughout because those presently available are too noisy for the low levels of the preamp and are too non-linear for higher levels of the post-amplifier. The AGC control voltage generator is a peak detector and a driver circuit with sufficient gain to charge the AGC filter circuit on 2 or 3 return pulses. The filter discharge time is approximately 0.25 seconds because the video return pulse changes amplitude relatively slowly with range, but the AGC control needs to be set quickly on acquisition. A signal threshold circuit consisting of a tunnel diode and the input logic level of a Motorola MECL III logic input gate determines when a range return is received. When the range return has an amplitude of 1.5 volts for 2 or more nanoseconds, the range return is confirmed.
3.7 Mode Control Electronics

The system mode control circuitry determines the type of radar scan to be used and the operation of the ranging and readout systems. Two basic modes are used – acquisition and track – which are pictorially shown in Figure 3-15. A general block diagram of the mode control functions is shown in Figure 3-16.

When the SLR system is turned on the mode control is reset to the acquisition mode. If the radar target has not been acquired or the radar loses track of a target, the mode control is also reset to the acquisition mode. When reset the mode control goes to ACQ #1 state, and in this mode all track control systems are reset, range and angle accumulators cleared, and readouts blanked. The angle deflection system then starts a raster scan from the particular instantaneous element of the $30^\circ \times 30^\circ$ total field that the system happens to be on when returning to the acquisition mode. The raster scan scans the instantaneous field-of-view $(0.1^\circ \times 0.1^\circ)$ in a line scan of 376 elements and a field of 376 lines. The scan pattern is a triangular form which produces a back and forth type of scan rather than the more common sawtooth form which produces a scan in one direction then a quick retrace in the opposite direction. A detailed schematic of the mode control logic is shown in Figure 3-17.

If the target is lost while being tracked, the target will be near the angular location of the last known tracking angle. Therefore a limited acquisition scan is made, centered about the last tracked location. This can greatly reduce reacquisition time, depending on where the target is lost. The limited acquisition field is 16 elements by 16 lines.
RECEIVING 2 SUCCESSIVE RETURN TRG WILL ADVANCE MODE CONTROL FROM ACQ. TO TRACK MODE. A 64 MSEC ELAPSED TIME WITHOUT A RETURN TRG WILL CAUSE MODE CONTROL TO RETURN TO ACQ. FROM TRACK MODE.

SELETS FOR ACCUMULATION THE FIRST 16 RANGE READINGS THAT ARE RECEIVED AFTER THE START OF EACH 0.1 SEC PERIOD IN TRACK MODE, AND WHICH OCCUR WITHIN 2 TRACK STEPS FROM BORESIGHT IN THE TRACKING APERTURE. A SELECTED RANGE READING CAUSES RTS LOCK TO = 1.

CONTROLS RANGE ACCUMULATION CYCLES TO PRODUCE TRUE AND COMPLETE RANGE AND RANGE RATE NUMBERS. ALSO CLEARS ACCUMULATION REGISTERS ON ANY INCOMPLETE ACCUMULATION.

DETECTS AN ACCUMULATION OF LESS THAN 16 RANGE READINGS DURING ANY 0.1 SEC PERIOD. RESETS RANGE READING SELECTOR AND RANGE ACCUMULATION MODE CONTROL AND CLEARS RANGE ACCUMULATORS IF LESS THAN 16 READINGS ARE RECEIVED OR SYSTEM IS IN ACQ. MODE.

ACQUISITION AND TRACK SCAN MODES

**Figure 3-15**

---

3-27
ACQUISITION MODE

30° X 30° TOTAL FOV
THE SIZE OF EACH SCAN IS
ENLARGED FOR BETTER
VISIBILITY

BLOCK DIAGRAM OF THE MODE CONTROL
FIGURE 3-16

3-28
SCHEMATIC OF THE MODE CONTROL

FIGURE 3-17

3-29
(1.28° x 1.28°). A detailed schematic of the limited acquisition control counter and control gates is shown in Figure 3-18. A limited acquisition control counter is used to control the main acquisition counters in such a fashion that the limited acquisition scan is made anywhere in the 30° x 30° total field-of-view and centered on the last known target position. After scanning 4 limited acquisition fields, if the target has not been reacquired, the acquisition scan returns to the full 30° by 30° acquisition scan.

Approximately 15 microseconds before $t_0$ for each millisecond period, the receiver and transmitter scan is commanded to go to a new position for that millisecond period and at $t_0$ the laser is pulsed for a range transmission. If there is a corner reflector target at some range in this scan position, a video return will be received through the vidissector and preamp. In the ACQ #1 mode the range gate is held open since the range of the target is unknown, and effectively the video return is a range return through range gate (TRG) and the range of the return is counted by the range counter even though it might be a noise pulse. If no video return is received in the first 1 millisecond period the acquisition scan proceeds to the next element in the acquisition scan pattern and goes through the same process looking for a return from a target in each successive element of the scan pattern. But if a range return (TRG) is received as described above on any scan element, this causes the mode control to go to ACQ #2 state. This state stops the acquisition scan on the scan element on which the first range return (TRG) was received and loads the range gate counter with the range measured on the first range return (TRG). Now the scan is stopped on the scan position of the first range return and a second range pulse is transmitted and the gate is opened about the range of the first range return. If a second range return is received through
SCHEMATIC OF THE LIMITED ACQUISITION CONTROL COUNTER

FIGURE 3-18
the range gate, acquisition is confirmed and the mode control is advanced to the track mode and track scan starts about this acquisition scan element. If no second range return (TRG) is received the mode control is reset back to ACQ #1 mode and the acquisition scan proceeds to the next element in the acquisition scan pattern. If the second range return (TRG) is received and the mode control goes to the track mode, the control system will stay in the track mode until no range returns (TRG) are received in the 64 millisecond track scan period. When this happens the mode control is reset to ACQ #1 mode and the acquisition scan starts again from this position in the field.

The range measurements used for accumulation and readout are selected by a circuit shown in Figure 3-17. The readings used for accumulation must be related to the time base to be able to derive range changes per unit time for range rate. Due to the track scan pattern part of the range transmissions do not produce a range return because the target is scanned outside of the image dissector aperture. Also if the target is close to the image dissector aperture edge, a time distortion occurs on the leading edge of the range return which distorts the range accuracy. And a sum of 16 range reading is more easily processed in binary circuits. Therefore, the range readings selected for accumulation and readout are the first 16 range readings received in each 0.1 sec period that are taken when the track scan is within ±2 track steps of the image dissector aperture center. Another circuit (16 Miss Count) is used to reset and clear all range accumulation registers if less than 16 range readings are accumulated in any 0.1 sec. period. And a 4 count circuit is used to control the 1.0 sec. range and range rate registers so that only complete range numbers are available for readout out.
3.8 Angle Tracker Electronics

3.8.1 General

The Scanning Laser Radar acquires and tracks a target in three dimensions; range and two angles. Target range is measured and range gates are generated to increase the SNR; however, the radar tracking loop depends primarily on the line-of-sight angle measurements to dynamically track a target. The SLR angle tracking subsystem is a dual-mode digital tracking system that locates and acquires a target within the $30^\circ \times 30^\circ$ FOV, and after acquisition, tracks the target within the FOV in terms of vertical (pitch) and horizontal (yaw) line-of-sight angles relative to boresight at the center of the FOV. The synchronously scanned transmitter beam and receiver instantaneous field-of-view are scanned about the total $30^\circ \times 30^\circ$ FOV.

