FINAL REPORT
CONTRACT NAS8—23973 PHASE III
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DESIGN OF A SCANNING LASER RADAR FOR
SPACEBORNE APPLICATIONS

TO
NASA
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA 35812

PREPARED BY
TERRY FLOM
H. DEAN COOMBES

OCTOBER 1971

AEROSPACE/OPTICAL DIVISION ITT
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FORWARD

This document is the final report for Phase III of Contract NAS8-23973, "Design of a Scanning Laser Radar for Spaceborne Applications". 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 D. O. Lowrey and J. Allen Dunkin.

This study contract was performed by the Aerospace/Optical Division of ITT, San Fernando, California. The program was performed in the Advanced Development Department under Thomas Dixon (Director) and Leo Cardone (Associate Director). The Study Program Manager was Terry Flom. Principal contributors to the study program were L. Cardone, D. Coombes, T. Flom, J. Priebe, R. Schmidt and W. Wilson.
1.0 INTRODUCTION

This is the final report for phase III of NASA contract NAS8-23973, "Design of a Scanning Laser Radar for Spaceborne Applications." Phase I and Phase II pertained primarily to math modeling of rendezvous and docking problems. The Phase III, reported here, is a paper design of a Scanning Laser Radar system that is to be used to acquire and track cooperative targets (i.e., targets that have corner cube reflectors). The Scanning Laser Radar acquires and tracks the target anywhere in a 30° x 30° field-of-view without the aid of mechanical gimbals, and has a maximum target range of 30–90 nautical miles depending upon the type of laser transmitter that is used. The system is designed to be relatively small, lightweight, and low-power consuming.

Three (3) different system configurations of the Scanning Laser Radar are described in Section 2.0 of this report. The three configurations differ primarily in the type of hardware that is allowed on the target vehicle. A list of the estimated system performance characteristics and the size, weight, and power estimates are also included in Section 2.0. An analysis of the acquisition and tracking capability of the Scanning Laser Radar and a laser power versus target range analysis is outlined in detail in Section 3.0. Also, a description of various techniques to determine target attitude with passive reflectors and an associated error analysis is included in this section.

The design of the Scanning Laser Radar is discussed and described in Section 4.0. Included are subsections on the laser transmitter, beam steerer, receiver optics, receiver detector, and the associated radar electronics.
2.0 SYSTEM DESCRIPTION

2.1 General

The Scanning Laser Radar (SLR) described in this report has been designed for 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. Precise knowledge of the relative position between two spacecraft performing a rendezvous maneuver is difficult and often impractical to obtain from ground-based radars and, therefore, accurate radars located on-board the spacecraft are desirable. Also, two spacecraft performing docking maneuvers require careful monitoring of closure rates and angular alignments, thus precision on-board radars can be a valuable aid in bringing them together safely. On-board radars can also be useful for continuous or periodic surveillance of small satellite spacecrafts that are parked in orbits nearby their mother spacecraft. Laser radar systems are presently being considered for use on future spacecraft such as the NASA space shuttle and space station. Space shuttles can use laser radar to aid the transferring of cargo into and out of their payload bay. Laser radar can also be used to aid the rendezvous and docking of space shuttles with space stations, and can allow space stations to monitor the location of small satellite spacecraft.

In order to better understand the general 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. Figure 2-1 pictorially depicts the general rendezvous and docking geometry for a chaser and target spacecraft. The first sequence in rendezvous and docking (rendezvous search) will set the limits on one of the most important parameters of the radar; maximum target range.
**RENDEZVOUS SEARCH**

TARGET EPHEMERIS

TARGET VEHICLE

CHASER VEHICLE

**RENDEZVOUS ACQUISITION**

TARGET LOCATED

**RENDEZVOUS CLOSURE**

CONTINUOUS OR PERIODIC TRACKING

**DETERMINE COARSE TARGET ATTITUDE**

Determine to $\pm 10^\circ$ over entire sphere ($360^\circ$)

**DETERMINE FINE TARGET ATTITUDE (AT DOCKING PORT)**

Determine to $\pm 0.5^\circ$ over $\pm 15^\circ$ range

**DOCKING CLOSURE**

NULL LOS angles and maintain closure-rate limits.

GENERAL RENDEZVOUS & DOCKING GEOMETRY

FIGURE 2-2
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. During the second sequence (rendezvous acquisition), 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 sequence three (rendezvous closure) because any navigation errors incurred will require additional fuel during corrective maneuvers. The fourth sequence (determine coarse target attitude) is necessary when the location of the docking port of the target vehicle is to be coarsely determined. Coarsely, meaning to within approximately ±10° over an entire sphere. Normally the attitude of a cooperative target is known to better than ±10° via other navigation aids and thus the on-board radar is usually not required to determine coarse target attitude. The design presented in this report does not include determination of coarse target attitude, however, it should be possible to add this feature in the future if it is needed. The fifth sequence (determine fine target attitude) requires the on-board radar to measure the relative angular positions between the docking ports. This is normally accomplished at a relatively close range (200 – 500 feet). The sixth sequence (docking closure) requires the on-board radar to 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 2-2. These line-of-sight angles must be nulled usually to approximately ±3°, or less, for successful and easy mating of the docking adaptors. Another measurement that is critical to a successful docking is the closure-rate measurement. Both
Null all Line-of-Sight Angles
\((\theta_x', \theta_y, \alpha_{XT}, \alpha_{YT}, \Phi) \to 0\)

Final Docking Closure

EXAMPLE OF GEOMETRY FOR DOCKING

FIGURE 2-2
the range-rate and angle rates must be continuously and accurately measured so that the contact velocities can be carefully controlled prior to and at docking impact. 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.

The data from the Scanning Laser Radar will be sent to the spacecraft Guidance and Control computer and to an instrumentation panel. Figure 2-3 shows the Scanning Laser Radar in a typical vehicle Guidance and Control block diagram. Since the Scanning Laser Radar was intended here for spaceborne applications, it was designed to be relatively small, lightweight, and low-power consuming.
VEHICLE GUIDANCE AND CONTROL SYSTEM
BLOCK DIAGRAM

FIGURE 2-3
Three System Configurations of the SLR

The description of the three (3) system configurations of the Scanning Laser Radar is presented in this section. All three configurations will directly or indirectly measure the line-of-sight angle and range components shown previously in Figures 2-1 and 2-2. The main differences between the three configurations are the type of hardware placed on the chaser and target vehicles and the scheme used to determine the target orientation or relative attitude \((a_{xt}, a_{yt})\) as shown in Figure 2-2. Figure 2-4 depicts the general type of hardware used in each of the three configurations.

The first system configuration of the Scanning Laser Radar (SLR-I) is a dual, or two-way, acquisition and tracking system. Acquisition and tracking are performed automatically without an operator. Figure 2-5 is a block diagram of Configuration SLR-I. Either vehicle, or both simultaneously, can acquire and track the other vehicle. A radar transmitter-receiver is placed on each vehicle in order to determine the line-of-sight range \((R)\), and the line-of-sight angles \((\theta_x, \theta_y)\) to the target. A corner cube reflector and receiver are also placed on each vehicle for the purpose of enhancing the reflected radar signal and to determine the target attitude \((a_{xy}, a_{yt})\). The reflector-receiver is referred to as the target equipment for the radar transmitter-receiver that is located on the chaser. In the SLR-I configuration, each vehicle can operate as the chaser or the target, or both simultaneously. If it is necessary to have all the radar data on one vehicle, then the target attitude \((a_{xy}, a_{yt})\) data will have to be telemetered to the chaser vehicle, or the radar transmitter-receiver data generated on the chaser vehicle \((R, \theta_x, \theta_y)\) will have to be telemetered to the target vehicle. It would be possible to use the radar transmitter as a low data rate telemeter line \((\approx 1,000 \text{ to } 5,000 \text{ bits/second})\) by modulating or pulse-coding the pulsed transmitter beam. A two-way laser radar and communication system is being investigated, however, this study pertains only to spaceborne laser radar and shall not concern itself with laser communications.
THREE CONFIGURATIONS OF THE SCANNING LASER RADAR
TRANSMITTER-RECEIVER ELECTRONICS

IMAGE DISSECTOR

REC. OPTICS

30° x 30°

B.S. (Boresight Axis)

C. C. REFLECTOR

REFLECTOR-RECEIVER

RECEIVER ELECTRONICS

BASIC BLOCK DIAGRAM
SLR-1 CONFIGURATION

FIGURE 2-5
2-9
The second configuration of the Scanning Laser Radar (SLR-2) is a single acquisition and tracking system. Acquisition and tracking is performed automatically without an operator. Figure 2-6 is a block diagram of SLR-2. In the SLR-2 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 (θ_x, θ_y) to the target vehicle and the receiver on the target will be used to determine the target orientation or relative target attitude (α_xt, α_yt).

Again, 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.

The third configuration of the Scanning Laser Radar (SLR-3) is also a single acquisition and tracking system, however, no active components or electronics are allowed on the target vehicle. Acquisition and tracking is performed automatically without an operator in this configuration as it is in the other two configurations. Figure 2-7 is a block diagram of SLR-3. In the SLR-3 configuration, one vehicle will have a radar transmitter-receiver and the other vehicle (the target) will have only reflectors that are passive (i.e., no electronics). As in the other two configurations, the radar transmitter-receiver is used to determine the line-of-sight angles (θ_x, θ_y) to the target. In addition, the radar transmitter-receiver in the SLR-3 configuration is used to determine the target orientation or relative target attitude (α_xt, α_yt) when the line-of-sight range (R) between the two vehicles is less than 500 - 1,000 feet. This will be accomplished by placing more than one corner cube reflector on the target such that by measuring the range to each corner cube reflector, and the angular separation between the corner cube reflectors, one can use a unique set of geometric equations to calculate the relative attitude (α_xt, α_yt) of the target vehicle with respect to the line-of-sight between the two vehicles. The relative
MULTI-REFLECTORS

CORNER CUBE #1

CORNER CUBE #2

CORNER CUBE #3

Bore sight Axis

30° x 30°

TRANSMITTER-RECEIVER

Beam Steerer
Laser Xmit.

REC. OPTICS

IMAGE DISSECTOR

TRANSMITTER-RECEIVER ELECTRONICS

BASIC BLOCK DIAGRAM
SLR-3 CONFIGURATION

FIGURE 2-7
2-12
roll angle ($\phi$) will also be calculated using the same unique set of geometric
equations. The most significant advantage that the SLR-3 offers over the other
two configurations is that all the basic geometry ($R$, $\theta_x$, $\theta_y$, $\alpha_{xt}$, $\alpha_{yt}$ and $\phi$) is
measured from one vehicle, the vehicle with the laser radar. All guidance and
control functions for docking alignment could be performed by this vehicle
without the need for a telemetry link between itself and the target.
2.3 Synchronously Scanned Transmitter-Receiver

The design of all three system configurations of the Scanning Laser Radar have one common feature, a synchronously scanned transmitter-receiver. 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 configuration chosen here is shown in Figure 2-8. The basic feature of this scheme is that the transmitter-receiver is scanned 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.
SYNCHRONOUSLY SCANNED TRANSMITTER-RECEIVER

FIGURE 2-8
In the transmitter beam steerer shown in the upper section of Figure 2-8 the output beam from the laser is converged to a small symmetrically focused spot by the first 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 tilt 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 beam steerer. 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 (i.e., ±0.25 degrees) by the piezoelectric driven mirrors can result in relatively large beam deflection (i.e., ±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. The control element causing the rotation of the mirror is a piezoelectric crystal that is cantilever mounted to the back side of the mirror as shown in Figure 2-9. When a voltage is applied across the piezoelectric crystal it bends proportionally to the applied voltage and effectively rotates the attached mirror about a reference axis. The bending action is essentially frictionless. A precision strain gage is also attached to the mirror to monitor the actual deflection in order to take care of the off-axis hysteresis in the piezoelectric crystal. Using a diffraction limited beam from a laser with a wavelength of 0.9 μm, and two 0.7 x 1.0 inch piezoelectric driven mirrors that are both rotated ±0.25 degrees can result in a square raster scan pattern that has approximately 350 x 350 resolvable scan elements.
PIEZOELECTRIC DRIVEN MIRROR SCHEMATIC

FIGURE 2-9
Simultaneously, when a given voltage is applied to the transmitter beam steerer to control the direction of the outgoing laser beam, a specified current will be applied to the electromagnetic deflection coils in the receiver so that the receiver's instantaneous field-of-view can be looking in the exact same line-of-sight angular direction as the outgoing beam. The receiver optics collect and focus the return laser beam to a small spot on the image dissector photocathode. The position of the focused spot will be directly proportional to the line-of-sight angular direction of the outgoing beam. The image dissector must now determine the location of the signal spot on its photocathode. When the photons of laser light strike one small spot on the photocathode electrons from the small spot are emitted. By varying the electromagnetic field, the image dissector can effectively scan the surface of the photocathode in order to precisely determine the spot location of the emitted electrons. For a 5 cm photocathode diameter and 0.01 cm instantaneous effective photocathode diameter (central aperture) an image dissector can provide 350 x 350 resolvable scan elements. Now both the transmitter and receiver are aligned and their positions are electronically controlled, thereby creating a synchronously scanned transmitter-receiver.