The angular deflection of the transmitter beam deflectors is proportional to the voltage applied to the piezoelectric element and the angular deflection of the receiver image dissector aperture is proportional to the current in the receiver deflection coil. Both the transmitter deflection voltage and the receiver deflection current are derived from the output of the deflection digital to analog converter as shown in both the simplified block diagram (Figure 3-19) and the detailed block diagram (Figure 3-20) of the angle tracker electronics. The analog output of the D/A Converter is directly proportional to the 14 bits of digital input information from the track acquisition counters. Therefore, the transmitter-receiver angular deflection is directly proportional to the digital information in the track-acquisition counters. Schematics of the vertical and horizontal counters (Drawing RT5A), Vertical Acquisition Counter (Drawing RT5C), and the Horizontal Acquisition Counter (Drawing RT5D) are shown on Pages A-14, A-16, and A-17 in the Appendix. The least significant bit of the track counter represents $0.0025^\circ$; therefore, with proper control of the track-acquisition counters, very precise angular deflection can be obtained. Optical boresight of the system is defined as zero deflection current in the receiver deflection coils and zero deflection voltage at the transmitter piezoelectric elements. This point is also defined, in the digital...
Piezoelectric Deflected Mirror

Spherical Mirror

Projector Lens

GaAs Laser (TEM\textsubscript{00} Mode)

INPUT BEAM

DEFLECTED OUTPUT BEAM

PIEZOELECTRIC DRIVEN MIRROR SCHEMATIC

MIRROR ROTATION

PIEZOELECTRIC CRYSTAL

ROTATION AXIS

SCHEMATIC OF THE BEAM STEERER OPTICS

FIGURE 3-5

3-10
SCHEMATIC OF THE BEAM DEFLECTOR ELECTRONICS

FIGURE 3-6

3-12
SIMPLIFIED BLOCK DIAGRAM OF THE ANGLE TRACKER ELECTRONICS

FIGURE 3-19

3-34
DETAILED BLOCK DIAGRAM OF THE ANGLE TRACKER ELECTRONICS

FIGURE 3-20
logic of the 14 bit track-acquisition counters, as the most significant bit being logic one and all other bits being logic zero. If the Scanning Laser Radar has not acquired a target after "turn-on", or has lost a target while in the tracking mode, the control will reset to acquisition mode. The magnitude of the track-acquisition bits in terms of degrees in the field-of-view are as follows:

1/4 track step (Bit 1) = 0.0025° - smallest increment of tracking angle correction

1 track step (Bit 3) = 0.01° - increment of angle movement of the track scan

1 acquisition step (Bit 6) = 0.08° - increment of angle movement of the acquisition scan - also equals the angle subtended by the instantaneous aperture minus the overlap.

16 acquisitions steps or lines (16 \times 0.08°) = 1.28° - the height and width of the limit acquisition field-of-view

376 acquisition steps or lines (376 \times 0.08°) = 30° - the height and width of the total field-of-view

The amount of logic circuits for the angle tracker is quite extensive, so integrated circuits and micropoint circuit boards were used in order to minimize the size of the electronics package. Photos of the micropoint circuit boards are shown in Figure 3-21. Each 8" x 8" circuit board will hold up to 140 integrated circuits. The integrated circuit modules are spot welded to the boards and the connections between the integrated circuit modules are made on the back side with wires also spot welded to the modules. Using wires, instead of printed circuits, allows for the greater flexibility needed in developmental or experimental systems. Interconnections between boards are made with a common multi-pin connector located in the center of each board.
SLR ELECTRONIC'S PACKAGE

BLANK BOARD

BACK SIDE

FRONT SIDE

PHOTO'S OF MICROPUNCT CIRCUIT BOARDS

FIGURE 3-21
3.8.2 Acquisition, Tracking and Reacquisition Electronics

The diagrams in Figure 3-15 illustratively depict the acquisition and track scan patterns and the controlling electronics. In the acquisition mode the deflection scan is controlled by the horizontal and vertical acquisition counters (the 9 most significant Bits of the track - acquisition counters and are synchronous up and down counters). A J-K flip flop is associated with each counter to determine the up or down mode of count, and one J-K flip flop to determine the field mode of both counters. Each counter has decoding gates which forms a pulse for count 68 (down end count) and Count 443 (up end count), these pulses supply J-K information to the 3 flip flops. A gate circuit, controlled by the field mode flip flop and the system mode control (Stop Acquisition Count), controls the Acquisition Clock Pulse (Acq. Cp), into the counter, counting out the 376 successive elements per line and the 376 successive lines per field or 16 successive elements per line and 16 successive lines per limited acquisition field. A diagram of the acquisition scan waveforms and field patterns is shown in Figures 3-22 and 3-23.

The acquisition scan pattern continues element by element line by line and field by field until a target is confirmed and the system mode control goes to track mode, then the track scan is started about the center of the element of the acquisition scan in which the target was confirmed. During all of the acquisition scanning the deflection D/A converters continuously converts the horizontal and vertical acquisition counter digital information to directly proportional deflection current for the receiver deflection and voltage for the transmitter deflection.
VERT. ACQUISITION SCAN

ACQUISITION SCAN PATTERN AND WAVEFORMS
(FAST HORIZONTAL, SLOW VERTICAL)

FIGURE 3-22

3-39
HOR. ACQUISITION SCAN

Vert Element 1
Vert Acq. Count 443

Vert Element 6
Vert Acq. Count 458

Vert Element 371
Vert Acq Count 73

Vert Element 376
Vert Acq. Count 68

Vert Element 1
Vert Acq. Count 443

Line 376
Vert. Element 1

Vert. Element 2

30° x 30°

Vert. Element 371

Vert. Element 376

ACQUISITION SCAN PATTERN AND WAVEFORMS
(FAST VERTICAL, SLOW HORIZONTAL)
FIGURE 3-23

3-40
A limited acquisition scan mode is used to decrease re-acquisition time if a target has been lost for some reason after a confirmed acquisition or tracking of a target. If a target has been confirmed or tracked, the target's position in the $30^\circ \times 30^\circ$ field-of-view is known to within $\pm 0.08^\circ$. A smaller acquisition scan consisting of 16 lines per field and four fields (each field being $1.28^\circ \times 1.28^\circ$) is scanned about the last known position of the target. This mini scan takes approximately 0.256 seconds to complete when the scan rate is 1 kHz.

In the mini scan mode, the same horizontal and vertical acquisition counters and mode control flip-flops are used as in the $30^\circ \times 30^\circ$ acquisition scan. A limited acquisition control circuit shown in Figure 3-18 is used to set up limited acquisition mode and to supply the up and down end counts to the main acquisition logic circuitry.

The limited acquisition control logic controls the size of the scan and centers the scan on the last known target position.

The angle tracking performed in the track mode is a closed loop tracking system which centers the center of the instantaneous aperture of the image dissector on the target position in the overall $30^\circ \times 30^\circ$ acquisition field-of-view. It also measures the horizontal (yaw) and vertical (pitch) line-of-sight angles in reference to boresight at the center of the $30^\circ \times 30^\circ$ field-of-view. The logic portions of the closed loop tracker are the track control counter, the horizontal and vertical position counters, the horizontal and vertical velocity counters, the horizontal and vertical track counters, and the acquisition counter deflection system. Schematics of this logic are shown on pages A-11, A-12, A-13, A-26 and A-27 in the Appendix.
The horizontal and vertical track counters are synchronous up and down counters and are the five least significant bits of the 14 bit track-acquisition counters. In the track mode of operation, the Acquisition Clock Pulse into the acquisition counters is inhibited and the carry clock from bit 5 of the track counter drives the acquisition counters. So, effectively, the 14 bit track-acquisition counters become 14 bit track counters in the track mode and hereafter will be referred to as track counters while in the track mode. The deflection D/A converters receive all 14 bits of digital information and the deflection is always proportional to this information.