The ability of the synchronously scanned transmitter-receiver to acquire and track moving targets is primarily a function of beam geometry, total search field-of-view, target range, and the radar signal-to-noise ratio. The synchronously scanned transmitter-receiver is line-of-sight acquisition and tracking system that will determine the relative location of the target by measuring the line-of-sight range to the target, and the pitch and yaw line-of-sight angles \((\theta_x, \theta_y)\) with respect to the radar boresight axis as shown in Figure 2-10. During the acquisition phase the maximum target range will determine the
TARGET

\[ \theta_x \text{ PITCH ANGLE} \]

\[ \theta_y \text{ YAW ANGLE} \]

BORESIGHT AXIS

LINE-OF-SIGHT

R RANGE

SCANNING LASER RADAR

SKETCH OF THE RADAR LINE-OF-SIGHT MEASUREMENT

FIGURE 2-10
maximum pulse repetition-rate or dwell time per scan element, and during the acquisition and track time some apriori knowledge of target range will allow the use of range-gates to increase the radar signal-to-noise ratio. When the radar signal-to-noise ratio is high enough to insure a high probability of detection and a low false alarm rate then the acquisition and tracking rate capability of the synchronously scanned transmitter-receiver will be primarily dependent upon the line-of-sight angular rates the target travels with respect to the boresight axis of the radar (i.e., the pitch and yaw line-of-sight angle-rates).
2.4 System Performance Characteristics

The estimated system performance characteristics for the Scanning Laser Radar designed for this study contract are summarized in Table 2-1. The analysis for the acquisition and tracking rates, and the maximum target range is in Section 3.0. The error analysis for the calculation of relative target attitude ($\alpha_x, \alpha_y$) is also in Section 3.0.
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>OPERATING RANGE</th>
<th>ACCURACY (±x)</th>
<th>DATA RATE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE</td>
<td>Low Power Laser</td>
<td>Medium Power Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slant range to target</td>
<td>0-56 km (30 ml)</td>
<td>0-56 km (30 ml)</td>
<td>±0.02% of range or</td>
<td>For 1 KHz PRF *</td>
</tr>
<tr>
<td></td>
<td>0.1-3.5 mm Avg. oul</td>
<td>0.1-3.5 mm Avg. oul</td>
<td>±0.2 cm whichever is greater.</td>
<td>160 individual readings per second</td>
</tr>
<tr>
<td>RANGE-RATE</td>
<td>0-3 km/sec</td>
<td>0-3 km/sec</td>
<td>±0.4% of range-rate or</td>
<td>10 smoothed readings per second</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±0.5 cm/sec whichever is greater.</td>
<td></td>
</tr>
<tr>
<td>ANGLE</td>
<td>Radar-to-target</td>
<td>Radar-to-target</td>
<td>±0.42°</td>
<td>15 per sec for 1 KHz PRF</td>
</tr>
<tr>
<td></td>
<td>line-of-sight angle (θ&lt;sub&gt;x&lt;/sub&gt;, θ&lt;sub&gt;y&lt;/sub&gt;)</td>
<td>(θ&lt;sub&gt;x&lt;/sub&gt;, θ&lt;sub&gt;y&lt;/sub&gt;)</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Relative target attitude</td>
<td>Relative target attitude</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Target-to-radar</td>
<td>Target-to-radar</td>
<td>(ω&lt;sub&gt;θ&lt;/sub&gt;, ω&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>line-of-sight angle (ω&lt;sub&gt;θ&lt;/sub&gt;, ω&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>(ω&lt;sub&gt;θ&lt;/sub&gt;, ω&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>±0.5°</td>
<td>15 per sec for 1 KHz PRF</td>
</tr>
<tr>
<td>ANGLE-RATE</td>
<td>Acquisition Mode</td>
<td>Acquisition Mode</td>
<td>±0.5°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Radar to target</td>
<td>Radar to target</td>
<td>±0.5°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>LOS angle-rate (δ&lt;sub&gt;θ&lt;/sub&gt;, δ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>(δ&lt;sub&gt;θ&lt;/sub&gt;, δ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Relative target attitude</td>
<td>Relative target attitude</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>target to radar</td>
<td>target to radar</td>
<td>(κ&lt;sub&gt;θ&lt;/sub&gt;, κ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>LOS angle-rate (κ&lt;sub&gt;θ&lt;/sub&gt;, κ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>(κ&lt;sub&gt;θ&lt;/sub&gt;, κ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Relative target attitude</td>
<td>Relative target attitude</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Target to wall</td>
<td>Target to wall</td>
<td>(λ&lt;sub&gt;θ&lt;/sub&gt;, λ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>LOS angle-rate (λ&lt;sub&gt;θ&lt;/sub&gt;, λ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>(λ&lt;sub&gt;θ&lt;/sub&gt;, λ&lt;sub&gt;α&lt;/sub&gt;)</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Relative target attitude</td>
<td>Relative target attitude</td>
<td>±0.6°</td>
<td>*</td>
</tr>
<tr>
<td>ACQUISITION TIME</td>
<td>0-160 seconds</td>
<td>0-160 seconds</td>
<td>±0.5% of angle-rate or</td>
<td>For 10 KHz PRF the maximum</td>
</tr>
<tr>
<td></td>
<td>For 1 KHz PRF</td>
<td>For 1 KHz PRF</td>
<td>±0.6% of angle-rate or</td>
<td>acquisition is 10 times less.</td>
</tr>
</tbody>
</table>

*Data rate 10 times higher for 10 KHz.
2.5 **Size, Weight and Power**

The size, weight, and power estimates for the Scanning Laser Radar designed for this study contract are summarized in Table 2-2.
<table>
<thead>
<tr>
<th>SIZE</th>
<th>LOW POWER LASER (GaAs)</th>
<th>MEDIUM POWER LASER (MINI-YAG)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLR-1</td>
<td>SLR-2</td>
</tr>
<tr>
<td></td>
<td>6&quot; x 9&quot; x 20&quot;</td>
<td>6&quot; x 9&quot; x 20&quot;</td>
</tr>
<tr>
<td>Radar Transmitter-Receiver</td>
<td>6&quot; x 9&quot; x 20&quot;</td>
<td>6&quot; x 9&quot; x 20&quot;</td>
</tr>
<tr>
<td>Radar Electronics</td>
<td>9&quot; x 9&quot; x 9&quot;</td>
<td>9&quot; x 9&quot; x 9&quot;</td>
</tr>
<tr>
<td>Reflector-Receiver</td>
<td>4&quot; x 5&quot; x 18&quot;</td>
<td>-</td>
</tr>
<tr>
<td>Reflector-Receiver Electronics</td>
<td>4&quot; x 9&quot; x 9&quot;</td>
<td>-</td>
</tr>
<tr>
<td>Multi-Reflectors</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>CHASER</td>
<td></td>
</tr>
<tr>
<td>Radar Transmitter-Receiver</td>
<td>30 lbs.</td>
<td>30 lbs.</td>
</tr>
<tr>
<td>Radar Electronics</td>
<td>10 lbs.</td>
<td>10 lbs.</td>
</tr>
<tr>
<td>Reflector-Receiver</td>
<td>10 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Reflector-Receiver Electronics</td>
<td>5 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Radar Transmitter-Receiver</td>
<td>30 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Radar Electronics</td>
<td>10 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Reflector-Receiver</td>
<td>10 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Reflector-Receiver Electronics</td>
<td>5 lbs.</td>
<td>-</td>
</tr>
<tr>
<td>Multi-Reflectors</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AVERAGE POWER (AT 28 VDC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHASER</td>
<td>35 W</td>
<td>35 W</td>
</tr>
<tr>
<td>TARGET</td>
<td>50 W</td>
<td>15 W</td>
</tr>
</tbody>
</table>

* Target values for Radar Transmitter-Receiver and Reflector-Receiver Electronics.
3.0 ANALYSIS

3.1 Acquisition and Tracking Analysis

When the radar signal-to-noise ratio is high enough to insure a high probability of detection and a low false alarm rate then the acquisition and tracking rate capability of the synchronously scanned transmitter-receiver will be primarily dependent upon the line-of-sight angular rates the target travels with respect to the boresight axis of the radar (i.e., the pitch and yaw line-of-sight angle-rates). Sketches of the scan patterns used for acquiring and tracking a target are shown in Figures 3-1 and 3-2. If during the acquisition phase a raster scan pattern with a beam overlap is used, as shown in Figure 3-1, then the maximum allowable line-of-sight angular velocity ($\dot{\theta}_{\text{max}}$) of the target with respect to the radar boresight axis is

\[
\dot{\theta}_{\text{max}} \text{ (Worst Case Acquisition)} = \frac{\theta_{\text{iFOV}} - \theta_{\text{AS}}}{2 \left( n_A \right) \left( t_d \right) + n_t t_d}
\]  

(3-1)

where

- $\theta_{\text{iFOV}}$: Instantaneous field-of-view
- $\theta_{\text{AS}}$: Acquisition step angle
- $n_A$: Number of acquisition steps per line
- $t_d$: Dwell time per acquisition step
- $n_t$: Number of track steps per cross scan (track mode)

This maximum angular acquisition velocity is for the worst case condition where the target trajectory is perpendicular to direction of the radar line scan. When the target is moving in the same direction and parallel to the scan, then the maximum allowable line-of-sight angular velocity ($\dot{\theta}_{\text{max}}$) is

\[
\dot{\theta}_{\text{max}} \text{ (Best Case Acquisition)} = \frac{\theta_{\text{iFOV}} - \theta_{\text{AS}}}{2 t_d + n_t t_d}
\]  

(3-2)

For a $30^\circ \times 30^\circ$ search FOV, 20% overlap between scan steps, and

- $\theta_{\text{iFOV}} = 0.1^\circ$
- $\theta_{\text{AS}} = 0.08^\circ$
- $n_A = 376$
- $t_d = 1$ millisecond (based on max PRF for an unambiguous range of 80 nautical miles)
- $n_t = 64$

3-1
A RASTER SCAN PATTERN

TARGET

NOT REPRODUCIBLE

TARGET

SKETCH OF TYPICAL ACQUISITION SCAN

FIGURE 3-1

SKETCH OF TYPICAL TRACK SCAN

FIGURE 3-2
then \( \dot{\theta}_{\text{max}} \) (Worst Case Acquisition) = 0.025 Deg/Sec
\( \dot{\theta}_{\text{max}} \) (Best Case Acquisition) = 0.303 Deg/Sec

For a coplanar earth orbit rendezvous maneuver between two spacecraft that are at an altitude of 200 miles and 210 miles respectively and separated by a slant range of approximately 80 miles, the relative line-of-sight angular velocity between the two spacecraft is approximately 0.003 degrees/second due to the difference in orbital velocities and position. Any attitude movements by the vehicle with the radar will also affect the line-of-sight angular velocity between the radar and target, therefore, during the acquisition mode the vehicle with the radar should be stabilized in attitude. The target vehicle does not have to be stabilized in attitude because the corner cube reflectors are relatively insensitive to attitude changes. Each corner cube has an acceptance angle of approximately \( \pm 30^\circ \), therefore, 15 corner cubes positioned with the proper orientation could provide a full \( 360^\circ \) acceptance angle for target acquisition.

After the target has been acquired a cross scan pattern is used to generate tracking error signals, as shown in Figure 3-2, and the maximum allowable line-of-sight angular velocity (\( \dot{\theta}_{\text{max}} \)) of the target with respect to the radar boresight axis is

\[
\dot{\theta}_{\text{max}} \text{(Track)} = \frac{\theta_{\text{iFOV}}}{2 \left( n_t \right) \left( t_d \right)}
\]

\( \theta_{\text{iFOV}} \) = Instantaneous field-of-view
\( n_t \) = Dwell time per track step

If a target is to be tracked anywhere in a \( 30^\circ \times 30^\circ \) FOV using

\( \theta_{\text{iFOV}} \) = 0.1\(^\circ\)
\( n_t \) = 64
\( t_d \) = 1 millisecond (based on maximum PRF for an unambiguous range of 80 nautical miles)

then \( \dot{\theta}_{\text{max}} \) (Track) = 1.10 Deg/Sec
During rendezvous closure maneuvers the relative line-of-sight angular velocities between two spacecraft increases due to decreased range and changes in spacecraft attitude. However, as the range decreases, the radar pulse repetition rate can be increased proportionally and the dwell time per scan element can be decreased proportionally. When the maximum range is reduced from 80 to 8 miles, the PRF can be increased from 1 to 10 KHz and the receiver dwell time \( t_d \) reduced from 1.0 to 0.1 milliseconds, thereby, the maximum angular tracking rate \( \dot{\theta}_{\max} \) is increased from 1.10 degrees/second to 10.1 degrees/second.

For the close range docking case where three (3) corner cube target reflectors are tracked simultaneously, then the maximum angular tracking rate capability will be approximately one third that for the single target case.
3.2 Power vs. Target Range Analysis

The required radar transmitter power needed to acquire a target for various target ranges will be examined. Equations for the average input power \( P_{\text{in}} \) into the laser transmitter as a function of the target range \( R \) for the cooperative (optical corner cube reflector) target case can be derived by examining the radar transmitter-receiver efficiencies, the propagation medium, the search and target geometry, and the probability statistics associated with choosing a minimum detectable signal that is suitable for the particular application. Figure 3-3 pictorially shows the basic elements that affect the average input power required \( P_{\text{in}} \). The average input power required \( P_{\text{in}} \) is directly proportional to the average minimum detectable signal \( P_{\text{MDS}} \).

\[
P_{\text{in}} \text{(watts)} = \frac{8}{11 \sum \frac{1}{\tau_i}} P_{\text{MDS}} \tag{3-4}
\]

where

\( \tau_1 \) (electrical-to-optical conversion efficiency) = Hardware Constant

\( \tau_2 \) (transmitter-optical transmittance) = Hardware Constant

\( \tau_3 \) (transmittance of propagation medium) = \( e^{-2 \alpha R} \)

\( \tau_4 \) (fraction of target subtended by trans. beam) = \( \frac{\Omega_{\text{cc}}}{\Omega_{\text{tb}}} \approx \frac{N_{\text{cc}}}{4} \frac{\pi}{d_{\text{cc}}^2} \frac{d_{\text{cc}}^2}{R^2} \)

\( \tau_5 \) (target reflectance) = Hardware Constant

\( \tau_6 \) (= \( \tau_3 \)) = \( e^{-2 \alpha R} \)

\( \tau_7 \) (fraction of receiver aperture subtended by return beam) = \( \frac{\Omega_{\text{FOV}}}{\Omega_{\text{rb}}} \approx \frac{\pi}{4} \frac{d_{\text{cc}}^2}{d_{\text{cc}}^2} \frac{d_{\text{cc}}^2}{R^2} \frac{\lambda^2}{\lambda^2} \)

\( \tau_8 \) (receiver optical transmittance) = Hardware Constant

\( P_{\text{MDS}} \) (minimum detectable signal) = \( \frac{\Delta t}{t_d} \frac{S_{\text{MDS}}}{S_{\lambda}} \)

The symbols used here are defined in Table 3-1
COMPONENTS OF RADAR POWER EQUATION

FIGURE 3-3
Table 3-1 Definition of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J_{\text{BS}} )</td>
<td>Backscatter radiant intensity (( \text{w/ster} ))</td>
</tr>
<tr>
<td>( \Omega_{i\text{FOV}} )</td>
<td>Receiver instantaneous field-of-view (( \text{ster.} ))</td>
</tr>
<tr>
<td>( \theta_{i\text{FOV}} )</td>
<td>Receiver instantaneous field-of-view (( \text{rad.} ))</td>
</tr>
<tr>
<td>( S_{\lambda} )</td>
<td>Receiver sensitivity at wavelength ( \lambda ) (( \text{a/w} ))</td>
</tr>
<tr>
<td>( H_{\lambda} )</td>
<td>Solar irradiance at wavelength ( \lambda )</td>
</tr>
<tr>
<td>( \Delta \lambda )</td>
<td>Optical bandwidth (meters)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Laser wavelength (meters)</td>
</tr>
<tr>
<td>( A_{T} )</td>
<td>Area of radar target (( \text{m}^2 ))</td>
</tr>
<tr>
<td>( \Omega_{R} )</td>
<td>Solid angle subtended by receiver (( \text{ster.} ))</td>
</tr>
<tr>
<td>( \Omega_{\pi} )</td>
<td>Solid angle for target reflection off lambertian surface (( \text{ster.} ))</td>
</tr>
<tr>
<td>( N_{B} )</td>
<td>Radiance of sunlit cloud background (( \text{w/cm}^2 \text{ ster.} \mu \text{m} ))</td>
</tr>
<tr>
<td>( A_{R} )</td>
<td>Area of receiver collector (( \text{m}^2 ))</td>
</tr>
<tr>
<td>( d_{R} )</td>
<td>Diameter of receiver collector (meters)</td>
</tr>
<tr>
<td>( I_{\text{dc}/A} )</td>
<td>Dark current noise of detector (( \text{a/cm}^2 ))</td>
</tr>
<tr>
<td>( k )</td>
<td>Boltzmann's constant (( 1.38 \times 10^{-23} \text{ joules/}^\circ\text{K} ))</td>
</tr>
<tr>
<td>( T )</td>
<td>Temperature (( ^\circ\text{K} ))</td>
</tr>
<tr>
<td>( \Delta F )</td>
<td>Electrical bandwidth (Hz)</td>
</tr>
<tr>
<td>( R_{L} )</td>
<td>Load Resistor (ohms)</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Atmospheric Attenuation Coefficient</td>
</tr>
<tr>
<td>( R )</td>
<td>Line-of-sight range to target (m)</td>
</tr>
</tbody>
</table>
Table 3-1 Definition of Symbols (Continued)

\[ \Omega_{cc} \]
Beamspread due to diffraction at corner cube (ster)

\[ \Omega_{tb} \]
Transmitter beamwidth (ster)

\[ \theta_{tb} \]
Transmitter beamwidth (rad.)

\[ d_{cc} \]
Diameter of corner cube reflector (meters)

\[ N_{cc} \]
Number of corner cube reflectors

\[ \Omega_T \]
Solid angle subtended by target (ster)

\[ \theta_{rb} \]
Reflected beam off corner cube target (rad.)

\[ K_{cc} \]
(1.22) Factor introduced by examining the central maximum to the first null of the diffraction pattern from an optical corner cube reflector.

\[ G \]
Detector gain

\[ \Delta t \]
Laser pulse width

\[ t_d \]
Period or dwell time between successive pulses
After inserting all the parameters into equation 3-4, the average input power required \( P_{in} \) for the cooperative target becomes

\[
P_{in}^{\text{coop}} = \frac{1}{\tau_1 \tau_2 \tau_5 \tau_8} \frac{1}{e^{-2 \alpha R}} \frac{16K_{cc}^2 \lambda^2}{\pi^2 R} \frac{2 \theta t_d}{R} \frac{R^4}{N_{cc}^2 d_{cc}^4} \frac{\Lambda t I_{MDS}}{S_{\lambda}}
\]  

(3-5)

If one uses a pulsed laser and the beam is scanned over the desired search field-of-view in a raster scan pattern, then the "average" minimum detectable signal \( P_{MDS} \) needed at the receiver will be proportional to the duty cycle times the "peak" minimum detectable signal as illustratively shown in Figure 3-4. The average minimum detectable signal \( P_{MDS} \) will be

\[
P_{MDS} = \frac{\Delta t}{t_d} \times \frac{I_{MDS}}{S_{\lambda}} \quad \text{(watts)}
\]  

(3-6)

where

- \( \Delta t \) = laser pulse width
- \( t_d \) = dwell time or period between successive pulses
- \( I_{MDS} \) = peak minimum detectable signal in amperes
- \( S_{\lambda} \) = sensitivity of the receiver detector in amperes/watt.

When using a photoemissive detector the photocathode will convert the incoming photons of light into electrons and thus the peak minimum detectable signal current \( I_{MDS} \) becomes

\[
I_{MDS} = \frac{n_e e}{\Delta t} \quad \text{(amperes)}
\]  

(3-7)

where

- \( n_e \) = minimum number of electrons per pulse
- \( e \) = \( 1.6 \times 10^{-19} \) coulombs
- \( \Delta t \) = laser pulse width
MINIMUM DETECTABLE SIGNAL ILLUSTRATION

FIGURE 3-4
In order to determine the minimum number of electrons per pulse \( \frac{n_e}{\Delta t} \) of return signal that will be needed, one must first look at the number of electrons of noise that will occur during the same time period \( \Delta t \). There are many possible contributors to the noise level and these are shown pictorially in Figure 3-5. The mean square value of the total noise is

\[
\sigma_n^2 = \left[ n_5 \sqrt{2e (n_1 + n_2 + n_3 + n_4 + I_s) \Delta F} \right]^2 + (n_6)^2
\]

where

\[
\begin{align*}
n_1 &= \text{backscatter noise} = J_{BS} B_0 \text{IFOV}^S \tau_8 \\
n_2 &= \text{target background noise} = H \Delta \lambda A_T \tau_5 \Omega_R \tau_8 S^\lambda \\
n_3 &= \text{sky background noise} = N \frac{A_T}{A_1} S_{\lambda} \Delta \lambda \tau_8 \\
n_4 &= \text{detector dark noise} = \frac{I_{dc} \text{IFOV}^S \tau_8}{\Delta \lambda} \\
n_5 &= \text{detector amplifier noise} = \text{Constant} \\
n_6 &= \text{amplifier noise} = \frac{1}{G} \sqrt{\frac{4kT \Delta F}{R_L}} \\
I_s &= \text{signal when present} = \text{Variable} \\
\Delta F &= \text{electrical bandwidth} = \frac{1}{2 \Delta t} \\
e &= \text{electron charge} = 1.6 \times 10^{-19} \text{coulombs}
\]

Normally for any given application one of the noise components dominates over the rest. For example, when the sky background \( n_3 \) is a sunlit cloud then its associated noise will usually be significantly larger than the other noise contributors. Table 3-1 defines all the symbols used here.
BASIC COMPONENTS OF RADAR NOISE EQUATION

FIGURE 3-5
After the average number of electrons per sample period \( \frac{n_e}{\Delta t} \) due to noise has been determined then the minimum number of "signal" electrons per pulse \( \frac{n_e}{\Delta t} \) can be chosen by evaluating the probability of signal and noise detection versus various detector threshold levels. For this application a high probability of signal detection (> 0.99) is desired in order to insure that the target will be recognized when it appears in the scan element. False alarms may occur during the raster scan as long as they do not significantly increase the total raster scan time. The amount of increased raster scan time due to noise exceeding the threshold will be

\[
t_L = \frac{P_n}{\Delta t} \frac{t_G}{N_A} t_d
\]

where
- \( P_n \) = probability of noise exceeding the threshold during \( \Delta t \)
- \( t_G \) = time period when receiver is gated open to look for the signal during each scan element
- \( \Delta t \) = laser pulse width
- \( N_A \) = total number of scan elements per raster scan
- \( t_d \) = dwell time per scan element

A special graph of the probability of signal and noise detection versus threshold level is shown in Figure 3-6 for use in this application. A poisson distribution is used because of the low number of electrons/\( \Delta t \).

The graph in Figure 3-6 can be used to quickly determine the minimum number of signal electrons/\( \Delta t \) that are needed for a particular problem. First the average number of electrons/\( \Delta t \) due to noise is calculated. Then after choosing how much search time can afford to be lost due to unnecessarily stopping on a scan element each time the noise level exceeds the threshold, equation 3-9 can be used to calculate the probability of noise detection \( (P_n) \). Now, by using the lower half of the graph in Figure 3-6, the proper threshold level needed to minimize noise detection can be obtained. For example, if the average noise was approximately 1.0 electron/\( \Delta t \) and a 1 x 10^{-7} or less probability of noise detection was desired then the threshold would be set at 10 electrons/\( \Delta t \) or higher. Going to the upper half of the
GRAPH OF THRESHOLD LEVEL VS PROBABILITY OF DETECTION

FIGURE 3-6
graph one sees that for a threshold level of 10 electrons/Δt approximately 20 signal electrons/Δt are needed to get a 0.99 probability of signal detection. It is interesting to note that as the average noise level is reduced significantly below 1.0 electron/Δt the required number of signal electrons/Δt can only be reduced by a small amount for the same probability of signal and noise detection.

The average input power required (\( P_{\text{in}} \)) as a function of target range (R) will be examined here for a specific case. The values for the parameters in the respective signal and noise equation used for this specific example are listed in Table 3-2.
**TABLE 3-2**

Values Used for Power vs. Target Range Example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_T$ (total FOV)</td>
<td>$30^0$</td>
</tr>
<tr>
<td>$J_{BS}$ (backscatter)</td>
<td>0</td>
</tr>
<tr>
<td>$\theta_{iFOV}$ (instan. FOV)</td>
<td>$0.1^0$</td>
</tr>
<tr>
<td>$S_{\lambda}$ (rec. sensitivity)</td>
<td>$2 \times 10^{-3}$ a/w at $\lambda = 0.9 \mu m$ (S-1 photocathode)</td>
</tr>
<tr>
<td></td>
<td>$6 \times 10^{-4}$ a/w at $\lambda = 1.06 \mu m$ (S-1 photocathode)</td>
</tr>
<tr>
<td>$\tau_{8}$ (rec. optical trans.)</td>
<td>0.5</td>
</tr>
<tr>
<td>$H_{S \lambda}$ (solar irrad.)</td>
<td>$0.09 \text{ w/m}^2 \text{ A at } \lambda = 0.9 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$0.07 \text{ w/m}^2 \text{ A at } \lambda = 1.06 \mu m$</td>
</tr>
<tr>
<td>$\Delta \lambda$ (Opt. bandwidth)</td>
<td>0.02 $\mu m$</td>
</tr>
<tr>
<td>$A_T$ (target area)</td>
<td>$10 \text{ m}^2$</td>
</tr>
<tr>
<td>$\tau_{S}$ (target reflect.)</td>
<td>0.8</td>
</tr>
<tr>
<td>$d_R$ (receiver dia.)</td>
<td>5 cm</td>
</tr>
<tr>
<td>$\Omega_{\pi}$ (target solid angle)</td>
<td>$\pi$</td>
</tr>
<tr>
<td>$N_b$ (sunlit cloud rad.)</td>
<td>$1 \times 10^2 \text{ w/cm}^2 \text{ ster} \cdot \mu m$ at $\lambda = 0.9 \mu m$</td>
</tr>
<tr>
<td></td>
<td>$0.78 \times 10^2 \text{ w/cm}^2 \text{ ster} \cdot \mu m$ at $\lambda = 1.06 \mu m$</td>
</tr>
<tr>
<td>$I_{dc}/A$ (det. dark current)</td>
<td>$1 \times 10^{-12}$ a/cm$^2$</td>
</tr>
<tr>
<td>$A_{i}$ (instant. aperture)</td>
<td>0.0035 inches</td>
</tr>
<tr>
<td>$G$ (detector gain)</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>$k$ (Baltzmann's const.)</td>
<td>$1.38 \times 10^{-23}$ j/$^0K$</td>
</tr>
<tr>
<td>$T$ (temp.)</td>
<td>290$^0$ K</td>
</tr>
<tr>
<td>$\Delta F$ (elec. bandwidth)</td>
<td>$2.5 \times 10^6$ Hz</td>
</tr>
<tr>
<td>$C_L$ (capacities at load res.)</td>
<td>25 pf</td>
</tr>
</tbody>
</table>
TABLE 3-2

Values Used for Power vs. Target Range Example

Continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_L ) (load resistance)</td>
<td>2,540 ohms</td>
</tr>
<tr>
<td>( \alpha ) (atmos. atten. coef.</td>
<td>0</td>
</tr>
<tr>
<td>( d_{cc} ) (corner cube dia.)</td>
<td>10 cm</td>
</tr>
<tr>
<td>( N_{cc} ) (Number of corner cubes)</td>
<td>3</td>
</tr>
<tr>
<td>( \theta_{tb} ) (trans. bandwidth)</td>
<td>0.1°</td>
</tr>
<tr>
<td>( K_{cc} ) (constant)</td>
<td>2.44 full angle</td>
</tr>
<tr>
<td>( \lambda ) (GaAs wavelength)</td>
<td>0.9 ( \mu )m</td>
</tr>
<tr>
<td>( \lambda ) (YAG wavelength)</td>
<td>1.06 ( \mu )m</td>
</tr>
<tr>
<td>( \Delta t ) (laser pulse width)</td>
<td>200 nanoseconds</td>
</tr>
<tr>
<td>( t_d ) (period between pulses)</td>
<td>1 ms (80 miles max.)</td>
</tr>
<tr>
<td>( e ) (electron charge)</td>
<td>( 1.6 \times 10^{-19} ) coulombs</td>
</tr>
<tr>
<td>( t_L ) (max. scan time lost due to false alarms)</td>
<td>10 seconds</td>
</tr>
<tr>
<td>( t_G ) (receiver gate)</td>
<td>1 millisecond</td>
</tr>
<tr>
<td>( N_A ) total # elements in raster</td>
<td>( (375)^2 = 140,625 )</td>
</tr>
<tr>
<td>( \tau_1 ) (trans. elec-to-optical efficiency)</td>
<td>0.01 (1% for both GaAs and YAG)</td>
</tr>
<tr>
<td>( \tau_2 ) (trans. optical transmittance)</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Using the values in Table 3-2, the various noise contributors are calculated to be:

- \( n_1 \) (backscatter) = \( J_{BS}^2 i \text{FOV} \lambda \tau_S \)
  = 0

- \( n_2 \) (sunlit target background) = \( H_\lambda S A_\lambda A_T \tau_R \tau_S \lambda S \)
  = \( \pi/4 \) (5 cm²)

\[ \text{for } \lambda = 0.9 \mu m \]
\[ \text{GaAs} \]
\[ = 2.6 \times 10^{-13} \text{amps} \ (0.033 \text{ electrons/} \Delta t) \text{ for } R = 10 \text{ miles} \]
\[ = 2.6 \times 10^{-15} \text{amps} \ (0.00033 \text{ electrons/} \Delta t) \text{ for } R = 100 \text{ miles} \]

\[ \text{for } \lambda = 1.06 \mu m \]
\[ \text{YAG} \]
\[ = 0.07 \frac{w}{m^2 A} \]
\[ = 0.007 \times 10^{-13} \text{amps} \ (0.0077 \text{ electrons/} \Delta t) \text{ for } R = 10 \text{ miles} \]
\[ = 0.007 \times 10^{-15} \text{amps} \ (7.7 \times 10^{-5} \text{ electrons/} \Delta t) \text{ for } R = 100 \text{ miles} \]

- \( n_3 \) (sunlit cloud background) = \( N_A R^2 i \text{FOV} \lambda \Delta \tau_S \)

\[ \text{for } \lambda = 0.9 \mu m \]
\[ = (100 \frac{w}{cm^2 \text{ ster} \cdot \mu m}) \left[ \frac{1}{4} \pi (5 \text{ cm})^2 \right] \left[ 1.75 \times 10^{-3} \text{ rad} \right]^2 \left( 2 \times 10^{-3} \frac{a}{w} \right) (0.02 \mu m) \]
\[ = 1.2 \times 10^{-11} \text{amps} \ (14.9 \text{ electrons/} \Delta t) \]

\[ \text{for } \lambda = 1.06 \mu m \]
\[ = (0.78 \times 10^{-2} \frac{w}{cm^2 \text{ ster} \cdot \mu m}) \left[ \frac{1}{4} \pi (5 \text{ cm})^2 \right] \left[ 1.75 \times 10^{-3} \text{ rad} \right]^2 \left( 2 \times 10^{-3} \frac{a}{w} \right) (0.02 \mu m) \]
\[ = 0.25 \times 10^{-11} \text{amps} \ (3.4 \text{ electrons/} \Delta t) \]
- $n_4$ (detector dark current) = \[ \frac{I_{dc}}{A} A_1 \]
  \[ = \left( 1 \times 10^{-11} \frac{a}{cm^2} \right) \left[ (0.0035 \text{ in})^2 \times 6.25 \frac{cm^2}{in^2} \right] \]
  \[ = 0.77 \times 10^{-15} \text{ amps (9.6} \times 10^{-4} \text{ electrons/\Delta t) } \]

- $n_5$ (detector Ampl. noise factor) = 1.25

- $n_6$ (thermal or Johnson noise) = \[ \frac{1}{G} \sqrt{\frac{4kT \Delta F}{R_L}} \]
  \[ \Delta F = \frac{1}{2 \Delta t} \]
  \[ R_L = \frac{1}{2 \pi \Delta F C_L} \]
  \[ = \frac{1}{10^5} \sqrt{\frac{4 \left( 1.38 \times 10^{-23} \frac{j}{K} \right) (290^0 K) (2.5 \times 10^8 \text{ Hz})}{2.540 \text{ ohms}}} \]
  \[ = 1.2 \times 10^{-14} \text{ amps (0.016 electrons/\Delta t) } \]
If we allow 10 seconds or less to be lost in the acquisition scan due to stopping to look for false alarms, then the probability of "noise" detection will be

\[
P_n = \frac{t_L \Delta t}{t_G N_A \tau_d} = \frac{(10 \text{ sec}) (200 \times 10^{-9} \text{ sec})}{(0.001 \text{ sec}) (140,625) (0.001 \text{ sec})} = 1.4 \times 10^{-8}
\]

The only significant noise contributor for this problem is the sunlit cloud background noise of 14.9 electrons/\(\Delta t\) (at \(\lambda = 0.9 \mu \text{m}\)) and 3.4 electrons/\(\Delta t\) (at \(\lambda = 1.06 \mu \text{m}\)).

Using the lower half of the graph in Figure 3-6, we now choose the corresponding threshold levels that will give us a \(1.4 \times 10^{-8}\) or lower probability of noise detection. For an average noise of 14.9 electrons/\(\Delta t\) (\(\lambda = 0.9 \mu \text{m}\)) the threshold must be set at 40 electrons/\(\Delta t\) or higher, and for an average noise of 3.4 electrons/\(\Delta t\) (\(\lambda = 1.06 \mu \text{m}\)) the threshold must be set at 17 electrons/\(\Delta t\) or higher. Using the upper half of the graph in Figure 3-6 we can now determine the minimum detectable signal in electrons/\(\Delta t\) for a desired probability of "signal" detection. For target acquisition we want a very high probability of signal detection (\(> 0.99\)) for each scan element because we will have to search 140,625 elements, and if we miss the signal when it is present then we may not get another chance to see it until we have recycled through the 140,625 element raster scan. For a probability of signal detection of 0.99 or greater, and a threshold level of 40 electrons/\(\Delta t\) (\(\lambda = 0.9 \mu \text{m}\)) the minimum detectable signal is approximately 57 electrons/\(\Delta t\). For a threshold level of 17 electrons/\(\Delta t\) (\(\lambda = 1.06 \mu \text{m}\)) the minimum detectable signal is approximately 28 electron/\(\Delta t\).
Summarizing these results we have the following:

<table>
<thead>
<tr>
<th></th>
<th>GaAs</th>
<th>YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Noise</strong></td>
<td>((\lambda = 0.9 \mu \text{m}))</td>
<td>((\lambda = 1.06 \mu \text{m}))</td>
</tr>
<tr>
<td>(Sunlit cloud background)</td>
<td>14.9 electrons/(\Delta t)</td>
<td>3.4 electrons/(\Delta t)</td>
</tr>
<tr>
<td><strong>Probability of Noise</strong></td>
<td>1.4 (\times 10^{-8})</td>
<td>1.4 (\times 10^{-8})</td>
</tr>
<tr>
<td>**Detection (P}_n)</td>
<td>40 electrons/(\Delta t)</td>
<td>17 electrons/(\Delta t)</td>
</tr>
<tr>
<td><strong>Threshold Level</strong></td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>Probability of Signal</strong></td>
<td>57 electrons/(\Delta t)</td>
<td>28 electrons/(\Delta t)</td>
</tr>
<tr>
<td>**Detection (P}_S)</td>
<td>((I_{\text{MDS}} = 4.56 \times 10^{-11} \text{a}))</td>
<td>((I_{\text{MDS}} = 2.24 \times 10^{-11} \text{a}))</td>
</tr>
</tbody>
</table>
After the minimum detectable signal ($I_{\text{MDS}}$) has been determined the average input power required ($P_{\text{in}}$) by the laser radar transmitter can be calculated. Using equation 3-5 and the assigned values in Table 3-2, we get:

$$P_{\text{in}} = \frac{1}{\tau_1 \tau_2 \tau_5 \tau_8} \frac{1}{e^{-2 \alpha R}} \frac{1}{\Delta t} \frac{I_{\text{MDS}}}{\gamma} \frac{16 K_2}{\pi^2} \frac{2 \lambda^2}{\theta b} \frac{R^4}{d^2} \frac{t \lambda}{d \lambda}$$

$$= \frac{1}{(.01) (.7) (.8) (.5)} \frac{1}{(1)} \left[ \frac{16 (2.44)^2 (0.9 \times 10^{-6} \text{ m}) (1.75 \times 10^{-3} \text{ rad})^2 R^4}{\pi^2 (5 \times 10^{-2} \text{ m})^2 (3) (1 \times 10 \text{ m})^4} \right] \frac{200 \times 10^{-9} \text{ sec} / \mu \text{sec}}{4.6 \times 10^{-11} \text{ a} / \text{sec}}$$

$$= \frac{1}{2.8 \times 10^{-3}} \left( \frac{0.32 \times 10^{-10} \text{ R}^4}{(2 \times 10^{-4}) (2.3 \times 10^{-8})} \right)$$

$$= 0.53 \times 10^{-19} \text{ R}^4 \quad \text{for GaAs, } \lambda = 0.9 \text{ \mu m}$$

$$\frac{P_{\text{in}} \text{ (GaAs, } \lambda = 0.9 \text{ \mu m)}}{P_{\text{in}} \text{ (YAG, } \lambda = 1.06 \text{ \mu m)}} = \left[ \frac{\lambda \text{ (GaAs)}}{\lambda \text{ (YAG)}} \right] \frac{2}{1} \left[ \frac{I_{\text{MDS}} \text{ (GaAs)}}{I_{\text{MDS}} \text{ (YAG)}} \right] \left[ \frac{\tau_1 \tau_2 \tau_5 \tau_8 S_\lambda \text{ (YAG)}}{\tau_1 \tau_2 \tau_5 \tau_8 S_\lambda \text{ (GaAs)}} \right]$$

$$= (.75) (2.04) (.3)$$

$$= 0.46$$

then

$$P_{\text{in}} = 1.17 \times 10^{-19} \text{ R}^4 \quad \text{for YAG, } \lambda = 1.06 \text{ \mu m}$$
The average input power required \((P_{\text{in}})\) is plotted versus target range \((R)\) in Figure 3-7 for both the single mode GaAs laser and the Mini-YAG laser transmitters. The single mode GaAs laser is operated at room temperature without cooling and is average powered limited in the milliwatt range. Assuming an average output limitation of 5 milliwatts \((\text{TEM}_0^0\text{ mode})\) and 1% electrical-to-optical efficiency, then for the radiometric problem described here, the maximum target range that the Scanning Laser Radar could achieve with the single mode GaAs laser is approximately 30 miles. The average input power required \((P_{\text{in}})\) for the laser transmitter would be 0.5 watts. The single mode GaAs laser is described in Section 4.1.

YAG lasers have exceeded 1,000 watts of average output power, but for this application only a "MINI" YAG is considered, "MINI" referring to the relative size, weight, and power characteristics when compared to the higher powered YAG lasers. The intent of this study was to design a Scanning Laser Radar that would be relatively small, lightweight and low powered, therefore, higher powered YAG lasers were not considered. A maximum of 100 watts average input power for the laser transmitter was chosen arbitrarily. However, it should be mentioned that as the power levels increase appreciably above this value the thermal problems quickly increase to the point where a cooling subsystem becomes a major design task. For 100 watts average input power \((P_{\text{in}})\) and 1% electrical-to-optical efficiency (1 watt average output power), then the maximum target range achievable using the "MINI" YAG is approximately 90 nautical miles. The MINI YAG is described in Section 4.1.
Figure 3-7

AVERAGE INPUT POWER REQUIRED ($P_{IN}$) VS TARGET RANGE ($d$)

TARGET RANGE (MILES)

AVERAGE INPUT POWER REQUIRED (WATTS)

- Single Mode
- Gas Laser
- Mini-VAG
- Small Cloud Backround
- Predominant Noise
3.3 Determining Target Attitude with Passive Reflectors

The third system configuration of the Scanning Laser Radar (SLR-3) described in Section 2.0 must have the capability of measuring the relative target attitude \((\alpha_x, \alpha_y)\) and the relative roll angle \((\phi)\) without the use of active equipment on the target vehicle. This capability can be obtained by placing more than one corner cube reflector on the target vehicle. Measuring the angles and ranges to the individual reflectors enables one to calculate the \(\alpha\) and \(\phi\) angles. The methods and their associated accuracies for various reflector configurations and measurement strategies are discussed in this section.

Description of Passive Target Configurations Investigated

Five different patterns of retroflector locations on the target vehicle and their corresponding measurement strategies are identified in this report. A sixth configuration utilizing a modified semi-active retroflector is also identified. A pictorial representation of the six configurations is shown in Figure 3-8. Circles represent the retroreflectors and the target vehicle is represented by a cube.

In Configuration I, line-of-sight angle \(\alpha\) is determined by SLR range and angular measurements of two retroreflectors placed a distance, \(D\), apart on a line parallel to the docking axis, shown perpendicular to a shaded reference surface on the target vehicle in Figure 3-8. The front retroflector need not necessarily be forward on the front of the vehicle, in the manner shown, the rear retroflector could be recessed within the vehicle, if desired. Roll angle \(\phi\) is measured by reference to a third retroflector placed in a plane parallel to the reference plane and containing one of the first two retroreflectors. With this configuration, when the SLR approaches the line containing the primary retroreflectors, angle \(\alpha\) approaches zero as a limit, and the two retroreflectors will
<table>
<thead>
<tr>
<th>PICTORIAL CONFIGURATION</th>
<th>MEASUREMENT STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Range and angle measurements to two retroreflectors: angle only to third retroreflector.</td>
</tr>
<tr>
<td>II</td>
<td>Range and angle measurements to all three retroreflectors.</td>
</tr>
<tr>
<td>III</td>
<td>Same as Configuration I, except that two lasers are required at two different wavelengths with corresponding narrow-bandpass filters over the retroreflectors. One wavelength over front retroreflector, the other wavelength over the two rear retroreflectors.</td>
</tr>
</tbody>
</table>
| IV                      | A. Range and angle measurements to all three retroreflectors.  
B. Range measurements, only, to all three retroreflectors.  