The track control counter (CA1-CA6) in the upper left of Figure 3-20 is a six bit synchronous counter that controls all of the timing of the tracking closed loop. It is reset to zero in the acquisition mode and starts counting the Acquisition Clock Pulses as soon as the target is acquired and the system mode control goes to the track mode. The Acquisition Clock Pulse (Acq. Cp) and CA4, 5 and 6 waveforms are shown with some of the track scan waveforms in Figure 3-24. The cycle time of the control counters is 64 milliseconds or 64 Acquisition Clock Pulses, which is also the time to complete a track mode cross scan. The track scan elements and the cross scan sequence are shown pictorially in Figure 3-25.

The vertical portion of track cross scan is made during the first half cycle of the track control counter. The first 32 Acquisition Clock Pulses of the cycle are gated into the clock input of Bit 3 of the vertical track counter. The mode control is gated up during the first 8 Acquisition Clock Pulses, down during the next 16 and up for the next 8. This causes the image dissector aperture to be deflected up 8 track steps.
Horizontal Scan (Yaw)

Vertical Scan (Pitch)

#Scan elements - 64
\[ \Delta t \text{ per elements} = 1 \text{ ms at 1KHz} \]
Track scan period - 64ms at 1KHz

\[ \theta_0 = \frac{1}{8} (0.1^\circ) = 0.0125^\circ \]

Smallest Angular Resolution Element

Instantaneous F.O.V.

\[ \theta = 0.1^\circ = 1.75 \text{ mrad} \]
\[ \Omega = (\theta)^2 = 3.05 \times 10^{-6} \text{ ster.} \]

DETAILED SCAN PATTERN AND SEQUENCE FOR TRACK MODE

FIGURE 3-25

3-44
for each of the first 8 Acquisition Clock Pulses, down during the next
16 and up for the next 8 and ends with the aperture back at the point
where it started. In a similar fashion the horizontal track counter,
during the last half of the cycle of the track control counter, causes
the image dissector aperture to be deflected 8 track steps to the
right, 16 track steps to the left and 8 track steps to the right and
ending at the original starting position. This forms the track mode
cross scan which is continuously repeated while the system is in the
track mode.

If the target is located at the center of the aperture when the cross
scan begins and the aperture is deflected more than 4 track steps in
any direction the target will be outside of the aperture and no return
pulses will be received while on any deflection step that is farther than
4 track steps from the aperture center. When the deflection is 4 track
steps or less a return will be received on each step. If the target is
at the center of the aperture during the scan, the number of returns
received while the aperture is above center will equal the number of
returns while the aperture is below center. In a similar fashion, during
the horizontal scan, the number of returns to the right will equal the
number of returns to the left. If the target was exactly one track step
above the aperture center during the scan, more returns would be
received during the upper half of the scan than during the lower half
of the scan; in fact, four more returns would be received while the
aperture was above center than while below center. If there were two
track steps above the center, eight more returns would be received in
the upper half of the scan. If the target was below the aperture center
during the scan, more returns would be received during the lower half
of the scan. In a similar fashion, the same difference in the number
of returns occurs during the horizontal scan if the target is to the
right or left of the aperture center during the horizontal portion of the tracking cross scan. Since 4 returns represents a target position error of one track step in relation to the aperture center, each return is equal to 1/2 track step error.

After the angle tracking direction and magnitude errors have been determined the corrections must be added to the deflection circuits to complete the closed loop angle tracking system. This is done with position and velocity correction counters in each angle. These counters are shown in Figure 3-20 and on pages A-11 and A-12 in the Appendix. The position and velocity counters are identical 6 bit synchronous up-down counters, only the input and output gating controls are different, depending on the function for which the counter is used. All the correction counters are reset to zero and the inputs are inhibited in the acquisition mode, and the timing to the counters in the track mode is controlled by the track control counter.

When the target is acquired and the system goes to the track mode, the track control counter starts counting and the vertical track scan starts in the upper half of the scan. The vertical correction counter modes are gated up for the duration of upper half of the vertical scan and the radar returns are used for clocks to count the vertical correction counters up one count for each return received during the upper half of the vertical scan. During the lower half of the vertical scan the correction counter modes are gated down, and each return received is used to count the correction counter down one count. Therefore, at the end of the vertical track scan, the vertical position and velocity correction counters hold the location of the target (in terms of 1/4 track steps) in relation to the aperture center in the vertical direction.
This has occurred during the first half cycle of track control counter. Also, during the same time period, the tracking information held by the horizontal correction counters is transferred to the horizontal track counter in preparation for the horizontal scan. During the horizontal scan the horizontal correction counter modes are gated up during the right half and down during the left half of the scan, and the returns are used as clocks to count the counters first up and then down so that at the end of the horizontal scan the horizontal correction counters hold the target location in the horizontal direction. Also, during this same period, the vertical tracking information held by the vertical correction counters is transferred to the vertical track counters and the updated vertical angle is read out. This process of alternately sensing the target position in relation to the aperture center and then correcting the vertical and horizontal track counters according to the sensed error completes the closed loop tracking system and continues as long as the system remains in the track mode.

The time periods of angle corrections and the angle readout periods are shown in relation to the track scan periods in Figure 3-24. A X4 Acquisition Clock Pulse is used to clock the angle error information from the correction counters into the track counters. Since the correction counters are all reset to zero in the acquisition mode, and zero is used as a reference count, the most significant bit of the counters will always give the direction of the target error from the aperture center. Therefore, the most significant bit is used to determine the direction (up or down) of count of the X4 Acquisition Clock Pulse into the correction counters and into the track counters during the correction periods. The number of X4 Acquisition Clock
Pulses required to count the correction counters back to zero is the number of 1/4 track steps of correction that is transferred to the track counters. So, if a position counter was counted up 3 counts during the track scan, during the position correction period the X4 Acquisition Clock Pulses would be enabled into the position counter until the counter was counted down to zero. This would require 3 clocks so the track counter would be counted up by these same 3 clocks, and the aperture would now be centered on the target and the position counter would be at zero ready to receive the error count during the next track scan.

The velocity correction counter receives its input error information in exactly the same manner as the position counter during the track scan, but differs from the position counter in that it stores angle error information and repeatedly corrects the track counter with this information, if the target has a velocity. The error information in the velocity counter changes only if the target velocity changes. This, in effect, predicts the target position for the next track scan according to the target velocity.

The up-down mode of the velocity counter and track counter during the velocity correction period is taken from the velocity counter's most significant bit just previous to and held through the velocity correction period. The velocity counter is a 6 Bit counter, so 64 clocks of the X4 Acquisition Clock Pulse are gated into it during the velocity correction period. This counts the counter around one cycle in either the up or down mode, depending on the target error direction in relation to the aperture center and the counter ends on the count stored in it when it started the cycle. The clocks into the velocity counter during the correction period are allowed into the track counter until zero
count in the velocity counter is reached, then the velocity correction
clocks to the track counter are inhibited for the rest of the cycle. The
velocity counter with its stored velocity information is now ready for
the next track scan to either confirm or update its stored velocity
information.

The total track scan period is 64 milliseconds for a 1 KHz scan rate,
but the vertical and horizontal scans are made alternately in each
32 millisecond period, so the angles are alternately updated every
32 milliseconds. This means that one angle shift register (ASO-AS15)
shown in Figure 3-20 and on page A-18 in the Appendix can shift both
angle readings into the readout system for visual readout and to the
control computer. Each angle reading is parallel loaded from the
horizontal and vertical 14 bit track acquisition counters just after
updating by their associated position and velocity counters.
3.8.3 Linearity Correction Map for the Synchronously Scanned Transmitter-Receiver

The Scanning Laser Radar steers or points a narrow laser beam \( (0.1^\circ) \) synchronously with an equally narrow receiver field-of-view \( (0.1^\circ) \). A linearity correction map, shown in Figure 3-26, is incorporated in the SLR receiver so that the receiver's \( 30^\circ \times 30^\circ \) field-of-view can be adjusted to match or be superimposed over the transmitter's \( 30^\circ \times 30^\circ \) field-of-view. The schematics for the linearity correction logic are shown on Pages A-20 through A-25 in the Appendix.