Angle measurements, only, to all four retroreflectors. |
| V                       | One retroreflector is semi-active, and modulates reflected beam. Range measurements to only one retroreflector; angle measurements to both. |
| VI                      | |

Pictorial Representation of Six Passive Target Configurations

FIGURE 3-8

3-26
appear in the same instantaneous field-of-view (IFOV) of the SLR receiver. Under this condition, the two retroflectors may be sensed separately for angular measurements, on the basis of range, as discussed in more detail in a later paragraph.

Configuration II is similar in concept to Configuration I, except that the forward and rearward retroflectors are on a line which is at an angle greater than 15 degrees (e.g., 20 degrees) from parallel to the docking axis. This angle must, of course, be accounted for in the subsequent calculations. Angle $\alpha$ is to be measured only up to 15 degrees, and this configuration ensures that, except under the most adverse conditions, which can occur only at relatively long ranges, the two retroflectors will not be within the same IFOV of the SLR receiver, and range and angular measurements can be made directly, without the complication of separating them on the basis of range, as required in Configuration I.

In Configuration II, three retroflectors are used, so mounted that the three lie within two mutually perpendicular planes whose line of intersection is parallel to the docking axis and contains one of the retroflectors. This allows the two components of $\alpha$ to be determined separately.

Configuration III is conceptually similar to Configuration I, and the deployment of retroflectors on the target vehicle is identical to that of Configuration I. The difference is in the method of separating the two retroflectors, for measurement purposes, when they appear together within the same IFOV. In this case, two transmitting lasers, transmitting at two different wavelengths, are placed one over each of the two retroflectors so that each retroflector responds only to one of the two transmitting lasers. A "two-notch" filter is placed over the receiver, passing both laser wavelengths. Of course, only one laser will be operated at a given time to measure the range and angle to its respective retroflector.
Configuration IV utilizes a different concept. Three retroreflectors are placed in a plane parallel to the reference plane (perpendicular to the docking axis) and range and angle measurements are made by the SLR to each of the retroreflectors. Angle $\alpha$ is calculated from these data, as discussed in a subsequent paragraph.

Configuration V is similar to Configuration IV, except that 4 retroreflectors are required and only angular measurements need be made. This configuration is of academic interest only, since the SLR produces range measurements directly, and calculation of range and range-rate (in addition to angle $\alpha$), by the more complicated and less accurate method made available by this configuration, is unnecessary.

Configuration VI is a totally different concept. It utilizes two retroreflectors, mounted in a plane parallel to the reference plane (perpendicular to the docking axis), with which angle $\phi$ is measured as in the previous concepts. However, one of the retroreflectors is semi-active, containing a small continuously-rotating element powered by a self-contained battery. This element is at the focal plane of an optical system, and modulates the incoming energy from the SLR as a function of the position of the SLR in the retroreflector's own field-of-view. The SLR receiver detects the modulated retroreflected energy and decodes the angle $\alpha$ measurement data. The modulation itself appears as a pulse envelope on the retroreflected beam, the duty-cycle of which is proportional to the angle $\alpha$, 100% duty-cycle representing the edge of the field, and zero duty-cycle representing the on-axis position, as discussed in greater detail in a subsequent paragraph.

**Error Analysis**

We will now derive the equations which express a relative target attitude error, $\Delta \alpha$, as a function of the radar errors, $\Delta \theta$ and $\Delta R$. Later paragraphs will
apply these equations quantitatively to a specific radar system. Some of the problems of implementation are discussed and graphs are included, showing accuracies attainable with the various hardware configurations and for various SLR measurement accuracies. For illustrative purposes, in all quantitative calculations, the distance between adjacent retroflectors is arbitrarily taken as 1.5 meters (≈5 feet). Other distances could be used on the actual hardware, depending upon trade-offs to be made during the final design stage. In the present design of the SLR, the instantaneous field-of-view of the receiver is 0.1 degree. Obviously, at long ranges, and in certain other cases, such as in Configuration I with the SLR nearly on the target vehicle's docking axis, two of the retroflectors can appear simultaneously within the SLR receiver's IFOV. In order to make angular measurements, it is necessary to sense the retroflectors separately. In the case of Configuration I, one retroflector will always be approximately 5 feet farther from the SLR than the other. It is possible then, to make the separation on the basis of range, since the returned pulses from the two retroflectors will arrive at the SLR receiver about 10 nanoseconds apart, the farther one always returning later. Also, since the two are both within the IFOV, their energies will add, and the receiver's output will have a total amplitude double that from a single retroflector. The returning pulses are sketched in Figure 3-9. The automatic gain control in the SLR receiver assures that the returning pulses have the proper amplitude for threshold detection. Logic circuits shunt the returning pulses to their respective circuitry for angle and range measurements. Of course, when the two retroflectors are not within the same IFOV, only the lower threshold is utilized for both return pulses.
Return Pulse From Nearer Retroflector

Return Pulse From Farther Retroflector

Combined Return Pulses When Both Retroreflectors in Same I.F.O.V.

NOTE: Pulses are shown at an arbitrary length in this figure.

FIGURE 3-9

Pulse Separation Based on Range
Configuration I, II and III

Referring to Figures 3-10(a) and (b), it will be assumed that the radar has acquired the target and brought C1 to its optical axis. Identification of C1 could be made for instance, on the basis of range measurements. By the law of sines,

\[
\sin \alpha = \frac{R_2 \sin \theta}{D} \quad \text{or} \quad \alpha = \sin^{-1} \left( \frac{R_2 \sin \theta}{D} \right).
\]

Differentiating partially

\[
\Delta \alpha_\theta = \frac{R_2 \cos \theta \Delta \theta}{D \left[ 1 - \left( \frac{R_2 \sin \theta}{D} \right)^2 \right]^{1/2}}
\]

\[
\Delta \alpha_{R_2} = \frac{\sin \theta \Delta R_2}{D \left[ 1 - \left( \frac{R_2 \sin \theta}{D} \right)^2 \right]^{1/2}}
\]

By definition, total

\[
\Delta \alpha = \left[ \left( \Delta \alpha_\theta \right)^2 + \left( \Delta \alpha_{R_2} \right)^2 \right]^{1/2}
\]

(3-10)
**FIGURE 3-10 (a)**

Configuration I, II and III Geometry

**FIGURE 3-10 (b)**

Configuration I, II and III Geometry
The application of the target attitude error equation $\Delta \alpha$ is identical for both Configurations I and III, and also applies to Configuration II, when the offset angle between the line joining the principal retroreflector with either secondary retroreflector and the target vehicle docking axis is properly taken into account.

Figures 3-11 and 3-12 show graphically the relationships between the target docking angle, $\alpha$, and its calculated accuracy, $\Delta \alpha$, as functions of range and measured angle, $\theta$, for retroreflector separation (arbitrarily chosen) of 5 feet, for range-measurement accuracy, $\Delta R = 0.1 \text{ ft (1 \sigma)}$, and for various angular-measurement accuracies, $\Delta \theta$, from 0.005 to 0.05 degrees. As expected, $\Delta \alpha$ improves with $\Delta R$ and $\Delta \theta$, and is better for short ranges than at long ranges. The upper graph of Figure 3-12 indicates that $\Delta \alpha$ is within the required $\pm 1.0$ degree for all ranges up to 1,000 feet, when $\Delta R = 0.1 \text{ ft}$ and $\Delta \theta = 0.005$ degrees. These accuracies are attainable with the SLR in the tracking mode and when the number of deflection steps per scanning aperture diameter is 32. The IFOV is 0.1 degree.
CONFIGURATIONS I, II & III

ΔR = 0.1 in

D = 5 ft.

RANGE, R in Feet

TARGET DOCKING ANGLE, θ, in Degrees

For Constant Measured Angle, θ:

Shaded Area: Show Probable Error, Δθ

FOR θ = 0.005°
Δθ = 0.0005°

FOR θ = 0.02°
Δθ = 0.02°

α vs. R (for θ = 0.005° and 0.02°)

FIGURE 3-11
Configuration I, II & III
$\Delta R = 0.1 \text{ ft}; D = 5 \text{ ft}$

Shaded areas show probable error, $\Delta \alpha$.

For constant measured angle, $\alpha$.

$\alpha$ vs. $R$ (for $\theta = 0.2^\circ$ and $0.05^\circ$)

FIGURE 3-12
Figures 3-13 and 3-14 show how $\alpha$ and $\Delta \alpha$ vary with measured angle $\theta$, at a range of 200 feet and 10 feet, respectively.

Figure 3-15 is a useful family of curves, relating the target docking angle, $\alpha$, with the SLR-measured angle, $\theta$, for ranges between 10 and 1,000 feet.

Figures 3-16 and 3-17 show the corresponding calculated accuracies for the docking angle, $\Delta \alpha$, for the cases where $\Delta \theta = 0.02$ degree and $\Delta \theta = 0.005$ degree, respectively. The values shown in Figure 3-17 are within the desired accuracy for all ranges up to 1,000 feet.
CONFIGURATION I AND II

\[ \Delta R = 1.0^\circ, \Delta R = 0.7 \text{ ft}, D = 5 \text{ ft} \]

MEASURED ANGLE \( \theta \) IN DEGREES

\( \alpha \) AND \( \Delta \alpha \) VS \( R \) (FOR \( R = 10 \) FEET)

FIGURE 3-14
CONFIGURATION I, II, AND III
D = 5 ft.; Δφ AND ΔR UNSTATED

TARGET DOCKING ANGLE, α IN ARC MINUTES (AND DEGREES)
α VS θ (FOR CONSTANT RANGES)

FIGURE 3-15
Configuration I, II, and III
$\Delta \theta = 0.02^\circ; \Delta R = 0.1 \text{ ft.}; D = 5 \text{ ft.}$

TARGET RANGE IN FEET

TARGET ANGLE PROBABLE ERROR, $\Delta \alpha$ IN ARC MINUTES (AND DEGREES)

$\Delta \alpha$ VS $\theta$ (FOR CONSTANT RANGES)

FIGURE 3-16
Configuration I, II, and III
$\Delta \theta = 0.005^\circ; \Delta R = 0.1 \text{ ft.}; D = 5 \text{ ft.}$
Configuration IV

A. Range and Angle Measurements to all Three Retroreflectors (IV-A)

Equations will be derived now for the case where the SLR vehicle is in the plane containing two of the retroreflectors and the target vehicle's docking axis, as shown in Figure 3-18. If the three retroreflectors are arranged in two mutually perpendicular lines, as shown in the Configuration IV sketch, the geometry will approach this condition as the docking procedure progresses, thus validating the equations, as derived.

It can readily be shown from the law of sines that

\[
\sin \alpha = \frac{R_2 \cos \theta - R}{D},
\]

and

\[
R_2 = \frac{D \cos \alpha}{\sin \theta}.
\]

Therefore, \( \sin \alpha - \cos \alpha \cot \theta = -\frac{R}{D} \)

Differentiating partially,

\[
\Delta \alpha_\theta = -\frac{\cos \alpha \Delta \theta}{\sin^2 \theta (\cos \alpha + \cot \theta \sin \alpha)}
\]

and

\[
\Delta \alpha_{R_1} = -\frac{\Delta R_1}{D (\cos \alpha + \sin \alpha \cot \theta)}
\]

By definition, as before,

\[
\Delta \alpha (IV-A) = \left( \left( \Delta \alpha_\theta \right)^2 + \left( \Delta \alpha_{R_1} \right)^2 \right)^{1/2}.
\]

(3-11)
CONFIGURATION IV GEOMETRY

FIGURE 3-18
Also, the above equation can be solved for \( \alpha \), directly;

\[
\sin \alpha = \sin^2 \theta \left[ -\frac{R_1}{D} \pm \left( \frac{R_1^2}{D^2} - \frac{R_1}{D^2} \cot^2 \theta \right)^{1/2} \right] \tag{3-12}
\]

It should be noted that there are two possible values for \( \alpha \), if only \( R \) and \( \theta \) are measured by the SLR. This ambiguity is removed if both \( R_1 \) and \( R_2 \) are measured, as they would always be in the actual implementation of this configuration.

B. Range Measurements, Only, to all three Retroreflectors (IV-B)

Again referring to Figure 3-18, and noting that

\[
| R_1 - R_2 | \leq | D |
\]

assume that the three retroreflectors on the target vehicle are arranged in a rigid isosceles triangle. Consider two retroreflectors on one of the equal orthogonal legs. Calculate \( \alpha \) for this. Repeat the process on the other leg. Then calculate the total docking angle. Let \( R_1 \) be the range to the retroreflector on the orthogonal corner, then

(See next page)
Angle \( R_1 D = 90^\circ + \alpha = \cos^{-1} \frac{D^2 + R_1^2 - R_2^2}{2 DR_1} \)

\[ \alpha = \cos^{-1} \frac{D^2 + R_1^2 - R_2^2}{2 DR_1} - 90^\circ \]

Differentiating partially,

\[ \Delta \alpha_{R_1} = \frac{\left( D^2 - R_1^2 - R_2^2 \right) \Delta R_1}{2 DR_1^2 \left[ 1 - \left( \frac{D^2 + R_1^2 - R_2^2}{2 DR_1} \right)^2 \right]^{1/2}} \]

\[ \Delta \alpha_{R_2} = \frac{R_2 \Delta R_2}{DR_1 \left[ 1 - \left( \frac{D^2 + R_1^2 - R_2^2}{2 DR_1} \right)^2 \right]^{1/2}} \]

and total

\[ \Delta \alpha_{(IV-B)} = \left[ \left( \Delta \alpha_{R_1} \right)^2 + \left( \Delta \alpha_{R_2} \right)^2 \right]^{1/2} \]

(3-13)
Figure 3-19 shows the results obtained when all three retroreflectors are in a plane perpendicular to the target vehicle's docking axis, and both range and angle measurements are made to all three retroreflectors. The results are shown in two families of curves in Figure 3-19, both plotted on a logarithmic base of $R_1/D$ vs. $\alpha$. The calculation arbitrarily assumed $D = 5$ feet, so that the range in Figure 3-19 will be 5 times the $R_1/D$ value shown.