The exact angular deflection of the receiver varies slightly from the angular deflection dictated by reading the image dissector deflection current. The deflection error becomes larger as the angular deflection from boresight increases and varies in a relative smooth curve over the field-of-view. Therefore, the tracker field-of-view can be divided into areas and a correction current added to or subtracted from the deflection current to correct the deflection errors for each area. A map is made of the deflection errors for each area in the total field-of-view. A series of gates reading the angular deflection causes the linearity correction digital to analog converters to add or subtract a calibrated amount of deflection current to correct the deflection errors for each area of the map.
LINEARITY CORRECTION MAP FOR THE RECEIVER FIELD-OF-VIEW

VERTICAL ADDRESS

VERTICAL ANGLE

+15.36°  +12.80°  +10.24°  +7.68°  +5.12°  +2.56°  0°  -2.56°  -5.12°  -7.68°  -10.24°  -12.80°  -15.36°

LINEARITY SPOT 8E

LINEARITY SPOT 5H

HOR. ADDRESS

V12 V11 V10 V9 V8 V7 V6 V5 V4 V3 V2 V1
3.8.4 Angle Tracker Data Outputs

The SLR angle tracker provides horizontal (yaw) and vertical (pitch) line-of-sight angle data. The angle data is updated every 64 milliseconds, the period for one track cross scan. The horizontal and vertical angles are alternately updated every 32 milliseconds. Referring back to the track cross scan in Figure 3-25 one can see that it takes 32 milliseconds for the vertical scan and 32 seconds for the horizontal scan. While one angular direction is being scanned, the other is being updated. The angle outputs are available in either straight binary or binary coded decimal (BCD). A visual data display subsystem that displays all the radar data in digital decimal form is described in Section 3.13. The raw angle outputs from the angle tracker are in binary form and Table 3-1 shows the correlation between the binary bits and the radar angles. The least significant bit represents 0.0025 degrees, and the 14th, or most significant bit, represents 20.48 degrees.

A block diagram of the SLR angle and range data outputs is shown in Figure 3-27. The 64 millisecond angle readings are sent to an accumulator where 16 consecutive readings are integrated to give one averaged, or smoothed reading every 1.024 seconds. Figures 3-28 and 3-29 show the timing and sequence of the raw angle and range binary data outputs. The example in Figure 3-28 shows the timing sequence for the vertical scan and the horizontal output reading. The horizontal angle is shifted out during step #26 of the vertical cross scan. The vertical angle measured during this vertical cross scan will be available for readout and shifted out 32 ms after the horizontal angle output or at step #58 of the vertical scan. All angle timing is synced to the shift clock pulses (32A, 32B, 32C) shown also in Figure 3-28. Figure 3-29 provides a more detailed look at the sequence of all the angle and range readings that are available from the present logic.
Timing & Binary Coding For Angle & Range Data Output

Figure 3-28
SEQUENCE TIMING DIAGRAM FOR ANGLE AND RANGE PROCESSING
(EXAMPLE CASE)
FIGURE 3-29
Angle-rate calculations are also performed in the SLR logic, the horizontal and vertical angle-rates are both computed and updated at an arbitrary data rate of one per 2.56 seconds. The angle-rates are derived by differentiating the angle data; therefore, an external computer can accept the raw angle data and compute the angle-rate at whatever data rate it chooses.
### Table 3-1

**Binary Coding for Angle Outputs**

<table>
<thead>
<tr>
<th>BIT #</th>
<th>ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0025 Degrees</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>0.16</td>
</tr>
<tr>
<td>8</td>
<td>0.32</td>
</tr>
<tr>
<td>9</td>
<td>0.64</td>
</tr>
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<td>1.28</td>
</tr>
<tr>
<td>11</td>
<td>2.56</td>
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<tr>
<td>12</td>
<td>5.12</td>
</tr>
<tr>
<td>13</td>
<td>10.24</td>
</tr>
<tr>
<td>14</td>
<td>20.48</td>
</tr>
</tbody>
</table>
3.9 Range and Timing Electronics

3.9.1 General

The pulse ranging subsystem determines target range by measuring the laser pulse propagation time from the transmitter to the target and back to the receiver in increments of 0.67 nanoseconds (1498 MHz). This allows the system to obtain a range accuracy of ±10 cm. The range pulse propagation time is resolved by using a stripline delay line and Motorola MECL III ultra high speed integrated circuit logic. Figure 3-30 is a basic block diagram of the range and timing electronics that will illustrate the general range and timing sequences for a given pulse repetition rate (1 KHz) and desired resolution (0.67 nanoseconds or 10 cm). The 1 KHz pulse repetition rate timing signals for the laser transmitter are generated by dividing down from either the 187.376 MHz Master Oscillator or the 187.376 MHz Sub Oscillator. A 1,000,000 MHz Reference Oscillator and a 1000 divider generate the 1 KHz reference. The phase of the Master Oscillator and Sub Oscillator are controlled by the Reference Oscillator so that their timing signals are locked in phase to the 1 KHz generated from the Reference Oscillator. The sequence starts with the Sub Oscillator running and subsequently generating the first 1 KHz signal that is sent to the laser transmitter. A laser pulse is transmitted toward the target. A light pulse detector mounted at the output of the laser senses the outgoing pulse and starts the 187.376 MHz Master Oscillator. The Sub Oscillator is then turned off. The Master Oscillator then generates the timing for the 1 KHz pulse repetition rate and the range circuitry. The 187.376 MHz is sent to the Fine Range circuitry which uses a stripline delay line to effectively multiply the frequency by eight to get the 1498.96 MHz which is needed to resolve the range into 10 cm increments. The highest frequency clock in the Scanning Laser Radar is 187 MHz, however, a phase shifting of this clock is used to obtain 1498 MHz. With the use of a stripline delay line and high speed "and gates" a master clock in a pulse ranging system can effectively have its frequency increased. The output
BASIC BLOCK DIAGRAM OF RANGE AND TIMING ELECTRONICS

FIGURE 3-30
from a master clock is sent down a stripline delay line and is tapped off into equal but increasing time increments as shown by a simplified example in Figure 3-31. The phase of the output from each succeeding stripline tap is shifted and if the radar signal is "and gated" with each of the shifted clocks, then the return signal can be resolved into a time or range bin equal to the delay of one stripline tap. For the Scanning Laser Radar an accurately calibrated stripline delay line and MECL III logic are used to obtain range resolution from 1498 MHz down to 23 MHz. Fine range circuitry provides the 21 bit Range Shift Register with the lowest 6 binary bits of range information (10 cm to 6.4 m). The Fine Range circuitry also sends a 23.422 MHz (6.4 m) signal to the Master Range circuitry which accomplishes the range counting in 6.4 m increments. The Master Range provides the 21 bit Range Shift Register with the highest 15 binary bits of range information (6.4 to 150 km). When the transmitted pulse is returned from the target, the receiver sends a stop signal to the Fine Range circuitry which stops the fine range and master range counters.

The calibrated stripline delay line is shown in the photos in Figure 3-32. The Fine Range circuits are mounted on the back side of the circuit board shown in the photo. The coarse range circuitry is located on separate circuit boards.
PHOTO OF THE STRIPLINE DELAYLINE-FINE RANGE CIRCUIT BOARD

FIGURE 3-32

3-62
3.9.2 **Range Circuitry**

To count range directly a frequency of \(1498.964\, \text{MHz}\) must be counted. No known integrated circuit can count at this speed, but a frequency eight times lower (\(187.3705\, \text{MHz}\)) can be counted with Motorola MECL III logic. In order to resolve the eight times higher frequency a system of eight delay lines was devised, each successive line was made longer than the previous line by a delay time of exactly \(0.667\) nanoseconds. Figure 3-33 is a detailed block diagram of the range and timing circuitry. Schematics of the logic are shown on page A-1 thru A-9 in the Appendix. The start of each line is driven in parallel by a master oscillator at \(187.3705\, \text{MHz}\). The end of each line drives one input of a 2 input nand gate. The other input of each nand gate is tied common and driven by the range return flip flop so as to inhibit all nand gates when a range return signal is received. Therefore, if the master oscillator is started each time a range light pulse is transmitted, and the gates at the ends of the lines are inhibited when a range return signal is received, then a direct count of the 0.1 meter increments of the range is obtained. The outputs of the 4 nand gates on the 4 shorter delay lines, shown in the upper right corner of Figure 3-33, set 4 successive nand gates on the 4 longer delay line resets of the 4 RS flip flops. This circuitry forms a type of Johnson counter with the output of each flip flop shifted in time by \(1/8\) of the \(187.3705\, \text{MHz}\) cycle time. The 4 RS flip flops outputs can be decoded into 3 binary bits, which is the divide by eight required to resolve \(1498.964\, \text{MHz}\). The most significant bit of the 3 decoded bits is used for the input clock of a binary ripple down counter of 18 bits, which is sufficient to count a maximum range of 150 KM. The binary range counts (FRI–FR6) and the corresponding Master Range Counter.
DETAILED BLOCK DIAGRAM OF THE RANGE AND TIMING ELECTRONICS

FIGURE 3-33
(MR1-MR15) is also depicted in Figure 3-33. Figure 3-44 shows the range and timing waveforms for the 8 delay lines and the binary counts (FR1-FR6).

At the end of each millisecond range measuring period, if a range return signal is received through the range gate, the range count in the range counter is parallel loaded into the range shift register (RSO-23) shown in Figure 3-17. This range reading in the range shift register is never destroyed and is updated only if a new range reading is received through the range gate. A range gate counter (MG2-15) shown on page A-8 in the Appendix is parallel loaded with the range reading that is contained in the range shift register just previous to each range transmission, so that the range counter can set up a narrow range gate about the range of the previously received range return. This range gate helps exclude false range returns (noise) and back scatter for any object near the range pulse path. The range shift register always contains the last good range reading.

The total system timing is controlled from the 187.3705 MHz master oscillator. This oscillator is a Motorola MECL III 4 input gate with delay of the gate, plus the delay line is equal to 1/2 cycle of the frequency of oscillation. This type of oscillator was chosen because of the ease of starting and stopping the oscillator in a known phase. The oscillator is not particularly stable with time and temperature variations, so its bias, which controls the frequency of oscillation, is controlled by an error voltage generated by a phase-locked loop sensing the phase difference between the master oscillator and a reference TXCO crystal oscillator shown on pages A-2 and A-3 of the Appendix. Since a continuous time base is needed in the system
and range measurement requires turning on and off the master oscillator, a sub oscillator identical to the master oscillator is used in conjunction with the master oscillator. When the master oscillator is turned off, the sub oscillator is turned on and vice versa. The two oscillator outputs are "ored" together for the input clock to the time base counter (FT1-3 and MT1-15) which divides the master oscillator frequency down to 1 KHz rate. Because of a discrete number of counts required in digital division a master oscillator frequency of 187.376 MHz was chosen to divide down to 1 KHz. This produces an error of less than 30 parts per million in the range measurements. All timing controls for the total system are generated from this master time counter.
3.9.3 Range Data Outputs

The SLR ranging subsystem provides slant or line-of-sight target range. Sixteen (16) range readings are taken every 0.1 seconds and these are integrated to provide an averaged or smoothed range reading. Figures 3-25, 3-26, and 3-27 show the basic block diagram and timing diagrams for the range outputs. The raw range outputs from the ranging subsystem are in binary form and Table 3-2 shows the correlation between the binary bits and the target range. The least significant bit represents 0.00625 meters and the 25th, or most significant bit, represents 104,857.6 meters. The output logic also provides a 1.0 second range reading that is obtained by averaging ten (10) of the 0.1 seconds readings. Range-rate is computed by differentiating the range data. The data rate for the range-rate is one per second, however, an external computer can take the raw range data and compute the range-rate at whatever data rate it chooses.
<table>
<thead>
<tr>
<th>BIT #</th>
<th>RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00625 Meters</td>
</tr>
<tr>
<td>2</td>
<td>0.0125</td>
</tr>
<tr>
<td>3</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
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<tr>
<td>9</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
</tr>
<tr>
<td>11</td>
<td>6.4</td>
</tr>
<tr>
<td>12</td>
<td>12.8</td>
</tr>
<tr>
<td>13</td>
<td>25.6</td>
</tr>
<tr>
<td>14</td>
<td>51.2</td>
</tr>
<tr>
<td>15</td>
<td>102.4</td>
</tr>
<tr>
<td>16</td>
<td>204.8</td>
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<tr>
<td>17</td>
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<td>18</td>
<td>819.2</td>
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<tr>
<td>19</td>
<td>1638.4</td>
</tr>
<tr>
<td>20</td>
<td>3276.8</td>
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<tr>
<td>21</td>
<td>6553.6</td>
</tr>
<tr>
<td>22</td>
<td>13107.2</td>
</tr>
<tr>
<td>23</td>
<td>26214.4</td>
</tr>
<tr>
<td>24</td>
<td>52428.8</td>
</tr>
<tr>
<td>25</td>
<td>104857.6</td>
</tr>
</tbody>
</table>
3.10 Power Converters

The SLR has power converters that enable the entire system to operate from a ±28 VDC primary power source. Figure 3-35 is a schematic of the power converters for the SLR transmitter-receiver and electronics. Photos of the power converter circuitry are shown in Figure 3-36. All the power converters are enclosed within the central electronics package for the entire radar system.
SCHEMATIC OF POWER CONVERTERS FOR THE TRANSMITTER-RECEIVER & ELECTRONICS

FIGURE 3-35

3-71
SLR ELECTRONICS PACKAGE

POWER CONVERTER
PHOTOS OF POWER CONVERTERS

FIGURE 3-36

3-72
3.11 Target Reflector and Receiver

For Phase II of Contract NAS8-20833, reported here, the radar target was allowed to have a passive corner cube reflector to enhance the reflected return signal, and an active receiver that would measure the incoming direction of the radar beam so that the orientation or attitude of the target relative to the radar could be determined. Figure 3-37 shows a block diagram of the target receiver and reflector, and photos of the hardware are shown in Figure 3-38. A 2-1/2" diameter solid glass (BSC-2) corner cube with a 3/4" diameter hole cut into the apex was mounted directly in front of the target receiver optics. The portion of the radar beam not entering the center of the corner cube reflector will be reflected directly back toward the radar as shown in the sketch in Figure 3-37. The corner cube reflector will reflect the incoming beam back toward the source regardless of the angular direction that the incoming beam strikes the corner cube reflector. Because of the geometry of the corner cube it will accept and reflect any beam over a ninety degree cone. The portion of the radar beam entering the center or hole of the corner cube reflector will be collected by a multi-elements lens. An Angenieux 50 mm f/1.0 lens is used here to image the radar beam onto the receiver detector. A narrow band optical filter (200 Å) is also placed in front of the lens to reduce the background noise. The receiver detector is an ITT F4011 image dissector like the one described in Section 3.5. The target receiver will measure the relative pitch and yaw angles between the radar and target. It should be mentioned here that for Phase III of Contract NAS8-20833, to be completed during 1972, the relative orientation or attitude of the target will be determined with only corner cube reflectors allowed on the target. Range and angle measurement to three or more corner cube reflectors will allow the relative target attitude to be calculated by the radar. This eliminates the need for an active target receiver and the telemetry link needed to get the relative target attitude data back to the vehicle with the radar.
TARGET REFLECTOR - RECEIVER

CORNER CUBE REFLECTOR

RECEIVER OPTICS

NARROW BAND OPTICAL FILTER

RECEIVER DETECTOR (IMAGE DISSECTOR)

OPTICAL CORNER CUBE REFLECTOR (TWO DIMENSIONAL EXAMPLE)

BLOCK DIAGRAM OF TARGET REFLECTOR - RECEIVER

FIGURE 3-37
PHOTO'S OF TARGET REFLECTOR-RECEIVER AND
INDIVIDUAL CORNER CUBE REFLECTORS
FIGURE 3-38
3.12 Target Electronics

The target electronics used to control and process the data for the target reflector-receiver primarily consists of a pre-amp, angle tracker, and power converters. A block diagram of the target electronics is shown in Figure 3-39. A photo of the electronics package is shown in Figure 3-40. The heart of the electronics is the angle tracker and is very similar to the angle tracker for the radar that is described in Section 3.8. The schematics for the target electronics are shown on pages A-53 through A-61 in the Appendix.