One family of curves is calculated for various values of the measured angle, $\theta$, and the other family shows contours of equal errors, $\Delta \alpha$, in the calculated angle, $\alpha$. Those curves are based on the values, $\Delta \theta = 0.02$ degree, and $\Delta R = 0.1$ feet. Comparison of Figure 3-19 with Figure 3-16, which was also calculated for $\Delta \theta = 0.02$ degree and $\Delta R = 0.1$ feet, shows that an accuracy of $\Delta \alpha = 4$ degrees can be reached with Configuration I (Figure 3-16) at a range $R = 1,000$ feet, while Configuration IV-A reaches this accuracy at only about 25 feet range. As noted above, Configuration I can reach an accuracy of $\Delta \alpha = 1$ degree at range of 1,000 feet, when the radar system permits the measured angle, $\theta$, to be measured with an accuracy of $\Delta \theta = 0.005$ degree.

The conclusion is inescapable that Configurations I, II and III are superior in accuracy to Configuration IV-A.

Figure 3-20 shows the results obtained when the retroreflectors are deployed, as in Configuration IV, but calculations are based on range measurements only, ignoring all angle measurements. This is Configuration IV-B, the equations for which have been derived. In this case, the best accuracy, $\Delta \alpha$, is obtained at certain angles which depend upon the range, but this best accuracy is, itself, nearly independent of range. At long ranges, the best accuracy is attained when the SLR vehicle is nearly aligned with the target vehicle's docking axis. At shorter ranges, the location of best accuracy becomes progressively farther from the docking axis. Figure 3-20 was calculated for $D = 5$ feet, and $\Delta R = 0.1$ feet. The accuracy of angular measurement, $\Delta \theta$, of course, does not enter into this calculation for Configuration IV-B.
CONFIGURATION IV-A FOR $\Delta \theta = 0.02^\circ$, $\Delta R = 0.1$ ft., $D = 5$ ft.

TARGET DOCKING ANGLE, $\alpha$ IN DEGREES

$R_1/D$, $\alpha$, $\Delta \alpha$, AND $\theta$ RELATIONSHIPS

FIGURE 3-19
3-47
Configuration V

It has been shown by Messrs. Len Johnson and Earle Blanchard of the MIT Draper Laboratories (Boston) that the range and line-of-sight angle, $\alpha$, at the target vehicle can be unambiguously determined by angular measurements alone, if four retroflectors are used. Use of less than four retroflectors, without range measurements, lead to ambiguous determinations. Since the SLR implementation always measures both range and angle to all retroflectors, this method becomes academic, and thus the equations for this configuration will not be derived in this discussion. It is intuitively obvious that the resulting accuracies would be close to those resulting from use of Configuration IV.

Configuration VI

A retroflector can be readily produced, using a specially-designed refractive lens system. In a lens made for zero astigmatism, the focal surface (known as a "Petzval" surface) is a paraboloid of revolution, concave toward the lens. Modifications of this design can correct for coma and spherical aberrations and, at the same time, produce a focal surface of sufficient resolution which is spherical, centered on the second nodal point of the lens. If this spherical surface is a specular reflector, the assembly is an efficient retroflector, and its field-of-view can easily be as large as $\pm 15$ degrees, fulfilling the requirement for the target vehicle retroflector. Figure 3-21 schematically illustrates this concept.

With this retroflector, a "point" image of the SLR laser transmitter will be formed on the spherical focal surface, at a location corresponding to angle $\alpha$, the line-of-sight angle of the active vehicle as seen from the target vehicle. This information can be made available to SLR receiver in the following manner: Since energy from the SLR's laser transmitter will be returned to SLR.
SPHERICAL MIRROR
FOCAL SURFACE

REFRACTIVE-LENS RETROREFLECTOR

FIGURE 3-21
receiver by the retroflector, this forms a carrier which can be modulated with the desired information. For instance, if an opaque radial line were placed at one location on the spherical focal surface, and if the spherical focal surface were then rotated about the optical axis, the retroflected beam would be interrupted once per revolution, and the duration of the interruption would be a function of the line width, the rotational rate, the size of the laser image on the focal surface, and most importantly, the angular distance of the SLR from the optical axis.

The information content of the resulting modulation can be greatly improved by substituting other types of reticles for the simple line on the spherical focal surface. Figure 3-22 illustrates one useful version. It consists of a single-turn archimedes spiral pattern, inside of which the focal surface is made 50% reflective and outside of which it is made fully reflective, as shown in the Figure. The result is a modulated envelope on the retroflected pulsed laser beam, the beam alternating between 50% and full strength. The duty cycle of this alternation is a direct function of the angular offset of the SLR from the optical axis of the retroflector.

The modulation described will indicate the total angle $\alpha$, but does not permit resolution of this angle into its two rectangular components with respect to the target vehicle, without additional information. This may be accomplished by the addition of a signal source, such as a low-power laser diode, synchronized to flash once per revolution of the reticle, when the reticle has a predetermined orientation with respect to the target vehicle. This laser diode would be located adjacent to the semi-active retroflector. The relative roll angle, $\phi$, would be determined by reference to a second (inactive) retroflector, as in other configurations.
ARCHIMEDES SPIRAL ROTATING RETICLE

FIGURE 3-22
The accuracy of angle $\alpha$ with this configuration is independent of the range between the SLR and the target vehicle. It is a function of the lens resolution (size of laser's image), lens focal length, reticle size, reticle angular velocity, and system signal-to-noise ratio. Proper design should readily bring this accuracy, $\Delta \alpha$, well within $\pm 1.0$ degree, approaching 0.1 degree. Since this is a semi-active system, and violates the letter, if not the spirit of the restriction of passivity imposed in this section, it is not analyzed further herein. It is pointed out that very little power would be consumed in rotating the reticle and flashing the diode and this could be furnished by relatively long-life batteries, self-contained within the retroreflector assembly. No power need be supplied from the target vehicle itself. In this sense, this system would be passive, so far as the target vehicle is involved.
4.0 DESIGN

All three of the Scanning Laser Radar configurations described in Section 2.0 have a basic laser radar transmitter-receiver and associated electronics that are common or interchangeable. This section will describe in detail the design of the basic laser radar transmitter-receiver and associated electronics that are needed by all three configurations. The design is broken into major subsystems which are depicted in Figure 4-1 and described in the following sections:

4.1 Laser transmitter
4.2 Beam steerer
4.3 Receiver optics
4.4 Receiver detector
4.5 Electronics
   4.5.1 Range and timing
   4.5.2 Angle tracker
   4.5.3 Pre-amp, AGC, and threshold
   4.5.4 Multi-target Range and Angle Data Processing
4.6 Self test and automatic checkout
4.7 Mechanical
SLR BASIC BLOCK DIAGRAM

FIGURE 4-1
4-2
4.1 Laser Transmitter

For spaceborne applications, the SLR is to be a small, lightweight, low-power-consuming radar system which will be used to acquire and track cooperative-type targets. The radar transmitting source directly affects the overall size, weight, and power requirements for a given system. The single-mode GaAs semiconductor laser and the Mini-YAG laser are presently the best candidates for the spaceborne SLR. Table 4–1 is a list of preliminary size, weight, and power specifications for these two lasers.

<table>
<thead>
<tr>
<th>TABLE 4–1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESTIMATED SIZE, WEIGHT, &amp; POWER - LASER TRANSMITTER</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Single Mode GaAs Laser</th>
<th>Mini-YAG Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>2&quot; x 2&quot; x 4&quot;</td>
<td>4&quot; x 4&quot; x 10&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td>2 Pounds</td>
<td>6 Pounds</td>
</tr>
<tr>
<td>Average Power Out (TEM₀₀)</td>
<td>0.005 Watts</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>Average Power In (1% Eff)</td>
<td>0.50 Watts</td>
<td>100 Watts</td>
</tr>
<tr>
<td>Maximum Target Range*</td>
<td>≈ 30 mi.</td>
<td>≈ 90 mi.</td>
</tr>
</tbody>
</table>

*Based on 30° total field-of-view, 0.1° beam, and 2" diameter receiver optics. See Section 3.2 for target range vs. power analysis.
In order to minimize the size and simplify the beam steering optics, the laser output should be nearly diffraction-limited or in the lowest order transverse mode \( \text{TEM}_{00} \). This laser output is often referred to as the single mode. The single mode \( \text{TEM}_{00} \) will also enable one to get a far-field radiation pattern that is gaussian-shaped, a highly desirable characteristic for a radar system, because in the multimode mode case the far-field radiation pattern has peaks and valleys that can cause the return signal to vary significantly, even to the point of preventing acquisition and to cause loss of track.

Semiconductor lasers normally emit a multimode beam, however, a GaAs semiconductor laser developed by IBM has been made to operate in single mode. To get single mode operation, a GaAs laser diode that has anti-reflection coatings on two parallel surfaces is placed in an external optical resonator formed by lenses and mirrors as depicted schematically in Figure 4-2. 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 spatial modes. If the laser diode is properly aligned inside an external optical resonator, the optical resonator will allow only one transverse electromagnetic mode \( \text{TEM}_{00} \) to oscillate with high gain, thus the resulting output beam is "single mode." The single mode GaAs laser operates at room temperature without cooling. For the YAG laser, if the front and rear mirrors, optical pump, and YAG rod are properly aligned in an elliptical cavity, the "single mode" can be selected. Figure 4-3 schematically depicts the optical resonator for the YAG laser. The YAG laser used in this report is referred to as the "Mini-YAG" because it is relatively small, low-powered, and can be operated without liquid cooling. The unit can be thermal-electrically or conductively cooled.
SINGLE MODE GaAs LASER-OPTICAL RESONATOR

GaAs SEMICONDUCTOR: LASER DIODE

CROSS SECTION

SPATIAL DISTRIBUTION

I

IN

λ OUT

GaAs LASER SPECTRAL OUTPUT

EYE'S VISIBLE SPECTRUM

BLOCKING FILTER

UV BLUE GREEN RED

0.4 0.5 0.6 0.7 0.8 0.9 1.0

WAVELENGTH (µMETERS)

SINGLE MODE GaAs LASER

FIGURE 4-2
Figure 4-3. YAG Laser

- Q-Switch or Mode-Locking Device
- YAG Laser-Optical Resonator
- Optical Pump
- YAG Rod

End View

- Optical Pump
- YAG Rod

Eye's Visible Spectrum

- UV
- Blue
- Green
- Red

Wavelength (μmeters)

1.06 μm

Spatial Distribution

Cross Section

YAG Laser Spectral Output

Figure 4-3. YAG Laser
The single mode GaAs laser is average powered limited. Approximately 1.0 milliwatt is obtainable now, and 5.0 milliwatts is predicted for a couple years from now (1973). The wavelength of the GaAs laser is 0.9 micron meters which is slightly outside the visible spectrum. The rest of the pertinent performance characteristics are listed in Table 4-2. The maximum average power output of the Mini-YAG laser is presently limited to about 0.5 watts for the thermo-electric or conductive-cooled cases. Up to 1,000 watts has been obtained by the YAG laser with liquid cooling, however, for the SLR design liquid cooling is not being considered for the spaceborne applications. With future improvements in efficiency 1.0 watt output for the Mini-YAG should be obtainable in a few years. The wavelength of the YAG laser is 1.06 micron meters. Table 4-2 lists the other pertinent performance characteristics.
<table>
<thead>
<tr>
<th></th>
<th>Single Mode GaAs Laser</th>
<th>Mini-YAG Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>0.90 micron meters</td>
<td>1.06 micron meters</td>
</tr>
<tr>
<td></td>
<td>0.85 - 0.90 micron meters</td>
<td>1.06 micron meters</td>
</tr>
<tr>
<td><strong>Optical Bandwidth</strong></td>
<td>0.020 micron meters</td>
<td>0.0001 micron meters</td>
</tr>
<tr>
<td></td>
<td>0.002 micron meters</td>
<td>0.0001 micron meters</td>
</tr>
<tr>
<td><strong>Peak Power Out (TEM$_{00}$)</strong></td>
<td>2 Watts</td>
<td>(A) 500 Watts</td>
</tr>
<tr>
<td></td>
<td>5 Watts</td>
<td>(A) 1,000 Watts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 200 Watts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 400 Watts</td>
</tr>
<tr>
<td><strong>Pulse Repetition Freq.</strong></td>
<td>0 - 4 KHz</td>
<td>(A) 0 - 2 KHz</td>
</tr>
<tr>
<td></td>
<td>0 - 10 KHz</td>
<td>(A) 0 - 2 KHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 2 - 10 KHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 2 - 10 KHz</td>
</tr>
<tr>
<td><strong>Pulse Width</strong></td>
<td>50 - 200 nanoseconds</td>
<td>(A) 250 nanosec.</td>
</tr>
<tr>
<td></td>
<td>50 - 200 nanoseconds</td>
<td>(A) 200 nanosec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 500 nanosec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(B) 500 nanosec.</td>
</tr>
<tr>
<td><strong>Average Power Out (Max.)</strong></td>
<td>1.0 milliwatt</td>
<td>0.5 watt</td>
</tr>
<tr>
<td></td>
<td>5.0 milliwatts</td>
<td>1.0 watt</td>
</tr>
<tr>
<td><strong>Electro-Optical Efficiency</strong></td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
4.2 Beam Steerer

The function of the Scanning Laser Radar beamsteerer subsystem is to take a narrow laser beam (0.1°) and steer or point it over a relatively large field-of-view (30°) without the use of mechanical gimbals. The active deflecting device is a mirror mounted to piezoelectric crystals and is illustrated in Figure 4-4. These mirrors are rectangular (0.7 x 1.0 inches) and will be rotated through approximately ±0.25°. When a voltage is applied across the 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 can thus be 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. Using a diffraction-limited beam from a laser with a wavelength of 1 micron meter, and two 0.7 x 1.0 inch piezoelectric-driven mirrors that are both rotated 0 ± 0.25 degrees, one can obtain a square raster scan pattern that has better than 300 x 300 resolvable scan elements. For a 0.1° beam and 30° field-of-view a minimum of 300 x 300 scan elements are needed just to cover the full 30° field-of-view. 376 x 376 scan elements are programmed into the acquisition raster scan logic here so that a 20% overlap between adjacent scan elements is obtained.