The target angle tracker electronics system differs from the radar angle tracker in a few areas. The target tracker has its own temperature controlled master oscillator for system timing control. A (VCO) oscillator could be used and phase locked to the received radar tracker transmitted light pulse. This was not done, but would keep the two systems (radar and target trackers) locked together for more precise timing control. The oscillator frequency is 2.928 MHz which is divided down to 1 KHz and 15.625 Hz, the same as in the radar tracker. The range gate is established with a combination of one shot signals rather than a counter as in the radar tracker. The deflection drivers develop deflection drives for the receiver only, since transmitter drive is not required. And no receiver linearity correction was used in the receiver to save time and money, but the deflection error in the receiver is the same magnitude as in the radar tracker receiver.
BLOCK DIAGRAM OF TARGET ELECTRONICS
FIGURE 3-39
PHOTO OF TARGET ELECTRONIC'S PACKAGE
FIGURE 3-40
3.13 Radar Data Displays

The Scanning Laser Radar has visual readouts of range, range rate, horizontal and vertical angles, and horizontal and vertical angle rates. These parameters are displayed by seven segment incandescent digital readout lamps. Photos of the radar data displays are shown in Figure 3-41. All data is converted from binary to digital decimal and slower data rates (smoothed data) were selected so that the data was easier to read. The following data was generated by the SLR and was either displayed visually or was available to be shifted out to an external computer.

- Horizontal and vertical angles (individual readings every 64 ms).
- Horizontal and vertical angles (averaged for 1.024 sec.).
- Horizontal and vertical angle-rates (averaged for 2.56 sec.).
- Range (individual readings, 16 per 0.1 seconds).
- Range (averaged for 0.1 sec.).
- Range (averaged for 1.0 sec.).
- Range-Rate (averaged for 1.0 sec.).

Some of the shifted out signal forms are shown in Figure 3-28, and their associated bit values are given in Tables 3-1 and 3-2. The logic schematics for processing these readout signals are shown on pages A-37 through A-52 in the Appendix. As each completed range reading is available to be shifted out to an external computer, it is also accumulated in the 0.1 sec. range accumulator (page A-39) and the 1.0 sec. range accumulator (page A-38). At the end of each 0.1 sec. period, the 16 accumulated range readings are shifted out as range (averaged for 0.1 sec.) and at the end of each 1.0 sec the 160 accumulated range readings are shifted out as range (averaged for
PHOTO'S OF SLR DATA DISPLAY
FIGURE 3-41

3-80
This same range (averaged for 1.0 sec.) is shifted into a binary to decimal converter (page A-46) for the visual range readout. Also this range (averaged for 1.0 sec.) is subtracted from the range (averaged for 1.0 sec.) obtained in the previous second and the difference is shifted out as range-rate (averaged for 1.0 sec.). This range-rate number is also shifted into the range-rate binary to decimal converter (page A-45) for visual range-rate readout.

Each angle reading is accumulated in the angle accumulators (page A-40) and the accumulated angles are shifted out as angles (averaged for 1.024 sec.). The accumulated angles are also shifted into the angle binary to decimal converter (page A-49) for the angle visual readouts. The angle readings are also accumulated in the angle rate accumulators (page A-41) for 2.56 seconds and subtracted from the previous 2.56 sec. angle accumulation to obtain angle-rate. This difference is shifted out as angle-rate (averaged for 2.56 sec.) and the same difference is also shifted into the angle-rate binary to decimal converters (page A-43) for the angle-rate visual readouts.

The binary to decimal converters (pages A-43 through A-46) are basically binary counters which are parallel loaded with binary range or angle information from a shift register; then the information is counted out of the binary counter into a decimal counter, clock for clock, by a 1.46 MHz clock pulse from the master time counter. The decimal counters (pages A-48, A-50, A-51, A-52) are also used as the holding registers for the visual readout indicators. A decade of a decimal counter and its associated decimal to seven segment converter (page A-49) is used to drive each decade readout lamp. Blanking, leading zero blanking, sign and decimal point drive circuits are also incorporated in the converter circuits.
4.0 TEST RESULTS

4.1 General

The primary objective of the test program was to collect acquisition, tracking, and docking test data on the Scanning Laser Radar under dynamic test conditions. A cooperative optical target was mounted on a moveable platform (Rendezvous and Docking Simulator) and was moved into and through the field-of-view of the Scanning Laser Radar which was mounted on a fixed platform. The target motions were computer controlled such that the line-of-sight velocities and accelerations could be programmed for various acquisition and tracking tests. Docking type tests were performed to evaluate the range and angle accuracy of the Scanning Laser Radar in a representative dynamic condition. Target simulator data and radar data were monitored simultaneously in real-time. Figure 4-1 is a sketch of the equipment configuration for the overall test set-up. A digital computer was used in real-time to

(1) Control the target position and attitude,
(2) Accept target position and attitude data from the target platform pickoffs,
(3) Accept Scanning Laser Radar Data

Tests to determine the maximum target range that the SLR could acquire and track a target at were originally scheduled using an aircraft. These tests were not performed, but it is estimated that the maximum target range would be approximately 30 miles for the SLR with the low powered single mode GaAs laser as the transmitter. Longer ranges could be obtained if a higher power laser was used.
4.2 **Maximum Acquisition-rate Tests**

Tests were performed to determine the capability of the Scanning Laser Radar to acquire and lock-on moving targets. Eight (8) basic test cases were performed. In each of the eight cases the target started at a position in the center of the radar field-of-view. This starting position was chosen because it was easy and convenient to reset or reposition the target to the same boresighted location. The target accelerated up to a predetermined velocity, the radar was put into its acquisition mode and then attempted to acquire the moving target. The objective was to determine the maximum line-of-sight (LOS) angular velocity that the target can be traveling with respect to the radar and still be acquired by the radar. The difference between the eight basic test cases are the LOS angular **directions** chosen for the target trajectories.

Figure 4-2 shows the basic geometry for the acquisition test set-up, and Figure 4-3 depicts the eight LOS angles chosen for the test runs. The starting position of the target and the coordinates of the radar in the target simulator reference frame are also shown. The acquisition scan was started near the center of the field-of-view (approximately $\alpha_{xc} = -15^\circ$, $\alpha_{yc} = +1.0^\circ$) in order to reduce the acquisition time. Acquisition occurred in the first 5 to 20 seconds. During this time the target was traveling with almost constant LOS angular velocity ($\alpha_c$).