The purpose of the beamsteerer optics is to amplify the initial beam deflection obtained by rotating a mirror ±0.25° into a ±15° beam deflection. Figure 4-5 schematically shows the beamsteerer optics and the deflection of a beam in one axis. A number of optical configurations have been considered for the beam-steerer. Most of these were refractive, and although suitable, will not be discussed here. A reflective technique was chosen because it offers:
SCHEMATIC OF BEAM STEERER OPTICS

FIGURE 4-5
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.

In Figure 4-5 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 (y) 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 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).
4.3 Receiver Optics

An optical lens is used to collect the energy from the laser radar signal that is returned by the target reflector. The lens focuses the return radar beam to a small spot on the focal plane of the lens. For each return signal the focused spot will be uniquely located at one place in the focal plane and this location will be directly proportional to a radar-to-target line-of-sight angle. Figure 4-6 is a pictorial of the receiver optics and the scanning optical detector (image dissector). Figure 4-7 is a schematic of a single element receiver lens and shows the basic correlation between the line-of-sight and the location of the focused spot at the focal plane. A multi-element lens assembly is used in the SLR receiver because good off-axis resolution and high speed (low f#) are needed. A 50 mm f/1.0 lens has been selected to image the $30^\circ$ 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. To maximize the transmission the optical components should have anti-reflective coatings.

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 can potentially be a large noise contributor, especially for a sunlit cloud background. Figure 4-8 graphically shows the sensitivity of the narrow passband optical filter as a function of wavelength. The bandwidth of each envelope is approximately $200 \, \text{Å}$ and they are centered at the wavelength of the GaAs laser ($0.9$ micron meters) and the YAG laser ($1.06$ micron meters). A $200 \, \text{Å}$ optical bandwidth is needed for the narrow passband optical filter even though the optical bandwidths of either laser is considerably less than $200 \, \text{Å}$. The $200 \, \text{Å}$ is needed because the filter must pass the return signal $\pm 15^\circ$ off the boresight axis, and if the filter bandwidth was less than $200 \, \text{Å}$ the off-axis shift in wavelength would reduce the effective signal transmission severely.
RECEIVER OPTICS AND SCANNING OPTICAL DETECTOR
(IMAGE DISSECTOR)

FIGURE 4-6
Linear displacement is directly proportional to incoming line-of-sight angle $\theta$. 

**Simplified Receiver Lens Schematic - Angle Correlation** 

**Figure 4-7**
RELATIVE SENSITIVITY (ARBITRARY SCALE)

OPTICAL FILTER ENVELOPE

YAG LASER RADIATION

GaAs LASER RADIATION

DETECTOR SENSITIVITY (S-1 PHOTOCATHODE)

NARROW BAND OPTICAL FILTER

WAVELENGTH $\lambda$ ($\mu$ METERS)

NARROW BAND OPTICAL FILTER

FIGURE 4-8
4.4 Receiver Detector (Image Dissector)

The component in the SLR receiver that detects the return signal is a scanning optical detector or "image dissector." It converts the optical (laser) energy to electrical energy and measures the amplitude and angular direction of the return signal. 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 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. Figure 4-9 shows electro-optical sketches of the TV-image dissector analogy.

Two significant advantages are obtained by only looking at or measuring the current from only one small spot on the photocathode. The entire background in the optical field-of-view will be imaged on the detector area, therefore, the background noise will be a function of the detector area sensed. Since the
TELEVISION-IMAGE DISSECTOR ANALOGY

FIGURE 4-9
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 be noted that the image dissector is a non-storage device, allowing random or variable scan rates without changes in signal amplitude.

For the SLR configuration described in this study, an image dissector with a 1.0 inch diameter photocathode (ITT F4011) and a central or instantaneous aperture of 0.0035 inches is chosen. The 30° total 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) and the YAG (1.06 micron meters) laser radiation. The average S-1 photocathode has a sensitivity of 0.006 amps/watt at 0.9 micron meters and 0.002 amps/watt at 1.06 micron meters. The dark current for the S-1 photocathode is typically $1 \times 10^{-12}$ amps/watt per cm$^2$ 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 typically set at $1 \times 10^5$. Figure 4-10 is an outline drawing and electrical schematic of an F4011 image dissector. The image dissector signal output will be a current pulse with approximately the same waveform as the incoming laser pulse. The peak level will be in the microampere range. This will be 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.
Photocathode External Lead Extends 2 Inches Beyond Tube Base, .005 x .040 Nickel Ribbon Covered with Mystic No. 7505 Teflon Tape.
4.5 **Electronics**

The Scanning Laser Radar system performs all the control, detection, timing, and data processing electronically without the aid of an operator. When the system is turned on, it immediately and automatically goes into the acquisition scan mode. A $30^\circ \times 30^\circ$ field-of-view is searched and, if a target is detected, the SLR automatically switches over to the track scan mode. The target is continuously tracked anywhere in the $30^\circ \times 30^\circ$ field-of-view. Target range and line-of-sight angle measurements are available in a digital format at a data rate of approximately 10-100 per second depending on the radar pulse repetition rate and scan rate. The SLR electronically steers or points a narrow angle (0.1 degree) laser beam over the $30^\circ \times 30^\circ$ FOV. The laser is pulsed (1-10 KHz) and has a pulse width of 50-200 nanoseconds. The timing and range resolution is 0.1 meters and the angle resolution is approximately 0.01 degrees.

The SLR electronics are almost entirely digital except for the beam deflector driver, the image dissector deflection driver, detector preamplifier, and the power converters. Figure 4-1 shows the major parts of the electronics, each of these will be described in the following sections.
4.5.1 Range and Timing Electronics

The digital 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 4-11 is a basic block diagram of the range and timing electronics that will be used here to 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 1.00000 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 1 KHz 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 "8" 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
Basic Block Diagram of Range and Timing Electronics

Figure 4-11
effectively have its frequency increased. The output 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 4-12. 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 m 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. Individual range readings are sent to the Range Adder and Accumulator, where smoothed range readings are generated. Range rate is determined by taking the range difference between two range readings and dividing by the precise time between the readings.

To count range directly a frequency of 1498.964 MHz must be counted. No known integrated circuit can count at this speed, but a frequency eight times lower (187.3705 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 4-13 is a detailed block diagram of the range and timing circuitry. The start of each line is driven in parallel by a master oscillator at 187.3705 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
RETURN

RADAR SIGNAL

NO RETURN

RETURN

MASTER CLOCK

STRIPLINE
DELAY LINE

GATES

RANGE BIN

SIMPLIFIED EXAMPLE OF PHASE SHIFTING
THE MASTER CLOCK

FIGURE 4-12
FIGURE 4-13

DETAILED BLOCK DIAGRAM OF THE RANGE AND TIMING ELECTRONICS
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 4-13, 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 \( \frac{1}{8} \) of the 187.3705 MHz cycle time. The 4 RS flip flop outputs can be decoded into 3 binary bits, which is the divide by eight required to resolve 1498.964 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 (FR1-FR6) and the corresponding Master Range Counter (MR1-MR15) is also depicted in Figure 4-13. Figure 4-14 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 (RS0-23). 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) 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.
.1 Nsec Delay Line
.767 Nsec Delay Line
1.434 Nsec Delay Line
2.101 Nsec
2.768 Nsec
3.435 Nsec
4.102 Nsec
4.769 Nsec

FS1
FS2
FS3
FS4

FR1 = (FS1 - FS2) + (FS3 - FS4) + (FS1 - FS2) + (FS3 - FS4)
FR2 = (FS2 - FS4) + (FS2 - FS4)
FR3 = FS4
FR4
FR5
FR6 → START RANGE COUNT

RANGE RETURN
RANGE = 3.5 METERS

RANGE AND TIMING WAVEFORMS

FIGURE 4-1A
The total system timing is controlled from the 187.3705 MHz master oscillator. This oscillator is a Motorola MECL III 4 input gate with a delay line from the inverting output back to one input. The total propagation 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. 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.

Residual errors in range measurements arise from two sources: 1) quantization error, and 2) errors introduced by noise at the threshold detector. Quantization error refers specifically to those errors which arise due to the finite range bins within which range measurements will yield the same value. The length $\Delta R$ of these bins is simply:

$$\Delta R = \frac{cT}{2n} = \frac{c\Delta T}{2}$$  \hspace{1cm} (4-1)$$

where $c$ is the velocity of light, $T$ is the period between pulses, $n$ is the number
of time increments into which the period $T$ has been divided through the use of delay line taps, and $T$ is the length of the individual time increments. Quantization error can be minimized by assuming that the actual time of detection $t_d$ occurred when the clock pulse leading edge was in the exact center of the delay line section following the last tap at which the clock pulse was observed. In other words, this error will be minimized if it is assumed that:

$$t_d = t_i + \frac{1}{2} \Delta t$$  \hspace{1cm} (4-2)

where $t_i$ denotes the time indicated by the last delay line tap to sense the presence of a clock pulse at the instant at which the echo pulse was detected.

Figure 4-15(a) shows a plot of quantization error $\epsilon_q$ as a function of the actual detection time after the beginning of the interval. Under the above assumption the peak quantization error will be $1/2 \Delta t$ corresponding to an error in range of $1/2 \Delta R$, which in this system is 5 centimeters. The rms quantization error $\epsilon_q$ will be

$$\bar{\epsilon}_q = \lim_{\xi \to \infty} \left[ \frac{1}{2} \xi \int_{-\xi}^{\xi} \epsilon^2_q(t) \, dt \right]^{1/2}$$  \hspace{1cm} (4-3)

Since $\epsilon_q(t)$ is repetitive, Equation (4-3) simplifies to

$$\bar{\epsilon}_q = \left[ \frac{1}{\Delta t} \int_{-1/2 \Delta t}^{1/2 \Delta t} \epsilon^2_q(t) \, dt \right]^{1/2}$$

which gives

$$\epsilon_q = \sqrt{\frac{3}{6} \Delta t}$$  \hspace{1cm} (4-4)
QUANTIZATION ERROR $\epsilon_q$ VERSUS TIME $\tau$ OF ACTUAL DETECTION

FIGURE 4-15(a)
Since $\Delta t = 0.667$ nanosecond for the SIR system, Equation (4-4) yields

$$\bar{\epsilon}_q = 0.192 \text{ nanoseconds},$$

Corresponding to a round-trip rms range error of 0.289 centimeter.

Let us now consider the effect of noise upon the accuracy of a range measurement. The presence of noise superposed upon the received pulse will introduce a Gaussian uncertainty as to the time that the threshold detector will sense the leading edge of the pulse. This effect exists due to the finite rise time of the pulse at the input of the detector. If we denote the slope of the leading edge of a received signal pulse at the threshold level of the detector as $\frac{dI_s}{dt}$ and the one-sigma value of the superposed noise current as $i_n$, the one-sigma uncertainty in the detection time of the received pulse will be

$$\sigma_t = \frac{i_n}{\frac{dI_s}{dt}} \quad (4-5)$$

Figure 4-15(b) illustrates this transformation of noise into time jitter around the leading edge of the received echo pulse. With a rise time of 20 nanoseconds and a peak signal-to-rms noise ratio of approximately 100:1, the range measurement can be made accurate to $\pm 10 \text{ cm}$ (3 $\sigma$).
The Effects of Gaussian Noise Upon Range Measurements

Figure 4-15(b)
4.5.2 Angle Tracker Electronics

The 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, described in Section 2.0, are scanned about the total $30^\circ \times 30^\circ$ FOV by piezoelectric beam deflectors in the transmitter and by an electromagnetic field deflecting the electron beam in the image dissector at the receiver.

The angular deflection of the beam deflectors is proportional to the voltage applied to the piezoelectric element and the angular deflection of the 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 4-16) and the detailed block diagram (Figure 4-17) 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. The least significant bit of the track counter represents $0.0025^\circ$ and the most significant bit of the acquisition counter represents $20.48^\circ$; 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 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
DEFLECTION COUNTER

CLOCK PULSE

ACQ.-TRACK MODE CONTROL

TRACK-ACQ. CONTROL COUNTER

VELOCITY COUNTER

POSITION COUNTER

TRACKING COUNTER CONTROL

TRACKING COUNTER

ACQUISITION COUNTER CONTROL

ACQUISITION COUNTER

VELOCITY ACCUMULATOR

ANGLE READOUT CONTROL

ANGLE RATE READOUT

ANGLE READOUT

IMAG DISSECTOR

SCANNED BEAM

TARGET

LASER

BEAM DEFLECTOR DRIVER

BEAM DEFLECTOR

MODULATOR INPUT

D/A

D/A

DEFLECTION COIL DRIVER

SIMPLIFIED BLOCK DIAGRAM OF THE ANGLE TRACKER ELECTRONICS

FIGURE 4-16

4-35
DETAILED BLOCK DIAGRAM OF THE ANGLE TRACKER ELECTRONICS

FIGURE 4-17
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.

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

The diagrams in Figure 4-18(a) and (b) 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, one to determine the up or down mode of count, and one to determine the field mode. 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. A diagram of the acquisition scan waveforms and field patterns is shown in Figure 4-19.
ACQUISITION MODE

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

SCAN PATTERN FOR ACQUISITION MODE

FIGURE 4-18(a)

TRACK MODE

SEE FIGURE 4-21 FOR DETAILS OF SCAN

SCAN PATTERN FOR TRACK MODE

FIGURE 4-18(b)
ACQUISITION SCAN PATTERN AND WAVEFORMS

FIGURE 4-19
The acquisition scan pattern continues element by element line by line and field by field until a target is recognized in one of the elements of the acquisition scan. If the 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.

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. Since, if a target has been confirmed or tracked, the target’s position in the 30° x 30° field-of-view is known to within ±0.08°. A smaller acquisition scan consisting of 16 lines per field and four fields (each field being 1.28° by 1.28°) is scanned about the last known position of the target. This mini scan takes approximately 1.0 second 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° by 30° acquisition scan. A limited acquisition control circuit shown in the lower left of Figure 4-17 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° x 30° 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° x 30° 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.

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 counter. The up-down mode control for the acquisition counters is taken from the track 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 4-17 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 4-20. 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 4-21.

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
NOT REPRODUCIBLE

ACQ. CP

VIDEO RETURN

TRACK MODE

CA4

CA5

CA6

VERT MODE

+ VERT SCAN  - VERT SCAN

VELOCITY  POSITION, READOUT  + VERT SCAN

VERT ANGLE CORRECTION

HOR MODE

VELOCITY  POSITION, READOUT  + HOR SCAN  - HOR SCAN  VELOCITY

HOR ANGLE CORRECTION

VERT SCAN

APERTURE EDGE

-(IX.0025°) Vert  VEL. CORR.  -(IX.0025°) Hor  POS. CORR.

HOR SCAN

APERTURE EDGE

TRACK SCAN WAVEFORMS

FIGURE 4-20
DETAILED SCAN PATTERN AND SEQUENCE FOR TRACK MODE

**FIGURE 4-21**

4-43
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 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, 4 more returns would be received while the aperture was above center than while below center. If there were 2 track steps above the center, 8 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 4-17. 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 counters 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 4-20. 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, so that the aperture would now be center 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 (AS0-AS15) shown in Figure 4-17, 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.
4.5.3 Pre-Amplifier, Automatic Gain Control and Threshold Circuits

The video signal amplifier for the image dissector anode load to the logic circuit inputs consists of a two-stage transistor preamplifier, 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 the circuit has an overall small signal gain of 50,000. The amplifier circuits are shown in the upper left of Figure 4-13.

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 signal 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 attenuator 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 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.
4.5.4 **Multi-Target Range and Angle Data Processing**

Tracking a multi-target corner reflector array on the target vehicle in order to determine the target vehicle's attitude in relation to the chaser vehicle requires additional circuitry to accumulate and compare the various targets' line-of-sight angles and range information. After acquisition, each target's angular location in the overall field-of-view must be accurate and available to quickly change the track scan from one target's location to another in order to update each target's stored location as fast as possible. Figure 4-22, a block diagram of the Multi-Target Control, shows the additional basic ranging and tracking circuits required.

A target control system is required to determine which target of the array is being tracked in order to control the accumulation of target range and angle data into the proper registers and to determine the time period and sequence of acquisition and tracking of each target. Target angle and range data comparison circuits are required to process the various target's range and angle data in order to obtain information for the target control circuits and to process the angle and range data for the target vehicle's attitude. Angle and range accumulator control systems and accumulators are used to store the target's data and to perform arithmetic operations on the data. About 75% of the data processing circuitry can be shift register integrated circuit modules and the balance can be gate modules.

The range and angle data outputs for guidance control are binary numbers shifted out serially with the least significant bit first.
VERT & HOR A1 - A9
VERT & HOR T1 - T5

ANGLE SHIFT REGISTER
(AS0 - AS15)
See Fig. 4-17

ANGLE ACCUMULATOR
CONTROL GATES

VERT ANGLE TARGET #1
ACCUMULATOR

HOR ANGLE TARGET #1
ACCUMULATOR

VERT ANGLE TARGET #2
ACCUMULATOR

HOR ANGLE TARGET #2
ACCUMULATOR

VERT ANGLE TARGET #3
ACCUMULATOR

HOR ANGLE TARGET #3
ACCUMULATOR

VERT ANGLE LOAD REGISTER

VERT TRACK-ACQ. COUNTER
VT1 - VT5  VA1 - A9
See Fig. 4-17

MR1 - MR15
FR1 - FR6

RANGE SHIFT REGISTER
(RS0 - RS23)
See Fig. 4-17

RANGE ACCUMULATOR
CONTROL GATES

RANGE TARGET #1
ACCUMULATOR

RANGE TARGET #2
ACCUMULATOR

RANGE TARGET #3
ACCUMULATOR

RANGE & ANGLE
COMPARISON
CIRCUITS

TARGET CONTROL SYSTEM

HOR ANGLE LOAD REGISTER

HOR TRACK-ACQ. COUNTER
HT1 - T5  VA1 - A9
See Fig. 4-17

FIGURE 4-22. BLOCK DIAGRAM - MULTI-TARGET CONTROL
4-51
A tabulation of the bit values in range and angle are listed below:

<table>
<thead>
<tr>
<th>BIT #</th>
<th>RANGE</th>
<th>ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00625 Meters</td>
<td>0.0025 Degrees</td>
</tr>
<tr>
<td>2</td>
<td>0.0125</td>
<td>0.005</td>
</tr>
<tr>
<td>3</td>
<td>0.025</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>0.2</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>0.16</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
<td>0.32</td>
</tr>
<tr>
<td>9</td>
<td>1.6</td>
<td>0.64</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>1.28</td>
</tr>
<tr>
<td>11</td>
<td>6.4</td>
<td>2.56</td>
</tr>
<tr>
<td>12</td>
<td>12.8</td>
<td>5.12</td>
</tr>
<tr>
<td>13</td>
<td>25.6</td>
<td>10.24</td>
</tr>
<tr>
<td>14</td>
<td>51.2</td>
<td>20.48</td>
</tr>
<tr>
<td>15</td>
<td>102.4</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>204.8</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>409.6</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>819.2</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1638.4</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3276.8</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>6553.6</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>13107.2</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>26214.4</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>52428.8</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>104857.6</td>
<td></td>
</tr>
</tbody>
</table>
4.6 Self Test and Automatic Checkout

All of the logic circuits of the ranging and tracking system, the readouts and logic signal to the guidance computer can readily be checked by replacing the video return pulse with pulses of known timing from the system master time counter to produce known range, range rate, angle and angle rate readouts. Substituting known fixed delays in the video return pulse and checking the range reading for the various delays will also check the master time counter and the frequency of the system master oscillator. These tests check the operation of the system except for the optical portion. The optical pick-off of the laser transmit pulse provides a constant monitoring of the laser transmitted power. A small folded optical path as shown in Figure 4-23 can be used to check the optical portion of the system. A folding 45° calibration mirror deflects the transmitted beam into a folded optical path to a small corner reflector at a known range and angle from the system boresight. The return pulse from is reflected back along the same folded optical path to the receiver. The system will read out the range and angle position of the corner reflector and can be compared to the known range and angle position.
SELF-TEST AND AUTOMATIC CHECKOUT OF THE SLR TRANSMITTER-RECEIVER

FIGURE 4-23
4.7 Mechanical Packaging

The packaging chosen for the Scanning Laser Radar separates the transmitter-receiver and the electronics. The transmitter-receiver head contains a complete laser transmitter subsystem and a complete receiver subsystem.

The transmitter-receiver head contains both the transmitting and receiving elements, the laser itself, the beam steering system, plus all associated optics. Figure 4-24 is an artist conception of the transmitter-receiver.

The design philosophy uses a brazed structure as the "backbone" of the head. An aluminum tube will house the image dissector, its coils, and the receiver optics. This tube will be brazed to a plate. This combination will be an extremely rigid structure. The plate will be utilized as an optical bench upon which the laser and all optical components are mounted. The upper surface of the plate will be machined flat, and will be parallel to the axis of the image dissector tube. The laser mounts to one end of the plate. Those optical components defining the path of the laser beam will be pin located and securely clamped in position.

The beam steerer assembly will be securely mounted at the front end of the plate. The laser beam leaving this assembly will be diverted to a spider-mounted mirror/exit lens assembly mounted in front of the receiver lens. This provides a coaxial system. The head will be enclosed by an easily removable case on all sides. Appropriate mounting points for the external interfaces can be provided.

The second package contains all the associated electronics for the system. All components will be board-mounted and capable of withstanding a rugged environment.
ARTIST CONCEPTION OF RADAR TRANSMITTER-RECEIVER AND THE ASSOCIATED ELECTRONICS PACKAGE

FIGURE 4-24
5.0 SPACE QUALIFICATION CONSIDERATIONS

Defining and implementing a hardware program necessary to space qualify a Scanning Laser Radar for use on future vehicles such as the NASA Space Shuttle, Space Station, Research Application Modules, etc., requires detailed specifications and requirements that are not presently available. However, assuming that the basic operating and performance characteristics of the Scanning Laser Radar described in this report are generally acceptable and would meet the requirements of a given space vehicle, then the following items can be used as guidelines for developing a space-qualified Scanning Laser Radar:

(A) Hardware subsystems and components that are potentially the best candidates for a space-qualified Scanning Laser Radar are:

(1) LASER TRANSMITTER

Single mode GaAs Laser and/or Mini-YAG Laser. The single mode GaAs Laser is presently under development at IBM and is expected to be space qualified as a component by 1973-74. Due to the precision alignment necessary for this laser, mechanical stability will be the biggest problem to overcome. Mini-YAG lasers have been built by numerous companies (Sylvania, T.I., IBM, Hadron, Holobeam, etc.) and developmental work to improve the optical pumping sources (lamps and light-emitting diodes) has increased significantly in the last year. The YAG Laser is being considered for both spaceborne communications and radar applications and new programs to build a small, lightweight, low-power-consuming YAG laser are presently under consideration. Poor electro-to-optical efficiency and lifetime of the pump source are the major problem areas for this laser.
(2) **BEAM STEERER**

The piezoelectric beam deflector is presently being space qualified by GT&E under contract to NASA. Drift in the relative mirror-position readout due to time and temperature is the major problem area for this device. Recently developed acousto-optical beam deflectors offer higher scan rates than the piezoelectric-driven mirror approach and further investigation into this beam deflector should be made.

(3) **RECEIVER OPTICS**

Off-the-shelf lens such as the Angenieux 50 mm f/0.95 is a reasonable good receiver for laboratory models of the Scanning Laser Radar, however a custom-designed receiver lens will probably have to be designed and built for the space-qualified system. Building high quality and rugged optics for this application should present no major problems because considerable hardware experience has been accumulated in similar receiver optics for spaceborne star trackers.

(4) **RECEIVER DETECTOR**

The ITT F4011 image dissector is an off-the-shelf receiver detector that is a large version of the F4012 which already is space qualified. There should be no problems in space qualifying the F4011.
ELECTRONIC COMPONENTS

The electronic circuitry for the Scanning Laser Radar is made up almost entirely of digital integrated circuits of the following types:

MECL III 1600 Series
SN 74L00
SN 74L04
SN 74L10
SN 74L20
SN 74L30
SN 74L72
SN 74L73
SN 74L78
SN 74L95
SN 7401
SN 7480

No major problems are expected in using these or equivalent types in spaceborne applications.

System and subsystem performance characteristics that should have a detailed performance analysis prior to and/or during the building of a space-qualified Scanning Laser Radar are:

1. Maximum and minimum target range
2. Range accuracy
3. Maximum range-rate
4. Range-rate accuracy
5. Acquisition and tracking-rate capability (for all possible target trajectory conditions).
(6) Angle accuracy
(7) Angle-rate accuracy
(8) Radial alignment accuracy for docking
(9) Lateral and translational velocity accuracy for docking
(10) Accuracy of determining target attitude
(11) Bright object background effects (i.e., How close can the sun be to the optical field-of-view?).
(12) Alignment and long-term repeatability of the synchronously-scanned transmitter-receiver over the full 30° x 30° FOV.
(13) System MTBF

(C) A computerized math model of the Scanning Laser Radar should be implemented for determining the dynamic range and angle accuracies for all operating conditions.

(D) A reliability and parts qualification should be implemented for the following critical subsystems or components:

(1) Laser (Single mode GaAs or Mini-YAG)
(2) Beam steerer (piezoelectric beam deflector and associated optics).
(3) Receiver optics
(4) Receiver detector (image dissector)

(E) Dynamic tests on the finalized engineering model of the space-qualified Scanning Laser Radar should be performed on rendezvous and docking simulators that are similar or equivalent to the spaceborne simulators at

(1) Martin Marietta (Denver)
(2) NASA/Langley Research Center
(3) NASA/Manned Spacecraft Center
The primary objective of the test program should be to collect acquisition, tracking, and precision docking test data on the Scanning Laser Radar under dynamic test conditions. A cooperative optical target should be mounted on a movable platform (Rendezvous and Docking Simulator) and should be moved into and through the field-of-view of the Scanning Laser Radar. The target motions should be computer-controlled such that the line-of-sight velocities and accelerations can be programmed for various acquisition and tracking tests. Representative "docking" type tests should be performed to evaluate the Scanning Laser Radar in a closed loop control system. Target simulator data and radar data should be monitored simultaneously in real-time so that dynamic accuracies can be determined. A digital computer should be 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
(4) Use the radar data, after target acquisition, in a real-time closed loop control system to control the relative position and attitude between the target and the radar.
(5) Plot the test data
(F) Major interfaces that the Scanning Laser Radar must concern itself with are:

(1) Electrical (power and external control)
(2) Data (transfer of SLR data to vehicle computer)
(3) Mechanical (mounting of SLR with respect to the docking axis and with respect to any rocket plumes)

(G) Based on a 1972 technology base, it is estimated that it will require approximately 2-1/2 years to space qualify the Scanning Laser Radar.