For each of the eight basic test cases the maximum LOS angular velocity ($\alpha_{xc}$, $\alpha_{yc}$) capability for the acquisition mode was determined. Figure 4-4 illustratively depicts these maximum values and the associated direction of the target trajectory. The test data shows acquisition at target angular rates of $0.166^\circ$/sec to $0.249^\circ$/sec.
SECTION A-A

TARGET LOS ANGLES ($\alpha_x$, $\alpha_y$)
AS SEEN BY RADAR

($0^\circ$, $+15^\circ$)
($-10.6^\circ$, $+10.6^\circ$)
($+10.6^\circ$, $+10.6^\circ$)
($-10.6^\circ$, $-10.6^\circ$)
($+15^\circ$, $0^\circ$)
($-15^\circ$, $0^\circ$)
($0^\circ$, $-15^\circ$)
($+15^\circ$, $-15^\circ$)

DIRECTION OF TARGET
FOR CASE #3

LOS ANGLES ($\alpha_x$, $\alpha_y$) FOR THE ACQUISITION TESTS

FIGURE 4-3
NOTE: See Figure 4-3 for geometry of target trajectory with respect to the radar.

MAXIMUM ACQUISITION-RATES

FIGURE 4-4

4-6
The lower rate was with the target traveling down slower than the radar scan (0.213°/sec). It should have acquired a target moving 0.196°/sec. for case #7 but the simulator Z-axis reached the negative travel limit before the radar scan caught up with the target. The absolute worst case condition was never realized during these tests. This would be when the target was moving perpendicular to the scan as in case #3 and the target was only captured by the line scan overlap (reference Final Report NAS-23973, section 3.1). Statistically this absolute worst case will less than 5% of the time for case #3, and since this condition could not be programmed into the test set-up it could not be checked. The absolute worst case condition would have only allowed the radar to acquire the target at 0.025°/sec. From Figure 4-4 it is obvious that all test data was considerable better. This test data should represent approximately 95% of the possible test conditions for target acquisition. The best case condition for target acquisition should be when the target is moving parallel to the scan as in case #1 or #5. For this condition the maximum angular velocity that the radar will acquire at is 0.303°/sec. A value of 0.224°/sec was obtained for case #1 and #5 and this is reasonable considering that the best case condition could not be programmed into the test set-up. A slightly higher value was obtained for case #4 (0.249°/sec). Again the values shown in Figure 4-4 (0.166 to 0.249°/sec) should be a representative range of maximum acquisition rates that the radar is capable of acquiring a target for almost all target trajectory conditions.
4.3 **Maximum Tracking-Rate Tests**

Dynamic tests were performed to determine the maximum tracking-rate (Velocity and Acceleration) capability of the SLR and to check its ability to re-acquire a moving target after a temporary loss-of-track condition is incurred.

**Velocity**

Two (2) basic test cases were performed to determine the capability of the SLR to track a target moving with a constant velocity. The differences between the two basic tests were the target starting position and the LOS angular direction chosen for the target trajectory. Each test run started with the SLR locked-on the target while it was stopped at a designated initial starting position. At a designated time the target was slowly accelerated \(0.3^\circ/\text{sec}^2\) up to a predetermined constant angular velocity (as seen by the radar), and the radar then attempted to track the target. The objective was to determine the maximum LOS angular velocity that a target can be travelling with respect to the radar and still be tracked by the radar.

Figure 4-5 shows the test set-up geometry for the tracking tests and Figure 4-6 depicts the two LOS angular directions chosen for the test runs.

The maximum target velocity that was tracked by the SLR was 0.9 degrees/second for the vertical target trajectory and 1.0 degrees/second for the 45° target trajectory. This agrees reasonably well with calculated or theoretical limit (1.10 degrees/second) for the SLR when it is operating with a 1 KHz PRF and scan rate.
ALLOWABLE TRAVEL OF TARGET SIMULATOR

\[ x_{\text{max}} = -25.90 \text{ m} \]

\[ y_{\text{max}} = -1.65 \text{ m} \]

\[ z_{\text{max}} = +5.41 \text{ m} \]

\[ x_{\text{max}} = +17.80 \text{ m} \]

\[ y_{\text{max}} = +1.87 \text{ m} \]

\[ z_{\text{max}} = -2.42 \text{ m} \]

NULL POSITION OF TARGET SIMULATOR

\[ x, y, z \]

\[ 0, 0, 0 \]

TARGET TRAJECTORIES

BORESIGHT AXIS

CASE #1

\[ x_{11}(0) = +6.228 \text{ m} \]

\[ y_{11}(0) = 0 \]

\[ z_{11}(0) = +.067 \text{ m} \]

CASE #2

\[ x_{12}(0) = +6.38 \text{ m} \]

\[ y_{12}(0) = -1.496 \text{ m} \]

\[ z_{12}(0) = +.604 \text{ m} \]

\[ x_{c} = +17.68 \text{ m} \]

\[ y_{c} = 0 \]

\[ z_{c} = -4.10 \text{ m} \]

TEST SETUP FOR THE TRACKING & DOCKING TESTS

FIGURE 4-5
4.3 Maximum Tracking Rate (Continued)

Acceleration

The tracking acceleration tests were run the same way as the tracking velocity tests except the target acceleration was the variable test parameter. The tracking acceleration tests were somewhat redundant because as soon as the angular velocity exceeded the maximum tracking velocity, the target was lost. The present SLR angle tracker makes position and velocity corrections in order to update the radar pointing, but acceleration corrections are not made. The system can stand a very high angle acceleration for a short period of time until the velocity becomes too great. But the acceleration tests did confirm the velocity tests, because track was lost in each case after the velocity exceeded approximately 10/sec.

Re-acquisition

The ability of the SLR re-acquisition mode to reacquire a target after temporary loss-of-track was checked by momentarily obstructing the path of the laser beam to the target. After the SLR loses track of a target it automatically goes into the reacquisition mode. In this mode the SLR synchronously scans its transmitter-receiver in a 1.28° x 1.28° square about the last known location of the target. Whenever the beam was obstructed for a time less than it took for the target to travel outside the 1.28° x 1.28° reacquisition the target was successfully reacquired within 0.256 seconds or less.
4.4 Range and Angle Accuracy

The line-of-sight range and angle accuracy of the Scanning Laser Radar was determined by evaluating the test data taken during two different tests. The range accuracy was examined for a typical docking maneuver when the target was closing slowly toward the radar. It is during the final closure of rendezvous and docking that the best resolution or accuracy from the radar is needed, and therefore, a typical docking maneuver was simulated. During the docking closure maneuver the line of sight angles are nulled to zero, and since the best LOS angle accuracy of the SLR is at boresight (LOS angles are zero), the LOS angle accuracy was examined for a tracking test when the target was crossing through the angular field-of-view of the SLR at various changing angles.

Figures 4-5 and 4-7 show the test set-up geometry for a typical docking maneuver test. The test starts when the radar acquires the target (Phase I - Acquisition). The target is then moved until it is positioned along the radar boresight (Phase II - Null LOS angles). The radar boresight axis is also the docking axis for these tests. After the target reaches the docking axis, it starts to close toward the radar with a trajectory along the docking axis (Phase III - Closure for Docking).

It was during this docking closure phase that the LOS range accuracy of the SLR was examined. A detailed plot of the individual range readings for one of the representative docking tests is shown in Figure 4-8. The plot shows all the range readings as a function of time for the section of the docking closure maneuver between the range of 8.4 meters and 5.3 meters. The SLR was operating a 1 KHz PRF and 16 range readings every 0.1 seconds were averaged and sent to the digital computer used in the test set up. The docking closure maneuver
PHASE I - ACQUISITION
PHASE II - NULL LOS ANGLES
PHASE III - CLOSURE FOR DOCKING

TARGET TRAJECTORY & CLOSURE-RATE SEQUENCE FOR DOCKING TESTS
FIGURE 4-7
TEST RUN ELAPSED TIME

RANGE COMMAND BY COMPUTER
CORRECTED RADAR 1.0 SEC RANGE READING

RADAR 0.1 SEC RANGE READING
RADAR 1.0 SEC RANGE READING

± 3σ ERROR IN CORR RANGE READINGS (+)
DATA POINT SHIFTED AFTER CORRECTION

PROJECTED HORIZONTAL LOS ANGLE

TARGET SIMULATOR TRAJECTORY

R = 8.4 METERS R = 5.3 METERS R = 0
DATA PLOTTED ABOVE

SCANNING LASER RADAR

VERTICAL LOS ANGLE
LAPSED TIME - SECONDS

85  90  95  100  105  110

IN CORRECTED READINGS (+5cm)

RADAR VERT ANGLE READOUT

VERT ANGLE COMMAND BY COMPUTER

RADAR HOR. ANGLE READOUT

HOR ANGLE COMMAND BY COMPUTER

DATA POINTS SHIFTED AFTER AGC CORRECTION IS APPLIED

PLOT OF LINE-OF-SIGHT RANGE VS. TIME (DOCKING CLOSURE TEST RUN)

FIGURE 4-8

4-14
between 8.4 meters and 5.3 meters took 53 seconds resulting in 530 range readings.

Ten (10) individual SLR range readings per second were averaged to obtain a range reading smoothed for one second for each of the 53 seconds in the period studied. The recorded AGC voltage was then read for each second from the analog recordings and the one second range readings were corrected by the following factor:

\[
\text{SLR Range} + \left[ \left( \frac{\text{Recorded AGC}}{\text{AGC}} \times \frac{1.3}{2.4} \right) - 2.0 \text{ V} \right] \times 1.75 \text{ M/V} = \text{Corrected Range}
\]

\[
\frac{1.3}{2.4} = \text{Recorder Scale Factor}
\]

\[
2.0 \text{ V} = \text{SLR Reference AGC}
\]

\[
1.75 \text{ M/V} = \text{Correction Factor (Meters per Volt)}
\]

The maximum corrected range deviation from the programmed range was +.06 M and -.08 M for the 53 sec test period. This deviation would have been less if the Z-axis motion of the target simulator has been constant.

The smoothed one-second range readings are shown in the plot with circles around them, and the smoothed/AGC corrected one second range reading are shown with squares around them. The target was commanded to follow a straight line trajectory and the calculated range values for the commanded target trajectory is shown by the heavy straight line. When the smoothed/AGC corrected one second range readings are compared to the commanded range values, the ±3
sigma (σ) variation between the two is ±5 centimeters. In actuality, the 3σ range error is really less than 5 cm because the actual trajectory that the target simulator followed was not a straight line, but was a staircase. The staircase trajectory occurred because the Z-axis motions (up and down) of the target simulator were not smooth due to imperfect counter-balancing, cable vibration, and control problems in the target simulator test set-up. The X and Y axis motions of the target simulator were reasonably smooth. The staircase Z-axis motions were large enough to be visible to an observer. They were also verified by looking at the vertical LOS angle readouts of the SLR. Figure 4-9 shows the vertical and horizontal angle readouts for a portion of the docking closure shown previously in Figure 4-8. The vertical angle readout shows a large cyclic motion about 0.28°. Projected to the Z-Y plane of the test set-up, one can observe that the actual target trajectory of this cyclic motion would be a staircase trajectory about the 0.28° projected LOS angle from the SLR. Instead of smoothly moving from point A to point B as commanded, the target simulator moved rapidly downward in the Z-axis and then moved along the X-axis with zero Z-axis movement until point B was reached. The LOS range readings from the SLR were effected by this cyclic motion of the target simulator and this is shown clearly when one compares the smoothed/AGC corrected one second range reading in Figure 4-9 with the vertical angle readouts. If the staircase trajectory has been smooth in the Z-axis, the ±3σ variation between the commanded range and the SLR range readings would have been less than ±5 cm. From the available test data it could not be quantitatively determined how much less the variation would be. The horizontal angle readout is also shown in Figure 4-9 and this verified the relative smoothness of the
PLOT OF SLR DATA AND TARGET TRAJECTORY VS TIME

FIGURE 4-9

4-17
The target simulator in the X and Y directions.

A detailed plot of the individual angle readings for one of the representative tracking tests is shown in Figure 4-10. The plot shows both the horizontal and vertical LOS angle readings for a track test that started at approximately $-7.0^\circ, 7.0^\circ$ and ended at $+7.0^\circ, +7.0^\circ$. The SLR was operating at 1 KHz PRF and scan rate, and used a 64 millisecond cross scan while in track mode, thus the angles were updated and sent to the external digital computer used in the test set-up every 64 ms. The solid lines in the angle plot in Figure 4-10 are the calculated angles of the target. The calculated angles were geometrically computed by using the X, Y, Z positions taken from position pickoffs located on the target simulator.

Offset bias errors between alignment of the test set-up to the SLR boresight caused the SLR angle readings to differ from the calculated values. After determining and subtracting out the offset bias error, the radar vertical angle readings were compared to the calculated target simulator vertical angles. The three sigma variation between the two was calculated to be 0.066 degrees. This can be considered the worst case angle error for the SLR angle tracker because of the cyclic motions of the target trajectory at the relatively high angular velocity (0.7 degrees) that was used for this test. The maximum tracking of the SLR is approximately 1.0 deg/sec. If the cyclic motions of the target has been larger and/or with a higher frequency, the SLR would have lost track of the target. The vertical angle data showed a target cyclic motion with a 2.2 second period and a higher frequency with a period of approximately 0.36 seconds. The SLR angle tracker uses 0.064 seconds to complete one cross scan period (for the 1 KHz scan rate...
used in this prototype). If the target has a large cyclic motion, greater than 0.1 degree movement in a 0.064 second period, then the radar will not be able to generate the necessary error signals to track the target. If the target trajectory had been smooth (constant angular velocity with no acceleration components), then the 3σ vertical angle error would have approached 0.0125 degrees (the angle resolution and static angle accuracy of the angle tracker). The SLR angle tracker makes an angle and angle-rate correction in the tracking loop but does not make angle-accelerations corrections.

The horizontal angle 3σ error was calculated to be 0.055 degrees for the same test run shown in Figure 4-10. The horizontal angle error should be less than the vertical angle error because the target trajectory was smoother in the horizontal direction.
TARGET WAS MOVING AT AN AVERAGE LOS ANGULAR VELOCITY OF 0.7 DEG./SEC. IN BOTH THE HORIZ. AND VERTICAL DIRECTIONS FOR THIS TEST.

SECTION A-A
LOS ANGLES TO TARGET AS SEEN BY RADAR

PLOT OF LINE-OF-SIGHT ANGLES VS. TIME
(TRACKING TEST RUN)
4.5 Summary of Test Results

The performance of the Scanning Laser Radar system during the field tests is summarized in the following table:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TABLE 4-1</strong></td>
<td><strong>SUMMARY OF TEST RESULTS</strong></td>
</tr>
<tr>
<td>Maximum Acquisition-rate</td>
<td>0.166 to 0.249 deg/sec (depending on direction of target trajectory)</td>
</tr>
<tr>
<td>Maximum Tracking-rate</td>
<td>0.9 deg/sec</td>
</tr>
<tr>
<td>Range Accuracy ($3\sigma$)</td>
<td>5 centimeters</td>
</tr>
<tr>
<td>Angle Accuracy ($3\sigma$)</td>
<td>0.06 degrees</td>
</tr>
</tbody>
</table>

**Note:**

These results were recorded with the Scanning Laser Radar system operating with a 1 kHz PRF and scan rate. The system will eventually operate with a 10 kHz or higher PRF and scan rate. For a 10 kHz PRF and scan rate, the maximum acquisition-rates and tracking-rates will be 10 times larger than those obtained with 1 kHz. The range and angle accuracies will be about the same at 10 kHz, but the data rates will be 10 times greater.